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Climate change impact on Sub-Saharan Africa? An overview and analysis of scenarios and models

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Abbreviations

A1	A SRES scenario (see Table 1)
A1B	A SRES sub-scenario (see Table 1)
A1C	A SRES sub-scenario (see Table 1)
A1F1	A SRES sub-scenario (see Table 1)
A1G	A SRES sub-scenario (see Table 1)
A1T	A SRES sub-scenario (see Table 1)
A2	A SRES scenario (see Table 1)
AGCM	Atmosphere General Circulation Model
AOGCM	Atmosphere-Ocean General Circulation Model
B1	A SRES scenario (see Table 1)
B2	A SRES scenario (see Table 1)
BCC-CM1	A climate model (see Table 2)
BCCR-BCM2.0	A climate model (see Table 2)
CCSM3	A climate model (see Table 2)
CGCM3.1	A climate model (see Table 2)
CMAP	A precipitation data set
CMIP3	Coupled Model Intercomparison Project Phase 3
CNRM-CM3	A climate model (see Table 2)
CSIRO-MK3.0	A climate model (see Table 2)
CO_2	Carbon dioxide
C3	A carbon fixation mechanism in photosynthesis
C4	A carbon fixation mechanism in photosynthesis
DJF	December, January, February
DSSAT	Decision Support System for Agrotechnology Transfer
EAF	East Africa
ECHAM5/MPI-OM	A climate model (seeTable 2)
ECHO-G	A climate model (see Table 2)
EMIC	Earth System Model of Intermediate Complexity
ENSO	El-Niño Southern Oscillation
EPIC	Erosion Productivity Impact Calculator
FACE	Free Air Carbon Enrichment
FGOALS-g1.0	A climate model (see Table 2)
GAEZ	Global Agro-Ecological Zones
GCM	General Circulation Model
GDP	Gross Domestic Product
GFDL-CM2.0	A climate model (see Table 2)
GFDL-CM2.1	A climate model (see Table 2)
GHG	Greenhouse Gas
GISS-AOM	A climate model (see Table 2)
GISS-EH	A climate model (see Table 2)
GISS-ER	A climate model (see Table 2)
hPa	Hectopascal (10^2 Pa)
IETC	International Environmental Technology Centre
INM-CM3.0	A climate model (see Table 2)

ITCZ	Inter-Tropical Convergence Zone
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM4	A climate model (see Table 2)
JJA	June, July, August
km	Kilometer(s)
MAM	March, April, May
MIROC3.2	A climate model (see Table 2)
MRI-CGCM2.3.2	A climate model (see Table 2)
MtC	Million tonnes of Carbon equivalent
NAO	North Atlantic Oscillation
PCM	A climate model (see Table 2)
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RCM	Regional Climate Model
SAF	Southern Africa
SON	September, October, November
SRES	Special Report on Emission Scenarios
SST	Sea Surface Temperature
UKMO-HadCM3	A climate model (see Table 2)
UKMO-HadGEM1	A climate model (see Table 2)
UNEP	United Nations Environment Programme
WAF	West Africa
WCRP	World Climate Research Programme
WRI	World Resources Institute

Summary

Significant climate change is expected over the 21st century; it will affect ecosystems and access to natural resources such as fertile land and water. Regions with low adaptive capacity due to poverty, lack of infrastructure, services, and appropriate governance will be most severely affected. Sub-Saharan Africa is, due to its low economic development and the diversity of local conditions, a region that needs special attention in developing adaptation strategies.

Climate impacts and the adaptive capacity of societies determine their vulnerability to climate change. The extent of climate change and spatial patterns of impacts are, however, highly uncertain. This report supplies background knowledge on climate change in sub-Saharan Africa, including uncertainties and basic assumptions of climate change projections. Impact studies are only roughly summarized here, as a systematic evaluation of the wealth of specific case studies available would by far exceed the scope of this report.

Climate will change in the future, driven by human emissions of greenhouse gases (GHGs), among which carbon dioxide (CO_2) is the most important and most prominent. Assessing future climate change is very uncertain for the following reasons:

- Future changes in drivers of climate change are uncertain, a circumstance usually addressed by employing different scenarios on GHG emissions (see Section 2.1);
- due to their high complexity, climate models can offer no more than reduced representations of the climate system, which is also not fully understood in terms of all mechanisms (see Section 2.2); and
- several feedbacks exist between climate change and its drivers, e. g. the impact on agricultural production, which affects land requirements for agricultural production, and these in turn drive land-use and land-cover change, a driver of climate change.

Most climate models are able to reproduce observed African climate in its general patterns (i. e. overall trends, large-scale spatial patterns), but they often display strong deviations on the more detailed level: average temperatures are too cool in most reference simulations (reproduction of observed historic climate), and annual and seasonal precipitation simulations sometimes deviate strongly from observations (see Table 3). Also, simulated rainfall intensities typically indicate too many days with light precipitation and too few heavy precipitation events. Research on more specific aspects of African climate, such as climate extremes, is limited and often highly uncertain. E. g. projections on changes in monsoon patterns and cyclones are too uncertain to allow for general conclusions. Despite these deviations and some systematic errors in reproducing observed climate patterns, climate models reproduce the observed climate trend at the continental and regional scale reasonably well. Climate projections can therefore be employed to assess the range of possible future climate change, keeping in mind the shortcomings of climate projections for Africa, and in general.

Downscaling projections of coarse climate models for assessments of regional and local climate change impacts adds to the overall uncertainty in climate change projections. This is especially true for Africa, where the climate observation network is not as dense as in other continents (see e. g. Figure 4), because downscaling methods require high-resolution reference data. Besides, downscaled regional climate data are less easily accessible and often only selected scenarios and time slices are available.

Climate change projections for Africa agree that Africa will experience a strong warming trend over the 21st century (roughly +2.0 to +4.5°C by 2100 in sub-Saharan Africa), which is expected to be stronger than the global average. Most climate models agree on the spatial pattern of temperature change in Africa (with the strongest warming in the Sahara region and southern Africa), although the magnitudes of temperature change projections differ considerably (see e. g. Figure 7). Projections of changes in precipitation patterns are less uniform among climate models. Even when considering only one driving emission scenario, there is, for almost every region in Africa, at least one climate model that projects an increase in precipitation and at least one that projects a decrease (see e. g. Figure 9). No focal area for climate change impact analyses can be identified from available climate change projections: all regions are expected to warm over the 21st century, and almost all will in all likelihood experience declining precipitation (see e. g. Table 4).

Climate projections and the underlying emission scenarios are highly uncertain, while general impact assessments are still largely lacking. Impacts of climate change have not been systematically evaluated yet and overviews of climate change impacts are typically based on a collection of case studies. These case studies typically differ in terms of basic assumptions as well as of cultural, social, and environmental conditions and are thus hard to compare or generalize. Large-scale studies on the other hand may fail to provide sufficient accuracy at the local level. For assessments of vulnerability and political advice, these gaps need to be bridged with general assumptions. Quantitative impact studies are not broadly available – and when they are, they only consider a small selection of scenarios, use general assumptions on climate change or stylized climate scenarios (see Section 3).

There is little consistency between different studies on time frame and coverage of climate projection uncertainty. Often studies address either short-term changes (up to 2020/2030), mid-term changes (2040–2050), and/or long-term changes (2080–2100), but there usually is no justification for the time frame selected.

Climate change impacts on agriculture at larger scales are usually assessed with statistical or econometric means deduced from changes in vegetation period or with the GAEZ model, a simplified crop model driven by a comprehensive database on climate, soil properties, and management. Smaller-scale assessments usually address very specific conditions and employ more detailed crop growth models such as DSSAT, EPIC, or many other field-scale crop models. There have been several attempts to apply detailed crop growth models at the global scale, but these are still in their infancy and no future projections are available yet.

Assessments of water stress often only consider surface water availability per capita, neglecting water quality, water demand, direct utilization of rainfall for plant growth, and the possibility of technical adaptation measures. Especially in African agriculture, measures of soil water conservation and rain water harvest yield some potential to mitigate water shortages.

In spite of all the uncertainties in climate change and impact projections, there is a broad consensus that Africa in particular will experience severe climate change. Even though the local specifics are uncertain, the likelihood of severe changes is too risky to ignore.

Adaptation strategies should therefore not be motivated by specific impact projections of climate change but could focus on vulnerabilities instead. Consequently, production systems and households should seek to become less dependent on environmental conditions (such as climate) and more flexible through diversification of income.

The large uncertainty in climate change projections and the lack of comprehensive impact studies for Africa strongly hamper any assessment of vulnerability to climate change in Africa. The broad variety of climate projections, considering all models and driving scenarios, cannot possibly be considered in its full breadth in smaller impact research projects. Data availability already limits the choice of emission-scenario-climate-model combinations, but not enough to circumvent a selection of data sets. Knowledge on climate change impacts, on the other hand, is currently too limited to allow for a comprehensive assessment of vulnerability to climate change. There are, however, several approaches to dealing with these constraints:

- In order to reduce the number of climate projections, a subset of scenarios could be selected with the objective of covering the full range of climate projections. This approach focuses by definition on extreme scenarios. Alternatively, multi-model averages could be considered as “consensus projections”, but these tend to be moderate, because extremes cancel out. This is especially problematic for precipitation projections, where patterns may differ markedly (see Section 2.3.2).
- On top of these difficulties in dealing with uncertainty, climate projections are often unable to provide the detail needed for impact assessments. Weather extremes can e. g. not be projected sufficiently accurately to assess the impact of extreme, harvest-devastating and soil-eroding precipitation events. A typical approach for dealing with these shortcomings as well as with uncertainty is the use of general assumptions. This is a traditional approach in constructing scenarios: the uncertainty that cannot be sufficiently accurately projected (e. g. future energy consumption and the energy mix in the SRES scenarios, see Section 2.1) is represented by different plausible assumptions. Falling back on assumptions even though quantitative projections are available is justified because the uncertainty cannot be handled quantitatively and because sufficient detail is not available. Available climate projections should be used, however, to define the assumptions, e. g. the range of possible changes in temperatures and precipitation, an increased likelihood of extremes due to more energy in the atmosphere, etc.
- As a third alternative, vulnerability assessments could also put climate change with all its uncertainty at the end of the analysis chain. With detailed knowledge about current systems, dangerous climate change could be defined in terms of its potential damage to these systems. Thresholds between tolerable and dangerous climate change defined in such a way could then be compared with their likelihood of occurrence in different climate change scenarios. This would avoid analyzing the entire breadth of climate change projections for sub-Saharan Africa and would make it possible to focus on specific regions where knowledge about vulnerabilities is available.

It is very hard to quantify climate change impacts explicitly in spatial terms, given the uncertainty in economic development and energy production and consumption, as well as in climate projections for specific emission scenarios. On top of that, there is considerable uncertainty in impact assessments, as e. g. in the case of the controversy over the effects of CO_2 fertilization in agricultural production.

Climate change projections for Africa are very uncertain, especially concerning local and temporal details. For impact and vulnerability assessments, they can thus only provide an indication of the range of possible climate changes.

In the foreseeable future, impact assessments will have to rely heavily on assumptions about drivers (such as emission scenarios or climate change) and the systems' response (e. g. a system's flexibility to adapt land-use patterns, or technological change). Modelling tools can help to maintain consistency in assumptions and to analyze the systematic consequences of these assumptions. However, models have to strongly reduce the system's complexity, which has the potential to heavily affect the system's response. Model improvements will make up for some of the current deficiencies, but assessments of impacts and vulnerability should always be only model-supported, not model-based.

1 Introduction

Significant climate change is expected over the 21st century, and it will affect ecosystems and access to natural resources such as fertile land and water (IPCC 2007a). Regions with low adaptive capacity due to poverty, lack of infrastructure, services, and appropriate governance will be most severely affected. Sub-Saharan Africa is, due to its low level of economic development and the diversity of local conditions there, a region that needs special attention in developing adaptation strategies.

Climate impacts and the adaptive capacity of societies determine their vulnerability to climate change. The extent of climate change and spatial patterns of impacts are, however, highly uncertain. This report focuses on climate projections, which are the basis for all climate impact studies. It gives consideration to emission scenarios as main drivers of climate models (Section 2.1) as well as to differences in climate projections due to uncertainties in climate models (Section 2.2). Section 2.3 discusses climate projections for sub-Saharan Africa as well as downscaling methods. Section 3 gives a rough overview of impact studies, including agriculture, water availability, and ecosystems. Section 4 concludes by discussing gaps and uncertainties in climate projections and impact studies (Section 4.1) as well as the policy relevancy of climate change and impact projections under given uncertainties (Section 4.3).

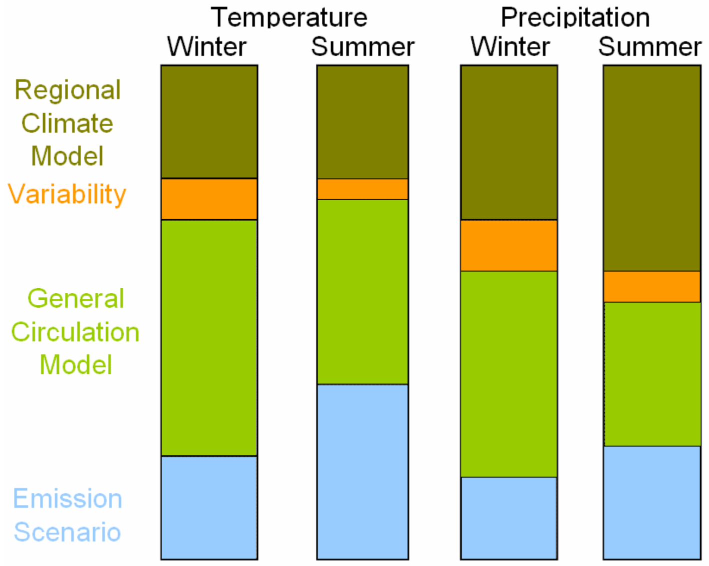
2 Climate projections

Climate will change in the future, driven by human emissions of greenhouse gases (GHGs) (Solomon et al. 2007), the most prominent and important of which is carbon dioxide (CO_2). The climate system is also affected by several additional mechanisms, e. g. aerosol concentrations and land-cover change. Assessing future climate change is very uncertain, a consequence of uncertainties in all aspects of climate change:

- Future changes in drivers of climate change are uncertain, a circumstance usually addressed by employing different scenarios for GHG emissions (see Section 2.1);
- due to the high complexity of climate systems, climate models can only generate reduced representations of the climate system, which is also not fully understood in terms of all its mechanisms (Solomon et al. 2007; see Section 2.2); and
- several feedbacks exist between climate change and its drivers, e. g. the impact on agricultural production, which affects land requirements of agricultural production, and this in turn drives land-use and land-cover change, a driver of climate change.

Figure 1 illustrates the relative contribution of different emission scenarios, use of different General Circulation Models (GCMs), internal GCM variability, and use of different regional climate models (RCM) to overall uncertainty in climate simulations. Although figure 1 is for Europe, it is included here to demonstrate that there are different sources of uncertainty in projecting climate change, a fact that holds true for any region in the world. No similar figure is available for Africa. Impacts of climate change (see Section 3), depend strongly on local conditions. Impact assessments are thus dependent on accurate regional climate projections (see Section 2.3), which adds another source of uncertainty. The uncertainties in the different stages of climate projections (emission scenarios => climate projection => regional climate projection) complicate projections of climate change as

Figure 1: Relative contributions to uncertainty in the simulation of climate change over Europe originating from various sources



Various Sources:

1. Use of different Regional Climate Models (RCMs, 8 models);
2. internal variability of General Circulation Models (GCMs);
3. use of different GCMs (4 models);
4. use of different emission scenarios (2 scenarios covering about half the range of the Intergovernmental Panel on Climate Change (IPCC) models). Winter is December, January, February; summer is June, July, August.

   Uncertainty due to GCMs and scenarios (when accounting for the reduced range considered) generally dominates, except for summer precipitation, when uncertainty due to RCMs is of comparable magnitude.

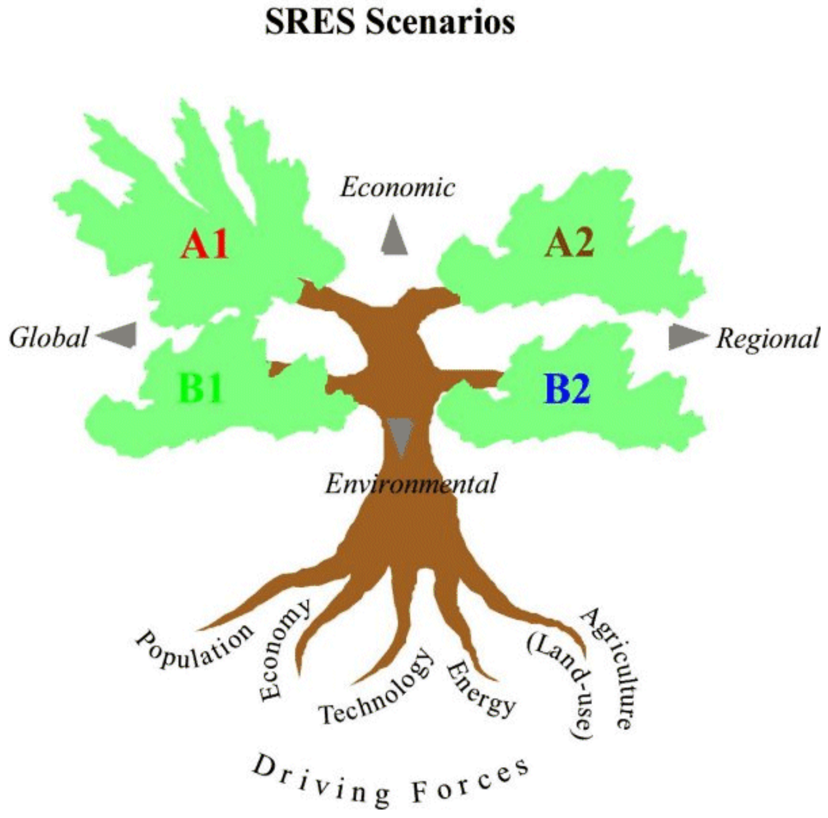
Source: Giorgi (2006), modified

well as of climate impacts. Nonetheless, climate change projections are indispensable in managing global change impacts through adaptation and mitigation, provided their limitations are understood and considered.

2.1 Common emission scenarios

Climate change is mainly driven by emissions of greenhouse gases (GHGs), aerosol concentrations and land-use change. To study the impact on the global climate system, GCMs are driven by scenarios on GHG emissions and also aerosols. Land-use change scenarios are often included in the form of CO_2 emissions only; more recently, GCMs have also attempted to account for changes in land surface properties (e. g. vegetation cover). All emission scenarios include assumptions on regional development and are globally consistent.

Figure 2: Schematic overview of the 4 Special Report on Emission Scenarios (SRES) scenario families (A1, A2, B1, and B2)



The "A" families have a general economic preference, while the "B" families are more environmentally oriented. The "1" families assume a globalized world, while the "2" families assume a regionalized world. The roots of the tree illustrate the basic assumptions driving the scenarios.

Source: Nakicenovic / Swart (2000)

The most common emission scenarios are the so-called "SRES" scenario families, as published in the "Special Report on Emission Scenarios" (SRES) by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic / Swart 2000). The SRES scenarios combine plausible assumptions on population growth, economic growth, energy use, fuel mix, and land-use change (illustrated as roots in Figure 2) and calculate CO_2 emissions over the 21st century with the help of 6 different integrated assessment models (Nakicenovic/Swart 2000). Table 1 summarizes the main characteristics of the most important SRES scenarios. The A1 and B1 scenarios assume low population growth and strong economic development, while the A2 and B2 scenarios assume higher population growth and only medium economic development. The "B" families, environmentally oriented scenarios, assume medium and low energy consumption, while the "A" families assume energy consumption to be high. Energy consumption and the choice of energy source (row 7, "favouring") largely determine the development of CO_2 emissions. Note the marked differences between A1T[1] and the other A1 scenarios as well as between the "B" scenarios and the "A" scenarios (except A1T).

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[1] A sub-scenario with emphasis on technological change and renewable energies.

Table 1: Overview of SRES scenario characteristics

Scenario Group	A1C	A1G	A1B	A1T	A2	B1	B2
Population growth	low	low	low	low	high	low	medium
Gross domestic product (GDP) growth	very high	very high	very high	Very high	medium	high	medium
Energy use	very high	very high	very high	high	high	low	medium
Land-use changes	low-medium	low-medium	low	low	medium / high	high	medium
Resource availability[2]	high	high	medium	medium	low	low	medium
Pace and direction of technological change	rapid	rapid	rapid	rapid	slow	medium	medium
favouring	coal	oil & gas	balanced	non fossils	regional	efficiency & dematerialization	"dynamics as usual"
CO_2 emissions in 1990 (MtC)	7312	7312	7312	7312	7312	7312	7312
CO_2 emissions in 2050 (MtC)	21086	21802	16789	12601	15044	8367	10983
CO_2 emissions in 2100 (MtC)	32988	30909	14397	4789	28493	4147	13634

Depending on variations of some scenario assumptions, there are several sub-scenarios for the four main scenarios A1, A2, B1, and B2. Not all sub-scenarios are shown here.

Source: Nakicenovic / Swart (2000)

Several other, more recent scenarios have been developed, for instance in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005), but none have been implemented in global integrated assessment models in a manner comparable to the implementation of the SRES scenarios. These are therefore often only available as verbal storylines, and they are seldom used in impact studies.

2.2 Climate models

General Circulation Models (GCMs) simulate the dynamics of the atmosphere, including the transport of heat and water. Usually GCMs are coupled to a model of oceanic circulation (Atmosphere-Ocean General Circulation Model, AOGCM), since lateral and vertical

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[2] Resource availability of conventional and unconventional oil and gas.

transport of heat in the oceans strongly affects the energy budget in the atmosphere. Land-surface properties are usually partially modelled (e. g. evapo-transpiration) and partially prescribed (e. g. vegetation cover). Recently, GCMs have sought to include full land-surface dynamics.

A broad range of climate models exist (see Table 2 for an overview of the IPCC GCMs); most of these are AOGCMs, the most comprehensive climate models available. The most important characteristics of GCMs are the resolution of the atmosphere and of the ocean, the detail of sea-ice and land surface modelling, and flux adjustments between atmosphere, ocean, and land. Table 2 shows these main characteristics for all 23 IPCC GCMs. The atmosphere is usually represented by different horizontal layers, defined not by specific altitudes but by pressure levels, which is more dynamic and thus more accurate. The top of the atmosphere is not a sharp border and needs to be defined in models. Most models do this via pressure levels. The lower the top pressure in the model is (ranging from 0.05 to 25 hPa), the more of the atmosphere is actually modelled. Only a few models prescribe the top of the atmosphere in altitude (km). Most climate models describe the motion of the atmosphere via a set of wave functions, which also determine spatial resolution via triangular spectral truncation level.[3] Atmospheric horizontal resolution is expressed either as degrees latitude by longitude or as a triangular (T) spectral truncation with a rough translation to degrees latitude and longitude, ranging from 1.1° x 1.1° to 4.0° x 5.0°. Vertical resolution (L) is the number of vertical levels, ranging from 12 to 56 layers. Oceanic horizontal resolution is expressed as degrees latitude by longitude, while vertical resolution (L) is the number of vertical levels. Rigid lid ocean models do not move under atmospheric momentum but translate it into fluid pressure. Flux adjustments are sometimes needed to avoid unrealistic model drifts (i. e. moving slowly into unrealistic states); these are employed by only 6 of the 23 GCMs presented in Table 2. The representation of land in GCMs is largely uniform, almost all models simulate several soil-water layers (except 4) and channel surface runoff via a river routing system to the oceans (except 3), all models include a vegetation canopy, which usually is prescribed and does not react to simulated climate.

AOGCMs are very expensive in computational terms and thus can be applied only to a limited number of scenarios. Strongly reduced, so-called simple climate models are employed to assess probabilistic distributions of climate projections (Harvey et al. 1997), but they provide only insights for global-scale questions. A class of intermediate climate models, so-called EMICs (Earth System Models of Intermediate Complexity), have evolved between AOGCMs and simple climate models (Claussen et al. 2002).

Climate projections are subject to considerable uncertainty, due to emission scenarios (see Section 2.1) and GCM simulations. While all climate models have their individual strengths

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[3] The so-called spectral conversion transforms the complex mathematical equations describing the 3-dimensional motion of the atmosphere into more simple wave functions via a Fourier Transformation. The precision with which these complex functions are represented in wave function sets depends on the number of wave functions included. The more wave functions are used to represent a complex function, the higher are the computational demands. Therefore, the precision of the model is usually truncated at a specific level (e. g. T42). The truncation point also determines the spatial resolution of the model, which is dependent on the density of wave nodes. A model with a high truncation point (e. g. T106 as model 18 "MIROC3.2(hires)" in Table 2) therefore has a relatively fine spatial resolution but also very high computational demands.

Table 2: Selected model features of the AOGCMs

Model ID, Vintage	Sponsor(s), Country	Atmosphere Top Resolution[4]	Ocean Resolution[5] Z Coord., Top BC	Sea Ice Dynamics, Leads	Coupling Flux Adjustments	Land Soil, Plants, Routing
1: BCC-CM1, 2005 (Xu et al. 2005)	Beijing Climate Center, China	top = 25 hPa T63 (1.9° x 1.9°) L16	1.9° x 1.9° L30 depth, free surface	no rheology or leads	heat, momentum	layers, canopy, routing
2: BCCR-BCM2.0, 2005 (Furevik et al. 2003)	Bjerknes Centre for Climate Research, Norway	top = 10 hPa T63 (1.9° x 1.9°) L31	0.5°–1.5° x 1.5° L35 density, free surface	rheology, leads	no adjustments	layers, canopy, routing
3: CCSM3, 2005 (Collins et al. 2006)	National Center for Atmospheric Research, USA	top = 2.2 hPa T85 (1.4° x 1.4°) L26	0.3°–1° x 1° L40 depth, free surface	rheology, leads	no adjustments	layers, canopy, routing
4: CGCM3.1 (T47), 2005 (Flato 2005)	Canadian Centre for Climate Modelling and Analysis, Canada	top = 1 hPa T47 (~2.8° x 2.8°) L31	1.9° x 1.9° L29 depth, rigid lid	rheology, leads	heat, freshwater	layers, canopy, routing
5: CGCM3.1 (T63), 2005 (Flato 2005)	Canadian Centre for Climate Modelling and Analysis, Canada	top = 1 hPa T63 (~1.9° x 1.9°) L31	0.9° x 1.4° L29 depth, rigid lid	rheology, leads	heat, freshwater	layers, canopy, routing
6: CNRM-CM3, 2004 (Deque et al. 1994)	Météo-France/ Centre National de Recherches Météorologiques, France	top = 0.05 hPa T63 (~1.9° x 1.9°) L45	0.5°–2° x 2° L31 depth, rigid lid	rheology, leads	no adjustments	layers, canopy, routing
7: CSIRO-MK3.0, 2001 (Gordon et al. 2002)	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research, Australia	top = 4.5 hPa T63 (~1.9° x 1.9°) L18	0.8° x 1.9° L31 depth, rigid lid	rheology, leads	no adjustments	layers, canopy

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[4] Horizontal resolution is expressed either in degrees latitude by longitude or as a triangular (T) spectral truncation with a rough translation to degrees latitude and longitude. Vertical resolution (L) is the number of vertical levels.

[5] Horizontal resolution is expressed as degrees latitude by longitude, while vertical resolution (L) is the number of vertical levels.

Model ID, Vintage	Sponsor(s), Country	Atmosphere Top Resolution[4]	Ocean Resolution[5] Z Coord., Top BC	Sea Ice Dynamics, Leads	Coupling Flux Adjustments	Land Soil, Plants, Routing
8: ECHAM5/ MPI-OM, 2005 (Jungclaus et al. 2006)	Max Planck Institute for Meteorology, Germany	top = 10 hPa T63 (~1.9° x 1.9°) L31	1.5° x 1.5° L40 depth, free surface	rheology, leads	no adjustments	bucket, canopy, routing
9: ECHO-G, 1999 (Min et al. 2005)	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group, Germany/Korea	top = 10 hPa T30 (~3.9° x 3.9°) L19	0.5°–2.8° x 2.8° L20 depth, free surface	rheology, leads	heat, freshwater	bucket, canopy, routing
10: FGOALS-g1.0, 2004 (Wang et al. 2004)	National Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)/Institute of Atmospheric Physics, China	top = 2.2 hPa T42 (~2.8° x 2.8°) L26	1.0° x 1.0° L16 eta, free surface	rheology, leads	no adjustments	layers, canopy, routing
11: GFDL-CM2.0, 2005 (Delworth et al. 2006)	U.S. Department of Commerce/ National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), USA	top = 3 hPa 2.0° x 2.5° L24	0.3°–1.0° x 1.0° depth, free surface	rheology, leads	no adjustments	bucket, canopy, routing
12: GFDL-CM2.1, 2005 (Delworth et al. 2006)	U.S. Department of Commerce/ National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), USA	top = 3 hPa 2.0° x 2.5° L24 with semi-Lagrangian transports	0.3°–1.0° x 1.0° depth, free surface	rheology, leads	no adjustments	bucket, canopy, routing

Model ID, Vintage	Sponsor(s), Country	Atmosphere Top Resolution[4]	Ocean Resolution[5]Z Coord., Top BC	Sea Ice Dynamics, Leads	Coupling Flux Adjustments	Land Soil, Plants, Routing
13: GISS-AOM, 2004 (Russell 2005)	National Aeronautics and Space Administration (NASA)/ Goddard Institute for Space Studies (GISS), USA	top = 10 hPa 3° x 4° L12	3° x 4° L16 mass/area, free surface	rheology, leads	no adjustments	layers, canopy, routing
14: GISS-EH, 2004 (Schmidt et al. 2006)	National Aeronautics and Space Administration (NASA)/ Goddard Institute for Space Studies (GISS), USA	top = 0.1 hPa 4° x 5° L20	2° x 2° L16 density, free surface	rheology, leads	no adjustments	layers, canopy, routing
15: GISS-ER, 2004 (Schmidt et al. 2006)	National Aeronautics and Space Administration (NASA)/Goddard Institute for Space Studies (GISS), USA	top = 0.1 hPa 4° x 5° L20	4° x 5° L13 mass/area, free surface	rheology, leads	no adjustments	layers, canopy, routing
16: INM-CM3.0, 2004 (Volodin/Dianskу 2004)	Institute for Numerical Mathematics, Russia	top = 10 hPa 4° x 5° L21	2° x 2.5° L33 sigma, rigid lid	no rheology or leads	regional freshwater	layers, canopy, no routing
17: IPSL-CM4, 2005 (Hourdin et al. 2006)	Institut Pierre Simon Laplace, France	top = 4 hPa 2.5° x 3.75° L19	2° x 2° L31 depth, free surface	rheology, leads	no adjustments	layers, canopy, routing
18: MIROC3.2 (hires), 2004 (K-1 model developers 2004)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	top = 40 km T106 (~1.1° x 1.1°) L56	0.2° x 0.3° L47 sigma/depth, free surface	rheology, leads	no adjustments	layers, canopy, routing

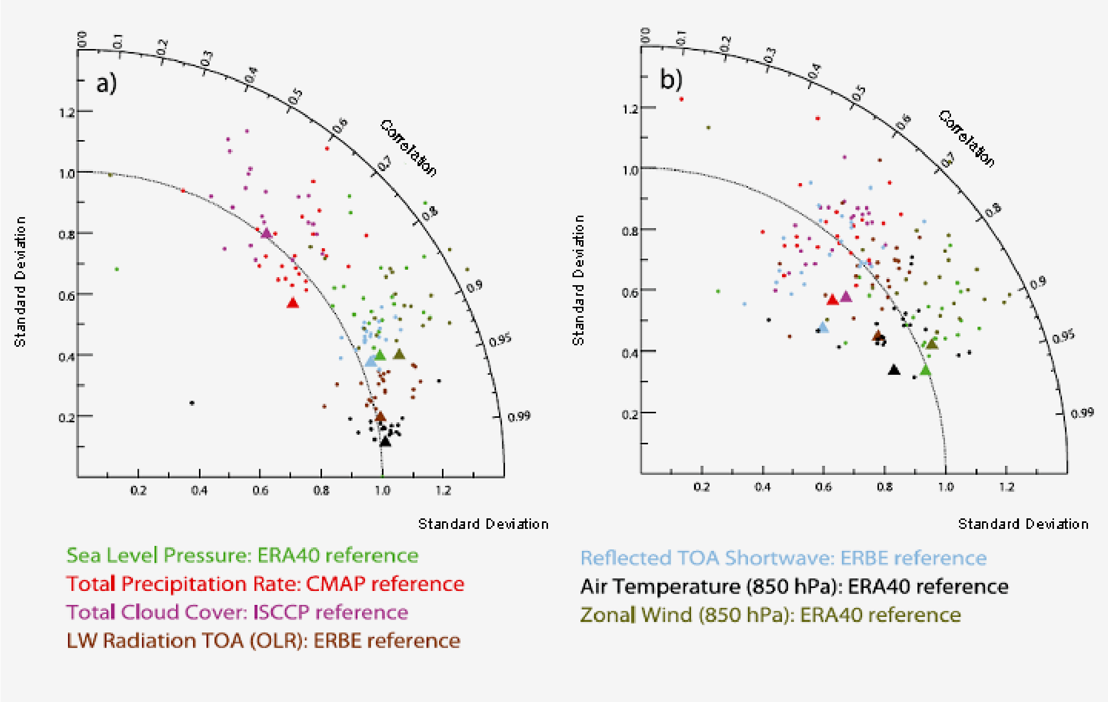
Model ID, Vintage	Sponsor(s), Country	Atmosphere Top Resolution[4]	Ocean Resolution[5] Z Coord., Top BC	Sea Ice Dynamics, Leads	Coupling Flux Adjustments	Land Soil, Plants, Routing
19: MIROC3.2 (medres), 2004 (K-1 model developers 2004)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	top = 30 km T42 (~2.8° x 2.8°) L20	0.5°–1.4° x 1.4° L43 sigma/depth, free surface	rheology, leads	no adjustments	layers, canopy, routing
20: MRI-CGCM 2.3.2, 2003 (Yukimoto/Noda 2003)	Meteorological Research Institute, Japan	top = 0.4 hPa T42 (~2.8° x 2.8°) L30	.5°–2.0° x 2.5° L23 depth, rigid lid	free drift, leads	heat, freshwater, momentum (12°S–12°N)	layers, canopy, routing
21: PCM, 1998 (Kiehl et al. 1998)	National Center for Atmospheric Research, USA	top = 2.2 hPa T42 (~2.8° x 2.8°) L26	0.5°–0.7° x 1.1° L40 depth, free surface	rheology, leads	no adjustments	layers, canopy, no routing
22: UKMO-HadCM3, 1997 (Cox et al. 1999) UKMO-HadGEM1, 2004 (Martin et al. 2004)	Hadley Centre for Climate Prediction and Research/Met Office, UK Hadley Centre for Climate Prediction and Research/Met Office, UK	top = 5 hPa 2.5° x 3.75° L19 Top = 39.2 km ~1.3° x 1.9° L38	1.25° x 1.25° L20 depth, rigid lid 0.3°–1.0° x 1.0° L40 depth, free surface	free drift, leads rheology, leads	no adjustments no adjustments	layers, canopy, routing layers, canopy, routing

Selected model features of the AOGCMs participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3) at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) are listed by IPCC identification (ID) along with the calendar year (‘vintage’) of the first publication of results from each model. Also listed are the respective sponsoring institutions, the pressure at the top of the atmospheric model, the horizontal and vertical resolution of the model atmosphere and ocean models, as well as the oceanic vertical coordinate type (Z) and upper boundary condition (BC: free surface or rigid lid). Also listed are the characteristics of sea ice dynamics/structure (e.g. rheology vs. ‘free drift’ assumption and inclusion of ice leads) and whether adjustments of surface momentum, heat or freshwater fluxes are applied in coupling the atmosphere, ocean and sea ice components. Land features such as the representation of soil moisture (single-layer ‘bucket’ vs. multilayered scheme) and the presence of a vegetation canopy or a river routing scheme also are noted.

Source: Randall et al. (2007)

and weaknesses, there are some general GCM performance characteristics. Global annual mean temperatures of the 20th century are simulated reasonably well by all GCMs, especially in the northern hemisphere, while precipitation and cloud cover, both important inputs for impact models (agriculture, vegetation, hydrology), are less well reproduced by the GCMs (see Figure 3). Regionally or locally, GCMs perform less accurately, with local temperature deviations of several degrees and strong distortions of precipitation patterns. A detailed overview of GCM performance and evaluation is given by Gleckler et al. (2008) and Randall et al. (2007).

Figure 3: Multivariable Taylor diagrams of the 20th century CMIP3 annual cycle climatology (1980–1999)



(a) Northern extra-tropics (20N–90N); (b) Tropical (20S–20N).

Each coloured dot represents an individual simulation made with a particular model, whereas each triangle represents the ensemble "mean model".

Source: Gleckler et al. (2008)

The quality of climate simulations is very hard to assess, due to its complexity. In principle, there are several criteria that need to be considered in assessing the quality of a climate simulation: the overall bias[6] of the simulation (Is the global average too dry/wet or hot/cold etc.?), the variation of the pattern (Are extremes represented well?), the correlation of the pattern (Are dry/wet areas where dry/wet area are being observed or are they somewhere else?), and the total error (i. e. some aggregate[7] of the total disagreement).

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[6] A bias in climate simulations is the deviation of the average from observations. If the simulated temperature (precipitation) is higher/lower than observations, the model has a warm/cool (wet/dry) bias.

[7] Usually the *root square mean* error is used.

This is becoming even more complicated since these criteria have to be evaluated for a broad range of variables[8] and should also reflect their temporal dynamics.

Gleckler et al. (2008) provide a range of performance metrics for climate models; these are still difficult to understand for persons outside the climate modeller community and are thus not shown here. Figure 3 shows so-called Taylor Diagrams (Taylor 2001), which make it possible to represent the correlation and standard deviation of several variables (distinguished by colours) and several models within one single graph. Each variable is normalized by the corresponding standard deviation of the reference data, which allows multiple variables to be shown in each panel of Figure 3. As a consequence of this normalization, the observation is located at a standard deviation of 1.0 and a correlation of 1.0. In this figure, each coloured dot represents an individual simulation made with a particular model, whereas each triangle represents the ensemble "mean model."[9] A perfect match of observations would in this case[10] have a standard deviation and a correlation of 1.0. The values here refer to annual mean values, i. e. they exclude temporal dynamics. The ability of GCMs to simulate specific variables better than others can be seen in Figure 3: In a (northern hemisphere), temperature simulations (black) resemble observations remarkably closely (except for a few outliers, correlation of >0.95, standard deviation between 0.9 and 1.1), while precipitation (red) is resembled less accurately (correlation of <0.8 and a standard deviation between 0.9 and 1.2). Comparing panels a) and b) shows that temperature simulations are much more accurate for the northern extra-tropics than for the tropics. An evaluation of models for the southern extra-tropics is not provided by Gleckler et al. (2008), since reference data sets (observation-based data) are generally of poorer quality for the southern hemisphere. It should be noted that temperature observations are the most reliable reference data sets. There are several precipitation observation data sets available, and they differ considerably. Generally, the data quality for observed climate is limited in Africa due to the low density of meteorological observation stations. See, for example, the network of temperature stations (Figure 4). Note that many stations in Africa are no longer active (small dots).

2.3 Regional climate change projections for Africa

2.3.1 GCM performance for Africa

Christensen et al. (2007) review the IPCC climate models' skills in reproducing present and past climates and also evaluating projections of temperature, precipitation, and extreme events. The main findings are summarized here.

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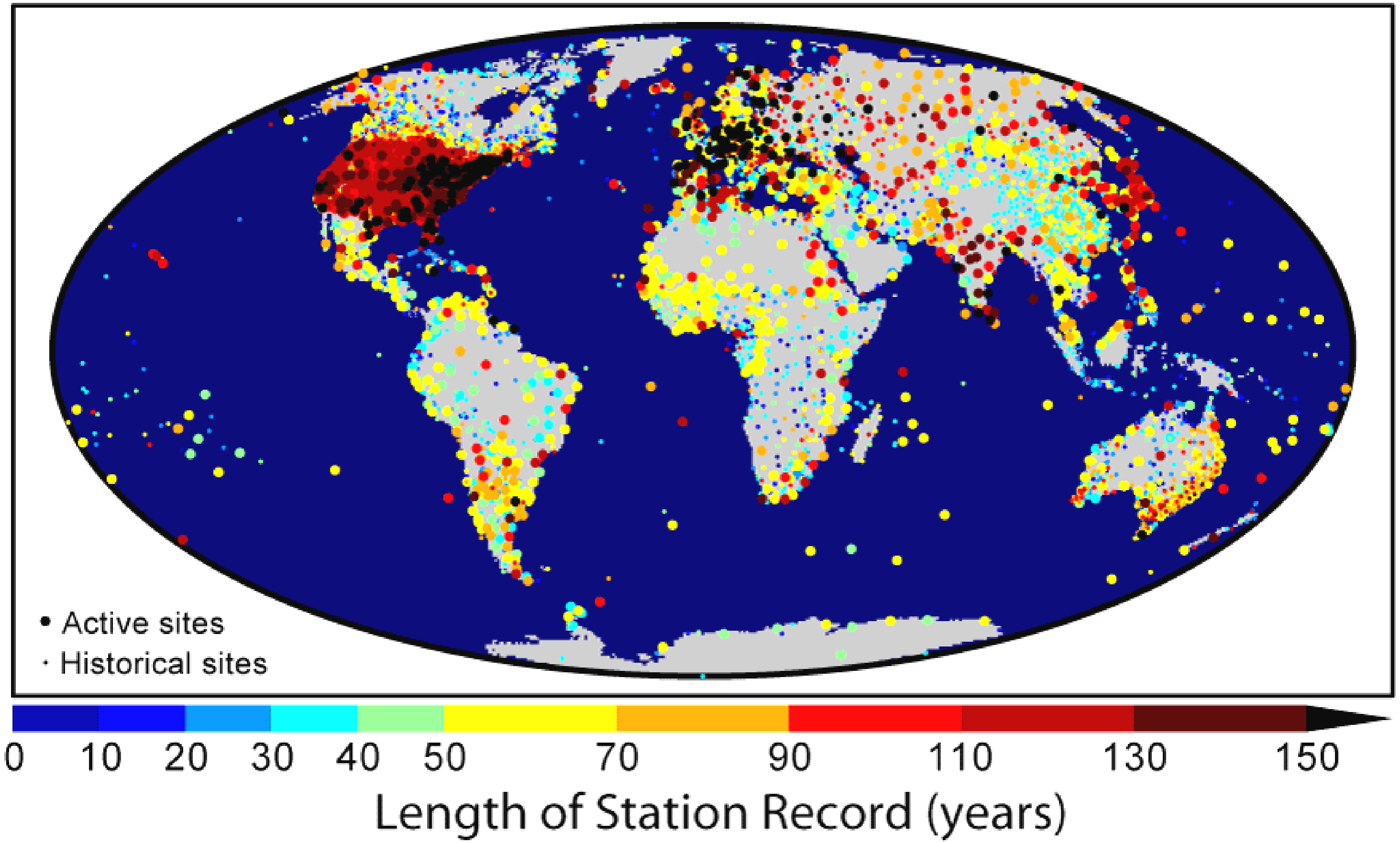
[8] These include temperature, precipitation, cloud cover, air pressure, wind speed, and short- and long-wave radiation.

[9] The "mean model" statistics are calculated after regridding each model's output to a common (T42) grid (~2.8° x 2.8°), and then computing the multimodel mean value at each grid cell.

[10] This is true only because of the normalization by the corresponding standard deviation of the observed data. Otherwise, the reference data would have a standard deviation of not necessarily the 1.0 that should be most closely represented by the models.

Figure 4: Global climate network temperature stations



The length of the station record is distinguished by colors. Note that many stations in Africa are no longer active (small dots).

Source: http://www.globalwarmingart.com/wiki/Image:GHCN_Temperature_Stations_png by RA Rohde, based on Peterson/Vose (1997)

Compared to temperature observations, almost all GCMs underestimate temperatures in Africa, on average, by 1.3°C (Table 3), i. e. GCM simulations are on average too cool compared to observations. Climate modellers consider this bias to be acceptable, i. e. it does not reduce the credibility of the model's simulations (Christensen et al. 2007, 867). Table 3 shows that temperature biases in GCM simulations of 1980–1999 average annual temperature vary between an underestimation of 6.4°C in the Sahara to an overestimation of 2.2°C. However, 50 % of all GCMs (i. e. 2nd and 3rd quartile, see columns 25, 50, and 75 in Table 3) underestimate temperatures in all 4 African regions, range between –2.8°C and 0°C. The uniformity of the models' bias is also illustrated by the purple shading in Table 3, indicating that at least 75 % of all models have a cool bias.

Precipitation biases of the GCMs are less uniform than temperature biases, ranging between an underestimation of annual precipitation by 86 % and an overestimation by 139 %. It should be noted that these extremes occur in the Sahara region (between 18° and 30° north and 20° and 65° east), where precipitation is low anyway, which indicates that high percentage deviations are not necessarily related to high absolute deviations. However, the 3 other African Regions with higher total annual precipitation still display strong precipitation biases, ranging from underestimations of annual precipitation by 30 % overestimates of 79 %. Especially Southern Africa (between 12° and 35° south and between 20° and 65° east), but also East Africa (between 18° north and 12° south and between 22° and 52° east) are simulated with a wet bias by at least 75 % of the GCMs, which is indicated by the light blue shading in Table 3.

The evaluation of seasonal temperatures and precipitation simulations typically considers units of 3 months only (December, January, and February (DJF); March, April, and May (MAM); June, July, and August (JJA); and September, October, and November (SON). This is insufficient to assess the GCMs' suitability to drive specific impact models such as agricultural models, where the length of the wet season and the rainfall distribution during the wet season is crucial. There are some assessments of specific GCMs' abilities to reproduce rainy seasons, using aggregates of 3–5 months to represent typical rainy seasons (e. g. December, January, and February for the southwest African rainy season or February to May for East Africa rainy season (Marengo et al. 2003), also specifically for South Africa (Zhao / Camberlin / Richard 2005), but these still operate on monthly units, and a more general overview of GCMs' abilities to reproduce rainy seasons is missing. Generally, sea surface temperatures (SSTs) strongly affect the circulation patterns and thus precipitation patterns over the African continent. There is a strong relationship between the West African monsoon, precipitation in the Sahel zone and SSTs (Lenton et al. 2008) and also between Indian Ocean SSTs and southern African precipitation (Funk et al. 2008). AOGCMs, however, have difficulties in representing the inter-annual variability of SSTs in this region, which shows in a stronger deviation of precipitation simulations from observations.

Temperature extremes are surprisingly well represented in GCM simulations, both in statistics and trend, given their coarse resolution and their large-scale systematic errors. Precipitation amounts and especially intensities are less well simulated (Randall et al. 2007): Typically, AOGCMs simulate too many days with light precipitation (<10 mm/day) and too few with heavy precipitation events. These errors partially cancel each other out in the

Table 3: Biases in present-day (1980–1999) surface air temperature and precipitation in the CMIP3 simulations

		Temperature Bias (°C)					Precipitation Bias (%)				
Region[11]	Season[12]	Min	25	50	75	Max	Min	25	50	75	Max
West Africa	DJF	– 5.7	– 2.5	– 1.6	– 0.6	1.8	– 35	– 2	11	30	63
	MAM	– 3.9	– 2.9	– 1.4	– 0.7	0.3	– 17	– 8	23	47	70
	JJA	– 3.1	– 1.5	0.4	0.1	2.1	– 44	– 17	– 5	16	40
	SON	– 3	– 2.2	– 0.9	0.1	1.5	– 28	– 8	0	31	60
	Annual	– 3.4	– 2.4	– 1.2	– 0.3	1.2	– 26	– 7	5	26	55
East Africa	DJF	– 3.9	– 2.7	– 1.8	– 0.6	0.1	– 11	19	45	56	66
	MAM	– 3.4	– 1.8	– 1.2	– 0.5	0.8	– 36	– 1	13	29	57
	JJA	– 3.4	– 1.5	– 1	0.2	1.2	– 48	– 15	3	28	78
	SON	– 2.7	– 1.8	– 1.2	– 0.3	0.7	12	34	48	71	110
	Annual	– 3.1	– 1.8	– 1.3	– 0.3	0.5	– 16	13	22	42	69
Southern Africa	DJF	– 2.6	– 1.6	– 1	– 0.4	1.6	– 28	5	27	35	63
	MAM	– 3.1	– 1.8	– 1.4	– 0.3	1.9	– 31	4	31	55	113
	JJA	– 4.6	– 2.2	– 0.6	0.7	2.6	– 36	– 6	28	48	246
	SON	– 2.2	– 0.8	0	1	2.3	– 51	19	39	65	130
	Annual	– 2.8	– 1.3	– 0.8	0	2	– 30	14	35	44	79
Sahara	DJF	– 8	– 4.4	– 2.9	– 1	2.7	– 87	– 80	– 72	– 37	13
	MAM	– 6.2	– 2.6	– 1.6	0	2.7	– 91	– 67	– 27	– 28	127
	JJA	– 5.5	– 1.3	– 0.4	1	3.1	– 96	2	50	110	534
	SON	– 6	– 3.1	– 1.9	– 0.7	1.9	– 87	– 29	30	57	287
	Annual	– 6.4	– 2.8	– 1.8	– 0.2	2.2	– 86	– 32	0	33	139

The simulated temperatures are compared with the HadCRUT2v (Jones et al. 2001) data set and precipitation with the CMAP (update of Xie / Arkin 1997) data set. Temperature biases are represented in °C and precipitation biases in per cent. What is shown are the minimum, median (50 %) and maximum biases among the models, as well as the first (25 %) and third (75 %) quartile values. Colours indicate regions/seasons for which at least 75 % of the models have the same sign of bias, with light violet indicating negative temperature biases and light blue signalling positive and light brown pointing to negative precipitation biases.

Source: Christensen et al. (2007)

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[11] Regions are defined by geographic extent, see also Figure 5: West Africa: 22°N to 12°S and 20°W to 18°E, East Africa: 18°N to 12°S and 22 to 52°E, Southern Africa: 12 to 35°S and 10 to 52°E, Sahara: 18 to 30°N and 20 to 65°E.

[12] Seasons are: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); September, October, November (SON), more regional specific definitions of seasons (e. g. rainy seasons) are not typically provided and would have to be computed individually for all GCMs.

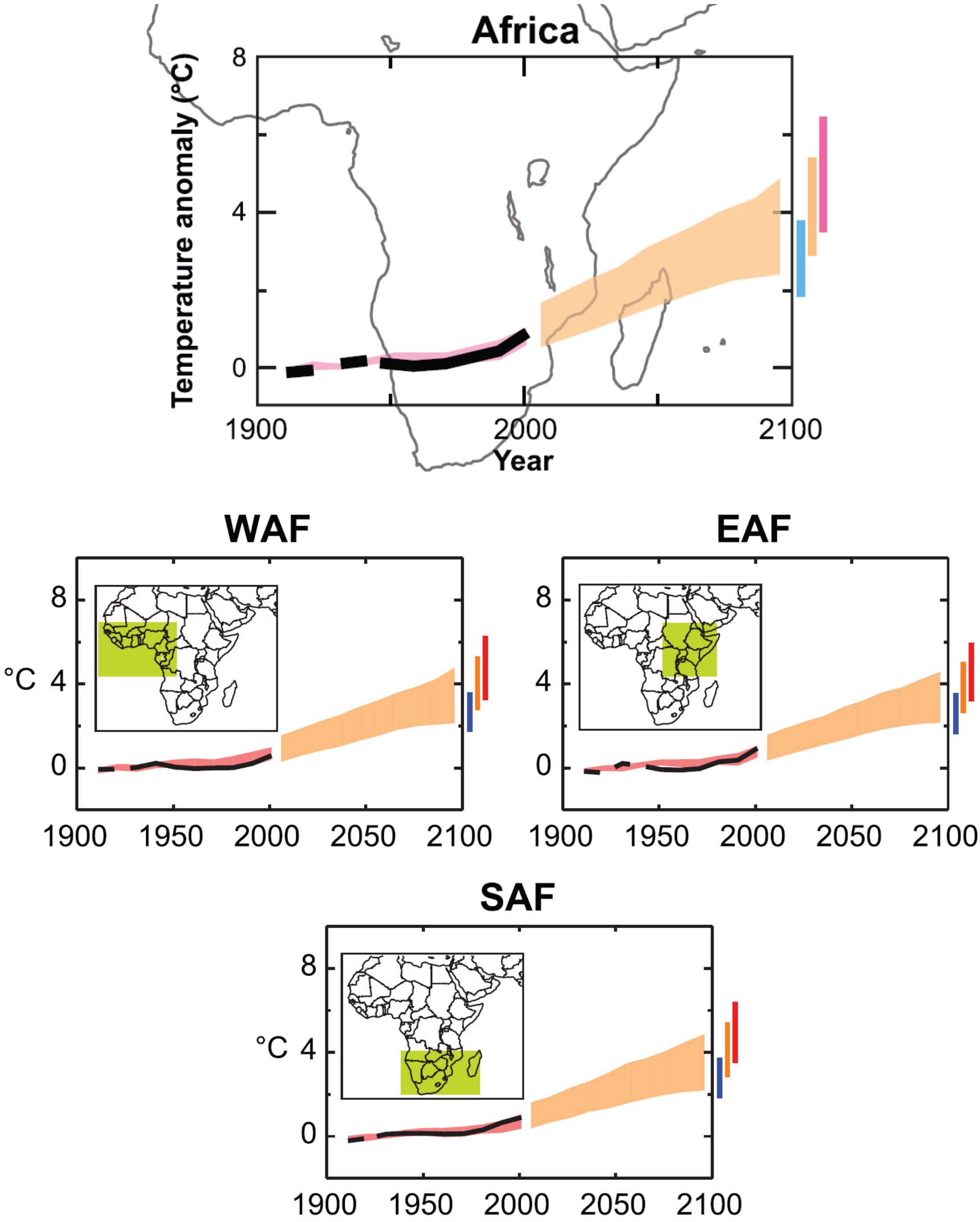
seasonal mean. The models' ability to simulate precipitation extremes increases with resolution, but with the same systematic errors (too many weak precipitation events, too few strong ones). Tropical cyclones cannot be simulated by AOGCMs at typical resolutions (around 2.5°, see Table 2). Atmosphere General Circulation Models (AGCMs, excluding the dynamic ocean part, which is replaced by prescribed sea surface temperatures) at high resolutions are able to resolve tropical cyclones, but they still have varying degrees of errors, sometimes substantial, in frequency and intensity. They also have problems with geographic accuracy (i. e. typical cyclone regions are misplaced) (Randall et al. 2007).

Studies on climate extremes specific to Africa are rare (Christensen et al. 2007), but there is evidence that rainfall intensity is increasing in southern Africa and areas of mean drying seem to be experiencing a decrease in frequency rather than intensity (Tadross / Jack/ Hewitson 2005).

2.3.2 GCM projections for Africa

GCM climate projections for Africa differ considerably between model projections for the same emission scenarios. The temperature trend for Africa is displayed in Figure 5. The range of uncertainty (shaded area) in climate projections becomes broader the further the projections reach into the future, but the increase is basically linear. The projected temperature increase is similar (roughly +2–4.5°C by 2100) in the three sub-Saharan regions (Figure 5,Table 4), which is lower than the projections for the Sahara region (+3–5°C by 2100, Table 4). Table 4 shows the projected temperature and precipitation changes from the average of 1980–1999 to the average of 2080–2099. The inter-model variability represented by the shaded area in Figure 5 is here presented as columns of the minimum, maximum, median, and the 25 and 75 % quartiles. It also allows for comparison of the four African regions: West Africa, East Africa, southern Africa, and the Sahara. For each of these regions, the average annual as well as the 4 standard seasons (December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), and September, October, November (SON)) temperature increases are presented in separate rows. East Africa has a high likelihood to become wetter by 2100, as 50 % of the models around the median projections agree on increasing precipitation (light blue shading in Table 4), while the second half of the year (June–November) in southern Africa and the first half of the year (December–May) in the Sahara region have a high likelihood of becoming dryer by 2100 (orange shading in Table 4) as well as on regional climate projections. The temperature increase in Africa is projected between 3 and 4 °C (median projections), and inter-model variation is relatively small, with 50 % of all models within a +/– 0.5°C range of the median projections. According to these projections, Africa will warm more than the mean global temperature response, approximately 1.5 times as much (Christensen et al. 2007). Projections of temperature increase are very similar for all three sub-Saharan African regions, as shown in Figure 5, with a slightly stronger temperature increase in Southern Africa. Almost all models agree that all of Africa will be extremely hot (see 3rd column from the right in Table 4) all year round. Seasons are defined as extreme if they are warmer/wetter/ dryer than the warmest/wettest/driest corresponding season in a 20-year control run of the period 1980–1999 in at least 14 of the 21 Coupled Model Intercomparison Project Phase 3 (CMIP3) models. Extreme wet seasons are projected to increase by 20 % in West and East Africa and dry seasons are projected to decrease in southern Africa by about 20 % in the second half of the year (June–November), see the two columns on the right in Table 4.

Figure 5: Temperature anomalies with respect to 1901 to 1950 for Africa and three sub-Sahara African land regions for 1906 to 2005



Temperature anomalies with respect to 1901 to 1950 for Africa and three sub-Saharan African land regions for 1906 to 2005 (black line) and as simulated (red envelope) by CMIP3 models incorporating known forcings; and as projected for 2001 to 2100 by CMIP3 models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). The black line is dashed where observations are available for less than 50 % of the area in the decade concerned.

Source: Christensen et al. (2007), modified

Table 4: Regional averages of temperature and precipitation projections for Africa from a set of 21 global models in the CMIP3 for the A1B scenario

		Temperature Response (°C)					Precipitation Response (%)					Extreme Seasons (%)		
Region[13]	Season[14]	Min	25	50	75	Max	Min	25	50	75	Max	Warm	Wet	Dry
West Africa	DJF	2.3	2.7	3	3.5	4.6	–16	– 2	6	13	23	100 (+)	21 (+)	4 (–)
	MAM	1.7	2.8	3.5	3.6	4.8	–11	– 7	– 3	5	11	100 (+)		
	JJA	1.5	2.7	3.2	3.7	4.7	–18	– 2	2	7	16	100 (+)	19 (+)	
	SON	1.9	2.5	3.3	3.7	4.7	–12	0	1	10	15	100 (+)	15 (+)	
	Annual	1.8	2.7	3.3	3.6	4.7	– 9	– 2	2	7	13	100 (+)	22 (+)	
East Africa	DJF	2	2.6	3.1	3.4	4.2	– 3	6	13	16	33	100 (+)	25 (+)	1 (–)
	MAM	1.7	2.7	3.2	3.5	4.5	– 9	2	6	9	20	100 (+)	15 (+)	4 (–)
	JJA	1.6	2.7	3.4	3.6	4.7	–18	– 2	4	7	16	100 (+)		
	SON	1.9	2.6	3.1	3.6	4.3	–10	3	7	13	38	100 (+)	21 (+)	3 (–)
	Annual	1.8	2.5	3.2	3.4	4.3	– 3	2	7	11	25	100 (+)	30 (+)	1 (–)
Southern Africa	DJF	1.8	2.7	3.1	3.4	4.7	– 6	– 3	0	5	10	100 (+)	11 (+)	
	MAM	1.7	2.9	3.1	3.8	4.7	–25	– 8	0	4	12	98 (+)		
	JJA	1.9	3	3.4	3.6	4.8	–43	–27	–23	– 7	–3	100 (+)	1 (–)	23 (–)
	SON	2.1	3	3.7	4	5	–43	–20	–13	– 8	3	100 (+)	1 (–)	20 (–)
	Annual	1.9	2.9	3.4	3.7	4.8	–12	– 9	– 4	2	6	100 (+)	4 (–)	13 (–)
Sahara	DJF	2.4	2.9	3.2	3.5	5	–47	–31	–18	– 12	31	97 (+)		12 (–)
	MAM	2.3	3.3	3.6	3.8	5.2	–42	–37	–18	– 10	13	100 (+)	2 (–)	21 (–)
	JJA	2.6	3.6	4.1	4.4	5.8	–53	–28	– 4	16	74	100 (+)		
	SON	2.8	3.4	3.7	4.3	5.4	–52	–15	6	23	64	100 (+)		
	Annual	2.6	3.2	3.6	4	5.4	–44	–24	– 6	3	57	100 (+)		

The mean temperature and precipitation responses are first averaged for each model over all available realizations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the table shows the minimum, maximum, median (50 %), and 25 and 75 % quartile values among the 21 models for temperature (°C) and precipitation (%) change. Regions in which the middle half (25–75 %) of this distribution is all of the same sign in the precipitation response are coloured orange for decreasing and light blue for increasing precipitation. Numbers in the Extreme Seasons columns indicate a change in frequency of extremes, with (+) indicating an increase and (–) a decrease.

Source: Christensen et al. (2007), modified

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[13] Regions are defined by geographic extent, see also Figure 5: West Africa: 22°N to 12°S and 20°W to 18°E, East Africa: 18°N to 12°S and 22 to 52°E, southern Africa: 12 to 35°S and 10 to 52°E, Sahara: 18 to 30°N and 20 to 65°E.

[14] Seasons are: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); September, October, November (SON), more regional specific definitions of seasons (e. g. rainy seasons) are not typically provided and would have to be computed individually for all GCMs.

Figure 7 shows as an example for the A1B SRES scenario that the 21 CMIP3 GCMs largely agree in the spatial pattern of temperature increase, i. e. the Sahara region and southern Africa are projected by most models to warm up more strongly than central Africa. However, the projected mean temperature increase differs considerably between the different GCMs. The GCMs PCM, CISRO-Mk3.0, FGOALS-g1.0 and MRI-DGCM2.3.2 project the lowest overall temperature increases, while UKMO-HadCM3, IPSL-CM4, MIROC3.2.hires, and ECHAM5/MPI-OM (all in the lower left hand corner of Figure 7) project the strongest temperature increases. Temperature projections differ considerably in magnitude between different GCMs (shown in exemplary form in Figure 7 for the A1B SRES scenario), but the general spatial pattern is consistently modelled in all models, with the strongest warming in sub-Saharan Africa to be found in southern Africa. Since the spatial pattern is in principle similar between the different models, computing a “mean model”, as in the lower right hand corner of Figure 7 and the upper row of Figure 8, is acceptable, since model extremes do not cancel out here. A mean model for precipitation projections, as in Figure 6, is less meaningful, since the spatial pattern differs significantly between the different models, as shown in exemplary form for the A1B scenario in Figure 9.

Except for the region of East Africa, especially around the Horn of Africa,[15] there is at least one GCM that projects substantial precipitation decrease under the A1B emission scenario (e. g. GFDL-CM2.0, GFDL-CM2.1) as well as at least one that projects substantial precipitation increases (e. g. CCSM 3), see Figure 9. Under such large inter-model variations, mean model tendencies such as those in the lower right hand corner of Figure 9 cannot be interpreted meaningfully. An alternative approach to describe the inter-model variability is shown in the bottom row of Figure 8. Here, the number of models that project an increase in precipitation is distinguished by colour. However, this approach falls short of communicating the whole of inter-model variability, since only the sign of change is compared but not the magnitude, i. e. even if all models agree that precipitation increases, differences may still be large. It should be noted that the range of disagreement is usually reported in mm/day and must be multiplied by 365 to get the annual deviation. The deviation displayed in the lower panel of Figure 6, for example, ranges from +5 to –5 mm/day, which refers to +/– 1825 mm/year. That is, even a “moderate” disagreement of 2 mm/day corresponds to 730 mm/year, which is more than total actual annual precipitation in many regions.

Changes in extreme precipitation events may be expected in Africa, as atmospheric water vapour is expected to rise. Rainfall intensities are expected to rise in southern Africa (Tadross / Jack / Hewitson 2005), and the West African monsoon could collapse, possibly causing increasing precipitation in the Sahel zone, but the mechanisms are uncertain (Lenton et al. 2008). The general expectancy of increasing extreme precipitation events is also supported by downscaled climate projections (Tadross / Jack / Hewitson 2005), although general research on African climate extremes is limited (Christensen et al. 2007). Projections of changes in tropical cyclones are not certain enough to allow for general conclusions, while extreme seasons are projected to increase in East and West Africa (see Table 4) (Christensen et al. 2007).

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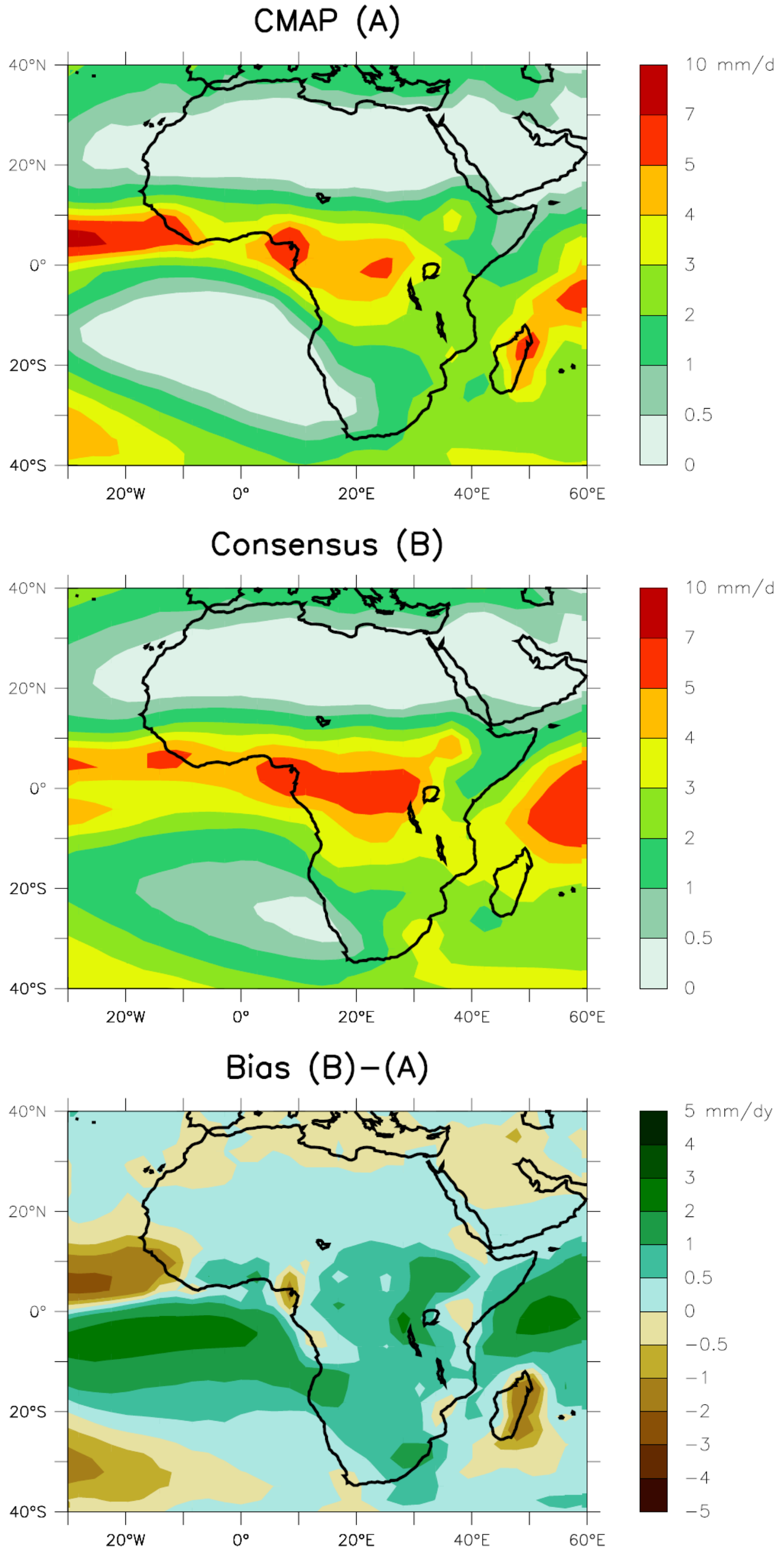
[15] The Horn of Africa is a region where GCMs tend to overestimate precipitation strongly in relative terms (up to +100 %, see Figure 6), casting doubt on the reliability of such projections.

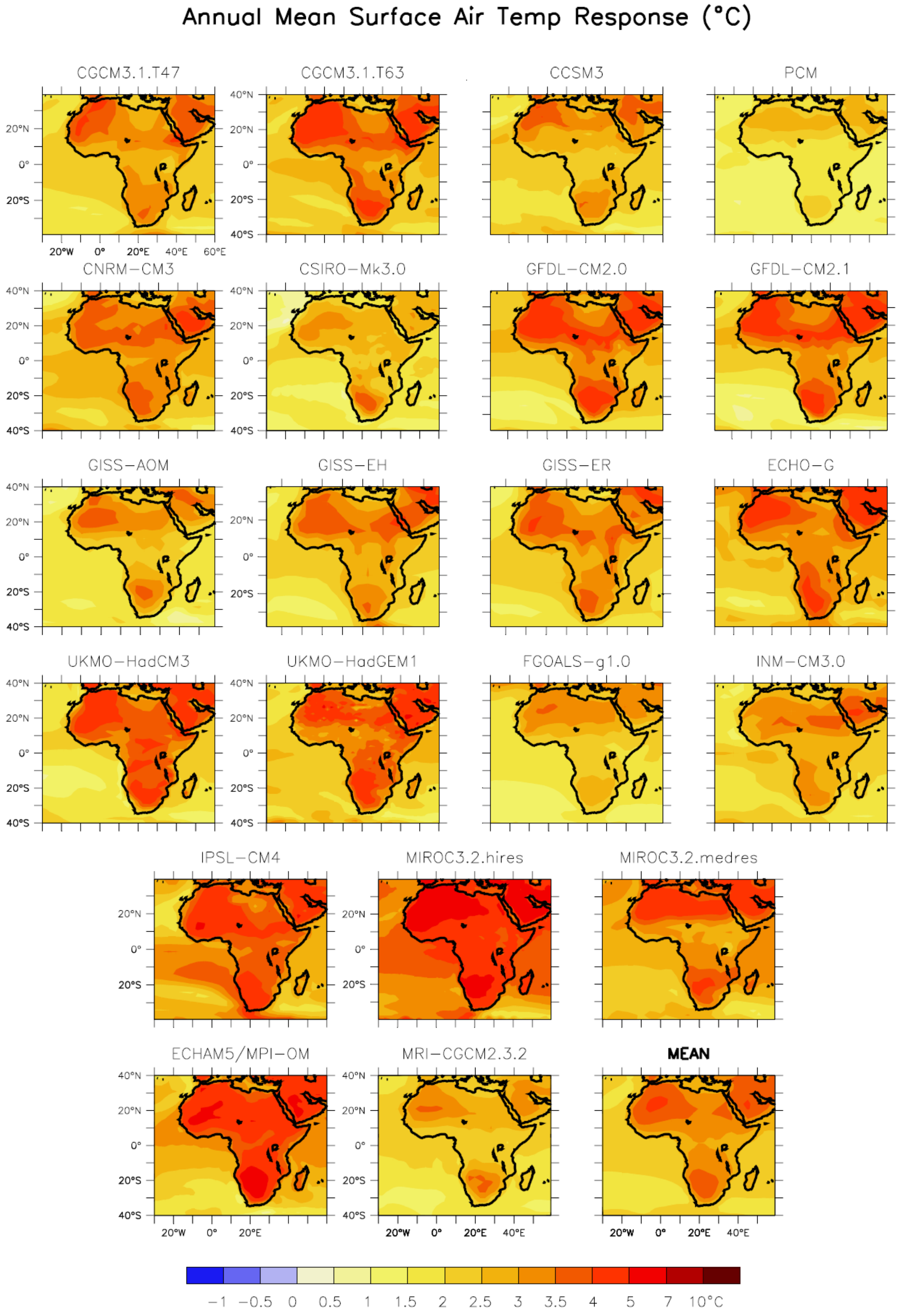
Figure 6: Annual mean precipitation in Africa in the years 1980–1999 (in mm/day)



(a) CMAP data set (update of Xie / Arkin (1997)); (b) mean of 21 CMIP3 models; (c) difference between the multi-model mean and the CMAP data.

Source: Christensen et al. (2007)

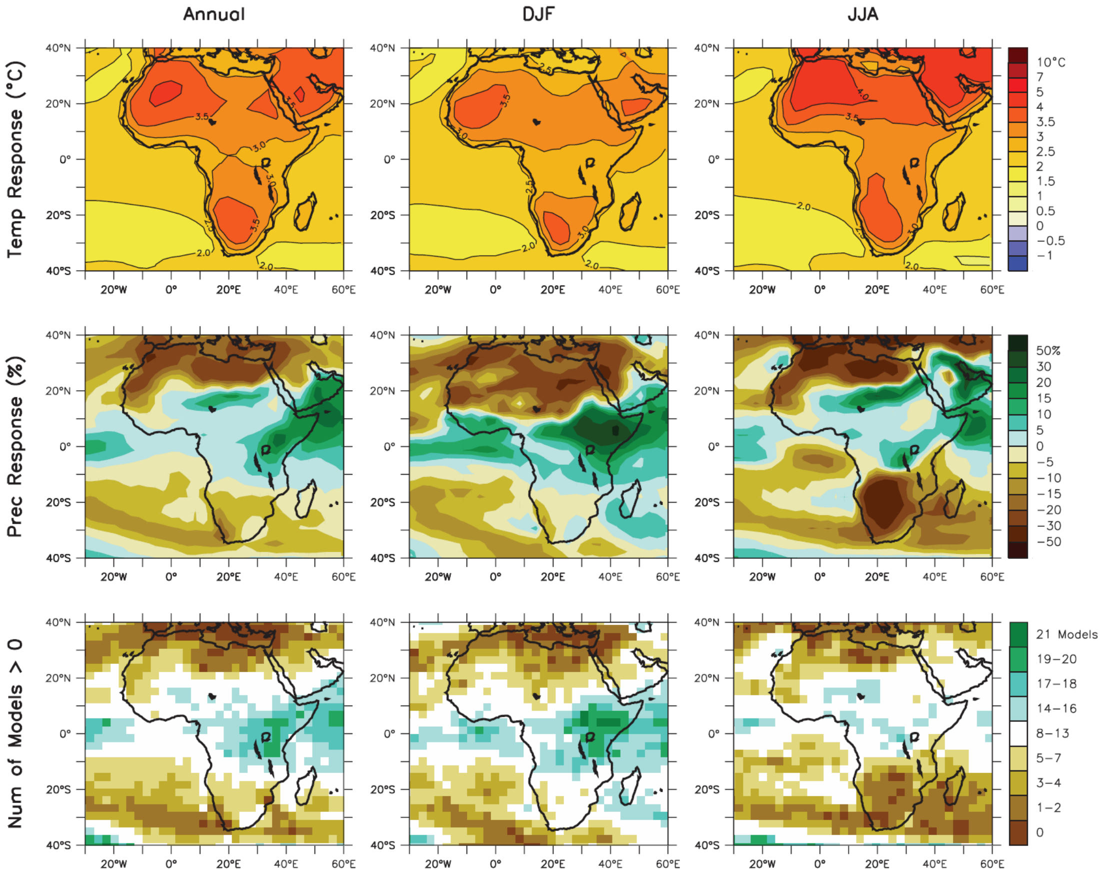
Figure 7: The annual mean temperature response in Africa in 21 CMIP3 models



What is shown is the temperature change from the years 1980–1999 to 2080–2099 under the A1B scenario, averaging over all available realizations for each model. The change averaged over all models is shown in the lower right hand corner.

Source: Christensen et al. (2007)

Figure 8: Temperature and precipitation changes over Africa from the CMIP3-A1B simulations



Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation.

Source: Christensen et al. (2007)

2.3.3 Downscaling of GCM climate projections

For regional impact studies, AOGCM or EMIC output can be downscaled with the help of regional climate models or statistical methods (Fowler / Blenkinsop / Tebaldi 2007; Giorgi 2006). However, RCM downscaling also adds considerable uncertainty to local climate projections, as there are notable differences between RCM projections (Tadross / Jack / Hewitson 2005), as shown as well in (for Europe). Statistical downscaling performs better for precipitation projections (Christensen et al. 2007), but can only be interpolated between measured station data, which is often limited by station density in Africa (Tadross, personal communication).

So far, RCMs do not provide enough evidence to modify large-scale temperature projections from GCMs, although Tadross / Hewitson / Usman (2005), using an RCM, project lower temperature increases than the driving GCMs for South Africa and Zimbabwe.

Downscaled climate data is less easily accessible than GCM outputs. Central facilities providing multi-model/scenario data are absent; and often RCM projections are not available as time series but for specific time slices only. The Climate Systems Analysis Group of Mark Tadross at the Department of Environmental and Geographical Science, University of Cape Town, South Africa,[16] seems to be the best reference for downscaled climate projections for Africa, which are not broadly available otherwise.

Some RCMs are publicly available, as are statistical methods, but none of these should be used without support of the developing and/or maintaining institutions.

2.4 Conclusions on the suitability of climate projections for impact assessments

Climate projections include considerable uncertainty rooted in the differences between emission scenarios, climate models and downscaling techniques. The wide variety of possible models and scenarios cannot possibly be considered in its full breadth in smaller impact research projects. Data availability already limits the choice of emission-scenario-GCM combinations, but not enough to circumvent a selection of data sets. The World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset[17] alone provides 151 different global climate projections.

Alternatively, only a few scenarios can be selected with the objective of covering the range of climate projections, which by definition focuses on extreme scenarios. Multi-model averages could be considered as "consensus projections", but they tend to be moderate as extremes cancel out. This is especially problematic for precipitation projections, where patterns may differ strongly (see Section 2.3.2).

On top of these difficulties of dealing with uncertainty, climate projections often cannot provide the detail needed for impact assessments. Weather extremes can e. g. not be projected sufficiently accurately to assess the impact of harvest-devastating and soil-eroding extreme precipitation events.

A typical approach to dealing with these shortcomings as well as with uncertainty is the use of general assumptions. This is a traditional approach in constructing scenarios: the uncertainty that cannot be sufficiently accurately projected (e. g. future energy consumption and energy mix in the SRES scenarios, see Section 2.1) is represented by different plausible assumptions. Falling back on assumptions even though quantitative projections are available is justified because the uncertainty cannot be handled quantitatively and because sufficient detail is not available. Available climate projections should be used, however, to define the assumptions, e. g. the range of possible changes in temperatures and precipitation, an increased likelihood of extremes due to more energy[18] in the atmosphere etc.

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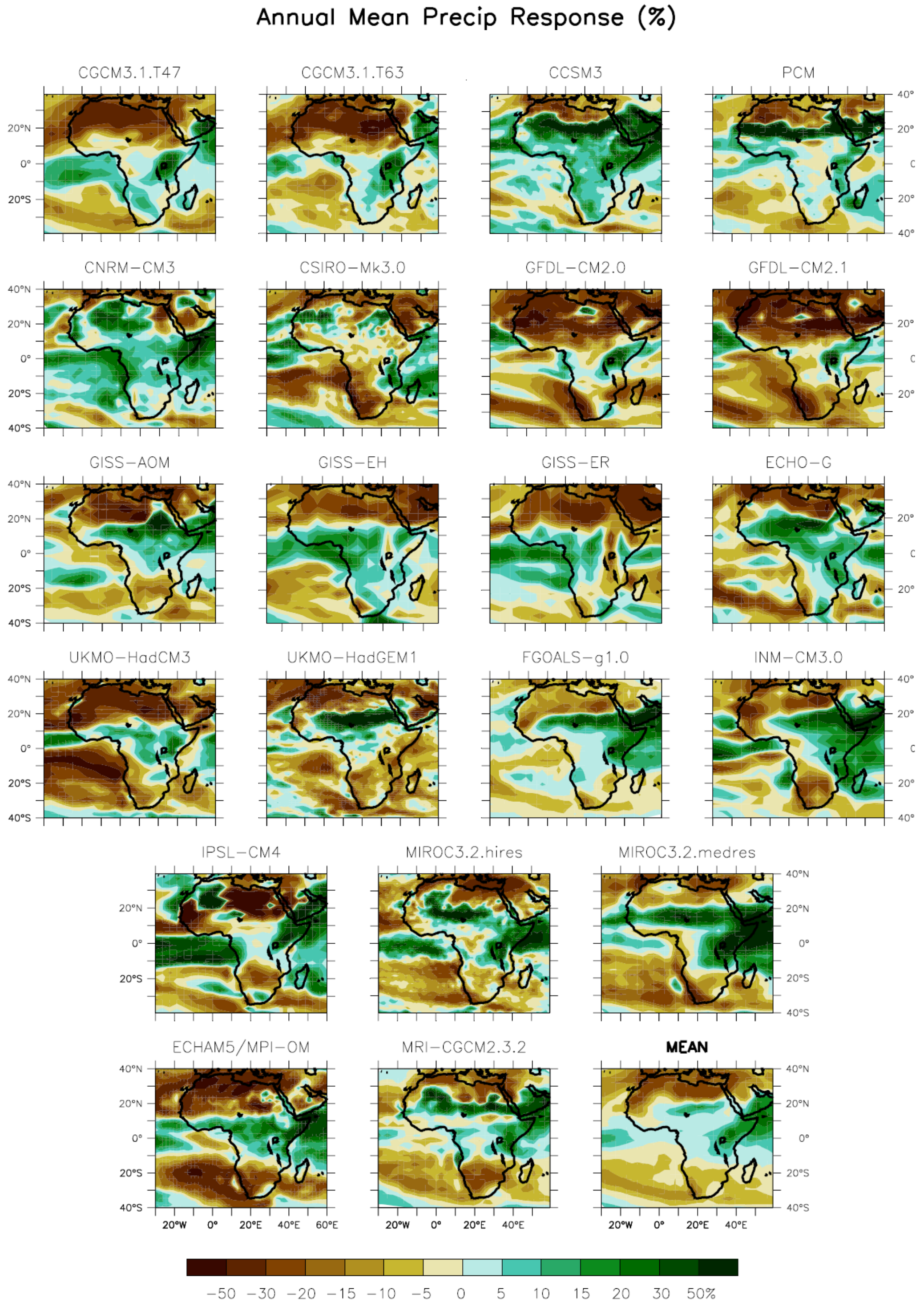
[16] http://www.csag.uct.ac.za

[17] https://esg.llnl.gov:8443/home/publicHomePage.do

[18] In the form of water vapour (latent heat) and heat.

Figure 9: The annual mean precipitation response in Africa in 21 CMIP3 models



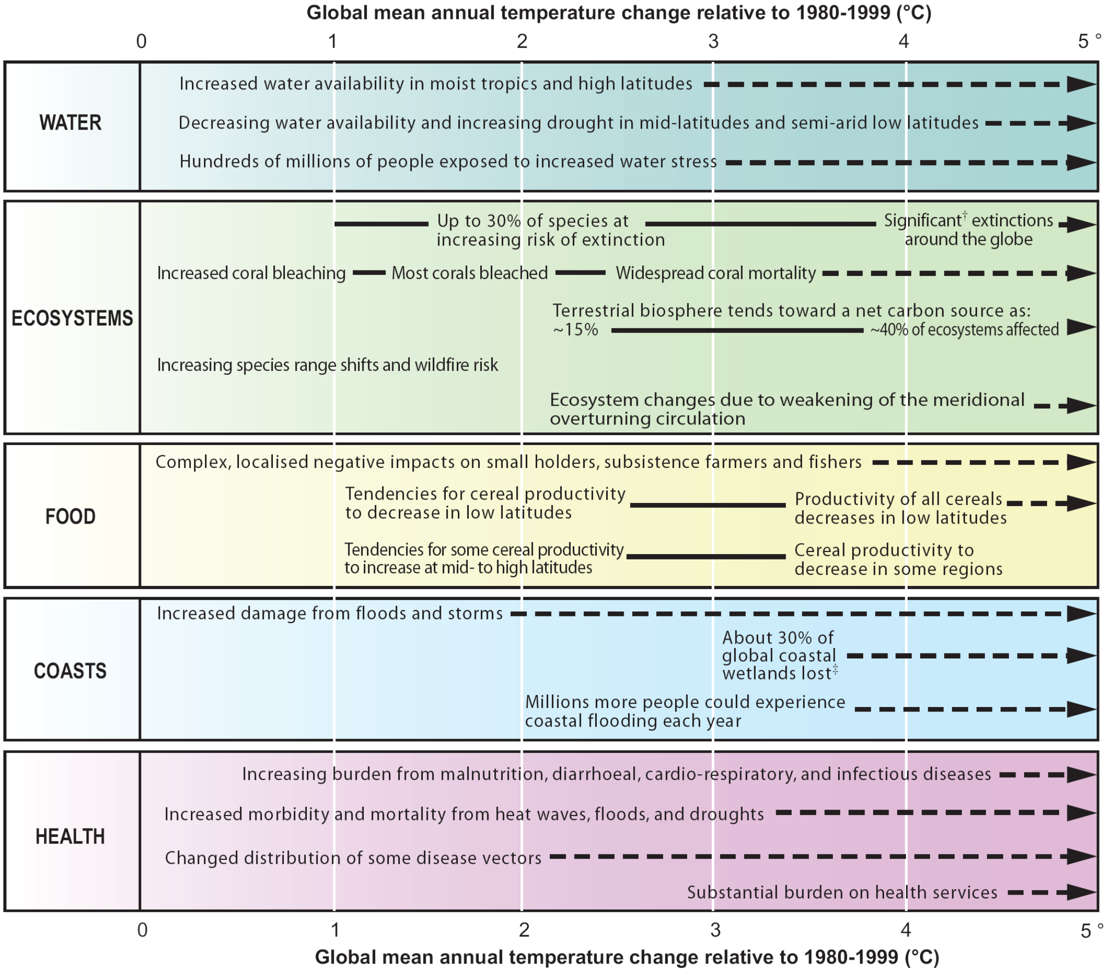
The figure shows the per cent change in precipitation from the years 1980–1999 to 2080–2099 under the A1B scenario, averaging over all available realizations for each model. Brown indicates a reduction in precipitation and green an increase. The per cent change in the precipitation averaged over all models is shown in the lower right hand corner.

Source: Christensen et al. (2007)

3 Impact projections

Climate change will affect societies and natural systems in various ways. Due to the considerable uncertainty in future climate change, which is smallest in temperature projections (see Section 2.3), temperature increase is often used as an indicator of the strength of climate change. Impacts of climate change have not been systematically evaluated yet, and overviews of climate change impacts, as exemplified for global-scale impacts in Figure 10, are typically based on a collection of case studies. These case studies typically differ in their basic assumptions and are thus hard to compare or generalize. Quantitative impact

Figure 10: Projected impacts of climate change, ordered by global mean annual temperature change relative to 1980–1999



Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide, where relevant) associated with different amounts of increase in global average surface temperature in the 21st century. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios A1FI, A2, B1 and B2 (see Section 2.1). Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the IPCC Fourth Assessment Report. Confidence levels for all statements are high.

Source: IPCC (2007b), modified

studies are still not broadly available, and those available only consider a small selection of scenarios (as e. g. Alcamo / Flörke / Märker 2007), use general assumptions on climate change (as e. g. Howden et al. 2007) or stylized climate scenarios (as e. g. Kurukulasuriya / Mendelsohn 2007).

Ordering climate change impacts by temperature as in Figure 10 allows for limited comparability of impacts, even though temperature may not always be the most important driver of climate change impacts. Ordering by temperature also makes impacts independent of temporal development, which is an important aspect in adaptation measures and also in vulnerability assessments. However, policy targets are often defined by temperature goals (e. g. +2°C maximum temperature increase), which are independent of transient development and also allow for overshooting.[19]

3.1 Agriculture

More than half of the population in sub-Saharan Africa is rural and depends directly on locally grown crops or food harvested from the immediate environment (WRI et al. 2005). Although only 8 % of the total land area is arable cropland and 34 % is permanent pasture land, agriculture is the major contributor to the economy and livelihoods in the African countries. On average, the agricultural sector's contribution to gross domestic product (GDP) accounts for 17 %, ranging from only 2 % in Botswana or 4 % in South Africa to 62 % in Guinea-Bissau or 58 % in the Democratic Republic of Congo (WRI et al. 2005). Despite considerable uncertainty as to the future economic development of African countries, economic development is likely to reduce the share of agriculture. In most countries the share could – under optimistic forecasts of economic development – decline to only 4 % by the end of the 21st century, while some may continue to have a large share of agriculture of over 10 % (Mendelsohn / Dinar / Dalfelt 2000).

Agriculture in sub-Saharan Africa is mostly subsistence and rain-fed agriculture. Although total water withdrawals for agriculture account for 88 % of total water abstraction (World Resources Institute (WRI) in collaboration with United Nations Development Programme 2005), on average only 3.7 % of the total agricultural land is irrigated (countries range from 18.7 % in Somalia to 0.1 % in Uganda and in the Democratic Republic of Congo) (Fields 2005).

In contrast to the global average trend, per capita food production in Africa has been declining over the past two decades. Currently, one third of the population is at risk from widespread hunger and malnutrition and most countries need emergency food aids (Desanker et al. 2001). Agricultural growth must rise to meet basic food requirements in the future. In theory, this can be reached by either a doubling of agricultural land, which would have strong implications for the natural environment, or by greater investment in agricultural management and technology on existing cropland (Desanker et al. 2001).

Climate is projected to change strongly in sub-Saharan Africa, with annual average temperature increases there between 1.8 and 4.8°C and annual changes in regional precipita-

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[19] In the concept of "overshoot" scenarios atmospheric concentrations and/or associated temperature increases could temporarily exceed target levels (Huntingford / Lowe 2007).

tion ranging between –12 and +25 % (seasonal changes range from –43 to +38 %) by 2100 (see Section 2.3, Table 4). Severe impacts on agricultural production throughout the continent are therefore expected. Countries in the arid and semi-arid tropics already have difficulties in coping with environmental stress. Decline in rainfall during the growing season in Ethiopia has caused serious damage in the past 10 years (Slingo et al. 2005). Increasing temperatures, changed precipitation patterns and more frequent droughts may lead to a substantial decrease in crop yields even if the production potential increases due to the fertility effects of enhanced CO_2 concentration (Sivakumar / Das / Brunini 2005).

Potential damage will be large; both in absolute terms and as a fraction of GDP. Mendelsohn / Dinar / Dalfelt (2000) indicate that average losses of agricultural GDP of African countries may reach 6 % if a set of adaptation measures is included. Here, adaptation means that variable production choices (inputs, crop types etc.) are varied over time to maximize net revenues. There is evidence that every region in Africa will experience some negative impacts. Mendelsohn / Dinar / Dalfelt (2000) provide more detailed and country-specific impact assessments. The basic assumptions underlying these impact assessments are highly uncertain. These assessments should therefore be interpreted on an aggregated level rather than on all detail provided: The impact assessments by Mendelsohn / Dinar / Dalfelt (2000) are based on 14 different GCMs, but the driving emission scenario is specified only as “an IPCC forecast of future atmospheric carbon dioxide levels by 2100” (Mendelsohn / Dinar / Dalfelt 2000, 3). In addition, the climate sensitivity of agricultural production in Africa was based on US- climate response functions, which cannot be assumed to be a good representation of African conditions, as the authors admit. Kurukulasuriya / Mendelsohn (2007) later calibrated climate change response functions for Africa based on a survey of >9000 randomly selected farms all over Africa. These functions, however, only explain 17–35 % of the variation in net revenue from farm to farm. These econometric assessments of climate change impacts on agricultural economy therefore have to be interpreted carefully even though they provide detailed quantitative impact measures. Besides, the economic impacts from biophysical impacts (e. g. length of growing period or actual yields, see below) are quite different since they include a lot of hidden assumptions on prices, choices, transition paths, etc. For methodological reasons, CO_2 fertilization cannot be considered in analyses of this type (Kurukulasuriya / Mendelsohn 2007).

Results of other studies also indicate that climate change will impact agriculture throughout the continent. Severe impacts will occur in countries located in the arid and semi-arid regions, especially in West Africa, where projected increased frequency of drought will heavily affect crop productivity. The share of arid and semi-arid land is likely to increase by 5–8 %, which amounts to 60–90 million hectares, and the extent and productivity of suitable rain-fed land is expected to decline by 2080 (Fischer et al. 2005). The length of the growing season, calculated by using temperature increases and changes in precipitation patterns, is likely to decrease across sub-Saharan Africa by 2050. Severe reductions of more than 20 % will occur in the Southern Sahara, in West Africa and in southern Africa in the border region of Angola and Namibia as well as in Zambia and Botswana (Thornton et al. 2006). Increases in the length of the growing season of at least 5 % in 2050 compared to the current length can be found in only a few areas. Gains are expected in parts of the Ethiopian highlands, Kenya and Uganda as well as in parts of southern Africa such as Zimbabwe and Mozambique (Thornton et al. 2006). The assessments of changes in the length of the growing period by Thornton et al. (2006) utilize a rigid definition of days contributing to the growing season (actual evapotranspiration/potential evapotranspiration >0.5 and daily average temperature >9°C). This static definition of the growing season may be unrealistic for some crops and cannot be directly linked to yields, which are determined by the interaction of selection of crop variety, and the temporal dynamics of water availability, temperature, and incoming radiation.[20] Therefore, changes in the length of growing period can only be regarded as indications that environmental conditions are changing, unless the assessment indicates that the length of the growing period may become too short to facilitate any cultivation at all.

The magnitude of projected impacts on crop productivity varies among different studies due to the use of different climate and crop models (an overview of the results of several studies can be found in Gitay et al. 2001). Nevertheless, they indicate that the response of crop yields to climate change in sub-Saharan Africa is mainly negative, and yields are likely to decrease in many parts of Africa (Challinor et al. 2007; Gitay et al. 2001) over the 21st century.

For example, Jones / Thornton (2003) suggest that by the middle of the 21st century climate change impacts will reduce maize production by 12 % on average in the territory of sub-Saharan Africa. The decline on maize yields will be greatest in the dry tropics, with a decrease of up to 24 %. In the temperate regions yields will be reduced by up to 20 %, while in the subtropical cold winter environment yields are likely to increase due to warmer and thus more favourable temperatures (Jones / Thornton 2003). A study of crop yield changes by the end of the 21st century indicates yield reductions for maize in the range of 23 to 29 % and a range of 15 to 20 % for wheat (Gitay et al. 2001).

Figure 11 shows a decline in cereal production potential for sub-Saharan Africa in the range of 12 % by the end of the century (i. e. 2080 here), though with large variation across the continent, as calculated by Fischer et al. (2005). Areas shaded in green are expected to experience improved conditions for cereal production by 2080; in areas shaded in brownish colours, cereal yields are expected to decline. Figure 11 shows in exemplary form how some of the uncertainty in climate change projections (see Section 2) strongly affects impact assessments. The GCMs CGCM2 and CSIRO project a strong decline in cereal production by 2080 under the A2 scenario (see Section 2.1) in the Sahel zone and also in large parts of southern Africa (upper row), while HADCM3 and ECHAM4 projections are more optimistic here (increases up to >50 % compared to current conditions). For central Africa, however, the picture is reversed, with CGCM2 and CSIRO projecting improvements in cereal production by 2080, while HADCM3 and ECHAM4 project smaller increases or even decreases here. Reductions of up to 40 % are expected mainly in West Africa and in the Southern Sahara but also in the south of Africa. However, gains are also predicted for some countries, including Zaire, Kenya, Uganda, Côte d'Ivoire, Benin, Togo, Ghana and Guinea (Fischer et al. 2005).

The response of agricultural productivity depends in large measure on projections of changes in precipitation. If sufficient water is available, direct effects of increasing temperatures on agricultural production can be ameliorated to some extent by means of relatively simple adaptation measures such as selection of crop varieties better suited for

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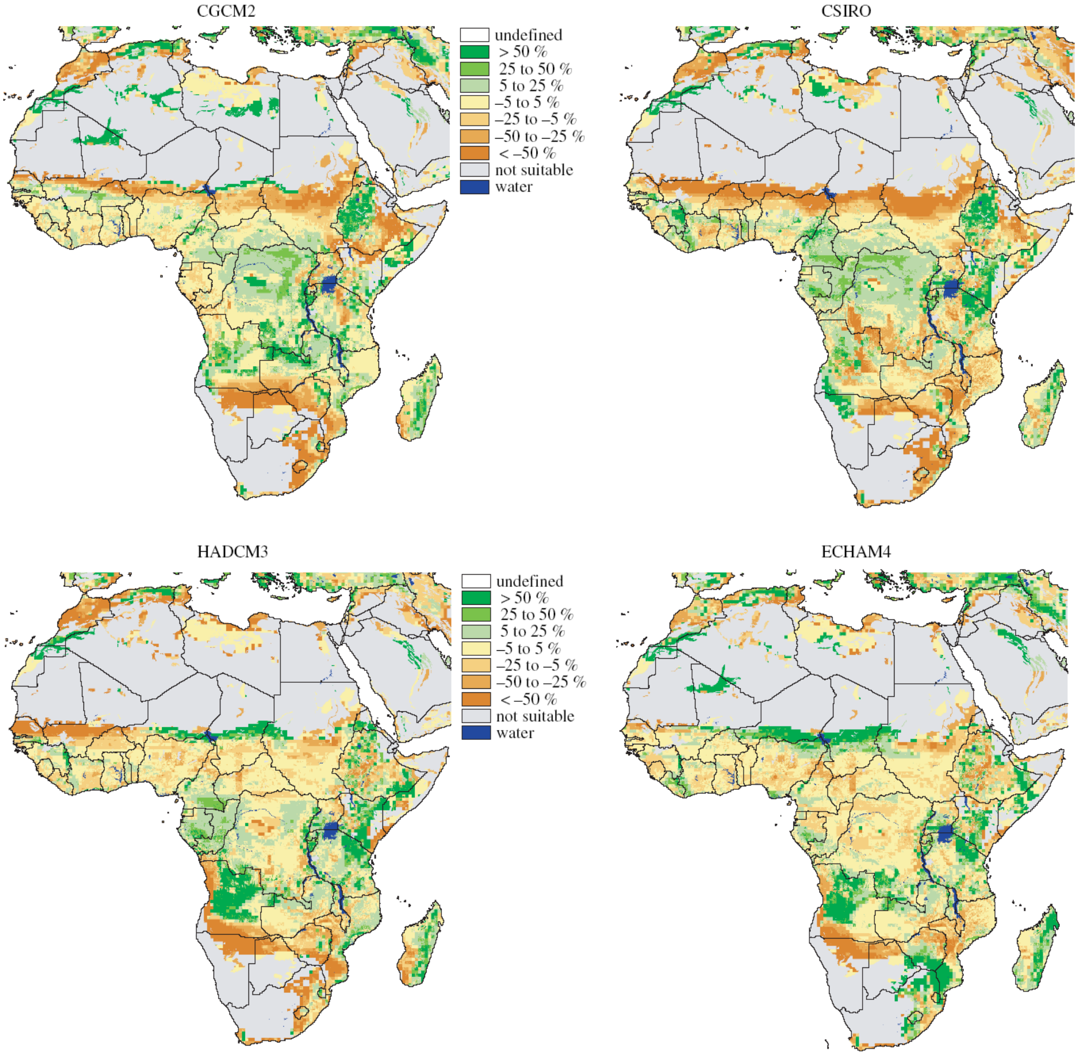
[20] The annual variation of incoming solar radiation increases with latitude, while cloudiness largely affects the partitioning of radiation in direct and indirect radiation and has smaller effects on plant growth.

higher temperatures or by moving to cooler periods of the year. This is of course not possible if temperatures are already very high all year through. The possible range of climate impacts on agricultural production also includes more favourable conditions, especially in dry regions under increasing precipitation, but also in high elevations, where low temperatures may at present set limits to crop production. However, even under a relatively favourable climate scenario the most densely populated areas have a high likelihood to be negatively affected by climate change impacts on agriculture, including West Africa the South of the Sahara, Central Africa and North- to South-East Africa (Kurukulasuriya / Mendelsohn 2007).

Figure 11: Climate change impacts on cereal production under the A2 scenario by 2080



Climate change impact scenarios for 4 different GCM projections: CGCM2, CISRO, HADCM3, and ECHAM4. The spatial pattern of climate change impacts of the A2 scenario on cereal production by 2080 varies greatly between the GCMs.

Source: Fischer et al. (2005)

Rising atmospheric CO_2 concentrations not only drive climate change, they also stimulate plant growth in C3 plants.[21] This effect has been demonstrated in various experiments, ranging from totally artificial growth conditions (chamber experiments) to free air carbon enrichment (FACE) experiments, where open air experimental plots are exposed to increased atmospheric CO_2 concentrations. For C3 plants, such as wheat, rice, and soybeans, crop yields increase by roughly 15–20 % when exposed to atmospheric CO_2 concentrations of 550 instead of 350 ppm (Tubiello et al. 2007). C4 plants, such as maize, sorghum, and millet, are not, or only marginally, affected by elevated atmospheric CO_2 concentrations due to their carbon fixation mechanism. All plants, including C3 and C4 plants, are expected to have higher water-use efficiency under elevated CO_2 concentrations.[22] Consequently, yield increases are to be expected in water-limited areas, but the magnitude of this effect remains uncertain.

Climate change impacts on agriculture at larger scales are at present usually assessed with statistical (e. g. Lobell et al. 2008) or econometric means (e. g. Kurukulasuriya / Mendelsohn 2007), deduced from changes in vegetation periods (Thornton et al. 2006), or with the GAEZ model, a simplified crop model driven by a comprehensive database on climate, soil properties, and management (Fischer et al. 2002). Smaller-scale assessments usually address very specific conditions and employ more detailed crop growth models such as DSSAT (Jones et al. 2003), EPIC (Williams / Renard / Dyke 1983; Williams / Singh 1995) or many other field-scale crop models. There are several attempts to apply detailed crop growth models at the global scale, but these are still in their infancy (Bondeau et al. 2007; Stehfest et al. 2007; Tan / Shibasaki 2003) and no future projections are available.

3.2 Water availability

Water availability is determined by water inflow (precipitation, lateral flows) and water losses (withdrawals, evapo-transpiration, lateral outflow). Water quality also determines water availability, as contaminated water is not available for certain applications, but this is generally ignored in large-scale assessments. Scientific studies often consider only specific aspects of water availability, such as stream-flow water, water withdrawals, water consumption, plant-available water etc., which may vary considerably.

Currently, about 25 % of the African population experiences water stress, i. e. there is less than 1000 m^3/year/capita available, while 69 % live under relative water abundance (Vörösmarty et al. 2005); however, access to water and water quality are not reflected in these numbers. Water stress is likely to increase in large parts of Africa over the 21st century (see Figure 12 and Figure 13) (Alcamo / Flörke / Märker 2007; de Wit / Stankiewicz 2006), and this will be driven not only by changes in precipitation but also by socio-eco-

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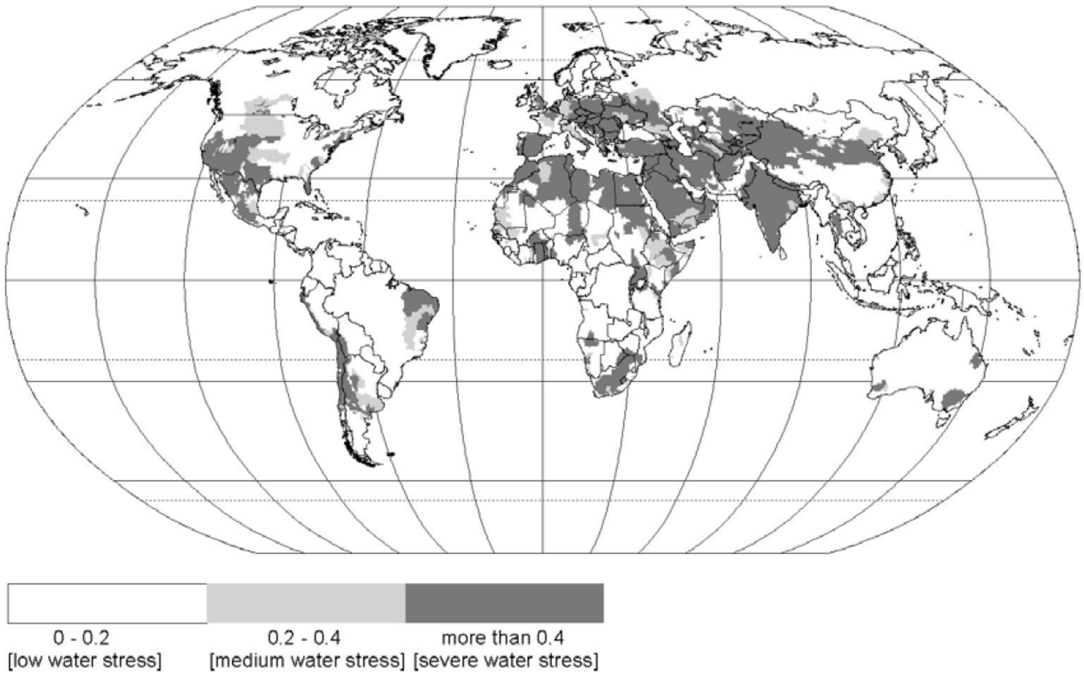
[21] There are two main types of carbon fixation mechanisms in photosynthesis: C3 and C4, named after the primary length of the carbon hydrate, which includes 3 and 4 carbon atoms, respectively.

[22] Plants take up CO_2 via openings in their leaves (stomata). These stomata regulate the transpiration of water at the same time and have to be closed under water stress conditions to avoid dehydration damage to the plant. Since the influx of CO_2 is stronger under elevated atmospheric CO_2 concentrations, plants can therefore close their stomata more often and are thus able to produce the same biomass at a lower transpiration rate.

nomic changes (Alcamo / Flörke / Märker 2007; Arnell 2004), as shown in Figure 13. Water availability is closely linked to health issues and agriculture (Section 3.1), especially for irrigation requirements (Döll 2002).

Assessments of water stress often only consider surface water availability per capita, neglecting water quality, water demand, direct utilization of rainfall for plant growth, and the possibility of technical adaptation measures. Especially in African agriculture, measures of soil water conservation and rain water harvest yield some potential to lessen water shortages (UNEP / IETC 1998; Critchley et al. 1991).

Figure 12: Water stress in the 2050s for the A2 scenario based on withdrawals to availability ratio

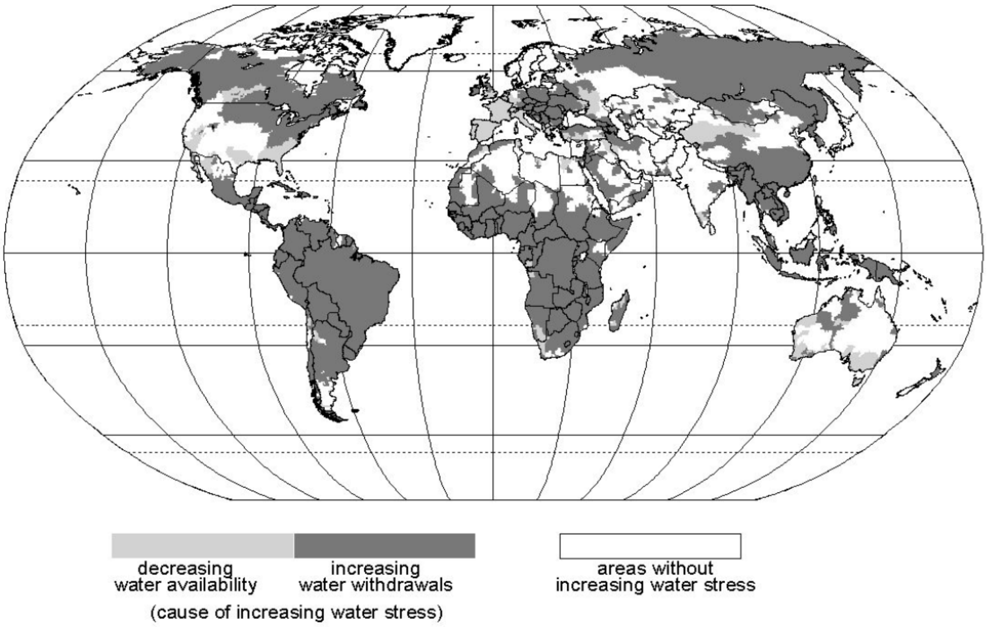


"Water withdrawals" are total annual water withdrawals from surface or groundwater sources within a river basin for various anthropogenic uses (excluding the maintenance of aquatic or riparian ecosystems). "Water availability" corresponds to annual river discharge, that is, combined surface runoff and groundwater recharge.

Source: Alcamo / Flörke / Märker (2007)

About one third of the African population live in drought-prone areas and are vulnerable to the impacts of droughts (World Water Forum 2000). Droughts have contributed to migration, dislocation of populations, cultural separation, and the collapse of African cultures in the past. Especially since the 1960s, droughts have mainly affected the Sahel, the Horn of Africa, and southern Africa, having severe impacts on societies. Rainfall in West Africa decreased by 20–40 % in the period 1968–1999, compared to the period of 1931–1960 (Nicholson / Some / Kone 2000). The variation of rainfall in South-West Africa is influenced by the El-Niño Southern Oscillation (ENSO) decadal variations and the North Atlantic Oscillation (NAO).

Figure 13: Changing water stress between "current conditions" and the 2050s for the A2 scenario



Areas of increasing water stress where decreasing water availability is more important, and areas of increasing water stress where increasing water use is more important.

Source: Alcamo / Flörke / Märker (2007)

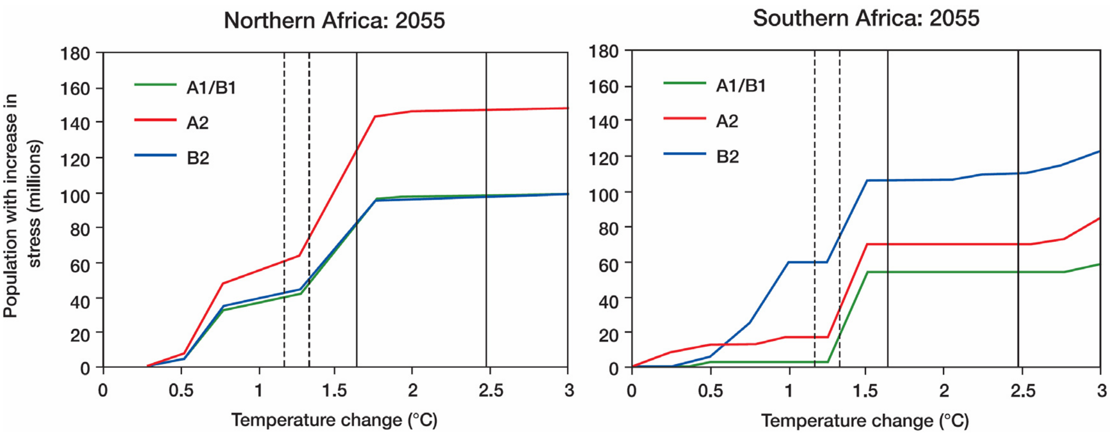
Arnell (2004) projects that the population at risk of increased water stress will increase to 75–250 million by the 2020s and to 350–600 million by the 2050s, considering the full breadth of the SRES scenarios. Figure 14 shows the population with increase in water stress in northern and southern Africa in 2055 (Arnell 2006). The different SRES scenarios employed here not only drive the HadCM3 climate model but also describe different trajectories in population growth (Nakicenovic / Swart 2000). These assumptions on population development also affect the regional impact: While the A2 scenario leads to the largest number of people experiencing increased water stress in northern Africa, the B2 scenario shows a larger impact in southern Africa (Figure 14). The steps in the functions in Figure 14 occur as more watersheds experience a significant decrease in runoff.

Climate change is not the only threat to the African water sector. Population changes, land-use changes, domestic growth strategies as well as overfishing, industrial pollution and sedimentation may be more important in water management decision-making than climate change alone (Boko et al. 2007).

3.3 General natural trends and biodiversity

Africa is home to about 1/5 of all known species of plants, mammals and birds. This rich biodiversity is currently decreasing and is projected to continue to decrease (Boko et al. 2007). Especially mountainous regions are projected to suffer from temperature in-

Figure 14: Number of people (millions) with an increase in water stress (Arnell 2006)



Scenarios all derived from HadCM3, and the red, green and blue lines relate to different population projections.

Source: Boko et al. (2007), modified

creases, most prominently demonstrated by the melting of the glacier on Mt. Kilimanjaro (Boko et al. 2007). Under climate and land-use change, habitats are projected to shift spatially or disappear completely, forcing species to migrate (McClean et al. 2005). An overview of significant African ecosystem responses to climate change is given in Table 5.

The ENSO dynamics have been linked to weather extremes in Africa, especially southern Africa. These ENSO-induced variations of precipitation have caused droughts as well as flooding (Boko et al. 2007). However, despite progress in modelling ENSO dynamics with AOGCMs, there are large systematic errors and the processes are not fully understood, and this reduces the models' ability to project future changes in ENSO dynamics (Randall et al. 2007). Lenton et al. (2008) see a "significant probability" of increased frequency and amplitude of ENSO events. The required temperature increase (>3°C) could be reached within this century, with the transition coming about within a millennium. Another important tipping point[23] in Africa is the West African monsoon, which is linked to SSTs in the Gulf of Guinea. If SSTs warm more than 3°C, there is a chance that the West African monsoon may break down, possibly leading to higher precipitation in the Sahel (Lenton et al. 2008). However, these mechanisms (break-down of West African monsoon and subsequent increase in Sahel precipitation) are not reproduced by many AOGCMs. A teleconnection between ENSO and monsoon regimes is only supported by 4 out of 21 AOGCMs (Randall et al. 2007). The Sahel could also support more vegetation due to the increased water-use efficiency possible under elevated atmospheric CO_2 concentrations (see Section 3.1, footnote 22). This increases the likelihood that the Sahara may switch to an alternative stable state, with vegetation growing there (Lenton et al. 2008). Land-use change and increasing land degradation in the Sahel could, however, prevent the Sahel from greening, keeping the system in the current state, without vegetation cover in the Saharan region.

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[23] A tipping point is the corresponding critical point – in forcing and a feature of the system – at which the future state of the system is qualitatively altered (Lenton et al. 2008).

Table 5: Significant ecosystem responses estimated in relation to climate change in Africa

Ecosystem impacts	Area affected	Scenario used and source
About 5,000 African plant species impacted: substantial reductions in areas of suitable climate for 81–97 % of the 5,197 African plants examined, 25–42 % vanish by 2085.	Africa	HadCM3 for years 2025, 2055, 2085, plus other models – shifts in climate suitability examined (McClean et al. 2005)
Fynbos and succulent Karoo biomes: losses of between 51 and 61 %.	South Africa	Projected losses by 2050, see details of scenarios (Midgley et al. 2002)
Critically endangered taxa (e. g. Proteaceae): losses increase, and up to 2 % of the 227 taxa become extinct.	Low-lying coastal areas	4 land use and 4 climate change scenarios (HadCM2 IS92aGGa) (Bomhard et al. 2005)
Losses of nyala and zebra: Kruger Park study estimates 66 % of species lost.	Malawi South Africa (Kruger Park)	(Dixon / Smith / Guill 2003) Hadley Centre Unified Model, no sulphates (Erasmus et al. 2002)
Loss of bird species ranges: (restrict-ion of movements). An estimated 6 species could lose substantial portions of their range.	Southern African bird species (Nama-Karoo area)	Projected losses of over 50 % for some species by 2050 using the HadCM3 GCM with an A2 emissions scenario (Simmons et al. 2004)
Sand-dune mobilisation: enhanced dune activity.	Southern Kalahari basin – northern South Africa, Angola and Zambia, Sahel	Scenarios: HadCM3 GCM, SRES A2, B2 and A1fa, IS92a. By 2099 all dune fields shown to be highly dynamic (Thomas / Knight / Wiggs 2005)
Lake ecosystems, wetlands	Lake Tanganyika	Carbon isotope data show aquatic losses of about 20 % with a 30 % decrease in fish yields. It is estimated that climate change may further reduce lake productivity (O'Reilly et al. 2003)
Grasslands	Complex impacts on grasslands including the role of fire (Southern Africa)	Various, see Fischlin et al. (2007)
Estimates based on a variety of scenarios.		
Source: Boko et al. (2007)		

4 Conclusions

4.1 Gaps and uncertainties in models and scenarios

The CMIP3 models have significant systematic errors in and around Africa (Christensen et al. 2007). Future projections are therefore not very reliable in Africa. Water availability is a key factor for most impact assessments in Africa. Yet precipitation projections in particular are contradictory and thus unreliable (see Section 2.3.2). Systematic errors of GCMs such as small displacements of rain belts or the Inter-Tropical Convergence Zone

(ITCZ) may have large local effects. This holds true as well for extreme events (droughts, flooding) and also for overall and seasonal availability of water.

Emission scenarios are reasonable future projections of energy demand and supply. These can include presumptions on technological progress (e. g. Edenhofer / Bauer / Kriegler 2005), which are highly uncertain.

Climate projections and the underlying emission scenarios are highly uncertain, while impact assessments are still largely lacking. Impact studies rarely address the full breadth of possible climate change projections and are still of a very general nature. Mostly, large impacts on different sectors (e. g. agriculture) are not quantified. For assessments of vulnerability and political advice, this gap needs to be bridged with general assumptions. Often, impacts are expected to be strong on the general basis that climate is expected to change significantly.

While temperature projections for Africa are relatively homogenous and largely agree on the trend (Table 4), precipitation projections are very controversial among GCMs and scenarios, although the models seem to agree that precipitation patterns will change (Figure 9).

Especially in the agricultural sector, there are contradictory assumptions on non-climatic drivers of agricultural production, e. g. the effects of CO_2 fertilization (Long et al. 2006; Tubiello et al. 2007) and technological development (Gregory / Ingram 2000; Rounsevell et al. 2005). Water demand and withdrawal, and thus water shortages, are also uncertain, even in the absence of climate change (Rosegrant / Cai 2003; Döll 2002).

There is little consistency between different studies on time frame and coverage of climate projection uncertainty. Often studies address either short-term changes (up to 2020/2030), mid-term changes (2040–2050), and/or long-term changes (2080–2100), but there usually is no justification for the time frame selected. In most impact studies, two different SRES scenarios (or other scenarios) are selected to cover the range of possibilities (e. g. A2 vs. B2, as used by Alcamo / Flörke / Märker 2007) and largely arbitrary selection of GCM implementations of these emission scenarios.

4.2 Dealing with uncertainty in climate change impact studies

There are a large number of climate change projections available. This breadth of scenarios, however, does not embrace the whole of uncertainty in possible future climate change, given just the relatively small number of different emission scenarios covered and the omission of other drivers such as the biophysical effects of land-use change.[24] Still, even this variety of projections alone requires considerable analytical capacities. Full quantitative assessments are thus not possible for smaller assessments. Alternative approaches therefore have to be considered. One is to employ a subset of available scenarios. This selection necessarily is largely random, as limited capacities also prohibit an in-depth analy-

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[24] Typically, land-use change emissions (CO_2) are implicitly included in the driving emission scenarios. Thus, climate projections account for the biogeochemical effects of land-use change (radiative forcing of emitted CO_2), but ignore biogeophysical effects on, inter alia, albedo and surface drag (Brovkin et al. 2006).

sis of scenario suitability. Subsets used in other studies can only provide limited orientation, since these selections are rarely justified and may be motivated by data availability only.

Another, possibly more promising approach is to transfer the uncertainty of climate change projections into specific assumptions on possible climate change (see also Section 2.4). Kurukulasuriya / Mendelsohn (2007) do this by driving their model with stylized assumptions on climate change (+2.5°C, +5.0°C, –7 % precipitation, –14 % precipitation). Given the large uncertainty in impact assessments of specific climate change,[25] it seems plausible to utilize assumptions on the level of impacts rather than on the level of climate change. Such assumptions on the impact level should be justified by currently available impact assessments and an assessment of the breadth of climate change projections considered in these studies. This requires a detailed analysis of available climate change impact studies, which are mainly specific case studies and possibly difficult to access.[26]

A third possibility is to rely on the expertise of external partners. There are several groups with detailed knowledge on specific regions/countries, and they are often in close contact with African partner institutions. Modelling groups could in principle provide quantitative assessments of specifically designed climate change scenarios. However, this requires either funding of those activities or offers of support in return.

External (regional) expertise is also essential to identify possible research focus regions. There are groups with regional expertise, especially in Southern Africa but also in some West African countries. A more detailed analysis of regional and local case studies would also be beneficial to identify hot-spots of vulnerability in sub-Saharan Africa. No focal area for climate change impact analyses can be identified from available climate change projections: all regions are expected to warm over the 21st century, and all have considerable likelihood to experience declining precipitation (see e. g. Table 4). For Southern Africa there is at least one active research group with regional climate expertise (University of Cape Town, South Africa).

A vulnerability assessment could also put climate change, with all its uncertainty, at the end of the analysis chain. With detailed knowledge about current systems, dangerous climate change could be defined via its potential damage to these systems. Thresholds between tolerable and dangerous climate change defined in such way could then be compared with their likelihood to occur in different climate change scenarios. This would avoid analyzing the entire breadth of climate change projections for sub-Saharan Africa, while at the same time making it possible to focus on specific regions where knowledge about vulnerabilities is available.

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[25] E. g. 17–35 % model accuracy in the study of Kurukulasuriya / Mendelsohn (2007), while others do not even quantify the accuracy of their impact projections.

[26] Partially published in the form of reports, which are not all accessible to the public, while publication in scientific journals often leads to delays of up to two years between assessment and publication.

4.3 Relevance for politics of uncertainty in climate change impacts

Food security and economic development are major challenges for sub-Saharan Africa, and would be even if climate change were completely absent. The current situation is already unsatisfactory in many regions and growing populations and climate change constitute additional threats.

Climate change and the impacts of climate change on societies and ecosystems are highly uncertain in Africa. There is agreement that the climate will change, even more strongly than the global average. However, there is hardly any agreement on the seasonal and regional distribution of these changes. Precipitation may both increase and decrease significantly in almost all regions and seasons; see the exemplary presentation in Figure 9 and Table 4. Many African natural and human systems are water-limited, and therefore precipitation may well be the most important aspect of climate in these regions.

Given the uncertainty as to economic development and energy production and consumption, as well as in climate projections for specific emission scenarios, it is very hard to quantify climate change impacts in a spatially explicit way. On top of that, there is considerable uncertainty in impact assessments, including e. g. the controversy over the effects of CO_2 fertilization in agricultural production (Long et al. 2006; Tubiello et al. 2007) or the potential of technological progress in the energy (Barker 2008; Edenhofer / Bauer / Kriegler 2005) and agricultural sectors (Gregory / Ingram 2000; Rounsevell et al. 2005).

In spite of all these uncertainties, there is a broad consensus that especially Africa will experience severe climate change (Christensen et al. 2007). Even though the local specifics are uncertain, the likelihood of severe changes is too risky to ignore. Consequently, production systems and households should strive to become less dependent on environmental conditions (such as climate) and more flexible through diversification of income. The focus in development measures should be on development plans that are (a) also beneficial in the absence of climate change and (b) also effective under a broad spectrum of possible climatic conditions (e. g. wetter – no change – dryer), including e. g. water-harvest techniques that could buffer both affluent and insufficient precipitation. Even in regions where the likelihood of increasing precipitation is high (e. g. East Africa), development measures should not rely on regular precipitation events, since the seasonality of precipitation events is even more uncertain than annual means (see Sections 2.3.1 and 2.3.2) – and extremes are likely to increase (Christensen et al. 2007).

The uncertainty as to the impacts of climate change makes it very hard to define specific adaptation strategies, and this will remain a challenge. The main foci in increasing adaptive capacity in sub-Saharan Africa should be (a) efforts to become more independent of stable and/or regular climate patterns, such as extending irrigation facilities where applicable, and (b) efforts to diversify income structures and increase societal flexibility to respond to changing environmental conditions.

In the foreseeable future, impact assessments will have to rely heavily on assumptions about drivers (such as emission scenarios or climate change) and systems' response (e. g. on a system's flexibility in adapting land-use patterns or on technological change). Modelling tools can help to maintain consistency in assumptions and to analyze the systematic consequences of these assumptions. However, models are often forced to strongly reduce the system's complexity, which has the potential to strongly affect the system's response. Even though model improvements will make up for some of the present shortcomings, assessments of impacts and vulnerability should always be only model-supported, not model-based. Specific local case studies are usually hard to extrapolate due to very heterogenic cultural, social, and environmental conditions, while large-scale studies may fail to provide sufficient accuracy at the local level.

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