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Review

Studies of 21st-century precipitation trends over West Africa

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ABSTRACT: West Africa includes a semi-arid zone between the Sahara Desert and the humid Gulf of Guinea coast, approximately between 10°N and 20°N, which is irrigated by summer monsoon rains. This article refers to the region as the Sahel. Rain-fed agriculture is the primary sustenance for Sahel populations, and severe droughts (in the 1970s and 1980s), therefore, have devastating negative societal impacts. The future frequency of Sahel droughts and the evolution of its hydrological balance are therefore of great interest. The article reviews 10 recent research studies that attempt to discover how climate changes will affect the hydrology of the Sahel throughout the 21st century. All 10 studies rely on atmosphere–ocean global climate model (AOGCM) simulations based on a range of greenhouse gas emissions scenarios. Many of the simulations are contained in the Intergovernmental Panel on Climate Change archives for Assessment Reports #3 and #4. Two of the studies use AOGCM data to drive regional climate models. Seven studies make projections for the first half of the 21st century and eight studies make projections for the second half. Some studies make projections of wetter conditions and some predict more frequent droughts, and each describes the atmospheric processes associated with its prediction. Only one study projects more frequent droughts before 2050, and that is only for continent-wide degradation in vegetation cover. The challenge to correctly simulate Sahel rainfall decadal trends is particularly daunting because multiple physical mechanisms compete to drive the trend upwards or downwards. A variety of model deficiencies, regarding the simulation of one or more of these physical processes, taints models' climate change projections. Consequently, no consensus emerges regarding the impact of anticipated greenhouse gas forcing on the hydrology of the Sahel in the second half of the 21st century. Copyright © 2010 Royal Meteorological Society

KEY WORDS West African monsoon; Sahel droughts; climate change

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1. Introduction

The transition zone between the Sahara Desert and the more humid Gulf of Guinea coast of West Africa includes a savannah irrigated by summer monsoon rains. The Sahel is the northern edge of the transition zone, south of the desert. In the following discussion, the nomenclature Sahel is used in its broadest sense to refer to the swath over West Africa situated approximately between 10°N and 20°N. Most of the Sahel's annual rainfall is received between June and September and none in the winter. Droughts can be characterized by late monsoon onset, early retreat or otherwise weak rain-producing systems, and droughts often create severe societal impacts (Dietz *et al*., 2004). According to Tarhule *et al*. (2009), about 95% of the land use in sub-Saharan Africa is devoted to agriculture and some 65% of the population is occupied with agricultural work. As large Sahel populations rely on rain-irrigated pastures and crops, droughts in this area have led to famines, population shifts and social upheaval. In recent history, copious Sahel rainfall in the 1950s gave way to droughts in the 1970s, which became the most severe in the mid-1980s. Since then, seasonal rainfall accumulations over the Sahel have somewhat recovered, but not to the 1950s level. Between 1972 and 1982, some 100 000 people in this region died from starvation and in 1974 about 750 000 were totally dependent on food aid (UNEP, 2004). Given such grim statistics, there is a clear mandate to investigate how global climate change will affect this region of the world. This article reviews a sample of the literature describing climate change studies for West Africa. Because a complete and exhaustive summary of all of the cited studies is prohibitive, the review highlights research results of selected projections of hydrological conditions in the 21st century.

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2. Intergovernmental Panel on Climate Change

Dietz *et al*. (2004) edit a volume of essays addressing past and future climate change, climate change impacts

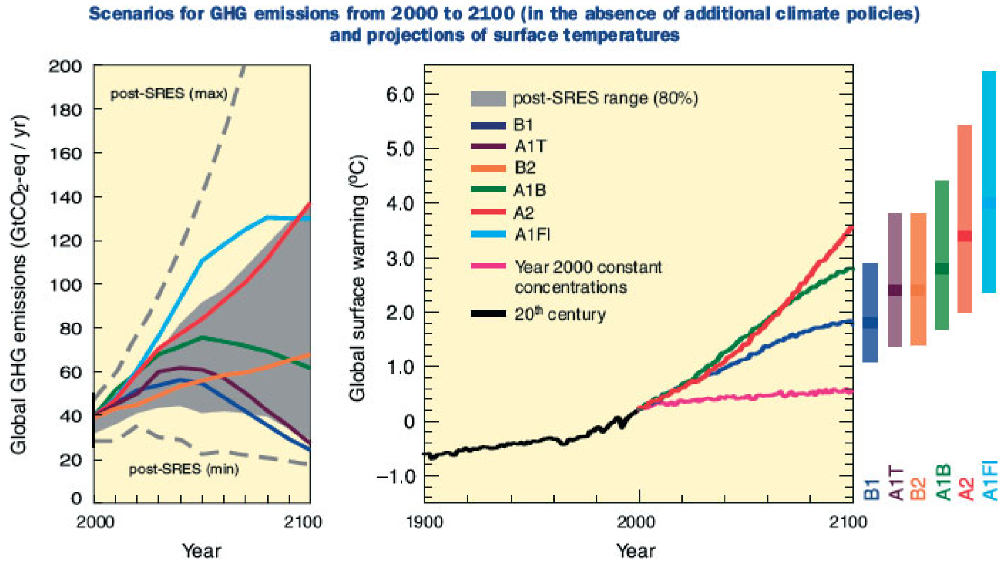

Figure 1. Left: Six illustrative IPCC GHG emission trends for the 21st century. Right: Multi-AOGCM averaged surface temperature anomaly trends for scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. The pink line represents simulations forced by GHG concentrations held constant at 2000 values. The bars at right indicate the range of projected temperature for 2090–2099 for six marker scenarios. All temperatures are relative to the period 1980–1999 (from Bernstein *et al*., 2007).

and mitigation strategies, all as they apply to West Africa. See also the review of the book by Druyan (2005). Although the volume is entirely devoted to these subjects, none of its chapters presents any original climate change research and the bibliography does not include journal articles. Rather, Dietz *et al*. (2004) provide discussions and graphics relevant to West Africa based on Intergovernmental Panel on Climate Change (IPCC) reports spanning 1990–2002. Unfortunately, no coherent prognosis for either drought or abundant rainfall emerges from the cited analyses of global climate model (GCM) products, since otherwise reliable GCMs differ in their projections for Africa. Nevertheless, essays on climate change impacts and mitigation strategies in Dietz *et al*. (2004) are predicated on a projection of more frequent Sahel droughts, perhaps because such a scenario presents the greatest challenges to society, especially the agricultural sector.

GCM transient greenhouse gases (GHG)-forced simulations archived for the IPCC Third Assessment Report (AR3) also did not indicate any consensus regarding the sign and magnitude of Sahel rainfall changes for the 21st century (Hulme *et al*., 2001). Hulme *et al*. (2001) show that seven AR3 models and three additional HadCM2 simulations indicate little GHG impact on Sahel rainfall until the mid-21st century, while the median result of all 10 models does predict a slight drying during the second half of the 21st century. This article relates the considerable disagreement between individual models to the flawed sensitivity of modelled precipitation to sea-surface temperature (SST) forcing, as evidenced by models' 20th century performance. In addition, Hulme *et al*. (2001) cite the absence of modelled dynamic land cover–atmosphere interactions and the absence of modelled dust and biomass aerosols.

Climate projections considered by the IPCC AR4 (hereafter IPCC AR4) were prepared for a range of GHG emission scenarios, prescribing a range of GHG concentration trends throughout the 21st century. Figure 1 shows emissions and modelled global mean surface temperature trends for several scenarios (from Bernstein *et al*., 2007). Note that 'A' scenarios assume steeper increases in GHG concentrations than 'B' scenarios (Nakicenovic and Swart, 2000).

A less ambiguous prognosis for Africa than implied in Hulme *et al*. (2001) or Dietz *et al*. (2004) does not emerge from the IPCC AR4 (Bernstein *et al*., 2007). However, IPCC AR4 does emphasize the importance of improving our understanding of the many ramifications of climate change for that continent: 'Africa is one of the most vulnerable continents because of the range of projected impacts, multiple stresses and low adaptive capacity'. IPCC AR4 climate change prediction models do not achieve a consensus about how water availability in West Africa will change towards the end of the 21st century (Bernstein *et al*., 2007).

3. Atmosphere–ocean global climate model projections

One early atmosphere–ocean global climate model (AOGCM) study projects a rainier Sahel towards the end of the 21st century. The Météo-France climate model ARPEGE-Climat AOGCM is used by Maynard *et al*. (2002) to run a time-dependent climate change experiment that studies the impact of increasing concentrations of GHG and aerosols on the West African monsoon (WAM) system. A transient climate simulation of 150 years is performed, forced by stratospheric ozone, aerosols and GHG changing annually from 1999

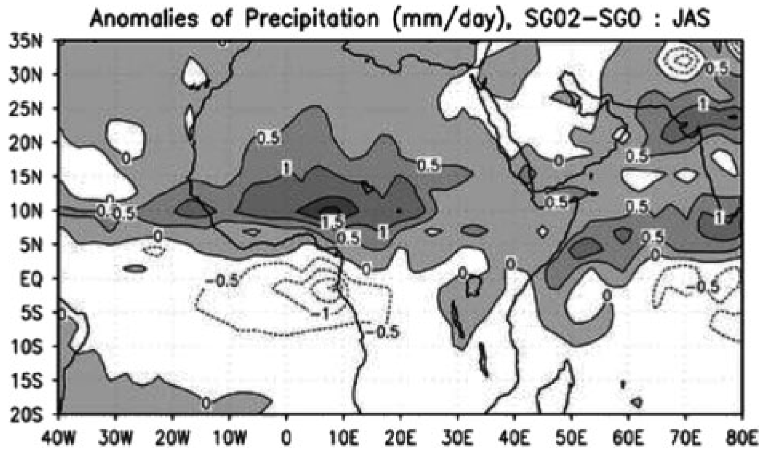

Figure 2. ARPEGE-simulated GHG impacts on precipitation, computed as rate anomalies during JAS, 2070–2099 minus 1980–2010. The simulation is forced with B2 scenario GHG trends from 1999. Contour interval is 0.5 mm/day (from Maynard *et al*., 2002).

onwards according to IPCC scenario B2. The simulated climate change is analysed as the difference between two 30-year time-slices, July–September 1980–2010 and July–September 2070–2100, respectively, with particular attention paid to the hydrological cycle. (*Note:* The article also identifies the periods alternatively as 1980–2009 and 2070–2099, respectively.)

The ARPEGE climate for 1980–2010 is validated by comparison to European Centre for Medium Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) reanalysis circulation and sea-level pressure (1979–1993) and to The CPC Merged Analysis of Precipitation (CMAP) precipitation observations (1979–1996). ARPEGE is able to reproduce the seasonal cycle of the African monsoon with realistic simulated rates over all but the western Sahel, where they are underestimated. This deficiency is a consequence of the model June–September rain band over West Africa being too far south.

The ARPEGE-simulated impact of GHG warming raises surface air temperatures up to 3–4 °C over North Africa, but by only about 25% of that over the Sahel. Maynard *et al*. (2002) found that this northward gradient in surface air temperature impact displaces the 2070–2100 monsoon trough northwards, decreasing dry advection of the northeast Harmattan winds towards the Sahel and displacing the monsoon rain band also northwards. ARPEGE-simulated precipitation changes for the end of the 21st century show intensification of the hydrological cycle and enhanced monsoon precipitation over West Africa, centred along 10°N (Figure 2), which is the northern edge of the rain band simulated for the earlier period. Simulated changes in precipitable water, water vapour recycling, moisture convergence, and precipitation efficiency are all consistent with the rainier Sahel climate.

Held *et al*. (2005) summarize results of AOGCMs from the IPCC AR4 and also discuss experiments with the Geophysical Fluid Dynamics Laboratory (GFDL) AOGCM, called CM2. They examine the database of climate simulations collected for 20 models from 14 modelling centres. One model in the archive produces a 50% increase in July–August–September Sahel rainfall in the A1B scenario by 2100, but a more typical result is an increase of 0–15%. Four of the models other than CM2 produce small (5–15%) reductions in Sahel rainfall. CM2 produces the strongest Sahel rainfall reduction in the 21st century of any of the models (≈25%). Nearly two-thirds of the models do hindcast a drying trend of at least 5% over the 20th century. Because most of these models do not continue the trend into the 21st century, Held *et al*. (2005) believe the 20th century trends in most models unlikely to be forced by GHG, with aerosol forcing being a more likely source.

A CM2 ensemble of six simulations based on B1, A1B and A2 GHG scenarios, projects a drier Sahel in the future, due primarily to increasing GHG concentrations. CM2 precipitation simulation results are shown in Figure 3. Note that even the 20th century portions are from the fully coupled CM2, so Sahel rainfall is not forced with actual SSTs. Consequently, only a general trend can be captured and not actual 20th century interannual variations. In the first few decades of the 21st century, there is some moistening or at least a cessation of the drying trend, but this is followed by rapid drying, with rainfall decreasing below that of the observed 1980s drought for the A1B and A2 scenarios. The temporary moistening may be related to the prescribed aerosol forcing.

Caminade and Terray (2010) also review A1B scenario predictions for the Sahel for 21 AOGCM models from the AR4 archive, and note the wide range of contradicting outcomes for African rainfall trends towards the end of the 21st century. They note that the AOGCM simulations exhibit both meridional dipole patterns, characteristic of a shift of the Intertropical Convergence Zone (ITCZ), and zonal patterns that appear to be related to a modification of the Walker circulation. Authors conclude that 'there is no clear consensus concerning the future rainfall mean changes over sub-Saharan Africa at the end of the 21st century'. Nevertheless, Caminade and Terray (2010) suggest that the GFDL CM2 prediction of enhanced dry

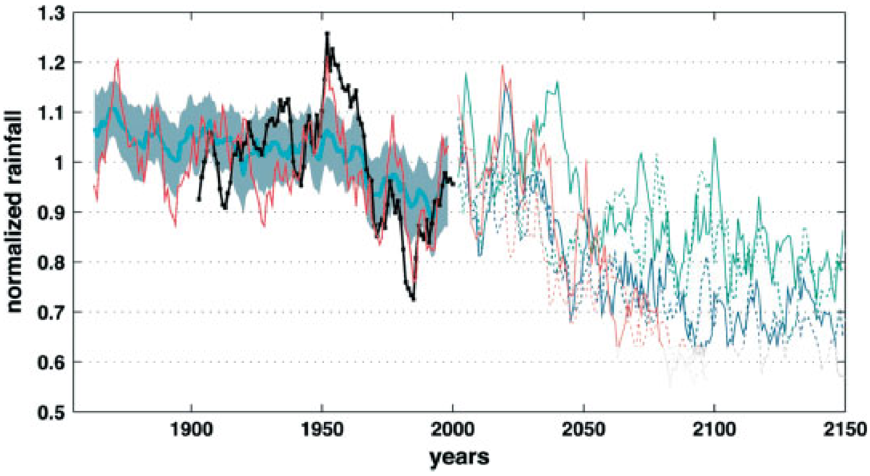

Figure 3. Observed (CRU) 5-year running mean (July–August–September) Sahel rainfall (10°–20°N, 20°W–40°E), normalized by its mean value over 1901–2000 (black line), historical CM2 ensemble mean normalized so that its mean value is unity over the same time interval (thick light blue line), and the historical realization that most resembles the observations in the period 1950–2000 (thick red line). The grey area represents ±1 SD within the ensemble. The future scenarios are B1 (green), A1B (blue), and A2 (red). There are two lines for each scenario, one from CM2.0 and another from CM2.1. CRU: Climate Research Unit, University of East Anglia, UK (from Held *et al*., 2005; Copyright (2005) National Academy of Sciences, USA).

conditions over sub-Saharan Africa at the end of the 21st century (Held *et al*., 2005) is reliable. According to their evaluation, the credibility of the CM2 prediction is bolstered by the model's consistent Sahel drying in the 20th century and the consistent relationship between its simulated Sahelian rainfall, its interhemispheric SST gradient and its tropical tropospheric temperatures. However, the relationships do not remain consistent for the projections of future climate.

Haarsma *et al*. (2005) integrate the CCM3 [Community Climate Model #3, National Center for Atmospheric Research (NCAR)] coupled with an ocean model, assuming the A2 emissions scenario for years 2000–2080. The ensemble of 62 parallel simulations shows Sahel July–September rainfall increases of 25–50% between 1980 and 2080 that they attribute to differential continental heating, because GHG warming should be more prominent over the summer continents than over the surrounding oceans. According to this reasoning, differential heating over the Sahara will deepen the monsoon low, enhance moisture convergence and therefore rainfall, similar to the analysis of Maynard *et al*. (2002) based on ARPEGE results. Figure 4 shows ensemble-simulated precipitation enhancement over the northwest Sahel of up to 2 mm day^{-1} for 2050–2080, relative to 1950–1980, and reductions of central pressure in the monsoon trough of more than 0.6 hPa. However, Figure 4 also shows some precipitation reductions over the southern edge of the Sahel. Haarsma *et al*. (2005) conclude that the frequency of prolonged droughts will be reduced towards the latter part of the 21st century, in contradiction to conclusions based on the CM2 (Held *et al*., 2005). Note, however, that simulations of a 10-member ensemble of the CCM3, forced by observed SST between 1945 and 2000, imperfectly reproduce the observed interannual variability of Sahel rainfall. The correlation of simulated annual means achieves a 0.48 correlation with observations, which improves to 0.89 for 10-year running means. The lower correlation means that the simulated interannual variability accounts for only 23% of the observed variance. No other assessment of CCM3 performance during the contemporary period is offered.

Kamga *et al*. (2005) study NCAR climate system model (CSM) simulations for 1980–2098, with A1, A2 and B2 scenarios GHG forcing. GHG-forced impacts are evaluated as the differences between CSM-simulated climate for the late 20th (1980–1999) and 21st (2080–2098) centuries, but the time series of simulated JJA Sahel rainfall 1993–2098 is shown as well. Results predict a wetter Sahelian region in the late 21st century in association with increases in atmospheric moisture convergence and stronger meridional winds from the Gulf of Guinea. The simulations also imply that rainier conditions will also prevail during the first half of the 21st century. Although the CSM seasonal march of Sahel precipitation simulated for the current climate is realistic, the mean summer monsoon rain band does not penetrate far enough inland, giving a dry bias in the northern Sahel relative to observations. In addition, CSM-simulated SST evolution in the

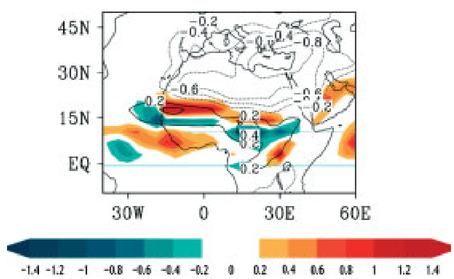

Figure 4. Difference in ensemble-simulated rainfall (mm day^{-1}) (colour bar) and sea-level pressure (hPa) (contours) during JAS between 2050 and 2080 minus 1950 and 1980 (from Haarsma *et al*., 2005, reproduced/modified by permission of American Geophysical Union).

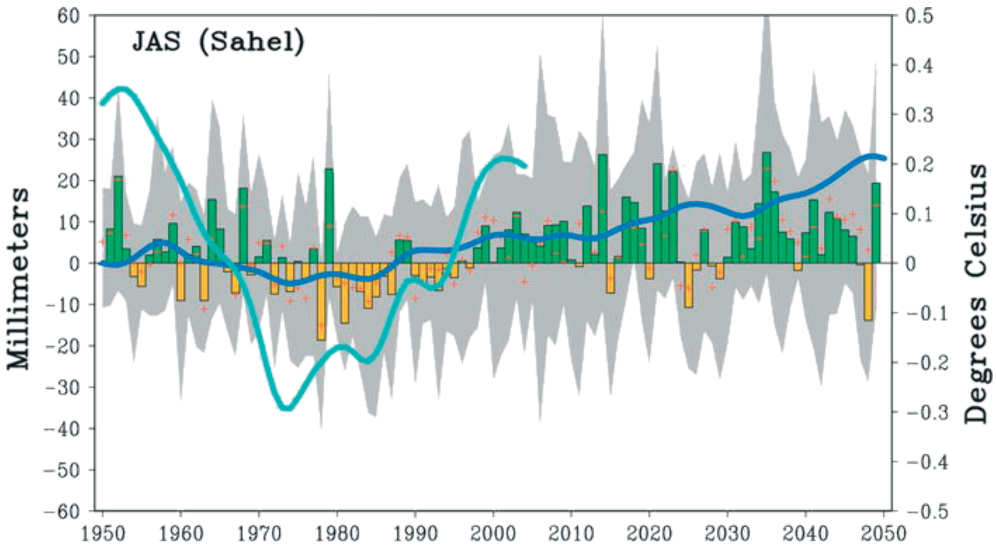

Figure 5. GHG-forced simulated time series of Sahel (10°–20°N, 17°W–38°E) JAS seasonal rainfall departures for 1950–2049 (A1B scenario), relative to 1950–99. Rainfall is based on the monthly, gridded output of the 18-model-averaged coupled AOGCM runs collected from the IPCC/PCMDI AR4 database. Bars denote the average of the 18-model ensemble mean rainfall departures. Red crosses denote the median value of the 18-model ensembles. Grey shading signifies the interquartile range of the 18-model ensemble rainfall departures. Superimposed dark (light) blue curves are the projected (observed) SST time series of the North Atlantic minus South Atlantic SST (from Hoerling *et al*., 2006).

21st century may not be an accurate reflection of future oceanic conditions.

Echoing the earlier studies by Maynard *et al*. (2002), Haarsma *et al*. (2005) and Kamga *et al*. (2005), Hoerling *et al*. (2006) also project a trend towards wetter Sahel summers, but in this case, the study refers only to the first half of the 21st century. The assessment is based on 42 IPCC AR4 A1B scenario climate change simulations of 18 AOGCMs (Figure 5). Hoerling *et al*. (2006) additionally propose that the physical mechanism of the projected trend is analogous to relationships between SST *versus* Sahel rainfall detected in the 1950–1999 record. According to this theory, more rapid warming of the North Atlantic relative to the South Atlantic will create meridional SST gradients that favour wetter summers over parts of the Sahel. This is somewhat consistent with the CM2, which showed some moistening over the Sahel during the first half of the 21st century, even though it projected an unambiguous drying trend after 2050 (Held *et al*., 2005). Limitations in the AOGCMs' simulation of the basic WAM climate and their simulation of SST trends and changing SST gradients in response to global warming, raise uncertainties about the interpretation of Hoerling *et al*.'*s* (2006) results.

Indeed, Cook and Vizy (2006) find that many AOGCMs in the IPCC fourth assessment archive simulate flawed representations of the WAM climate. They point out that climate projections of WAM changes from models with unrealistic reference climates are compromised. Moreover, they determine that results from the more successful models disagree with each other in their projections of Sahel hydrology for the second half of the 21st century. Cook and Vizy (2006) find the climate change projection of the Japanese Meteorological Institute (MRI AOGCM) to be most credible in that it produces frequent dipole events – wet along the Gulf of Guinea coast and dry over the Sahel. Compared with 12 dry Sahel/wet Guinean coast years in the second half of the 20th-century integration, the MRI model simulation of the A2 scenario produces 15 dry/wet years in the first half of the 21st century, and 20 events in the second half. This climate change signal is attributed to warming of Gulf of Guinea SST and the authors conclude that Sahel droughts will become progressively more frequent, although decadal mean WAM precipitation may not change very much. Figure 6 shows the precipitation anomalies projected by MRI AOGCM ensemble simulations for three 20-year periods relative to 1949–2000. Note that anomaly patterns for all three periods are similar for both the A2 and B1 scenarios. The projected precipitation anomalies for 2001–2020 are small and limited to slightly wetter conditions along the Gulf of Guinea coast. These coastal excesses in rainfall increase in the 2041–2060 period, with little impact over the Sahel. Precipitation anomalies projected for 2081–2100 for the A2 scenario show the dipole pattern of lower precipitation rates over the Sahel in juxtaposition with wetter conditions along the coast. Note that these conclusions of Cook and Vizy (2006) contrast with the Maynard *et al*. (2002) and Kamga *et al*. (2005) predictions of a wetter Sahel.

Biasutti *et al*. (2008) do not agree with Hoerling *et al*. (2006) that 20th century SST *versus* Sahel rainfall relationships will dominate in determining precipitation changes during the first half of the 21st century (Figure 5). Biasutti *et al*. (2008) conclude that GHG-forced future changes in Sahel rainfall will be controlled by different mechanisms that cannot be captured by the simple linear relationship with SST that has characterized the past. Their examination of the results of 18 AOGCM

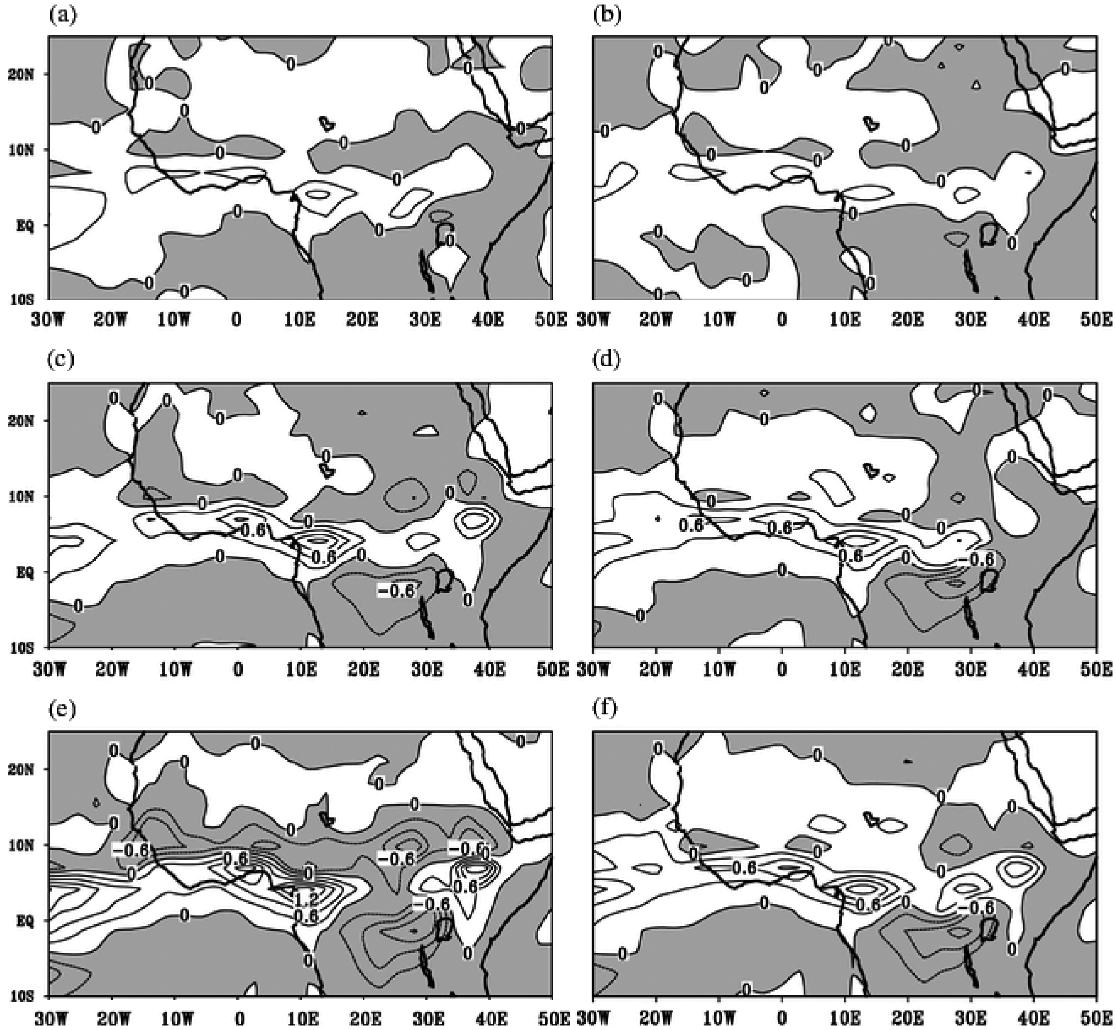

Figure 6. JJAS precipitation differences (mm day^{-1}) from the 1949–2000 mean from the MRI model for (a) the 2001–2020 A2 scenario mean, (b) the 2001–2020 B1 scenario mean, (c) the 2041–2060 A2 scenario mean, (d) the 2041–2060 B1 scenario mean, (e) the 2081–2100 A2 scenario mean and (f) the 2081–2100 B1 scenario mean (from Cook and Vizy, 2006).

A1B simulations finds mixed signals for the WAM. 'The outlook for rainfall in the Sahel is very uncertain: we do not know whether we should expect positive or negative rainfall anomalies in the Sahel under global warming'. Among 18 AOGCMs in their study, some predict strong dry anomalies, others strong wet anomalies and most predict more modest anomalies of both signs. This is the same assessment given by Held *et al*. (2005) regarding AR4 AOGCMs. Another of the interesting conclusions of Biasutti *et al*. (2008) is that similar Sahel precipitation responses of models to 20th century forcing do not guarantee parallel responses to GHG forcing into the 21st century. Because contradicting scenarios of climate change cannot all be accurate, one may conclude that a faithful simulation of historical climate trends does not guarantee the reliability of future projections.

4. Regional model nesting

Patricola and Cook (2010) attempt to overcome the limitations of global models by nesting a higher resolution regional model over West Africa. In their study, climate change signals are taken from IPCC 4th assessment AOGCMs, but these projections are used as lateral forcing for simulations over Africa using the Weather, Research and Forecasting (WRF) model on a grid with 90 km spacing. Mean results from nine AOGCMs, integrated according to the IPCC A2 GHG emissions scenario, are used to create lateral boundary conditions (LBC) for nine WRF simulations of climate change. Patricola and Cook (2010) find a very mixed precipitation change signal for West Africa in the second half of the 21st century, characterized by June–July drought, followed by copious rainfall towards the end of the summer. Figure 7 shows that the most extreme negative anomalies during June and July are along the Gulf of Guinea coast. The implications are inconclusive, as July is normally rather dry along the Gulf coast, following the northward excursion of the monsoon rain band. However, the July–August monsoon rainfall band for the WRF 20th century simulation (forced by reanalysis) was indeed situated too far south over West Africa. This obvious model bias adds ambiguity to the interpretation of the computed

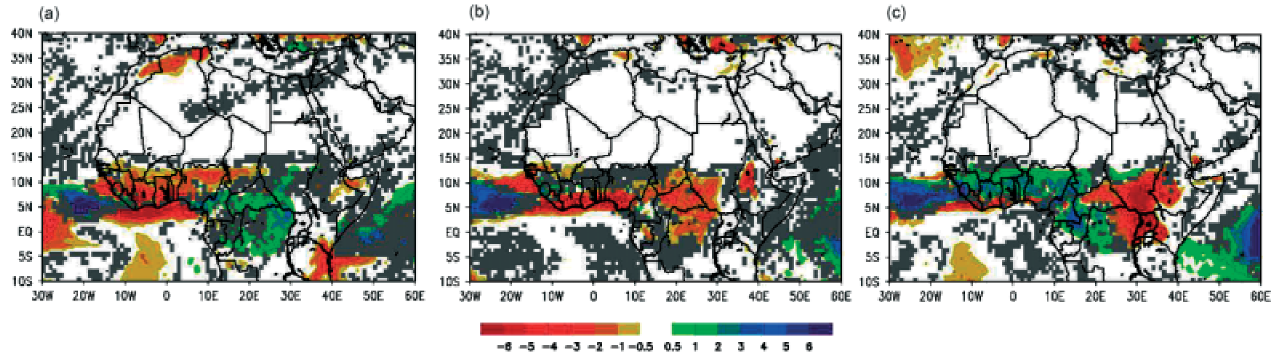

Figure 7. Ensemble of averaged monthly precipitation anomalies (21st century minus 20th century) from nine WRF simulations for (a) June, (b) July and (c) August. Units are mm day^{-1}. Areas where less than 77% of the ensemble members agree are shaded grey (from Patricola and Cook, 2010).

precipitation change signal. For example, do projected negative rainfall anomalies along the Gulf of Guinea coast in July imply future droughts over the Sahel? Note also that smaller negative anomalies occur in June along 10°N (Figure 7(a)), the northernmost edge of the climatological rain band. Additional non-uniformity of results is reflected by the positive anomalies over the Sahel in Figure 7(c), which imply wetter Augusts in the second half of the 21st century.

Climate projections for the first half of the 21st century by Paeth *et al*. (2009) predict drier conditions for West Africa's future. The study downscales A1 and B1 IPCC scenarios simulated by the ECHAM5 (European Community–Hamburg Atmospheric Model) AOGCM, using the REMO regional climate model on a 0.5° grid. The REMO 1960–2000 base period simulation, also forced by the fully coupled ECHAM5 AOGCM, is quite realistic, except for underestimates of the time variance of surface temperature and precipitation, which authors attribute to the low variability of ECHAM5 SST forcing. Although the lower emission rates of the B1 scenario do not have much differential impact on precipitation trends compared to the A1 scenario, climate change projections are quite sensitive to a prescribed degradation of vegetation cover. When applied together with increasing GHG concentrations, changes in the lower boundary conditions prescribed all over Africa, representing deforestation and increased urbanization, produce distinctly warmer and drier climates over West Africa for the first half of the 21st century.

Figure 8 shows the linear changes in annual precipitation amount for the REMO ensembles forced by ECHAM5 A1B scenario simulations. During the 20th century (not shown) the trend pattern is quite heterogeneous. In the A1B (all) ensemble for 2001–2050 (Figure 8(a)), the combination of GHG forcing and land degradation causes reductions in annual rainfall amounts of about 100 mm in the southern Sahel zone, which is about 20–25% of 20th century annual amounts in most of sub-Saharan Africa. The trend pattern for the A1B (GHG only forcing) ensemble, on the other hand, shows some drying over the western Sahel, but not uniformly over the central and eastern Sahel (Figure 8(b)). Paeth *et al.* (2009) conclude that, should the assumed pace of land degradation occur, the negative rainfall trend would be accelerated by almost 30 years, compared with the GHG forcing alone. The study further implies that controlled agriculture and preservation of forests would greatly mitigate the mounting heat stress and increasing frequency of dry spells.

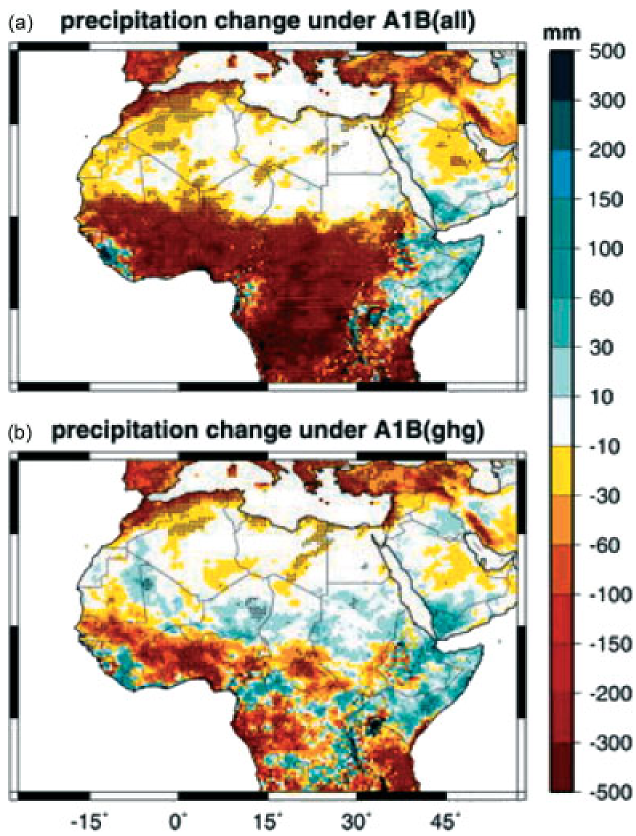

Figure 8. REMO-simulated ensemble mean changes in annual precipitation expressed as linear trends (multiplied by number of years) between 2001 and 2050 for the scenarios: (a) A1B (all), strong greenhouse gas emissions and land cover changes and (b) A1B (GHG), strong greenhouse gas emissions and no land cover changes (from Paeth *et al*., 2009).

5. Ensembles and the coordinated regional climate downscaling experiment

A European multi-institutional climate modelling effort ENSEMBLES, funded by the European Commission, has compiled regional model simulations at 50-km grid spacing for a domain centred over West Africa (van der Linden and Mitchell, 2009). Simulations are made for the recent past (1989–2007) forced by reanalysis, and for future climate scenarios (1970–2050), forced by AOGCMs. Projected linear precipitation trends over the Sahel by four ENSEMBLES regional models for two intervals, 2011–2030 and 2031–2050, do not indicate much consensus. Results from additional regional models have since been added to the archive. However, assessments of these results are expected to contribute to the IPCC AR5 (anonymous reviewer), due out by 2013–2014.

The climate change signal for hydrology over West Africa may become clearer from a new international effort. Coordinated regional climate downscaling experiment (CORDEX) is an initiative of the World Climate Research Project (WCRP) of the United Nations. It aims to improve coordination of international efforts in regional climate downscaling, both by dynamical and statistical methods. The Africa domain is the priority CORDEX focus region, and results are also intended to provide evidence for the anticipated IPCC AR5. CORDEX regional modelling groups will perform new multi-year simulation experiments focused on Africa, using common LBC for driving each model. LBC data will be taken from a $0.75^{\circ} \times 0.75^{\circ}$ version of the ECMWF interim reanalysis and from global AOGCM climate change projections [from the Coupled Model Intercomparison Project (CMIP5)], for the future climate and for the base period. Two AR5 climate change scenarios, designated *representative concentration pathways* RCP4.5 and RCP8.5 (Moss *et al*., 2008), are to be considered. Each downscaling will produce projections of climate anomalies for the 21st century, assessed relative to base period simulations and CORDEX will compile multi-model mean results. The consensus from the combined results of forcing with multiple AOGCMs embraces a range of possible outcomes. An additional range of outcomes will be archived by CORDEX based on the results from at least 10 different regional models. A more definitive prediction of 21st century hydrology for West Africa may emerge from this planned regional model intercomparison project, although results will still be limited by the quality of the AOGCM forcing.

6. Discussion and conclusions

As societal sustainability of many regions of West Africa is acutely sensitivity to climate, reliable projections of climate trends could be quite valuable for mitigating negative impacts. Nevertheless, implementation of mitigation strategies requires political will and finesse. Sustainability will of course also be affected by non-climatic factors such as population growth, urbanization, technological advances, etc.

Caminade and Terray (2010) summarize the physical processes associated with summer rainfall anomalies over the Sahel. Conditions that enhance Sahel rainfall include positive (negative) SST anomalies north (south) of the Equator, La Niña events, differential heating of the African continent relative to the adjacent ocean with concomitant deepening of the Sahara low and increased water vapour holding capacity of warmer air. Conditions that favour lower summer rainfall include negative (positive) SST anomalies north (south) of the Equator, El Niño events, increased vertical thermal stability from a warming troposphere and deterioration of vegetation cover, which increases albedo and decreases evapotranspiration. Caminade and Terray (2010) suggest that the challenge to correctly simulate Sahel rainfall trends is particularly daunting because multiple physical mechanisms compete to drive the trend upwards or downwards. Moreover, Shanahan *et al*. (2009) cite evidence of extended periods of drought in Ghana over the last 3000 years, apparently related to the Atlantic Multi-decadal Oscillation (AMO). Any model deficiencies in simulating any one or a combination of these physical processes will taint the climate change projections. For example, Cook and Vizy (2006) associate future dry Sahel/wet Gulf coast dipoles with differential warming of Gulf of Guinea SST. How well do coupled AOGCMs simulate Gulf of Gunea SST? Richter and Xie (2008) report that the IPCC AR4-coupled AOGCM ensemble mean does not successfully represent the summertime cold SST tongue in the western Gulf of Guinea, a prominent climatological feature. Such limitations in simulating the mean SST imply limitations in simulating anomalies and future trends of Gulf SST that may be driving Sahel precipitation evolution.

Table I summarizes the range of impacts on Sahel rainfall in the 21st century, as simulated for a variety of GHG scenarios by a variety of climate models. The table makes no effort to differentiate between results for different emissions scenarios. In fact, the studies indicate a very weak to none dependence of Sahel rainfall changes on scenario. Three of the seven studies that address impacts during the first half of the 21st century predict a wetter Sahel. Only one of them (Paeth *et al*., 2009) projects drier conditions, and that only for radical degradation in vegetation cover. Five of the nine studies that address impacts during the second half of the 21st century project some drying, but results in only two of those are unambiguous (Held *et al*., 2005; Cook and Vizy, 2006). Two studies project a distinctly rainier Sahel during the second half of the 21st century (Maynard *et al*., 2002; Kamga *et al*., 2005). Biasutti *et al*. (2008) unequivocally find that evidence for any projection is uncertain. Cook (2008) suggests that Biasutti *et al*. (2008) 'may be overly pessimistic about the level of agreement among the coupled GCMs as the large spread in the projected Sahel rainfall depends primarily on only two models'.

Table I. Summary of climate change impacts on projected Sahel rainfall for selected studies. Impacts are relative to late 20th-century Sahel rainfall.

Study	First half of 21st century	Second half of 21st century
Hulme *et al.* (2001)	Small impacts	Ensemble drying; No consensus among GCMs
Maynard *et al.* (2002)	–	Enhanced rainfall
Held *et al.* (2005) (CM2)	Slightly rainier	Progressively drier
Haarsma *et al.* (2005)	–	Drier, NW & E Sahel; rainier, S Sahel
Kamga *et al.* (2005)	Progressively rainier	Progressively rainier
Hoerling *et al.* (2006)	Progressively rainier	–
Cook and Vizy (2006)	No impact	Drier, only last 20 years
Biasutti *et al.* (2008)	Uncertain	Uncertain
Patricola and Cook (2010)	–	Drier, June–July; Rainier, August
Paeth *et al.* (2009)	Heterogeneous spatial distribution of impacts; Drier, with land surface vegetation degradation	–

Hoerling *et al.* (2006) expect the recovery of recent rainy summers in the Sahel to continue throughout the next four decades, as the tropical North Atlantic warms faster than the tropical South Atlantic, and CSM simulations support this finding (Kamga *et al.*, 2005). Biasutti *et al.* (2008), presumably analysing simulations from the same 18 AR4 AOGCMs as Hoerling *et al.* (2006), conclude that future interannual variability of Sahel rainfall will not be determined by the sensitivity to meridional SST gradients that is detected in 20th century data.

Results of the two regional model studies (Patricola and Cook, 2010; Paeth *et al.*, 2009) cannot be compared because each focused on opposite halves of the 21st century. Both, however, favour desiccation, albeit with caveats regarding intraseasonal and spatial variability. The ENSEMBLES regional models' hydrological projections are likewise ambiguous. However, the relatively higher spatial resolution of regional models *versus* global models could eventually contribute to more realistic simulations of climate systems and processes that are relevant to the Sahel's hydrological trend. For example, simulations of transient synoptic African easterly waves and mesoscale squall lines should benefit from high spatial resolution. Similarly, seasonal precipitation anomalies are sensitive to the timing of monsoon onset and retreat and land/vegetation–atmosphere interactions, processes that should be simulated more realistically with the relatively higher resolution of regional models. CORDEX dynamic downscaling research may therefore provide more decisive projections of the future hydrological balance in West Africa.

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