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The sensitivity of Sahel rainfall to global warming: implications for scenario analysis of future climate change impact

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Abstract Inter-decadal rainfall variability in the Sahel during the course of the present century has been large and, on occasions, its impacts on environment and society have been catastrophic. Our understanding of the causes of this variability has progressed substantially over the last 25 years. The roles of land cover change, ocean circulation, and atmospheric aerosol concentrations have been stressed by various authors and in recent years there has been the establishment of an embryonic seasonal forecasting capability for Sahel rainfall. This paper explores the ability of the latest generation of Global Climate Models (GCMs) to simulate historic Sahelian rainfall variability and evaluates the sensitivity of simulated Sahel rainfall to future changes in greenhouse gas and sulphate aerosol concentrations under different emissions assumptions. Results from the suite of experiments performed by the UK Hadley Centre in 1995 and 1996 using the HADCM2 model, including ensemble simulations, are used. The implications of this analysis for scenarios of future rainfall change in the Sahel are highlighted and suggestions made about the conduct of future regional climate change impact assessments on environmental resources such as water and agriculture.

INTRODUCTION

Of the world's major dryland regions, the Sahel is unique in that it displays substantial multi-decadal desiccation during the period of instrumental measurements (Hulme, 1996). Since the 1960s, annual rainfall in the Sahel has averaged between 300 and 500 mm, compared to values of 400 to 600 mm recorded in earlier decades this century (Fig. 1). This represents a rainfall reduction of the order of 20% sustained over two to three decades. Such a desiccation has clearly had consequences for resource management and human society in the region (Middleton & Thomas, 1997), although a full quantification in monetary and non-monetary terms of the human and ecosystem welfare impact of this climate change remains elusive.

Understanding the reasons for this substantial change in Sahelian rainfall remains a major challenge for climate science. Various hypotheses remain unresolved including those pertaining to large-scale oceanic circulation (Rowell *et al.*, 1995), regional land cover changes (Xue, 1997) and regional atmospheric aerosol concentrations (Tegen *et al.*, 1996). It has also been speculated that changing atmospheric composition due to greenhouse gas and sulphate aerosol precursor emissions may be important (Hulme & Kelly, 1993). Although these issues remain

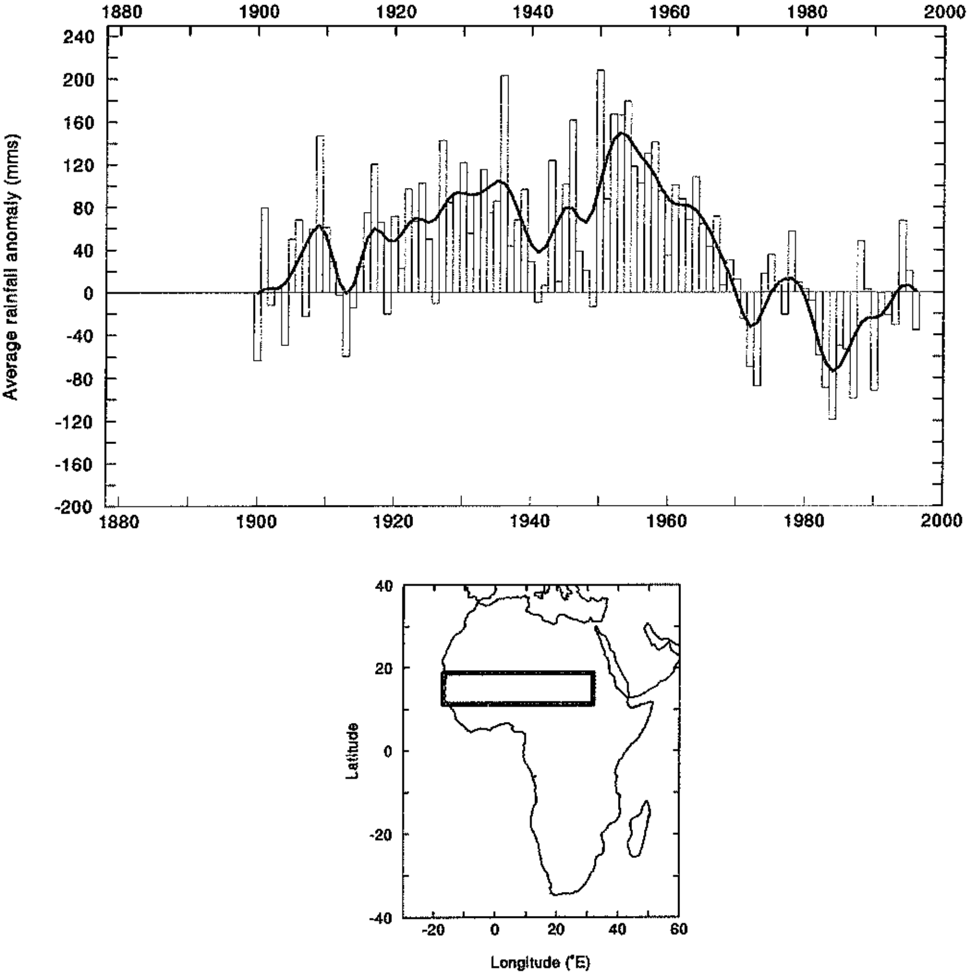

Fig. 1 Annual rainfall anomalies for the Sahel (1900–1996) expressed as mm anomalies from the 1961–1990 mean (428 mm). The smooth curve results from a 10-year low-pass filter. The domain is shown is the map and contains 39 gridboxes (3 by 13) on the HADCM2 model resolution.

unresolved, the interannual behaviour of the Sahelian wet season has been successfully forecast on a seasonal time-scale by a number of different forecasting schemes (e.g. Folland *et al.*, 1991; Stockdale *et al.*, 1998). These seasonal forecast developments have improved our understanding of tropical rainfall predictability (Rowell, 1998), but we remain unable to forecast climate on decadal or mutli-decadal timescales.

In this paper, we examine a series of Global Climate Model simulations forced with greenhouse gas and sulphate aerosol scenarios for the next century. These types of simulations are now typically used as the basis of scenarios of future climate change, scenarios that then form the basis for regional climate change impact assessments such as those summarized recently for Africa by Hulme *et al.* (1996) and IPCC (1998). We consider what confidence may be attached to such rainfall scenarios for the Sahel and conclude with a discussion about the appropriate specification of climate change scenarios for use in climate change impacts assessments in the Sahel, including assessments of impact on water resources.

THE MODEL SIMULATIONS AND OBSERVED DATA

The Hadley Centre completed a series of GCM simulations in 1995 and 1996 using the coupled ocean-atmosphere model referred to as HADCM2. Details of the model and the simulations can be found in Mitchell & Johns (1997) and Johns *et al.* (1997). For this analysis we extracted 240 years of surface air temperature and precipitation data for the Sahel region (defined in Fig. 1) from 16 model scenario simulations and also from 240 years of the unforced multi-century control simulation. These various simulations are summarized in Table 1. The observed data are extracted from the gridded global precipitation dataset of Hulme (1994; updated). This dataset contains estimates of monthly precipitation for 1900–1996 on the same global grid as HADCM2, namely 2.5° latitude by 3.75° longitude.

SIMULATED RAINFALL VARIABILITY

Sahelian rainfall in the control simulation of HADCM2 is rather lower than that observed (annual 1961–1990 mean: 272 mm simulated versus 428 mm observed), although the annual cycle of rainfall with a pronounced JJAS wet season is quite well simulated by the model, as is the strong south–north gradient in mean annual rainfall (not shown). One of the characteristic features of the observed Sahelian rainfall

Table 1: List of HADCM2 simulations used in this analysis, together with the forcing scenarios and the eventual global warming by the period 2070–2099 expressed with respect to the 1961–1990 mean. Atmospheric CO_2 concentrations by the period 2070–2099 rise to 498 ppmv for the GGd and GSd scenarios and to 697 ppmv for the GGa and GSa scenarios.

	Forcing		Global warming by 2070–2099 (°C)
	1860–1989	1990–2100	
Control	None	None	0.0
GGa (four ensembles)	Observed greenhouse gas	1% per annum increase in greenhouse gas concentration	3.2 3.0 3.1 3.0
GSa (four ensembles)	Observed greenhouse gas and sulphate aerosols	1% per annum increase in greenhouse gas concentration plus IS92a aerosol forcing	2.6 2.5 2.5 2.5
GGd (four ensembles)	Observed greenhouse gas	0.5% per annum increase in greenhouse gas concentration	1.9 1.9 2.0 1.9
GSd (four ensembles)	Observed greenhouse gas and sulphate aerosols	0.5% per annum increase in greenhouse gas concentration plus IS92d aerosol forcing	1.8 1.8 1.8 1.9

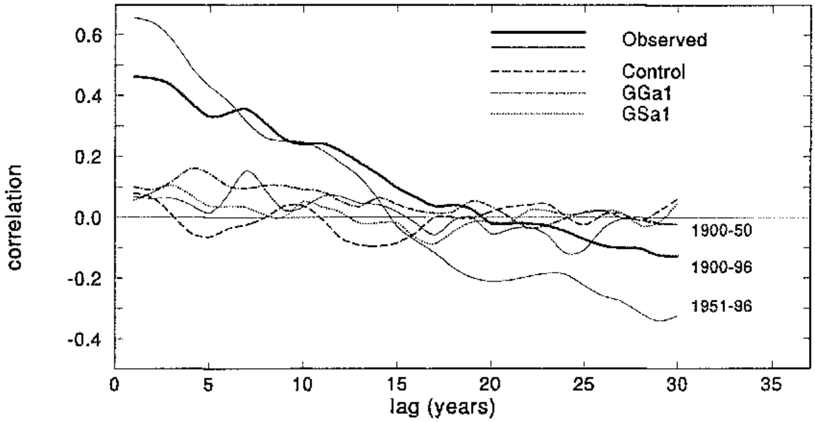

Fig. 2 Autocorrelation functions for various Sahel annual rainfall series. The observed *acfs* are shown for the full record and for two sub-periods; the control *acf* is calculated from the 240 year control simulation and the GGa1 and GSa1 are calculated from the 240 years of data from the first realizations of the GGa and GSa scenario experiments (see Table 1). All autocorrelations are smoothed with a 5-point low-pass filter.

record is the strong interannual persistence in rainfall in the second half of the century. This is related to the marked decline in rainfall since the 1950s. This behaviour is summarized in the autocorrelation function (*acf*) of the rainfall series (Fig. 2). The control simulation of HADCM2 fails to display any such persistence, the *acf* remaining close to zero at all frequencies. At the same time, although the interannual variability of the model control is quite similar to that observed (control standard deviation = 55.7 mm; observed = 70.3 mm), there is no evidence of strong multi-decadal variability in the model simulation (Fig. 3).

Acfs for the GGa and GSa scenario simulations are slightly stronger than for the control (Fig. 2), although still well below late twentieth century persistence values. The lower interannual and reduced interdecadal variability of the observed early twentieth century Sahel rainfall (1900–1950) is much better reproduced by the model simulations than is the later twentieth century observed record. This feature of the HADCM2 simulations has also been found at global and zonal-mean scales by Hulme *et al.* (1998). This suggests that the cause(s) of the recent desiccating trend in the Sahel is(are) to be found in mechanisms not included in the HADCM2 experiment. Land cover changes or atmospheric dust aerosols would be two such forcing mechanisms.

SCENARIO CHANGES

To examine the range of simulated Sahelian annual rainfall changes in the HADCM2 experiment due to anthropogenic forcing, we extracted data from the final 30 years of the ensemble simulations, namely the period 2070–2099. We display these results in Fig. 4, expressing the rainfall changes as a function of the respective global-mean warming of each simulation (see Table 1 for these values). Also in Fig. 4, we include the results from the eight independent 30-year climates extracted from the control simulation (note the global warming values for these climates are very small because the control simulation is unforced) and also the two observed 30-year

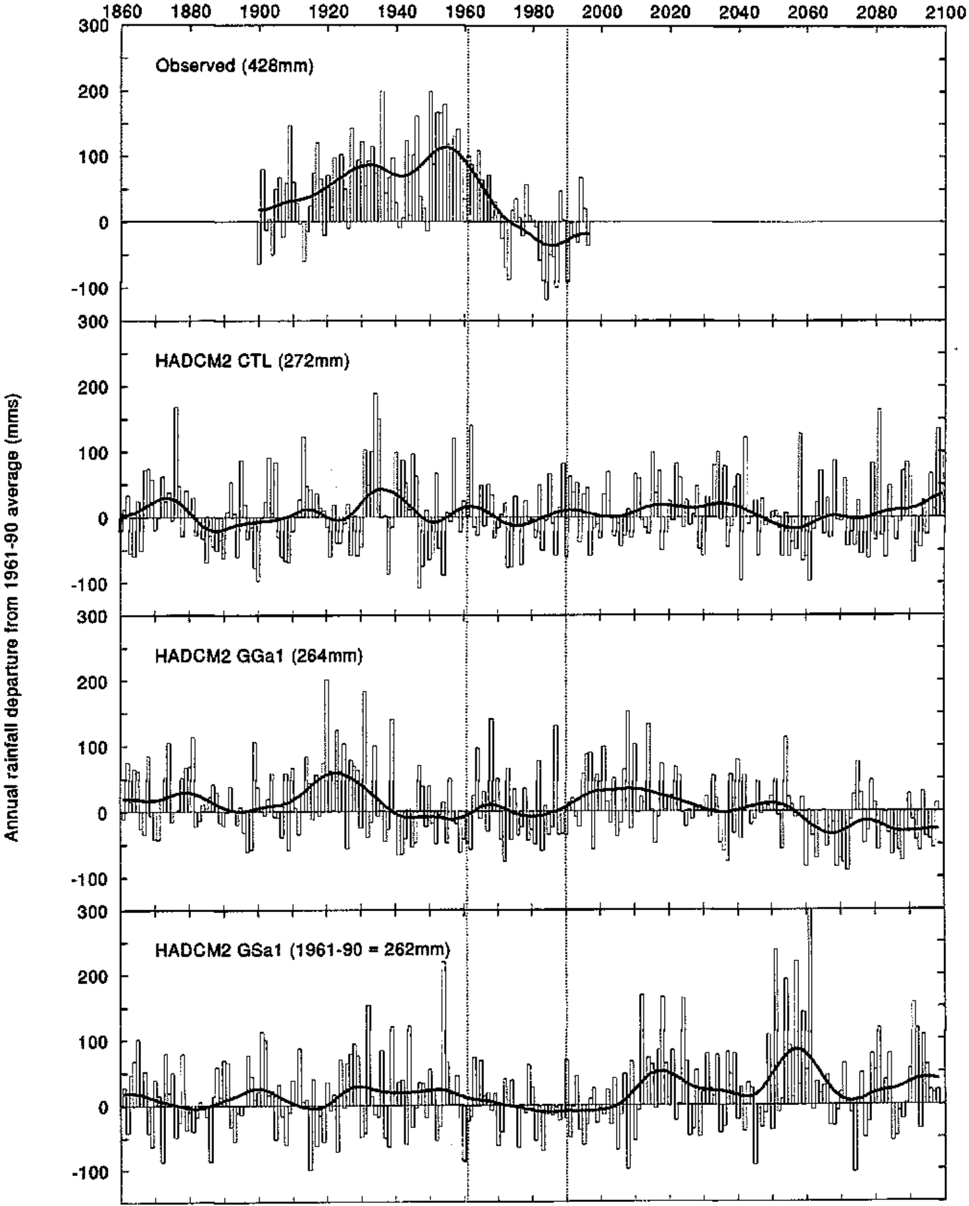

Fig. 3 Observed and model-simulated annual rainfall anomalies for the Sahel expressed as mm anomalies from the 1961–1990 mean. HADCM2 series are for the period 1860–2100 from the control simulation and also from the first realizations of the GGa and GSa scenario experiments. The smooth curves result from a 30-year low-pass filter.

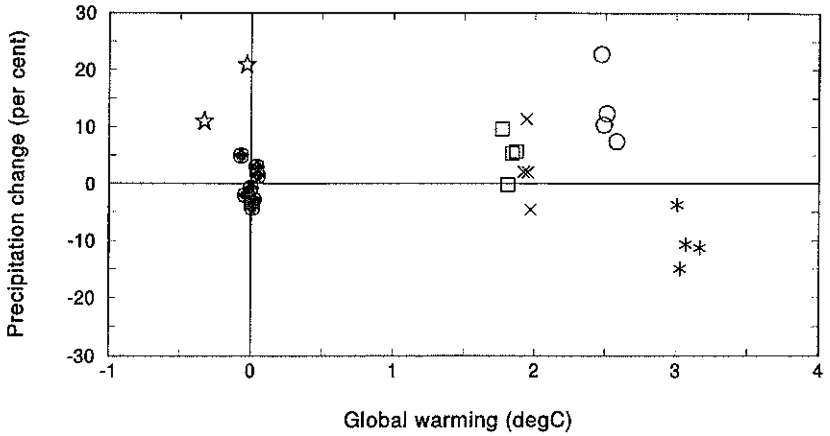

Fig. 4 Bi-variate scatter plot of global warming versus 30-year mean annual rainfall anomalies for the Sahel. All anomalies are expressed with respect to the 1961–1990 mean. ☆ indicates the observed 1901–1930 and 1931–1960 anomalies; ● indicates 30-year anomalies from the 240-year HADCM2 control simulation (i.e. model simulated natural climate variability). All other anomalies are for the 2070-2099 period: o from the GSa ensemble simulations; * from the GGa ensemble; □ from the GSd ensemble; and × from the GGd ensemble.

climates from earlier in the century, 1901–1930 and 1931–1960. All of these changes are expressed with respect to the respective 1961–1990 mean climates.

A number of important features emerge from these diagnostics. First, greenhouse gas only forcing (GGa) leads to an *decrease* in mean annual Sahelian rainfall by the end of next century, whereas the combined greenhouse gas and aerosol forcing (GSa) leads to rainfall *increases*. These changes are significantly different from model-simulated natural variability at the 95% level using a two-tailed t-test to compute the differences between the control sample (n = 8) and the ensemble samples (n = 4). This response is the opposite to that found for rainfall over the south Asian monsoon region (Mitchell & Johns, 1997) where the inclusion of sulphate aerosols weakened the monsoon and led to reductions in JJAS rainfall. Neither do these results support the speculation of Hulme & Kelly (1993) that Sahelian desiccation may be a result of the inter-hemispheric contrast in sulphate aerosol distribution.

Second, the more modest forcing scenarios of GGd and GSd do not lead to any significant rainfall changes by the period 2070–2099; all of the GGd and GSd ensemble rainfall changes fall within, or nearly within, the changes simulated by the unforced control simulation. Third, the intra-ensemble differences (*c.* 10–15% range) are comparable with the intra-control climate anomalies (*c.* 10% range). This suggests that anthropogenic forcing has not substantially altered the model-simulated multi-decadal rainfall variability. Fourth, in the context of observed twentieth century rainfall changes in the Sahel, none of these scenario rainfall changes are extreme, even those resulting from the high forcing simulations of GGa and GSa. The early and mid-century 30-year climates were, respectively, 11% and 22% wetter than the observed 1961–1990 period. The magnitudes of these observed anomalies are comparable with the changes induced by high anthropogenic forcing scenarios by the end next century, of similar sign to the GSa-induced changes and opposite sign to the GGa-induced changes. Finally, the observed drying trend of recent decades remains unprecedented either in the control simulation or in any of the scenario simulations.

DISCUSSION

The observed Sahel rainfall record presents a unique problem for anthropogenic climate change scenario construction and application. The substantial desiccation observed over recent decades may either be natural in origin or related to human forcing of the regional or global climate system. If it is natural, then such a magnitude change in rainfall conditions may occur again in the future—back towards wetter conditions if the pre-1960s period was the "norm" or towards either wetting or further drying if the post-1960s period is the "norm". On the other hand, if the desiccation is related to human forcing of the climate system, then a return to wetter conditions seems unlikely given that regional land cover changes are unlikely to be reversed and that future greenhouse gas concentrations are unlikely to fall.

Either way, such desiccation is not simulated by coupled GCM climate change experiments as represented by HADCM2—and such a model represents the current state-of-the-art for GCMs. We should therefore be cautious about using scenario rainfall changes from such GCM experiments in impact assessments, at least for this region. Kittel *et al.* (1998) have shown similar problems in defining greenhouse gas-induced Sahel rainfall changes from the earlier generation of equilibrium and transient GCM experiments—their sample of nine independent experiments yielded JJA rainfall changes in the Sahel of ±20%, with a mean change of close to zero.

What lessons do we learn from this exercise about studying the effects of possible future climate change in the Sahel on a variety of natural and social systems in the region, such as water resources, agricultural and human settlement? Three things I think emerge. First, regional assessments of climate change impact in the Sahel should consider a wide range of rainfall scenarios, from a return to rainfall magnitudes typical of the 1930s and 1950s, as well as further drying of up to another 10 or 20%. Given the state of climate modelling and our uncertainties about the relative importance of different human factors that affect Sahelian climate, neither of these possibilities can be excluded. Second, it is worth exploring the sensitivity of the region to further rises in temperature and carbon dioxide concentrations alone. We have not dwelt on these results in this paper, but the simulated rises in surface air temperature in the Sahel are in the order of an additional 2° to 4°C in mean annual temperature by the end of next century, increases that are well outside natural variability limits. Temperature is also more robustly simulated by climate models than is precipitation. Carbon dioxide concentrations are likely to be in the range of 500 ppmv (GGd and GSd scenarios) to 700 ppmv (GGa and GSa scenarios) by this period (Table 1), a rise of about 40% or 100% over 1990 levels. Such exercises would, for example, examine very carefully the effects of temperature and CO_2 concentration increases on evaporation, crops and vegetation and building design.

Finally, it should be appreciated that the last 30 years of observed climate change in the Sahel provides a very powerful analogue for understanding the way in which dryland ecosystems and human societies are impacted by major climate change and how they attempt to adapt to such change. The 20–30% change in annual rainfall sustained over three decades in the Sahel is larger than most scenarios of greenhouse gas-induced regional rainfall change. Reducing the region's vulnerability to rainfall fluctuations of this observed magnitude will be a necessary—if not sufficient—response to the threat of future climate change.

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