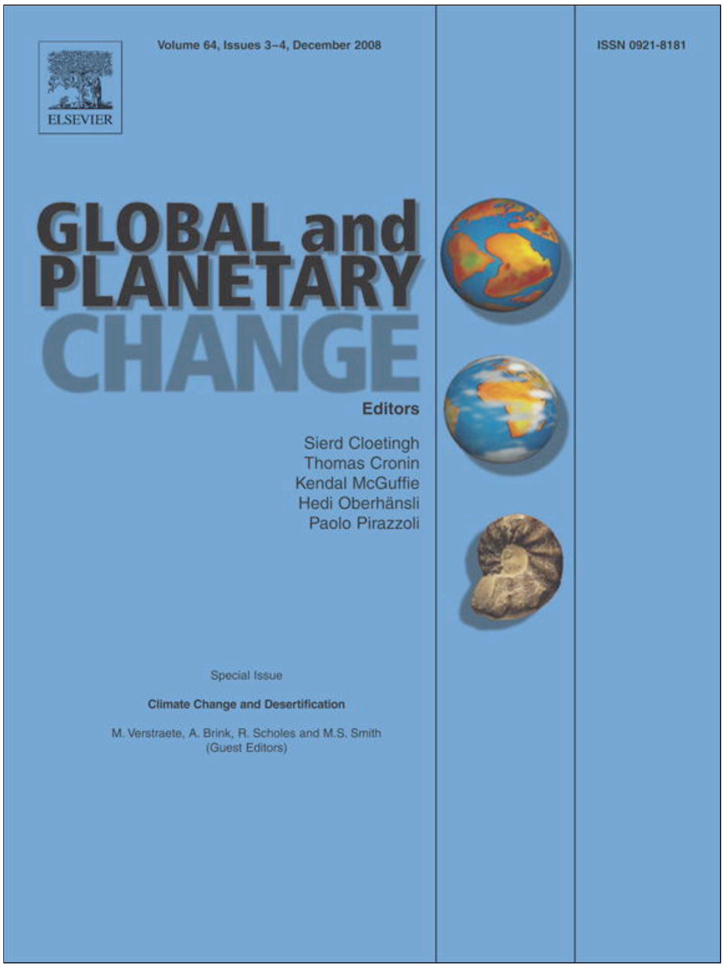
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A climate model-based review of drought in the Sahel: Desertification, the re-greening and climate change

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ABSTRACT

We review the evidence that connects drought and desertification in the Sahel with climate change past, present and future. Advances in climate modeling point to the oceans, not land, as the cause of the recent persistence of drought in the Sahel. The current generation of global climate models reproduces the spatial extent, continental in scale, and the timing and duration of the shift to dry conditions that occurred in the late 1960's given knowledge of observed surface oceanic conditions only. The pattern statistically and dynamically associated with drought is one of warming of the tropical oceans, especially the Pacific and Indian Oceans, superimposed on an enhanced warming of the southern compared to the northern hemisphere most evident in the Atlantic. These models, which include a prognostic description of land surface and/or vegetation, albeit crude, indicate that positive feedbacks between precipitation and land surface/cover may act to amplify the ocean-forced component of continental climate. Despite the advances made in understanding the recent past, uncertainty dominates as we move forward in time, to the present, partial greening of the Sahel, and to the future of climate change projections.

1. Introduction

The African Sahel stretches from the Atlantic coast of Senegal and Mauritania to the Red Sea coast of Sudan and Eritrea. It forms the southern margin of the Sahara desert,[3] or, alternatively, the northern margin of the region influenced by the northern summer African monsoon. It is a semi-arid environment, characterized by a highly variable climate (Nicholson, 1980), with an intense rainy season, centered on August and no more than 4 months long, and a prolonged dry season.

During the second half of the 20th century the Sahel experienced one of the most striking shifts in climate known globally since instrumental records began to be kept—from anomalously abundant rains in the 1950's and 1960's to progressively drier conditions in the 1970's and 1980's [Fig. 1 here] (Nicholson, 1979; Lamb, 1982; Katz and Glantz, 1986; Lamb and Peppler, 1992; Hulme, 1996; IPCC, 2007). The year-to-year persistence of drought[4] was initially attributed to human mismanagement of land resources (Charney, 1975). It was postulated that economic activities such as the expansion of agriculture into marginal zones, overgrazing, and woodcutting for fuel had affected the vegetation cover, making the savanna desert-like, and that the regional atmospheric circulation had responded, reinforcing and perpetuating that change. We call this framework–one where drought and desertification[5] are deemed to have local anthropogenic causes and solutions–the *desertification paradigm* of Sahel climate change, or *Charney's hypothesis*.[6]

In response to the resultant humanitarian crisis, in 1973 nine countries of the West African Sahel, from Cape Verde to Chad, organized themselves into a regional entity called the Comité permanent Inter-états de Lutte contre la Sécheresse au Sahel (CILSS,

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[3] *Sahel*, or *Sahil*, comes from the Arabic word for *shore*.

[4] *Drought* is used here to indicate seasonal accumulation of rainfall that is significantly below the long-term average, and endangers livelihood systems locally adapted to average conditions. For alternative definitions, of meteorological, agricultural, or other, the reader is referred e.g. to Landsberg (1982), Glantz (1987) or Wilhite (2000).
[5] The official definition of *desertification* is "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UN Convention to Combat Desertification 1994—*http://www.unccd.int/convention/text/convention.php*; Millennium Ecosystem Assessment, 2005; also see Verstraete, 1983, 1986a). See Thomas and Middleton (1994) for a comprehensive critique of desertification.
[6] Also see the studies of Otterman (1974) and Jackson et al. (1975) on the observational evidence for a biogeophysical feedback.

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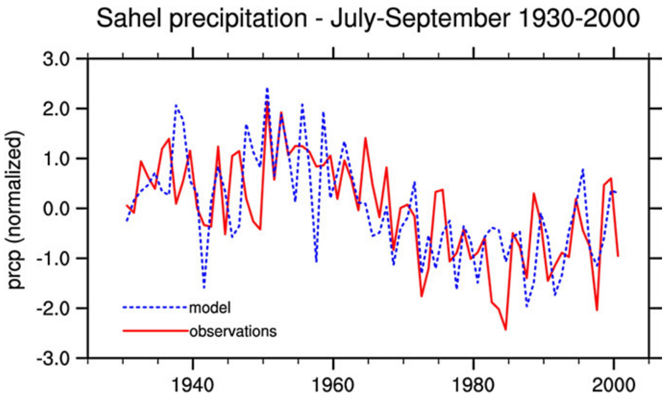

Fig. 1. Indices of Sahel rainfall variability. Observations used the average of stations between 10°N and 20°N, 20°W and 40°E. Model numbers were bases on the ensemble-mean average of grid boxes between 10°N and 20°N, 20°Wand 35°E. The correlation between observed and modeled indices of rainfall over 1930–2000 is 0.60. (Time series are standardized to allow for an immediate comparison, because variability in the ensemble mean is muted in comparison to the single observed realization. The ratio of observed to ensemble-mean standard deviations in the Sahel is 4.)—*from* Giannini et al. (2003). *Reprinted with permission from AAAS.*

or Inter-state committee to combat drought in the Sahel), whose primary mandate to date remains to invest in research to ensure food security and to reduce the impact of drought and desertification.[7] The global response to the drought emergency was largely predicated on the twin assumptions that (1) desertification was man-made, and (2) that it would drive reinforcing changes in the local climate, in part because when framed is such a way, the problem seemed tractable (Verstraete, 1986b; Thomas and Middleton, 1994). In 1977, a United Nations Conference on Desertification (UNCOD) was convened in Nairobi. A Plan of Action to Combat Desertification (PACD) followed suit. Since little progress in monitoring and/or contrasting desertification had been noted by the time the UN Conference on Environment and Development (UNCED) was convened in Rio de Janeiro in 1992, the UN Environment Program (UNEP) launched a new process, which culminated with the negotiations and ratification of the desertification convention. A sister to the other environmental ("Rio") conventions, on biodiversity and climate change, the UN Convention to Combat Desertification (UNCCD) entered into force in December 1996.

With time, evidence to the inadequacy of Charney's hypothesis accumulated. As early as the mid-1980's Chris Folland and colleagues at the UK Meteorological Office had shown that drought in the Sahel could be simulated in climate models in response to a global pattern of sea surface temperature (SST) change obtained as the difference in SST observed during dry and wet years (Folland et al., 1986; Palmer, 1986; Rowell et al., 1995). In recent years, with increased computing power, it has become possible to simulate the climate of the Sahel over periods of many decades. The numerical models used in these studies simulate the complexity of atmospheric weather. Just as they reproduce the progression of seasons in response to the periodic change in insolation, they can reproduce climate variability in response to variability in SST–where SST has an impact, as in the Sahel–when the history of global observed SST is imposed as the lower boundary forcing to the model atmosphere, and nothing else. These simulations provide evidence that it is the oceans that trigger climate variability in the Sahel at interannual to interdecadal time scales, i.e. that it is forces external to the Sahel itself that shape its characteristic year-to-year and longer-term variability. The strength of this argument, relating drought in the Sahel to SST, hinges on the successful reproduction of that historical climate shift, both in spatial scale and timing, when the oceanic forcing, and only oceanic forcing, is explicitly included. It does not exclude a role for land surface processes, rather it redefines such role as a potentially important, but secondary role—the land surface response in its interaction with the atmosphere can enhance locally what is remotely forced from the oceans.

This paper is divided into two main sections, with the degree of uncertainty increasing as the discussion progresses. Section 2 provides an assessment of current understanding of the recent past of climate change in the Sahel. It highlights the dominant role of oceanic forcing in explaining late 20th century drought, and provides the context for consideration of land–atmosphere feedbacks. This section also includes discussion of attribution of past climate change: what can we say about the role of anthropogenic emissions of greenhouse gases and aerosols in the recent persistence of drought in the Sahel? Section 3 connects the recent period to the uncertainty in projections of future change by highlighting the questions that remain unanswered: has there been a recovery in the rains/vegetation since the mid-1980's? What does the future hold? Section 4 concludes.

2. Causes of late 20th century drought in the Sahel

Publication of Giannini et al. (2003) revived interest in Sahelian drought in the climate modeling community. Since then studies have accumulated that strongly indicate that the cause of persistent drought in the Sahel in the 1970's and 1980's lay in the oceans, not over land. Given that *drought* in this region is related to an overall *warming* of the tropical oceans, can we go so far as to attribute the Sahel drought to global warming? In this section we review the state-of-the-art in climate modeling addressing these questions.

2.1. Oceanic forcing of Sahel rainfall

The multi-decadal evolution of rainfall variability in the Sahel can be simulated given knowledge of the history of global sea surface temperature (SST) only, as shown by Giannini et al. (2003; their Fig. 1, reproduced here in Fig. 1) and Lu and Delworth (2005; see their Fig. 2) with two different atmospheric models,[8] and by Hoerling et al. (2006) in a multi-model ensemble. Tippett (2006) compares the performance of the set of models in use at the International Research Institute for Climate and Society (IRI) to make seasonal climate predictions (Goddard et al., 2001; Barnston et al., 2003).

Fig. 1 presents a comparison of observed and modeled indices of Sahelian rainfall. The observed time series, in the solid red line, represents the average of July–September anomalies at 51 stations in the domain between 10°N and 20°N, 20°W and 40°E (from the Global Historical Climate Network; Vose et al., 1992). Stations are from the CILSS countries, from Dakar, Senegal to N'Djamena, Chad, as well as from northern Benin (e.g. Kandi) and Sudan (e.g. El Fasher, in northern Darfur). The modeled time series, in the dashed blue line, is the average over essentially the same domain–between 10°N and 20°N, 20°W and 35°E, to avoid the spurious maximum in modeled precipitation over Yemen–in the ensemble mean of nine integrations forced with the same historical SST, but starting from different atmospheric conditions.[9]

The correlation between the observed and modeled time series is 0.60, statistically significant at the 99% level. The progression from the wetter-than-average 1950's and 1960's to the drier-than-average

7 http://www.cilss.bf/htm/mandat.htm.

8 Developed respectively at the U.S. National Aeronautics and Space Administration (NASA)'s Goddard Space Flight Center (Bacmeister et al., 2000) and at the U.S. National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory (GAMDT, 2004).

9 Ensemble averaging is used in climate predictability studies when the goal is to separate the potentially predictable signal, e.g. that forced from the slower-varying oceanic boundary conditions, from the noise, e.g. due to internal variability of the atmosphere (Shukla, 1998). By starting each simulation with different initial conditions, but running it over the same boundary conditions, one is sure to simulate a different realization of atmospheric noise each time, while maintaining the unifying boundary forcing unaltered. Where such forcing matters, response to it can be detected in the ensemble mean.

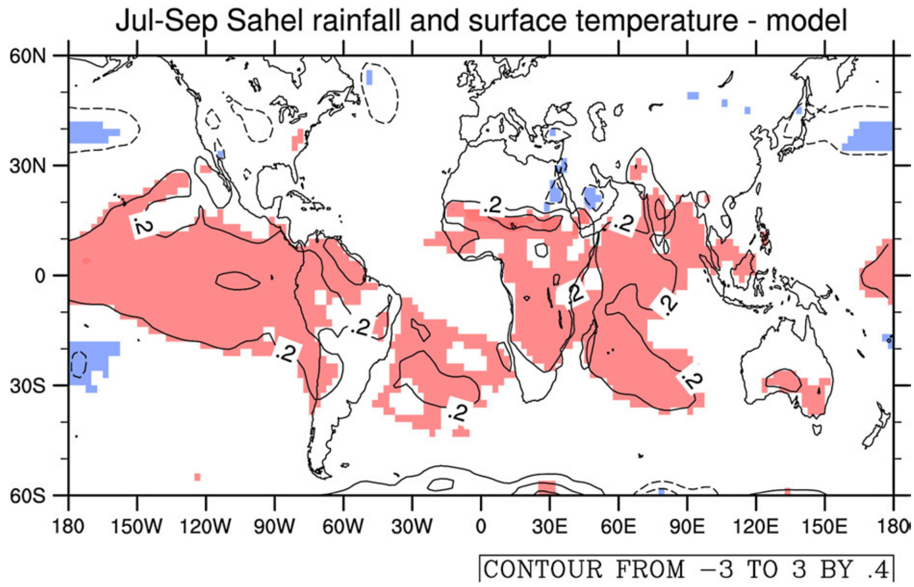

Fig. 2. Regression map of an index of Sahel rainfall (the second model Principal Component) with ensemble mean surface temperature. Contour interval is every 0.4 K, starting at 0.2 K, and shading represents statistical significance of the anomalies at the 99.9% level. Solid lines represent positive anomalies, dashed lines negative anomalies—*adapted from* Giannini et al. (2003).

1970's and 1980's, evident in observations and captured in the model, is related to a generalized pattern of warming of the global tropical oceans (Fig. 2, from Giannini et al., 2003[10]), especially of the Indian Ocean, combined with enhanced warming of the southern compared to the northern tropical Atlantic Ocean.

Bader and Latif (2003) highlight the role of the Indian Ocean in idealized simulations. When they impose a 1 °C *cooling* of the entire Indian Ocean with respect to climatological conditions, their model–version 4.5 of ECHAM, the model developed at the Max Planck Institute for Meteorology in Hamburg, Germany (Roeckner et al., 1999)–responds with a *wetter* Sahel, with pronounced positive rainfall anomalies in the region west of 20°E (see their Figs. 2 and 3; their Fig. 3 is reproduced here in Fig. 3). Hagos and Cook (2008) impose the *positive* SST anomalies in the Indian Ocean typical of the 1980's–the driest decade in the Sahel–and obtain *drying*. The atmospheric teleconnection in their regional climate model (Vizy and Cook, 2002) is modulated by a westward-propagating Rossby wave (Gill, 1980) that brings about subsidence in the Sahel. They also argue that the partial recovery of the rains in the 1990's is consistent with the competing effects of Indian and Atlantic SST.

Lu and Delworth (2005) revisit Palmer's 1986 study. Besides running their atmospheric model over the observed record of global SST from 1950 to 2000, and simulating the downward trend (see their Fig. 1), they also consider the separate effects of changes in SST in the Atlantic, Pacific and Indian Oceans. In their Fig. 3, reproduced here in Fig. 4, they show that all ocean basins contribute to a drying of the Sahel, and that the sum of the effects of the basins taken separately is comparable to the effect of simultaneously changing SST in all the basins, i.e. the system is approximately linearly additive.

When the Sahel time series is filtered by means of a 21-year running mean, the temporal separation in the contributions of the Pacific Ocean to interannual variability, and of the Atlantic and Indian Oceans to interdecadal variability becomes apparent (Giannini et al., 2003, 2005). The Pacific Ocean affects the Sahel through the occurrence of El Niño-Southern Oscillation (ENSO) events, which recur on a 2–7 year time scale—a warm ENSO or El Niño is typically associated with drought, a cold ENSO or La Niña with abundant rainfall. The oceans around Africa dominate on longer time scales: both a warming of the equatorial Indian Ocean, and a warmer South Atlantic compared to the North Atlantic are dynamically consistent with a drier Sahel, be it because the Intertropical Convergence Zone follows the warmest waters (Folland et al., 1986; Hoerling et al., 2006), or because the atmosphere over land does not find the means to sustain deep convection as the oceans warm (Chou et al., 2001; Chiang and Sobel, 2002; Neelin et al., 2003; Giannini et al., 2005, 2008).

While simulation of the timing and duration of the historical Sahel drought is accurate, most climate models still fail to capture the observed magnitude of rainfall change. Simulated variability at all time scales tends to be muted compared to observations. Thus, even in the context of a dominant forcing of the oceans, it makes sense to consider land–atmosphere interaction as a feedback that can potentially intensify ocean-forced rainfall anomalies.

2.2. What role for land–atmosphere feedbacks?

Prior to the studies just reviewed, which highlight the role of the oceans, many climate model simulations had been conducted that sought to relate changes in land surface properties such as albedo or land cover to a response in rainfall (e.g. Charney, 1975; Charney et al., 1977; Sud and Fennessy, 1982; Laval and Picon, 1986; Xue and Shukla, 1993). These studies were successful in proving rainfall sensitivity to local surface conditions, but only partially, in that either the prescribed change in surface conditions was exaggerated with respect to reality, to trigger a measurable rainfall response, or, when realistic estimates of land cover change were applied, they did not lead to the reproduction of the observed magnitude of rainfall change (Taylor et al., 2002; Wang et al., 2004).

Consistent with the framework of a dominant oceanic forcing put forth here, it makes sense to consider land–atmosphere interaction as a feedback on precipitation. Zeng et al. (1999), Wang and Eltahir (2000) and Giannini et al. (2003), among others, discuss some of the potential mechanisms, which involve soil moisture, dust and vegetation (see Fig. 5, taken from Zeng et al., 1999). Evaporation plays a central role in these feedbacks. With increased rainfall and soil moisture can come increased evaporation and atmospheric instability, locally fueling further moisture convergence and rainfall enhancement. Such an interaction between precipitation, soil moisture and evaporation, or evapo-transpiration mediated by vegetation, would constitute a positive feedback–above-normal precipitation leads to a

[10] Or equivalently, see Fig. 2 in Folland et al. (1986).

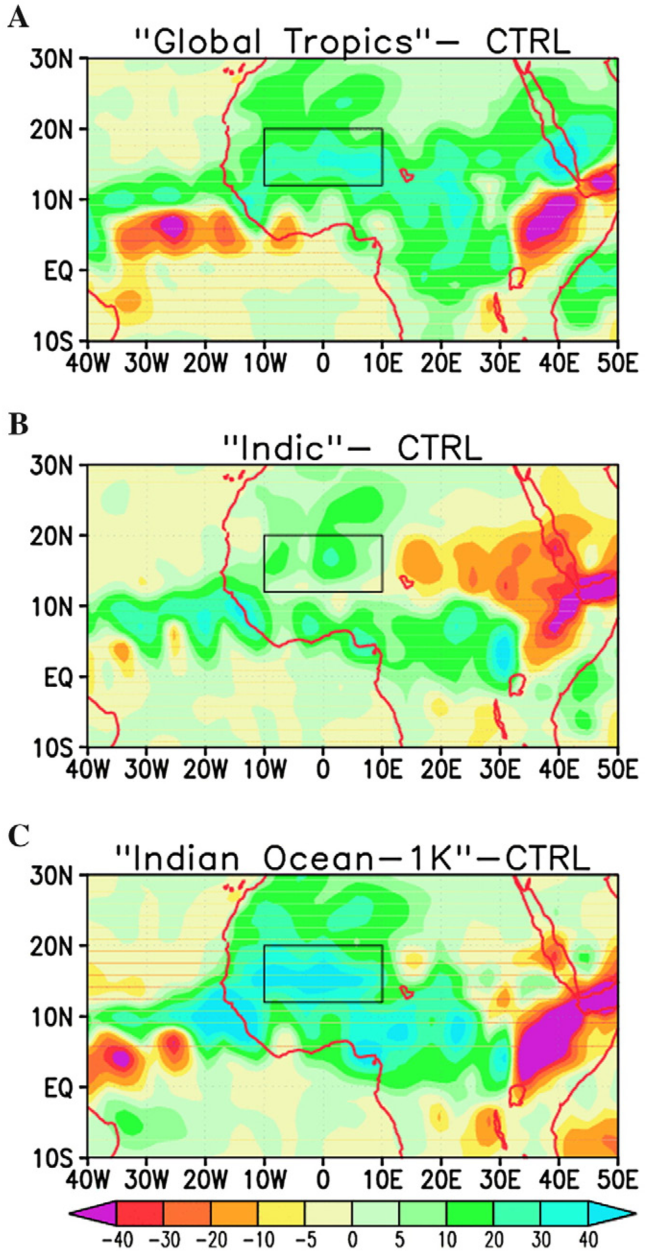

Fig. 3. Simulated June–September rainfall anomaly (relative to the control integration) for the experiments with: (A) global SST anomaly ("Global Tropics"); (B) Indian Ocean portion ("Indic"); (C) idealized SST anomaly ("Indian Ocean minus 1 K"). Units: mm/month. The box indicates the West Sahel—from Bader and Latif (2003).

further enhancement–but observational studies are inconclusive in this regard (Taylor and Lebel, 1998; Taylor and Ellis, 2006; Taylor, 2007). This may in part be because the cloud cover that accompanies precipitation can reduce the energy available at the surface to the point that it may become insufficient to evaporate the available moisture. Cloud cover, much like albedo, acts on the net surface energy budget. Only, cloud cover provides a negative feedback on precipitation, while in Charney's biogeophysical feedback albedo provided a positive feedback. To the extent that dust acts on the surface energy balance primarily by reducing the net solar radiation at the surface, dust also provides a positive feedback[11]: less precipitation leads to more dust, and to less net solar radiation at the surface, hence reduced evaporation, and reduced precipitation (Prospero and Lamb, 2003; Yoshioka et al., 2007). Dust particles acting as cloud condensation nuclei have also been hypothesized to reduce the efficiency of precipitation (Rosenfeld et al., 2001).

If positive feedbacks dominate, then it is straightforward to conceive that a rainfall anomaly that has its origin in oceanic change can be amplified by the subsequent coupled land–atmosphere response. Alternatively, if negative feedbacks dominate, e.g. between rainfall, clouds and net solar radiation, then one has the means to limit oceanic impact on continental climates. We will return to this topic in the section on the uncertainty of projections of future change.

2.3. Attribution of late 20th century drought

The explicit connection between drought and oceanic warming makes it inevitable, in this age of increased awareness about global warming, to reflect on whether persistent drought was indeed an early manifestation of anthropogenic impact (Zhang et al., 2007; Kerr, 2003). Only now "anthropogenic" is not related to mismanagement of land resources at the regional scale, rather it relates directly to the global scale of emissions of greenhouse gases and aerosols associated with industrialization. The question becomes: can the recent persistence of drought be attributed to industrialization?

One indirect way to argue in the affirmative is to consider, as already mentioned, the nature of the oceanic warming associated with drought. Warming of the oceans, not just the surface oceans, but the heat content down to several hundred meters' depth, is well observed (Levitus et al., 2000) and has been attributed to anthropogenic causes (Barnett et al., 2005). However, given the sensitivity of Sahel rainfall to the details of the spatial pattern of surface warming, one would like to gather further, more direct proof, e.g. that changes in global tropical SST and in Sahelian precipitation are coherent, and consistent with a modeling framework where ocean and atmosphere are coupled and subject only to forcing from industrialization.

This type of evidence is currently not available. Biasutti and Giannini (2006) show that the coupled ocean–atmosphere models that participated in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 4AR), also known as the CMIP3 models,[12] do reproduce a drier Sahel at the end of the 20th century when forcings include greenhouse gases and sulfate aerosols (their Fig. 2a, reproduced here in Fig. 6). However, most coupled models reproducing a statistically significant drying of the Sahel also include prescription of natural forcings such as variability in insolation and impact of volcanic aerosols. Some go so far as to include prescription of land use change and of aerosols from biomass burning. So, while Sahel drought is seen to be consistent with late 20th century forcings of the climate system, it is currently not possible to unequivocally separate the contributions of anthropogenic forcings from the industrialized world—a proposition that would carry considerable political weight in the policy arena of global environment and development negotiations. Zhang et al. (2007) attempt such a separation, and argue that anthropogenic causes played a significant role in the 20th century drying of northern hemisphere tropical latitudes, but only hint at the case of the Sahel.

The CMIP3 multi-model average simulates a global pattern of SST change similar to that observed in relation to Sahel drought (compare Fig. 7, taken from Biasutti and Giannini (2006), with Fig. 2) and, associated with it, reduction in precipitation all across the Atlantic Intertropical Convergence Zone, from the Caribbean basin to the highlands of Ethiopia. The simplest interpretation of this pattern of

[11] The direction of dust feedbacks is still in question. Dust suspended in the lower atmosphere has been hypothesized to induce localized atmospheric heating that could enhance the monsoon circulation and rainfall (Lau et al. 2006). Such an interaction would constitute a negative feedback on precipitation.

[12] The models that participated in phase 3 of the World Climate Research Program (WCRP)'s Coupled Model Intercomparison Project (CMIP3). Model output is available from http://www-pcmdi.llnl.gov/ipcc/about ipcc.php.

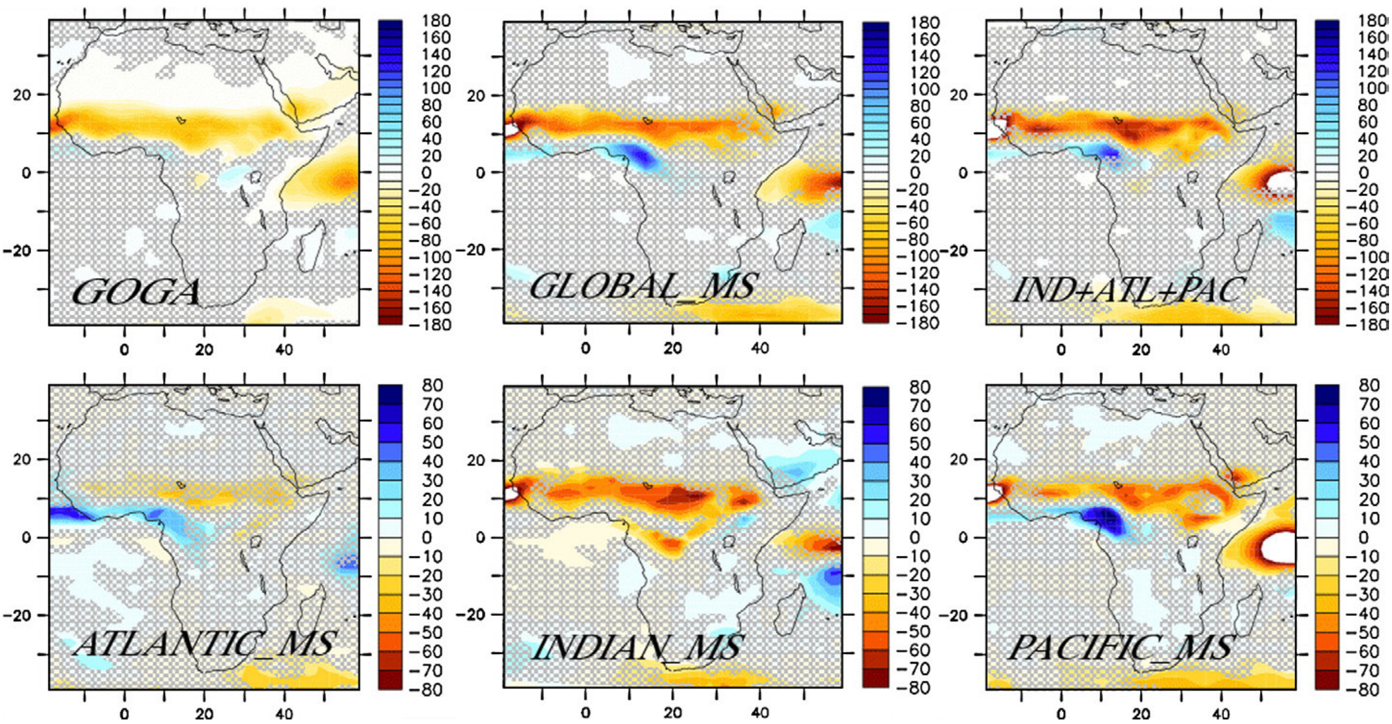

Fig. 4. July–September mean response of African rainfall to SST forcing in different experiments. For GOGA experiment, plotted is the linear trend of rainfall from 1950–2000. For the other runs, plotted are the difference between the SST anomaly runs and control runs. All the patterns have been scaled to correspond to the trend during 50 years, with unit of mm/month/50 years. The hatched areas are not significantly different from zero at 95% levels based on *t*-test—*from* Lu and Delworth (2005).

late 20th century SST change, ignoring changes in oceanic circulation, is that it results from the superposition of a global warming effect due to greenhouse gases, which are well mixed in the atmosphere, and the cooling imparted by reflective aerosols,[13] which is localized to the northern hemisphere and particularly pronounced over the mid-latitude oceans, i.e. downwind from sources. Thus, the CMIP3 simulations are consistent with the argument already put forth by Rotstayn and Lohmann (2002), who argued that the effect of anthropogenic sulfate aerosols on SST and on tropical rainfall was to produce both cooling of the northern hemisphere, and drying of the Sahel.

The notion that aerosol emissions from industrialization may have played the leading role in causing Sahel drought is also indirectly supported by comparison of the response in the CMIP3 models when they are driven by the all-inclusive set of 20th century forcings as opposed to CO_2 only. While in the former case no model simulates a wetter Sahel, and many models simulate significant drying (Fig. 6), in the latter, the divergence among model parallels that found in projections of future change (see Fig. 2b in Biasutti and Giannini, 2006), topic of the next section.

3. Is the past a prologue to the future?

While the shift to a drier climate that affected the Sahel at the end of the 1960's is well documented, and its ties to global tropical SST are understood, the same cannot be said of trends in the years since the driest mid-1980's. Uncertainty only grows as we look forward to projections of future change. Here we explore the issues, and give an interpretive key based on the knowledge exposed in the previous section.

3.1. A recovery of the rains?

A line of research parallel to climate modeling had since the early 1990's already called into question Charney's hypothesis of desertification as a locally driven, man-made process. Studies of land use/land cover change questioned the irreversibility of such processes. In "reframing deforestation", Fairhead and Leach (1998) documented the rich history of local management strategies aimed at preserving a functional ecosystem, thus exposing the fallacy of colonial forestry studies, which had characterized the trajectory of land cover change in West Africa as a recent, progressive and inexorable denudation, largely driven by population growth.[14] Tucker et al. (1991) and Helldén (1991) analyzed the remotely sensed imagery[15] that had come online in the early 1980's to show how vegetation that had been under stress, e.g. due to inadequate rains, could respond with minimum delay to an improvement in physical conditions. These conclusions were confirmed more recently by Eklundh and Olsson (2003). Thus, external forcing affects the Sahel at large spatial and long temporal scales, and overrides the processes that control local or short-lived variations.

The Sahel has been greening in recent times (Polgreen, 2007). Olsson et al. (2005) and Herrmann et al. (2005) have gone so far as to suggest that in certain locations, *greening* of vegetation has exceeded what can be explained linearly by a *recovery* in the rains since the driest mid-1980's.[16] Whether this change has to do with a recovery of

[13] Commonly referred to as *global dimming*—see e.g. Stanhill and Cohen (2001); Liepert (2002).

[14] Also see Chapter 2 of Thomas and Middleton (1994) for a brief history of human modification of the African environment on time scales of tens, if not hundreds of thousands of years.

[15] These studies, and those cited in the following, are all based on interpretation of the Normalized Difference Vegetation Index (NDVI), which has long been known to be sensitive to instrumental and geophysical factors extraneous to vegetation itself. They should only be taken as a rough preliminary indication of gross trends that remain to be investigated with state-of-the-art tools.

[16] The lively debate on the interpretation of recent trends in rain use efficiency (e.g. Prince et al. 1998; Hein and DeRidder, 2006), and their relation to equilibrium v. non-equilibrium approaches in drylands management, is beyond the scope of this paper.

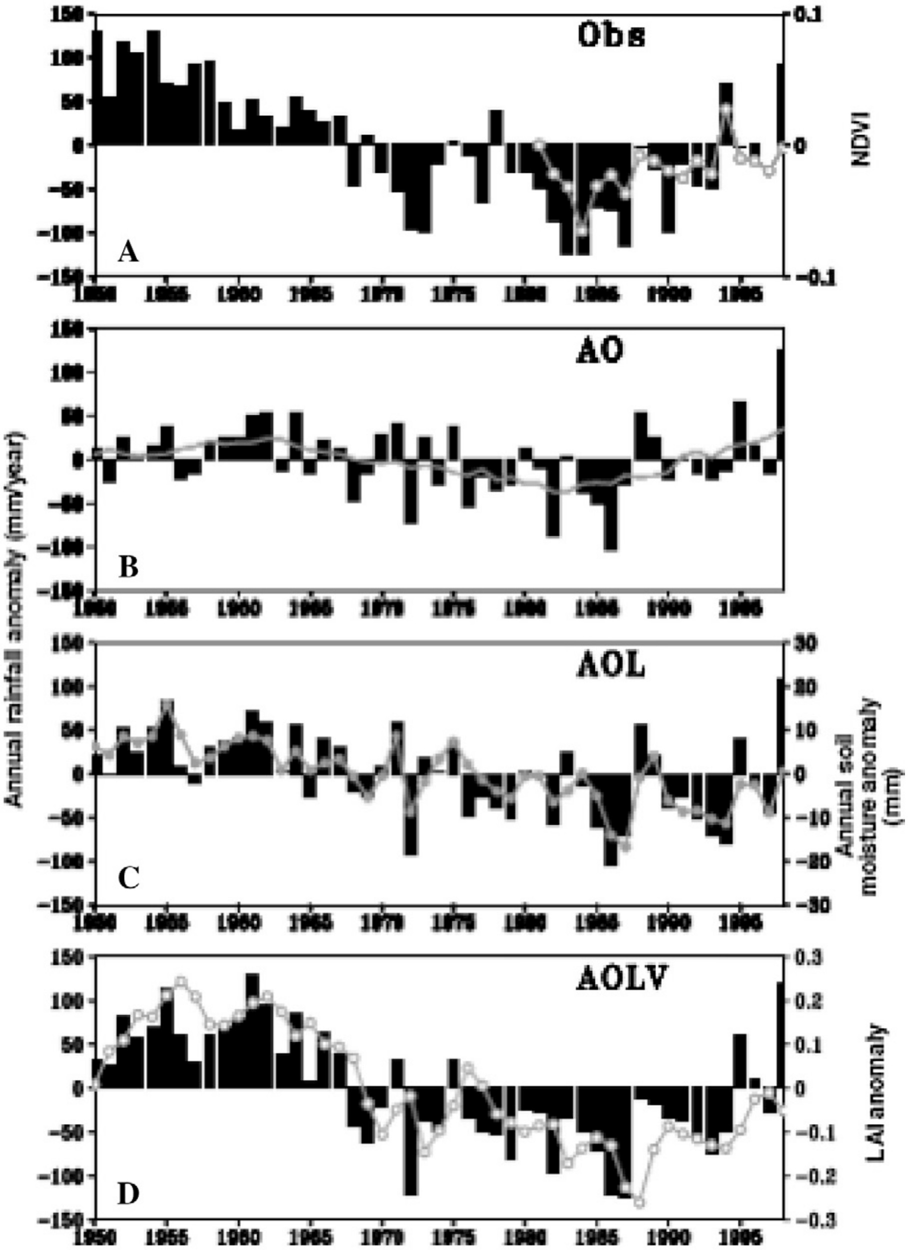

Fig. 5. Annual rainfall anomalies (vertical bars) over the West African Sahel (13°N–20°N, 15°W–20°E) from 1950 to 1998. (A) Observations from (Hulme). (B) Model with non-interactive land surface hydrology (fixed soil moisture) and non-interactive vegetation (SST influence only, AO). Smoothed line is a 9-year running mean showing the low-frequency variation. (C) Model with interactive soil moisture but non-interactive vegetation (AOL). (D) Model with interactive soil moisture and vegetation (AOLV). Also plotted (as connecting circles, labeled on the right) are (A) the normalized difference vegetation index (NDVI), (C) the model simulated annual soil moisture anomaly, and (D) the model simulated LAI anomaly. All the anomalies are computed relative to the 1950–98 base period, except that the NDVI data is relative to 1981—*from* Zeng et al. (1999). *Reprinted with permission from AAAS*.

the rains was discussed at a workshop convened in Nairobi in 2003—see Herrmann and Hutchinson (2005), and companion papers in the special issue of *Journal of Arid Environments* published in November 2005.

A positive trend over the past 20 years is visible in any time series of total seasonal Sahel rainfall (e.g. Fig. 1 here): the mid-1980's were so dry that inspection of any time series representative of the region gives the impression that rainfall has been improving since. This interpretation is supported by a long-term study of streamflow in the Senegal river (Hubert et al., 2007), and by the climate modeling study of Hagos and Cook (2008) discussed in Section 2.1. However, it has been refuted in studies of recent rainfall variability (L'Hôte et al., 2002), and its impact. In the Central Plateau of Burkina Faso, farmers who experienced the dry conditions in the 1970's and 1980's as a shorter and more volatile rainy season have not noticed a return to the pre-drought character (West et al., 2008).

One way to reconcile an increase in seasonal totals with a volatile rainy season is to hypothesize that while the frequency of rainfall events has not changed since the 1970's, i.e. it is still lower than during the preceding wetter period (Lebel et al., 2003), the intensity of events may be increasing. This effect would be consistent with what expected of global warming on the basis of a purely thermodynamic argument—a warmer atmosphere is also moister, hence wetter (Trenberth et al., 2003). Resolution of this issue will require a regional scale analysis of trends in extremes in precipitation that is currently not available. Likewise for a reassessment of dryland environments: there is room

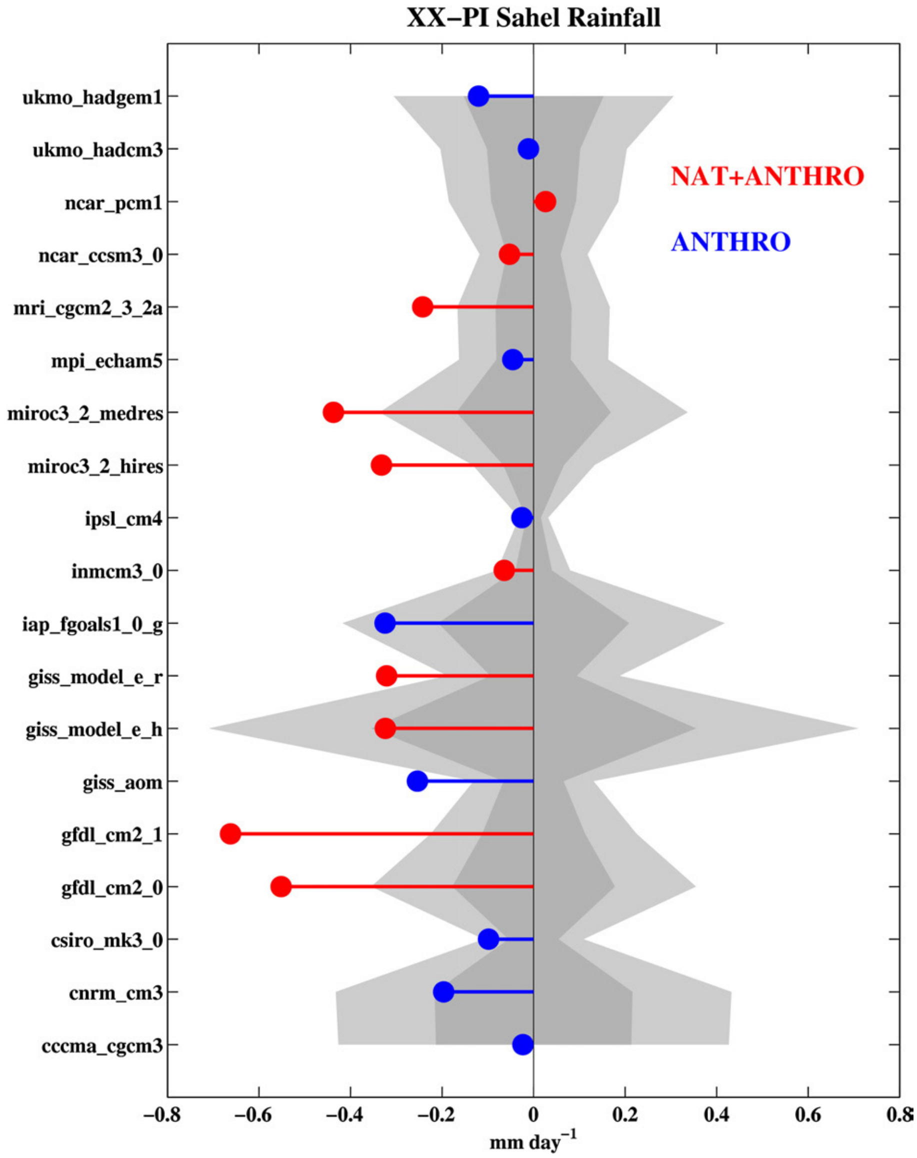

Fig. 6. The June–September Sahel rainfall difference between the end of the 20th century (1975–1999 ensemble mean for each model) and PI (long-term mean). The dark (light grey) shading is one (two) sigma deviations in 25-year mean Sahel rainfall in each PI simulation. Models forced by both natural and anthropogenic forcings are shown in red circles, those forced only by anthropogenic forcings in blue circles. Note that the "red circle" models also tend to have a more complete treatment of aerosol forcings and to include land-use changes. Except for CCMA, PCM1 and HADCM3, drying is significant at the 95% level—*from* Biasutti and Giannini (2006).

for improvement of remote sensing techniques, perhaps in the context of a Global Drylands Observing System (GDOS), to monitor and understand the spatial extent and processes leading to greening.

Or, is the greening man-made? In pointing to successful land management interventions (implemented largely with the support of Non-Governmental Organizations) as the cause for the recent greening, Kaboré and Reij (2003), and Reij et al. (2005) demonstrate that we have come full circle with respect to the desertification paradigm: not only was environmental mismanagement not the cause of drought, but also appropriate land management solutions such as soil water conservation techniques derived from local knowledge can be implemented to the benefit of rural communities even in times of drought.

3.2. Uncertainty in projections of future change

Current projections of climate change in the Sahel are uncertain (Christensen et al., 2007; Biasutti and Giannini, 2006; Cook and Vizy, 2006; Douville et al., 2006). Models are in disagreement with regard to the sign of future change—while some are locked in a persistently dry mode, others predict an improvement in the rains. Based on understanding of the underlying mechanisms of recent drought, and of the environmental change that has occurred in the Sahel, two interpretations can be given of future change (Giannini et al., 2008). These are complementary, in the sense that both mechanisms are physically sound, but we do not understand the interactions well enough to predict which will dominate.

One interpretation centers on the overall warming of the oceans and predicts a drying of the continents. In a warmer future, we would expect the enhanced oceanic evaporation to fuel convection and rainfall over water, at the expense of continental convection; if the ocean sets up the environmental conditions favorable for convection to occur, and those conditions cannot be met over land because moisture is not readily available, then continents dry out. A positive land–atmosphere feedback would further lock the system into a dry state. A slightly more nuanced hypothesis is that the continental

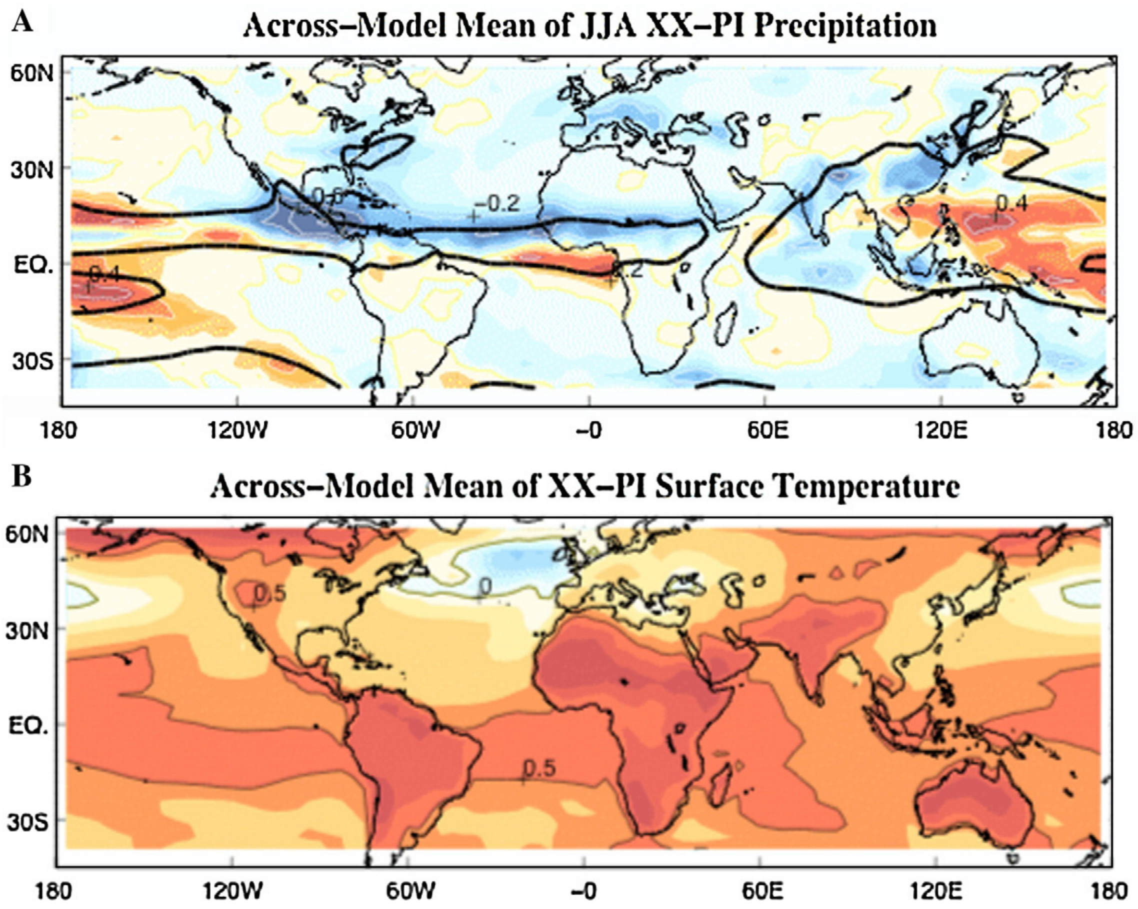

Fig. 7. Difference between the 1975–1999 mean climate in the 20th century simulations and in pre-industrial (PI) climate. (A) Annual mean surface temperature. (B) June–August mean rainfall. Warm colors and solid contours indicate positive anomalies and cool colors and dashed contours indicate negative anomalies. Panels show cross-model means (contour interval is 0.1 °C for temperature and 0.1 mm/day for rainfall), the thick black line in panel (B) is the 4 mm/day contour in the 20th century simulations—from Biasutti and Giannini (2006).

centers of convection can meet the necessary conditions, because enough moisture is converged towards them, but the margins cannot, because the air converging into them is not as moist—hence the margins of tropical convection, meaning possibly the Sahel, dry out (Neelin et al., 2003; Chou and Neelin, 2004; Held et al., 2005).

Another interpretation relates the location of moisture convergence and rainfall to gradients in surface properties (Lindzen and Nigam, 1987; Eltahir and Gong, 1996; Cook, 1999). The role of the reduced warming of the North compared to the South Atlantic is emphasized in the recent drying of the Sahel. Such oceanic variability has been argued to be related to internal variability of the oceans (Knight et al., 2006), to aerosols (Rotstayn and Lohmann, 2002), or to both internal variability and external, anthropogenic forcings (Ting et al., submitted for publication). A future wetter Sahel can be conceived as the response to a reversal in such pattern of sea surface temperature (Hoerling et al., 2006), due either to a reduction of aerosol loading, or to an oscillation of Atlantic Ocean variability with multi-decadal time scale. Alternatively, a wetter Sahel might follow from an enhanced warming of land compared to oceans, which would be responsible for driving a stronger monsoonal flow inland (Haarsma et al., 2005).

Whether there has been a recovery of rains in the Sahel or not is of relevance to making sense of projections of future change in view of the recent past. Given the continued warming trend of the oceans, the association between warming of the oceans, especially the Indian Ocean, and drying of the Sahel is more straightforward to support if the rains have not recovered. If this were to be found to be the dominant association, it would give more credence to projections of further future drying. Conversely, a recent recovery of the rains would be consistent with arguments that relate the strength of the African monsoon to an increased temperature contrast, either between land and ocean (e.g. Haarsma et al., 2005), or between the sea surface temperatures of the northern and southern tropical Atlantic (Hoerling et al., 2006), and to projections of improved seasonal rainfall.

4. Conclusions

The goal of this paper was to review advances in climate science which point to changes in the global oceans as the cause of the recent continental-scale change in the climate of the African Sahel. State-of-the-art atmospheric models driven by the observed long-term history of global sea surface temperature (SST) reproduce the timing and decadal time scale of change in Sahel rainfall–the shift from anomalously wet to persistently dry that occurred at the end of the 1960's, as well as its spatial extent–from the Atlantic coast of Senegal and Mauritania to the Red Sea coast of Sudan and Eritrea, but not its magnitude. Though models have in the past shown sensitivity of rainfall to both land surface (e.g. Charney, 1975) and oceanic conditions (e.g. Folland et al., 1986), it is their simulation of the spatial and temporal scales of Sahel change given knowledge of sea surface temperature only that favors the hypothesis according to which the origin of persistent drought in the Sahel is global in scale, and external to the region. Because changes in rainfall drive changes in continental environments, including in land surface properties, dust, vegetation, and streamflow, it makes sense to consider land processes as feedbacks to the oceanic forcing, not independent of it—potentially positive feedbacks that can locally reinforce the change, and account for its observed magnitude. The challenge then becomes to separate the changes in land properties that one would expect from ocean-forced changes in precipitation from those that may have been effected locally, by human activity. When analyzing land cover change one should contrast the spatial coherence of physical drivers against the heterogeneity of social, economic and political systems in this region (Raynaut, 1997), understanding that the latter may lead to a diversity of local responses.

The association between warming of the tropical oceans and Sahel drought opens up for consideration of drought and desertification in the context of global climate change (see also Kerr, 2003; Ban, 2007). The evidence, as summarized here, is not conclusive—we discussed 3 questions that still need an answer to potentially connect science, policy and action: (1) Can late 20th century Sahel drought be attributed to anthropogenic causes, i.e. to industrialization in the North? (2) Have the rains been recovering in recent decades (post–mid-1980s)? (3) What is the more plausible projection of future change—a recovery of the rains or persistence of drought?

Still, even if climate science were to answer these questions in short order, the recent past of Sahel drought–the divergence of science and policy (Corell, 1999), and the limiting socio-political context (Glantz, 1976; 1977)–constitutes a lesson learned not to be forgotten. Ensuring that interdisciplinary knowledge is brought to bear on the pressing issues of drylands development (Reynolds et al., 2007), requiring that scientists, policymakers and stakeholders come together in a conscious, concerted effort to effect change, will likely only be the starting point.

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References

Bacmeister, J.T., Pegion, P.J., Schubert, S.D., Suarez, M.J., 2000. Atlas of Seasonal Means Simulated by the NSIPP1 Atmospheric GCM. NASA Tech. Memo-2000-104606. 100 pp.
Bader, J., Latif, M., 2003. The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation. Geophys. Res. Lett. doi:10.1029/2003GL018426.
Ban, K.-M., 2007. A climate culprit for Darfur. Washington Post. 16 June 2007.
Barnett, T.P., Pierce, D.W., AchutaRao, K.M., Gleicker, P.J., Santer, B.D., Gregory, J.M., Washington, W.M., 2005. Penetration of human-induced warming into the world's oceans. Science 309, 284–287.
Barnston, A.G., Mason, S.J., Goddard, L., DeWitt, D.G., Zebiak, S.E., 2003. Multimodel ensembling in seasonal climate forecasting at IRI. Bull. Am. Meteor. Soc. 84, 1783–1796.
Biasutti, M., Giannini, A., 2006. Robust Sahel drying in response to late 20th century forcings. Geophys. Res. Lett. 11, L11706. doi:10.1029/2006GL026067.
Charney, J.G., 1975. Dynamics of deserts and drought in the Sahel. Q. J. R. Meteor. Soc. 101, 193–202.
Charney, J., Quirk, W.J., Chow, S.-H., Kornfeld, J., 1977. A comparative study of the effects of albedo change on drought in semi-arid regions. J. Atmos. Sci. 34, 1366–1385.
Chiang, J.C.H., Sobel, A.H., 2002. Tropical tropospheric temperature variations caused by ENSO and their influence on the remote tropical climate. J. Climate 15, 2616–2631.
Chou, C., Neelin, J.D., 2004. Mechanisms of global warming impacts on regional tropical precipitation. J. Climate 17 (13), 2688–2701.
Chou, C., Neelin, J.D., Su, H., 2001. Ocean–atmosphere–land feedbacks in an idealized monsoon. Q. J. R. Meteorol. Soc. 127, 1869–1891.
Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., 2007. Regional climate projections. Climate Change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 847–940.
Cook, K.H., 1999. Generation of the African Easterly Jet and its role in determining West African precipitation. J. Climate 12, 1165–1184.
Cook, K.H., Vizy, E.K., 2006. Coupled model simulations of the West African monsoon system: 20th century simulations and 21st century predictions. J. Climate 19, 3681–3703.
Corell, E., 1999. The negotiable desert: expert knowledge in the negotiations of the Convention to Combat Desertification. Ph.D. Dissertation, Linköping, Sweden, Linköping Studies in Arts and Sciences.
Douville, H., Salas-Melia, D., Tyteca, S., 2006. On the tropical origin of uncertainties in the global land precipitation response to global warming. Clim. Dyn. 26, 367–385.
Eklundh, L., Olsson, L., 2003. Vegetation index trends for the African Sahel 1982–1999. Geophys. Res. Lett. Apr 2003.
Eltahir, E.A.B., Gong, C., 1996. Dynamics of wet and dry years in West Africa. J. Climate 9, 1030–1042.
Fairhead, J., Leach, M., 1998. Reframing Deforestation. Global Analyses and Local Realities: Studies in West Africa. Routledge, London and New York. 238 pp.
Folland, C.K., Palmer, T.N., Parker, D.E., 1986. Sahel rainfall and worldwide sea temperatures, 1901–85. Nature 320, 602–607.
GAMDT, 2004. The new GFDL global atmosphere and land model AM2–LM2: evaluation with prescribed SST simulations. J. Climate. The GFDL Global Atmospheric Model Development Team, vol. 17, pp. 4641–4673.
Giannini, A., Saravanan, R., Chang, P., 2005. Dynamics of the boreal summer African monsoon in the NSIPP1 atmospheric model. Clim. Dyn. 25, 517–535. doi:10.1007/s00382-005-0056-x.
Giannini, A., Saravanan, R., Chang, P., 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. Science 302, 1027–1030 Published online 9 October 2003. 10.1126/science.1089357.
Giannini, A., Biasutti, M., Held, I.M., Sobel, A.H., 2008. A global perspective on African climate. Climatic Change 90, 359–383. doi:10.1007/s10584-008-9396-y.
Gill, A.E., 1980. Some simple solutions for heat-induced tropical circulation. Q. J. R. Meteor. Soc. 106, 447–462.
Glantz, M.H., 1976. The value of a long-range weather forecast for the West African Sahel. Bull. Am. Meteor. Soc. 58 (2), 150–158.
Glantz, M.H., 1977. Nine fallacies of natural disaster: the case of the Sahel. Clim. Change 1, 69–84. doi:10.1007/BF00162778.
Glantz, M.H., 1987. Drought and Hunger in Africa — Denying Famine a Future. Cambridge University Press. 457 pp.
Goddard, L., Mason, S.J., Zebiak, S.E., Ropelewski, C.F., Basher, R., Cane, M.A., 2001. Current approaches to seasonal to interannual climate predictions. Int. J. Climatol. 21, 1111–1152.
Haarsma, R.J., Selten, F., Weber, N., Kliphuis, M., 2005. Sahel rainfall variability and response to greenhouse warming. Geophys. Res. Lett. doi:10.1029/2005GL023232.
Hagos, S., Cook, K.H., 2008. Ocean warming and late 20th century Sahel drought and recovery. J. Climate. doi:10.1175/2008JCLI2055.1.
Hein, L., De Ridder, N., 2006. Desertification in the Sahel: a reinterpretation. Glob. Chang. Biol. 12, 1–8. doi:10.1111/j.1365-2486.2006.01135.x.
Held, I.M., Delworth, T.L., Lu, J., Findell, K., Knutson, T.R., 2005. Simulation of Sahel drought in the 20th and 21st centuries. Proc. Nat. Acad. Sci. 102, 17891–17896. doi:10.1073/pnas.0509057102.
Helldén, U., 1991. Desertification — time for an assessment? Ambio 20, 372–383.
Herrmann, S.M., Hutchinson, C.F., 2005. The changing contexts of the desertification debate. J. Arid Environ. 63, 538–555.
Herrmann, S.M., Anyamba, A., Tucker, C.J., 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. Glob. Environ. Change 15, 394–404.
Hoerling, M.P., Hurrell, J.W., Eischeid, J., Phillips, A.S., 2006. Detection and attribution of 20th century northern and southern African monsoon change. J. Climate 19, 3989–4008.
Hubert, P., Bader, J.-C., Bendjoudi, H., 2007. Un siécle de débits annuels du fleuve Sénégal. Hydrol. Sci. J./J. Sci. Hydrol. 52, 68–73.
Hulme, M., 1996. Recent climatic change in the world's drylands. Geophys. Res. Lett. 23, 61–64.
IPCC, 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. United Kingdom and New York NY, U.S.A.
Jackson, R.D., Idso, S.B., Otterman, J., 1975. Surface albedo and desertification. Science 189, 1012–1015.

Kaboré, D., Reij, C., 2003. The emergence and spread of an improved traditional soil and water conservation practice in Burkina Faso. Paper Presented at the InWEnt, IFPRI, NEPAD, CTA Conference on "Successes in African Agriculture", Pretoria, 1–2 December 2003.

Katz, R.W., Glantz, M.H., 1986. Anatomy of a rainfall index. Mon. Wea. Rev. 114, 764–771.

Kerr, R.A., 2003. Warming Indian Ocean wringing moisture from the Sahel. Science 302, 210–211.

Knight, J.R., Folland, C.K., Scaife, A.A., 2006. Climate impacts of the Atlantic Multidecadal Oscillation. Geophys. Res. Lett. 33, L17706. doi:10.1029/2006GL026242.

Lamb, P.J., 1982. Persistence of Subsaharan drought. Nature 299, 46–48.

Lamb, P.J., Peppler, R.A., 1992. Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought. J. Climate 5, 476–488.

Landsberg, H.E., 1982. Climatic aspects of droughts. Bull. Am. Meteor. Soc. 63, 593–596.

Lau, K.M., Kim, M.K., Kim, K.M., 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. Clim. Dyn. 26, 855–864 10.1007/s00382-006-0114-z.

Laval, K., Picon, L., 1986. Effect of a change of the surface albedo of the Sahel on climate. J. Atmos. Sci. 43, 2418–2429.

Lebel, T., Diedhiou, A., Laurent, H., 2003. Seasonal cycle and interannual variability of the Sahelian rainfall at hydrological scales. J. Geophys. Res. doi:10.1029/2001JD001580.

Levitus, S., Antonov, J.I., Boyer, T.P., Stephens, C., 2000. Warming of the world ocean. Science 287, 2225–2229.

L'Hôte, Y., Mahe, G., Some, B., Triboulet, J.P., 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. Hydrol. Sci. J./J. Sci. Hydrol. 47, 563–572.

Liepert, B.G., 2002. Observed reductions in surface solar radiation in the United States and worldwide from 1961 to 1990. Geophys. Res. Lett. doi:10.1029/2002GL014910.

Lindzen, R.S., Nigam, S., 1987. On the role of sea surface temperature gradients in forcing low-level winds and convergence in the Tropics. J. Atmos. Sci. 44, 2418–2436.

Lu, J., Delworth, T.L., 2005. Oceanic forcing of late 20th century Sahel drought. Geophys. Res. Lett. 32, L22706. doi:10.1029/2005GL023316.

Millennium Ecosystem Assessment, 2005. World Resources Institute, Washington, D.C. http://www.millenniumassessment.org/.

Neelin, J.D., Chou, C., Su, H., 2003. Tropical drought regions in global warming and El Niño teleconnections. Geophys. Res. Lett. 30 (24), 2275. doi:10.1029/2003GL0018625.

Nicholson, S.E., 1979. Revised rainfall series for the West African subtropics. Mon. Wea. Rev. 107, 620–623.

Nicholson, S.E., 1980. The nature of rainfall fluctuations in subtropical West Africa. Mon. Wea. Rev. 108, 473–487.

Olsson, L., Eklundh, L., Ardö, J., 2005. A recent greening of the Sahel—trends, patterns and potential causes. J. Arid Env. 63, 556–566.

Otterman, J., 1974. Baring high-albedo soils by overgrazing: a hypothesized desertification mechanism. Science 186, 531–533.

Palmer, T.N., 1986. Influence of the Atlantic, Pacific and Indian Oceans on Sahel rainfall. Nature 322, 251–253.

Polgreen, L., 2007. In Niger, Trees and Crops Turn Back the Desert. New York Times. 11 February 2007.

Prince, S.D., Brown De Coulston, E., Kravitz, L.L., 1998. Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. Glob. Chang. Biol. 4, 359–374.

Prospero, J.M., Lamb, P.J., 2003. African droughts and dust transport to the Caribbean: climate change implications. Science 302, 1024–1027. doi:10.1126/science.1089915.

Raynaut, C., 1997. Societies and Nature in the Sahel: Rethinking Environmental Degradation. Routledge, UK.

Reij, C., Tappan, G., Belemvire, A., 2005. Changing land management practices and vegetation on the Central Plateau of Burkina Faso (1968–2002). J. Arid Environ. 63, 642–659.

Reynolds, J.F., Stafford Smith, D.M., Lambin, E.F., Turner II, B.L., Mortimore, M., Batterbury, S.P., Downing, T.E., Dowlatabadi, H., Fernández, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B., 2007. Global desertification: building a science for dryland development. Science 316, 847–851.

Roeckner, E., Bengtsson, L., Feichter, J., Lelieveld, J., Rodhe, H., 1999. Transient climate change simulations with a coupled atmosphere–ocean GCM including the tropospheric sulfur cycle. J. Climate 12, 3004–3032.

Rosenfeld, D., Rudish, Y., Lahav, R., 2001. Desert dust suppressing precipitation: a possible desertification feedback loop. Proc. Nat. Acad. Sci. 98, 5975–5980. doi:10.1073/pnas.101122798.

Rotstayn, L., Lohmann, U., 2002. Tropical rainfall trends and the indirect aerosol effect. J. Climate 15, 2103–2116.

Rowell, D.P., Folland, C.K., Maskell, K., Ward, M.N., 1995. Variability of summer rainfall over tropical North Africa (1906–92): observations and modeling. Q. J. R. Meteorol. Soc. 121, 669–704.

Shukla, J., 1998. Predictability in the midst of chaos: a scientific basis for climate forecasting. Science 282, 728–731.

Stanhill, G., Cohen, S., 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. For. Meteorol. 107, 255–278.

Sud, Y.C., Fennessy, M., 1982. Study of the influence of surface albedo on July circulation in semiarid regions using the GLAS GCM. J. Climatol. 2, 105–125.

Taylor, C.M. 2007. Land–atmosphere feedback in the West African monsoon. GEWEX News. November 2007.

Taylor, C.M., Ellis, R.J., 2006. Satellite detection of soil moisture impacts on convection at the mesoscale. Geophys. Res. Lett. doi:10.1029/2005GL025252.

Taylor, C.M., Lebel, T., 1998. Observational evidence of persistent convective-scale rainfall patterns. Mon. Wea. Rev. 126, 1597–1607.

Taylor, C.M., Lambin, E.F., Stephenne, N., Harding, R.J., Essery, R.L.H., 2002. The influence of land use change on climate in the Sahel. J. Climate 15, 3615–3629.

Thomas, D.S.G., Middleton, N.J., 1994. Desertification: Exploding the Myth. John Wiley and Sons, Chichester, United Kingdom.

Ting, M., Kushnir, Y., Seager, R., Li, C., submitted for publication. Forced and internal 20th century SST trends in the North Atlantic. J. Climate. March 2008.

Tippett, M.K., 2006. Filtering of GCM simulated Sahel precipitation. Geophys. Res. Lett. doi:10.1029/2005GL024923.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bull. Am. Meteor. Soc. 84, 1205–1217.

Tucker, C.J., Dregne, H.E., Newcomb, W.W., 1991. Expansion and contraction of the Sahara desert from 1980 to 1990. Science 253, 299–301.

Verstraete, M.M., 1983. Another look at the concept of desertification. In: Wells, S., Haragan, D. (Eds.), Origin and Evolution of Deserts. University of New Mexico Press, pp. 213–228.

Verstraete, M.M., 1986a. Defining desertification: a review. Clim. Change 9, 5–18.

Verstraete, M.M., 1986b. The United Nations Organization and the issue of desertification. In: El Baz, F., Hassan, M.H.A. (Eds.), Physics of Desertification. Martins Nijhoff, Dordrecht, pp. 42–51.

Vizy, E.K., Cook, K.H., 2002. Development and application of a mesoscale climate model for the tropics: influence of sea surface temperature anomalies on the West African monsoon. J. Geophys. Res.-Atmospheres 107 (D3) 10.1029/2001JD000686.

Vose, R.S., Schmoyer, R.L., Steurer, P.M., Peterson, T.C., Heim, R., Karl, T.R., Eischeid, J., 1992. The Global Historical Climatology Network: long-term monthly temperature, precipitation, sea level pressure, and station pressure data. ORNL/CDIAC-53, NDP-041. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 300 pp.

Wang, G., Eltahir, E.A.B., 2000. Ecosystem dynamics and the Sahel drought. Geophys. Res. Lett. 27 (6), 795–798.

Wang, G., Eltahir, E.A.B., Foley, J.A., Pollard, D., Levis, S., 2004. Decadal variability of rainfall in the Sahel: results from the coupled GENESIS-IBIS atmosphere–biosphere model. Clim. Dyn. 22, 625–637. doi:10.1007/s00382-004-0411-3.

West, C.T., Roncoli, C., Ouattara, F., 2008. Local perceptions and regional climate trends of the Central Plateau of Burkina Faso. Land Degrad. Dev. 19, 289–304. doi:10.1002/ldr.842.

Wilhite, D.A., 2000. Drought—a Global Assessment. Routledge, London and New York.

Xue, Y., Shukla, J., 1993. The influence of land surface properties on the Sahel climate. Part I: desertification. J. Climate 6, 2232–2245.

Yoshioka, M., Mahowald, N.M., Conley, A.J., Collins, W.D., Fillmore, D.W., Zender, C.S., Coleman, D.B., 2007. Impact of desert dust radiative forcing on Sahel precipitation: relative importance of dust compared to sea surface temperature variations, vegetation changes and greenhouse gas warming. J. Climate 20, 1445–1467. doi:10.1175/JCLI4056.1.

Zeng, N., Neelin, J.D., Lau, K.-M., Tucker, C.J., 1999. Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. Science 286, 1537–1540.

Zhang, X., Zwiers, F.W., Hegerl, G.C., Gillett, N.P., Solomon, S., Stott, P.A., Nozawa, T., 2007. Detection of human influence on twentieth-century precipitation trends. Nature 448, 461–466. doi:10.1038/nature06025.