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Drought in the African Sahel: long term perspectives and future prospects

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Summary

The African Sahel experienced a prolonged dry episode in the latter decades of the twentieth century, characterised by years in which annual rainfall totals were consistently below the long term mean for the century, and punctuated by years of severe drought. Since the late 1990s there has been some amelioration of the regional climate, and in 2003 there was abundant rainfall throughout much of the Sahel, and also in parts of the Sahara, prompting speculation that the region was experiencing a shift to a wetter climate. This paper examines the possibility that the Sahel is experiencing such a shift, examining observed rainfall variability in the context of historical and palaeo-environmental evidence and model-based studies of recent and potential future climate variability and change. A review of the literature leads to the conclusion that dry conditions in the late twentieth century were most probably driven by changes in ocean surface temperatures, and in particular a warming of the southern hemisphere oceans and the Indian Ocean, which led to changes in atmospheric circulation. Interactions between the Sahelian land surface and the regional atmosphere via the medium of vegetation dynamics (and possibly dust production) appear to have played a role in modulating interannual and decadal scale variations in rainfall. While the principal forcing mechanisms of Sahelian rainfall over the past few decades are consistent with human-induced global warming, a causal mechanism linking human activity and drought in the Sahel cannot be proven, and models of future climate change suggest that such warming may ultimately lead to a more humid regime in the Sahel and parts of the Sahara.

1 Introduction

The Sahel is the semi-arid transition zone situated between the arid to hyper-arid Sahara and humid tropical Africa. The Sahel region is characterised by a strong north-south rainfall gradient and high interannual rainfall variability, with annual rainfall amounts varying from 600-700 mm in the south to 100-200 mm in the north (e.g. Nicholson, 1978). The vast majority of the region's rainfall is the result of the northward penetration of the West African Monsoon in the boreal summer, with most rainfall occurring in the period July-September as a result of the generation of lines of organised convective disturbances often referred to as squall lines or *lignes des grains* (Rowell and Milford, 1993). The strength and maximum northward displacement of the monsoon rains vary on timescales of years to millennia, meaning that the boundaries of the Sahel as defined in terms of rainfall are not fixed. Nonetheless, the Sahel may be viewed in biogeographical terms as the region situated approximately between 12° and 18° North, although the mean rainfall gradient is somewhat steeper in the westernmost parts of the Sahel, and there is a tendency for the isohyets, or lines of constant rainfall, to be displaced further north towards the west (Figure 1).

The Sahel has been the subject of extensive study as a result of an extended period of desiccation commencing in the late 1960s and continuing into the 1990s (Hulme, 1996, 2001). This dry period followed a particularly wet episode in the 1950s, and was associated with severe drought episodes in the early 1970s and early-mid 1980s (Figure 2). There was some amelioration of dry conditions in the 1990s, and the positive trend in annual rainfall totals has continued into the early years of the twenty first century (Figure 2). Rainfall was particularly abundant throughout much of the region in 2003, causing flooding and landslides in parts of the Sahel. Summer rainfall in 2003 also extended into the Sahara, with some normally dry parts of northern Mali and Mauritania receiving in the region of 75 mm of rainfall in the space of a few days in August (FEWS NET, 2003). Nonetheless, dry conditions persisted in some areas, notably northern Senegal and southwestern Mauritania, illustrating the high degree of spatial variability typical of rainfall in the Sahelian.

The heavy and persistent rains of 2003 represent a significant departure from the climatic regime that has persisted in the Sahel since the late 1960s. At the time of writing, gridded rainfall data for 2003 are unavailable. However, it is unlikely that spatially aggregated 2003 rainfall totals for the Sahel are unusual when viewed in the context of the twentieth century as a whole; the situation in 2003 is more likely to reflect the conditions that prevailed in the 1930s or 1950s. Early reports indicate that rains have been above average in 2004, consistent with forecasts (UK Meteorological Office, 2004).

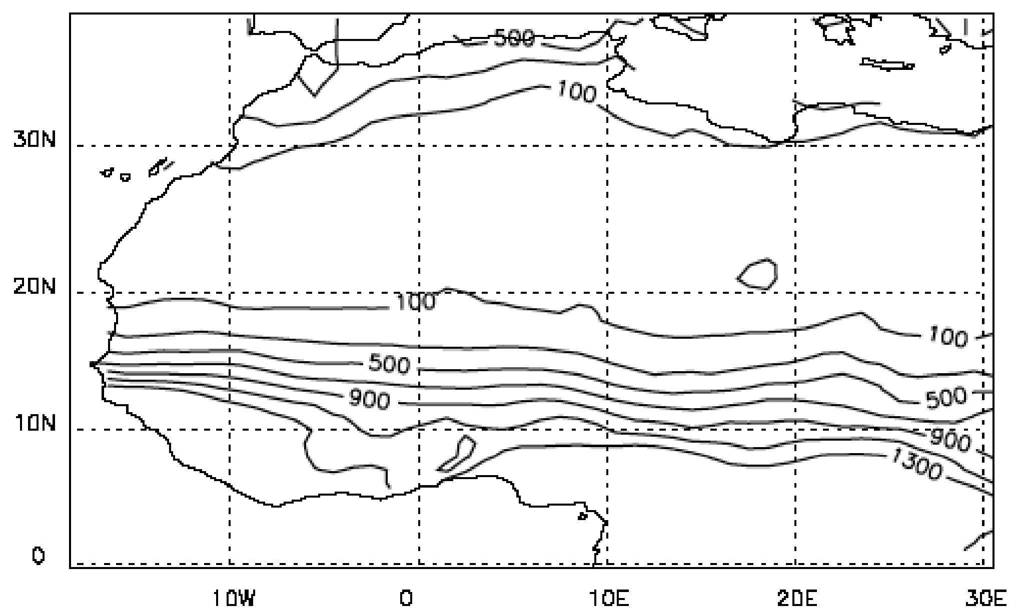

Figure 1: Isohyets representing mean annual rainfall in mm over northern Africa for the period 1901-1996. The Sahel corresponds approximately to the zone of high south-north rainfall gradients where annual rainfall amounts average 100 mm to 700 mm. The data were obtained from the Climatic Research Unit and are described in New et al (1999).

The approximately century-long rainfall record represented in Figure 2 indicates that the Sahel experiences alternating wet and dry episodes on annual to decadal timescales. Nonetheless, the dry episode at the end of the twentieth century was of a particularly long duration, and has been described by Hulme (2001) as unprecedented in the Sahel and also in any other dryland regions within the context of the observational record. Evidence for a qualitative change in the nature of the Sahelian climate also comes from studies of persistence annual rainfall totals. Persistence, expressed in mathematical terms as the autocorrelation coefficient of the rainfall series, represents the tendency of one year's rainfall to reflect that of the previous year or years. The Sahelian rainfall series exhibits a marked increase in persistence after 1950, indicative of a shift from a regime dominated by interannual variability to one characterised by decadal-scale variability (Hulme, 2001). As discussed in more detail below, this shift has been associated with changes in global patterns of sea-surface temperatures, supporting the hypothesis that changes in Sahel rainfall in the twentieth century are associated with wider global change. However, this conclusion does not necessarily mean that drought conditions may be expected to persist; the wet decade of the 1950s and the dry decades after 1970 all fall within the period of increased rainfall persistence.

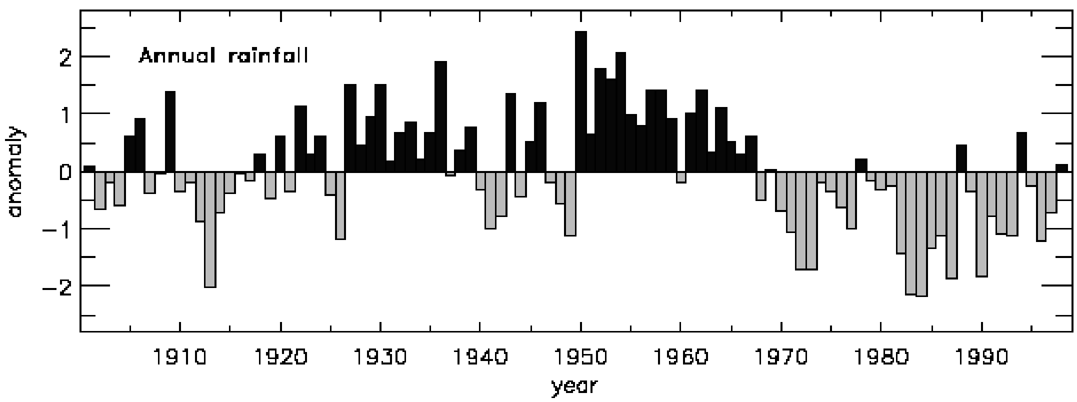

Figure 2: Spatially aggregated annual rainfall anomalies (in standard deviations) representing the region 10º - 20º N; 25º W – 30º E, roughly corresponding to the Sahelian zone. Anomalies are calculated with respect to the mean for the entire series (1901-1998) from the dataset of New et al (2000).

The purpose of this paper is to provide a context for understanding rainfall variability in the Sahel, and to explore the various mechanisms that are believed to modulate rainfall in this region. While no firm conclusion will be drawn as to whether the recent changes in rainfall patterns in the Sahel may be associated with long-term climate change, particularly climate change associated with increasing concentrations of atmospheric greenhouse gases due to human activity, the paper will provide an overview of current thinking and research in this area, and will seek to identify the principal areas of uncertainty in our understanding of Sahelian climatic variability and change.

2 Climate variability in northern Africa over long timescales

Long-term climatic and environmental change in the Sahel is associated with variations in the strength and position of the African Monsoon. On millennial timescales and longer, the monsoon is influenced by orbital factors and associated glacial cycles; palaeoclimatic data indicate greatly enhanced aridity in the northern African subcontinent, and indeed throughout the entire northern hemisphere sub-tropical belt, during glacial periods (Goudie, 1992; Jolly *et al*., 1998; Sweezy, 2001). At the last glacial maximum (LGM) some 21 thousand years ago (ka), the Sahara desert covered a much larger area than at present, as apparent from the dating of fossil dunes some 5° south of the present extent of mobile dunes (Talbot, 1983). A combination of factors leads to increased aridity during periods of glaciation, including reduced atmospheric moisture availability, decreased solar heating of the land surface, and large-scale changes in atmospheric and oceanic circulation (Goudie, 1992; Kukla and Gavin, 2004). Over the past 1.65 million years, approximately corresponding to the Quaternary period, there have been some seventeen glacial cycles, each lasting approximately 100ka (Goudie, 1992). While environmental reconstructions for northern Africa tend to focus on the Late Quaternary, evidence from lake sediments in the central and southern Sahara indicates a succession of arid and humid episodes broadly coincident with glacial and interglacial periods respectively (Kowalski *et al*., 1989; Szabo *et al*., 1995; Cremaschi, 1998; Martini *et al*., 1998).

On multi-millennial timescales shorter than those represented by the 100ka glacial cycles, monsoon dynamics are modulated by the Earth's 21ka precessional cycle, which determines the angle at which the Earth's axis is inclined to the plane of the ecliptic (the plane in which the planets orbit the sun) (Kukla and Gavin, 2004). When this angle is large, the northern hemisphere is inclined more steeply towards the sun in summer, resulting in increased solar insolation or heating of the Earth's surface, and a larger differential heating between the northern hemisphere land masses and the oceans, which intensifies the global monsoon system. When the angle of inclination of the Earth's axis is small, boreal summer heating is reduced and the monsoon system is weak. The 21ka and 100ka cycles interact, and an increase in boreal summer insolation is believed to have contributed to the process of deglaciation after the LGM (Goudie, 1992). By around 10ka, maximum inclination had been reached, resulting in an increase in incident solar radiation at the Earth's surface associated with intensified monsoon activity throughout the northern hemisphere subtropics (Tuenter *et al*., 2003). Although northern hemisphere summer insolation declined from around 8ka (Fleitmann *et al*., 2003), wet conditions persisted in the northern hemisphere subtropics from around 10-5 ka, and there is widespread evidence of a much wetter climate in the Sahel and Sahara in the first half of the Holocene (Petit-Maire *et al*., 1997; Jolly *et al*., 1998). This period was characterised by an effective northwards shift in the Sahelian bioclimatic zone of hundreds of kilometres, the extent of which varied with longitude and would have been influenced by regional topography within the Saharan region.

A weakening of the monsoon ultimately led to the aridification of the northern African subcontinent, and by 5ka the process of desertification was well established throughout the Saharan region (Cremaschi, 1998; Grandi *et al*., 1999; Jolly *et al*., 1998; Lioubimsteva 1995). However, this process did not occur smoothly, as a linear response to gradual reductions in summer heating. Palaeoenvironmental evidence and modelling studies suggest that climatic desiccation occurred relatively rapidly (Petit-Maire and Guo, 1996; Cremaschi, 1998). Studies by Claussen *et al*. (1999) with a coupled ocean-atmosphere-vegetation model of intermediate complexity, run from 9ka and driven only by changes in orbital parameters, simulate an abrupt decrease in precipitation over the Sahel-Sahara region around 5.6ka, followed by a rapid decrease in vegetation cover over the following three centuries. The abrupt nature of the desertification, contrasting with the smooth change in solar insolation, is the result of feedback processes between the vegetation and atmosphere components of the model, which are mediated by regional to global scale factors including patterns of sea-surface temperature and ice extent.

In the model of Claussen *et al*. (1999), rapid desertification associated with vegetation-atmosphere interactions follows an abrupt cooling event at 5.8ka focused on the high latitude North Atlantic. Evidence from palaeoenvironmental proxies indicates that such a cooling event occurred in reality, and that it was broadly coincident with an arid phase in the Sahara. Bond et al (1997) identified a North Atlantic cooling episode at 5.9ka from ice-rafted debris, as well as other such events that indicate the existence of a quasi-periodic cycle of Atlantic cooling events, which occur approximately every 1500 years. It has been proposed that these events are associated with a weakening of the thermohaline circulation, a process in which warm tropical waters travel north in the Atlantic ocean, cooling and becoming more saline (the latter due to the rejection of salt in the process of ice formation) in the North Atlantic, therefore becoming more dense and sinking. This process plays a crucial role in driving the global ocean circulation and in regulating global climate, and may be disrupted by warming of North Atlantic surface waters or inputs of freshwater (from either precipitation of ice-melt) at high latitudes. In such an event, surface waters may be too buoyant to sink, and instead of warm water being drawn up from the tropics, cool surface waters may spread south from the North Atlantic. There is concern that such a process may result from human-induced climate warming as high-latitude ice melts due to warmer air temperatures (Alley, 2003).

Ice-rafting events are dated at 11.1, 10.3, 9.4, 8.1, 5.9, 4.2, 2.8 and 1.4 ka (Bond *et al*.., 1997), and there is evidence that these events were associated with periods of aridity in northern Africa (Cremaschi *et al*.., 2001, 2002; Di Lernia and Palombini, 2002; Goodfriend, 1991; Smith, 1998; Guo *et al*.., 2000). Arid episodes associated with the earlier of these events were followed by recovery, as attested by the wealth of evidence of humid conditions in the Sahara between 10 and 6 ka (summarise by Petit-Maire *et al*., 1997). However, it appears that the 5.9ka event was followed by a partial recovery at best, with accelerated desiccation in the millennium that followed. For example, Cremaschi (1998) describes evidence of rapid aridification in the Acacus mountains of southwestern Libya, in the form of increased aeolian erosion, sand incursions and the collapse of the roofs of rock shelters. Pollen extracted from dung associated with pastoral sites in the Tadrart Acacus Massif in the same region indicates a desiccation from around 5000 to 3900 BP (Grandi *et al*., 1999).

The evidence therefore suggests that century to millennial timescale shifts in the range of the African summer monsoon are associated with variations in the Earth's orbital parameters and resulting changes in boreal summer insolation. However, monsoon behaviour is influenced by a variety of other factors which may change over timescales of years to millennia. Monsoons may be enhanced by regional vegetation-atmosphere interactions in a positive feedback cycle. They are also modulated by patterns of sea surface temperature and global and hemispheric ice extent, which affect atmospheric circulation and moisture availability. Monsoon strength and extent may also be influenced by transient climate perturbations such as those associated with Atlantic cooling events as describe above. Variability associated with these processes is thus superimposed on the multi millennial-scale variability resulting from gradually changing solar insolation associated with orbital cycles.

For northern Africa we may postulate thresholds of boreal summer insolation below which the monsoon system "collapses", or retreats southwards by a significant amount (of the order of tens to hundreds of kilometres) over a relatively short timescale (of the order of years to decades). Such insolation thresholds are likely to vary for different patterns of SSTs and ice extent. In a given global climate regime, low-insolation thresholds may exist below which insolation is simply insufficient to sustain the monsoon system at certain latitudes, resulting in the collapse of vegetation systems without additional external forcing from climate perturbations such as those associated with Atlantic cooling events. However, there may also be higher-insolation thresholds below which monsoon systems are sustained by vegetation and other feedbacks until such systems collapse as the result of transient climate perturbations. After such a perturbation there may be a partial recovery or no recovery of the regional coupled vegetation-monsoon system. This conceptual model provides a potential explanation for the apparent abrupt desertification of the Sahara in the mid-Holocene.

Claussen *et al*. (1999) describe a difference of some 500 years in the timing of abrupt Saharan desertification in an interactive vegetation-atmosphere model forced with changes in solar insolation, between simulations in which SSTs and ice extent are held constant in configurations representing 9ka and the present day. Their results indicate that global surface conditions can weaken or enhance the African monsoon system, although it is arguably unrealistic to hold surface conditions constant while varying insolation, given that the former are influenced heavily by the latter.

In terms of understanding the termination of the Saharan humid period in the mid-Holocene, it is also instructive to examine the impact of different vegetation configurations on the African monsoon in models in which dynamic SSTs and ice extent are coupled with varying insolation. Such an approach has been taken by Irizarry-Ortiz *et al*. (2003), who describe simulated northwards shifts of the Sahel-Sahara boundary relative to the present day of 1.1º, 2.4º and 5.1º when they modelled mid-Holocene conditions using fixed present-day vegetation distributions, dynamic vegetation, and dynamic vegetation initialised to palaeovegetation, respectively. These results suggest that vegetation played an important role in sustaining and enhancing the African Monsoon over the Sahara prior to the mid-Holocene desiccation. The results of Irizarry-Oritz *et al*. (2003) suggest that if the 6 ka cold/arid episode evident in the palaoenvironmental record was associated with a collapse of Saharan vegetation to a configuration closer that that of today than to that of the early Holocene, recovery partial resulting in a net southward displacement of the Sahel-Sahara boundary of several degrees. Palaeoenvironmental data indicate that the process of monsoon retreat was mediated by geography and topography, with rainfall persisting for some millennia in parts of the south-central Sahara, for example (Cremaschi, 1998; Grandi *et al*., 1999).

Renssen *et al*. (2003) use a three dimensional coupled global climate model to simulate the end of the Holocene Saharan humid period and find that the potential for "green" and desert states becomes equal between 7.5 and 5.5 ka, causing the Sahara to fluctuate between these states on decadal to centennial timescales. This "multiple steady state" situation is reproduced in other climate models (Brovkin, 2002). Foley *et al*. (2003), interpreting a number of modelling studies, propose that non-linear vegetation-atmosphere feedbacks can lead to alternating vegetated and unvegetated stable states.

3 Climate variability in the Sahel during the late Holocene and the historical period

Palaeoenvironmental data are relatively scarce for the late Holocene (including much of the historical period) compared with the early and middle Holocene, largely as a result of the absence of humidity-related indicators. Such data are also more scarce for the Sahel than for the Sahara (Vernet and Faure, 2000; Stokes *et al*., 2004). Instrumental records do not exist for the Sahel prior to the very end of the nineteenth century, so interpretation of climatic variability during the historical period is based largely on written records. Nonetheless, it appears that northern Africa has continued to experience alternating sub-millennial scale arid and humid periods, albeit against a background of much greater aridity than existed prior to the Saharan desiccation which commenced around or sometime before 5ka. Brooks (1998: p147) describes an arid period from c. 300 BC - 300 AD, during which "the Sahara may have been more desiccated than at any time during the past 2000 years," followed by a wetter period from c. 300-1100 AD and a progressive desiccation from 1100-1500 AD that "contributed to the disintegration of the Mali Empire" (Brooks, 1998: p151). Rainfall increased significantly around 1500, followed by aridity from c. 1630-1860, with drought and famine conditions pertaining in Senegambia and the Niger Bend area during the 1640s and 1660s-70s. Citing Nicholson (1979), Curtin (1975) and Becker (1985), Brooks (1998: p154) states that

> "Senegambia suffered droughts in each decade from the 1710s to the 1750s, in the 1770s and 1780s, and frequent famines between 1790 and 1840. Lake Chad experienced rapid falls in lake levels around 1680-1690, 1740-1760, and 1800-1840, attesting to desiccation in the area of northern Nigeria."

Reader (1997: p464) offers a slightly different, although not necessarily contradictory interpretation of the late historical period, writing, with reference to Lovejoy (1983) that

> "During the early nineteenth century the Sahelian savannas, extending from the Atlantic coast of Senegal in the west to the Red Sea in the east, 'for the first time in centuries' did not experience any prolonged and severe droughts such as had repeatedly undermined the region's economic development in the past … there

were local droughts, but the overall production of foodstuffs, livestock and legitimate commodities expanded - especially in the new Islamic theocracies."

While millennial-scale changes in the strength and position of the monsoon prior to the late-Holocene may be associated with changes in solar insolation and the growth and decay of ice sheets (and the subsequent modification of regional to global temperature and circulation patterns), causal mechanisms associated with changes in Sahelian rainfall over the historical period are more obscure, largely as a result of the more subtle nature of climatic variability over the past several thousand years. The 1.4ka Atlantic cooling event identified by Bond *et al*. (1997) does not appear to be associated with dry conditions in the Sahel according to the work summarised above, contrary to what might be expected given the apparent correspondence between such events and periods of aridity in the northern hemisphere sub-tropics (including northern Africa) in the early and middle Holocene. The most recent episode of cooling, often associated with the so-called "Little Ice Age" remains controversial; it appears that hemispheric or even global cooling began around 1000 AD and persisted until around 1900, although there was considerable spatial and temporal variability within this period (Bradley, 2000). The onset of this cooling phase is broadly coincident with the progressive desiccation of the Sahel described by Brooks (1998). According to Bradley and Jones (1993), the coldest periods within this phase were from around 1570-1730 and during the nineteenth century, although not all of the proxy temperature records they examine are consistent. These two cold periods broadly coincide with periods of desiccation in the Sahel as described above; the warmer intervening period corresponds to the unprecedented (in many centuries) period free of prolonged and severe droughts described by Reader (1997). This evidence is suggestive of a link between global or hemispheric temperatures and rainfall in the Sahel over the past millennium, although data of a higher spatial and temporal resolution are required before such a link can be clearly demonstrated (relationships between global temperature patterns and twentieth century rainfall in the Sahel are discussed below).

The historical studies described above are significant for our understanding of recent drought in that they demonstrate the high degree of variability in Sahelian rainfall on interannual to century timescales in the relatively recent past. While the periods covered by these records are not exactly analogous to the present day (particularly given the rise in atmospheric greenhouse gas concentrations during the industrial period and continuing into the present century), they are not radically different in terms glacial conditions or solar insolation. The frequent droughts in successive decades described, for example, during the early eighteenth century, are reminiscent of conditions in the late twentieth century. However, the absence of meteorological data in the form of records of annual or monthly rainfall in mm, means that we cannot make quantitative comparisons of rainfall deficits or variability between the recent dry period and episodes of drought prior to the twentieth century.

Recording practices should also be taken into account when interpreting rainfall histories prior to the period of instrumental records. The impact of drought on a society depends not only on the severity and duration of the drought, but is also mediated by social factors which determine that society's vulnerability to, or ability to cope with, drought. A drought might be remembered as particularly severe if it leads to famine, but a resilient society with well-developed coping strategies may survive a severe drought without suffering widespread famine or collapse. Conversely, a society that is already weakened by other factors such as conflict or economic collapse might suffer significantly from a drought event of smaller magnitude and short duration. The importance of the interaction between climatic hazards and socially-determined vulnerability in mediating the risk of events such as famines is exemplified by the late twentieth century histories of sub-Saharan Africa. In the low-altitude Sahelian zone famine was most acute during the drought years of the early 1970s, when a number of factors conspired to increase the vulnerability of (particularly rural) populations to drought (Adger and Brooks, 2003). Similar or greater rainfall deficits in the 1980s and 1990s, while still problematic for many communities, did not lead to a repeat of the famine of the 1970s (Cross and Barker, 1992; Mortimore, 2000).

Historical records of famine associated explicitly or implicitly with drought should therefore be interpreted with caution as they may lead to both overestimation and underestimation of the severity of previous drought episodes, depending on the evolution of underlying social vulnerability. Nonetheless, Tarhule and Woo (1997) have suggested that historical records may be used to derive semi-quantitative estimates of past rainfall deficits, and have found that in northern Nigeria during the twentieth century, years recalled by local populations as being associated with severe and problematic drought are typically associated with rainfall deficits greater than 1.3 standard deviations between the local long-term mean.

A further consideration in historical reconstruction is that recorded drought years might represent anomalously dry conditions within an otherwise wet episode, or the extreme years of an extended arid episode lasting decades or centuries. An unusually dry year within the context of a prolonged wet episode may be less extreme when compared with mean annual rainfall averaged over a longer period incorporating both wet and dry episodes. Subjective historical records representing temporally localised extremes may be misleading given a gradually evolving (on timescales of centuries) baseline of mean rainfall, given the fact that over such timescales human societies adapt so as to cope with prevailing environmental conditions Caution must therefore be exercised when interpreting the recent dry episode within a longer historical context using qualitative data.

4 Mechanisms associated with 20th century drought

The research described above demonstrates that on century to millennial timescales Sahelian (and Saharan) rainfall is modulated by orbitally-driven changes in solar insolation, patterns of surface (particularly ocean) temperatures and high latitude ice dynamics. Feedbacks between vegetation cover and atmospheric processes also appear to be important, particularly in mediating the nature of the rapid desiccation of the Sahara in the mid-Holocene. Over the past ten thousand years these processes have resulted in dramatic shifts in the position of the monsoon belt in Africa, and in considerable variability in rainfall, including century scale droughts in the first half of the Holocene in the then humid Sahara.

Similar mechanisms have been proposed to explain the late twentieth century desiccation of the Sahel, and there has been considerable controversy over the relative roles of "endogenous" processes such as overgrazing and deforestation, and "exogenous" processes such forcing of Sahelian climate by global temperature patterns. The various mechanisms that have been proposed as causes of or influences on drought in the Sahel are described in more detail below.

4.1 Land degradation resulting from human activity

One of the earliest, and most influential, explanations of the cause of drought in the Sahel was that of Charney *et al*. (1977), who suggested that reductions in rainfall were the result of human activity. In what has come to be known as Charney's model, decreases in vegetation cover caused by overgrazing and deforestation cause an increase in the reflectivity or albedo of the land surface, as dark vegetation yields to bare, sandy, light-coloured soils. The essence of Charney's hypothesis is that this increase in reflectivity results in a reduction in the heating of the ground, which in turn reduces the heating of the atmosphere by the ground surface, resulting in a reduction in the convection that is essential for the formation of rainfall-generating cloud.

The notion that the people of the Sahel have systematically degraded their lands through forest clearing, overgrazing, and inappropriate land-use practices has been an article of faith to many observers and researchers since the early twentieth century. This view of the Sahelian environment has been promoted since the 1920s by visitors to the region who have very often misinterpreted variations in annual rainfall amounts and vegetation cover as evidence for trends of environmental change or the encroachment of the Sahara (Hubert, 1920; Renner, 1926; Stebbing, 1935, cited in Mortimore, 1998). The idea that environmental changes were the result of inappropriate land use practices was propagated in the colonial era by observers from outside the Sahelian region who were unfamiliar with indigenous Sahelian cultivation systems and strategies for dealing with climatic variability, at a time when Europeans and Americans were sensitised to the issue of desertification as a result of the "Dustbowl" phenomenon in the United States (Anglo-French Forestry Commission, 1937; Aubréville, 1949, cited in Mortimore, 1998).

The idea that the Sahel had experienced widespread and significant land degradation and desertification was well established by Charney's time, and supported by an influential report by Lamprey (1975), who claimed that the Sahara had advanced by some 90-100 km in the north Kordofan region of Sudan between 1958 and 1975. Lamprey also claimed that "…ecological degradation….largely due to past and current land use practices….accelerated during periods of drought." Sand encroachment was "….the result of several thousand years of abuse of the fragile ecosystems which formerly existed in the Sahara and Nubian areas." He concluded that there was a "….need to educate the rural population, particularly as many of the problems are due to traditional and hitherto unquestioned practices." The publication of the World Atlas of Desertification by UNEP in 1992 also did much to highlight concerns over the state of the Sahelian environment, suggesting widespread desertification in the region.

Despite the concerns raised by individuals such as Lamprey and Charney, and by bodies such as UNEP, there is little, if any, evidence for regional-scale trends of widespread, systematic and irreversible land degradation and desertification in the Sahel. Following the work described above, a study by Helldén (1988) failed to find any evidence for severe desertification in north Kordofan over the period investigated by Lamprey (1975), although it did demonstrate a short-term impact of drought on the vegetation in the region. The accuracy of the Global assessment of Soil Degradation (GLASOD) for the period from 1950 to 1980, on which the World Atlas of Desertificaiton (UNEP, 1992) was based, has also been questioned, and the caveats of the authors on data reliability and extent are often ignored. The GLASOD was constructed by extrapolating relatively few data, which are generally concentrated around inhabited areas, where human impacts on the land will be greatest. Wint and Bourn (1994) found livestock numbers (including livestock associated with pastoral activity) to be highly correlated with the distribution of permanent human settlements, and only very weakly related to the extent of rangeland, suggesting that widespread overgrazing of the Sahelian rangelands is unlikely away from settled areas.

The assumption that traditional land use practices have had a detrimental effect on the Sahelian environment leading to land degradation and desertification is based to a large extent on the concept of carrying capacity. The usefulness of models based on theoretical upper limits to livestock numbers or human population densities has been widely questioned, as has the application of such models, initially developed for temperate latitude agricultural systems, to the very different agricultural and pastoral systems of the sub-tropics (Mortimore, 1998; Sullivan and Homewood, 2003). Even if carrying capacities can be defined they will be determined by a wide range of factors relating to varying climatic conditions and the way in which systems are managed, and there will not be a single value of carrying capacity for any given unit of land. Evidence from parts of the Sahel and from other semi-arid parts of Africa strongly challenges ideas that land degradation and desertification are the result of the approaching or breaching of carrying capacities. There is evidence that productivity and soil fertility have been maintained in parts of the Sahelian zones of northern Nigeria and Niger, despite reduced rainfall and increased population densities. Successful adaptation to climatic desiccation in these areas has been achieved through more intensive but small-scale agricultural practices involving higher livestock densities, soil and water conservation, crop diversification and integrated farm management approaches (Mortimore, 1998, pp150-151; Mortimore and Adams, 2001). Timmer *et al*. (1996) describe indigenous management techniques of trees in central Burkina Faso as contributing to a sustainable use of tree resources.

The most convincing evidence that the Sahel has not experienced systematic degradation and irreversible desertification at the regional scale as a result of human activity comes from remote sensing studies of the Sahelian land surface. Whereas Lamprey (1975) interpreted the different locations of the "desert boundary" in 1958 and 1975 to be the result of a systematic expansion of the Sahara, studies by Tucker et al (1991, 1994) using the Normalised Difference Vegetation Index (NDVI), a proxy for the amount of vegetation cover, have shown that vegetation quickly recolonises areas that have apparently experienced desertification or land degradation, when rainfall permits. The location of the desert boundary, defined in terms of vegetation cover, is closely correlated with rainfall; the decline in NDVI up to 1984 was followed by a rapid increase in summer NDVI values, indicating that the impact of successive dry years on the land surface is reversible (Tucker et al., 1991). Changes in the state of the land surface, at least on the relatively large spatial scales represented in remote sensing studies, thus appear to be driven by climatic variability rather than local human activities. Nicholson and Tucker (1998) state that there has been "…no progressive change of either the Saharan boundary or vegetation cover in the Sahel…, nor has there been a systematic reduction of 'productivity' " between the early 1980s and late 1990s. Rasmussen *et al*. (2001), using a combination of aerial photographs, satellite imagery, field studies, interviews with local people and literature review, conclude that an apparent desertification in northern Burkina Faso between the early 1970s and mid 1980s had been reversed in the 1990s.

Prince *et al*. (1998) used vegetation indices derived from satellite measurements to calculate the rainfall use efficiency (RUE) - the ratio of net primary production (NPP) to precipitation for the entire Sahel for the period 1982-1990. They found NPP to be in step with rainfall (reflecting the findings of Tucker *et al*. (1991, 1994) and Nicholson and Tucker (1998), with little variation in RUE, indicating a resilience in the ability of the regional ecology to recover from drought which is not consistent with widespread, subcontinental-scale land degradation. The impact of livestock on the land surface has also been investigated indirectly by Hanan *et al*. (1991), who found no consistent relationship between primary production (determined by NDVI values determined by NOAA AVHRR data) and proximity to wells at a resolution of 1.1 km in the North-Ferlo region of Senegal.

The evidence summarised above clearly associates large-scale observed changes in the Sahelian land surface to climatically-driven oscillations of the location of the transition zone from the semi-arid Sahel to the arid Sahara, and convincingly refutes suggestions that regional-scale changes in the Sahelian coupled land-atmosphere system are due to the systematic abuse of the land by the region's inhabitants. What has been interpreted as desertification in many instances appears to be the natural response of semi-arid landscapes and ecosystems to climatic variability. If desertification is defined as the spread of desert-like conditions, then we may say that parts of the Sahel have experienced transient desertification associated with drought and climatic desiccation, and this process has had a severe adverse impact on may of the region's inhabitants. This process should not be confused with a degradation of the land surface resulting in an irreversible decrease in the land's productive potential.

This is not to suggest that there are no problems associated with the over-exploitation of natural resources and more localised land degradation resulting from human activity. Such problems can be exacerbated by climatic variability in the marginal Sahelian environment, and the interaction of regional-scale physical processes and local-scale socio-economic factors is associated with complex pathways of causality that are not easily interpreted. Osbahr *et al*. (2003, p458) recognise this when they write, citing a number of sources, that “Agriculture in dry Africa is undoubtedly suffering some serious environmental, socio-economic and political problems. Changes in soil fertility have been associated with population growth, low inherent biological productivity, long-term rainfall decline, inadequate infrastructure, inappropriate agricultural policies, unsustainable intensification, international debt and unfavourable global market trends.”

Gonzalez (2001) describes declines in forest species richness (of 33% between 1945 and 1989), of trees above 3m in height (of 23% between 1954 and 1989), and of standing wood biomass in northwest Senegal, associated with a southwards shift of Sudanian and Guinean tree species to areas of higher rainfall at an average rate of 500 to 600 metres per year, and a concomitant expansion of arid Sahelian species in the north. However, such quantitative studies are extremely rare; Gonzalez (2001, p224) claims, with some justification, that his results “constitute unique evidence for land degradation and desertification in the Sahel.” While Gonzalez (2001) does describe detrimental human impacts on the land surface, he concludes that the observed vegetation changes in northwest Senegal are the result of long-term drought rather than anthropogenic in origin. Rather, he is concerned with the implications of drought-induced species loss for current and future human food security, livelihoods and well being, particularly given the possibility of future droughts and the observed decline in the availability of emergency food plants. He also describes how farmers and herders promote the natural regeneration of trees and shrubs as part of their land management strategies, and (citing Lericollais, 1973 and Kessler, 1992) how such practices have doubled tree densities in parts of Senegal and Burkina Faso. Fairhead and Leach (1996a and b) also describe how traditional land management practices south of the Sahel in Guinea have led to increases in forest density, refuting the notion that Guinean forests are simply the remnants of continuous woodland that has been cleared for agriculture.

The issue of human-climate-land interaction in the Sahel is clearly a complex one. Clearly there has been a decline in vegetation cover in certain areas. However, quantitative empirical studies of land degradation at the local scale are extremely rare. Such changes in vegetation cover and soil as have been observed cannot automatically be blamed wholly (or perhaps even partly) on human activity, or necessarily extrapolated to the regional scale. While natural climate variability and human activity can combine to put pressure on Sahelian ecosystems, traditional land management practices and indigenous agricultural innovation can and do constitute sustainable use of natural resources, and encourage the regeneration of vegetation. Exaggerated claims of human-induced land degradation and the subsequent refutation of such claims have led to a polarisation of the debate about human impacts on the land surface that risks obscuring the complex interactions between human systems, climate variability and the land surface, and distracting us from the very real challenge of how to achieve sustainable development in a climatically variable and sensitive region.

4.2 Global temperature patterns

Modulation of the African Monsoon by regional and global-scale patterns of sea-surface temperature (SST) provides the best explanation for variations in Sahelian rainfall on multi-year to decadal timescales throughout the twentieth century. Relationships between SST patterns and Sahelian rainfall are well established from statistically-based climatological analyses and have been used with some success in seasonal rainfall forecasts in the region (Folland *et al*., 1986; Ward *et al*., 1993). Folland *et al*. (1986) demonstrated that dry conditions in the Sahel during the period of instrumental records have been associated with a particular configuration of global SST patterns characterised by positive (warm) anomalies in the southern hemisphere and northern Indian Oceans, and negative (cool) anomalies in the remaining northern hemisphere oceans. A marked warming of the southern hemisphere (and northern Indian Ocean) and a simultaneous cooling of the northern hemisphere occurred in the late 1960s, as the Sahel was entering a period of desiccation; the amelioration of drought conditions after the early 1980s occurred at a time when the northern hemisphere was experiencing warming (Folland *et al*., 1986).

Recent work by Giannini *et al*. (2003) further identifies SSTs as the principal driver of Sahelian rainfall variability, which they model successfully for the period 1930-2000 using only SST forcing, using a model that also represents land-atmosphere interaction via moisture feedbacks. They identify warming in the Indian Ocean as "the proximate cause for the negative rainfall trend observed in the Sahel from the late 1960s to the 1980s" which, they suggest, in combination with a more intermittently warmer-than-average eastern equatorial Atlantic reduced the land-ocean temperature contrast that is crucial in monsoon dynamics, causing the deep convection associated with monsoon rainfall to migrate southwards. Giannini *et al*. (2003) also quantify the modelled relationship between SST anomalies and Sahel rainfall, finding that a positive rainfall anomaly of one standard deviation in rainfall for the Sahel region is associated with negative SST anomalies in the tropical Pacific and Indian Oceans of 0.2°C or more. The role of the Indian Ocean in the desiccation of the Sahel is also emphasised by Bader and Latif (2003).

Trends in global SST patterns explain the recent period of desiccation in the Sahel, but do not provide an exact explanation for rainfall in individual years. Janicot *et al*. (1996) distinguish between the role of the Indian Ocean and the equatorial Pacific, which they associate with low frequency rainfall variations (on timescales of more than 8 years), and that of the eastern equatorial Atlantic and Pacific Oceans, which they associate with high frequency variations (less than 8 years) in rainfall. This work presages the conclusions of Giannini *et al*. (2003) in suggesting a long term drying trend resulting from warming in the Indian ocean, modulated on shorter timescales by variations in the equatorial Atlantic. However, Janicot *et al*. (1996) also address the role of the El Niño Southern Oscillation (ENSO) in influencing Sahelian rainfall. They find that correlations between rainfall in the Sahel and the Southern Oscillation Index increased during the 1970s and 1980s and suggest a causal mechanism through which ENSO influences the climate of the Sahel, in which shifting patterns of warming at the ocean surface result in changes in the distribution of atmospheric deep convection, reorganising atmospheric circulation and shifting the positions of areas of monsoon rainfall. Otto-Bliesner (1999) presents results from model simulations which demonstrate connections between ENSO-related SST anomalies for the present day, but which suggests that such connections were absent during the mid-Holocene, when variability in the more extensive rainfall in the Sahel and Sahara was driven predominantly by SST anomalies in the equatorial Atlantic.

4.3 Vegetation feedbacks

Feedback mechanisms involving vegetation appear to play some role in influencing present-day Sahelian rainfall, and studies using climate models are more successful in reproducing observed interannual rainfall variability when they represent such mechanisms. Zeng *et al*. (1999) found that the inclusion of a vegetation-atmosphere feedback in a model forced using SSTs enhanced decadal variability in annual rainfall totals, but reduced interannual variability, producing a more realistic model representation of rainfall in the latter half of the twentieth century. Similar results are found by Giannini *et al*. (2003).

It is important to emphasise that these studies include dynamic land-atmosphere interaction as one component of a coupled system which is driven by ocean forcing; vegetation responses mediate the linkage between variations in ocean surface temperatures and rainfall, and do not drive rainfall variability. The role of vegetation in these studies is therefore both more complex and more subtle than in Charney's model, and is not necessarily associated with human impacts on the land surface.

Taylor *et al*. (2002) use a global climate model to assess the impact of recent land use change in the Sahel and conclude that "recent historical land use changes are not large enough to have been the principal cause of the Sahel drought. However, the climatic impacts of land use change in the region are likely to increase rapidly in the coming years." Forcing their model with estimates of recent historical land use, they find a decrease in rainfall of 4.6% and 8.7% respectively with respect to 1961 due to land use change, linked to a later onset of the main part of the wet season in July, after which the sensitivity of rainfall to land surface conditions is greatly reduced.

Claussen *et al*. (1998) found that the western part of the Sahara, where the vegetation-atmosphere feedback is strongest, has a "two-state" solution in which both desert and green conditions may be stable under present day global climatic conditions. Indeed the western Sahara does experience greater rainfall than the central and eastern Sahara today, and the isohyets (lines of constant mean annual rainfall) are displaced somewhat further to the north in the western part of northern Africa.

4.4 Dust feedbacks

Another potential feedback mechanism associated with interactions between the atmosphere and the land surface is the mobilisation and transport of dust. The Sahara is the world's largest source of airborne mineral dust, and up to one billion (10^9) tonnes of dust is exported from the Sahel-Sahara region according to some estimates, although annual production is highly variable (Andreae, 1995; Duce, 1995; D'Almeida, 1986). Atmospheric dust is a prominent feature of the Saharan and Sahelian environments, and dust generation events can give rise to dust clouds that are transported large distances, traversing northern Africa and adjacent regions and depositing dust as far away as Europe, Western Asia and the Americas (Moulin *et al*., 1997). Dust was proposed as a possible mechanism of drought reinforcement/generation in India in the 1960s (Bryson and Baeriss, 1967), and again in the Sahel after the droughts of the early 1970s (MacLeod, 1976).

Atmospheric dust has been shown to modify the temperature structure of the atmosphere on local to regional scales. Dust will reduce the amount of solar radiation reaching the Earth's surface through scattering and reflection of incoming solar radiation (Li *et al*., 1996; Williams and Balling, 1996). However, dust will also absorb outgoing longwave radiation from the Earth's surface, acting in a similar manner to a greenhouse gas, trapping heat and causing warming of the atmosphere (Chen *et al*., 1994; Duce, 1995). The net effect of dust on the heat balance of the localised Earth-atmosphere system will depend on the reflectivity of the surface (Overpeck, 1996; Tegen *et al*., 1996). If the dust layer is more reflective of solar radiation than the underlying surface, the effect is likely to be one of cooling as more solar radiation will be reflected to space. Such an effect has been observed in the eastern equatorial Atlantic by Schollaert and Merrill (1998). If the dust layer is less reflective than the surface, less solar radiation will be reflected to space and the overall effect is likely to be one of heating. Near-surface cooling due to reduced incoming solar radiation may be offset by heating resulting from the emission of long-wave radiation from the dust layer.

In addition to affecting the overall thermal balance of the Earth-atmosphere system, dust can affect the vertical temperature profile of the local atmosphere, affecting its stability and ability to support the convection necessary for rainfall generation. In particular, where dust is present as an elevated layer, cooling near the Earth's surface due to reduced incoming solar radiation can combine with heating in the dust layer due to absorption on outgoing long-wave radiation, reducing the vertical temperature gradient, thus increasing atmospheric stability and inhibiting convection. Brooks (2000) finds that for the period 1984-1993, the presence of dust in the atmosphere over the Sahel is associated with cooling in the lower troposphere (at and below approximately 3km altitude) and warming at approximately 4 km altitude during the spring and summer, when the moist monsoonal air mass undercuts the dry, dust-laden Saharan Air Layer. Atmospheric dust therefore provides a plausible mechanism for drought reinforcement, although further research is necessary before such a link can be demonstrated.

The frequency of dust events increased in at least some parts of the Sahel between the wet 1950s/1960s and the period of desiccation during the 1970s and 1980s (N'Tchayi et al, 1994, 1997). Most authors have explained such increases as a result of a combination of climatic desiccation and local human impacts - overgrazing, vegetation clearing and assorted "inappropriate" land use practices - and it has been suggested that such processes have led to the creation of new dust sources, and even that the Sahel is now a more significant source of dust than the Sahara (N'Tchayi et al., 1997). Tegen and Fung (1995) suggest that 30-70% of the global atmospheric dust budget is the result of mobilisation from soils disturbed by climatic desiccation or human mismanagement, and that the Sahel makes a major contribution to this budget, based on the results of modelling studies.

The lack of evidence to support claims of widespread land degradation which might result in new dust sources or enhanced dust mobilisation has been discussed in some detail above. Furthermore, the hypothesis that there are significant and extensive new dust sources throughout the Sahel that exceed the Saharan sources in importance is not supported by remote sensing studies, which indicate that the major sources are located in Saharan regions and in areas that have long been accepted as dust sources in the Sahel-Sahara transition zone, such as the Bodèle Depression and the Mali-Mauritania-Algeria-Western Sahara border region (Brooks and Legrand, 2000; Goudie and Middleton, 2001). Brooks and Legrand (2000) also examine the latitudes of maximum dust production and their seasonal evolution using remote sensing data for the period 1984-1993, and find that the zone of maximum dust production lies to the south of 18°N only in December, January and June. During most of the year maximum dust production occurs in the Sahara or the Sahel-Sahara transition zone north of the more densely populated areas capable of supporting dry farming, where most overexploitation of the land might be expected to occur. There is a latitudinal maximum in dust production between 18° and 20°N from July to September, when dust is mobilised at the edge of the monsoon air wedge by convective disturbances that are not associated with rainfall due to the small thickness of the monsoonal air mass.

Bell and Lamb (1994) found that dry years in the Sahel are associated with an increase in the proportion of small, poorly organised convective disturbances that are less likely to produce significant rainfall. The suppression of convective activity by atmospheric dust is a plausible explanation for a shift towards such systems. However, evidence from studies of ocean temperatures and Sahel rainfall, described above, indicates that the causal mechanism of drought lies outside the African continent. Given that the same systems that generate rainfall also mobilise dust, it is possible that increases in dust event frequency are the result of an increase in the frequency of atmospheric disturbances associated with dry convection (Brooks and Legrand, 2000). Such systems may mobilise dust but generate little or no rainfall, resulting in enhanced atmospheric dust content due to reduced wet deposition. Given the lack of evidence for the type of widespread land degradation that would be required to produce new dust sources, changes in atmospheric mechanisms associated with dust mobilisation might provide a more appropriate explanation for increased dust event frequency, at least during the summer. N'Tchayi et al (1994) report that the period of maximum dust storm activity shifted from spring to summer at Gao in Mali, which is consistent with such an hypothesis, although far from conclusive. While it appears unlikely that dust has been a major cause of drought in the Sahel, dust does provide a possible feedback mechanism for the reinforcement of drought through atmospheric stabilisation; during the summer months localised positive feedbacks may consist of weak convective disturbances that mobilse dust which is not subsequently removed from the atmosphere by rainfall, and which further reduced the convective potential of the atmosphere.

4.5 Anthropogenic climate change

The debate over the causes of the recent period of desiccation in the Sahel may be viewed as one between proponents of "endogenous" mechanisms resulting from the actions of the region's inhabitants, and "exogenous" processes driven by large-scale changes in ocean surface temperatures and atmospheric circulation. A further dimension to this debate is provided by the suggestion that the exogenous processes that appear to have driven Sahelian rainfall variability in recent decades may have been a consequence of anthropogenic climate change associated with increased concentrations of atmospheric greenhouse gases (principally CO_2) from the burning of fossil fuels. If it were to be demonstrated that anthropogenic climate change was the principal cause of drought in the Sahel, the responsibility for the drought would be transferred from the region's inhabitants to the industrialised nations responsible for the majority of historical greenhouse gas emissions, raising questions of attribution and liability (Hulme, 2001).

Given the highly variable nature of Sahelian rainfall, the lack of reliable high resolution data prior to the twentieth century, and the difficulty in attributing single events to anthropogenic climate change, it would be premature to blame the travails of the Sahel on global warming and thus on the industrialised north. A number of studies, discussed in more detail below, also suggest that increased atmospheric CO_2 concentrations might lead to increased rainfall in the Sahel. However, the possibility that the recent dry episode was associated with anthropogenic climate change should not be discounted. The observed warming of the southern hemisphere and Indian Ocean relative to the northern hemisphere, which has been associated with dry conditions in the Sahel, is consistent with anthropogenic global warming offset in the northern hemisphere by cooling resulting from the presence of atmospheric aerosols originating from industrial and agricultural activity (Rotstayn and Lohmann, 2002; Giannini *et al*., 2003). It has also been demonstrated that dry conditions in the Sahel have coincided with a weakening of the north-south (Hadley) circulation over Africa, associated with a warming of the troposphere consistent with the modelled impacts of anthropogenic global warming (Kidson, 1977; Kidson, 1983; Shinoda, 1990; Eltahir and Gong, 1995; Cubasch *et al*, 2001).

5 Projections of future climate change

Predictions of future climate change are fraught with difficulty for a number of reasons. Most fundamentally, climate change resulting from human-induced increases in atmospheric greenhouse gas concentrations will be a function of the rate and magnitude of greenhouse gas emissions, which will be determined by a range of socio-economic, developmental and political factors. In order to predict future changes in climate accurately, we must therefore be able to predict socio-economic trajectories, the emergence of new energy technologies, and the policy choices of governments and the private sector. This is, of course, impossible, although we may examine the potential consequences of different plausible scenarios of greenhouse gas emissions, an approach that has been adopted by the Intergovernmental Panel on Climate Change (IPCC). Studies of near-future climate change are also made less problematic by the fact that the climate system does not respond immediately to greenhouse gas emissions, meaning that changes over the next few decades will be largely determined by historical emissions (Zwiers, 2002). Greenhouse gas emissions in the near future are also less difficult to predict given the time taken for new technologies to be adopted. Nonetheless, there are considerable gaps in our knowledge of the climate system, and these mean that studies of the impacts of climate change on the Sahel should be treated with some caution.

The Third Assessment Report (TAR) of the IPCC (IPCC, 2001) highlights a number of areas of concern regarding the possible impacts of climate change on Africa, particular in the related areas of water resources and food security. However, the IPCC has little to say specifically regarding the Sahel; while the TAR suggests that climate change is likely to be associated with increased water stress in much of Africa, it reports that scenarios for the Sahel region, based on Hulme *et al*. (2001) are ambiguous (IPCC, 2001: p496). However, since the publication of the TAR, a number of modelling studies have examined the possible climatic consequences for northern Africa of anthropogenic global warming resulting from increased concentrations of atmospheric greenhouse gases. For example, Liu *et al*. (2002) use models that produce realistic climatological representations of the present-day Sahara, to examine the impact of an increase in atmospheric CO_2 of one per cent per year for 80 years, and find that the Sahara shifts northwards in a number of models.

Brovkin (2002) describes the results of simulations with a number of models that reproduce the mid-Holocene "green Sahara" and which "reveal multiple steady states in the region due to strong interactions between vegetation and monsoon precipitation." Sensitivity studies using these models suggests that "some expansion of vegetation cover into the Sahara is possible under CO_2-induced climate changes." Similar results are obtained by Claussen *et al*. (2002), who report a potential increase of vegetation cover of up to 10 % of the Saharan land area per decade as a result of increased CO_2 concentrations which trigger increased rainfall which is then sustained through vegetation-atmosphere feedbacks. The greening of the Sahara is not as complete as during the mid-Holocene, and vegetation cover does not exceed 45 % throughout the Sahara.

A wetter regime in the Sahel and southern Sahara as a consequence of global warming is also suggested by Maynard *et al*. (2002), who perform a transient climate simulation of 150 years with a coupled ocean-atmosphere-sea-ice model driven by changes in CO_2 and atmospheric aerosols based on a plausible greenhouse gas emissions scenario from the IPCC, with a mean atmospheric CO_2 concentration of 577 ppm. They find an enhanced monsoon over West Africa towards the end of the twenty first century, although their model does not represent vegetation-atmosphere interaction.

Mechanisms of rainfall enhancement and vegetation expansion in CO_2-induced global warming scenarios are not the same as those that led to the greening of the Sahara in the Holocene, a fact acknowledged by Claussen *et al*. (2002). During the Holocene, climatic changes over the Sahel-Sahara zone were driven by changes in solar insolation resulting from variations in the Earth's orbital parameters, and humid conditions were associated with enhanced seasonality and increased incident solar radiation over the northern African subcontinent in spring and summer. Global warming due to human activity is associated with a more general warming of the Earth's atmosphere due to enhanced concentrations of uniformly distributed greenhouse gases, and the distribution of heating is likely to be somewhat different from that pertaining in the Holocene warm period. Nonetheless, Biasutti *et al*. (2003) find that annual climatological cycles over land in the tropics and sub-tropics are driven by a combination of solar insolation and SSTs, with the relative importance of these factors varying throughout the year. Changes in SST patterns alone due to global warming may therefore lead to changes in the African monsoon precipitation, unsurprising in the light of the body of work demonstrating the important role of SSTs in modulating twentieth century Sahel rainfall (e.g. Giannini *et al*., 2003).

Wang and Eltahir (2002) perform a modelling study that reproduces the observed dry period in the Sahel during the late twentieth century, when atmospheric CO_2 concentrations are fixed at 300 parts per million (ppm), representing "pre-industrial" levels. When the CO_2 concentration is increased to 350 ppm and the simulation is repeated for the same period, there is no prolonged dry episode. Wang and Eltahir (2002) therefore conclude that the Sahelian "biosphere-atmosphere system at higher CO_2 levels is more resilient to drought-inducing external forcings," and suggest that global warming will be associated with more prolonged humid periods and shorter dry episodes in the Sahel. They suggest that vegetation changes associated with this increased resilience are partly the result of an enhanced CO_2 fertilisation effect; this is unlikely to be sustained at higher CO_2 concentrations.

It should be noted that even if the results of Wang and Eltahir (2002) are realistic, the concentration of atmospheric CO_2 was estimated at 368 ppm in 2000, and the most optimistic targets for the stabilisation of atmospheric greenhouse gas concentrations lie in the range of 400-450 ppm, well above the concentration associated with their drought-resilient Sahel.

Grubb (2001) suggests that CO_2 concentrations can be maintained below 450 ppm even if all known conventional oil and gas reserves are consumed. However, whether such an eventuality represents the end of the fossil fuel economy will depend on policy and investment decisions that in turn determine the extent to which energy is generated by low- or no-CO_2 "renewable" technologies as opposed to the burning of "unconventional" fossil fuels emphasising coal and oil reserves that are currently uneconomic. In the latter case, atmospheric CO_2 concentrations may be expected to rise well above 450 ppm by the latter part of the twenty first century.

A modelling study by Mitchell *et al*. (2000) suggests that stabilising atmospheric CO_2 concentrations at 550 and 750 ppm by the end of the twenty first century will result in a warming of the southern hemisphere oceans and northern Indian Ocean relative to the remaining northern hemisphere oceans. This configuration of global temperatures is associated with dry conditions in the Sahel, so higher (and perhaps more likely given the slow progress in reducing greenhouse gas emissions) stabilisation levels may see a return to drought in northern Africa. Mitchell *et al*. (2000) report that at higher levels of atmospheric CO_2 (representing no attempt to reduce greenhouse gas emissions) this relative warming of the southern hemisphere does not occur, suggesting that the Sahel is more likely to experience aridity at "intermediate" levels of anthropogenic greenhouse warming. Such a conclusion must remain tentative however; atmospheric greenhouse gas concentrations over the coming decades will significantly exceed those of the past several hundred thousand years, and it cannot be assumed that the behaviour of the global climate system will be similar to that of the periods for which past analogues are available.

Simulations of future climate change should also be treated with particular caution given the apparent inability of many climate models to reproduce the type of abrupt, non-linear changes in climate and related physical systems that are apparent in the palaeoclimatic record (Alley, 2003). The probability of such events under different greenhouse gas emissions scenarios is not known, but it appears that events such as abrupt weakening of the thermohaline circulation may have occurred in the past with little or no external forcing (Alley, 2003; Alley et al, 2003). Anthropogenic climate change may well increase the likelihood of such events occurring in the future, and it is reasonable to assume that the probability of abrupt climate shifts increases with increasing rates and magnitudes of greenhouse gas emissions and consequent increases in global mean surface temperature. The consequences of such events for the Sahel would be dramatic; palaeoclimatic analogues indicate that the result would probably be a rapid onset of aridity lasting decades to centuries.

6 Conclusions

The Sahel is a climatically sensitive region in which rainfall exhibits considerable variability on multiple timescales. Representing the transition zone between humid tropical Africa and the arid Sahara, it is particularly sensitive to changes in the position and intensity of the African Monsoon, which are modulated by changes in solar insolation and sea-surface temperatures. While the Sahel has experienced numerous dry episodes in the past, data prior to the beginning of the twentieth century are inadequate to determine conclusively whether the period of desiccation in the latter part of the twentieth century is unprecedented within the context of climate variability over the historical period.

The most satisfactory explanation for the recent dry episode involves changes in atmospheric circulation driven by a warming of the southern hemisphere oceans, and in particular the Indian Ocean. The modelling studies that have been most successful in reproducing the recent dry episode are those that are forced with sea-surface temperature data representing the observed warming of the Indian Ocean since the 1950s, and which represent feedback processes between the atmosphere and the Sahelian land surface mediated by vegetation cover. However, vegetation-atmosphere interactions appear not to have played any major role in triggering drought, and claims of widespread negative impacts of human activities on the Sahelian land surface appear to have been greatly exaggerated. Atmospheric dust may play a role in reinforcing drought conditions on relatively short timescales, although further research is required to demonstrate such a mechanism.

The mechanisms associated with the prolonged dry episode in the Sahel are consistent with anticipated and modelled scenarios of anthropogenically-driven global warming, although it is not possible to attribute Sahelian desiccation to human-induced climate change given the current state of knowledge. Modelling studies of future climate change suggest that global warming may enhance the African summer monsoon, leading to an expansion of vegetation from the Sahel into the southern Sahara. Work by Wang and Eltahir (2002) even suggests that the recent amelioration of the period of climatic desiccation in the Sahel could be the result of increased atmospheric CO_2 concentrations. Indeed it is possible that both the onset and persistence of dry conditions, and their subsequent amelioration, have been influenced by anthropogenic climate change, which in effect simply adds another dimension to the variability of the global climate, and need not have a single (benign or detrimental) impact on the Sahel.

Nonetheless, higher rates and magnitudes of anthropogenic warming (from 550 to 600 ppm upwards) may increase the risk of extended drought in the Sahel by generating patterns of sea surface temperatures and increasing the likelihood of abrupt climate changes that historically have been associated with enhanced (and in the latter case severe) aridity. Climate models have difficulty representing abrupt, non-linear changes in climate, and model-based studies may well underestimate the probability of "climate surprises" such as a rapid weakening or collapse of the thermohaline circulation, which could lead to the onset of rapid and catastrophic drought in northern Africa and much of the northern hemisphere sub-tropics.

This review of the literature, much of which represents research that is only beginning to unravel the complex interplay of climatic variability, environmental response and human impacts on the land surface and global climate, suggests that sustainable livelihoods in the Sahel are most likely to be guaranteed by:

- international efforts to stabilise atmospheric greenhouse gas concentrations below around 500 ppm (while there are suggestions that high levels of greenhouse warming may lead to a "greening" of the region, such a future may also present significant risks to the Sahel in terms of abrupt climate change and further desiccation)
- local and regional development policies that recognise the dynamic nature of Sahelian environments and livelihoods while supporting soil and water conservation, traditional indigenous land management practices and emerging adaptations to climate change and longer-term climate variability.

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