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Drought in the Sahel – global and local driving forces and their impact on vegetation in the 20th and 21st century

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Abstract

The Sahel is a region of large interannual and interdecadal climatic variability. In the late 20th century it experienced a period of pronounced drought that lasted from the late 1960 to the early 1990s, where precipitation values reached only about 40% of the long-term mean. This is why this period counts among one of the most striking climatic phenomena worldwide in the 20th century. The consequences on societies and ecosystems of the region include reduced water availability leading to crop failures, livestock decline and food shortages. Extensive research has been carried out on the driving forces behind this period. In the beginning it was attributed to mismanagement of the land by the local people, leading to land degradation and desertification. However, with an improvement in modelling it has been revealed that the droughts can mainly be attributed to changes in the sea surface temperatures (SSTs). A warming of the Indian and the Pacific as well as a differential heating of the Atlantic Ocean have been found to lead to drought conditions. Despite varying modelling results, the Indian Ocean is likely to play the dominant role. However, models reproduce past droughts more successfully if they additionally include local feedback mechanisms. The most important ones are vegetation and atmospheric dust, which can both amplify or dampen the initial change. Apart from the natural driving forces there is a growing anthropogenic effect on droughts in the form of the rising concentration of greenhouse gases (GHGs). Their contribution is still disputed, but is likely to grow in the future. Due to the large variability in precipitation, the vegetation underwent considerable changes in the 20th century. After substantial declines it recovered again in the 1990s along with rising precipitation values. The effect of humans through demographic and agricultural pressures has been found to be small, but it may well grow in the future. Future projections of rainfall as well as vegetation cover in the Sahel region are highly uncertain. Some models simulate drying, whereas others predict a further improvement in rains. Together with an increased GHG forcing this may even cause a greening up of the Sahel. Under present climatic conditions, both the dry and the green state have been found to be stable, identifying the region as a possible “tipping element”.

Keywords: Geography • Physical Geography • Sahel • Drought • Vegetation

Torkan i Sahel – globala och lokala drivkrafter
och deras påverkan på vegetationen under 1900- och 2000-talet

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Sammanfattning

Klimatet i region Sahel varierar på en årlig och decennielång basis. Under slutet av 1900-talet har den utsätts för en period av markant torka. Mellan 1960 och 1990 nådde nederbörden nivåer av bara 40 % av genomsnittet. På grund av detta skattas perioden en av de makantaste klimatiska fenomen i hela världen under 1900-talet. Torkan har orsakat stora konsekvenser för invånarna och ekosystem i området, till exempel i form av begränsad tillgänglighet i vatten som därmed har lett till förlust i gröda, boskap och hungersnöd. En stor mängd studier har utförts på drivkrafterna som orsakad torkan. I början skyllde man på befolkningen som anklagades för att använt marken på fel sätt. En förbättring i modellering har avslöjat att torkan i stort sett är orsakad av förändringar i ytvattentemperaturen. Uppvärmningen av Indiska oceanen och Stilla havet samt skillnaden i temperaturer mellan norra och södra delar av Atlantiska oceanen är orsaken till torkan. Förändringar i den Indiska oceanen har tydligt den största påverkan. Modellerna som representerar torkan är mer framgångsrika i fall lokala återkopplingsmekanismer ingår i evalueringen. De viktigaste återkopplingsmekanismer, vegetation och partiklar från jordytan, kan förstarka och dämpa den initiala förändringen. Utom de naturliga drivkrafterna finns det antropogena processer som har en påverkan på torkan, i praktiken har den växande användningen av västhusgaser en ökande betydelse. Det finns ingen enighet i växthusgasernas relativa påverkan, men de kommer att ha en större roll i framtiden. På grund av den stora variationen i nederbörd har vegetationen i Sahel förändrats mycket under 1900-talet. Efter en period av stark nedgång har vegetationen återhämtat sig på grund av en växande nederbörd på 90-talet. Människans påverkan i form av växande population och landsbruk, har visat sig ha haft en liten effekt, men som troligen kommer växa i framtiden. Det är oklart hur nederbörden och vegetationens mängd kommer att förändra situationen i framtiden. Vissa modeller simulerar torkan medan vissa förutser mer regn. Större regnnivå tillsammans med en växande användning av växthusgas kan även leda till en grönare Sahel. Under det nuvarande klimatförhållandet, förblir både torkan och det gröna Sahel stabila. Regionen identifieras såvida som en möjlig ”tipping element”.

Nyckelord: Geografi • Naturgeografi • Sahel • Torka • Vegetation

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Abbreviations

AEJ	African Easterly Jet
AGCM	Atmospheric General Circulation Model
AR4	Fourth Assessment Report of the IPCC
ENSO	El Niño Southern Oscillation
GCM	General Circulation Model
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
LAI	Leaf Area Index
LPJ-DGVM	Lund Potsdam Jena-Dynamic Global Vegetation Model
NPP	net primary production
RCM	Regional Climate Model
SRES	Special Report on Emissions Scenario of the IPCC
SST	sea surface temperature
TEJ	Tropical Easterly Jet

1 Introduction

The Sahel region of Africa has experienced strong climatic variability for thousands of years at both interannual and interdecadal time scales. In the 20th century, it has experienced one of the most striking climatic phenomena worldwide. A strong decadal trend could be observed in the rainfall pattern: the 1950s and 1960s experienced anomalously strong rainfall, whereas from the late 1960s until the early 1990s, severe drought conditions persisted. The drought had far-reaching socio-economic implications, reaching from crop failures and livestock decline to famines and epidemics as well as to a flood of refugees. These are the reasons for why research on the causes for drought in the Sahel has been conducted for quite some time – and there is a constant interest in the topic. The more advanced models become, the more reliable past climate variability can be reproduced. While in the beginning of research in the 1970s, droughts had been found to be the consequence of human mismanagement of the land causing desertification, soon evidence grew that the explanations lay external to the region itself. Today, there is scientific agreement that the main driver of drought are changes in the sea surface temperatures (SSTs) of the tropical oceans. However, land surface-atmosphere feedbacks play a significant role in controlling the SST forcing on a local scale. Adding to that, anthropogenic climate change in the form of rising concentrations of greenhouse gases (GHGs) is likely to have its share, too. The strong climatic variability is reflected in the vegetation. Satellite observations of the Sahel, dating back to the middle of the 20th century, give valuable information about its dynamics and help finding their potential driving forces. Recently, a greening trend has been observed, which may well be due to the recovery in rainfall that occurs since the 1990s.

The interplay of the multitude of driving forces behind the climatic variability makes it difficult to disentangle their relative impact. The uncertainties are reflected in modelling; there is a variety of different models that produce sometimes contrasting results, both in reproducing the past as well as in simulating the future climate, as this work shows. The future Sahel may experience a decline in rainfall or just as well a recovery in rains, even leading to a greening up of the Sahara.

This literature study aims to identify the reasons for climatic variability on an interannual and interdecadal scale in the Sahel, with a focus on the persistent drought period that peaked in the 1980s, and the implications that that period had for the regional vegetation. The background-chapter gives a short introduction on the Sahel and its climatic characteristics; furthermore it outlines the concept of drought and describes the conditions that persisted in the late 20th century. In chapter 3, the main driving forces behind drought in the 20th century are analyzed. Chapter 4 focuses on the driving forces in the 21st century and presents the possible future trajectories for the Sahel. In chapter 5, the vegetation dynamics of the Sahel in the course of the past century are assessed. Furthermore, the possible future of the Sahara/Sahel as a "tipping element" is discussed. Unfortunately, an analysis of the socio-economic implications of drought is beyond the scope of this paper.

2 Background

2.1 Definition of the Sahel

2.1.1 Geographical boundaries

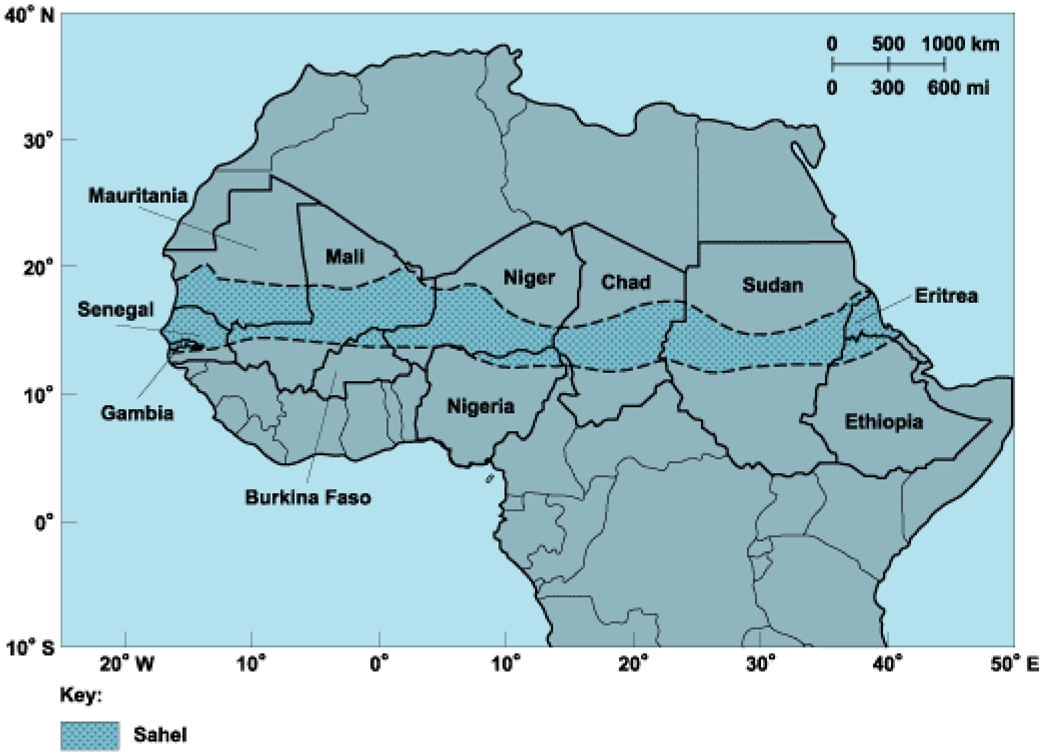

Figure 1: Map of North Africa with the location of the Sahel. Reprinted from Aondover (2008).

The Sahel is a latitudinal band spanning the African continent from the Atlantic Ocean in the West to the Red Sea in the East. From North to South, it roughly stretches out from 10°N to 20°N (see Fig. 1), whereas definitions differ from source to source as to its extent. That is because the Sahel-Sahara border as well as the boundary between the Sahel and the moist tropics cannot be unambiguously defined according to precipitation values or vegetation cover, as these are parameters that are subject to large interannual and decadal fluctuations (e.g. Bader and Latif, 2003).

2.1.2 Climatic characteristics

The most common way to define the Sahel is as a transition zone between the dry climate of the Sahara north of 20°N and the humid tropics south of 10°N (e.g. Hoerling et al., 2006). The location between the two very distinct climates leads to a strong meridional North-South rainfall gradient, with 100-200mm/yr on its northern and 400-600 mm/year on its southern boundary. It has been found to be somewhat steeper in the western part (Anyamba and Tucker, 2005). The

"Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel" (a committee of nine countries of the Sahel that joined together to combat drought) characterizes the core Sahelian zone with precipitation values between 150 and 400 mm (Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel (CILSS), 1999). The annual average of precipitation is 371 mm, derived from the period 1961-1990. One has to note that this 30-year period was itself a substantially dry period with a 25% rainfall reduction in comparison to preceding decades (Hulme et al., 2001). The climate is characterized by pronounced seasonality, with a rainy season is in the summer. It starts in June or July and lasts until September, with peak values in August. The rest of the year is dry (Herrmann et al., 2005). This is associated with the seasonal movement of the Intertropical Convergence Zone (ITCZ), a region that spans the Earth around the Equator due to the convergence of the northeast and southeast trade winds. This causes large-scale vertical upward movements of air, convection and heavy precipitation over the tropics. The ITCZ moves with the seasons, following the warmer waters northward (southward) when solar insolation reaches its maximum in the Northern (Southern) hemisphere in the boreal (austral) summer. When it reaches its northernmost position in the boreal summer it provides the Sahel with rain, when it moves southward during the austral summer it leaves the Sahel dry and under the influence of the subtropical high pressure belt.

The moisture supply of the Sahel is dependent on horizontal convergence of moisture that evaporated from the adjacent oceans, particularly the tropical southern Atlantic. The strongest flow inland occurs across the coast of Guinea (between 10°E and 15°W), which represents the most important source of moisture for the Sahel (Hagos and Cook, 2008). Evaporation from the land surface plays a minor role; its contribution to precipitation is about one third (Giannini et al., 2003). This is the direct way in which soil moisture and precipitation are linked; the other way is indirectly due to the soil moisture gradient between the Sahara and the tropics, which influences the African Easterly Jet (AEJ) (Paeth and Hense, 2004). The sinks for moisture are condensation and vertical mixing over the Indian Ocean and the Sahel (Hagos and Cook, 2008).

In summer, the Sahel is under the influence of the low-level West African monsoon, which is formed due to the strong land-ocean contrast in summer, causing moist air from the ocean sweeping into the continent from the southwest, supplying it with moisture and causing precipitation events (Hagos and Cook, 2008). As the monsoon has such a significant influence for the moisture supply of the Sahel, it drives the long-term climatic and environmental change in the region (Brooks, 2004). This also means that the Sahel is particularly sensitive to variations in strength and position of the monsoon (Brooks, 2004). These variations are not unusual, as the monsoon system is controlled by a variety of external climatic drivers such as changes in SSTs and ice extent (Brooks, 2006) as well as by local factors like changes in the land cover near the West African coast and near the border of the Sahara as well as moisture availability, which may enhance the monsoon through feedback mechanisms between the vegetation and the atmosphere (Claussen et al., 2003) (for a definition of the term feedback see chapter 3.3). It may well be that the monsoon system is more responsive to global SSTs than any other monsoon system in the world (Hoerling et al., 2006). This is one of the reasons for why the climate of the Sahel belongs

to one of the most variable in Africa (Gommes and Petrassi, 1996) and the whole world (Bader and Latif, 2003), in terms of both interannual and decadal variability. Extreme years appear to be more likely than average ones (Gommes and Petrassi, 1996), as the large interannual and decadal fluctuations in precipitation in the 20th century show. Spatially, absolute rainfall variability increases with the total sum of precipitation. This holds true within the Sahel, where the variability is greatest along the western coast, as well as when comparing the Sahel with the adjacent regions of the arid Sahara and the humid Guinean coast. The Sahel and the region of the Guinean coast are dominated by low-frequency rainfall variability on a decadal scale (Paeth and Hense, 2004). The region is also under the influence of the Tropical Easterly Jet (TEJ) and the AEJ. The TEJ is located at about 200 hPa and develops during the monsoon in the summer months, while the AEJ at 700 hPa and 15°N is temporary and develops due to the temperature contrast between the Sahara and the Guinean coast. It shifts with the seasons and reaches its northernmost position during boreal summer, analogous to other atmospheric systems such as the ITCZ or the subtropical high pressure belt. Its maximum is in August. Their position and intensity plays a significant role in precipitation fluctuations (Paeth and Hense, 2004).
With its large climate variability, the Sahel is a region that is particularly prone to the occurrence of droughts (Elasha et al., 2006), which will be explained in the following chapter.

2.2 Definition of drought

Despite the different approaches to define drought, one can generally agree on the idea that drought is a deficit in moisture caused by significantly lower-than-average precipitation amounts over a certain time period. It is usually accompanied by negative effects on the local societies and ecosystems (Giannini et al., 2008b). The difficulties in delineating drought mostly arise from determining the time period and the connection of precipitation deficits to water shortages and their effects (Mc Kee et al., 1993). In 1985, Wilhite and Glantz (1985) made an effort to include all the different ideas and categorize them into four overall approaches: meteorological, hydrological, agricultural and socio-economic drought. This work reflects the authors' ideas that the definition of drought should be formulated in a broad sense and should incorporate both physical and social aspects with a regional or local significance.
Meteorological drought may well be the concept that first comes to mind; it is defined on the basis of the severity of the departure of precipitation from the average and the duration of the dryness. One of the earliest works that aimed at identifying this kind of drought was conducted by Palmer in 1965. The Palmer Drought Severity Index (PDSI) is calculated from temperature and precipitation values (Palmer, 1965). Although the first approach to drought is through analyzing changes in precipitation, the entire hydrological cycle should be taken into consideration. The most relevant parameter for assessing it is the soil moisture. It is more appropriate than precipitation since it reflects the combined effects of precipitation, evaporation and runoff (Maynard et al., 2002). This is reflected in the concept of hydrological drought, which associates the effects of precipitation deficits to surface or subsurface water content, such as river

discharge, lake levels and groundwater (Wilhite and Glantz, 1985). Agricultural drought associates the characteristics of meteorological or hydrological drought to their impacts on agriculture, i.e. when the soil moisture content is insufficient to meet the demands of a particular crop and livestock (Gommes and Petrassi, 1996). Socio-economic drought combines all the aforementioned concepts, as it describes a situation in which water shortages are sufficiently pronounced in order to negatively affect the supply of an economic good and thus the living conditions of local people or entire societies (Wilhite and Glantz, 1985).

High rainfall variability with episodically low precipitation values is as much a characteristic of the climate of a region as the total or average climatic values, and does not necessarily lead to the occurrence of drought. Neither can drought periods automatically be related to low precipitation values, meaning that there are other climatological as well as environmental and anthropogenic factors that contribute their share to the onset and duration of drought events (Gommes and Petrassi, 1996).

In regions that have been subject to large climatic fluctuations for thousands of years, people have developed coping strategies to manage periods of water shortages. However, with a dry period so severe as the one that occurred globally in 1982-83 (Wilhite and Glantz, 1985), the traditional adaptation measures of institutions and individuals lag behind, increasing the population's vulnerability. The drought of the late 20th century was accompanied with widespread famines that cost the lives of hundreds of thousands of people (Elasha et al., 2006). In the long term, they may encourage measures to increase the adaptive capacity of societies and local people.

A region that is permanently exposed to dry conditions may be at risk of undergoing desertification, defined by the UNCED in the year 1992 as a process of land degradation in arid, semi-arid and dry sub-humid environments that occurs due to human activities in conjunction with climatic factors (United Nations Conference on Environment and Development (UNCED), 1992). The Sahel may well be the one region in the world that is most at risk from undergoing desertification (Helldén, 1991).

2.3 Rainfall variability in the late 20th century

In the 20th century, the Sahel underwent large rainfall fluctuations in the form of alternating wetter- and drier-than-usual periods of varying length and intensity (see Fig. 2). Until the 1950s, rainfall variability appeared to be dominated by variations on an interannual scale. Thereafter, there seemed to be a change in the nature of rainfall variability, shifting towards a regime characterized by interdecadal variability (Hulme et al., 2001).

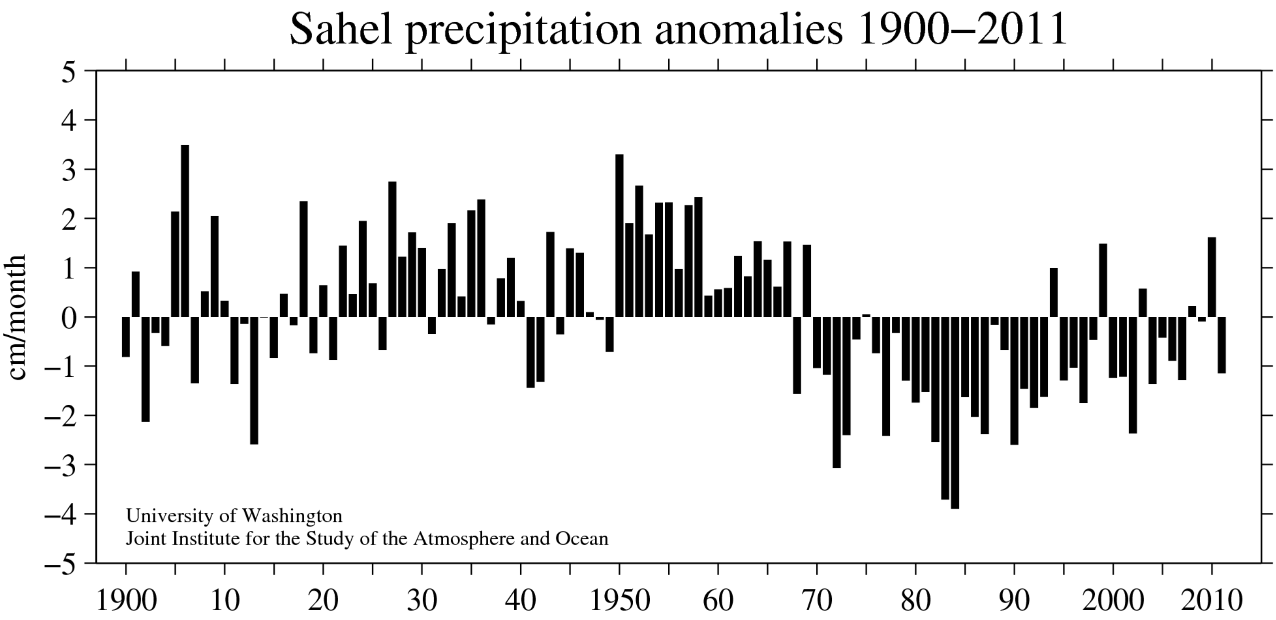

Figure 2: Sahel precipitation anomalies of the rainy season (June-October) for 1900-2011 in cm/month. Anomalies with respect to the June-October mean of 1900-2011. Reprinted from Mitchell (2011).

In the 1950s and 1960s, precipitation amounts in the Sahel were unusually high relative to the 20th century mean (Brooks, 2006). During that time, precipitation values lay high above the long-term mean (1961-1990) and reached the highest values within the entire 20th century (Paeth and Hense, 2004).

From then on, precipitation amounts dramatically decreased. The exact onset, duration and magnitude of the drought period cannot be determined unambiguously, but it lasted approximately from the late 1960s until the late 1980s or early 1990s and was characterized by precipitation values of about 40% of the long-term average across the whole Sahel (Hagos and Cook, 2008). The 1980s marked the peak of that dry period (Paeth and Hense, 2004). Regionally, the drying was most pronounced over the western Sahel, the region which also has the highest average precipitation rates (Hagos and Cook, 2008). The average of 24 stations in that region showed a downward trend since 1951 and even fell below the 1901-1990 average since the year 1971 (Gonzalez, 2001). For 1950-2000, Lu and Delworth (2005) obtain a reduction of 20-50% in JAS rainfall over the entire Sahel. Hoerling et al. (2006) find that JAS precipitation deceased by 35% over the Sahel since the 1950s. Another convincing parameter is the 300 mm isohyet (line of equal precipitation) that runs approximately through the centre of the Sahel and shifted southward 100 km between 1950-1967 and 1986-1997 (Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel (CILSS), 1999).

The drought was accompanied with higher surface air temperatures. The reason for this becomes apparent when considering the links between precipitation, temperature and evaporation: incoming solar energy is used for evaporating moisture rather than for heating the surface, which is why under conditions of little rainfall, the soil moisture content decreases and the surface heats up (Giannini et al., 2003). This increase is probably hard to disentangle from the warming due to the rise in GHGs. In the 20th century, surface temperatures have increased by about 0.5°C across the African continent. The warming was more pronounced in summer and autumn than during the rest of the year. The six warmest years of the century have occurred since 1987, with 1998 being the absolute warmest (Hulme et al., 2001).

Interestingly, the Sahel was not the only region in Africa that experienced drought in the second half of the 20th century – Hoerling et al. (2006) find a drying trend in Southern Africa in the same years as the Sahel, but with a smaller magnitude. Anyway, the 1980s was a decade of unusually severe droughts globally. But the development in the Sahel was unparalleled anywhere else on Earth in the 20th century (Held et al., 2005), and it appears to be unprecedented also in the history of the Sahel (Hulme et al., 2001). The severity of the drought becomes apparent when reviewing its effects on the population: one million people starved and about 40-50% of the livestock died (Nicholson et al., 1998).

The shift from wet to dry conditions in the 1960s is fairly well-documented and understood. The reasons behind the period since the peak in low rainfall in the mid-1980s, on the other hand, are posing greater difficulties (Giannini et al., 2008b). Since then, precipitation values have started to rise again. Annual precipitation rates reached up to the 1961-1990 climatological mean in the central and eastern Sahel. Parts of the western Sahel remained dry, illustrating the large spatial rainfall variability. In general, the precipitation anomalies of the 1990s are smaller than those of the preceding drought period (Hagos and Cook, 2008). It is very likely that the rainfall frequency has been stable since the 1970s and therefore still lies below the pre-drought period. However, the intensity of the precipitation events has increased, which fits very well in the context of global warming, as a warmer atmosphere contains more moisture and can thus provide heavier rains (Giannini et al., 2008b).

The fact that precipitation variability is dependent on its total amounts shows when comparing the Sahel with its adjacent regions: in the observational values used by Paeth and Hense (2004), the Sahel reaches maximum positive precipitation anomalies of about 70 mm in the 1950s and maximum negative ones of about 50 mm in the mid-1980s relative to the 1961-1990 mean. The Sahara was characterized by little interannual or decadal fluctuations during the second half of the 20th century. The maximum anomaly, both positive and negative, of a single year relative to the 1961-1990 average was about 30 mm. In the region of the Guinean coast, on the contrary, the anomalously wet and dry periods were more pronounced than in the Sahel. Around 1950 precipitation values lay almost 200 mm above the average, whereas the driest year was 1980 with negative precipitation anomalies of almost 150 mm (Paeth and Hense, 2004).

3 Driving forces in the 20th century

3.1 Anthropogenic causes

In the course of research on the driving forces behind the major drought events of the 20th century, two main opposing hypotheses have developed: the first one was brought forward by J.G. Charney in 1975, which claimed that the reasons for the drought lay in changes in the land surface, brought about by human mismanagement and overuse of the vegetation and the soil, such as the expansion of agricultural land, overgrazing and deforestation. These changes lead to localized feedbacks between land surface conditions and atmospheric radiation (Hagos and Cook, 2008). This causes an increase in surface albedo, which reduces surface heating and thus atmospheric heating. As this lessens convection, precipitation decreases and as a consequence, the vegetation cover diminishes (Brooks, 2004). The atmospheric circulation thus amplifies the initial change. This became known as “Charney’s hypothesis” (Giannini et al., 2008b).

As research progressed, Charney’s assumptions became increasingly challenged. Although the advocates of his theory did obtain changes in the rainfall pattern when they forced their models with land surface conditions only, the magnitude the models produced remained behind the observed anomalies. And in the cases their models did reproduce the observed values the prescribed land use changes usually exceeded the real developments (Hagos and Cook, 2008). Also, the albedo changes prescribed by Charney (1975) and others have been proven to be exaggerated (Nicholson et al., 1998).

The second approach, focussing on external forcings, will be discussed in the following chapter.

3.2 External forcings: Sea surface temperature changes

3.2.1 Model agreement

In the mid-1980s, a new theory started to replace the prevalent opinion of a regional-scale, widespread and irreversible land degradation and desertification evoked by detrimental human activity (Brooks, 2004). Models were run that were successful in reproducing the drought events in the Sahel as a response to changes in global SSTs (Folland et al., 1986). That means that positive SSTs in the tropical Indian, Atlantic and Pacific Ocean lead to drought over the Sahel. The anomalously wet periods could consequently be associated with colder-than-average SSTs. Since the first studies, the possibilities of modelling have improved along with increasing computing power. The more recent simulations (e.g. Giannini et al., 2003, using the Seasonal to Interannual Prediction Project 1 (NSIPP1) Atmospheric General Circulation Model (AGCM) by the National Aeronautics and Space Administration (NASA)) support the findings by Folland and colleagues, as they hindcast Sahelian climate variability on interannual and interdecadal time scales with oceanic forcing only. The typical climate of alternating wet and dry periods is thus mainly controlled by external forces (Giannini et al., 2008b).

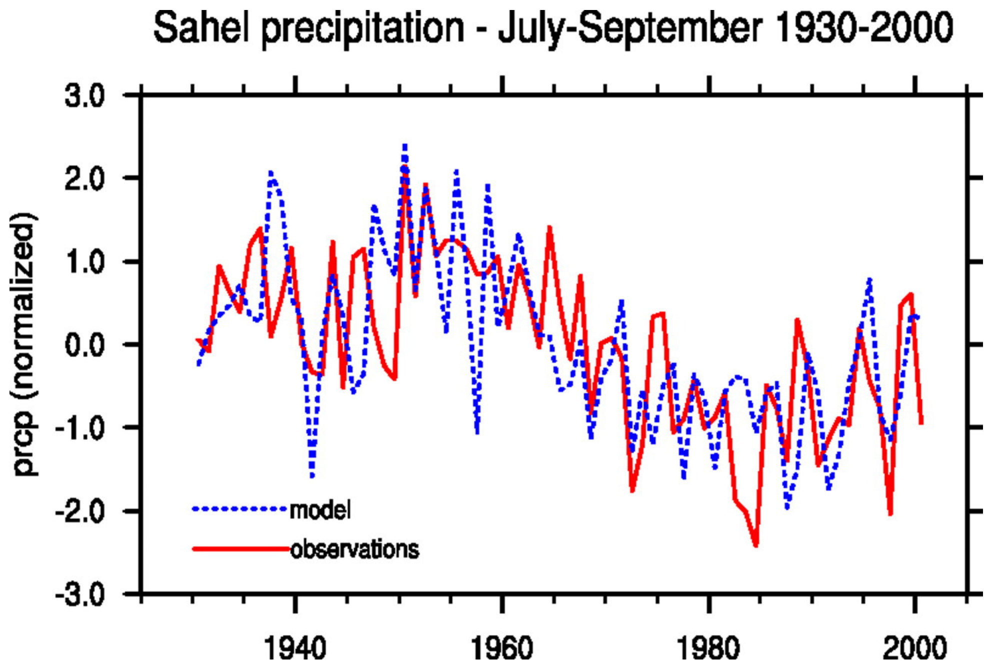

Figure 3: Index of Sahel rainfall variability from July-September from the years 1930-2000, displaying observed and modelled values. Reprinted from Giannini et al. (2003).

Figure 3 shows an index of Sahel precipitation in the rainy season (July-September) for the years 1930-2000. Their ensemble of nine simulations was forced only with the observed SSTs from 1930-2000, holding CO_2 values at a constant level and allowing only seasonal vegetation dynamics. When comparing the observed values with the modelled results, large agreements can be observed: the correlation is 0.60. One can clearly identify the strong negative trend starting in the 1960 and lasting until the mid-1980s, as well as the slow recovery in rains from then on. However, the models did apparently not simulate the largest negative precipitation anomaly in the mid-1980s. Lu and Delworth (2005) conducted a similar study and obtained comparable results, using the Geophysical Fluid Dynamics Laboratory Climate Model Version 2.0 (GFDL CM2.0) AGCM developed at the GFDL of the National Oceanic and Atmospheric Administration (NOAA). It was forced with the observed SSTs and sea ice extent for the time period 1950-2000 and produced the observed interdecadal variability in precipitation. The amplitude as well as the spatial pattern of the simulated rainfall compares well with the observed values. They also demonstrate that an increasing SST of any of the oceans has a negative effect on Sahelian rainfall; furthermore does the simultaneous warming of the oceans have the same effect as warming them separately and adding up their effects. However, while the drying trend could successfully be reproduced, the recovery of the 1990s is not very well captured. Also the result by Paeth and Hense (2004) suggest that the drought of the 1980s seems to be better understood than the switch to wetter conditions in the 1990s. They do not obtain the recovery trend with an SST-only forcing, but rather a continuous decrease from the 1980s on. Bader and Latif (2003), using the AGCM ECHAM 4.5 (a 24-member ensemble of simulations, developed at the Max-Planck-Institute for Meteorology) forced with observed SSTs from the period 1951-1994, also successfully reproduce the decadal trend. A study of five different AGCMs (CAM2, ECHAM4.5, ECHAM3, NSIPP1, ARPEGE, some of which have also been used by previously mentioned authors) with a total of 80 experiments run by Hoerling et al. (2006) confirms that both the temporal evolution of Sahelian rainfall as well as the spatial structure of precipitation from 1950-1999 can be attributed to global SSTs (see Fig. 4). They simulate a precipitation decline of 23%, compared to their proposed observed decline of 35% since the 1950s.

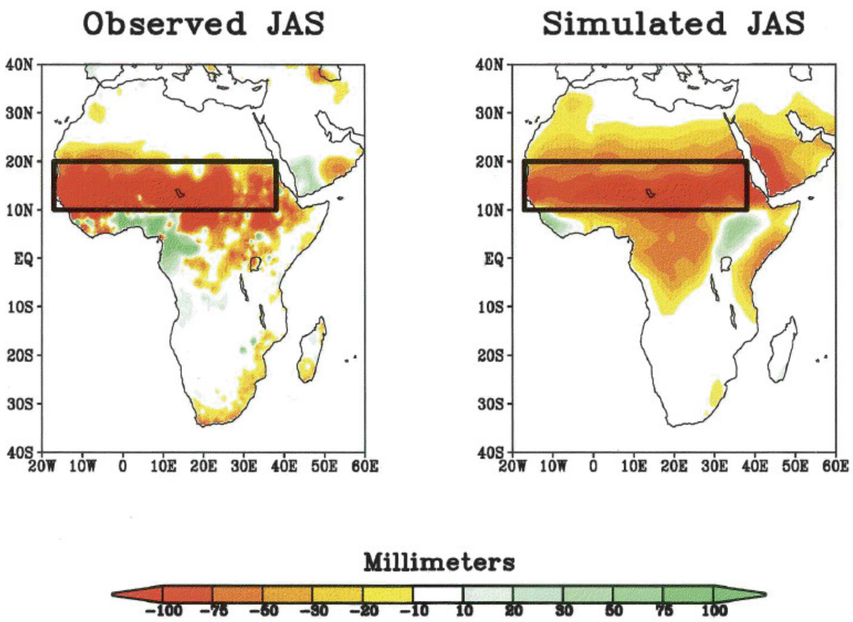

Figure 4: Observed and simulated JAS total seasonal precipitation change in mm over the time period 1950-1999. Simulations as a response to global SST forcings, mean of five different AGCMs. Reprinted from Hoerling et al. (2006).

Paeth and Hense (2004), using the AGCMs ECHAM4 and HadAM2 (the latter developed at the Met Office Hadley Centre), studied the main patterns of the decadal rainfall anomalies in West Africa and suggest that the effect of SSTs on precipitation is strongest over the southern part of West Africa, whereas towards the central part of West Africa the influence of the oceans may come second to the effect of atmospheric variability. On a seasonal scale the rainfall response to external effects is strongest in summer when the Sahel is under the influence of strong monsoon dynamics. However, the results obtained by Paeth and Hense have to be looked at with care, as the models they use do not represent the newest generation of models. The direction the climate system has been found to take can still be considered valid though (Paeth and Hense, 2004).

Although these models successfully capture the decadal drying trend, they have up to now not been able to explain the rainfall in individual years (Brooks, 2004).

3.2.2 Mechanisms of SST-induced drought

The question arises as to the way SSTs are linked to the precipitation regime in the Sahel.
It has been found that drought occurs due to a warming of the equatorial Indian Ocean as well as a differential heating of the tropical Atlantic, i.e. a warmer South than North Atlantic and a warming of the Pacific Ocean (Giannini et al., 2008b). The temperature changes in the Indian and Atlantic Ocean influence the ITCZ. Due to its seasonal movement, the northernmost point which the tropical rains usually reach is the Sahel. What happens when the equatorial Indian or the South Atlantic Ocean warm, is that the ITCZ moves further south than usual, following the warmer waters, so that it does not reach as far north anymore in order to be able to provide the Sahel with rain (Held et al., 2005).
Since tropical precipitation is generally a process that results from atmospheric instability, a way in which precipitation is modified is through changes in the atmospheric stability. A rainfall decrease may therefore be due to a cooling of the near-surface air or rather, since this was not the case in the Sahel in the course of the 20th-century drought, due to a warming of the atmosphere at higher levels (Giannini et al., 2008a). Apart from these atmospheric changes, the influence of SSTs on the transport of moisture into the Sahel is crucial for understanding the way in which SSTs shape Sahelian precipitation. When the oceans warm, two main processes result: the land-ocean temperature contrast weakens and evaporation from the ocean surface increases (Hagos and Cook, 2008). The former refers to a warming of the South Atlantic and implicates a disturbance of the conditions necessary for the establishment of the West African monsoon, resulting in a weakening of the low-level inland moisture transport along the Guinean coast and thus a reduction in precipitation over the continent (Hickler et al., 2005, Giannini et al., 2008a). Paeth and Hense (2004), on the contrary, suggest that a warming of the equatorial Atlantic SST leads to an increased flux of latent heat into the monsoon circulation, leading to the advection of more humid air masses across the West African coast. The other important effect of the ocean warming is increased evaporation, leading to an enhancement of local deep convection over the ocean (Giannini et al., 2003). As the distribution of atmospheric deep convection changes, the atmospheric circulation is reorganized, which shifts the location of the regions of monsoonal rains from the continent to the oceans (Brooks, 2004). Convection over the ocean thus occurs at the expense of monsoon-driven convergence and convection over land, depriving the continent of rainfall (Giannini et al., 2008b).
Another effect of increased evaporation has been found by Hagos and Cook (2008). It leads to an enhancement of the local moisture content, which has been found to lead to localized convergence of moisture. Hagos and Cook (2008) modelled the conditions of the 1980s and revealed that regions of maximum moisture convergence were located over both the Atlantic and Indian Ocean. The warming of the Indian Ocean brought about an anomalous upward motion,

latent heat release and upper tropospheric divergence together with an anomalous outflow. The enhanced easterly winds over Africa linked the motions of wind and moisture over the Indian Ocean to the continent. There, upper-level convergence resulted in sinking of air and low-level divergence with a maximum over the Sahel. This inhibited upward motion, convection and precipitation (Lu and Delworth, 2005, Bader and Latif, 2003, Hagos and Cook, 2008). Regions of divergence are associated with an anticyclonic circulation, which drove moisture away from the continent, a process that was reinforced by a strengthened easterly jet. While the Indian Ocean was responsible for the development of a region of divergence over the continent, the warmer Atlantic caused a region of strong moisture convergence over the northern tropical Atlantic just off the West African coast. The associated cyclonic circulation was located at the same latitude as the Sahel, so that the moisture from there converged into the cyclonic circulation, depriving the Sahel of its moisture. The maximum outward flux of moisture was located at 700 hPa, outweighing the low-level surface inland flow. This process accounted for a moisture loss of about 50% from the Sahel region across the West African coast (Hagos and Cook, 2008).
Other atmospheric circulation anomalies that accompany the drought periods include that the upper-level TEJ at 200 hPa is somewhat reduced and the AEJ is displaced further south (Lu and Delworth, 2005).
With the mechanisms described above, an increase in SSTs leads to a desiccation of the Sahel.

When considering that an increase in tropical Indian Ocean SST can be made responsible for the drying of the Sahel in the 1980s, it is interesting to note that precipitation values have increased in the 1990s despite a continuous warming of that ocean basin (Giannini et al., 2008b). One possible explanation is that the divergence over the continent associated with a warming of the Indian Ocean changed its location and in the 1990s was located over the Atlantic and not over the continent (Hagos and Cook, 2008). It is also likely that the differential heating of the tropical Atlantic played its part again. Opposite to the conditions in the 1980s, the North warmed relative to the South, which caused a cyclonic circulation providing the Sahel with rain (Hagos and Cook, 2008, Lu and Delworth, 2005).

3.2.3 The role of the three oceans

As has been shown, models widely agree on the paramount role of SSTs for Sahelian climate variability. That means that changes in the temperature of the tropical Indian, Atlantic and Pacific Ocean put changes in the atmospheric circulation in motion, which lead to conditions over the Sahel that cause drought. However, the three tropical ocean basins differ in their relative importance for the length, intensity and geographic extent of dry and wet periods.

It seems that SST anomalies of the Indian Ocean play a paramount role in determining Sahelian precipitation anomalies. Giannini et al. (2003), Hagos and Cook (2008) and Lu and Delworth

(2005) successfully reproduce the main trend in precipitation anomalies of the late 20th century by forcing their models with the observed positive SST anomaly of the Indian Ocean of that decade.
Bader and Latif (2003) ran simulations where the oceans' SSTs were changed to their 1950's values (i.e. colder than average), one ocean at a time. When only the Indian Ocean experiences the negative SST anomaly, rainfall increases over West Africa, the ITCZ intensifies over the tropical Atlantic and precipitation decreases over East Africa. Hagos and Cook (2008) come to similar conclusions with a model forced with the observed 1980's positive SST anomalies. In contrast to most other authors who base their analyses on AGCMs, they use the tropical regional climate model RegCM (an adaptation of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model). An imposed 0.4 K warming of the Indian Ocean produces reduced precipitation over the western and central parts of the Sahel and the Ethiopian highlands; however, the Guinean coasts becomes wetter.

Despite the leading role of the Indian Ocean, the areal coverage and the magnitude of the observed drying of the 1980s can best be produced with a combined forcing of Indian and Atlantic SSTs. The RCM used by Hagos and Cook (2008), forced with SSTs of the Atlantic and Indian Ocean of the 1980s, produced a 50% decline in precipitation, which is similar to the observed values. As has been mentioned earlier, the Atlantic has been found to influence Sahelian precipitation anomalies through a differential heating of the North and the South. A warmer South is associated with drought, a warmer North with wetter-than-usual conditions. The spatial influence of the Atlantic Ocean appears to be most pronounced over the West Sahel, the Guinean coast and the ocean itself. This was both shown by experiments where the SSTs were increased to their 1980s values (Hagos and Cook, 2008) as well as when they were colder, like in the 1950s (Bader and Latif, 2003). Paeth and Hense (2004) found a correlation of 0.7 between the precipitation over the Guinean coast and eastern Atlantic SSTs for the period 1903-1994. The connection to the North Atlantic appears to be much weaker. The Atlantic experiment by Lu and Delworth (2005), forced with the interhemispheric SST dipole, yielded a divided precipitation response: the tropical tropospheric circulation system are displaced toward the Equator, leading to a southward shift of the precipitation maxima. The region of the Guinean coast receives more rain, whereas the Sahel becomes drier. Yet, when the warming exceeds a certain threshold, the ensuing effect is mainly a weakening of the land-ocean contrast, which weakens the monsoon dynamics and leads to drought across the entire region (Paeth and Hense, 2004).
These studies identify the Atlantic Ocean as the second largest influence on Sahelian drying after the Indian Ocean. However, Hoerling et al. (2006) challenge these results. Their AGCM ensemble forced with a positive Indian Ocean SST anomaly does not lead to the observed Sahel drying. Their model produces higher precipitation over the central and eastern Sahel, whereas drying mainly occurs over the tropical equatorial region and southern Africa. However, they too obtain drying over the western part of the Sahel. These authors bring up the dominant role of the Atlantic Ocean; their model ensemble forced with only Atlantic SSTs for the period 1950-1999

generates widespread drying over the whole region. Also on a temporal scale their results are in accordance with observations. Their modelled time series of the 20th century is mainly characterized by two rainfall regimes: a wet period until 1965 and a dry period from then on, lasting for at least 30 years. A strong Atlantic Ocean forcing was also identified by Yoshioka et al. (2007), whose model explained 50% of the observed precipitation decline with changes in the SSTs of North and South Atlantic. However, Brooks and Legrand (2000) come to the conclusion that the sensitivity of Sahelian precipitation to Atlantic SST forcing is actually lower than assumed by Hoerling et al. (2006), as their experiment produces only a marginal negative precipitation anomaly in response to Atlantic forcing that explains one fourth of the observed decline.

Finally, the Pacific Ocean influences rainfall patterns through teleconnections of the El Niño Southern Oscillation (ENSO) that occur on average every 2-7 years. An El Niño year typically leads to drought in many parts of the world, and so it does in the Sahel. A La Niña year has the opposite effect (Giannini et al., 2008b). The results by Hulme et al. (2001) confirm that ENSO has significant effects on African climate but that its effects seems to be more pronounced in eastern equatorial Africa and in south-eastern Africa during the respective rainy seasons than in the Sahel. This spatial pattern was partly confirmed by Bader and Latif (2003), who ran a simulation where the Pacific SSTs were changed to their 1950's values (i.e. cold anomaly). They obtained no rainfall response over the western Sahel, whereas the eastern Sahel experienced an increase in rain. Although these results lead to the conclusion that Pacific Ocean SST anomalies come third in influencing Sahelian precipitation, Lu and Delworth (2005) find Pacific Ocean forcing to be stronger than forcings by the Atlantic. They furthermore suggest that circulation patterns associated with a Pacific forcing are similar to the ones of Indian Ocean forcing.

Apart from varying influences on the spatial extent and magnitude of precipitation changes, the ocean basins influence climate variability at typical time scales. In general, SSTs affect rainfall variations on decadal and longer timescales, whereas interannual changes are found to be controlled by atmospheric variability (Paeth and Hense, 2004). However, Giannini et al. (2003) claim that only the Indian and Atlantic Ocean control the interdecadal variability, whereas changes in the Pacific Ocean's SST have power over the variability on an interannual scale.

It is interesting to note that the oceanic influence on precipitation itself seems to be varying with time. Paeth and Hense (2004) found that during a 20-year period around the year 1960, the Sahel appeared to be decoupled from oceanic influence. Surprisingly, the external influence is decreasing towards the end of the 20th century over most regions. This may be due to a gain in influence of a GHG forcing, which will be discussed in chapter 3.4.

3.3 Internal mechanisms: Land surface-atmosphere feedbacks

3.3.1 The role of feedback mechanisms

It has become clear that the external forcing of changing SSTs are the key driver of Sahelian wet and dry periods. However, the land surface responds to the external climatic forcing through interactions with the atmosphere and hence plays a significant role in controlling the rainfall anomalies on a regional or local scale (Giannini et al., 2008b, Zeng et al., 1999). These interactions are known as feedback mechanisms, which are defined as responses of the climate system to an external forcing, which leads to amplify or dampen the initial change – a positive or a negative feedback (Hansen et al., 1984). Hence, they do not drive rainfall variability, but are interposed between the variations in SSTs and the precipitation response; as a result they prolong the time scale of the response of the atmosphere (Paeth and Hense, 2004). The most relevant feedback mechanisms are vegetation and dust. They are interlinked through soil moisture, albedo changes and evaporation, which are key processes involved in these feedbacks.

It is crucial to include the effects of the feedbacks into global modelling. The deficiencies in GCMs, for example in reproducing the observed magnitude of rainfall anomalies, can in many cases be eliminated when a dynamic vegetation model is coupled to the atmospheric model (Paeth and Hense, 2004). Another argument for incorporating feedback processes in GCMs is that they probably played a critical role for African climate change during the Holocene. They amplified the orbitally driven climate change by an enhancement of the African monsoon, which among other factors lead to a considerable greening up of the Sahara (Hulme et al., 2001, Claussen et al., 2003). However, the number of processes involved and their complexity makes it difficult to capture feedback cycles in models, let alone forecast their effects in the future.

3.3.2 Vegetation feedback

Models that reproduce the observed interannual rainfall variability in the Sahel are more successful when they include feedback mechanisms of the vegetation. A well-known study by Zeng et al. (1999) reveals that when the model is driven with a combined forcing of SST changes and a vegetation-atmosphere feedback that includes soil moisture, interdecadal rainfall variability is enhanced whereas interannual variability decreases, which is a more realistic representation of the conditions of the late 20th century (see Fig. 5).

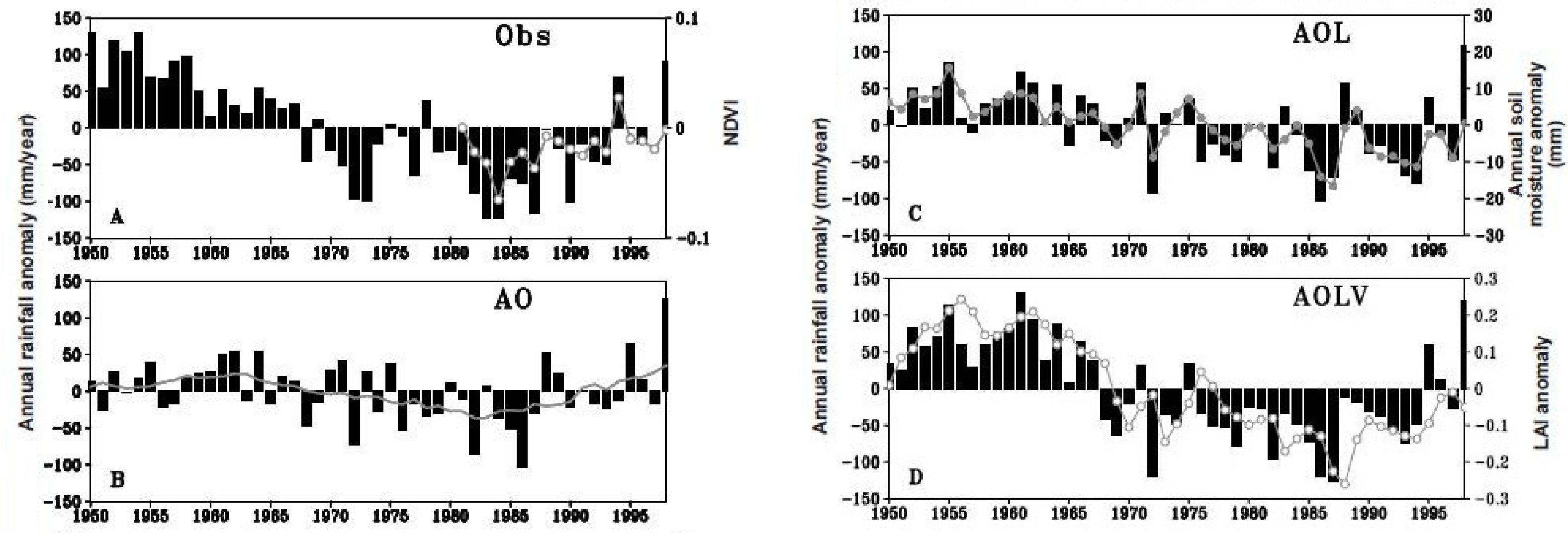

Figure 5: Rainfall anomalies (vertical bars) from 1950-1998 over the West African Sahel (13°N-20°N, 15°W-20°W). A: Observations, B: Model forced only with SSTs; soil moisture is fixed and vegetation is non-interactive, C: Model additionally forced with interactive soil moisture; vegetation remains non-interactive, D: Fully coupled model with additional interactive vegetation. Also plotted (connected circles) are for A: NDVI, C: simulated soil moisture anomaly, D: simulated LAI anomaly. All anomalies relative to 1950-1998, except the NDVI which is relative to 1981. Adapted from Zeng et al. (1999).

The coupled atmosphere-land-vegetation model used in the study (Quasi-equilibrium Tropical Circulation Model (QTCM) coupled to land surface model Simple Land (SLand)) is forced with the observed SST variations for the period 1950-1998. The SST-only experiment (B) shows only a small interannual and an even weaker interdecadal variability, but the drought is reproduced. When soil moisture is added as a forcing (C), the interdecadal variability slightly increases. Only when the vegetation feedback is included (D) does the modelled variability come close to the observed one, with a correlation of 0.67. The interdecadal variability can be reproduced a lot better than the interannual one (correlation of 0.97 vs. 0.1). A deficit of this model, however, may be that it does not take into account surface roughness or modifications of the properties of the soil (Zeng et al., 1999).

The effects of vegetation on climate can be identified through changes in evapotranspiration and surface albedo. Many studies point to the important role of albedo changes for climate-vegetation interactions, because the Sahelian climate system is very sensitive to changes in land surface conditions. In the study by Taylor et al. (2002), the modelled rainfall responded to albedo changes of less than 0.01. However, Taylor et al. (2002) find that these changes were not strong enough so that they could have been the main driver behind the recent droughts, contrasting the findings by Charney (1975) and others. Nicholson et al. (1998) confirm this: they found albedo changes of the magnitude of 0.02-0.03 from 1980-95, which they find too little in order to be able to call albedo the main driver. However, they are still significant for amplifying the SST forcing.

The vegetation also takes influence on the local moisture availability: directly through transpiration and indirectly through modifying the soil moisture content and thus the evaporation from the soil. Although moisture advection from the oceans is the main contributor to the overall moisture budget, the moisture that comes from transpiration is crucial because it is a significant local contribution to the hydrological cycle. A decline of the vegetation cover thus has a direct negative impact on precipitation (Gonzalez, 2001): less rainfall decreases the water availability and consequently the vegetation cover; surface albedo is increased; the resulting cooling decreases evapotranspiration. Therefore, the flux of moisture and latent heat through convection is reduced, which negatively affects precipitation – a positive feedback loop (Maynard et al., 2002). Yoshioka et al. (2007) suggest that vegetation loss in the Sahel accounts for about 10% of the observed decline in precipitation. On the other hand, higher precipitation rates also mean that there is an increased cloud cover. It will possibly reduce the amount of solar radiation reaching the surface, which will then dampen evaporation rates (Giannini et al., 2008b). This indicates the difficulty of estimating not only the magnitude but even the direction of this feedback.

Vegetation affects precipitation both through its natural variability and human-induced land cover changes. The effects of land-cover changes on climate are not uniform across the region though and they are rather small today in comparison to natural variability. By 2015, however, they may well lead to a precipitation decline of almost 9% (Taylor et al., 2002). Interestingly, Zheng and Eltahir (1997) suggest that regional rainfall is rather sensitive to vegetation degradation that occurs south of the Sahel along the Guinean coast possibly due to deforestation. Due to a drop in continental evapotranspiration, the West African monsoon was possibly deprived of its moisture, causing a widespread precipitation decline. This in turn would have negative effects on vegetation in the Sahel (Gonzalez, 2001). Also deforestation in the West African coast region may play its part: it may even lead to the collapse of the monsoon system. Changes along the Sahara-Sahel boundary, on the other hand, have been found to have a minor impact (Zheng and Eltahir, 1998). The western Sahel may well be the region where the vegetation-atmosphere feedback is strongest (Brooks, 2004). The vegetation feedback also has a possible impact on zonal air flow, as models of an increased vegetation cover in the Sahara show. Both a reduced Sahara in today's climate as well as the reproduced green Sahara of the mid-Holocene lead to an increase in strength of the TEJ and a weakening of the AEJ relative to their current strengths (Claussen et al., 2003).

One characteristic of the vegetation-atmosphere feedback is its non-linearity. That was revealed by a modelling study of the Holocene period by Claussen et al. (2003), who found that the vegetation of the Sahara changes non-linearly. Insolation changes are considered the main driving force of vegetation dynamics in the Holocene, and the vegetation was changing sometimes slower and sometimes faster than insolation.

3.3.3 Atmospheric dust feedback

Another feedback that is related to the interactions between the land surface and the atmosphere is dust, its source regions and its transport. This mechanism is of particular importance as the Sahara is the world's largest source of atmospheric mineral dust (Elasha et al., 2006). As soon as the dust is airborne, it may be transported in large clouds over great distances, hence its substantial impact on the Sahelian environment is not surprising (Brooks, 2004).

Dust is mobilized from soils that have been disturbed by climatic factors and human activity (N'Tchayi Mbourou et al., 1994). These two drivers of dust mobilization may be responsible for 30-50% of the global dust budget (Tegen and Fung, 1995). Up to now, an increase in dust event frequency can best be explained with atmospheric conditions, as the type of land degradation necessary for providing new dust sources is unclear (Brooks, 2004). The mobilization of dust is caused by the same atmospheric disturbances responsible for the occurrence of drought episodes (Brooks and Legrand, 2000). That means that when the frequency of these disturbances increases, i.e. notably a lack of rain, the mobilization of dust is further favoured and new areas of dust are likely to be created, causing an increase in the frequency and magnitude of dustiness (N'Tchayi Mbourou et al., 1994). Also in the 20th century, the atmospheric dust content over the Sahel clearly followed the evolution in rainfall (N'Tchayi Mbourou et al., 1997). The atmospheric dust load was elevated during the wet period, particularly from 1957-1966, and even more during the dry period, stretching the years 1977-1986. The magnitude of the dust haze is assessed according to visibility, which was particularly low after the severe droughts of 1972-1973 and 1982-1984. The rate of dustiness is subject to regional differences, which can be explained by the spatial rainfall variations (N'Tchayi Mbourou et al., 1994).
Also the regions of maximum dust production vary spatially and seasonally. Most of the year, they are located in the Sahara or the Sahara-Sahel transition zone. The transition zone may be the major dust source because soils are affected by the shift of the Sahara/Sahel boundary (Tegen and Fung, 1995). The time of the year most favourable for the mobilization of dust is from July-September. Dust is mobilized by the edges of the monsoon air mass where no precipitation occurs. In December, January and June, the most significant dust sources lie south of 18°N (Brooks and Legrand, 2000).

The effect of dust, i.e. the direction of the feedback is controversial. Atmospheric dust modifies the atmospheric temperature structure on local and regional scales. The most obvious effect is that of preventing incoming solar radiation from reaching the surface through reflection and scattering, leading to a cooling of the Earth's surface (Giannini et al., 2008b). In the same way it reduces the amount of longwave radiation leaving the Earth's surface through absorption, thus contributing to the greenhouse effect through warming. It depends on the amount and the reflectivity of the dust which of the effects dominate and hence, if the outcome will be a net cooling or warming (Brooks, 2004). These feedback processes do not only affect the temperature though, but are linked to a precipitation feedback. Reduced incoming solar radiation means that less moisture will be evaporated from the surface, leading to less convection and thus less precipitation, which would make it a positive feedback (Yoshioka et al., 2007). These authors find that the positive dust feedback can explain 30% of the observed Sahel drought. It could even be enhanced because the abundance of dust affects the vertical temperature profile, possibly creating a more stable atmosphere. In that way, convection is hampered, with negative consequences for precipitation (Brooks, 2004). However, an increased dust load in the lower atmosphere may also induce atmospheric heating on a local scale. Heating favours evaporation, so that in the ensuing convective process latent heat and moisture are transported into the atmosphere, enhancing the monsoon circulation. The resulting increase in precipitation would make it a negative feedback loop (Lau et al., 2006). In any case, the effect of dust is believed to be limited to shorter timescales. Uncertainties as to which of the effects may dominate show that more research is needed in this field. Despite the abovementioned effects, atmospheric dust can negatively impact agriculture, infrastructure and health (Elasha et al., 2006).

3.4 Anthropogenic climate change

In addition to the debate about the role of external forcings and internal feedbacks, the question arises as to the attribution of the warming of the tropical oceans. In how far is it due to internal natural variability, and in how far can it be related to external anthropogenic climate change, driven by increasing amounts of atmospheric CO_2? If the latter driving force dominated, that would allow attributing the Sahelian droughts to global warming. Also, the relative impact of natural and GHG forcings on precipitation variability is subject to uncertainties. In case the GHG forcing is found to contribute significantly to precipitation declines, an interesting shift in the question of responsibility for the droughts could result: in the 1980s, the local population was mainly made responsible for causing the droughts (e.g. Charney, 1975) whereas then, the blame would be put on the industrialized nations that have the largest share in the emission of GHGs (Brooks, 2004, Hulme et al., 2001).

Increasing GHG concentrations may have an indirect effect on precipitation in the Sahel through a warming of the oceans, and a direct effect because they may evoke a purely atmospheric response through changes in the midtropospheric circulation, which affects for example the AEJ (Paeth and Hense, 2004). When trying to identify the relative impact of natural variability and GHGs on SSTs and precipitation, Hoerling et al. (2006) have found that the relative role of natural climate variability for the drying of the late 20^{th} century cannot be determined unambiguously when models use fixed chemical constituents. Therefore, they forced coupled models with the estimated changes in the chemical composition of the atmosphere since 1950.

3.4.1 The effects on SSTs

It seems that the ongoing increase in not only the surface waters' temperature but down to a couple of hundred meters cannot be explained by natural variability alone. According to Knutson et al. (1999) and Stott et al. (2000) it is likely to have anthropogenic origins. Paeth and Hense (2004), using the AGCM ECHAM3, substantiate this hypothesis. According to them, increased GHG concentrations can explain 80% of the total variability in SSTs. The response of the Atlantic Ocean to an anthropogenic forcing is more complex due to the differential heating of the North and South Atlantic, which has been found to be mainly due to a warming of the South. Despite that, a cooling of the North would add to the temperature gradient. This is likely to be caused by the larger concentration of anthropogenic aerosols (mostly sulfate aerosols) in the northern hemisphere due to the high industrial activity there. The cooling of the ocean surface occurs because the aerosols scatter and absorb the incoming solar radiation (Paeth and Hense, 2004). Indirectly, they cool the climate by altering the reflectivity and lifetime of clouds. On the contrary, increasing GHGs are thought to contribute to the interhemispheric SST gradient by a faster warming of the North than the South. The question remains as to which effect may gain the upper hand (Held et al., 2005). In that context it is important to note that the atmospheric lifetime of aerosols is short in comparison to GHGs such as CO_2. Their effect on climate is therefore mostly localized and temporary, and so may only be masking the underlying GHG warming trend (Hulme et al., 2001).

Despite the plausibility of these studies, different models always produce different results. In the detection/attribution analysis made by Hoerling et al. (2006), the observed SSTs cannot be seen as a response to GHG forcing, which leads them to the conclusion that they are mainly controlled by natural variability.

3.4.2 The effects on precipitation

A study conducted by Biasutti and Giannini (2006) was able to reproduce the Sahelian drought with anthropogenic forcings only, i.e. the increased abundance of GHGs and sulfate aerosols. They were using the coupled ocean-atmosphere CMIP3 models (phase 3 of the Coupled Model Intercomparison Project by the World Climate Research Programme (WCRP), also used in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC)). The same result was accomplished by the ensemble mean of coupled atmosphere-ocean models used by Held et al. (2005). A CO_2-forcing alone, however, does not seem to be appropriate for the reproduction of rainfall variability, as it underestimates the interdecadal variability over the 20th century (Paeth and Hense, 2004). The GHG-forced experiments conducted by Hoerling et al. (2006) obtained quite different results, using the 18 models that were also used in the AR4 of the IPCC. They do produce a precipitation decline for the 20th century but it lags behind the observed development. On the contrary, the modelled recovery in precipitation in the 1990s exceeds the observed values. These results imply that models forced with GHGs only are unsuccessful in explaining the observed drought in Africa in the 20th century. In any case, the question remains as to why the above-mentioned studies produce contrasting results. It may be due to differences in the models; however, the model used by Biasutti and Giannini was part of the model ensemble that Hoerling et al. used. Another explanation may lie in the different forcings: Biasutti and Giannini used a combined forcing of GHGs and sulfate aerosols whereas Hoerling et al.'s models were only forced with GHGs. It remains to be proven if sulfate aerosols alone could account for the opposite modelling results.

Most studies confirm that GHGs alone are incapable of explaining the drought. Experiments conducted with the coupled model GFDL CM2.0 were forced with the observed 20th-century changes in GHGs, aerosols, volcanic activity, solar insolation and land use. The obtained amplitude of the drying represents only 50% of the observed trend (Lu and Delworth, 2005). The remaining part is probably due to an SST forcing. Held et al. (2005) confirm that the variability in 20th-century Sahelian rainfall can be explained by internal decadal SST variations for the most part, whereas the remaining variability may well be explained by anthropogenic forces.

In order to disentangle the signals of SSTs and GHGs for Sahelian precipitation, Paeth and Hense (2004) ran two model ensembles: the first one an ensemble of ECHAM4 experiments forced with SSTs and GHGs, the second one an ensemble of HadAM2 simulations forced with SSTs only. Both their SST-only and SST+GHG simulation reproduces the observed drying trend. However, the additional GHG forcing produces significantly different precipitation anomalies in recent years, i.e. positive anomalies that reach up to the climatological mean, as observed in the 1990s. This indicates that the additional effect of GHGs leads to increased precipitation and contributes to a more realistic representation of the rainfall trend. When looking at regional effects of the forcings, their experiment reveals that over the Gulf of Guinea and southern West Africa the SST+GHG forcing accounts for 70% of the rainfall variability. The strong correlation between SSTs and rainfall anomalies along the coast can be explained by the summer monsoon dynamics that take influence through the transport of latent heat from the ocean into the continent. Over the Sahara and the Sahel the combined forcing also has a significant impact. Their experiments lead to the conclusion that over most of the 20th century, the effect of SSTs outweighed GHGs, but that the latter became effective after the 1970s. The recovery in rains of the past two decades may thus be an early sign of the GHG forcing, which is likely to gain importance in the future (Paeth and Hense, 2004).

In any event, there is no evidence for causal mechanisms linking human activities and drought events in the Sahel (Brooks, 2004).

4 Driving forces in the 21st century

4.1 Reasons for the variety in future simulations

Uncertainty grows with time, which already became apparent in the 20th century when explaining the shift to wetter conditions in the 1990s, in comparison to the well-understood dry shift in the 1960s. This is even more pronounced when estimating possible future scenarios for the climatic development of the Sahel.
There are various reasons for the existence of a range of very different but probable future climate scenarios. Not only is the understanding of the climate system incomplete but also is the unpredictability an inherent characteristic of the climate system, such as e.g. the possible appearance of yet unknown forcings and different regional responses of the climate system to the same global forcing (Hulme et al., 2001). The large spread in simulations of future precipitation trends may be due to the variety in projections for future SSTs or rather due to the models' incapability of capturing the effect of SSTs on rainfall pattern (Hagos and Cook, 2008). Model incapability plays a crucial role, as most GCMs fail to represent potentially important drivers of climate variability, such as the large internal variability driven by the oceans, particularly ENSO, and the role of anthropogenic land cover change (Hulme et al., 2001). Despite poor representation of some processes, other processes are not included in the majority of models at all, such as land-surface interactions, soil moisture changes and the effect of aerosols. The latter must not be excluded from models though, as they have a significant impact on temperature. For example, a model driven with a combined GHG and aerosol forcing gave a global temperature increase by 2100 that was between one quarter and one third less than with a GHG forcing only (Hulme et al., 2001). The seven coupled ocean-atmosphere GCMs used by Hulme et al. (2001) (among them ECHAM4 and HadCM2) for example, used to forecast 21st century precipitation trends, excluded processes that might have been crucial for the past desiccation, such as dynamic land-surface atmosphere feedbacks and changing atmospheric dust loading. This might explain the striking fact that none of the individual simulations produced multi-decadal precipitation variability for the 21st century that was so typical for the 20th century (see Fig. 6).

A significant source of uncertainty arises from the possible future concentrations of GHGs. The question of the relative impact of anthropogenic climate change on drought events of the past persists into the future, and is likely to even gain in importance. As the possible future concentrations of GHGs exceed the level of concentrations of anytime in the past of which we know, it is hard to tell how the climate system could react. Even more as anthropogenic climate change is likely to increase the likelihood of unforeseeable non-linear changes in the climate system (Brooks, 2006). The basis for possible projections of the 21st century is a realistic estimate of GHG concentrations. They in turn depend on future emissions, which are going to be controlled by a variety of socio-economic and political factors in countries all around the world – a widely discussed issue, approached among others by the IPCC in the Special Report on Emissions Scenario (SRES) (Nakicenovic et al., 2000).

4.2 Dry or wet? The Sahara/Sahel region in a bistable state

The question whether the Sahel is going down the dry or the wet path in the future is difficult to answer when considering its nature of a transition zone between two regions for which climate models produce opposing trends – the Sahara is believed to dry even further, whereas the West African tropics will likely be wetter (Paeth and Hense, 2004). Whereas the direction and magnitude of future precipitation change is largely disputed, the temperature increase is unequivocal. The four scenario runs by Hulme et al. (2001), using the scenarios of the SRES by the IPCC (A1, A2, B1, B2), yielded a temperature response of 0.9°C to 2.6°C by 2050 and 2 to 6°C by 2100 for the African continent.

The uncertainties about the future precipitation trend find expression in a disagreement between the coupled models, as some forecast a dry Sahel whereas others simulate a further recovery in rains at quite varying magnitudes (see Fig. 6). The disagreement may seem somewhat surprising when considering that the same coupled models were quite successful in simulating the present climate, when driven with the forcings of the 20th century (Biasutti et al., 2008).

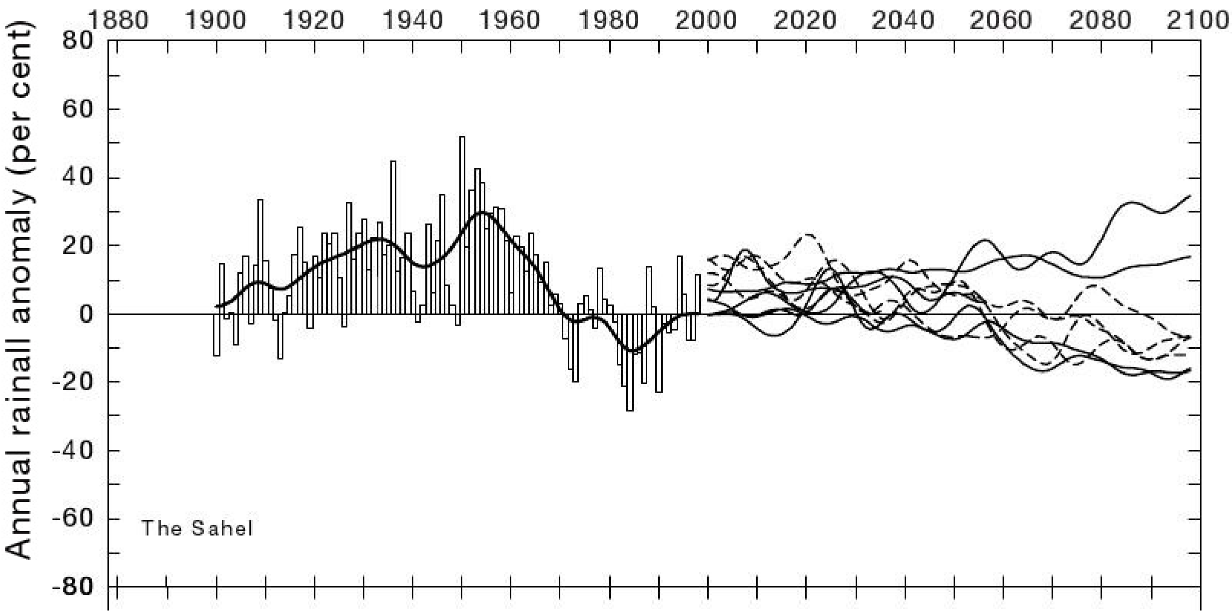

Figure 6: Observed annual rainfall anomalies for 1900-98 and simulated anomalies for 2000-2099 in percent relative to 1961-1990, obtained from 10 individual model simulations from 7 GCMs. Dashed curves represent the four HadCM2 simulations. Adapted from Hulme et al. (2001).

Actually, the fact that both the dry and the wet state would be possible is not surprising, yet for other reasons than model disagreement. Feedback mechanisms between the vegetation and the atmosphere in response to precipitation changes maintain a situation of bistable states under the current climatic conditions. One possibility is the maintenance or aggravation of the dry state in

which the region is today, the other a vegetation increase in the Sahel and a greening up of the Sahara (Brovkin et al., 1998, Claussen et al., 2003).
In the following two chapters, the possibility of the dry and wet state as a response to natural and anthropogenic forcings is going to be presented. The concept of a continuously dry or possible greener region will be discussed in chapter 5.4, as it is mainly controlled by the vegetation response and a vegetation-atmosphere feedback.

4.2.1 Wetter Sahel

With the ongoing global warming, a heating of all ocean basins can be expected, which is associated with drying. But since precipitation values have recovered in the recent past despite an increase in SSTs, one has to look for other arguments. Global warming also causes the land-ocean temperature contrast to increase, as the continent heats up a lot faster than the ocean. This would cause an intensification of the monsoonal flow. As evaporation from the oceans increases as they warm, more moisture would then be transported inland, supplying the West African monsoon with moisture and increasing precipitation over the continent (Giannini et al., 2008a, Giannini et al., 2008b). This is also the reason for the increase in summer (JAS) precipitation projected by Maynard et al. (2002), using a coupled atmosphere-ocean-sea-ice model and spanning the time period 2070-2100. However, the intensification of the hydrological cycle due to increased GHG concentrations is still subject to uncertainties. Other experiments that simulate a future wetter Sahel attribute this to a warming of the North relative to the South Atlantic Ocean, such as the one by Hoerling et al. (2006), covering the period 2000-2049. The reversal in the Atlantic SST pattern could have natural origins or be the result of a reduction in the concentration of aerosols in the northern hemisphere (Giannini et al., 2008b). Since Paeth and Hense (2004) suggest that the recent precipitation recovery can be attributed to a warmer North Atlantic driven by increased GHG concentrations, a future wetter Sahel seems likely considering that GHG concentrations are going to rise continually in the 21st century. This is what they project using the ECHAM4 model. Hoerling et al. (2006) substantiate this as the differential heating of the Atlantic is unanimously simulated by all of the 18 AR4 models they use. Also, 14 of the 18 AR4 models produce a continuous increase in precipitation for the first half of the 21st century in response to a GHG forcing, yet there is a large spread as regards its magnitude. The remaining models project a further drying trend.
A study by Paeth and Hense (2004), using the ECHAM4, obtain a divided precipitation response to GHG forcings for the 21st century. In their study they succeeded to partly disentangle the effects of CO_2 and sulfate aerosols on precipitation at the Guinean coast. The CO_2-only forcing produces a remarkable, steady increase from the 1970s on. By the middle of the 21st century, rainfall will lie 150 mm above the 1961-1990 mean. The second run combines CO_2 with sulfate aerosol forcing and the precipitation increase lies about 100 mm lower than in the first run. This confirms the assumption that aerosols counteract the warming effect of CO_2. In the combined

run, also the interdecadal variability is enhanced, which indicates that projections including aerosol forcings represent the decadal variability of the region more realistically.
These results may lead to the conclusion that the Sahel is to benefit from the effects of anthropogenic climate change. However, the levels of CO_2 that e.g. Maynard et al. (2002) use in their study of the 21st century are very likely to be exceeded (Brooks, 2006).

4.2.2 Drier Sahel

The future effect of GHGs on Sahelian precipitation is disputed though, as simulations predicting a drier Sahel in the 21st century show (e.g. Held et al., 2005). CO_2 concentrations of 550 and 750 ppm by the end of the 21st century will warm the southern Atlantic and equatorial Indian Ocean, conditions that are associated with a dry Sahel. Surprisingly, very high CO_2 concentrations do not seem to produce this ocean warming (Mitchell et al., 2000). The coupled ocean-atmosphere model used by Held et al. (2005) is forced with the estimated conditions of the IPCC A1B and A2 scenarios that assume CO_2 concentrations of 720 and 860 ppm by 2100, respectively. They produce slightly positive rainfall anomalies for the first few decades of the 21st century, whereupon a rapid decline in precipitation values ensues, that even drops below the drying of the 1980s. They assume that a GHG forcing causes widespread Sahel drying and that it is going to be the dominant forcing in the 21st century. The HadAM2 model used by Paeth and Hense (2004) produces a similar response, with a trend of positive anomalies from the 1990s until the second half of the 21st century, whereupon a constant drying tendency ensues, which may even drop below the 1961-1990 mean. The reasons for this are not clear yet. They may lie in the model itself, as it is known to be less sensitive to enhanced GHGs (Paeth and Hense, 2004) or in a negative feedback mechanism of the oceans to the warming. Another possible explanation is the reduced land-ocean temperature gradient, whose effects may dominate when the ocean warming exceeds a certain threshold.

As Hulme et al. (2001) show, the effects of different climate change scenarios on precipitation vary in strength and geographic extent (see Fig. 7). For example the A2-scenario, assuming a rather slow economic growth and continuously increasing global population (Nakicenovic et al., 2000), yields significant increases in summer precipitation over the central Sahel, whereas the western part experiences the most significant decreases relative to 1961-1990. In a B1 world, the economy is focussed on clean and efficient technologies; the population is going to peak in the mid-21 century with a decline thereafter (Nakicenovic et al., 2000). The Sahelian precipitation only shows a weak response, but a negative trend in the western Sahel and a slightly positive one in its centre can nonetheless be identified (Hulme et al., 2001).

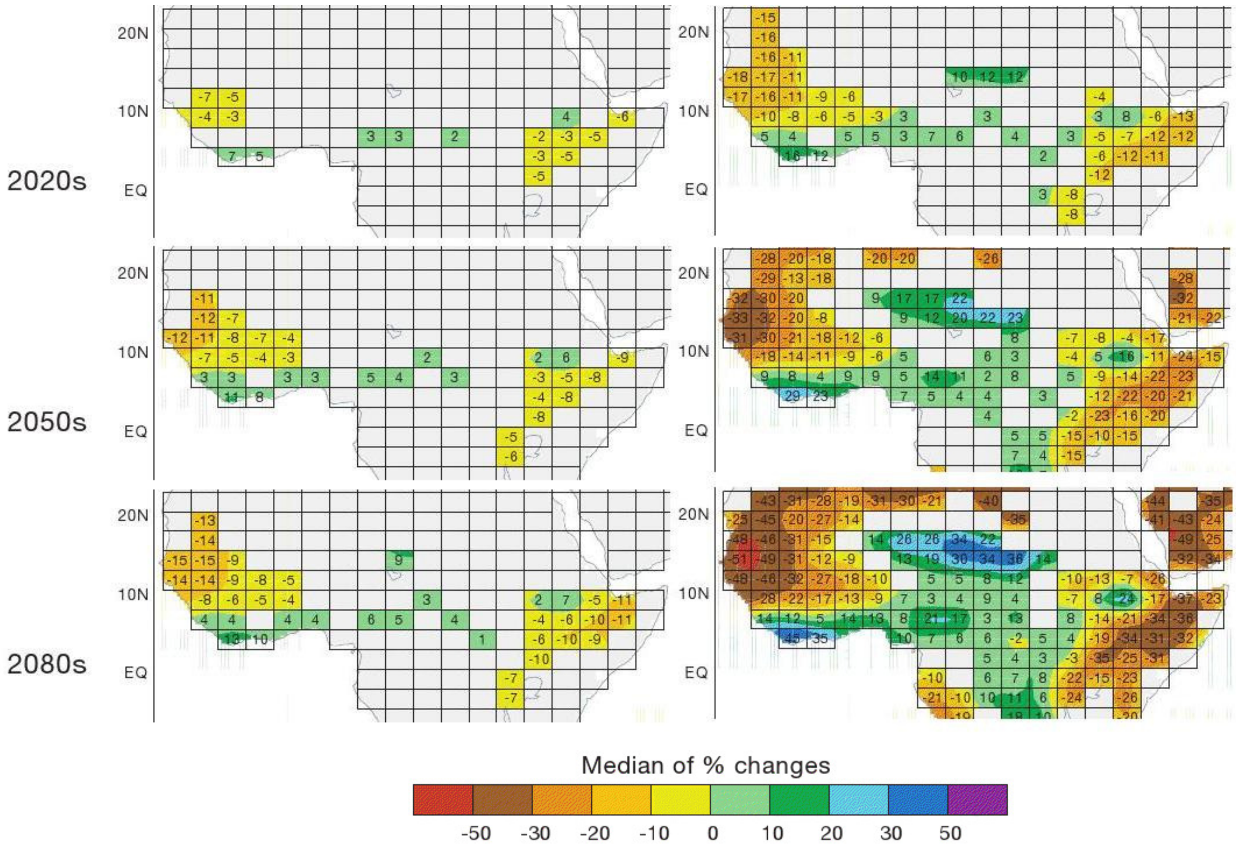

Figure 7: Change in mean JJA precipitation for the 2020s, 2050s and 2080s relative to 1961-1990, for the B1 scenario (left) and A2 scenario (right), median of 7 GCMs. Adapted from Hulme et al. (2001).

The same authors ran a scenario for Senegal, located by the Atlantic Ocean on the western edge of the Sahel, with a mean of seven GCMs across all four scenarios. Despite the large spread, the negative precipitation trend together with a temperature increase for the year 2050 relative to 1961-1990 is pronounced in most simulations; actually more distinct than in any other region in Africa (Hulme et al., 2001).

These results show that the rainfall response to future forcing is neither going to be linear, nor uniform across the Sahel. A final answer whether the region is going to dry or become wetter cannot be given. Cook and Vizy (2006) argue that the wetting of the region due to increasing moisture inflow from the ocean is more mechanistically probable, but it would require a warming of 3°C of the SST of the Gulf of Guinea.

5 Vegetation Dynamics

5.1 Vegetation parameters

An effective way of observing vegetation and its dynamics, i.e. the changes in distribution, density and composition of species (Vanacker et al., 2005), is through remote sensing. The parameter most widely used to measure vegetation is the Normalized Difference Vegetation Index (NDVI). The NDVI gives information about the density of a vegetation cover and whether the vegetation is alive or not, as green leaves reflect radiation back in a different spectrum than brown ones do (Pettorelli et al., 2005). Another common index is the Leaf Area Index (LAI), defined as the total area of green leaves relative to the ground area of a canopy (Scurlock et al., 2001). NDVI and LAI are very useful parameters in representing vegetation structure, as they also provide information on photosynthetic activity, net primary production (NPP), transpiration, and the like. Since they are parameters, their deficiencies lie in the simplification of processes, for example are they hardly able to distinguish between the actually very different vegetation types of drylands. Therefore they would not be able to reflect some significant changes in the vegetation structure, such as species' shifts (Seaquist et al., 2009).

5.2 Vegetation changes in the 20th century

With the help of the abovementioned indices, it has been revealed that the vegetation cover dramatically decreased in the 1970s and 1980s. The vegetation density, the total amount of biomass, the species' composition and the vegetation zones underwent considerable changes. Between 1945 and 1989, Sahelian species' richness declined by 14 ± 4% (Gonzalez, 2001). During the same period, tree density went down. Even a shift in the Sahel and Guinean vegetation zones could be observed in the course of a case study of an area in Senegal during 1945-1993: the vegetation moved 25-30 km towards the southwest, which makes a 500-600 m displacement per year. The shift was accompanied by a loss of mostly mesic species, which left behind a species' composition dominated by drought-resistant ones (Gonzalez, 2001). This study also revealed biomass changes: the total biomass in 1993 was 15 t/ha, 12 t/ha were wood. In the period 1956-1993, the biomass of trees had declined by 2.1 t/ha. The decline of tree density accompanied by a displacement in the vegetation zones signify a considerable degradation of land, which Gonzalez (2001) considers as desertification.

Satellite observations of the NDVI laid open that the Sahel has been re-greening starting in the early 1980s (Seaquist et al., 2009, Hickler et al., 2005, Olsson et al., 2005, Herrmann et al., 2005). Interestingly, the Sahel was not the only region that experienced a greening up during the period 1982-2003, but regions around the world such as the Mediterranean and East Asia underwent a similar, yet smaller trend (Helldén and Tottrup, 2008). The increase in photosynthetic activity in the Sahel becomes apparent when observing the NDVI for the time period 1982-2003 (see Fig. 8) (Herrmann et al., 2005). The NDVI increased almost consistently by 10-20% in the western and central Sahel. However, the vegetation did not immediately recover; Nicholson et al. (1998) found that it responded to increasing precipitation values with a one year-delay. The lag in the vegetation response has also been found by Zeng et al. (1999); it shows in Fig. 5D. The fully coupled atmosphere-vegetation model produces the maxima and minima in rain with a slight delay relative to the observed values (Fig. 5A). The lag can be explained with the severity of the 1980s drought, which damaged the vegetation in such a way that it took longer to recover than it might have otherwise been capable of.

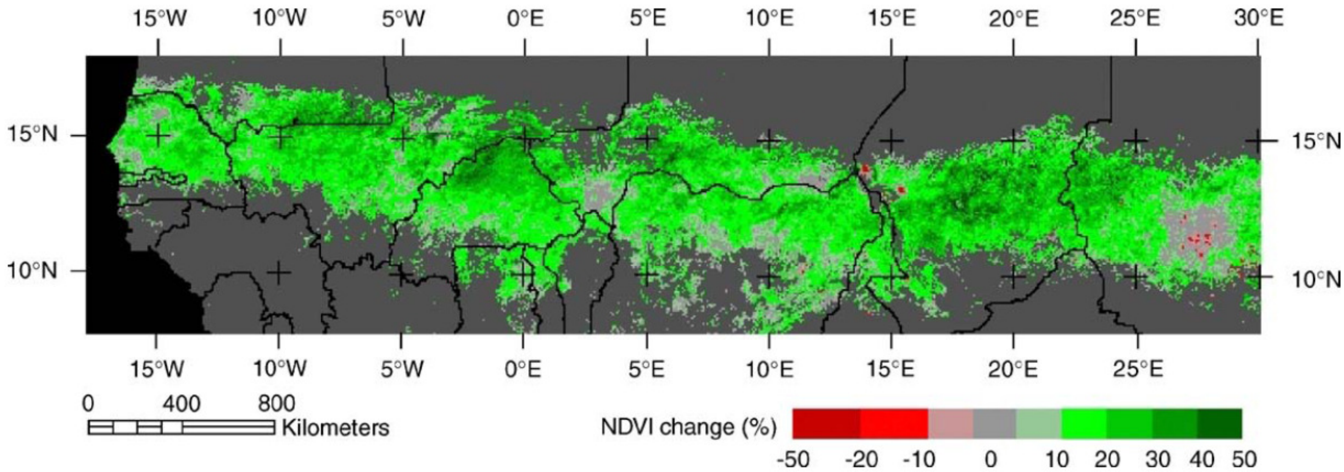

Figure 8: Trends in vegetation greenness, expressed as NDVI changes in percent during the time period 1982-2003, derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite data. Reprinted from Herrmann et al. (2005).

Although satellite data shows that there has been a recovery in the vegetation cover, field studies reveal that the species' composition changed in many areas. The change happens mostly to the detriment of the local people as now many of the species used for firewood, medicine and food disappeared. Like that, the human carrying capacity of the Sahelian ecosystems was reduced in such a way that it dropped even below the actual population. The implications for the living conditions are already severe today, let alone the effects future droughts would have (Gonzalez, 2001). A measure to counteract the negative effects of declining vegetation is by natural regeneration of local shrubs and trees, which is practiced by the local population all across the Sahel (Sendzimir et al., 2011). Apart from this method, exotic trees are often planted by foreign aid projects. However, due to a lack of water their survival rate is only 18%, making the undertaking time-consuming and costly: every surviving tree costs $50. Up to now, plantations make up only 0.4% of the total biomass (Gonzalez, 2001).

5.3 Natural and anthropogenic drivers

What can these vegetation dynamics be attributed to – climatic variability or anthropogenic land-use? The assumption of earlier investigations was that the main controls of Sahel vegetation

dynamics lay in desertification associated with land mismanagement (Herrmann et al., 2005). This hypothesis has been overcome, as more recent studies demonstrate.
In order to separate the climatic from the human impacts in the form of demographic and agricultural pressures, Hickler et al. (2005) and Seaquist et al. (2009) compared the observed actual vegetation dynamics derived from satellite measurements with the simulated potential vegetation cover obtained from the LPJ- DGVM (Dynamic Global Vegetation Model, a coupled biogeography-biogeochemistry model) for the time period 1982-1998 and 1982-2002, in the respective study. Any difference between the two could then be attributed to an anthropogenic influence. In both time series, the observed NDVI matches closely with the modelled LAI (Hickler et al., 2005). Neither the total population nor changes in population density nor cropping intensity significantly affected either NDVI or LAI. However, the model produced an increase in NDVI/LAI with increasing pasture intensity (Seaquist et al., 2009). Still, the issue remains unsettled whether the people do either not significantly affect the vegetation, or if their effect can simply not be identified due to a vegetation response too subtle to be captured (Seaquist et al., 2009). It is likely that the human influence plays a role on a local scale (Hickler et al., 2005). However, the negative influence of human activities on vegetation dynamics may well grow in the future along with demographic and agricultural changes, which becomes apparent when considering that the regional population is presently doubling every 20 years (Taylor et al., 2002).
Vegetation dynamics have shown to be rather the natural response of a semi-arid ecosystem to precipitation variability rather than to human land-use change. This particularly holds true as the land degradation caused by the prolonged drought was only temporary and reversible and the vegetation recovered after precipitation values picked up again (Brooks, 2004).
An important part in understanding how climatic factors are influencing vegetation dynamics is to individually assess their relative importance on vegetation. In order to identify the driving forces behind the 1990s greening, Hickler et al. (2005) forced the LPJ-DGVM with changes in one of the variables at a time (temperature, precipitation, sunshine hours and CO_2-concentrations) while holding the others at their average values. These experiments revealed that greenness can basically be attributed to rainfall changes only. Temperature and sunshine have a negligible effect and an increase in CO_2 causes a slight increase. This is due to the beneficial effect of elevated levels of CO_2 on some species through increasing their photosynthetic rates, known as “fertilization effect” (Lioubimtseva and Adams, 2004). The CO_2 concentration seems to affect NPP, LAI and carbon pools, whereas the vegetation structure is determined by precipitation and also temperature (Claussen et al., 2003). A study by Vanacker et al. (2005) confirms that the vegetation dynamics can be related to rainfall fluctuation. The strongest correlation was obtained between vegetation dynamics and both seasonal and annual rainfall changes. The response of the vegetation has also been found to depend on the phenology, physiology and morphology of the species: grass- and shrubland have shown to be most sensitive to short-term variations in rain in the order of years, whereas forest and woodland species are more resilient to these changes (Vanacker et al., 2005). The dynamic of trees takes place on time

scales from decades to centuries (Claussen et al., 2003). Resilience to rainfall fluctuations is also dependent on the species' diversity: the higher the amount of different species, the less dynamic the whole community shows (Vanacker et al., 2005). Studies such as the one by Tucker et al. (1991) and Nicholson et al. (1998) showed that also the fluctuations of the Sahara-Sahel border over time can principally be explained by interannual rainfall variability. They explored shifts in the 200-mm isohyet, which they considered as the Sahara's southern boundary, and the vegetation, using the NDVI. They found that from 1982-84 both variables progressively shifted southward, followed by a northward retreat from 1985 until the year 1989. In 1990 there was again a southward shift, whereupon they both moved to the north again. The correlation between rainfall and NDVI is 0.9. Gonzalez (2001) had a similar approach and found that the observed displacement of vegetation zones during the period 1945-1993 followed the isohyets. A strong correlation between rainfall anomalies and NDVI anomalies has also been found by Helldén and Tottrup (2008). However, a correlation between the anomaly trends of the two parameters was found only in about half of the sample locations, indicating that the strength of the rainfall forcing is not uniform across the region. Also the NPP developed along with precipitation values during the time period 1982-1990 (Prince et al., 1998).

Some studies (e.g. Olsson et al., 2005) have even suggested that the vegetation has recovered more than what can be explained by the observed increase in precipitation. This raises the question whether the greening may partly be due to positive effects of human practices. These could include a change in agricultural practices such as well-working land and soil water management (Olsson et al., 2005) as well as reforestation, as mentioned above. In this context, one should bear in mind that the effects of farming and livestock grazing on Sahelian ecosystems do not necessarily have to be negative. The negative effects result for example from a more recent growing pressure on food production. However, the traditional agricultural practices are mostly sustainable, as they are adapted to the semi-arid landscape and water shortage. The recollection of these practices can therefore be capable of encouraging the regeneration of the vegetation (Brooks, 2004).

Despite all modelling efforts that try to attribute land surface changes and vegetation dynamics to single driving forces, one has to take into account that the answer to that question is usually not one-sided at all; it is more an interplay between various factors of natural and anthropogenic origin. Even though climate variability may play the leading role, the way societies face that variability plays a significant part. An over-exploitation of natural resources such as the groundwater or inappropriate agricultural policies and practices may lead to exacerbate the effects of natural rainfall shortage.

5.4 The regional vegetation in a bistable state

5.4.1 The past and the present

A look into the palaeoclimatic record of the Sahara and Sahel shows that the region has not always been as dry as it is today. In the mid-Holocene there was a strong greening of the region. That condition can mainly be attributed to changes in the Earth's orbit, causing insolation changes. The resulting climatic optimum around 6,000 years ago was characterized by warmer conditions and an enhanced summer monsoon compared to today, which was then amplified by vegetation-atmosphere feedbacks. The result was a more northern Sahara-Sahel boundary at about 23°N and thus a green Sahara (Giannini et al., 2008a, Brooks, 2004, Claussen et al., 2003). Under the conditions of the mid-Holocene, the only possible state that was stable for the region was the green one. After about 3,600 years ago, the green state became less stable, the region switched into the dry state in which it is still today and the Saharan desert came into existence (Brovkin et al., 1998). In general, the switch from one state to another depends on a sufficiently large trigger in the atmosphere-vegetation system. In the late Holocene this might have been a change in vegetation due to anthropogenic practices (Brovkin et al., 1998). The critical threshold at which a tiny perturbation causes a strong non-linear response in the system that will qualitatively alter its state is known as a "tipping point" (Lenton et al., 2008). Some shifts may be irreversible, just as tipping over a glass of water.

As has been indicated earlier, under the global climatic conditions of today, the Sahara/Sahel region finds itself in a situation where two stable states are possible: the desert or the green state (Claussen, 1998, Claussen et al., 2003). The desert equilibrium is characterized by low precipitation values and sparse vegetation the way it is today, whereas in the green equilibrium the precipitation is moderate and the vegetation cover permanent. The savannah and its xerophytic scrub vegetation would move 600 km northwards into the Sahara, greening it up (Claussen, 1998). The possibility of the bistable state has been successfully simulated by coupling an AGCM to a vegetation model – the ECHAM model to the BIOME model (which simulates the major biomes, i.e. biotic communities and the environment which they are adapted to, developed by Prentice et al. (1992)) (Brovkin et al., 1998). The bistable states are sustained by a vegetation-climate feedback, of which important components are the different albedos of the Sahara and the vegetation-covered Sahel (Brovkin et al., 1998). The possibility of a bistable state is greatest in the western part of the region, where the amount of rainfall as well as the vegetation-atmosphere feedback is strongest and the isohyets are located further north than in the rest of the region. An interesting question is whether the feedbacks between the vegetation and the climate would be capable of sustaining the possibility of two stable states on a regional or global scale (Brovkin et al., 1998).

5.4.2 The future – the region as a potential "tipping element"

For large-scale components in the Earth system that may cross a tipping point in the future, Lenton et al. (2008) have introduced the term "tipping element" (see Fig. 9). The map only includes tipping elements that are considered "policy-relevant", indicating that they are accessed by human activities and may play a potentially important role in policy-making.

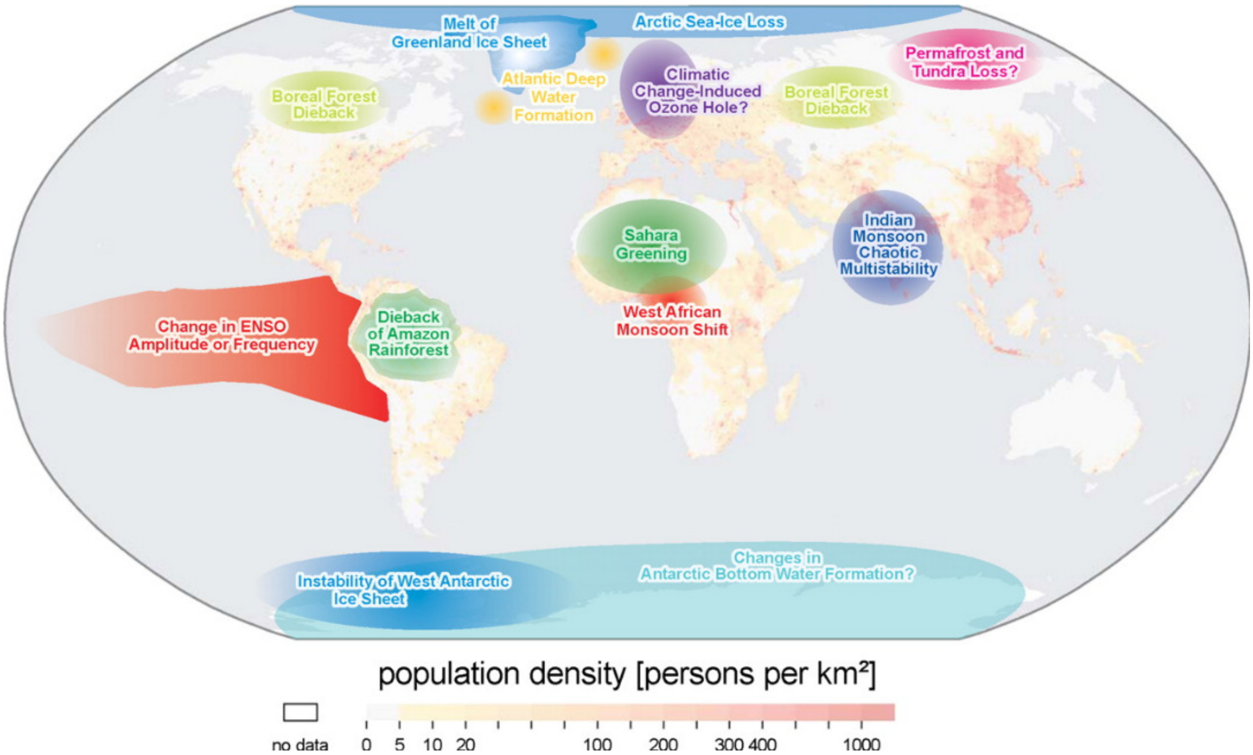

Figure 9: Potential policy-relevant tipping elements in the climate system. The systems indicated may cross a tipping point in the future due to anthropogenic forcings and as a consequence undergo significant changes in their state. Question marks point to an uncertain status as a tipping element. Reprinted from Lenton et al. (2008).

A system that has undergone a transition in the past may well be a potential tipping element in the future under anthropogenic forcings (Lenton et al., 2008). However, the boundary conditions that drove the change in the past are very different from a future GHG forcing. In case of the Sahara, despite the similarities in their appearance, the greening in the Holocene cannot be considered analogous to a possible future greening. The driving forces behind the developments are quite different from each other, as the past climatic changes can be attributed to insolation changes due to variations in the Earth's orbit, whereas the future climate change will be driven by increased concentrations of GHGs. While the former development affects the climate on a seasonal and regional scale, the latter is known to influence the climate globally and rather homogenously (Claussen et al., 2003).

In a world where CO_2 concentrations are significantly increased above their pre-industrial values, such as a doubling to 560 ppm, the Sahara/Sahel region would no longer be in a bistable state: a rise in CO_2 increases the probability of the green equilibrium (Brovkin et al., 1998). Claussen et al. (2003) used the coupled ocean-atmosphere-vegetation model of intermediate complexity CLIMBER-2 (developed at the Potsdam Institute for Climate Impact Research) in order to study a possible Saharan green-up due to a CO_2 forcing. The greening would depend on the rate and magnitude of the CO_2 increase but a migration of the vegetation cover into the Sahara of 10% of its area per decade could be possible. However, the greening would be unlikely to cover more than 45% of the area of the Sahara (Claussen et al., 2003). In the model, the vegetation of the Sahara shows a non-linear reaction to the steady increase in CO_2 values. Also, it lags behind the enhanced CO_2 levels: it reaches its maximum a few decades after CO_2 values peak (Claussen et al., 2003).

Lenton et al. (2008) try to define the threshold that the system would have to cross in order to switch to the green stable state. They propose that a critical precipitation value of 100 mm/year would be necessary together with a global warming of +3-5°C which will probably trigger the precipitation increase. As described, the precipitation increases with the enhancement of the monsoon, possibly driven by increased GHG concentrations and amplified by vegetation-atmosphere feedbacks. The timescale of the transition is estimated at about 10 years, which is rapid compared to some other tipping elements such as the Greenland or the West Antarctic Ice Sheet. The key impact for the region would be an increased carrying capacity, as the increased vegetation cover could supply more people with food, building material, firewood, etc. The Sahara/Sahel region is thus a beneficial potential tipping element, which is rare in comparison to the others.

6 Synthesis and outlook

Data

The first problem that arises when analyzing Sahelian rainfall is that of lacking climate data. In many cases it is unavailable at the desired high resolutions and is often temporally not continuous (Hoerling et al., 2006). The absence of observational data prior to the 20th century for example makes it difficult to put the droughts of the 20th century in a historical context and to assess if they remain within the range of historical variability. The same holds true for vegetation data: there are no regional-scale observations from the time before the 1960s, which makes it difficult to evaluate how the vegetation has changed in the course of the 20th century and especially to attribute changes to either natural forcings or land-use change (Taylor et al., 2002). Improving the spatial coverage of surface climate stations and the quality of climatic data is every bit as important as difficult.

Modelling

Data limitations have implications on the quality of climate modelling. This results in a generalization of data sets, errors in the model inputs of climate data and poor model performance. In general, a large possible source of uncertainty arises from models. A climate model can be considered reliable when it is able to reproduce the observed long-term climatological mean and variability (Paeth and Hense, 2004). Most of the simulations for the Sahel were successful in reproducing the timing and the duration of the past drought events in the Sahel, however, some models still fail to simulate their magnitude and geographic extent. Also, the simulated variability is weaker than the observed one (Giannini et al., 2008b). Hagos and Cook (2008) argue that the reasons for the simulations' deficiencies lie in the widespread use of GCMs instead of RCMs. When comparing the results of different models with each other, one has to be aware of and try to estimate the extent of variations between models. These are differences in the model set-up such as for instance the represented processes and forcings. In any case do the models used by Giannini et al. (2003), Bader and Latif (2003), Lu and Delworth (2005) and Hoerling et al. (2006) belong to the most recent generation of atmospheric models. Apart from these model-inherent troubles one has to bear in mind that the strong climatic variability that is so characteristic of the Sahel is very difficult to capture.

Uncertainties in defining the driving forces behind drought

Using models to reproduce past climate variability is the key to understanding the driving forces behind drought. The main driving forces of drought have been presented in this work and it has been tried to present them separately and to isolate their relative importance. However, this could not always be accomplished, besides is it not always appropriate as they are all interconnected in shaping the magnitude, duration and geographic extent of droughts. Furthermore, they are complex and act on different spatial and temporal scales. Modelling has significantly improved since the first simulations were conducted on the effect of SSTs in the 1980s. Even though SSTs have been identified as the main driver of interannual and interdecadal rainfall variability, their contribution has not fully been identified thus far. The same is valid for the relative importance of Indian, Atlantic and Pacific Ocean. Although most models could identify the Indian Ocean as the main control, others find the role of the differential heating of the Atlantic most important. In any event do they affect Sahelian precipitation on different spatial and temporal scales. In order to shed light on these questions, the processes that govern the relationship between SST changes and Sahel precipitation anomalies have to be understood.

Models forced with changes in SSTs only typically fail to reproduce the observed magnitude in precipitation changes. The importance of land-atmosphere feedbacks for amplifying or dampening the SST forcing is undisputed; however, due to the amount and complexity of processes involved, their direction and magnitude cannot be identified unequivocally. This stands in contrast to early studies that emerged in the 1970s, claiming that soil and vegetation dynamics due to land degradation are the main driving force behind precipitation change. However, the effect of humans in the Sahel has been overestimated in a lot of studies.

It has to be noted that despite the severity of the past drought events, they seem to be within the range of natural climate variability and were not unusual or extreme when seen from a palaeoclimatic perspective. However, as mentioned above, the lack of recorded meteorological data makes it unfeasible to quantitatively compare the recent drought period with droughts prior to the 20th century.

Apart from natural variability, anthropogenic factors have been found to play a role in affecting both the change in SSTs and precipitation trends. Today, their impact is likely to come second to natural drivers, but is probably going to grow in the future together with a rising abundance of GHGs. Their role adds an interesting aspect to the question of driving forces, as their effect is superimposed on the global and local natural variability. Therefore it is difficult to disentangle the anthropogenic from the natural effect. One should be careful attributing the trend reversal and recent recovery in rains to a GHG signal, as it is only a very recent phenomenon occurring since the 1990s, in a region that is subject to strong decadal variability anyway. Also, future GHG concentrations will be higher than ever before, so there are no past periods to compare the possible reaction of the climate system with.

The external forcings of SSTs and GHGs is not equally strong across the whole region – it may well be strongest in the western Sahel, possibly because it is the region with highest precipitation values. This is also why many regional studies focus on this area.

The uncertainty about driving forces of the past and the present persists into the future. The reasons for a variation in projections are manifold, and it cannot be said with certainty whether a drying or an improvement in rains persists in the 21st century. Some models also simulate a trend reversal in the middle of the 21st century, switching from increasing precipitation values to a profound decline. In any case, the future trajectories of the individual ocean basins will certainly play a significant role in determining the future of Sahelian rainfall. The difficulties that remain are that the future of the oceans cannot be predicted with certainty and that even probable scenarios do not necessarily provoke a linear response of Sahelian rainfall patterns. Other factors

that interplay are how the land-ocean temperature contrast will develop and how it will affect the monsoon and the moisture supply of the continent.
The divergent results of the various studies imply that there is neither a simple answer to the question, nor can one driving force alone be made responsible for the Sahel drying.

Uncertainties in defining the driving forces behind vegetation dynamics
In the same way that drought was once mainly attributed to human land-use, the vegetation decline in the 1970s and 1980s was believed to have primarily anthropogenic origins. Although humans possibly play their part, the main reason has been found to lie in the rainfall decrease of these decades. Likewise can the recent greening trend be attributed to the recovery in precipitation. Correlation studies have convincingly demonstrated the links between vegetation and rainfall, just as they ruled out a dominating human influence. This shows that the semi-arid ecosystems are adapted to fluctuations in rainfall and are capable of recovering after pronounced drought periods. It also contests the widespread opinion that deserts are expanding due to anthropogenic pressures. However, observational and modelling studies have shown that the vegetation seems to lag behind external forcings. It declined or regrew sometime after changes in precipitation and CO_2, whereas the period of the lag depends on the forcing: about one year for precipitation, a couple of decades for possible future levels of CO_2. That emphasizes the relative importance that these two forcings have for the vegetation. Precipitation changes have the greatest impact, whereas CO_2 changes only have a small impact. The unsure future of Sahelian precipitation is also reflected in the vegetation cover. Natural and anthropogenic drivers put the Sahara/Sahel zone in a situation of bistable states, where a green Sahara like in the Holocene would be possible. Although this hypothesis might seem surprising at first, it fits well in the context of large climate variability and the multitude of factors determining the climate of the region.

The greatest difficulty lies in trying to evaluate the differing model results and drawing conclusions about the relative impacts of the various driving forces behind droughts and vegetation dynamics. Only when the processes that govern the present conditions are understood can a range of possible future climate scenarios be made. These are the basis for working out adaptation strategies to face climate variability and climate change, which are necessary for securing the water and food supply for millions of people in the Sahel. Through the spread of knowledge among scientists, governments, NGOs and foreign aid donors can then famines such as the one following the major past drought be prevented in the future. When looking for ways towards a sustainable agriculture, traditional land use practices should be considered, as they are adapted to conditions of sparse water resources. The impact of drought events on societies depends on their vulnerability or ability to face the decline in precipitation. In that context it is of particular importance to understand how the local feedback mechanisms work. Since one cannot take influence on the main driving force of drought (SST changes), a possibility in actively modifying the severity of the drought is for instance through increasing the vegetation cover, which is being done through multilocal reforestation efforts.

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