KEY FACTORS IN AFRICAN CLIMATE CHANGE EVALUATED BY A REGIONAL CLIMATE MODEL

With 15 figures and 1 table

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Zusammenfassung: Regionale Klimamodellierung zur Evaluation der Hauptfaktoren einer voraussichtlichen Klimaänderung in Afrika

Ausgeprägte Niederschlagsvariabilität und geringe Frischwasserverfügbarkeit stellen eine fundamentale Einschränkung für die Wirtschafts- und Ökosysteme Westafrikas dar. Vor dem Hintergrund einer stetig wachsenden Bevölkerungsdichte und eines zunehmenden Bedarfs an landwirtschaftlichen Produkten ist ein besseres Verständnis der klimatischen Prozesse, welche die Gesamtmenge und räumliche Verteilung des Niederschlages im tropischen und subtropischen Afrika bedingen, von entscheidender Bedeutung. Die vorliegende Arbeit widmet sich den Hauptakteuren der Klimavariabilität und zielt dabei insbesondere auf die zukünftigen Veränderungen des afrikanischen Klimas ab. Ein regionales Klimamodell wird über Afrika eingesetzt, um die individuellen Auswirkungen von veränderten Meeresoberflächentemperaturen (SSTs), steigenden Treibhausgaskonzentrationen (GHG), Vegetationsrückgang und Bodendegradation zu quantifizieren und miteinander zu vergleichen. Die Validation des regionalen Modells zeigt eine exzellente Übereinstimmung zwischen Simulation und Beobachtungsdaten während der letzten 20 Jahre. Insbesondere die Monsunzirkulation und Niederschlagsverteilung sind weitestgehend realistisch reproduziert. Die Niederschlagsvariabilität wird in erster Linie durch SST-Anomalien in den tropischen Ozeanen hervorgerufen. Dabei induzieren warme tropische SSTs allgemein mehr Niederschlag über den Küstenstreifen West- und Ostafrikas, während in der Sahelzone und im Kongobecken trockenere Bedingungen vorherrschen. Da ein verstärkter Treibhauseffekt eine direkte Aufheizung der tropischen Ozeane impliziert, ist zu erwarten, dass die globale Erwärmung exakt dieses Muster der Niederschlagsänderungen im tropischen Afrika bis zum Ende des 21. Jahrhunderts verursachen wird. Eine Verringerung der Vegetationsbedeckung wirkt diesem Strahlungsantrieb in vielen Regionen entgegen, indem im gesamten Modellgebiet eine Verringerung der Niederschlagsmenge simuliert wird. Eine mit der Vegetationsdegradierung in Zusammenhang stehende Veränderung der Bodeneigenschaften verstärkt diesen Effekt zusätzlich. Von großer Relevanz für die Einleitung von politischen Maßnahmen zum Klimaschutz ist die Tatsache, dass eine lokale Veränderung der Landoberfläche auch eine lokale Anomalie im hydrologischen Zyklus verursacht.

Summary: Rainfall variability and scarce freshwater availability represent the major limiting factors for West African economies and ecosystems. Given a remarkable increase in population density and agricultural needs, it is of basic importance to improve our knowledge of the climatic processes, which affect the amount and distribution of rainfall over tropical and subtropical Africa. The present study is dedicated to the main players in African climate variability with special emphasis on future climate changes. A regional climate model is run over Africa in order to quantify and compare the individual effects of oceanic heating, greenhouse forcing, vegetation loss and soil degradation with each other. The numerical model is found to reproduce the recent climate in excellent agreement with the observations. In particular the simulated monsoon circulation and rainfall distribution are most realistic. Rainfall variability is primarily related to changes in the tropical sea surface temperatures (SSTs). A warm oceanic surface is generally associated with abundant rainfall in the coastal areas of tropical West and East Africa, whereas drier conditions prevail over the Sahel Zone and the Congo Basin. Since increasing greenhouse-gas (GHG) concentrations directly heat up the tropical oceans, global warming is likely to induce exactly this pattern of precipitation anomalies at the end of the 21st century. A reduction in vegetation cover is partly counteracting the GHG forcing with deficient rainfall over the entire subcontinent. Related changes in the soil properties additionally contribute to a deterioration of freshwater availability. A local change in land cover is directly linked to a local anomaly of the hydrological cycle – a matter which is of high relevance to political measures and planning.

1 Introduction

Large parts of tropical and subtropical Africa are characterized by a limited natural potential (ACHENBACH 1994). Among the physical causes the crucial limiting factor is deficient freshwater availability due to intense rainfall variability at various time scales (NICHOLSON 1993; SPITTLER 1994; HERBERS 1999). The most prominent feature in recent African climate was the severe drought period between the 1960s and the late 1980s (NICHOLSON 2001; LE BARBÉ et al. 2002), which implied enormous economic loss (BENSON a. CLAY 1998), large-scale migration processes (FINDLEY 1994; RICHTER 2000) and irreversible land degradation (MENSCHING 1993; HAMMER 2000). These partly disastrous processes are tied to a complex interaction between climatic, social and economic factors (ACHENBACH 1994; SPITTLER 1994; BRAUN a. SCHOLZ 1997; STURM 1999; HAMMER 2000). Beside the drought years, severe floods after heavy rainfall events represent a further problem in tropical and subtropical Africa, causing soil erosion, damage and even loss of life (RICHTER 2000; BALZAREK et al. 2003). From a demographic point of view life conditions in tropical Africa are supposed to deteriorate progressively into the 21st century, given the strongest population growth on earth (ZECH 1997; SCHULZ 2001; ULRICH 2001) and accelerated urbanization (GAEBE 1994). Thus, great importance is assigned to the future availability of freshwater in Africa.

After the prominent drought period during the second half of the 20th century, rainfall is partly recovering since the 1990s (NICHOLSON et al. 2000). The basic question concerns the future behaviour of African precipitation: will climate become more humid, as indicated in the most recent years, or return to frequent drought periods, as observed between 1960 and 1990? The prediction of future changes in the hydrological cycle is a prerequisite for any kind of political measurements and planning, for instance in the form of reforestation and emission protection (ANHUF et al. 2000; GEROLD 2002). Thus, improved knowledge of the key factors, like greenhouse warming and land degradation in African climate variability and change, is required in order to provide a scientific basis for national down to local decision makers. Beside this climatological time scale, seasonal forecast of precipitation is also a scientific challenge with great relevance to agriculture and food security (GARRIC et al. 2002; MO a. THIAW 2002).

Many processes in tropical climate and especially the interactions with the land surface are taking place at the local to regional spatial scale (SAHA a. SAHA 2002). Thus, global climate models, which are designed to distinguish between the variety of key factors in global climate, are not appropriate to describe these small-scale processes in the low latitudes of Africa. More regional insight can either be gained by statistical down-scaling approaches, using statistical relationships between rainfall and surface parameters like elevation, exposure and land cover (GOLDBERG a. BERNHOFER 2000), or by dynamical down-scaling in the form of regional climate models (VIZY a. COOK 2002). The large need for regional climate modeling studies with respect to African climate change has recently been expressed by DESANKER and JUSTICE (2001) and JENKINS et al. (2002). The benefit of regional climate models for hydrological applications is further mentioned by LEBEL et al. (2000).

In addition, the application of a regional climate model is a basic requirement, when determining the role of various impact factors in African climate change. On the one hand, the station data cover is largely insufficient in Africa for climatological studies at the regional scale. On the other hand, observed climate variability is simultaneously affected by different mechanisms, including internal noise due to the stochastic nature of the atmosphere and external factors such as changes in solar irradiation, volcanic activity, interactions with the ocean surfaces, and finally anthropogenic emissions of GHGs and sulphate aerosols (HOUGHTON et al. 2001). A reliable separation of these impact factors is not possible in real-climate data sets. The best tool is to make a climate model operating, which solves the known equations of all basic processes in the climate system, as for instance atmospheric motion, mass and temperature distribution, radiation budget and hydrological cycle. This model can be run under specific assumptions like land cover changes or increasing GHG concentrations, whereas the remaining external factors in climate variability are kept constant. By means of such sensitivity experiments with isolated forcing parameters, the relative importance and effect of the key factors in climate change can be quantified and compared with each other. With respect to tropical and subtropical Africa, many climate processes and interactions with the land surface are taking place at the regional to local scale (SAHA a. SAHA 2002). Thus, state-of-the-art global climate models, which are usually based on a 300 km grid point resolution, are barely appropriate to account for the full variety of spatial scales involved in African climate change. Therefore, this study relies on a regional climate model. So far, only one dynamic down-scaling approach over tropical Africa has been published (VIZY a. COOK 2002). However, this model was only integrated over a three-month period and at a much coarser resolution.

The regional climate model in the present study covers most of the African continent, the Mediterranean region, southern Europe and the Arabian Peninsula. The modelling approach basically addresses two main issues: (1) Given the insufficient availability of observational data in large parts of Africa, the regional climate model is used to reproduce the recent climate. Provided that the model is able to simulate African climate in a realistic way, the computed three-dimensional, complete and consistent data can enter various kinds of applications as for instance high-resolution climatological analysis, hydrological modelling and vegetation studies. Therefore, a considerable part of this paper is dedicated to the validation of the regional model, including an extensive description of the phenomena and processes associated with the West African monsoon system. (2) Several key factors are evaluated by sensitivity experiments with the regional climate model. The aim is to separate the effects of SST changes, increasing GHGs, vegetation loss and soil degradation from each other and to determine their quantitative contributions to the expected future changes in rainfall amount and distribution over tropical and subtropical Africa. The relatively high spatial resolution of the climate model affords a detailed insight into the regional nature of the climate change signals. Thus, the simulation results are supposed to supply a suitable basis for political and agricultural measures in the 21st century at the national and regional scale. Improving our knowledge of how and where the effects of land use changes and global warming on African precipitation anomalies may be counteracting or intensifying each other, is of crucial importance to effective and expedient protection measures. Therefore, the major part of this paper is concerned with the quantification and comparison of the individual impacts of land degradation and radiative heating on future changes in African rainfall.

In the following section, a variety of important key factors is presented as revealed by previous studies mainly based on observational data and global climate models. Section 3 introduces the regional climate model under consideration. Section 4 gives a detailed survey of all model experiments. Some prominent observed characteristics of African precipitation during the 20th century are discussed in section 5. Section 6 describes the model validation and some basic features of the African monsoon circulation, whereas the sensitivity studies are addressed in section 7. All results are summarized and discussed in section 8.

2 *Important players in African climate*

There are a number of studies dealing with rainfall fluctuation over Africa in the context of various climate components and processes. Whereas the northern and northwestern parts of Africa are closely tied to extratropical ocean basins and atmospheric phenomena like the North Atlantic Oscillation (NAO) (Cullen a. de Menocal 2000; Los et al. 2001; Rodriguez-Fonseca a. de Castro 2002; Rowell 2003), sub-saharan West Africa is mainly affected by tropical sea surface temperatures (SSTs) (Palmer et al. 1992; Sutton et al. 2000; Chang et al. 2000; Camberlin et al. 2001). This region is characterized by a prominent monsoon system with a dry north-westerly flow in boreal winter, named Harmattan, and south-westerlies with advection of humid air masses, large-scale atmospheric instability and deep convection in summer (Saha a. Saha 2001). In general, oceanic heating in the tropical Atlantic is coming along with more abundant precipitation during the summer rainy season in the southernmost part of West Africa, covering the coastal area along the Gulf of Guinea (Ruiz-Barradas et al. 2002; Paeth a. Hense 2003a). Simultaneously, the Sahel Zone is subject to more arid conditions (Mo et al. 2001; Paeth a. Stuck 2003). This dipole structure in African rainfall variability has already been reported by Nicholson and Palao (1993) and will be shown to represent a crucial quantity in future climate change. Vizy and Cook (2001) have given a physical explanation of the opposing rainfall anomalies over the Guinea Coast and the Sahel Zone, referring to a complex atmospheric wave response to the tropical heat source. Furthermore, there is also a teleconnection to the El Niño-Southern Oscillation (ENSO) phenomenon in the eastern tropical Pacific (Nicholson et al. 2000; Janicot et al. 2001). Usually, warm events (El Niño) are associated with less monsoonal rainfall over southern West Africa. This remote response is governed by the Walker circulation and a time-delayed anomaly in the tropical Atlantic (Latif a. Grötzner 2000). The Sahel Zone is again reacting in the opposite way, emphasizing the existence of a dipole feature in African rainfall fluctuations (Saravanan a. Chang 2000). In addition, large parts of tropical East Africa are affected by SSTs in the Indian Ocean (Black et al. 2003). Thus, African rainfall variability is largely embedded in the anomalies of the tropical ocean basins.

There is also some indication from global climate model simulations that increasing greenhouse-gas (GHG) concentrations may play a role in recent and future climate over West Africa (Hulme et al. 2001; Paeth a. Hense 2003b). Radiative heating is supposed to warm up the tropical Atlantic, which in turn intensifies the African summer monsoon circulation via enhanced latent heat fluxes into the atmosphere, surface wind convergence and deep convection over the southern part of West Africa. In the opposite, the subtropical dry belt will probably experience more arid conditions in the context of global warming, inducing a general strengthening of the subtropical anticyclones (Houghton et al. 2001; Paeth a. Stuck 2003).

It has been suggested by several authors that the prevailing droughts during the second half of the 20th century were at least partly caused by the remarkable land cover changes in tropical and subtropical Africa (Zeng a. Neelin 2000; Pielke 2001; Semazzi a. Song 2001; Zeng et al. 2002). Sahelian rainfall especially appears to be closely tied to vegetation cover (Wang a. Eltahir 2000; Lotsch et al. 2003), whereas the Guinea Coast region is less sensitive due to the compensating effect of stronger near-surface wind convergence and deep convection (Clark et al. 2001). Satellite data reveal a distinct relationship between the occurrence of drought years in the Sahel Zone and vegetation (Eklundh a. Olsson 2003). Changes in vegetation cover basically affect the energy balance at the land surface, including albedo and radiation budget as well as latent and sensible heat fluxes into the atmosphere (Bounoua et al. 2000). In addition, soil moisture, surface run-off and the turbulent mixing in the atmospheric boundary layer are modified. Van den Hurk et al. (2003) have described the positive correlation between the leaf area index (LAI) and the seasonality of rainfall in many tropical and subtropical regions of the globe. Of course, the relationship between rainfall and vegetation cover is fully interactive – a feature which is so far barely represented in state-of-the-art climate models (Dirmeyer 2000; Zeng a. Neelin 2000; Pielke 2001; Schnitzler et al. 2001).

Soil moisture is a further key factor in African climate. In general, increasing soil moisture favours the formation of rainfall at the local to regional scale through intensified latent heat fluxes. The African monsoon is much more sensitive than, for instance, the Indian subcontinent (Douville et al. 2001). Fontaine et al. (2002) have even revealed a lead-lag relationship between the West African rainy season and preceding soil moisture anomalies. An indirect impact via the African Easterly Jet (AEJ) has been described by Cook (1999).

Although these studies tend to blame human activity to be responsible for the severe drought period since the 1960s, proxy-data from paleo-studies indicate that comparable dry conditions already occurred in former times, for instance in the early 19^{th} century (Nicholson 2001). The strong response of African rainfall to solar variability, and hence natural players in the climate system, during the holocene has also been reported by Texier et al. (2000) and Gasse (2001). Thus, the detection of individual influences on the African monsoon variability is quite complex. Meanwhile most authors agree that rainfall fluctuations are primarily imposed by changes in the tropical SSTs and secondarily enhanced by numerous feedbacks with the land cover, involving vegetation, soil moisture and surface albedo (Zeng et al. 1999; Long et al. 2000). These interactions imply an intensification of the rainfall variations with respect to the amplitude and the duration (Nicholson 2001). In fact, the Sahel Zone is characterized by the most pronounced persistence of climate anomalies within the African continent (Long et al. 2000). As mentioned above, GHG emissions may additionally complicate this picture.

From this discussion it is obvious that an objective analysis of African climate change is required to account for all those impact factors. In particular, the relative effects of land degradation and greenhouse warming need to be evaluated and compared with each other (Douville et al. 2000). In terms of Chinese and European climate, Zhao and Pitman (2002) have found that land use changes and radiative heating induce climate anomalies in the same order of magnitude. On the other hand, the impact of soil degradation in Africa is minor compared with global warming (Feddema a. Freire 2001). In contrast to most previous works, the present study can rely on a regional climate modelling study of the key factors in African climate variability and change.

3 Model description

The regional climate model considered here is called REMO (Jacob 2001; Jacob et al. 2001). It has been developed and put forward at the Max-Planck-Institut für Meteorologie in Hamburg at the basis of the former operational weather forecast model "Europamodell of the Deutscher Wetterdienst" (Majewski 1991). The dynamical core consists of simple equations, which compute temperature, surface pressure, horizontal wind components, cloud water content and water vapour as prognostic variables. REMO is a so-called hydrostatic model, implying that simplified diagnostic, instead of prognostic, equations for the vertical wind velocity and the mass budget are used (Kraus 2001). These model equations are solved on a geographical grid with 0.5° resolution, covering most of the African continent from 30°W to 60°E and from 15°S to 45°N. REMO is composed of 20 vertical atmospheric levels up to the lower stratosphere. These levels are terrain-following near the surface and analogous to pressure levels in the upper atmosphere. The typical integration step is 5 min.

Atmospheric processes like deep convection, cloud formation and convective precipitation are subgrid-scale and hence not resolvable at the 0.5° model grid. Therefore, physical parameterizations are usually implemented in global and regional climate models. Such parameterizations are based on empirical knowledge of the processes for instance from detailed observational studies and high-resolution measurements (Tiedtke 1989). In this case, the atmospheric parameterization schemes are derived from the global climate model ECHAM4 (Roeckner et al. 1996) and adjusted to the 0.5° resolution of REMO. Soil processes are represented by a 5-layer soil model, which extends down to 10 m depth and computes fully interactive soil temperature profiles, soil moisture, snow pack over land, infiltration and surface runoff. Note that no lateral flow of ground and surface water is simulated. Thus, there is no horizontal communication between the grid boxes in the soil layers, rather surface run-off and drainage are directly assigned to the nearest ocean grid point in order to close the hydrological cycle.

In contrast to global climate models, a regional model requires input data at the lateral and lower boundaries. In all considered model experiments, REMO is forced with analysis and reanalysis data from the European Centre of Medium-range Weather Forecast (ERA15), which are available for the period 1979 to 2004 (GIBSON et al. 1997). (Re)analysis data are based on all available observational data from climate stations, radiosondes and satellites, which enter an operational weather forecast model. The resulting three-dimensional and globally complete data sets, albeit originating from a numerical model, are considered to represent the observed climate in a most realistic way. The SSTs as oceanic lower boundary conditions are also taken from the ERA15 data. Land surface parameters like orography, vegetation cover, albedo, roughness length, and soil properties are derived from NOAA satellite observations and the GTOPO30 data set, respectively. Although an idealized annual cycle of the surface parameters is prescribed, especially in terms of vegetation, no inter-annual changes in the land cover are taken into account in the normal climate mode. However, the sensitivity studies are subject to altered surface and soil parameters (see section 4). For all experiments, REMO is once at the beginning initiated by the ERA15 data at every model grid box. Then, the global ERA15 input data are prescribed every 6 hours only at the lateral and lower boundaries. Given the large model domain over 90° of longitude and 60° of latitude, REMO can thus develop its own dynamics in the interior of the simulation area, computing the atmospheric processes at the synoptic spatio-temporal scale (JACOB 2001).

A prerequisite for reliable sensitivity studies is that REMO is able to reproduce the observed climate in a realistic way. Therefore, a sophisticated validation attempt is made with respect to various observational data sets. The simulated large-scale dynamics are compared with the ERA15 quasi-observational data (GIBSON et al. 1997). The monthly rainfall and cloud characteristics refer to the Climatic Research Unit (CRU) data, which are based on a statistical interpolation of all available station data between 1901 and 1998 and build a regular grid over all land masses except Antarctica (NEW et al. 2000). POCCARD et al. (2000) have demonstrated that this data set better represents the observed rainfall variability over West Africa than re-analysis products. Finally, a data set of daily precipitation in 1991 is provided by the Institut de la Recherche et de Développement (IRD) for large parts of sub-saharan Africa (DIEDHIOU et al. 2001).

4 *Experimental design*

An overview of all realized model experiments is given by table 1. One long-term simulation and four sets of sensitivity runs are carried out. All realizations are run in 0.5° resolution over the entire model area mentioned above and driven by the ERA15 data at the lateral boundaries. The model period 1979 to 1993 is forced with re-analysis data, whereas analysis data are prescribed for the more recent period. The difference between both observational data sets is that the re-analyses are based on the same numerical model, re-run over the whole period of available observations, while the analyses are computed with progressively updated versions of the weather forecast model in the operational service. At the surface the input data are also derived from ERA15 and NOAA satellite observations. For the sensitivity studies these lower boundary conditions are modified, according to specific scenarios described below.

The long-term climatology extends from January 1979 to January 2004 and is continuously updated, as soon as the ECMWF analysis data is available. This experiment is required to reproduce the observed climate features over Africa in a realistic way. Therefore, the most realistic input data are prescribed. In addition, the convection scheme of REMO is tuned in order optimally to fit the observed rainfall characteristics (PAETH et al. 2003). The validation attempt in terms of the ERA15, CRU and IRD data mainly refers to this long-term simulation. Given the limited availability of the IRD data, 1991 is chosen as the reference year of validation. However, other simulated years show the same skill and deficiencies.

The first sensitivity study is dedicated to the role of SST anomalies in the tropical and subtropical oceans. Four experiments are integrated over the rainy season period July–August 1988, prescribing progressive warming and cooling once in the tropical Atlantic and Indian Ocean once at the subtropical ocean surfaces within the REMO domain. This kind of idealized SST forcing is not suitable to determine a realistic climate anomaly, but to detect the general response of African rainfall, temperature and circulation to changes in the adjacent ocean basins. In addition, the most relevant SST regions can be defined.

The GHG experiments are set up similarly: given the prior knowledge that global greenhouse warming

Table 1: Overview of the conducted model experiments with the regional climate model REMO with corresponding integration periods, horizontal resolution, forcing data at the lateral margins and prescribed land and sea surface conditions

Überblick über die durchgeführten Modellexperimente mit dem regionalen Klimamodell REMO mit zugehörigen Integrationszeiträumen, horizontaler Auflösung, Antriebsdaten an den seitlichen Rändern und vorgeschriebenen unteren Randbedingungen über Land und über Meer

Experiment	Integration period	Resolution	Lateral boundary conditions	Surface boundary conditions
"Present-day" climate	01'79 – 01'04	0.5°	ECMWF reanalysis	ECMWF re-analysis, NOAA
SST forcing	07'88 – 08'88	0.5°	ECMWF reanalysis	(sub)tropical oceans –2°C (sub)tropical oceans –1°C (sub)tropical oceans +1°C (sub)tropical oceans +2°C
GHG forcing	07'87 – 08'87 07'88 – 08'88 07'90 – 08'90	0.5°	ECMWF reanalysis	GHG-induced SST changes
Vegetation loss	05'91 – 10'91	0.5°	ECMWF reanalysis	vegetation cover –25% vegetation cover –50% vegetation cover –75% vegetation cover –100%
Soil degradation	05'91 – 10'91	0.5°	ECMWF reanalysis	strong soil parameter change weak soil parameter change

may primarily heat the tropical oceans (Houghton et al. 2001; Paeth et al. 2001), SST changes are derived from a global climate model simulation with the coupled atmosphere-ocean model ECHAM4/OPYC3 (Roeckner et al. 1996). This global run is subject to increasing GHG concentrations between 1860 and 2099. Before 1985 observed GHG changes are implemented in the model, afterwards a constant annual growth rate of almost 1% is prescribed, according to the so-called business-as-usual scenario of the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al. 2001). It is assumed that the global climate change experiment provides a reasonable estimate of the SST fields under radiative heating at the end of the 21st century. Paeth et al. (2001) have demonstrated that the greenhouse forcing may account for up to 90% of the future SST changes in the tropical oceans. These strongly affected SST fields are interpolated to the REMO grid and used as lower boundary conditions during three July–August simulations with REMO. The results are suggested to represent the basic response of African climate to global warming via the oceanic surfaces at the end of our century. Note that no changes in GHG concentrations are implemented in the REMO atmosphere. This deficiency is minor, since it is likely that tropical African rainfall is predominantly governed by changes in the tropical SST field rather than directly by atmospheric GHG concentrations (Paeth a. Hense 2003b). The GHG experiments are carried out for three years with different lateral input data (Tab. 1), in order to account for uncertainties in the initial and lateral boundary conditions, and can be understood as a kind of ensemble approach for GHG-related African climate change. Such ensemble experiments are a general requirement of state-of-the-art climate change analyses, distinguishing between internal stochastic variability, for instance imposed by varied initial conditions, and an interpretable climate change signal (Paeth a. Hense 2002).

One main issue of the present study is to compare the effects of future greenhouse warming and land use changes. Previous studies have shown that climate in tropical Africa is particularly sensitive to variations in the vegetation cover and soil moisture (e.g. Wang a. Eltahir 2000; Clark et al. 2001; Douville et al. 2001; Feddema a. Freire 2001; Semazzi a. Song 2001). Especially the scarce vegetation in the Sahel Zone and the rain forests in tropical Africa are threatened by increasing acquisition of land for agriculture and pasture-ground. Illegal settlements with shifting cultivation and animal grazing cause considerable damage in the original vegetation cover. So far, many authentic woodlands have disappeared or degraded. Moreover, the Sahel Zone is undergoing a large-scale desertification process (MENSCHING 1993; HAMMER 2000), which, however, is partly natural (TEXIER et al. 2000). Against the background of excessive population growth, these negative developments are expected to intensify into the 21st century. In terms of African climate, a reduction in vegetation cover is associated with multiple effects in nature and in the regional climate model (JACOB et al. 2001): (1) the surface albedo rises with implications for the radiation budget and the energy balance at the land surface. (2) The Bowen ratio, describing the ratio between sensible and latent heat fluxes, is modified. In general, transpiration and interception by plants are reduced remarkably and hence total evaporation from the land surface is fairly dimished. Furthermore, the heat and moisture budget in the soil model are affected, with negative consequences for soil moisture and evaporation from soils. (3) The roughness length, which is a measure of the frictional effect of land surfaces and responsible for the turbulent fluxes and exchanges in the atmospheric boundary layer, is largely reduced. In order to perform a realistic scenario of land cover changes, all these surface parameters have to be changed consistently.

REMO comprises 5 surface quantities, which are directly related to a change in vegetation cover. These are the vegetation ratio in a model grid box, the forest fraction, the LAI, the surface albedo and the roughness length. The land cover scenarios are composed of consistent changes in all those 5 parameters: The same reduction factor is applied to all of them except albedo. The changes in albedo are derived from a multiple linear regression (von STORCH a. ZWIERS 1999) on to vegetation ratio, forest fraction and LAI. Four experiments with progressive land degradation are realized, amounting to 25, 50, 75, and 100% vegetation loss with respect to the present-day conditions (Tab. 1). Aside from this, the 4 simulations are subject to the same SST and atmospheric input data and cover the period May–October 1991. The vegetation loss is equally applied to all land grid boxes in the model domain. Thus, the spatial heterogeneity of land use changes along rivers, roads, axes of settlement and regions with high soil fertility is not taken into consideration, since future estimates of these processes are barely available. Note that vegetation in REMO is not fully interactive. Thus, atmospheric anomalies can not feedback on to the vegetation cover.

The last set of sensitivity experiments concerns the soil degradation. Changes in the vegetation cover are also affecting the soil hydrology, i.e. soil moisture and the ratio between infiltration, drainage and surface run-off. While soil moisture is fully interacting with the REMO atmosphere and directly influenced by the vegetation parameters, drainage, infiltration and surface run-off are governed by soil parameters, which are usually kept constant in the regional climate model (JACOB 2001). However, these soil properties are assumed to be also modified, especially if land cover changes are persisting over longer periods (HAMMER 2000; GEROLD 2002). In order to access the response of African rainfall to vegetation-related soil degradation, 2 REMO experiments have been conducted, covering the period May–October 1991 (Tab. 1): both runs only differ in terms of the magnitude of changes in the soil parameters. The modifications can be summarized as follows: surface run-off is enhanced, drainage is accelerated and infiltration decreases. In addition, the wilt point rises, implying that soil water is less available to the transpiration by plants. Vegetation cover is kept at the present-day level in order to isolate the impact of soil degradation.

5 Observations of 20th-century African climate

The most prominent feature in African climate has been the severe drought period during the second half of the 20th century (NICHOLSON 2001; LE BARBÉ et al. 2002), which has excited much scientific and political attention, especially to the Sahel Zone with its low natural potential (MENSCHING 1993; ACHENBACH 1994). The time series of seasonal-mean precipitation (June–September) averaged over the Sahel Zone (15°W–20°E; 12°–21°N) and the Guinea Coast region (15°W–20°E; 4°N–12°N) are depicted in figure 1. The values represent departures from the period 1961 to 1990 in mm. The black curves denote the 9-year running-mean low pass filtered time series. Both regions have been characterized by intense inter-annual rainfall variability throughout the last century. In addition, there are low-frequency variations at the decadal time scale. The most striking characteristic is the long-term negative trend after a period with abundant monsoonal rainfall in the middle of the 20th century. Extreme droughts have prevailed in the 1970s and 1980s. Afterwards, precipitation amount is slightly recovering, but still negative anomalies predominate (NICHOLSON et al. 2000). The amplitude of the year-to-year rainfall fluctuations is much higher near the Guinea Coast than in the Sahel Zone. However, the variational coefficient, relating the standard deviation to the mean (von STORCH a. ZWIERS 1999), indicates more important inter-annual variability in the Sahel Zone.

It has been suggested that the long-term sahelian drought tendency may be caused by anthropogenic land degradation due to agriculture and pasturage (WANG a. ELTAHIR 2000; CLARK et al. 2001). Nonetheless, there is some evidence that this view is too simple: first, the Guinea Coast region has also experienced a substantial reduction in total rainfall amount, although land degradation occurred to a much lower extent (LE BARBÉ et al. 2002). Second, global climate model experiments with prescribed observed SSTs are found to reproduce the negative rainfall trend over subsaharan West Africa in-phase with the observations, even if the models are not aware of any land cover changes (e.g. PALMER et al. 1992; SUTTON et al. 2000; PAETH a. HENSE 2003b). Thus, the oceanic surfaces appear to be a main player in the African monsoon system. However, it is likely that land cover changes enhance the amplitude and persistence of the SST-induced climate anomalies in tropical Africa, since the same global climate models usually underestimate the magnitude of climate variability and trends (ZENG et al. 1999; LONG et al. 2000; SCHNITZLER et al. 2001). Third, given the ongoing population growth and land acquisition in tropical Africa, the recent recovery in rainfall amount is counter-intuitive. If this feature is not an expression of decadal-scale variability, it may be indicative of a new player in African climate change: anthropogenic GHG emissions (PAETH a. HENSE 2003b). Thus, previous studies suggest a variety of impact factors, which need to be evaluated and compared carefully at the regional scale. This is the basic motivation of the present study.

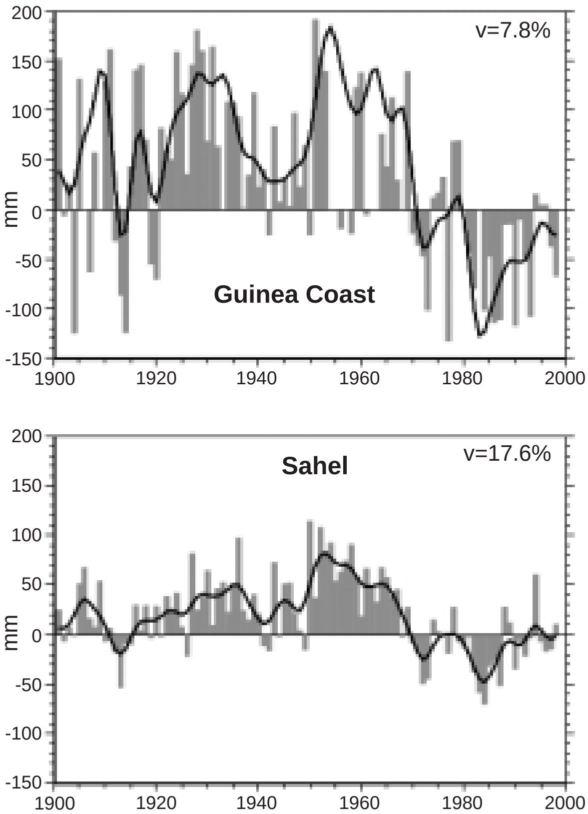


Fig. 1: JJAS mean (grey bars) and 9-year lowpass filtered (black curves) time series of observed rainfall in subsaharan West Africa as departures from the 1961–1990 mean. V denotes the variational coefficient

Saisonale (Juni–Sep.) (Balken) und 9-jährig tiefpassgefilterte (Linien) Zeitreihen des subsaharischen Niederschlages als Anomalien gegenüber der Klimanormalperiode 1961–1990. V bezeichnet den Variationskoeffizienten

In detail, the picture of observed rainfall variability is much more complex than that reflected by the two time series in figure 1. While a certain mechanism is associated with a more or less homogeneous precipitation decrease over entire subsaharan Africa, another characteristic of rainfall variability consists of a dipole response with opposing centres in the Guinea Coast region and the Sahel Zone (PAETH a. STUCK 2003). Such modes of African climate variability have also been differentiated by NICHOLSON and PALAO (1993). Since the Guinea-Sahel dipole governs the spatial gradients in freshwater availability over tropical Africa, it is of major interest to gain insight into the driving forces and the future behaviour of the dipole. In recent decades, this meridional gradient in rainfall amount has continuously strengthened over West Africa (PAETH a. STUCK 2003) and is supposed to have caused large-scale migration processes from the Sahel Zone to the more humid Guinea Coast region (FINDLEY 1994; RICHTER 2000). Therefore, this study is also focussed on the Guinea-Sahel dipole response in rainfall.

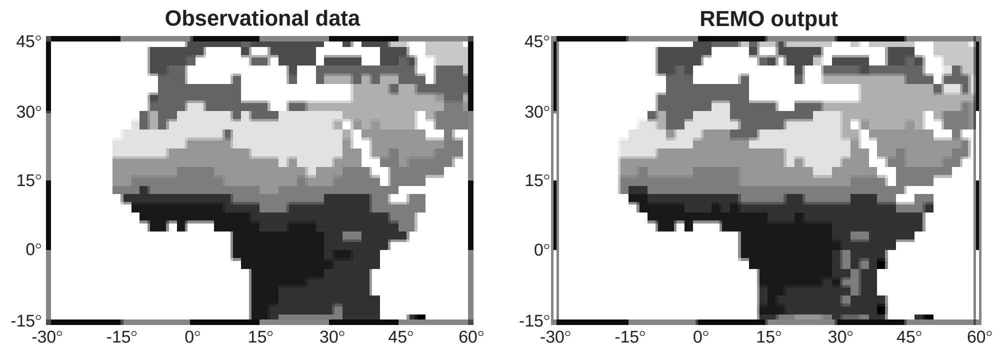
6 *Model validation*

6.1 Near-surface climate

Before addressing the sensitivity of African climate to all the impact factors mentioned above, it has to be ensured that the regional climate model REMO is able to provide a realistic description of the observed climate characteristics. Instead of comparing a multitude of individual patterns with each other, a cluster analysis is carried out, based on 7 basic parameters of near-surface climate over land: annual rainfall, surface temperature, annual temperature amplitude, mean cloud cover, sea level pressure (SLP), zonal and meridional wind near the surface (Fig. 2). All values except the annual rainfall sums represent annual means. The cluster analysis uses a centroid method and a subsequent correction with randomized regroupment (BAHRENBERG et al. 1992). The measure of distance is given by the Mahalanobis distance in order to account for inter-correlations between the 7 input parameters, like for instance between rainfall and cloud cover. For reasons of clarity, the original REMO grid is interpolated to a 2° × 2° λφ grid. The clusters are derived from the observational data, being composed of the CRU data (rainfall and cloud cover) and the ERA15 data (remaining variables). Afterwards, the REMO grid boxes are also classified into these clusters. 10 clusters have been chosen, taking care that each cluster is sufficiently represented by the data. 1991 is selected as reference year of the validation.

The table in figure 2 indicates the anomalies of each cluster from the overall spatial mean of each climate parameter within the model area. The grey shading is arranged from more humid climates (dark grey) to relatively arid climates (light grey). The distribution of the clusters is highly reminiscent of the typical climate classification by Köppen and Geiger (KRAUS 2001): in the inner tropics, humid and warm conditions with southwesterly winds prevail, whereas the central Sahara is characterized by extremely dry climate with above-average annual temperature amplitude, high SLP and north-easterly wind directions. Southern Europe experiences relatively humid and cool climate and the Carpathian mountains are subject to a cold climate with pronounced seasonal temperature variations.

At first sight, the simulated near-surface climate almost perfectly fits the observed clusters. Thus, REMO is able to simulate the observed distribution of climate parameters near the surface in an excellent way. PAETH and STUCK (2003) have shown that the correct classification of simulated grid boxes into the observed clusters has some statistically significant skill at the 1% error level. Note that the cluster analysis is based on one individual year, rather than a 30-year climatology. This means that REMO has some considerable skill in reproducing the observed African climate, not only with respect to the long-term climatology but also at the annual time scale. This finding leads to the question down to which time and spatial scale the simulated climate is



stand. anomaly:	PRE	T1000	Tampli	TCC	SLP	U1000	V1000
1	3.01	0.39	-1.21	1.10	1.07	-1.44	2.94
2	1.66	0.38	-1.32	1.61	-0.54	1.23	0.93
3	0.86	0.70	-0.95	0.70	-0.25	-0.27	0.84
4	0.38	-2.18	1.24	0.74	1.60	0.08	0.06
5	-0.44	-1.04	0.82	0.21	1.15	-0.12	-0.10
6	-0.33	0.78	-0.45	-0.24	-0.88	-0.03	-0.39
7	-0.84	0.62	0.25	-0.98	-0.65	-0.27	-0.79
8	-0.57	-0.29	0.80	-0.78	-0.26	1.46	-0.70
9	-0.72	-2.70	2.54	0.17	2.82	-1.05	0.14
10	-0.96	-0.26	0.67	-1.05	-0.60	-1.10	-1.32
spatial mean:	560.76	22.16	23.79	0.46	1013.42	-0.42	-0.57

Fig. 2: Cluster analysis of near-surface climate parameters based on the observational data in 1991 and associated cluster mean values of each surface variable

Cluster-Analyse auf Basis beobachteter bodennaher Klimaparameter im Jahr 1991 sowie die zugehörigen Cluster-Mittelwerte jedes Parameters in-phase with the observations (see following subsection).

6.2 Precipitation

Precipitation can generally be regarded as the most pretentious climate parameter to be simulated by climate models. This arises from the fact that cloud and rainfall processes are taking place at various spatial scales, which are often subgrid-scale. The cloud microphysics especially is far beyond the typical model resolution. Consequently, the formation of rainfall has to be parameterized by convection schemes. Thus, rainfall is the ultimative measure of model skill. Likewise, most climatological and hydrological applications in Africa are predominantly interested in precipitation data. Therefore, the typical time and spatial scales of the in-phase relationship between REMO and observations is demonstrated with the example of daily rainfall.

Figure 3 shows the spatial-mean coefficients of determination (squared correlation coefficient, von Storch a. Zwiers 1999) between simulated and observed daily rainfall in 1991 over the sub-saharan part of West Africa. The observational data set is provided by the IRD and based on rain gauge stations, which are interpolated to a regular 1° grid (Diedhiou et al. 2001).

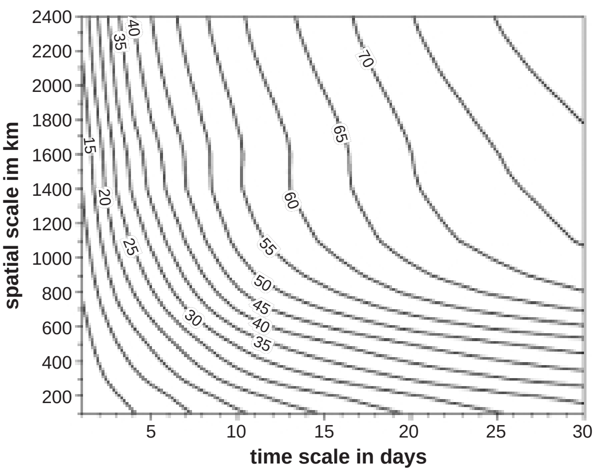


Fig. 3: In-phase relationship between observed and simulated rainfall in sub-saharan West Africa at different temporal and spatial scales in 1991. The values denote the coefficient of determination

Phasenbeziehung zwischen dem beobachteten und simulierten Niederschlag im subsaharischen Westafrika auf unterschiedlichen zeitlichen und räumlichen Skalen über das Jahr 1991. Dargestellt ist das Bestimmtheitsmaß

The axes denote different extents of spatial and temporal aggregation, starting from daily values and one 1° grid box up to monthly and large regional means. The more the regional model is able to simulate a rainfall event in-phase with the observations at a given spatio-temporal scale, the more variance is explained reciprocally. It is found that REMO does not simulate a specific rainfall event exactly on the right day and at the right location. However, monthly precipitation averaged over a larger area is in excellent agreement with the observations, the explained variance amounting to almost 85%, equivalent to a correlation coefficient of r = 0.92. A reasonable comparison is also possible, when considering monthly values at high spatial resolution or pentadal values at high spatial aggregation (up to 40% explained variance or r = 0.63). This result is neither surprising nor discouraging: given the large model domain of around 10,000 km × 6,500 km, it cannot be expected that each individual rainfall event is fully determined by the lateral boundary condition, which are used to drive the regional model. Rather REMO is free to perform its own dynamics over Africa, leading to realistic rainfall formation, but not exactly at the observed date and position. Thus, a regional climate model is not required to simulate all climate features exactly in-phase with the observations, but to reproduce the climatology of real climate, i.e. the long-term mean state and the variability. Such skill is sufficient for many climatological and hydrological applications. In the case of REMO, the model additionally provides monthly or regional-mean precipitation to be directly compared with the observational data sets. The model also simulates a most realistic seasonal cycle of rainfall and circulation (not shown).

An example for demonstrating the ability of REMO in simulating the observed annual sum and standard deviation of daily rainfall in 1991 is given by figure 4 for the sector of Morocco and western Algeria. This region is characterized by extremely low rain gauge station cover (data provided by P. Knippertz). It is obvious that the model fits the observed distribution and total values, as far as this is inferable from the sparse station data, remarkably well. Conclusively, REMO is a reliable tool in creating rainfall climatologies for applications, which require data with complete spatial distribution.

Case studies with REMO have also been found to simulate the inter-annual variability of sub-saharan precipitation (Paeth et al. 2003). However, the amplitude of the year-to-year fluctuatons is systematically underestimated. This is a typical deficiency of climate models and most probably related to the missing interaction with the vegetation cover (Zeng a. Neelin 2000; Schnitzler et al. 2001; Zeng et al. 2002). A further misjudgement of REMO is the under-estimation (over-estimation) of total rainfall amount over (off) the Guinea Coast region (PAETH et al. 2003). This model error is of systematic nature throughout the entire summer rainy season and likely due to the 0.5° grid box resolution of orography: when the moist and unstable air masses in the south-westerly summer monsoon flow are advected against the coast of West Africa, deep convection is abruptly initiated in the model due to an artificial topographic step. Fortunately this deficiency is systematic and can be corrected for instance by model output statistics (PAETH a. HENSE 2003a).

6.3 Atmospheric dynamics

The seasonal cycle in precipitation over tropical Africa is embedded in a complex three-dimensional monsoon circulation (SAHA a. SAHA 2001). Near the surface the seasonal displacement of the inter-tropical convergence zone (ITCZ) governs the distribution of rainfall over West Africa. A Hovmöller diagram of simulated and observed near-surface wind divergence with the x-axis referring to a day in year 1991 and the y-axis denoting the meridional cross-section at 0°E is illustrated in figure 5. For reasons of clarity, the values are running 5-day means and interpolated to a 2° grid. The reddish colours indicate the seasonal shift of a band with distinct wind convergence, extending from around 6°N in boreal winter to almost 23°N in summer. This band describes the ITCZ. In addition, there is a weaker band of wind convergence between the equator and the Gulf of Guinea coast. This double ITCZ has also been reported by HASTENRATH (2000). The tropical Atlantic ocean is characerized by subsidence and wind divergence (VIZY a. COOK 2001). Over the Sahara a heterogeneous picture with alternating small-scale cells of wind divergence and convergence prevails. The simulated near-surface wind divergence is in excellent agreement with the observed one. Even the double ITCZ is well captured by REMO.

Note that the position of the ITCZ is not consistent with the location of maximum rainfall amount. This is

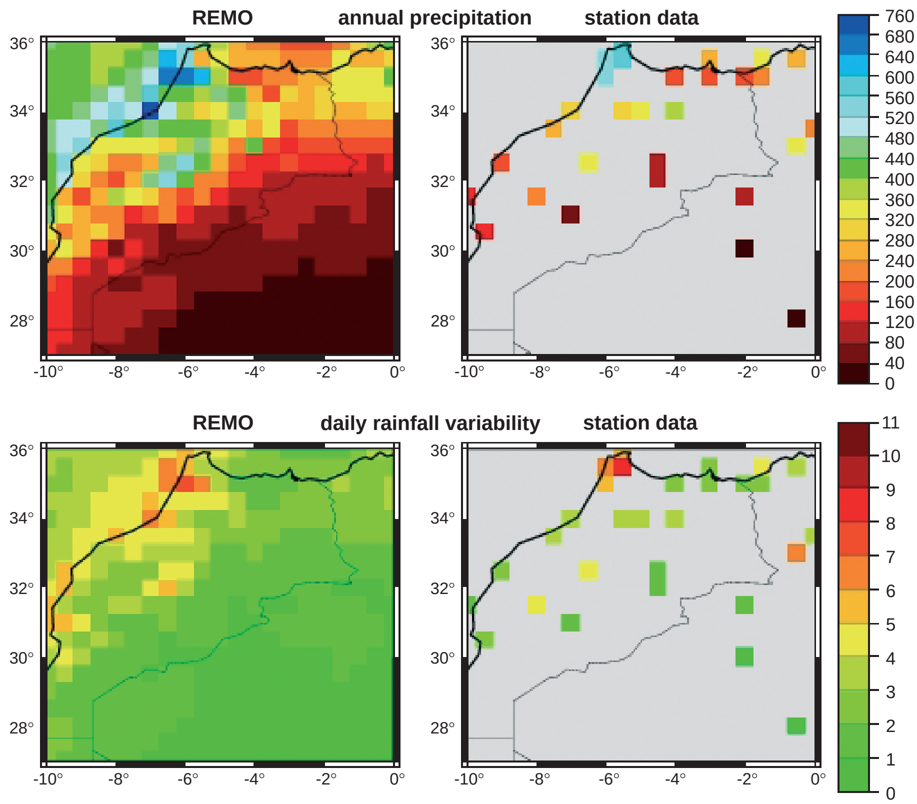


Fig. 4: Comparison of REMO with available rain gauge stations in Morocco and West Algeria, total annual precipitation and daily variability in 1991

Vergleich von REMO mit den verfügbaren Niederschlagsstationen in Marokko und Westalgerien, Gesamtjahresniederschlagssumme und tägliche Niederschlagsvariabilität due to the so-called tropic front, a peculiarity of the West African monsoon system, which arises from the north-westerly Harmattan wind being warmer than the south-westerly monsoonal flow. The dry and hot air masses from the Sahara are gliding over the less hot monsoon air masses and cause a temperature inversion in the lower troposphere, which in turn prevents deep convection in the vicinity of the ITCZ at 20°N. This results in a remarkable southward shift of the rainfall maxima to around 8–10°N.

Another important element of the African monsoon circulation is the lower-tropospheric AEJ (Hastenrath 2000). Easterly winds arise from the thermal gradient over West Africa: the Sahara is much warmer than the southern coastal region. According to the thermal wind equation this induces an easterly wind at around 15°N. The easterly wind maximum in 700–600 hPa results from the fact that the dry and hot air masses over central West Africa follow the dry-adiabatic ascent, while the humid monsoon air masses in the south obey the moist-adiabatic upflow. As a consequence, the thermal gradients are compensated near the 600 hPa level on average and the wind speed accumulates up to this level. The zonal AEJ becomes easily unstable due to surface heating or orographic effects and begins to meander in the form of the African Easterly waves (AEWs). The AEWs in turn represent a crucial factor in the formation of squall lines, describing meso-scale organized thunderstorm supercells, and are responsible for up to 80% of total annual rainfall over the Sahel and Sudan Zone (Thorncroft a. Hudges 2001; Saha a. Saha 2002).

Figure 6 displays the simulated and observed AEWs (top panels) and AEJ (bottom panels) in 600 hPa during the validation year 1991 in the form of Hovmöller diagrams. The AEWs can be illustrated by drawing the daily meriodional wind along the cross section 30°W to 60°E at 15°N (Grist 2002). The seasonal cycle of the AEJ is simply given by the daily zonal wind along the cross section 15°S to 45°N at 0°E. The AEWs are indicated by the stripe-like alternation of southerly and northerly winds between May and October (top panels). The slope of the stripes implies that the meriodional wind anomalies propagate from east to west with a time scale of 4–6 days. The simulated AEWs largely agree with the observed ones in terms of seasonality, amplitude and time scale. The same holds for the AEJ (bottom panels): REMO and observational data equally describe a seasonal displacement of the jet maximum from the equator in Northern Hemisphere winter to around 15°N in summer. Strong westerlies prevail north of the AEJ region. Again phase and amplitude are in remarkable agreement between regional model and real climate. This result is very encouraging for the

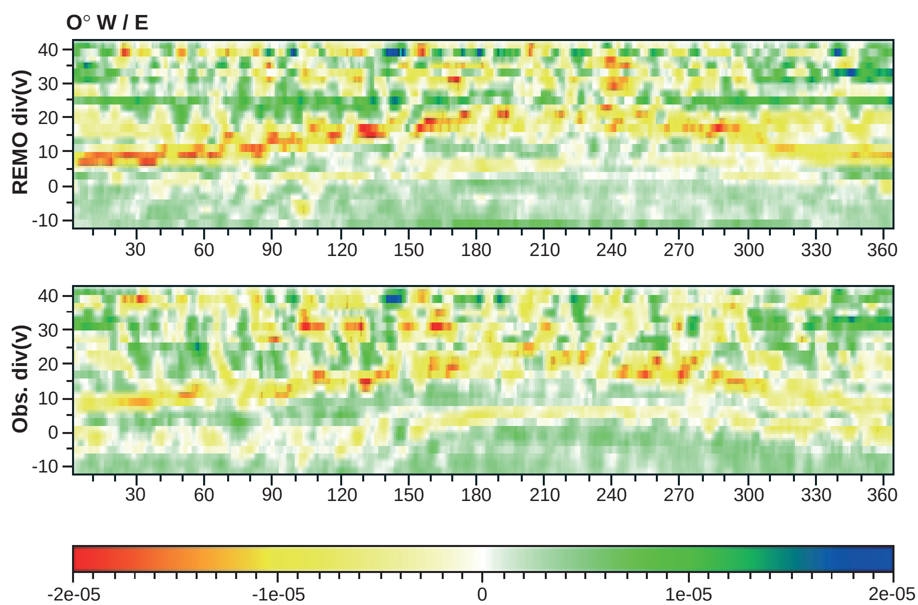


Fig. 5: Hovmöller diagramm of near-surface wind divergence in 1991 in the observations and REMO in s^{-1}, cross section 15°S–45°N at the prime meridian. Reddish (bluish) colours indicate convergence (divergence)

Hovmöller-Diagramm der bodennahen Winddivergenz im Jahr 1991 in den Beobachtungsdaten und REMO in s^{-1}, Querschnitt bei 15°S–45°N am Nullmeridian. Gelbrote (grünblaue) Farbtöne bezeichnen Konvergenz (Divergenz) general reliability of REMO: the lower-tropospheric jet dynamics result from a complex interaction of different air masses. If REMO is able to reproduce the observed circulation that reliably, it can be concluded that the entire monsoon system is well represented by the model. Therefore, REMO is supposed to be a useful tool for the subsequent sensitivity studies to detect the key factors in African climate variability and change.

7 *Sensitivity studies*

7.1 Sea surface temperatures

Previous studies have highlighted the role of SSTs in African rainfall (e.g. Palmer et al. 1992; Sutton a. Jewson 2000; Camberlin et al. 2001). Therefore, the first issue is to evaluate the impact of SST changes on

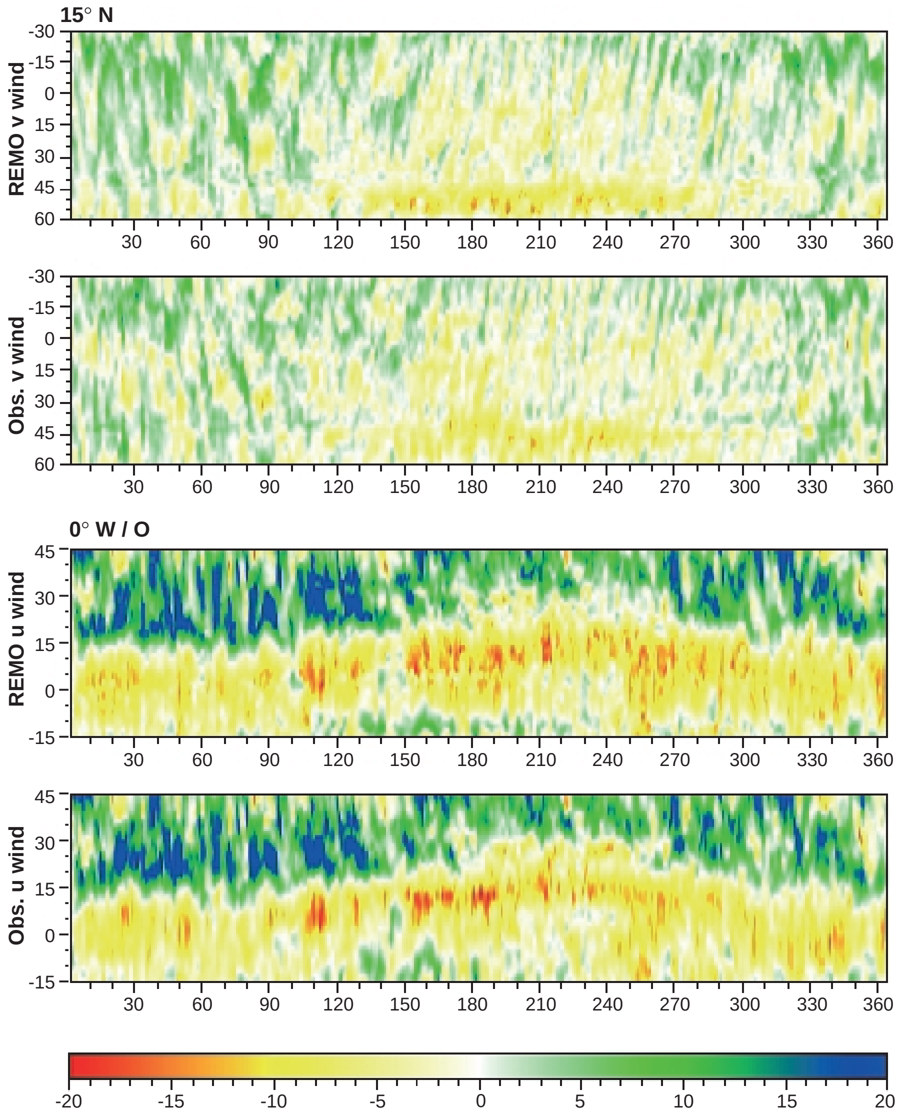


Fig. 6: Hovmöller diagramm of meridional and zonal wind components in 600 hPa in 1991 in the observations and REMO in ms^{-1}, cross sections 30°W–60°E at 15°N and 15°S–45°N at the prime meridian, respectively. Reddish (bluish) colours indicate easterlies / northerlies (westerlies / southerlies)

Hovmöller-Diagramm der meridionalen und zonalen Windkomponenten in 600 hPa im Jahr 1991 in Beobachtungsdaten und in REMO in ms^{-1}, Querschnitte bei 30°W–60°E und 15°N beziehungsweise 15°S–45°N am Nullmeridian. Gelbrote (grünblaue) Farbtöne beschreiben Ost- / Nordwinde (West- / Südwinde) precipitation anomalies at the regional scale. Two sets of experiments have been conducted: cooling and warming the tropical and subtropical oceans respectively (cf. section 4 and Tab. 1). The SST forcing is highly idealized, simply prescribing a constant warming or cooling rate over all oceanic regions, once south once north of 10°N. This pattern is not at all realistic and aims at gaining insight into the general response of African rainfall to SST changes.

In terms of the tropical oceanic heating and cooling, figure 7 shows the related mean patterns for different SST forcings and the maximum precipitation anomalies over the main rainy season period July–August 1988. At first sight, rainfall amount is increasing over most of tropical West Africa due to warmer SSTs in the tropical Atlantic and Indian Ocean. The difference pattern between the warmest and coldest experiment reveals remarkable changes, amounting to almost +1,000 mm in the Guinea Coast region and, to a lower extent, over the tropical East African coast. Slightly dryer conditions prevail over parts of the Sudan and Sahel Zone as well as central tropical Africa. The remaining parts of the model area are barely affected by variations in tropical SSTs. A detailed comparison of the mean patterns in figure 7 has demasked a nonlinear response of tropical African rainfall to a warming in the low latitude ocean basins (Paeth et al. 2003): warmer tropical SSTs are coming along with a more pronounced precipitation anomaly with respect to the unchanged case than colder tropical SSTs. The amplitude of the simulated rainfall changes is indeed realistic, compared with observed variations throughout the 20th century (Paeth et al. 2003).

The physical mechanism, which translates tropical Atlantic SST variations into regional rainfall changes over Africa, involves the full complexity of atmospheric circulation in the tropical Atlantic sector (Vizy a. Cook 2001). Usually, the relatively cool Gulf of Guinea region is characterized by atmospheric subsidence due to a downward branch of the Walker circulation, a phenomenon of zonal wind anomalies in the vicinity of the equator (Latif a. Grötzner 2000). Accordingly, an ascending branch of the Walker circulation is located over the Congo Basin and central tropical Africa, leading to abundant rainfall in this area. If a warm SST anomaly occurs in the Gulf of Guinea, the uplift over the continent is weakening, which induces negative rainfall anomalies over central tropical Africa

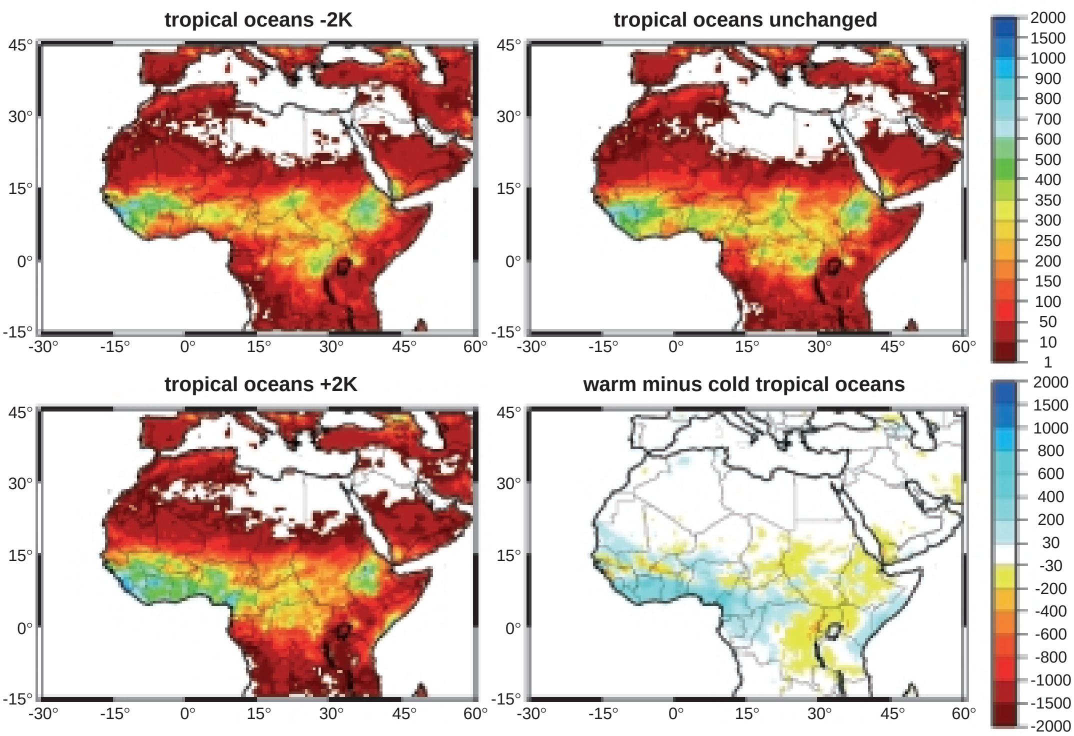


Fig. 7: Rainfall response in REMO in mm to prescribed idealized changes in the tropical SSTs south of 10°N, July–August 1988

Niederschlagsänderungen in mm durch vorgeschriebene idealisierte Anomalien in den tropischen SSTs südlich von 10°N, Juli–August 1988 as revealed by figure 7. Simultaneously the subsidence over the eastern tropical Atlantic is reduced, but still sufficient to prevent deep convection directly over the ocean basin. This implies that the monsoonal air masses, which are abnormally enriched with moisture from the warmer ocean surface, are advected by the south-westerly monsoonal flow to the southern part of West Africa, where deep convection is finally initiated. The large-scale ascent of humid air masses over the Guinea Coast region enhances rainfall there, but also requires wind convergence at the surface. This in turn strengthens the dry north-easterly Harmattan wind, which causes dryer conditions in the Sudan and Sahel Zone. Thus, the complete picture of rainfall anomalies in figure 7 is explainable by this mechanism. Obviously, REMO is able to simulate this complex process, like the regional climate model presented by VIZY and COOK (2002).

The second set of SST experiments varies the SSTs in the subtropical ocean regions included in the REMO domain. This concerns the subtropical Atlantic, the Mediterranean Sea and the northern Indian Ocean. The subtropical SST forcing pattern tends to induce approximately opposite rainfall anomalies compared with the pattern in figure 7, but the magnitude of the response is minor and hence the figure is not shown. A weak local rainfall response is simulated over Morocco, relating more abundant precipitation to warmer subtropical Atlantic SSTs. This in agreement with RODRIGUEZ-FONSECA and DE CASTRO (2002). The positive correlation between Mediterranean SSTs and Sahelian rainfall has also been reported by ROWELL (2003). Nonetheless, the present SST sensitivity study demasks the tropical Atlantic Ocean to be the main player in African climate variability.

7.2 Greenhouse gases

The prior knowledge that African climate is closely tied to variations in the SST field is also used to infer the role of increasing GHG concentrations. Now the SST forcing field is not idealized, but derived from a coupled

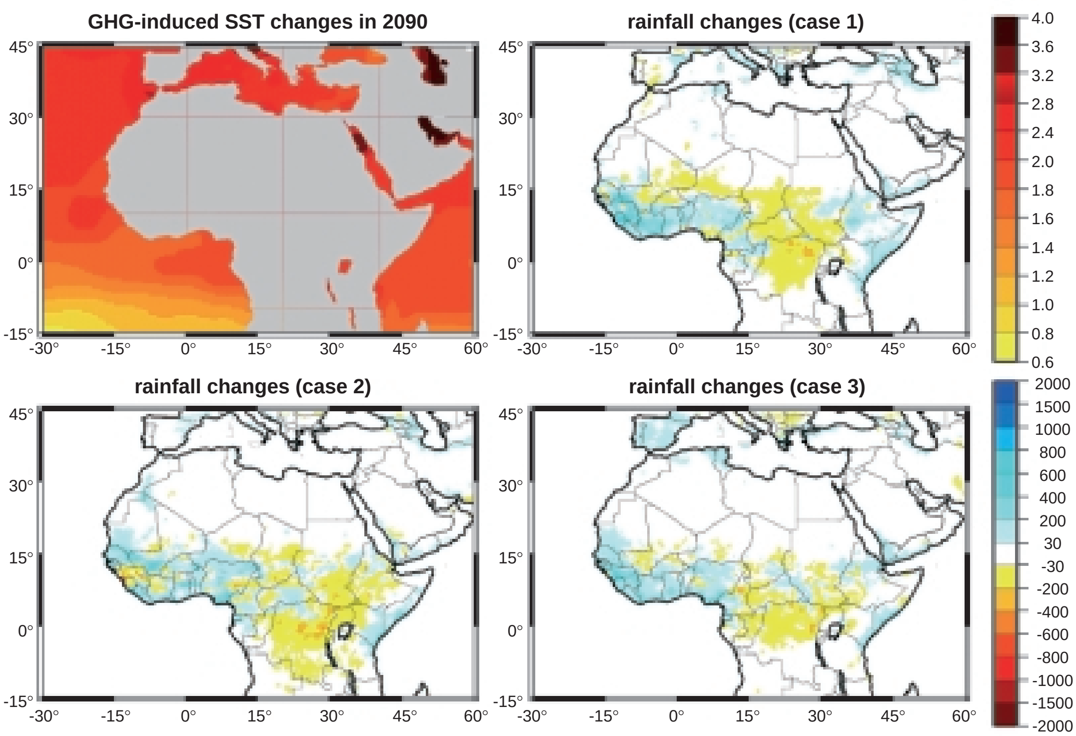


Fig. 8: GHG-induced SST forcing pattern in 2090 in °C (top colour scale), as predicted by the ECHAM4/OPYC global climate model, and rainfall response in REMO in mm (bottom colour scale), July–August in 3 years with different initial and lateral boundary conditions

Treibhausgas-induziertes Antriebsmuster der SST in °C (obere Farbskala), durch das globale ECHAM4/OPYC-Klimamodell für 2090 vorhergesagt, und Niederschlagsänderungen in REMO in mm (untere Farbskala), Juli–August in 3 Jahren mit unterschiedlichen Anfangs- und Randbedingungen global climate model simulation, which was subject to an anthropogenically enhanced greenhouse effect until the end of the 21st century (see section 4 and Tab. 1). The resulting SST changes in the year 2090 are depicted in figure 8 (top left panel): the greenhouse warming causes an overall heating of the considered oceanic regions. The largest amplitude is found in the subtropical North Atlantic, the Mediterranean and the inland seas (Red Sea, Persian Gulf, Caspian Sea), amounting to 2–4°C. The tropical SSTs are still rising by up to 2°C. The somewhat weaker warming signal in low latitudes is probably related to an intensified hydrological cycle with more frequent cloud cover and less solar irradiation (HOUGHTON et al. 2001). The GHG-induced heating of the tropical and subtropical oceans is striking against the background of natural SST variability: during the whole 20th century the minimum-maximum range of SST variations in the tropical Atlantic was not more than 1°C.

The resulting simulated response in July–August African rainfall is also shown in figure 8, referring to three years with different initial and lateral boundary conditions. The patterns are similar to each other and to the anomaly pattern in figure 7: the greenhouse forcing via the oceanic heating induces more abundant precipitation over the southernmost part of West Africa and tropical East Africa, whereas the Congo Basin and the Sahel Zone experience more arid conditions. The magnitude of the changes is substantial, ranging from +600 mm over Guinea to –400 mm in central tropical Africa. The negative rainfall anomaly over the Sahel Zone does not exceed –200 mm, but given the low total amount of annual rainfall this response is still severe. In detail, there are some distinct differences between the response patterns in figure 8, for instance over the western Guinea Coast region and the Sahel Zone. This reflects the uncertainty of the greenhouse signal, as imposed by the varied initial conditions and large-scale forcing fields at the lateral boundaries (cf. PAETH a. HENSE 2002). Nonetheless, there is some evidence that increasing GHG concentrations may be coming along with a strengthening of the meridional gradient in freshwater availability over West Africa. While a dryer climate is expected over the Sahel Zone, the coastal area may be favoured by more abundant precipitation. If this scenario is finally realized, it is easily inferable that north-south directed migration processes will be motivated (cf. FINDLEY 1994; RICHTER 2000).

The associated response in the near-surface wind is illustrated by figure 9, separately for each of the three years. The length of the wind vectors is a measure of the wind speed anomaly. Note that the arrows do not describe the mean circulation, but the GHG-related departures from the mean state. There are two basic features to be mentioned explicitly: (1) the GHG-induced oceanic heating is linked to an intensification of the summer monsoon circulation with accelerated southerlies and partly north-easterlies. This results in stronger surface-wind convergence over the Guinea Coast region and the typical pattern of rainfall changes shown in figure 8. Thus, the same physical mechanism, including the Walker circulation and deep convection over the coastal region is responsible, as described in the previous subsection. (2) West of Senegal a clear cyclonic anomaly is simulated in response to warmer SSTs. The close relationship between SST and tropical cyclogenesis has for instance been described by SCHADE (2000). Indeed, the sensitivity study with REMO suggests that tropical storms may become more frequent,

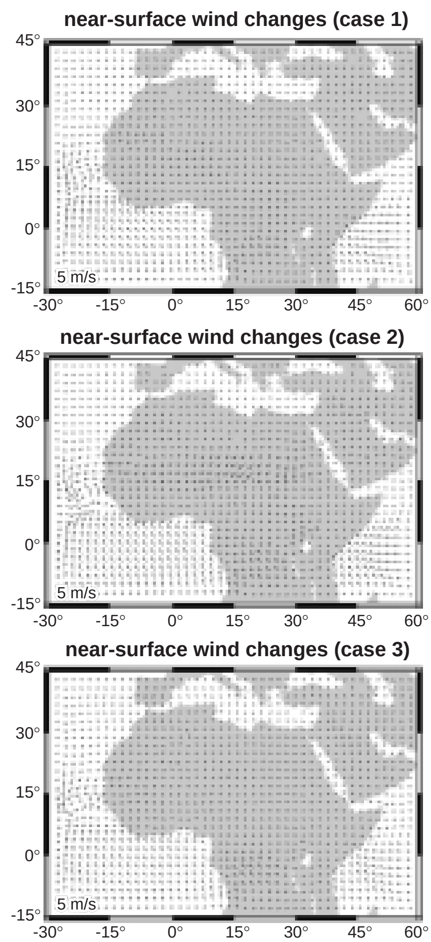


Fig. 9: Same as Fig. 8 but for near-surface wind response in REMO

Wie Abb. 8, aber für die bodennahen Windänderungen in REMO

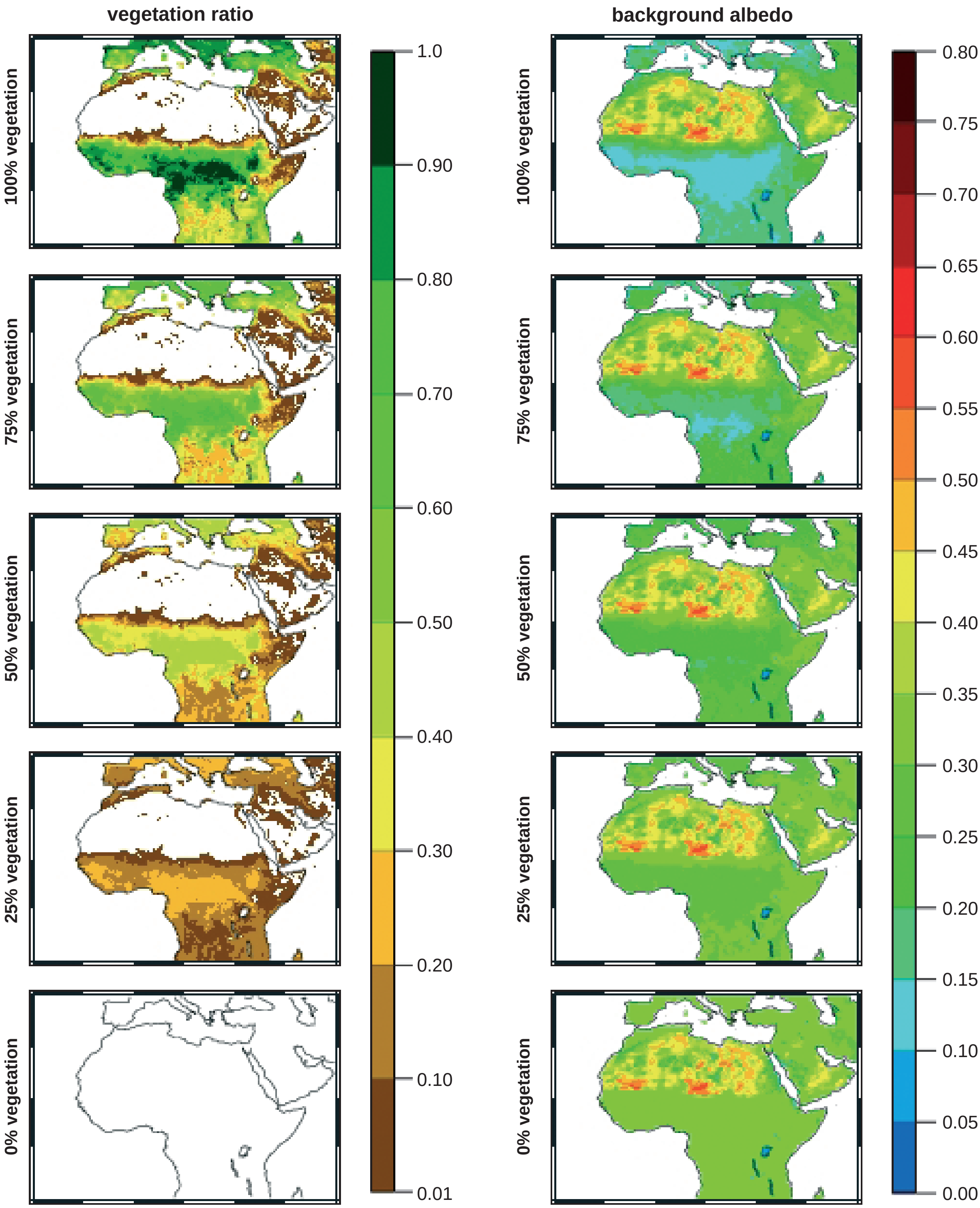


Fig. 10: Idealized vegetation scenarios for REMO, July conditions
Idealisierte Vegetationsszenarios für REMO, Juli-Bedingungen

when the tropical and subtropical oceans are warmed up by an enhanced greenhouse effect. This important feature is independent of the initial and lateral input data. Consequently, more extreme weather and rainfall events may be expected over tropical Africa.

7.3 Vegetation cover

So far, the REMO experiments have indirectly detected the crucial role of increasing GHG concentrations in the African summer monsoon system. Given that African climate is largely affected by land surface conditions (e.g. DOUVILLE et al. 2000; CLARK et al. 2001; FEDDEMA a. FREIRE 2001), the GHG-induced precipitation changes have to be evaluated against the effect of future land use changes. The land degradation experiments are composed of 4 simulations, covering the summer rainy season May–October 1991. Each simulation refers to a progressive scenario of vegetation loss, amounting to 75, 50, 25, and 0% compared with the present-day vegetation cover (see section 4 and Tab. 1). The reduction is equally applied to all land grid boxes, neglecting the heterogeneous pattern of land acquisition along the axes of settlement. By the way, such detailed information is difficult to be predicted for several decades into the future. Thus, the present sensitivity study aims at providing a very general view of the impact of land use changes on African climate to be compared with the GHG-imposed anomalies.

Some of the forcing patterns of vegetation loss are depicted in figure 10. As explained in section 4, 5 surface parameters in REMO are directly associated with a reduction in vegetation cover. The most intuitive parameter is the vegetation ratio, indicating the portion of a 0.5° land grid box covered with any kind of vegetation instead of bare soil. The typical pattern of present-day vegetation ratio is characterized by high vegetation density in the inner tropics of Africa and over most parts of southern Europe (top left panel in Fig. 10). The Congo Basin in particular is almost completely covered by dense vegetation (in the form of forests). No vegetation is found in the central Sahara and the Arabian Peninsula. Between these peak regions a broad symmetric and regular transition zone is found. The 4 progressive scenarios imply that the vegetation ratio is successively reduced until it completely vanishes in the worst case scenario (left panels in Fig. 10). It is unlikely that this worst case will once be realized. However, it is taken into account in order to quantify the maximum response of African rainfall to land degradation. The same reduction rate is applied to the forest fraction, the LAI and the roughness length (not shown), whereas the changes in surface albedo are determined by a linear multiple regression on to vegetation ratio, forest fraction and LAI. The resulting forcing patterns are listed in the right column of figure 10. In the undisturbed case (top right panel) the reflectivity of incoming shortwave radiation is low over the regions with dense vegetation, not exceeding $\alpha = 0.15$. This is indicative of the high absorption of solar radiation by plants and especially trees. In the Sahara, up to 60% of the incoming solar energy is directly reflected back to the space by light bare soils. The multiple regression model reveals that a reduction in vegetation cover is accompanied by with a general rise in surface albedo. In the extreme scenario of total vegetation loss, albedo increases from around 0.15 to almost 0.35 in the regions with formerly dense vegetation. Of course, the surface albedo is not modified in regions without natural vegetation cover.

Imposing the consistent land cover changes, including all 5 parameters mentioned above, on the rainy season 1991, leads to the total precipitation amount and anomalies shown in figure 11. It is obvious that an increasing extent of land degradation causes a substantial reduction in rainfall, in the worst case scenario reaching up to −1,500 mm during the May to October period in the Congo Basin and over central tropical Africa. Over the Guinea Coast up to –600 mm occur, while the Sahel Zone still experiences −200 mm. Hardly any changes are found in regions without natural vegetation cover. Interestingly, rainfall in southern Europe is barely affected by the land cover changes, although the original vegetation cover is comparable with tropical Africa. This suggests that the interaction with land cover mainly takes place in the low latitudes, whereas rainfall and climate in the extratropics are rather governed by large-scale circulation, which is not modified in the present sensitivity study. The small number of squattered positive precipitation anomalies is negligible.

The precipitation response is not a linear function of the land cover changes. The strongest anomalies relative to the forcing are simulated, if the vegetation is reduced to 25% of the present-day level (right panels in Fig. 11). The difference between the 0% and 25% scenario is much smaller than between 50% and 25%. Assuming that 25% may be the most likely land use scenario at the end of the 21st century, this implies that the worst case conditions in terms of rainfall deficiency may almost be realized.

Given the 4 vegetation experiments with different surface forcing but identical initial and lateral input data, a so-called ensemble of climate change simulations is given (PAETH a. HENSE 2002). This specific data constellation can be used to evaluate the treatment effect, in this case continuing land degradation, with re-

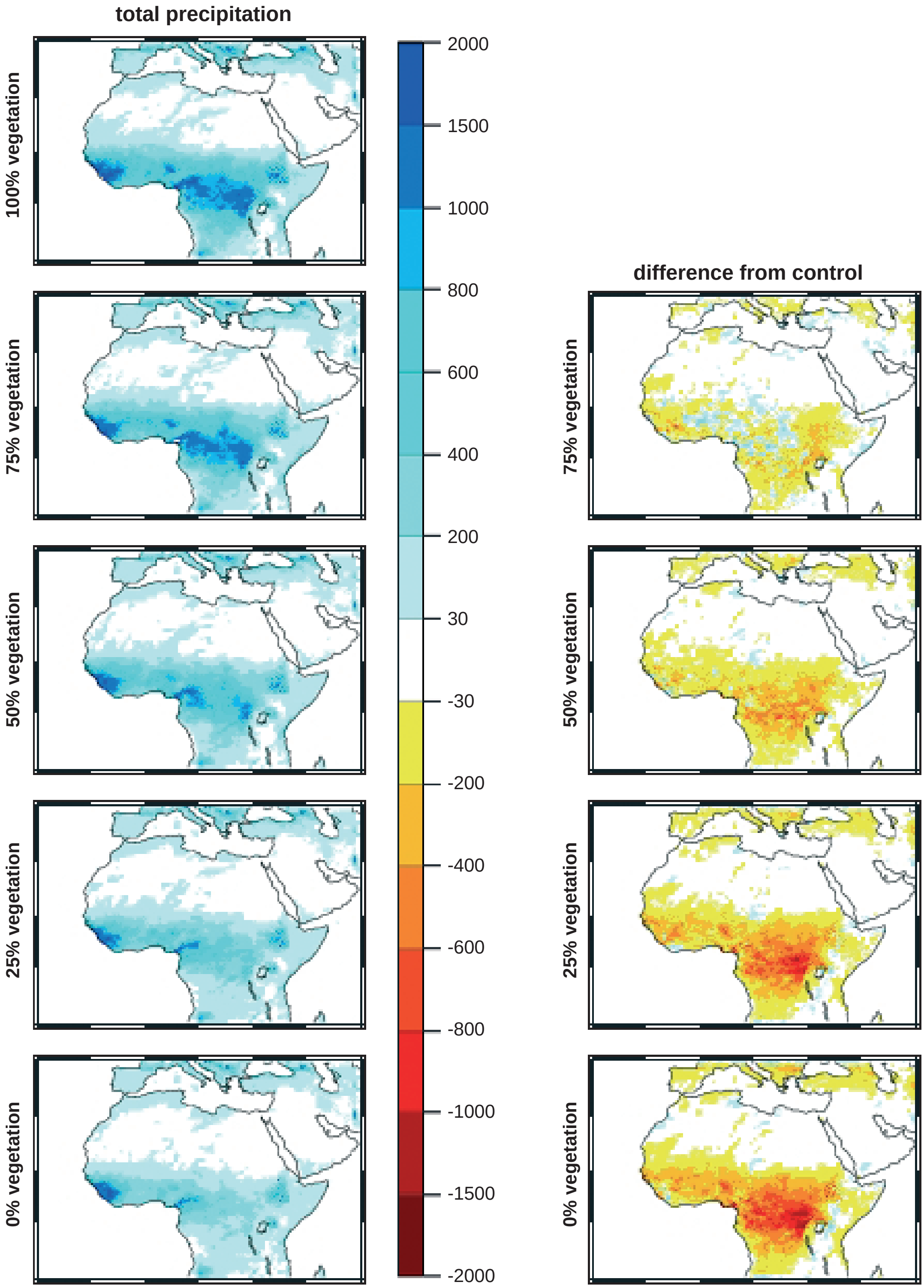


Fig. 11: Rainfall response in REMO in mm to a prescribed idealized reduction in vegetation cover over the land surfaces, May–October 1991

Niederschlagsänderungen in mm durch eine vorgeschriebene idealisierte Abnahme der Vegetationsbedeckung über den Landoberflächen, Mai–Oktober 1991 spect to natural daily rainfall variability within each experiment. An appropriate statistical tool for this type of issue is the analysis of variance (von Storch a. Zwiers 1999). It is found that the vegetation changes impose a statistically significant effect on total African precipitation variability at an error level of only 1%. This is remarkable given the strong day-to-day fluctuations of rainfall in the low latitudes (Saha a. Saha 2001).

The rainfall response patterns in figure 11 are highly reminiscent of the distribution of original vegetation cover in figure 10 (top left panel). This leads to the question of which atmospheric processes are mediating between land degradation on the one hand and precipitation changes on the other hand. As will be discussed later, it is of particular political interest to access the relative importance of local and large-scale dynamic effects. Among the various impacts of land degradation two effects appear to be most relevant to African climate: the reduction in surface evapo-transpiration and the resulting increase in sensible heat fluxes. The latter over-compensate the surface cooling by rising albedo and cause a distinct warming of surface climate in tropical Africa (not shown). This in turn modifies the thermal gradients over the entire sector, which represent a basic factor in the monsoon circulation. Indeed, REMO simulates a visible change in the near-surface winds (Fig. 12): A stronger wind convergence occurs over the Guinea Coast region and the Congo Basin, where the vegetation loss and hence the surface heating is most pronounced. As a part of the converging air masses originates from the tropical Atlantic, the moisture advection is also enhanced over tropical Africa. This indirect dynamic response to land degradation should principly favour more abundant large-scale precipitation over the continent. However, the opposite is true in figure 11.

The moisture budget in an imaginary atmospheric column is governed by two terms: the vertically integrated moisture advection and the latent heat fluxes from the surface. If the change in moisture advection is indicative of more rainfall, but negative precipitation anomalies are prevailing, the local effect of latent heat flux must conclusively overcompensate the large-scale dynamical effect of moisture advection. Figure 13 supports this conclusion: while the whole region of tropical Africa is usually characterized by intense latent heat fluxes of up to 120 W/m^{-2}, the vegetation loss induces a reduction in the same order of magnitude (–110 W/m^{-2}). Thus, surface evaporation is almost completely forestalled. Of course, this has a considerable impact on atmospheric humidity, cloud water, precipitable water and finally rainfall. Consequently, the local effect of land degradation is one of the main players in

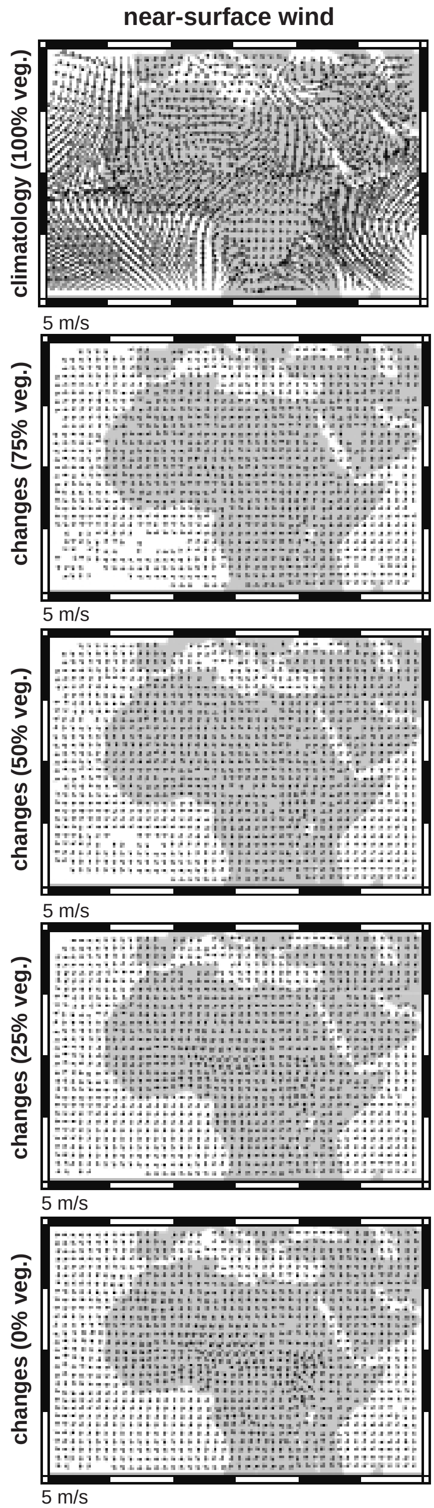


Fig. 12: Same as Fig. 11 but for near-surface wind response in REMO

Wie Abb. 11, aber für die Änderungen des bodennahen Windes in REMO

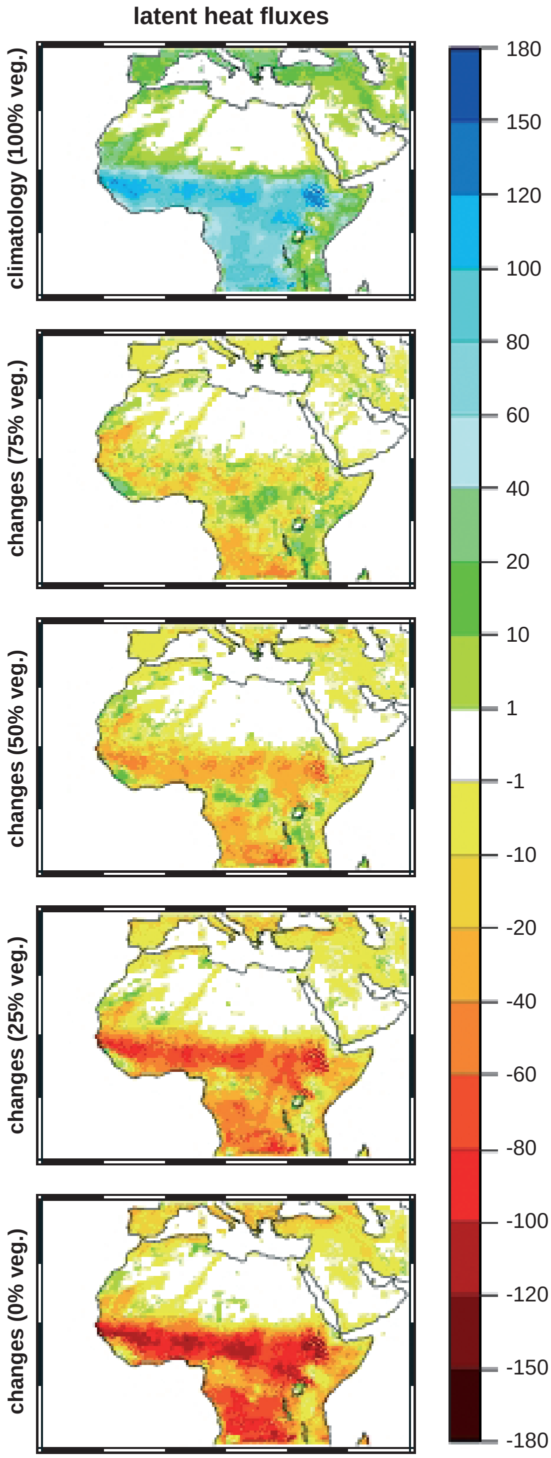


Fig. 13: Same as Fig. 11 but for latent heat flux response in REMO in W/m^{-2}. Positive values represent fluxes from the surface into the atmosphere

Wie Abb. 11, aber für die Änderungen des latenten Wärmeflusses in REMO in W/m^{-2}. Positive Werte zeigen Flüsse von der Oberfläche in die Atmosphäre an

African climate change. For this reason, the rainfall response patterns in figure 11 basically reflect the distribution of natural vegetation in figure 10. This means that cause and effect are spatially corresponding with each other or in other words: local freshwater availability benefits from local protection of forests and natural vegetation.

7.4 Soil parameters

The last set of sensitivity experiments is dedicated to the role of soil degradation in African rainfall changes. As described in section 4, several soil parameters are altered such that surface runoff and drainage are enhanced to the disadvantage of infiltration and soil moisture. These effects are expected, if vegetation cover is reduced (DOUVILLE et al. 2001). Note that the prescribed amplitudes of soil parameter modifications are fairly arbitrary, since reliable information from observational studies was not available. Thus, the results again have to be interpreted as a general, not a fully realistic response to soil degradation.

The simulated total rainfall amount and changes during the May–October 1991 rainy season are listed in figure 14. As under the vegetation scenarios, precipitation tends to be reduced in most model grid boxes. The strongest signal is found in central tropical Africa and sub-saharan West Africa. Even southern Europe is slightly affected by the soil parameter changes. However, the amplitude of the signal is much lower, usually not exceeding the –200 mm category, although some subregions in the Congo Basin experience a rainfall decrease by up to –600 mm. In addition, the response is spatially more heterogeneous with some squattered positive rainfall anomalies all over tropical Africa, especially under the weaker scenario (middle panels). The analysis of variance reveals that the impact of soil degradation on African precipitation is barely significant with respect to the large extent of daily rainfall variability. Nonetheless, the isolated effect of changes in the soil properties tends to enhance the vegetation-induced climate change signal in tropical Africa. Thus, this key factor cannot be neglected when performing comprehensive and realistic scenarios of future African climate.

8 Summary and Conclusions

The present study has elucidated and evaluated some of the crucial mechanisms which are responsible for African climate variability and change. By means of a regional climate model the presumable key factors are isolated and their impacts on African precipitation anomalies are quantified. The regional climate model REMO is found to simulate the observed African climate in a reliable way, enhancing the believe in the sensitivity experiments. Four key factors are addressed, including SSTs, GHG concentrations, vegetation loss and soil degradation. The specific results are summarized in figure 15, splitting up tropical Africa into three basic regions. The bars indicate the regional-mean changes in total rainfall amount during a two-month July–August period, relating to land and soil degradation as well as greenhouse forcing. The SST effect is inherent in the global warming impact, since the latter is prescribed via a heating of the SST field. In the Guinea Coast region the enhanced greenhouse effect clearly wins out, causing 130 mm more July–August rainfall. Soil degradation and especially vegetation loss counteract the radiative forcing and together induce a decrease in precipitation amount by –70 mm. Thus, at the final count more freshwater availability can be expected until the end of the 21st century. The Sahel Zone will probably experience a further deterioration of life conditions, since land and soil degradation may reduce summer rainfall by around 80 mm. Given the low total precipitation amount, this reduction is of tremendous relevance to ecosystems and human activity. Global warming can barely compensate this negative development in the Sahel Zone. In the Congo Basin all three factors agree in causing a drier climate: –190 mm in the regional mean and during two months even stands out from the naturally abundant rainfall.

This study has contributed to shedding light on the main players in future African climate change at a

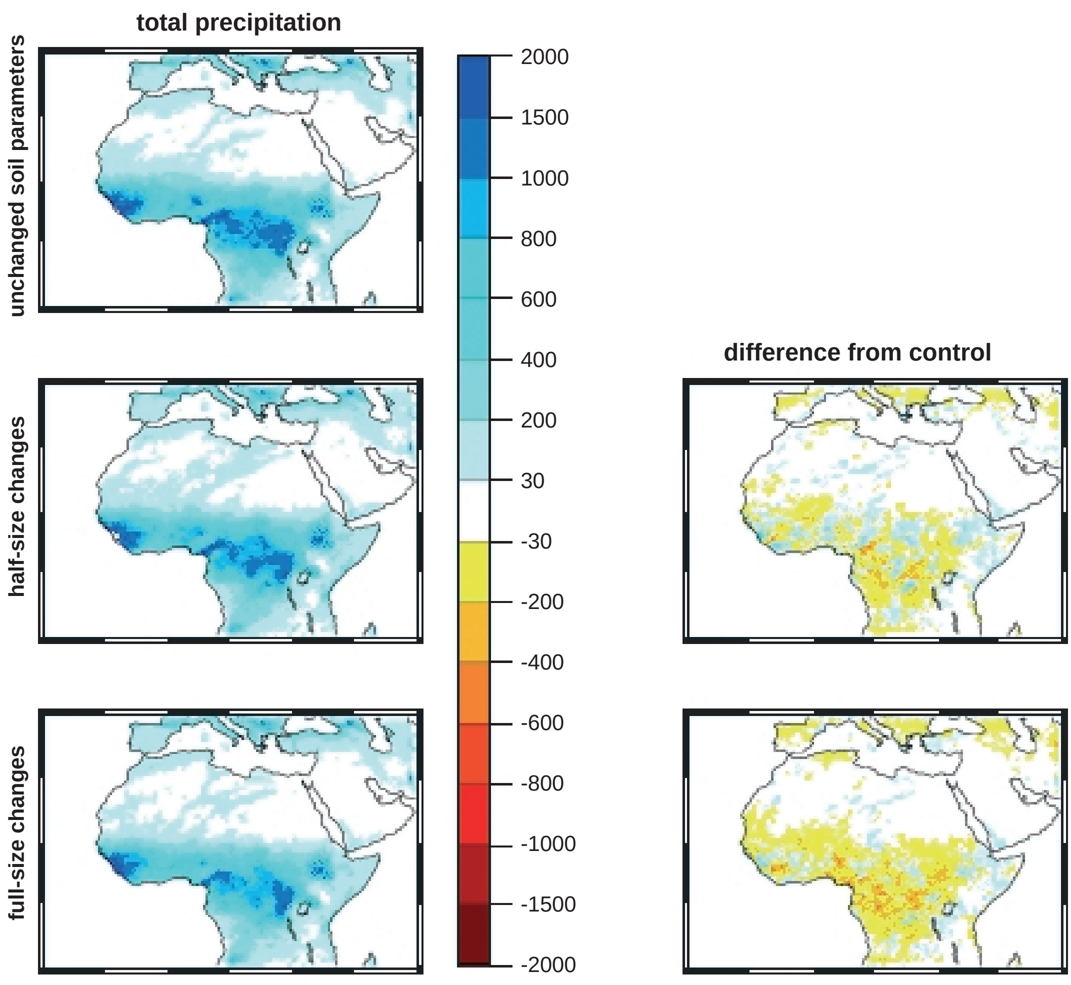


Fig. 14: Rainfall response in REMO in mm to a prescribed change in the vegetation-related soil parameters, May–October 1991

Niederschlagsänderungen in mm durch eine vorgeschriebene Veränderung jener Bodenparameter, die an eine Abnahme der Vegetationsbedeckung gekoppelt sind, Mai–Oktober 1991 regionally differentiated scale. Several main conclusions are to be drawn from this analysis: (1) regional dynamical downscaling with REMO represents a meaningful tool to detect and quantify the key factors in African climate. (2) The causes for African climate variability and change are quite complex, including the teleconnections to the tropical ocean basins, interactions with the land surface charateristics and indirectly global GHG concentrations. Thus, creating realistic scenarios of future climate conditions in Africa requires to involve all these mechanisms at once. (3) In general, freshwater availability tends to get worse over most parts of tropical Africa except the Guinea Coast region. In particular the reduction in natural vegetation cover is responsible for this deterioration of life conditions. (4) The overall positive effect in the southernmost part of West Africa may lead to large-scale migration processes from regions with increasing handicap and finally endanger the remaining natural potential in the Guinea Coast region.

Assuming a continuation of critical processes like excessive population growth, urbanization and desertification, policymakers are asked to take protection measures against this disastrous scenario of future African climate. In this respect, the results of this study are encouraging, revealing that land degradation is often the most important factor in African climate change. While tropical SSTs and global warming are hardly to be influenced by political measures at a national scale, the vegetation cover can indeed be saved by national programmes (ANHUF et al. 2000; GEROLD 2002). In this context, it is of major relevance that the local effect of vegetation loss predominates. This implies that local future rainfall will directly profit from nature protection and re-forestation – a convincing argument for local to national decision makers.

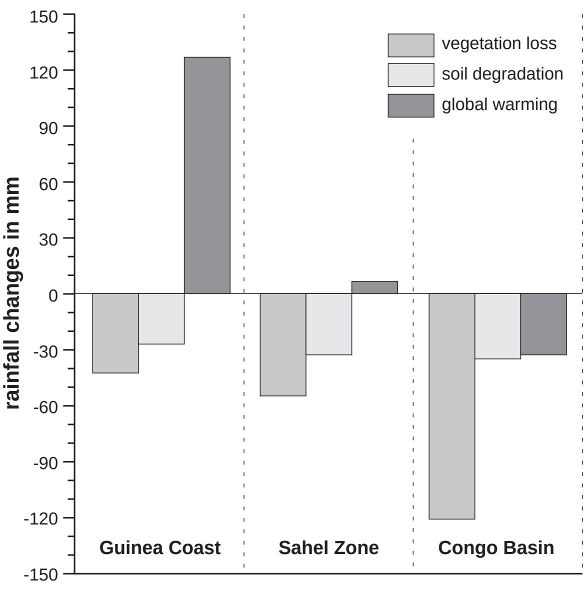


Fig. 15: Quantitative comparison between all impact factors, expressed as total rainfall change during the July–August main rainy season averaged over 3 major regions in tropical Africa. 25% is considered as most likely vegetation scenario

Quantitativer Vergleich zwischen allen Einflussfaktoren, ausgedrückt als Gesamtniederschlagsänderung während der Hauptregenzeit im Juli und August im Mittel über die 3 Hauptregionen im tropischen Afrika. Das 25%-Vegetationsszenario wird als wahrscheinlichstes eingeschätzt

Of course, the findings of this analysis can only be regarded as a preliminary estimate of future climate changes in tropical Africa. For a more realistic climate prediction into the 21st century, the prescribed scenarios need to be improved. As mentioned before, the greenhouse forcing only enters the sensitivity study indirectly. In addition, the land cover changes are somewhat arbitrary and do not account for the typically squattered pattern of land acquisition in the tropics. Some uncertainty is also imposed by the prescribed modification of the soil parameters. However, more realistic forcing fields require information from other disciplines. Therefore, the present study is embedded in the multi-disciplinary GLOWA-IMPETUS project, including co-disciplines like hydrology, vegetation remote sensing, botany, geology, agricultural economy, ethnology, medicine and finally meteorology. In the near future, available estimates of future land use and soil property changes, based on recent measurements, field campaigns and observed trends, will be used to perform more realistic experiments with REMO. Furthermore, the enhanced greenhouse effect will be implemented in the REMO atmosphere and the model simulations are driven by a global climate model, which has been run under increasing GHG concentrations, in order to consider the effect of changed large-scale circulation at the lateral boundaries. These simulations will probably provide the best regional-scale estimate of future African climate so far, also accounting for some nonlinearities in the interaction between the forcing parameters. However, the scientific basis for the pre-selection of the key factors and the expected individual contributions to future climate change is given by the present study.

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