

## Understanding the mechanism of land-cover related climate change in the low latitudes

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**सार** – वर्षा की परिवर्तनशीलता सामान्य रूप से न्यून अक्षांशों और विशेष रूप से उष्णकटिबंधीय तथा उपउष्णकटिबंधीय अफ्रीका में वनस्पति आवरण, एलबिडो और मृदा आर्द्रता जैसे भू-सतही अभिलक्षणों द्वारा व्यापक रूप से प्रभावित होती है। अफ्रीका की जनसंख्या में बढ़ती तथा कृषि की बढ़ रही आवश्यकताओं को देखते हुए भू-आवरण परिवर्तनों के स्थानीय एवं गतिकीय प्रभावों से भविष्य की जलवायु की प्रागुक्ति का पता लगाना कठिन है। इस शोध पत्र में अफ्रीका में कम वनस्पति आवरण के आदर्श दृश्य विधानों को निर्धारित करते हुए सिनाप्टिक मान क्षेत्रीय जलवायु निदर्श सहित अति संवेदनशील अध्ययनों का एक सेट प्रस्तुत किया गया है। इसके अतिरिक्त, वनस्पति आवरण में परिवर्तन सहित संभावित परिवर्तित मृदा प्राचलों सहित जाँच का दूसरा सेट तैयार किया गया है।

जब मौजूद वनस्पति स्तत रूप से लुप्त हो जाती है तो मौसमी वर्षा की मात्रा में भारी कमी आती है। कोंगो बेसिन और पश्चिमी अफ्रीका के उपसहारा क्षेत्र में सबसे अधिक परिवर्तन देखे गए हैं जहाँ पर ग्रीष्मकालीन मानसून वर्षा क्रमशः 2000 मि.मी. और 600 मि. मी. तक घट जाती है। अफ्रीका के उपसहारा क्षेत्र के बहुत से भागों में वनस्पति परिवर्तनों से वर्षा की प्रतिक्रिया अरैखिक और सांख्यिकीय रूप से उल्लेखनीय होती है। बृहत-मान वर्षा की अपेक्षा संवहनी वर्षा अधिक संवेदनशील होती है।

भू-अपकर्ष के प्रमुख प्रभाव से गुप्त (संवेध) ऊष्मा फ्लक्सों में कमी (वृद्धि) होती है। परिणामस्वरूप अफ्रीका में मानसूनी प्रवाह के प्रमुख कारक के रूप में पश्चिमी अफ्रीका के दक्षिणी छोर के भागों तथा मध्य कोंगो बेसिन में संवर्धित नमी संवहन के दक्षिणाभिमुखी परिवर्तन की ओर अग्रसर बृहत मान उष्मीय प्रवणताओं को संशोधित किया गया है। मध्य क्षोभमंडलीय जेट और तरंग गतिक केवल भू-आवरण परिवर्तनों से प्रभावित होते हैं। हालांकि बृहत-मान गतिकीय प्रतिक्रिया वर्षा की अधिक मात्रा के अनुकूल होती है। सकारात्मक गतिकीय प्रभाव की क्षतिपूर्ति करते हुए और क्षेत्रीय मान जल पुनः चक्र को कमजोर कर प्रभावित करते हुए आर्द्रता बजट कम वाष्पोवाष्पत्सर्जन द्वारा प्रबल रूप से नियंत्रित होते हैं। मृदा की विशेषताओं में संबद्ध परिवर्तन, यद्यपि न्यून अक्षांशों में वर्षा की मात्रा में कमी के लिए अतिरिक्त रूप से सहयोग दे सकते हैं।

**ABSTRACT.** Rainfall variability in the low latitudes in general and over tropical and sub-tropical Africa in particular, is largely affected by land surface characteristics like, vegetation cover, albedo and soil moisture. Understanding the local and dynamical effects of land-cover changes is crucial to future climate prediction, given ongoing population growth and increasing agricultural needs in Africa. Here, a set of sensitivity studies with a synoptic-scale regional climate model is presented, prescribing idealized scenarios of reduced vegetation cover over Africa. Beside the vegetation ratio itself, the leaf area index, forest ratio, surface albedo and roughness length are changed as well, in order to obtain a consistent scenario of land surface degradation. In addition, a second set of experiments is realized with altered soil parameters as expected to be coming along with a reduction in vegetation cover.

Seasonal rainfall amount decreases substantially when the present-day vegetation continuously disappears. The strongest changes are found over the Congo Basin and subsaharan West Africa, where the summer monsoon precipitation diminishes by up to 2000 mm and 600 mm, respectively. The rainfall response to vegetation changes is non-linear and statistically significant over large parts of subsaharan Africa. Convective precipitation is more sensitive than large-scale precipitation.

The most prominent effect of land degradation is a decrease (increase) of latent (sensible) heat fluxes. As a consequence, the large-scale thermal gradients, as a key factor in the monsoonal flow over Africa, are modified leading to a southward shift of the intertropical convergence zone and enhanced moisture advection over the southernmost part of

West Africa and the central Congo Basin. The mid-tropospheric jet and wave dynamics are barely affected by land-cover changes. Although the large-scale dynamical response is favourable to increasing rainfall amount, the moisture budget is predominantly governed by reduced evapotranspiration, overcompensating the positive dynamical effect and inducing a weakening of the regional-scale water recycling. The related changes in the soil properties may additionally contribute to a reduction in rainfall amount, albeit of lower amplitude.

**Key words** – Climate change, Africa, Land cover, Regional climate modeling.

## 1. Introduction

Large parts of sub-Saharan Africa have experienced a substantial drought period since the late 1960s (Nicholson 2001). This has led to severe economical loss and large-scale migration processes, particularly in the Sahel Zone (Findley 1994; Benson and Clay 1998). The southernmost Guinean Coast region has also been affected by a series of deficient rainy seasons (Le Barbé *et al.* 2002). Although precipitation amount is slightly recovering since the last decade (Nicholson *et al.* 2000), it is of basic importance to understand the mechanisms and processes, which affect rainfall variability over the low latitudes of Africa. Given a fast growing population with increasing agricultural needs, the freshwater demand is supposed to rise enormously throughout the 21<sup>st</sup> century (Houghton *et al.* 2001). Thus, the prediction of future climate changes represents a crucial factor in political measures and agricultural planning in order to avoid a further deterioration of livelihood in tropical and sub-tropical Africa.

One important driving force of African rainfall variability is given by land surface conditions. The impact of vegetation cover on atmospheric dynamics and deep convection is quite complex, incorporating for instance sensible and latent heat fluxes from the ground into the atmosphere, soil moisture, surface albedo and roughness length (Bounoua *et al.* 2000; Pielke 2001). Global climate model simulations have revealed that the effect of land degradation is strongest in the Sahel Zone, whereas the vegetation impact is partly compensated over the Guinean Coast region by an enhancement of moisture convergence, favouring the formation of rainfall (Clark *et al.* 2001). On the other hand, Semazzi and Song (2001) report that central tropical Africa is even more affected by deforestation than West Africa. In general, Africa is much more sensitive to changes in vegetation cover than the South Asian monsoon system (Texier *et al.* 2000). Wang and Eltahir (2000) have highlighted the role of vegetation feedbacks in the 20th-century Sahelian drought (cf. Lotsch *et al.* 2003). Van den Hurk *et al.* (2003) have pointed to the intensification of seasonal variability in response to the seasonality of the Leaf Area Index (LAI). At the millennial time scale albedo feedbacks may have been more relevant since the mid Holocene than orbital forcing (Knorr and Schnitzler 2006). Some authors argue that the

deficiency of climate models in simulating the amplitude and variability of West African rainfall as well as the seasonal shift of the Inter Tropical Convergence Zone (ITCZ) arises from the missing interactions between vegetation cover and atmospheric processes (Zeng and Neelin 2000; Schnitzler *et al.* 2001, Zeng *et al.* 2002).

However, land-cover changes do obviously not represent the only factor in longer-term variations of African precipitation. This is demonstrated by the fact that rainfall is slightly recovering over most of the Sahel Zone since the late 1980s (Nicholson *et al.* 2000) despite the ongoing process of land degradation. Satellite data reveal that vegetation cover also responds directly to changes in the hydrological cycle, showing a recovery since the 1990 according to the increasing amount of precipitation (Eklundh and Olsson 2003). Thus, other key factors appear to overcompensate the impact of land cover during certain periods.

Nonetheless, more attention has been drawn in recent years to the relevance of land-use changes when simulating future global climate under the greenhouse (Douville *et al.* 2000; Feddema *et al.* 2005; Lamptey *et al.* 2005). Zhao and Pitman (2002) have compared the counteracting effects of radiative forcing and vegetation loss over China and Europe and found opposite responses in the same order of magnitude. It is conceivable that the impact of land cover changes is even more prevailing in tropical Africa (cf. Texier *et al.* 2000). An indirect effect of deforestation consists of the emission of aerosols from biomass burning. The enhanced aerosol burden over Africa may also contribute to a weakening of the hydrological cycle (Paeth and Feichter 2006).

Furthermore, soil moisture and soil characteristics are prominent factors in the formation and distribution of rainfall over Africa (Fontaine *et al.* 2002). In general, decreasing soil moisture is coming along with reduced surface evaporation and precipitation (Douville *et al.* 2001). Again, Africa seems to be more affected than the South Asian monsoon region. There is also an indirect influence on rainfall, the soil moisture modifying the intensity and position of the African Easterly Jet (AEJ) (Cook 1999). Feddema and Freire (2001) have evaluated the relative impacts of soil degradation and global warming with respect to water resources in Africa and

conclude that, while the GHG forcing still wins out, soil moisture enhances the amplitude of the response. Most climate models have a fully interactive soil model such that prescribed vegetation scenarios automatically imply changes in soil moisture and surface fluxes. However, long-term variations in the vegetation cover may also alter some soil parameters, which govern infiltration rate, drainage and surface runoff. These soil properties are important for surface evaporation but usually kept constant in the model experiments. Thus, consistent scenarios of land-cover changes have to take a modification of the soil parameters into account.

In this study, impacts of modified vegetation cover and soil moisture on the hydrological cycle and monsoon circulation have been examined. The land-cover effect on rainfall takes place at the regional to local scale (Long *et al.* 2000). Thus, global climate models do not account for the full variety of atmosphere-land surface interactions. Therefore, Desanker and Justice (2001) as well as Jenkins *et al.* (2002) have pleaded for regional dynamical downscaling approaches over Africa. Here, sensitivity studies with the regional climate model REMO (Jacob *et al.* 2001) are presented. Idealized scenarios of reduced vegetation cover are prescribed over entire tropical and northern African, the Mediterranean region and the Arabic Peninsula. In a second set of experiments soil parameters are changed as to be expected under vanishing vegetation. In a previous study, the same model has been used to simulate the isolated GHG-induced response of West African rainfall at the end of the 21<sup>st</sup> century (Paeth and Stuck 2004). It was found that global warming *via* the tropical oceans induces more abundant precipitation over the Guinean Coast region (up to 600 mm) during the summer monsoon season, whereas the Sahel Zone and the Congo Basin are hit by deficient rainfall (up to -350 mm). A subsequent question is as to what extent this response is modulated by man-made land-cover changes. The idealized nature of the forcing scenarios does not allow for a quantitative prediction of future changes in African climate. Hence, it is intended to elucidate the mechanism of land-cover related African climate change at the regional scale and to highlight the large potential inherent to the process of ongoing land degradation. This aspect is of high relevance to policy and decision makers in tropical Africa. Particular emphasis is laid on the specific effects of land degradation on the local and large-scale components of the hydrological cycle.

## 2. Model description

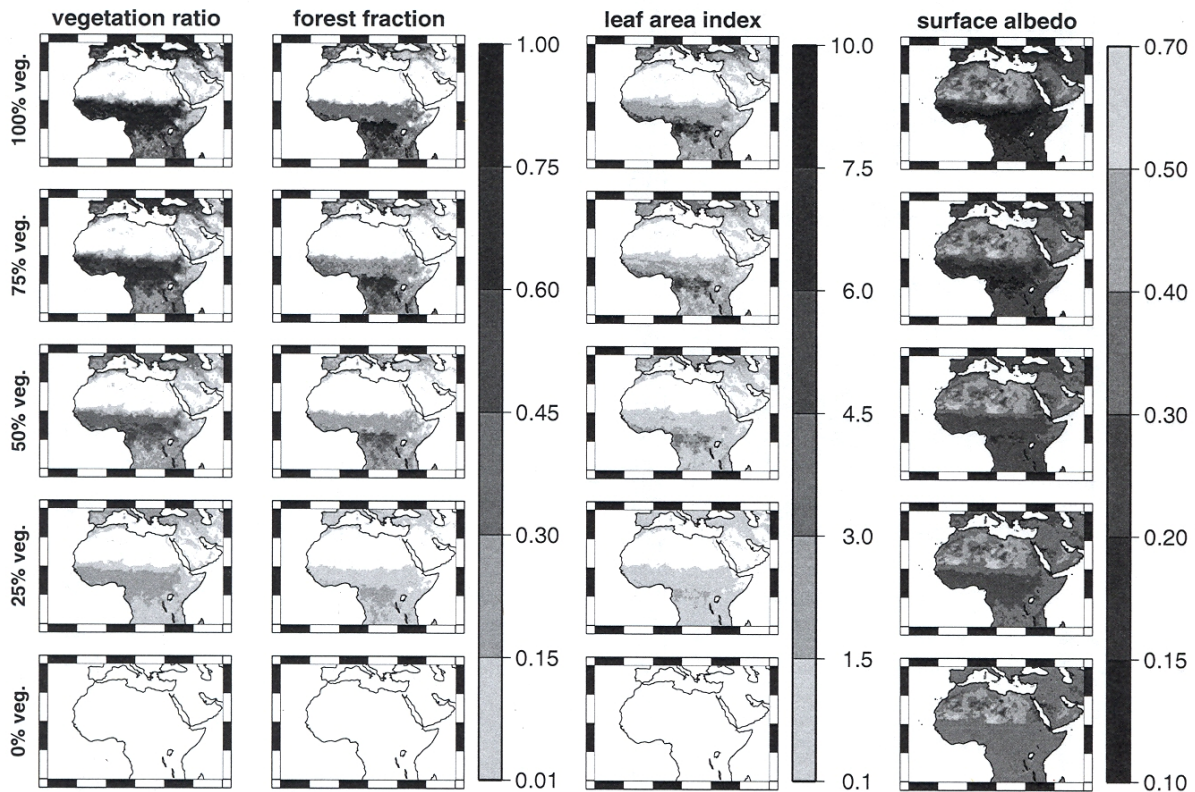
The hydrostatic regional climate model REMO has been developed at the Max-Planck Institute for Meteorology (Jacob 2001), based on the former operational weather forecast model Europa-Modell of the

German Weather Service (Majewski 1991). The model equations are transformed on a geographical  $\lambda - \Phi$  grid with a terrain-following vertical coordinate, split up into 20 hybrid vertical levels (Jacob *et al.* 2001). In the present version, the horizontal resolution amounts to  $0.5^\circ$ , equivalent to about 55 km grid spacing at the equator (Paeth *et al.* 2005). The model area extends from  $30^\circ$  W to  $60^\circ$  E and from  $15^\circ$  S to  $45^\circ$  N, covering the West African subcontinent, the Arabic Peninsula and the Mediterranean Sea.

Physical parameterizations are implemented, according to the global climate model ECHAM4 (Roeckner *et al.* 1996) and adjusted to the scale of REMO. Moist convection is parameterized by the mass flux scheme by Tiedtke (1989). In order to adjust REMO to the low latitudes, some parameter modifications have been carried out in the Tiedtke convection scheme (Paeth *et al.* 2005). Land surface processes are described by a 5-layer soil model down to 10 m depth with zero heat flux at the bottom. This model component is taken from the well-established ECHAM3 global climate model (Roeckner *et al.* 1992; Voss *et al.* 1998) and has been tested for many applications, for instance for the IPCC TAR (Houghton *et al.* 2001).

The model is nested in the global ECMWF reanalysis data (ERA15) (Gibson *et al.* 1997). Land surface parameters like vegetation, albedo, soil characteristics, roughness length and orography are taken from NOAA and GTOPO30 data. Vegetation cover, LAI and surface albedo are given as monthly-mean data linearly interpolated to the daily scale, assuming an idealized annual cycle. In the normal mode, the same surface parameters are prescribed each year. In the present case however, the vegetation-related surface parameters are changed, according to the prescribed scenarios. Here, REMO is run in the uncoupled mode, where the SST lower boundary conditions are also derived from the ERA15 data set. The model domain is initialized only once by the ERA15 data at the beginning of the integration period. Afterwards, the atmospheric and oceanic boundary conditions are prescribed every 6 hours.

In the model equations, a reduction in vegetation cover has a multiple effect: (i) The surface albedo is altered, implying a modification of the local radiation and energy balance at the ground. (ii) As vegetation is intercepting rain water until its water holding capacity is exceeded, soil moisture and energy balance in the soil model are modified, which in turn affect the latent and sensible heat fluxes from the surface into the atmosphere. (iii) LAI, forest and vegetation ratio enter the calculation of vertical diffusion and turbulent fluxes. (iv) Roughness



**Fig. 1.** Prescribed idealized scenarios of vegetation-related surface parameters in REMO : Vegetation ratio, forest fraction, leaf area index and surface albedo for the undisturbed simulation (top row) and the 4 sensitivity experiments, July conditions

length is partly arising from vegetation cover and also influences the turbulence in the atmospheric boundary layer.

In previous studies, REMO has been used for hindcast simulations (Paeth *et al.* 2005) and sensitivity studies with prescribed changes in SST (Paeth and Stuck 2004). The model performs well with respect to the observed main characteristics of African climate, including the mid-tropospheric jet and wave dynamics like the AEJ, the Tropical Easterly Jet (TEJ) and the African Easterly Waves (AEWs). In addition, the model's sensitivity to SST forcing agrees with estimates from other modelling and observational studies.

### 3. Experimental design

Four sets of experiments have been realized :

(i) One control run with present-day land cover and four simulations with progressively reduced vegetation have been integrated throughout the period May to October

1991. This period represents the summertime monsoon season over tropical West Africa, accounting for around 70 % of total annual precipitation amount. Note that this time slice selection omits seasonal feedbacks between the dry and rainy periods. The choice of the reference year 1991 is arbitrary because all experiments start from the same initial conditions and are forced with the identical lateral atmospheric and lower oceanic boundary conditions from ERA15. While the absolute values reflect the typical climate conditions in 1991, the differences between the time slices unambiguously arise from the effect of reduced vegetation cover. The idealized vegetation scenarios consist of a spatially homogeneous reduction of total vegetation cover by 75 %, 50 %, 25 % and 0 % with respect to the present-day conditions. No spatial differentiation along rivers, roads or corridors with high soil fertility or enhanced population growth is taken into account.

In REMO, there are several land surface parameters directly linked to changes in vegetation cover, *e.g.*, vegetation ratio, LAI, forest ratio, surface albedo and

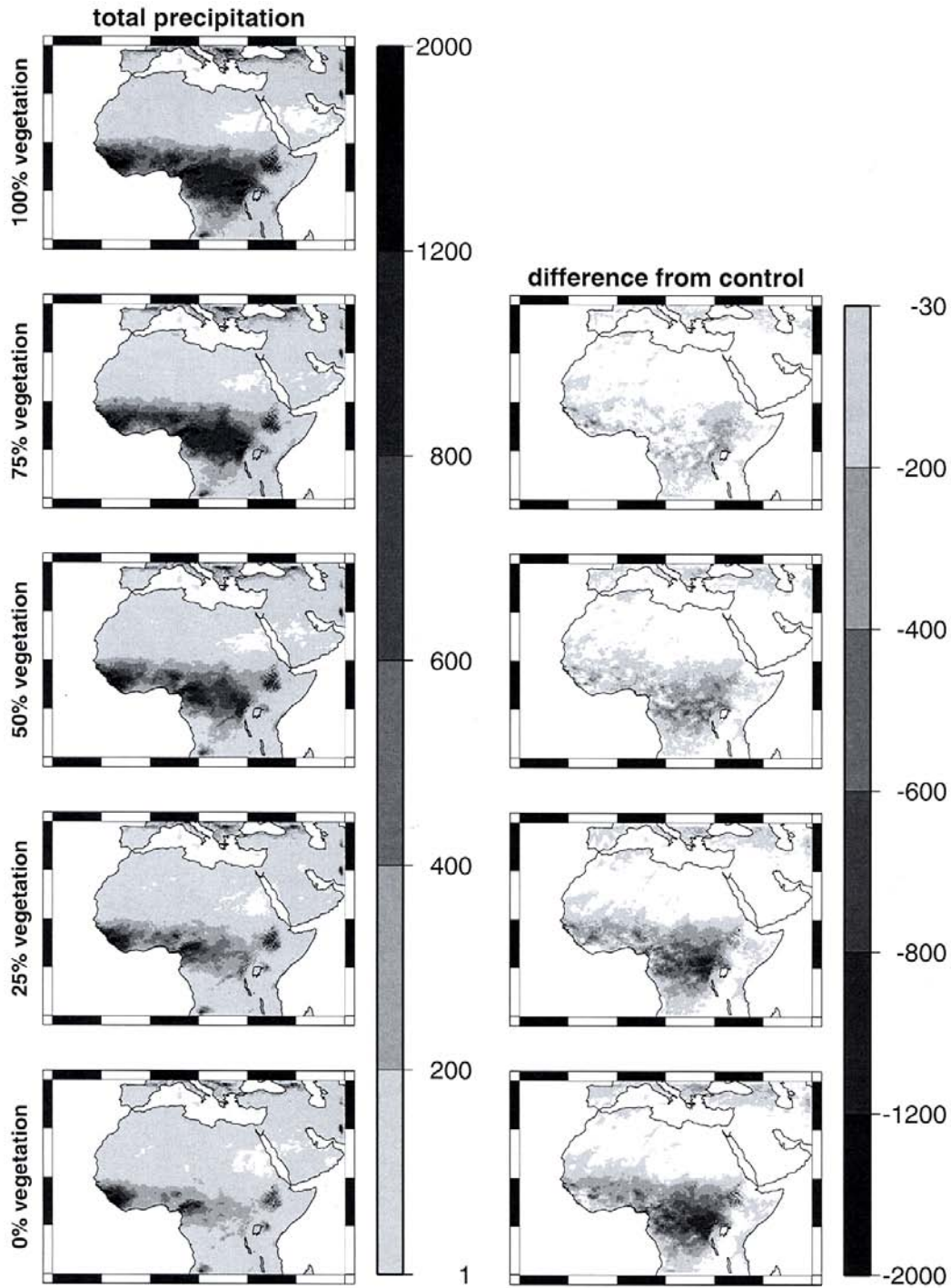


Fig. 2. Total rainfall in mm during the rainy season May-October 1991 in the control experiment and all experiments with changed vegetation (left column), changes in total rainfall due to reduced vegetation cover with respect to the control case (right column)

roughness length. In order to create a consistent scenario of land-cover changes, all these parameters have been modified accordingly. In terms of vegetation ratio, LAI, forest ratio and the vegetation-related part of roughness

length, the prescribed patterns are simply produced by multiplying the original fields by a factor of 0.75, 0.5 and so on. However, the related change in surface albedo is a simultaneous function of vegetation ratio, LAI and forest

fraction. Therefore a multiple linear regression analysis has been applied to all land grid points in order to derive the albedo changes from a combination of the three predictors. Vegetation ratio, LAI and albedo are additionally subject to a seasonal cycle whereas the other two forcing fields are constant through out the whole integration period. Fig. 1 displays four of the five prescribed forcing patterns: vegetation ratio, forest fraction, LAI and surface albedo. Roughness length is not explicitly displayed because the vegetation-related part is very small compared with the orographic contribution. In the undisturbed case (top panels), the highest vegetation density is located over tropical Africa with a distinct meridional gradient into the Sahara. This pattern is also reflected by forest fraction and LAI. Albedo amounts to around 0.15 in the tropics and up to 0.7 over the central Sahara. In the worst case scenario (bottom panels), vegetation completely vanishes and albedo substantially rises to about 0.4 over tropical Africa, whereas no changes occur in regions without vegetation cover under present-day conditions.

(ii) In order to gain insight into the relative importance of the five vegetation-related forcing parameters mentioned above, five 1-month experiments have been carried out for July 1991. In each run only one of the five input fields – vegetation ratio, forest fraction, LAI, albedo (from multiple regression) or roughness length - is set to 50%, whereas the others are kept unchanged according to present-day conditions.

(iii) The sensitivity study with respect to modified soil properties consists of 2 two simulations, covering the same May to October period in 1991. Both runs only differ in terms of the amplitude of the prescribed changes. The considered soil parameters are as follows (values in brackets denote the warker forcing): Surface runoff is assumed to increase under reduced vegetation cover and is multiplied by a factor of 10 (5). Evaporation from soil is initiated if 90 % (82.5 %) saturation is reached instead of 75 %. Lateral drainage in the soil body is allowed from 95 % (92.5 %) saturation onward instead of 90 %, equivalent to an increase in surface runoff. The wilt point is set from 0.35 to 0.5 (0.425), implying that soil water is less available to the transpiration by plants. Fast drainage is accelerated from  $2.8 \cdot 10^{-8} \text{m/s}$  to  $2.8 \cdot 10^{-7} \text{m/s}$  ( $1.4 \cdot 10^{-7} \text{m/s}$ ). The same holds for the slow drainage but exactly two orders of magnitude below these values. Fast and slow drainage govern the amount of rainfall, which does not enter the skin reservoir and hence affects the ratio of soil infiltration and surface runoff. All six soil parameters are combined to one presumed scenario of “soil degradation”. In order to isolate the impact of the soil parameters from the land-cover scenarios described above, the five vegetation-related surface parameters are not changed

with respect to present-day conditions (upper panels in Fig. 1).

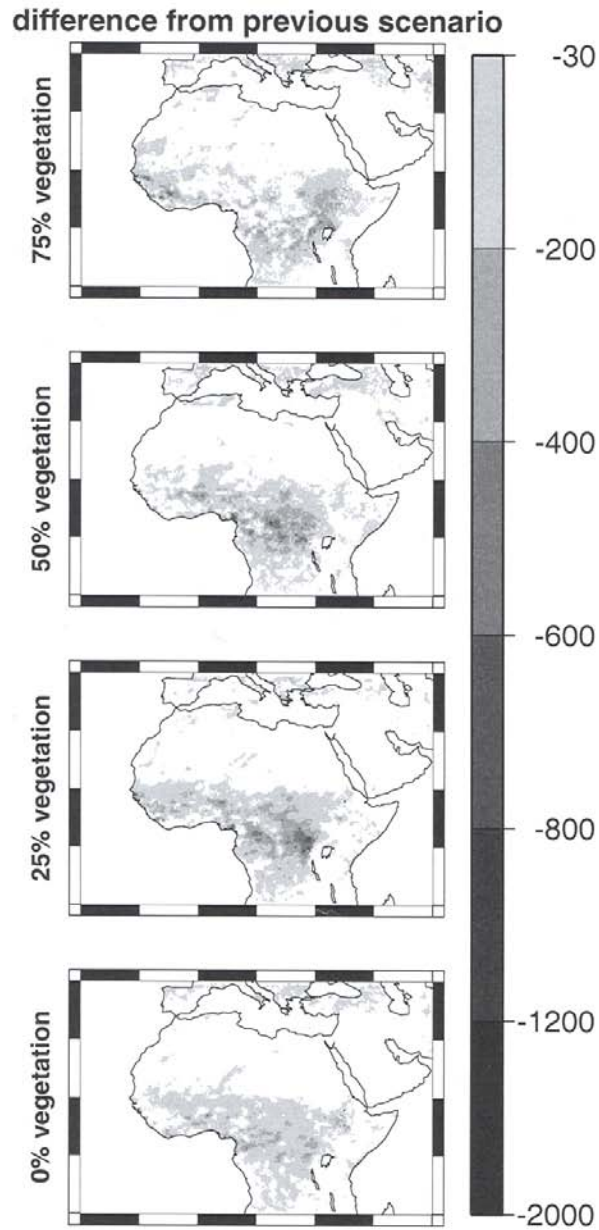
(iv) According to the second set of experiments, six one-month simulations have been integrated for July 1991, each being subject to only one altered soil parameter. Assigning the present-day level to the other five parameters allows to compare the relative impacts of the individual soil properties on African rainfall with each other.

Note that the model does not account for feedbacks of the atmosphere onto the land cover. Thus, some damping or reinforcing effects between land degradation and climate change may be missing. Further uncertainty arises from the idealized nature of the response because it is assumed that vegetation cover directly changes to bare soil. As a consequence, the amplitude of the simulated changes may be higher than expected in reality. It is obvious that the results presented here cannot be interpreted as providing final quantitative accuracy. As mentioned above, the goal of this study is to highlight the physical mechanisms and the potential sensitivity of African climate to land degradation. In addition, the most affected regions can be detected.

## 4. Results

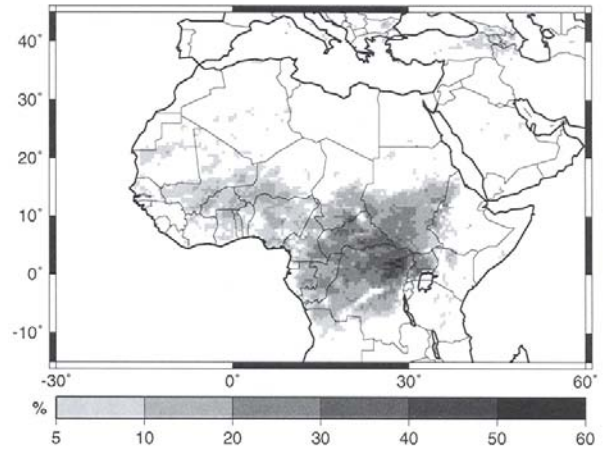
### 4.1. Changes in rainfall characteristics

The first subsection is dedicated to rainfall changes in response to decreasing vegetation cover. The change in total rainfall amount during the summertime monsoon season is displayed in Fig. 2 (left column). In the undisturbed case (100 % vegetation) precipitation peaks occur over the Congo Basin and the western Guinean Coast, reaching up to 2000 mm over the May-October period. The model also simulates the so-called Dahomey gap which is characterized by slightly less rainfall over the central Guinean Coast region (cf. Saha and Saha 2001). Towards the Sahel Zone and the inner Sahara the climate conditions are steadily becoming more arid. This pattern is in excellent agreement with the observed rainfall climatology (cf. Paeth *et al.* 2005), except a systematic underestimation of total rainfall amount over subsahelian West Africa. Proportional to the extent of land degradation, summer precipitation gradually decreases by up to - 1700 mm over the eastern Congo Basin in the extreme case of entire vegetation loss (Fig. 2, right column). The response patterns are spatially coherent, affecting large parts of subsaharan Africa. There is no intraseasonal variation in the signal, all months showing more or less the same amplitude of rainfall decrease (not shown).

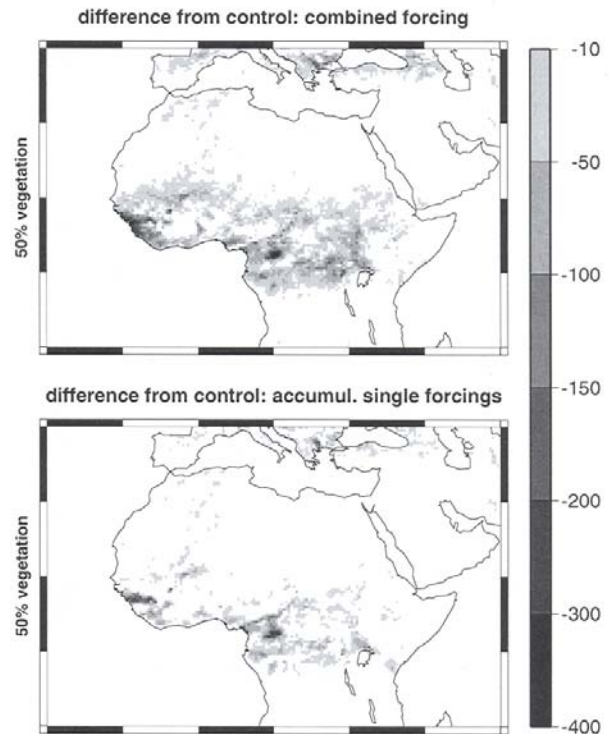


**Fig. 3.** Nonlinearity of the response as depicted by the changes in total rainfall in mm with respect to the previous vegetation scenario

Given the currently observed trends of deforestation and population growth (Pahari and Murai, 1997), the 50 % scenario in Fig. 1 may draw a more realistic picture of what may happen until 2100: the monsoonal precipitation is still diminished by about 400 mm over a huge region with some peaks over central Africa even amounting to - 800 mm. Compared with the simulated impact of increasing GHGs (Paeth and Stuck 2004, see section 1), the vegetation effect is in the same order of magnitude.

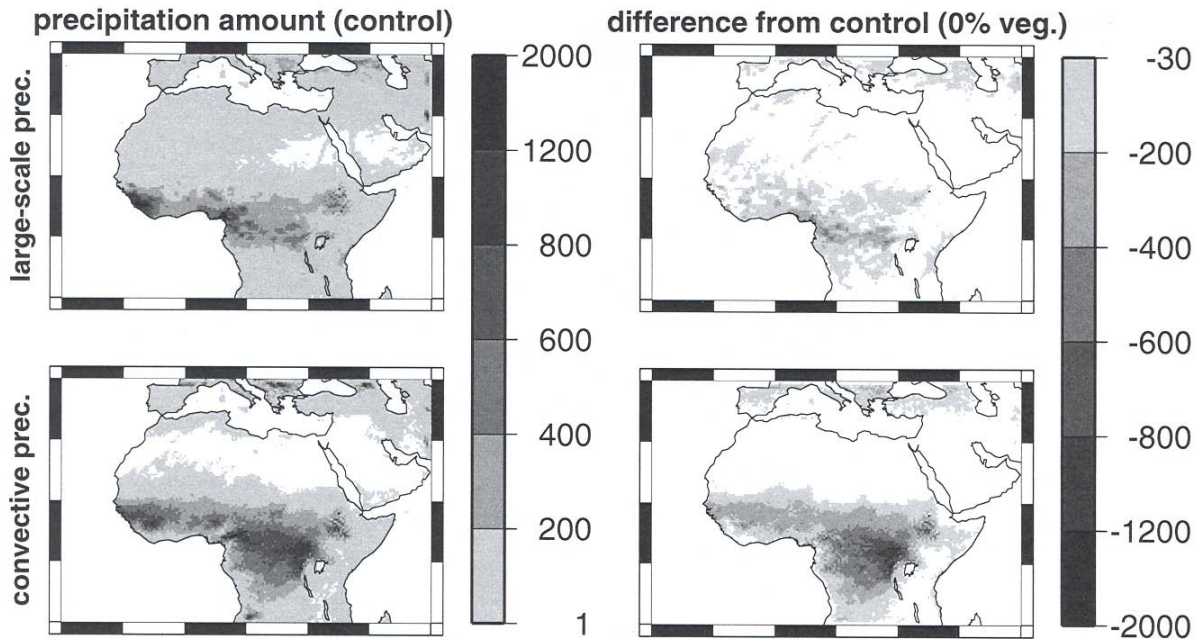


**Fig. 4.** Impact of vegetation changes in % on total pentadal rainfall variability during May to October 1991 as quantified by analysis of variance. Only values significant at the 1% level are plotted



**Fig. 5.** Total rainfall response in July in mm given a vegetation decrease of 50% : Combined forcing *versus* accumulated individual forcings, including vegetation ratio, leaf area index, forest ratio, roughness length and surface albedo

While a compensation of both forcing factors may occur over the Guinean Coast region, global warming and land degradation equally tend to favour drought conditions



**Fig. 6.** Large-scale and convective precipitation in mm during May to October 1991 in the control experiment and the respective changes under vanished vegetation cover

over central tropical Africa and the Sahel Zone. The Sahara and Arabic Peninsula with hardly any vegetation cover under present-day conditions are barely affected by land degradation. Surprisingly, the same holds for southern Europe. These findings may be interpreted as follows: (i) The vegetation impact on summer precipitation predominantly works at the local scale, modifying rainfall in the direct vicinity of the land-cover changes and (ii) Precipitation in the tropics is more related to local feedbacks with the land surface than in the extra tropics, where rainfall events are rather governed by large-scale atmospheric circulation. Before returning to these basic issues, some more characteristics of the rainfall response are described.

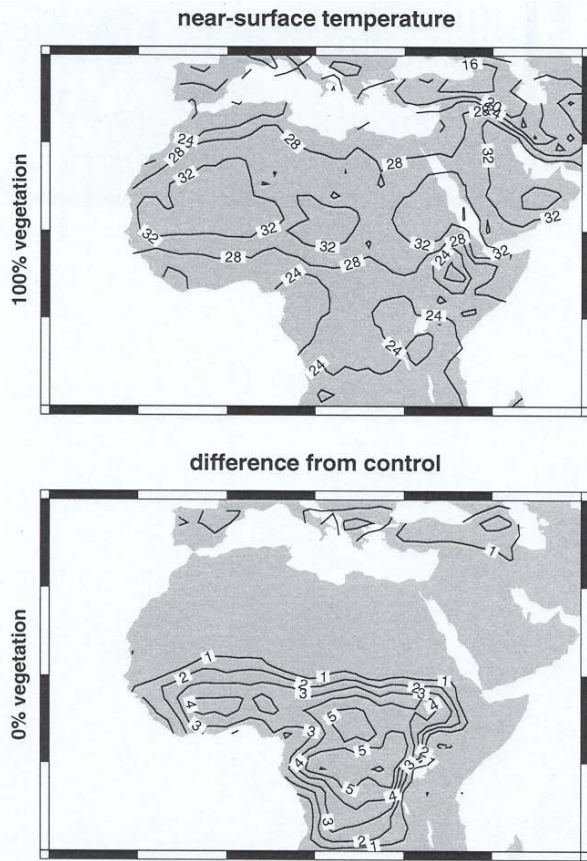
Fig. 3 shows the seasonal rainfall changes over Africa with respect to the previous (weaker) vegetation scenario. It is obvious that the amplitude of the precipitation anomalies, albeit systematically of negative sign, is not equal for equidistant changes in vegetation cover. This implies that the rainfall response to land-cover changes is nonlinear. Reducing vegetation to 75 % of the present-day level, is related to a minor decrease in monsoonal rainfall. The strongest relative changes are simulated, if vegetation cover is reduced by 50 and 75 % - a scenario which cannot be excluded until 2100.

Given 5 experiments with the same initial and lateral boundary conditions but different treatments in the form

of reduced vegetation, the contribution of this treatment effect to total climate variability can be quantified by applying analysis of variance with random treatment (ANOVA) (von Storch and Zwiers 1999). The method is designed to distinguish between the externally forced part of variance between the time slices and internal variability within the time slices. Note that this type of ANOVA is different from the classical approach in Paeth and Hense (2004) where a transient forcing effect is tested against internal variability as imposed by varied initial conditions. Since the method requires that the data is normal distributed, pentadal instead of daily rainfall data are used. The alternative hypothesis is that changes in vegetation cover induce a systematic response in African rainfall which stands out from the internal pentadal variations within each May-October integration period. It is evaluated with a Fisher F-test, taking the auto-correlation of pentadal precipitation into account. Fig. 4 illustrates the contribution of land-cover changes to total pentadal rainfall variance at each grid point of the model domain. Large parts of sub-saharan West Africa are characterized by a prominent and spatially coherent vegetation signal.

Especially, over central tropical Africa the land-cover effect accounts for up to 60 % of total rainfall variability. This signal is statistically significant at the 1 % level and stands out from the remarkable intraseasonal variability of the monsoonal precipitation.





**Fig. 7.** May-October mean near-surface temperature in °C under present-day conditions (top) and changes related to a total loss of vegetation cover (bottom)

In the next step, the individual contributions of the 5 forcing fields - vegetation and forest ratio, albedo, LAI and roughness length - to the overall rainfall signal are estimated. For this purpose, each of these surface parameters has been isolated and used as 50 % scenario in 5 individual experiments covering July 1991 (see section 3). It is found that none of the factors is outstanding from the others (not shown). Rather all forcing fields are associated with a similar amplitude and direction of the rainfall response. Accumulating the precipitation anomalies of the 5 individual runs results in a weaker and spatially less coherent signal than using the combined vegetation scenario described above (Fig. 5). Thus, the interaction of vegetation cover with albedo and roughness length is essential to the amplitude of the rainfall changes in REMO. This implies that the regional climate model handles the imposed land-cover changes in a nonlinear way.

Fig. 6 (left column) reveals that tropical Africa is predominantly governed by convective rainfall, whereas

large-scale precipitation is mainly related to orography like in the western Guinean Coast region and in the vicinity of the Cameroon mountain. In the extratropics the ratio is rather well-balanced. A total loss of vegetation cover leads to a considerable response in convective rainfall but small changes in large-scale precipitation (Fig. 6, right column). The latter is closely tied to the large-scale atmospheric circulation, while the convective component is generally assumed to be more affected by local feedbacks with the land surface (Zeng *et al.* 1999; Long *et al.* 2000). Thus, the prevailing signal in convective rainfall may be interpreted as a further indicator of the local impact of land-cover changes.

From these model results it is obvious that African rainfall is largely sensitive to changes in vegetation cover, especially in the tropics. Convective rainfall appears to be more affected by land degradation than large-scale precipitation. This leads to the question of the physical mechanisms linking land-cover changes to rainfall anomalies. In the following two subsections, the various simulated climate responses are split up into a dynamical and a local component in order to gain insight into the underlying processes.

#### 4.2. Dynamical effects

The following figures are all composed in the same way: The top panel represents the undisturbed May-October climatology as a reference, while the lower panel illustrates the maximum climate anomaly as revealed by the worst-case vegetation scenario (0 %). In general, the changes are approximately proportional to the imposed reduction in vegetation cover (Figs. 2 & 3). In addition, there is hardly any intraseasonal variation in the signal. Oceanic grid points are mostly masked out in order to concentrate on the climate changes over the land masses.

Fig. 7 displays the mean and difference patterns of 2-meter temperature. In Northern Hemisphere summer the maximum temperature is simulated in the central Sahara, amounting to about 32 °C even in the 6-month mean. Towards the Gulf of Guinea with relatively cold SSTs and the atlas mountains near-surface temperature is steadily decreasing to less than 24 °C (cf. Saha and Saha 2001). A complete loss of vegetation cover causes a substantial warming in the lower atmosphere by about 5 °C in the Congo basin and 4 °C over parts of subsahelian West Africa. A weaker response by up to 2 °C occurs over some regions in southern Europe. Near-surface temperature is mainly governed by net radiation and further depends on the partitioning between latent and sensible heat fluxes (the so-called Bowen ratio). Thus, the warming is assumed to arise from reduced soil moisture and latent heat fluxes whereas sensible heat fluxes increase. On the

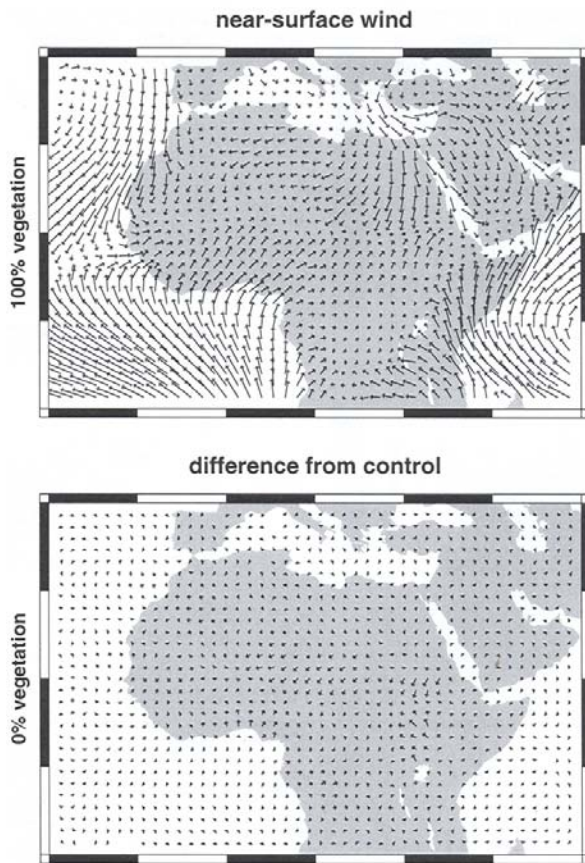


Fig. 8. Same as Fig. 7 but for near-surface wind vectors

other hand, vegetation loss is coming along with higher surface albedo (Fig. 1), which in turn should imply surface cooling. Obviously, the shift in the Bowen ratio is the more dominant player in the physical relationship between land-cover changes and climate anomalies as is the increase in surface albedo. This aspect will be picked up later. In contrast to near-surface temperature, the free atmosphere is cooling over most of West Africa, albeit of a much weaker amplitude ( $<0.8$  °C, not shown). The cooling can be explained by a decrease in latent heat release from condensation of water vapour in the middle troposphere.

The thermal gradients over Africa represent a key factor in the large-scale monsoon circulation. The West African summer monsoon is characterized by a strong southwesterly flow into the subcontinent which is converging at around  $17^{\circ}$  N with a weaker northeasterly wind, called Harmattan (Saha and Saha 2001) (Fig. 8, top). The difference pattern shows that land-cover changes tend to intensify the Harmattan and, albeit to a lower extent, the southwesterlies over some parts of the Guinean

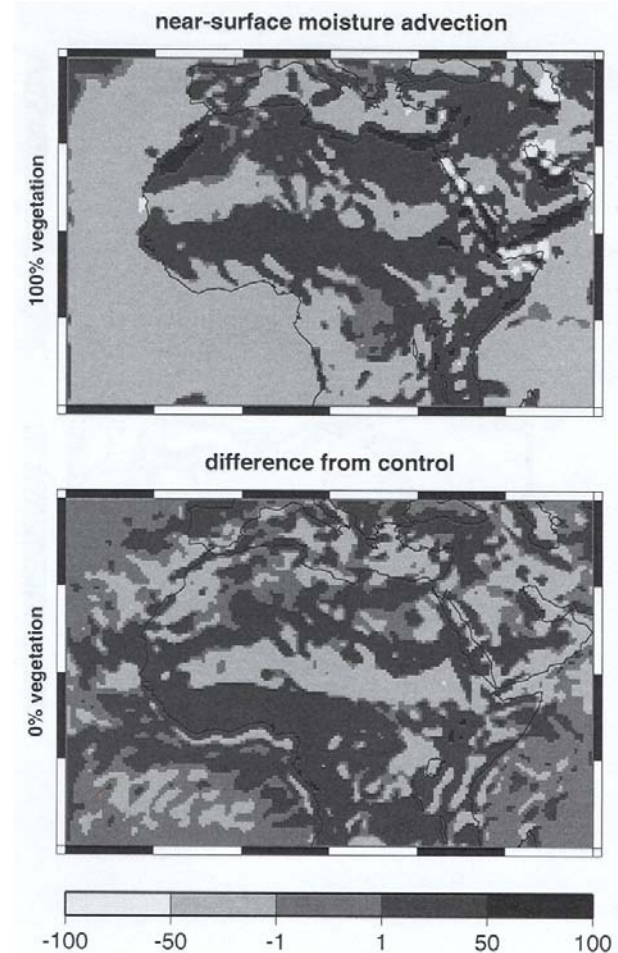
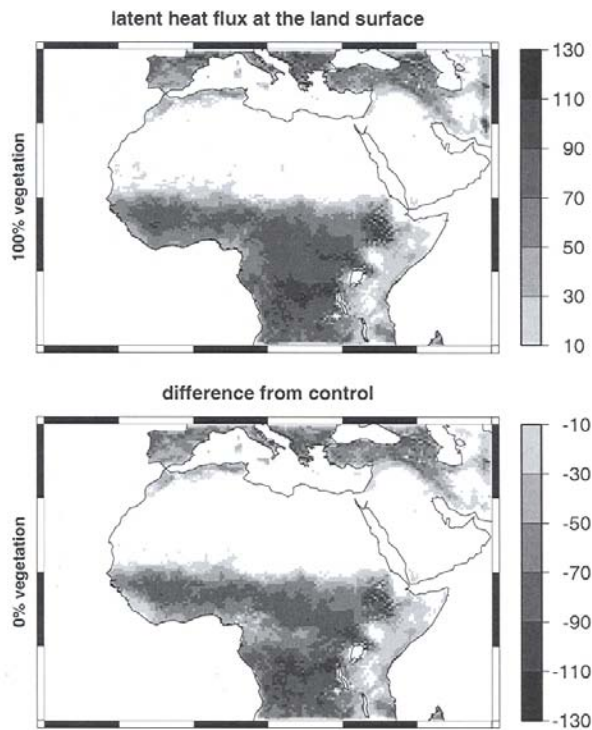


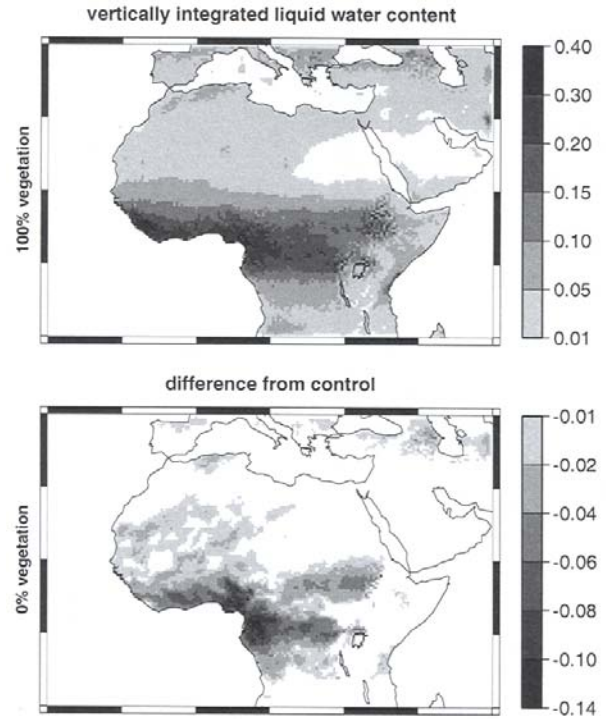
Fig. 9. Same as Fig. 7 but for near-surface moisture advection in  $10^{-9}\text{kg/kg}\cdot\text{s}$ , positive values indicating a net transport of moisture into the grid box

Coast region *via* enhanced surface heating (Fig. 8, bottom). The consequence is a slight southward shift and strengthening of the ITCZ (not shown). This anomaly in the monsoon circulation should favour the formation of rainfall over the Guinean Coast region and is, at first sight, in disagreement with the overall reduction in precipitation amount (cf. Fig. 2). This discrepancy will be further discussed in subsection 4.3.

The near-surface position of the ITCZ is not a stringent indicator of the precipitation maximum in West Africa, since atmospheric moisture content is an important pre-requisite of deep convection and rainfall formation. Therefore, particular emphasis is laid on the simulated moisture advection into an imaginary atmospheric column. This process represents one of the basic components in the atmospheric moisture budget. Here, it is defined over a  $0.5^{\circ} \times 0.5^{\circ}$  model grid box. The black and dark grey shading in Fig. 9 (top) indicates that the



**Fig. 10.** Same as Fig. 7 but for latent heat fluxes at the surface in  $\text{w/m}^2$ , positive values denoting fluxes from the surface into the atmosphere



**Fig. 11.** Same as Fig. 7 but for vertically integrated liquid water content in  $\text{kg H}_2\text{O/kg Luft}$

May-October mean moisture advection by near-surface winds implies a prominent moisture enrichment over the northern Guinean Coast region, the Sudan and the southern Sahel. This zone is located southward of the mean position of the ITCZ at about  $17^\circ \text{N}$ . Divergent flow prevails to the south and north. The vegetation-related surface heating causes a southward displacement and enhancement of moisture advection over the entire Guinean Coast region and the Congo Basin (Fig. 9, bottom). This tendency is somewhat weaker but still prevailing, when the moisture advection is vertically integrated (not shown). Thus, the large-scale dynamical response to reduced vegetation cover should principally be associated with more abundant rainfall over the southern West African monsoon region. Obviously, other terms in the atmospheric moisture budget equation overcompensate this dynamical component (see subsection 4.3).

Another large-scale component of the West African monsoon system is the lower-tropospheric AEJ, which is usually meandering in the form of the AEWs. Both dynamical phenomena are well-known to be directly linked to African rainfall during the summer monsoon season (Hastenrath 2000; Thorncroft and Hudes 2001).

The AEJ is characterized by easterly wind directions and the peak velocity is shifting between  $0^\circ$  in the transitional seasons and  $15^\circ \text{N}$  in boreal summer (not shown). The AEWs can be described as an alternation of northerly and southerly wind anomalies in a band westward of  $30^\circ \text{E}$ , which are propagating westward with a time scale of 4 to 6 days. The simulated AEJ and AEWs are in excellent agreement with the observed characteristics (Grist 2002; Paeth *et al.* 2005). Comparing the undisturbed and vegetation-less climates with each other hardly reveals any sensitivity of the lower-tropospheric jet dynamics to changes in the land cover (not shown). As the AEJ is not directly linked to the ITCZ position at the surface but to heating sources in the central and eastern Sahara which itself is barely affected by the land-cover changes, the insensitivity of mid-tropospheric circulation is not surprising.

#### 4.3. Local effects

There is still some disagreement between the results of subsections 4.1 and 4.2 : while the simulated dynamical response of the monsoon circulation should cause an increase in rainfall amount over tropical Africa, an overall

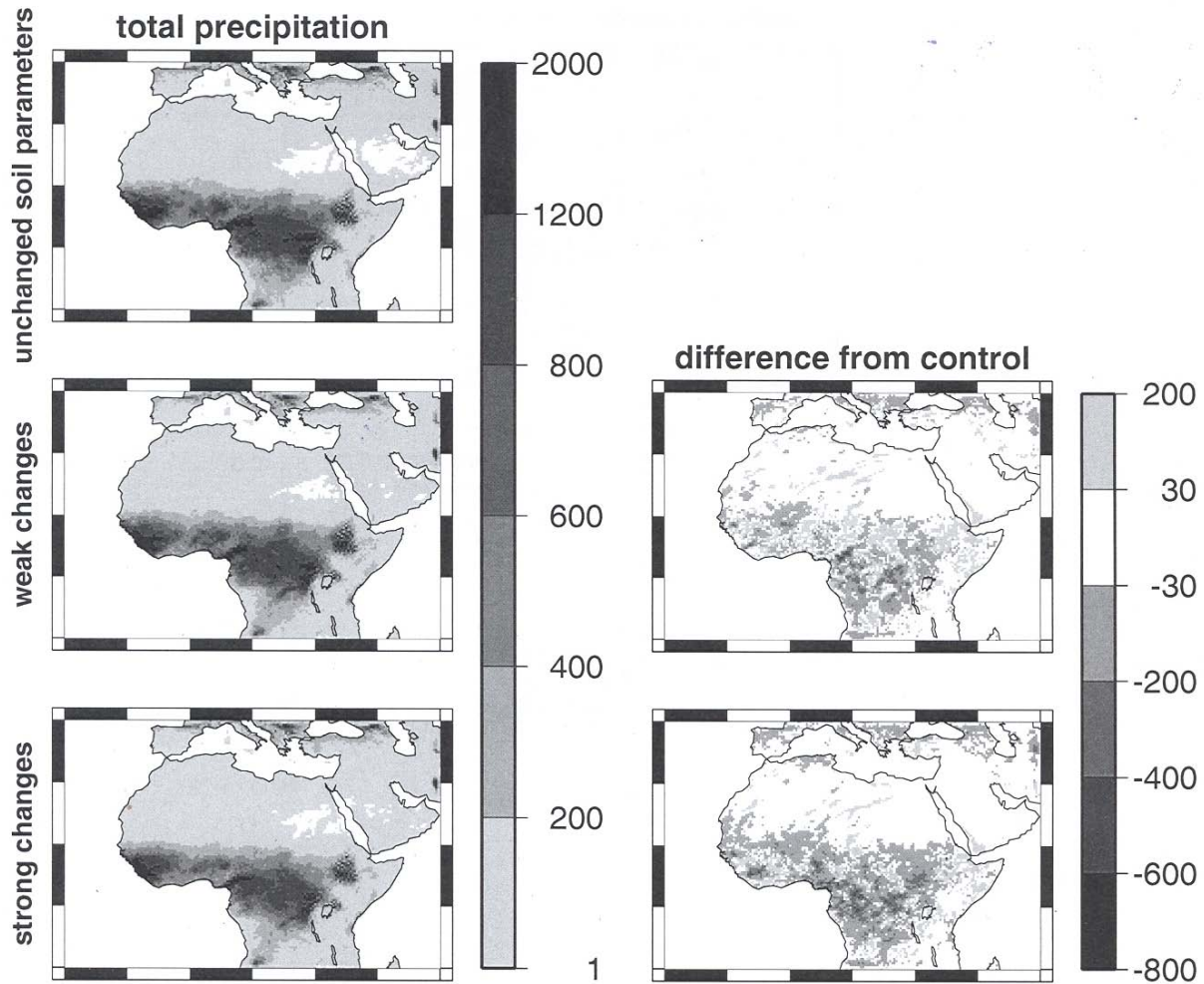


Fig. 12. Same as Fig. 2 but for modified soil parameters and present-day vegetation cover

decrease is actually simulated by the regional climate model. Thus, another component of the atmospheric moisture budget must play a more important role over Africa than large-scale circulation. The moisture content in an atmospheric column, which is a precursor of the atmospheric liquid water content and hence rainfall formation, is governed by two processes: the moisture advection integrated over the whole vertical extent of the column and the latent heat fluxes into the column. There is some indication that the latter term is more relevant to the precipitation changes due to land degradation. Fig. 10 shows the mean and response patterns of the latent heat fluxes, positive values denoting fluxes from the surface into the atmosphere. In the undisturbed climate, latent heat fluxes peak in the inner tropics, the West African

monsoon region and the southern part of Europe with up to  $60\text{-}120\text{ w/m}^2$  in the 6-month mean. Minor fluxes occur over the Atlas region and East Africa, while almost no evaporation is simulated over the central Sahara and the Arabic Peninsula. This pattern is highly reminiscent of the distribution of dense vegetation (Fig. 1, top left panel) and rainfall amount (Fig. 2, top left panel). Indeed, surface evaporation depends on soil moisture, interception and transpiration by plants and of course preceding rain event. Therefore, it is not astonishing that under a scenario of reduced or vanished vegetation cover, the latent heat fluxes decrease remarkably (Fig. 10, bottom). Actually, the decrease is in the same order of magnitude as the mean values in the top panel, implying a substantial drying of the soils. The striking response in evaporation is directly

arising from the missing interception and transpiration by plants and indirectly from reduced soil moisture. In addition, less freshwater input by rainfall also feeds back on surface evaporation. The response may be somewhat weaker, if horizontal groundwater and surface water flow were simulated by the model, transporting enhanced surface runoff to wetlands and lakes.

The bottom panel in Fig. 11 finally reveals that the vertically integrated liquid water content is substantially diminished over most of sub-Saharan West Africa and the Congo Basin. This atmospheric parameter is a precursor of rainfall formation within a model grid box. The decrease is not only a consequence of reduced atmospheric moisture content but also an indication of atmospheric heating which hampers condensation and cloud formation. Thus, the presumed causal relationship between land degradation and decreasing African rainfall, as suggested by the regional climate model, works *via* reduced surface evaporation into the atmosphere, a decrease in the atmospheric liquid water content and a prevention of deep convection. This process is taking place at the local scale and inhibits the local recycling of water as a key component of the hydrological cycle in the low latitudes.

#### 4.4. Role of soil parameters

The last issue of this study concerns the specific role of soil degradation, as expected under reduced vegetation cover (Sections 2 and 3). The imposed changes in the soil parameters tend to enhance surface runoff and to decrease evaporation. Note that the prescribed changes in the soil properties are quite intuitive, since reliable information on the exact soil response to large-scale land-cover changes was not available for the continental view of this study. The response of total May-October rainfall amount to the effect of soil degradation is displayed in Fig. 12. Over most of tropical Africa, negative precipitation anomalies prevail. However, the amplitude of the changes is much weaker than in the case of the vegetation scenarios, not exceeding -600 mm in central Africa. Assuming weak changes in the soil parameters, the signal is not spatially coherent. In addition, the impact of the imposed soil parameter changes is barely significant, as indicated by ANOVA (not shown). None of the considered soil parameters is standing out from the others, rather all of them are associated with a similar amplitude and pattern of rainfall anomalies (not shown). Of course, it is questionable whether the soil model in REMO and the prescribed modifications account for the full variety of relevant soil processes. Nonetheless, these findings suggest that a vegetation-induced soil degradation tends to aggravate the problem of deficient precipitation amount in tropical and subtropical Africa.

## 5. Concluding remarks

The present study aims at improving our understanding of the vegetation impact on African climate. Time slice experiments with a regional climate model are carried out under gradually enhanced scenarios of reduced vegetation cover and modified soil properties, respectively. A consistent vegetation scenario is performed. The idealized nature of the forcings implies that there is still uncertainty in the simulated climate changes from a quantitative point of view. Therefore, the main goal of this study rather is to highlight the potential sensitivity of African climate to ongoing land degradation and to determine the regions with highest vulnerability under enhanced forcing conditions.

The major effect of reduced vegetation cover is a remarkable decrease in May-October precipitation over most of tropical and subtropical Africa. The rainfall response in REMO is nonlinear and statistically significant. Convective precipitation is more sensitive to land-cover changes than the large-scale component. At the local scale, the most prominent signal is a decrease in surface evaporation. Accordingly, enhanced sensible heat fluxes lead to a substantial surface warming and a modification of the thermal gradients, which represent a key factor in the African monsoon circulation. The middle troposphere is cooling due to less latent heat release from the condensation of water vapour in this level. The strongest surface heating is simulated over the southern part of West Africa, resulting in an intensified surface wind convergence in this area. Simultaneously the ITCZ is slightly shifted to the south. In contrast, the lower tropospheric jets and waves are hardly affected by land degradation. The large-scale dynamical response favours an enhanced summer monsoon flow and moisture enrichment over the Guinean Coast region and Congo Basin. This dynamical effect is overcompensated by a decrease in the latent heat fluxes. The resulting reduction in the vertically integrated liquid water content and precipitation amount clearly reveals that the local effect of land-cover changes finally wins out. The isolated impact of soil degradation is minor and barely significant but contributes to the slowdown of local water recycling in tropical Africa. Comparing the individual vegetation-related surface and soil parameters with each other, it is found that none of these factors alone is outstanding from the others (cf. Maynard and Royer 2004).

There are three main conclusions to be drawn from this sensitivity study: (i) An ongoing degradation of the present-day vegetation cover may be associated with a substantial decrease in rainfall amount during the West

African summer monsoon season. Assuming that the 50 % scenario may be realized by the end of the 21<sup>st</sup> century, rainfall presumably decreases by 200 to 800 mm over large parts of tropical Africa where food security, human welfare and health are already alarming under present-day conditions. (ii) The local effect of land-cover changes is obviously more relevant than the large-scale dynamical response, inhibiting the local recycling of water as a major component of the hydrological cycle in the low latitudes. (iii) When simulating anthropogenic climate change in Africa, it is essential to account for the aspect of man-made land-cover changes as well. Particularly, the second main conclusion is of high political relevance because it implies that there is a national or even regional scope of action with respect to climate protection measures. In contrast, the problem of increasing GHG emissions can only be handled in an international effort.

The vegetation impact described here has to be evaluated against the background of other driving forces in future African climate. REMO has also been used to determine the response of African rainfall to enhanced greenhouse conditions (Paeth and Stuck 2004). Comparing these experiments with each other reveals that greenhouse forcing and land degradation induce climate changes in the same order of magnitude. It is a challenge for future modeling studies to develop more complex anthropogenic forcing scenarios including enhanced GHG and aerosol concentrations as well as ongoing land degradation. This may provide more realistic predictions of future African climate as a scientific basis for political measures and planning.

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