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Mesoscale modelling of interactions between rainfall and the land surface in West Africa

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With 9 Figures

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Summary

Within the joint research project IMPETUS (An integrated approach to the efficient management of scarce water resources in West Africa), the effect of interactions between the Earth's surface and the atmosphere on fresh water availability is investigated. Explorations are conducted for a river catchment in Benin by means of simulations with a non-hydrostatic mesoscale meteorological model. A combination of idealised ensemble simulations with a column version of the model and 3-D modelling of real precipitation events is employed to assess the sensitivity of precipitation to variations in the land surface. Simplified ensemble studies exhibit a dominant influence of initial soil water content and an enhanced dependence of precipitation on vegetation when soil water availability is reduced. For wet soils, the influence of parameters that determine the intensity of near-surface turbulence is dominant. 3-D modelling confirms that these relationships are useful to identify critical land use changes in realistic settings, but do not comprehensively account for the effect of heterogeneous land surface changes on regional precipitation. Instead, the interplay between surface properties, atmospheric dynamics and precipitation systems can generate intrinsic precipitation anomaly patterns that are incongruent with the imposed surface anomalies. Hence, assessments of land use change effects on precipitation for a specific region should be based on an integrated consideration of the interactions between surface processes, atmospheric forcing and precipitation systems. Based on these findings, possible effects of successive land degradation are investigated by sensitivity studies of land surface and rainfall system interaction for the Haute Vallée de l'Ouémé (HVO). In a first series of 3-D model simulations, a successive increase of the surface fraction with adverse conditions for the development of precipitation systems is performed. Within the scope of a second series a successive reduction of surface vegetation and soil water at randomly distributed areas that cover half of the simulation domain is carried out. Basically, a uniform decrease of average precipitation forced by changing conditions and a strong reduction of rainfall in some parts of the HVO are found. As a whole, the results strongly support the hypothesis of a growing risk of rainfall decrease as a result of land use changes.

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1. Introduction

Possible rainfall reduction by land surface changes in the vulnerable Sahel/Soudan zone in West Africa has been a research topic throughout the past three decades. The evolution of convective precipitation systems as the primary rainfall source in this zone is considered to be substantially influenced by surface-atmosphere exchanges of water and energy (e.g., Guichard et al, 1996). Exchange processes depend on surface and soil characteristics that vary with soil and interception water, which are in turn influenced by antecedent rainfall. Through this feedback, land surface changes can affect regional precipitation. As shown by a review written by Nicholson (2000), current knowledge is not sufficient to evaluate the effects of land surface changes on regional rainfall in the Sub-Saharan belt. In particular, it is still unclear to which extent the land surface plays an active role. While, among others, Taylor and Lebel (1998) find observational evidence for a positive feedback between soil moisture and rainfall anomalies, other studies (e.g., Taylor et al, 1997) attribute a dominant role to the large-scale atmospheric flow. Numerous model studies that suggest a significant effect of the surface-precipitation feedback (cf. Nicholson, 2000 for an overview) are either based on simplified conceptual models or on global circulation model (GCM) simulations that are too coarse for a regional interpretation.

This study contributes to an exploration of rainfall reduction risks by land surface changes in the Haute Vallée de l'Ouémé (HVO) catchment in Benin, West Africa. These risks are given if an active role within the surface-precipitation feedback mentioned above can be attributed to the land surface. Such an active role is potentially related to mechanisms of evaporation and heating which affect the life cycles of individual precipitation systems. The state of the surface itself may be influenced by earlier rainfall events. Our study addresses the question whether these short-term feedbacks between the land surface and precipitation can substantially alter rainfall amounts and rainfall patterns on time scales of single precipitation episodes. If so, the hypothesis of an active role of the land surface and an associated risk of rainfall reduction caused by land surface changes would be substantially supported. Our activities are part of the joint research initiative IMPETUS (An integrated approach to the efficient management of scarce water resources in West Africa). Within IMPETUS, our study contributes to establish a basis for an evaluation of tolerable regional land use changes with respect to rainfall availability in the HVO.

Surface-precipitation interactions on the regional scale can be feasibly investigated by sensitivity studies with high-resolution mesoscale models that resolve regional land surface heterogeneity and simulate individual precipitation systems. For this purpose, the model FOOT3DK (Flow Over Orographically Structured Terrain, 3-dimensional, Köln Version) is employed. A twofold strategy of sensitivity studies with FOOT3DK is pursued. Idealised ensemble studies with a single column version of the model are compared with 3-D simulations of a real precipitation episode. The economical consumption of computing resources by the idealised simulations enables the generation of a large, statistically meaningful ensemble. Analysis of the ensemble then yields the relevant parameters for an inductive introduction of hypothetical land use variations in 3-D sensitivity studies. This strategy allows to consider the regional applicability of simplified approaches as well as to improve the understanding of the mechanisms that affect precipitation in realistic settings.

2. The model FOOT3DK

FOOT3DK is a prognostic non hydrostatic limited-area model that is designed for horizontal resolutions from 10 km to several 100 m. Recent applications include the development of advanced convection parameterisations for the mesoscale (Sogalla and Kerschgens, 2001), process studies of the interaction between land surface and atmosphere (e.g., Shao et al, 2001; Hübener et al, 2004, or Heinemann and Kerschgens, 2005) and studies of local circulation patterns (Heinemann, 2003). FOOT3DK is based on the primitive equations, which are solved for a divergence-free flow. Terrain-following η-coordinates with highest resolution near the surface are used in the vertical (Brücher et al, 1998). Atmospheric model physics include schemes for radiation, turbulence and moist physics. FOOT3DK is equipped with parameterisations of condensation, precipitation and convection that are designed for the mesoscale and tested for horizontal grid sizes of a few km (cf. Sogalla and Kerschgens, 2001, for details). In particular, the convection scheme, which is originally based on the Tiedtke (1989) parameterisation, is enhanced for application on the mesoscale, including its extension to a hybrid version (Frank and Cohen, 1987). The latter yields optimal results by combination with a three dimensional transport scheme for precipitation and a subgrid-scale condensation scheme (Sommeria and Deardorff, 1977). The soil-vegetation-atmosphere transfer (SVAT) scheme in FOOT3DK is based on the two layer force-restore model ISBA (Interaction Soil Biosphere Atmosphere, Noilhan and Planton, 1989). A detailed description of the SVAT scheme is given in Shao et al (2001).

3. Idealized ensemble studies

Fundamental influences of land surface parameters on convective rainfall are identified with a one-dimensional column version of the model that reflects horizontally homogeneous conditions and a steady atmospheric forcing. This configuration is used to create an ensemble that represents a large number of different states of the land surface which covers the range of variations in land surface parameters in the Sub-Saharan belt. From this ensemble, the SVAT parameters that predominantly influence model precipitation are obtained by statistical analysis.

3.1 Ensemble configuration

In the one-dimensional column version, the model simulates turbulent and thermodynamic surface-atmosphere interactions while the forcing wind field has to be prescribed. Atmospheric forcing is identical for all ensemble members. All runs are initialised with the atmospheric sounding at Niamey on August 25 1999, 00 UTC. The sounding depicts typical atmospheric conditions in the Sahel/Sudan zone that favor the development of precipitation over large parts of the region. Therefore it should display atmospheric characteristics sufficient for one-dimensional sensitivity studies. The corresponding weather situation lead to partly intense rainfall in Benin and its neighbouring countries during the following days.

The vertical structure of the atmosphere is resolved by 25 layers with a model top at 18 km. The model is integrated over seven days. Following the approach by De Ridder (1998), atmospheric moisture and temperature profiles are relaxed towards the initial structure with a time constant of 50000 s to compensate for the absence of advective processes. Tests revealed that our results are basically independent of the specific choice of the relaxation time (not shown).

Synthetic soil and surface states are generated by SVAT parameter variations, which are summarised in Table 1. Surface parameters are varied randomly within the ranges indicated in Table 1. While the resulting parameter combinations are not designed to correspond with regionally characteristic surfaces, the choice of the parameter ranges covers the variations which are characteristic for the region. By this procedure, statistical independence of each parameter as a prerequisite for an individual assessment of each parameter is granted. Saturation soil water content W_s is chosen to represent soil characteristics for our statistical analysis, as the other soil parameters are by and large monotonically related to W_s. Initial soil water content W is varied identically for the two model layers. All parameter combinations yield a set of 216 different states of the SVAT scheme. Our ensemble is generated by performing one simulation for each SVAT state.

3.2 Sensitivity of precipitation to SVAT parameters

The different states of the surface induce considerable variability in accumulated precipitation. After 72 hours, rainfall sums vary between

Table 1. SVAT parameter values and ranges used to establish the set of independent surface states

Parameters	Low	Middle	High
Roughness length z_0 (m)	0.05–0.35		0.6–1.2
Albedo α (%)	5–15		25–40z
Relative vegetation cover veg (%)	1–20	35–60	80–99
Leaf area index LAI (–)	0.5–1.5	2.5–3.5	4.5–6.5
Soil type	Sand		Loam
Saturation soil water content W_s ($cm^3 \cdot cm^{-3}$)	0.395		0.435
Relative initial soil water content W/W_s (%)	35	60	75

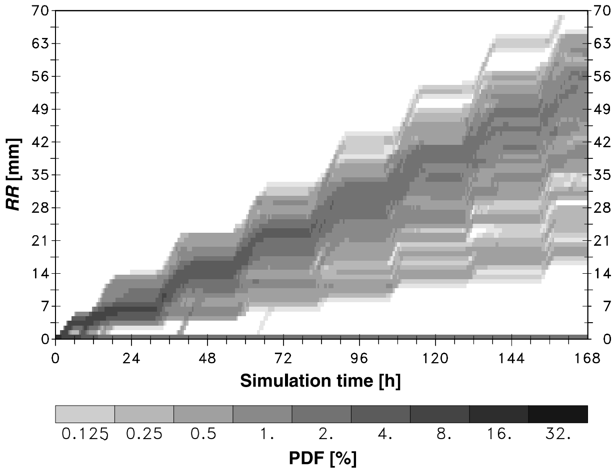

Fig. 1. Probability density function of time-dependent rainfall accumulation generated from the total of all ensemble runs. Variability evident in the dispersion of the ensemble which increases with time demonstrates the sensitivity of modelled rainfall to the 216 different states of the land surface

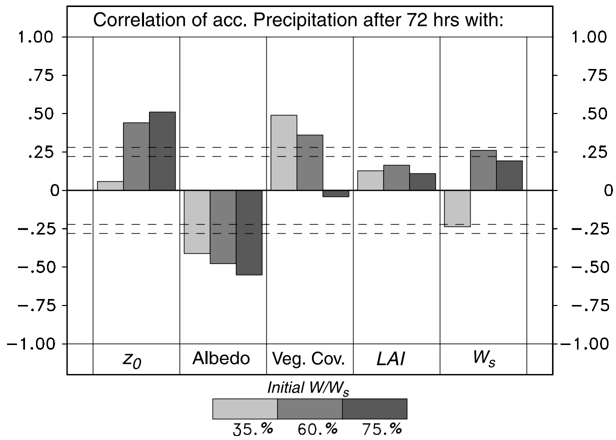

Fig. 2. Correlation of accumulated precipitation after 72 hours with SVAT parameters for sub-ensembles with equal initial soil water content. Dashed lines: 95% and 99% significance levels

Table 2. Correlation r of accumulated rainfall after 72 hours $RR_{72\,h}$ with SVAT parameters. Significant values on the 95% (99%) level according to a Gaussian error test are underlined (bold)

Parameter Φ	$[z_0]$	$[\alpha]$	Veg	LAI	W_s	Init. W/W_s
r ($RR_{72\,h}$,Φ)	0.15	**−0.31**	**0.24**	0.09	0.05	**0.67**

0 mm and 32 mm. By the end of the seventh day, the spread of the ensemble increases to a range between 0 mm and more than 70 mm. The considerable sensitivity of rainfall to the different states of the surface is illustrated in Fig. 1. The relative importance of each SVAT parameter on rainfall variability is evaluated by a correlation analysis between our selection of SVAT parameters and accumulated precipitation after three days integration time (Table 2). Analogous results are obtained for other accumulation times between 2 and 7 days (not shown).

Model precipitation reacts most sensitively to initial soil water content. This is not astonishing, as in the model parameterisations (cf. Shao et al, 2001) soil water content strongly determines surface evaporation. Accumulated evaporation itself is highly correlated with precipitation by a coefficient of around 0.96 for days 2 to 7. Surface parameters albedo (α) and vegetation cover explain a smaller yet considerable fraction of precipitation variability. Roughness length plays a minor role while leaf area index and saturation soil water do not exhibit a significant influence.

Further insight into the mechanisms that potentially control land surface influence on rainfall is gained by stratifying the ensemble according to initial soil water content and repeating the correlation analysis for the sub-ensembles (Fig. 2).

Influence of vegetation cover is highly important for initially dryer soils, while vegetation becomes irrelevant when the soil is wet enough to evaporate at potential rates. In the latter case, variations in evaporation are dominated by changes in the intensity of turbulent motions. Hence, the influence of roughness length increases for wetter soils. The same effect is evident in albedo. However, albedo maintains a significant influence for drier soils by confining the radiative energy gain of the surface and thus its capacity to destabilise the atmosphere. Leaf area index exhibits only statistically insignificant influences. Saturation soil water shows signs of a weakly negative influence on rainfall for relatively dry soils and an opposed positive influence for medium water content which tends to become insignificant when water content reaches field capacity. As a whole, the effects of leaf area index and saturation soil water are clearly less important than the influence of the other parameters.

In summary, soil water content, vegetation cover, and albedo can be qualified as the most critical surface properties with respect to rainfall within the highly simplified framework applied. It will be discussed in the next section to which extent these results can be applied to 3-D simulations of a real precipitation event.

4. Sensitivity study of a real precipitation event

Sensitivity studies are extended to complex realistic settings by simulations of a precipitation episode in July 28–29, 2000 in the HVO. According to satellite observations and surface rain measurements for this episode, disturbances that travel with a south-westerly near-ground flow from the monsoon region in the Guinea Zone to the northern parts of Benin repeatedly cause intense precipitation in the HVO. The sensitivity of model rain in this situation is examined by a comparison of a control simulation with sensitivity tests that are based on hypothetical land use changes.

4.1 Experimental set-up

All simulations are started on 2000-07-28 00 UTC and integrated until 2000-07-30 06 UTC. FOOT3DK is operated with 9 km horizontal resolution, 23 vertical layers and a model top at 19 km height. Moist physics of the convection scheme are represented by the optimal combination of parameterisations described in Sect. 2. Larger-scale forcing is accomplished by passive nesting of FOOT3DK into the "Lokal-Modell" (LM), (Doms and Schättler, 1999), which is the current operational mesoscale model of the German Weather Service (DWD). The employed LM-simulations are performed at the Meteorological Institute, University of Bonn, as part of activities in IMPETUS.

The quality of presently available surface, soil and initial hydrologic data for this region is rather limited, as existing data sets are not adapted for an optimal regional representation. Surface description is based on the USGS EROS data sets "Global 30 Arc-Second Elevation Data Set" (GTOPO30, orography – http://edcdaac.usgs.gov/gtopo30/gtopo30.asp) and "Global Land Cover Characterization" (GLCC, land use – cf. Loveland et al, 2000, or http://edcdaac.usgs.gov/glcc/glcc.asp). Land use classes from the GLCC set were grouped into ten categories. For these ten categories, SVAT parameters (cf. Shao et al, 2001; Hübener et al, 2004) were derived at hand of general considerations that reflect current accuracy in surface representation for operational weather forecasts and regional model studies (e.g., Noilhan et al, 1997, or Farah and Bastiaanssen, 2001) and preliminary regional estimates provided by other IMPETUS working groups (e.g., Paeth, 2004). Soil types and initial soil water stem from LM data. Soil types employed by LM are based on FAO data (FAO-ISSS-ISRIC, 1998). Depiction of vegetation cover and orography in the model area is given in Fig. 3. The simulation domain covers a square of 270 km side length. The HVO catchment is located in the centre of the domain. Effects of land surface variations on precipitation are investigated by introducing heterogeneous surface disturbances that, according to the results of our ensemble study, potentially act adversely on rainfall. Manipulations are performed at about 50% of the grid points within the simulation domain. Separate simulations are performed for anomalies in surface parameters, initial soil water and a combination of both. Parameter variations and simulation nomenclature are given in Table 3.

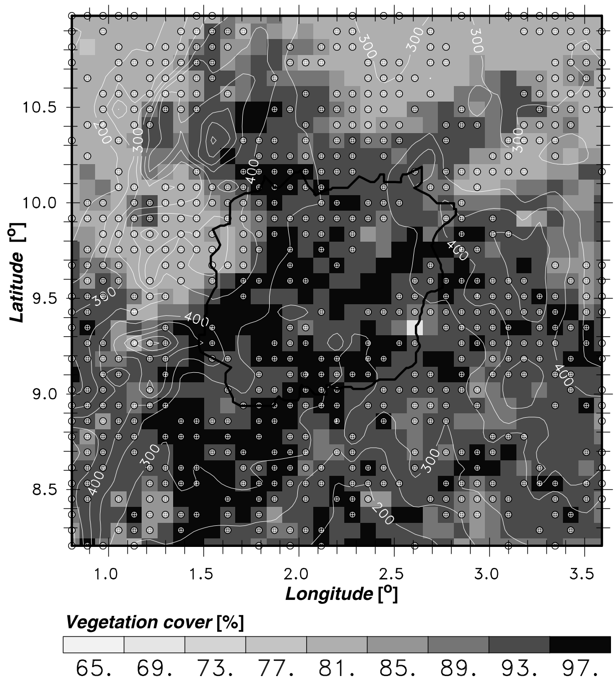

Fig. 3. Simulation domain with vegetation cover, orography (%, contour interval 50 m) and location of the HVO catchment. Grid points with altered SVAT quantities in the sensitivity runs are marked by white dots

Table 3. Simulation names and parameter variations at the grid points depicted in Fig. 3

Simulation	Variation of parameters			
	z_0	α	Veg	Init. W/W_s
CTRL	0%	0%	0%	0%
SFC	−50%	+15%	−50%	0%
INIT	0%	0%	0%	−66%
SFINIT	−50%	+15%	−50%	−66%

4.2 Response of precipitation to surface anomalies

The most prominent feature in the accumulated precipitation field of run CTRL (Fig. 4a) consists of a strong precipitation band that extends diagonally from south west to north east through the simulation domain. It is accompanied by a secondary band located west of the HVO. Analysis of the temporal development in model rainfall and related flow patterns (not shown) reveals that both bands owe their existence to organised convection along an extended quasi-stationary low-level convergence zone. The central band develops during daytime hours on both July 28 and 29. The corresponding convergence zone is evident in the 48 hour-time average of near-surface winds (Fig. 4a). The westerly band evolves in the early morning hours of July 29. Simulated precipitation along these structures is predominantly generated by the convection scheme. Currently available observations are not sufficient for a comprehensive model validation, as neither area-covering data of all relevant meteorological parameters nor vertical atmospheric profiles are available from the sparse operational measurements in the region (cf. Sect. 5). Comparison is thus restricted to model rainfall with a ground-based rainfall observation network in the area (Fig. 5). The areas of pronounced model rainfall are also evident in observed precipitation. Consistently with modelled precipitation, the overall distribution of point measurements of accumulated rainfall given in Fig. 5 suggests more pronounced rainfall in the western part of the simulation domain than in the eastern part and a satisfactory agreement between modelled and measured rainfall amounts for the majority of the stations in the HVO. Given the limitations of comparability between modelled rainfall sums as averages over grid meshes and

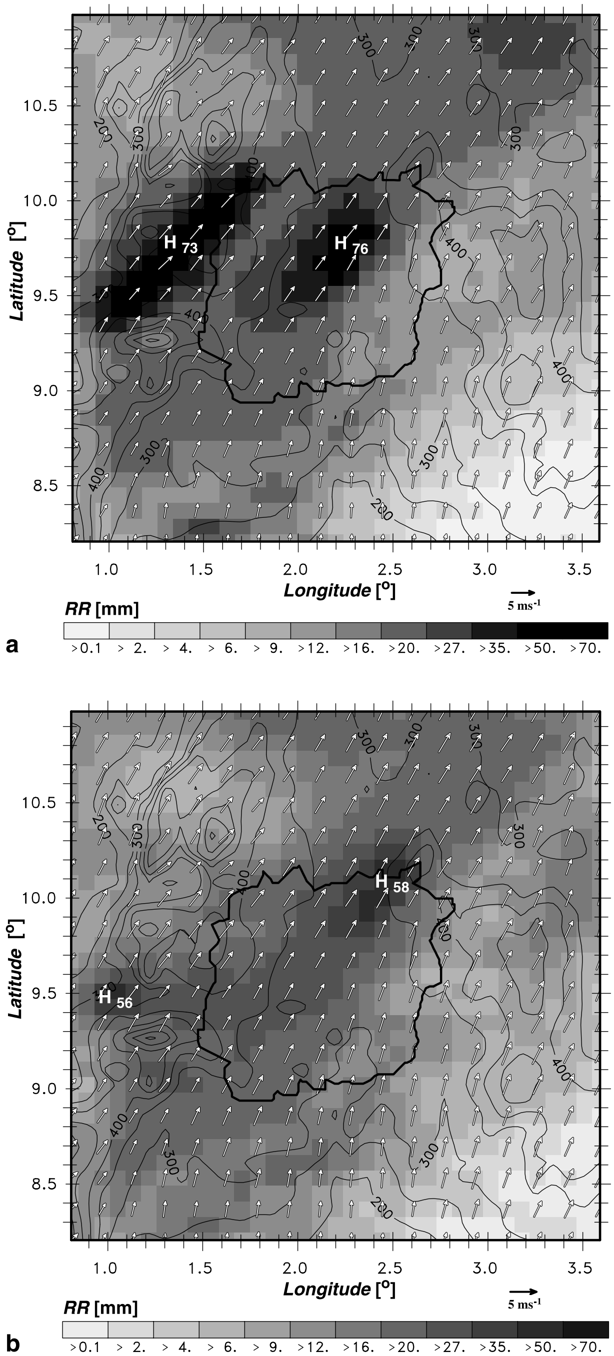

Fig. 4. Accumulated precipitation and temporally averaged near-surface wind from July 28, 06 UTC to July 30, 06 UTC in CTRL (**a**) and SFINIT (**b**). The maximum values are denoted by an "H" label

observed point measurements, extreme local deviations at single stations from the overall distribution are expectably not reproduced by the model. The model produces less rainfall than evident from several observations near the southern boundary of the simulation domain. As the episode given exhibits predominant lower atmo-

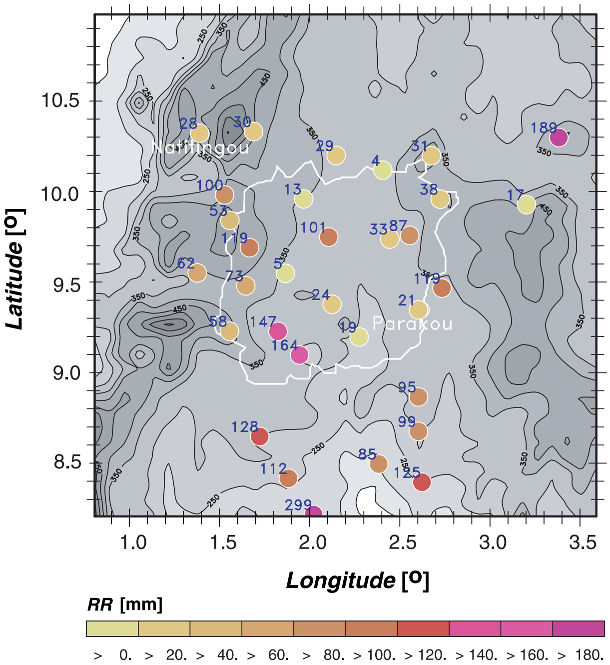

Fig. 5. Accumulated precipitation from July 28, 06 UTC to July 30, 06 UTC at observational stations

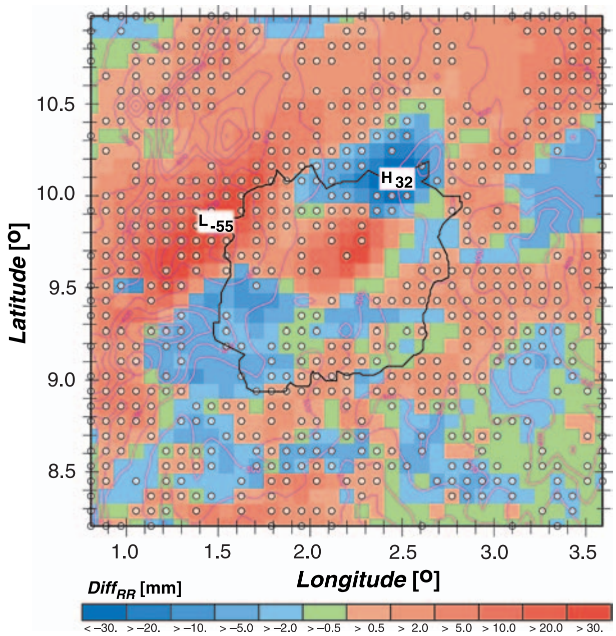

Fig. 6. Precipitation difference SFINIT-CTRL accumulated from July 28, 06 UTC to July 30, 06 UTC. Grid points where surface anomalies are imposed are marked by white dots. The maximum and minimum values are denoted by "H" or "L" labels, respectively

spheric inflow into the domain from southerly directions, (cf. Fig. 4a), this underestimation of rainfall hints at a lack of moisture supply by the coarser forcing fields within the nesting procedure. As a whole, notwithstanding the serious difficulties that limit the comparability of model precipitation fields with ground-based point measurements, our comparison suggests a reasonable agreement between modelled and observed precipitation for most parts of the simulation domain.

Effects of surface anomalies on precipitation are most pronounced in SFINIT when compared with the other sensitivity experiments. Discussion will thus be restricted to this simulation, while conclusions from our analysis qualitatively apply to SFC and INIT as well. As in CTRL, the two primary bands of strong precipitation arise in run SFINIT. These two bands in run SFINIT (Fig. 4b) are basically similar to the bands shown in run CTRL (Fig. 4a). However, the rainfall area located west of the HVO is restricted to a smaller domain than in CTRL (Fig. 4b in comparison to Fig. 4a), while the maximum of the central band is shifted to the northeast. Local rainfall maxima are attenuated for both bands. The temporal development of the precipitation centres occurs analogously to the one in CTRL.

Differences in accumulated precipitation between SFINIT and CTRL are shown in Fig. 6. The imposed changes induce a rainfall reduction for 52% of the simulation domain. On average, reduction is modest, with 2.4 mm decrease compared to 18.7 mm average rainfall in CTRL. For some regions, however, rainfall is considerably reduced with decreases up to 55 mm. In other parts, precipitation increases by values up to 32 mm. While they are not confined to areas with undisturbed surface, regions of substantial rainfall increase are either orographically structured or exhibit a downstream shift that indicates delayed development of the respective precipitation system.

The generation of positive rainfall anomalies is consistent with interactions between land surface, convection, and atmospheric flow. On July 28 (not shown), convection along the main convergence zone (visible on basis of the near surface winds in Fig. 4a) is weakened over areas where surface anomalies are imposed in accordance with inferences from our idealised study (Sect. 3). Associated vertical circulation patterns, that tend to stabilise the atmosphere in the vicinity of the convection line by subsidence,

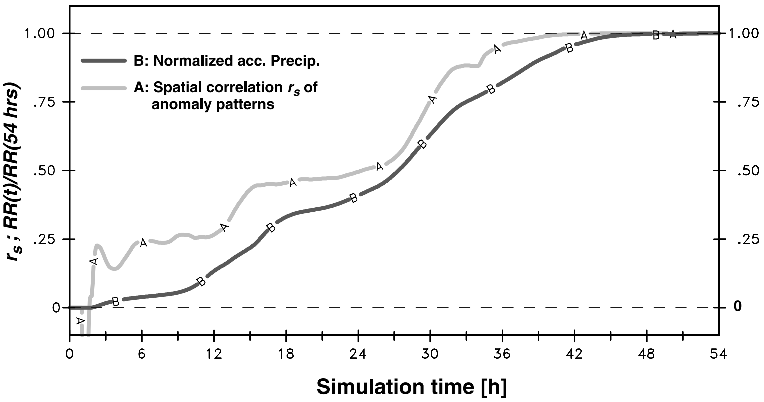

Fig. 7. Spatial correlation of precipitation anomaly fields at a given time with the anomaly pattern at the end of the simulation (grey curve A) and spatially averaged accumulated rainfall in CTRL normalized to its final value (black curve B)

are correspondingly reduced. Hence, convection cells in some distance to the main convergence zone have better chances to develop in SFINIT than in CTRL. Through this interplay, a pattern of both positive and negative rainfall anomalies develops by the afternoon of July 28.

The tendency of rainfall anomaly patterns to maintain their structure is investigated by means of spatial correlations between normalized anomaly patterns at a given time with the normalized final rainfall anomaly field as a measure for the similarity of the patterns. Normalization is done by dividing rainfall anomalies at each grid point by the local average of absolute accumulated rainfall after 54 hours between CTRL and SFINIT. By this procedure, an excessive influence of large anomalies at individual grid points on the correlation analysis is subdued in order to properly represent the similarity of the anomaly patterns as a whole.

Once the pattern is established, it exhibits a notable tendency to maintain its structure for the remainder of the simulation. The temporal development of spatial correlations as a quantification of similarity between the patterns at a given time and the final pattern (Fig. 7) indicates that the fundamental structure of the final anomaly field (Fig. 6) is already established during the first 24 hours of the simulation. Around 50% of rain is still to fall in the subsequent 30 hours. Within the latter time interval, the majority of precipitation anomalies still grow in amplitude while basically maintaining their structure (not shown). This self-maintenance supports the hypothesis of a positive short-term surface-precipitation feedback and thus of an active role to the land surface on time scales of a single rainfall episode (cf. Sect. 1).

4.3 Sensitivity to successive land degradation

Further investigations of the rainfall response to hypothetical land degradation in the HVO, are based on the findings presented in Sects. 4.1 and 4.2. In Sect. 4.1, the prevailing influence of initial soil water content and an enhanced dependence of precipitation on vegetation were demonstrated in case of limited soil water availability. In Sect. 4.2, a combination of reduced vegetation cover and low soil water content was applied to yield adverse conditions for the development of a rainfall system in the HVO. Based on these findings the response of rainfall with respect to two different scenarios of hypothetical land degradation is investigated with the same methodology as presented in Sect. 4.2. For this purpose, two series (I and II) with each nine 3-D modelling sensitivity studies are carried out. In the first series, we regard the consequences to a successive increase of the surface fraction with adverse conditions for the development of precipitation from 10% to 90% by 10% intervals. At second, the response of rainfall is investigated with respect to a successive reduction of surface vegetation and initial soil water, which is carried out at randomly distributed areas that cover half of the simulation domain. The choice of grid points with disturbed surface is the same as in the sensitivity experiments presented in Sect. 4.2 (c.f. Fig. 3). At these grid points, vegetation cover and initial soil water are reduced from 10% to 90% of their original values by steps of 10%.

For both series, albedo and roughness length are adjusted to consistently mimic the reduction of vegetation cover.

All sensitivity studies are carried out for the same episode and on the same grid as described in Sect. 4.2 (e.g., shown in Fig. 4). The integration time for each run is 54 hours and calculations are forced by atmospheric conditions of July 28–30, 2000. The response to successive surface changes (series I) can be delineated by comparing number density distributions of rainfall differences between CTRL and the particular sensitivity experiment. Distributions reflect the sample of all grid points in the domain (cf. Figs. 8 and 9) for the last 48 hours of each run. This response consists of a nearly monotonous decrease of average rainfall for the whole subcatchment and furthermore an enhanced tendency to a rainfall reduction in some parts of the area for both series. The median may serve as a suitable indicator to identify this trend. In particular, series II (Fig. 9) exhibits a remarkably systematic behavior. The spatial variability of rainfall anomalies is the higher the more vegetation and initial soil water are reduced. This behavior is nearly uniform (with exception of the 80% reduction level) in series II. Considering the first and last four reduction levels of series I a similar tendency is observable for the increase of disturbed area fraction.

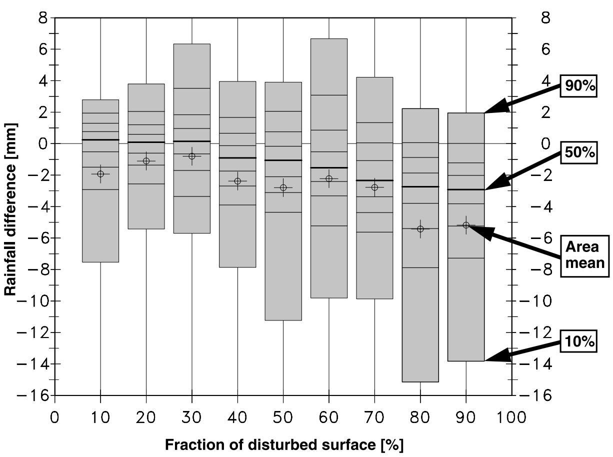

Fig. 8. Sensitivity of precipitation event to successive increase of disturbed surface expressed by rainfall difference number distributions over model domain. Successive increase of disturbed area fraction from 10% to 90% is indicated on the x-axis. Rainfall differences are based on a comparison between a reference run for July 28–30, 2000 rainfall event and 9 sensitivity experiments for each series after 48 hours. Distributions are sampled from all grid points of the simulation domain. Each box refers to one simulation, representing the deciles of the domain that exhibits differences below the corresponding value on the y-axis from 10% to 90%. Medians: bold horizontal lines. Arithmetic area means: cross-circles

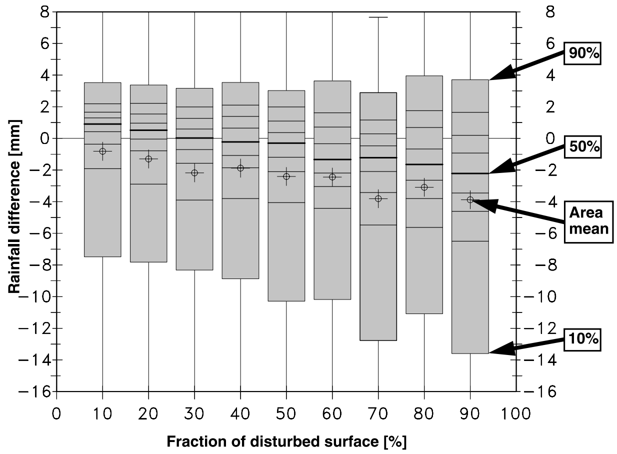

Fig. 9. Sensitivity of precipitation event to successive reduction of vegetation/initial soil water within 50% of the simulation domain (depiction analogous to caption of Fig. 8). Further explanation is given in the text

The results demonstrate that the methodology presented in this subsection enables the assessment of both systematic performance and uncertainties in the response of rainfall systems to land surface changes. Overall, the presented results hint at a substantial risk of precipitation decrease in case of unfavorable land surface changes.

5. Conclusions

The findings of our study support the relevance of surface-precipitation feedback for regional rainfall on the time scale of a single precipitation episode in the HVO area in Benin. The analysis of highly simplified ensemble studies proves to be a viable tool to identify land surface properties that critically influence rainfall, i.e. soil water content, vegetation cover and albedo. The complex case study of a real precipitation episode corroborates the substantial influence of land use variations on rainfall in terms of these parameters. The resulting regional structure of precipitation anomalies cannot exclusively be attributed to the surface anomaly pattern. The interplay of convection cells, land surface processes, and larger-scale atmospheric dynamics as a whole is, however, consistent with the resulting rainfall anomalies.

It still has to be established to which degree this interaction is influenced by the specific choice of model parameterizations, in particular of the convection scheme, which predominantly accounts for rainfall in the simulations presented. Additional sensitivity tests and validation with improved observational data are thus necessary before more general conclusions can be drawn from our results. An intensive observation campaign has been carried out for the rainy season 2002 to obtain feasible validation data. Results are to follow from the measurements. Likewise, the database for land surface characterisation and hydrological initialisation is to be improved in order to augment regional appropriateness and reliability of model simulations in the HVO. The corresponding data sets in need are in the process of being enhanced by joint efforts of several working groups within the framework of the IMPETUS project.

It is an open question whether regional rainfall anomalies induced from individual episodes tend to cancel out or to intensify on the time scale of an entire rainy season. An answer will be sought by incorporation of our sensitivity analysis into a statistico-dynamical approach based on a classification of characteristic regimes that account for the rainfall in the HVO. Together with this classification, sensitivity tests for each regime will form the basis for a regional assessment of rainfall reduction risks by future land use changes.

Acknowledgements

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References

Brücher W, Kerschgens MJ, Martens R, Thielen H, Maßmeyer K (1998) Tracer experiments in the Freiburg-Schauinsland area – Comparison with flow and dispersion models. Meteorol Z 7: 36–40

De Ridder K (1998) The impact of vegetation cover on sahelian drought persistence. Bound Layer Meteorol 88: 307–321

Doms G, Schättler U (1999) The nonhydrostatic limited-area model LM (Lokal-Modell) of DWD. Part I: Scientific documentation. Offenbach: Deutscher Wetterdienst (DWD), Geschäftsbereich Forschung und Entwicklung, 172 pp

FAO-ISSS-ISRIC (1998) World reference base for soil resources (Spaargaren O, ed), 165 pp

Farah HO, Bastiaanssen WGM (2001) Impact of spatial variations of land surface parameters on regional evaporation: a case study with remote sensing data. Hydrol Process 15: 1585–1607

Frank WM, Cohen C (1987) Simulation of tropical convective systems. Part I: A cumulus parameterization. J Atmos Sci 44: 3787–3799

Guichard F, Redelsperger JL, Lafore JP (1996) The behavior of a cloud ensemble in response to external forcings. Quart J Royal Meteorol Soc 122: 1043–1073

Heinemann G (2003) Forcing and feedback mechanisms between the katabatic wind and sea ice in the costal areas of polar ice sheets. The Global Atmosphere and Ocean System 9/4: 169–201

Heinemann G, Kerschgens M (2005) Comparison of methods for area-averaging surface energy fluxes over heterogenous land surfaces using high-resolution non-hydrostatic simulations. Int J Climatol 25: 379–403

Hübener H, Schmidt M, Sogalla M, Kerschgens M (2004) Simulating evapotranspiration in a semi-arid environment. Theor Appl Climatol 80: 153–167

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. Int J Remot 6–7: 1303–1330

Nicholson SE (2000) Land surface processes and Sahel climate. Rev Geophys 38: 117–199

Noilhan J, Planton S (1989) A simple parameterization of land surface processes for meteorological models. Mon Wea Rev 117: 536–549

Noilhan J, Lacarrere P, Dolman AJ, Blyth EM (1997) Defining area-averages parameters in meteorological models for land surfaces with mesoscale heterogeneity. J Hydrol 190: 302–316

Paeth H (2005) The impact of vegetation changes on West African rainfall: Local versus dynamical effects in a regional climate model. Int J Climatol (submitted)

Shao Y, Sogalla M, Kerschgens M, Brücher W (2001) Effects of land surface heterogeneity upon surface fluxes and turbulent conditions. Meteorol Atmos Phys 78: 157–181

Sogalla M, Kerschgens M (2001) Berechnung lokaler Niederschlagsfelder zur Parameterisierung der nassen

Deposition auf der Basis größerskaliger Vorhersagemodelle. In: Mitteilungen aus dem Institut für Geophysik und Meteorologie der Universiät zu Köln (Kerschgens M, Neubauer FM, Pätzold M, Speth P, Tezkan B, eds), University of Cologne, 81 pp

Sommeria G, Deardorff JW (1977) Subgrid-scale condensation in models of nonprecipitating clouds. J Atmos Sci 34: 344–358

Taylor CM, Lebel T (1998) Observational evidence of persistent convective-scale rainfall patterns. Mon Wea Rev 126: 1597–1607

Taylor CM, Harding RJ, Thorpe AJ, Bessemoulin P (1997) A mesoscale simulation of land surface heterogeneity from HAPEX-Sahel. J Hydrol 188–189: 1040–1066

Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Mon Wea Rev 117: 1779–1800

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