Investigation of feedback mechanisms between soil moisture, land use and precipitation in West Africa

HARALD KUNSTMANN & GERLINDE JUNG

Institute for Meteorology and Climate Research (IMK-IFU), Forschungszentrum Karlsruhe GmbH, Kreuzeckbahnstraße 19, D-82418 Garmisch-Partenkirchen, Germany

harald.kunstmann@imk.fzk.de

Abstract To investigate the effects of the ongoing intensification of agriculture in West Africa on precipitation, we applied the mesoscale meteorological model MM5 for the identification of feedback mechanisms between land surface (soil and vegetation) and atmosphere. Great differences in the ability to quantitatively describe the observed meteorological data were found between different model parameterizations. The main research question was to what extent regional (intra-domain) evapotranspiration determines rainfall within the domains (precipitation recycling ratio and precipitation efficiency). The effect of decreased and increased initial soil moisture on the total rainfall was investigated. Scale dependent, positive as well as negative, feedback mechanisms were found. Sensitivity of precipitation with respect to soil moisture was found very variable over space and takes on negative as well as positive values. To investigate the effect of land use change, we computed the total rainfall distribution under the assumption of the observed land use substitution from cropland woodland mosaic into shrub land and finally into grassland, *ceteris paribus*. Again, resulting precipitation change response was found to be very heterogeneous over space.

Key words land use change effects; mesoscale meteorological modelling; precipitation recycling; soil-moisture-precipitation feedbacks

INTRODUCTION

The ongoing intensification of agriculture in West Africa leads to a change in surface and subsurface characteristics, which directly affects evapotranspiration rates. If these changed evapotranspiration rates in turn affect regional rainfall patterns, rainfed and irrigated agriculture in West Africa may face changed boundary conditions because rainfall can decrease in specific areas due to feedback mechanisms between land use change, soil moisture change and subsequent precipitation change.

To identify the feedback mechanisms between land surface (soil and vegetation) and atmosphere, an extensive numerical experiment was carried out within the GLOWA–Volta project (Sustainable Water Use under Changing Land Use, Rainfall Reliability and Water Demands in the Volta Basin; http://www.glowa-volta.de). We applied the mesoscale meteorological model MM5 for the investigation of soil-moisture-precipitation and land use-precipitation feedback effects in West Africa and in particular the Volta Basin (which covers 400 000 km^2 and extends from Burkina Faso to Ghana, Togo, and the Ivory Coast). For that purpose, MM5 was prepared for runs in West Africa.

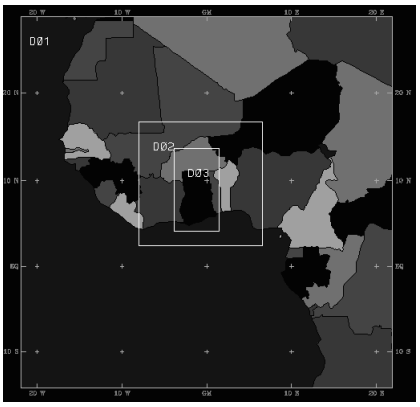

Fig. 1 The water balance of the Volta Basin (domain 3) is investigated by dynamically downscaling the global reanalysis down to 9×9 km^2 using a two-way-nesting approach.

SETUP OF THE MESOSCALE METEOROLOGICAL MODEL MM5

MM5 was applied in non-hydrostatic mode, using three domains having a horizontal resolution of 81×81 km^2 (61×61gridpoints), 27×27 km^2 (61×61), and 9×9 km^2 (121×67) and 26 vertical layers extending up to 30 mbar at the model top (Fig. 1). The first domain is run with Four-Dimensional-Data-Assimilation (FDDA) allowing the use of observations obtained from radio-sondes during the model run. Global reanalysis fields are obtained from NCEP (National Centres for Environmental Prediction).

MM5 was applied with the Oregon-State-University Land-Surface-Model (OSU–LSM) (Chen & Dudhia, 2001), allowing to account for the feedback mechanisms between soil, vegetation and the planetary boundary layer. Elevation, land use and soil data are taken from NCAR data archives, as well as from data sets compiled by the land use cluster of the GLOWA-Volta project. The OSU–LSM is capable of predicting soil moisture and temperature in four layers (10, 30, 60, and 100 cm thick), as well as canopy moisture and water equivalent snow depth. It also computes surface and underground run-off accumulations. The OSU–LSM makes use of vegetation and soil type when handling evapotranspiration and accounts for effects such as soil conductivity and gravitational flux of moisture. It takes surface-layer exchange coefficients as input along with radiative forcing, precipitation rate and outputs the surface fluxes back to the PBL-scheme. It is the OSU–LSM within the MM5 that allows investigation of feedback mechanisms between land use change and precipitation.

VALIDATION OF THE METEOROLOGICAL SIMULATIONS

The third domain (having an area of 660 000 km^2) covers the Volta Basin for which precipitation data at 28 stations were available. For validation purposes, the period 15 July 1998 to 14 August 1998 was chosen because it extends from the first maximum of the bimodal rainy season to the intermediate minimum of the 'Little-Dry-Season' in August. As criteria judging the quantitative performance of the model, the Root-Mean-Square-Error (RMSE) is taken, describing the mean quadratic deviation of the

Table 1 RMSE (in mm) of precipitation for different parameterizations of microphysics, cumulus scheme, radiation scheme and nesting configuration.

Radiation: cloud-radiation-scheme					Grell, Mixed phase Graupel	
	Anthes-Kuo	Grell	Kain-Fritsch	Betts-Miller	Cloud-radiation	56.09
Warm rain		78.75		143.1	CCM2 Radiation scheme	94.39
Simple ice		63.5		109.8	RRTM Longwave scheme	62.76
Mixed phase	75.7	72.36	89.3	153.8	1 way *vs* 2 way nesting	
Goddard-microphysics		72.57		113.3	Grell, Mixed phase Graupel, cloud radiation	
Mixed phase Graupel		56.09		160	2 way	56.09
Schulz microphysics		59.82			1 way	57.4

observed precipitation and the mean precipitation of the closest four model grid points. Averaging grid points is necessary since model meaningfulness starts at two- to four-fold model resolution. An entire set of 16 simulations was performed to determine the optimal model configuration. The use of the OSU–LSM restricted us to a single choice for the parameterization of the planetary boundary layer, which is the MRF–PBL scheme (Hong & Pan, 1996). The results for the different configurations are given in Table 1. Convective (i.e. cumulus) parameterization according to Grell *et al.* (1991), microphysics according to Reisner *et al.* (1998) (Mixed Phase Graupel) and the radiation scheme according to Dudhia (1993) showed the smallest RMSE and are therefore assumed to be the optimal model configuration for simulating rainfall in West Africa and the Volta Basin. There is no major difference between the one-way and the two-way nesting approach.

Figure 2 shows the quality of simulated precipitation compared to the 28 station data. While stations with little precipitation (mainly in the south of domain 3) show a

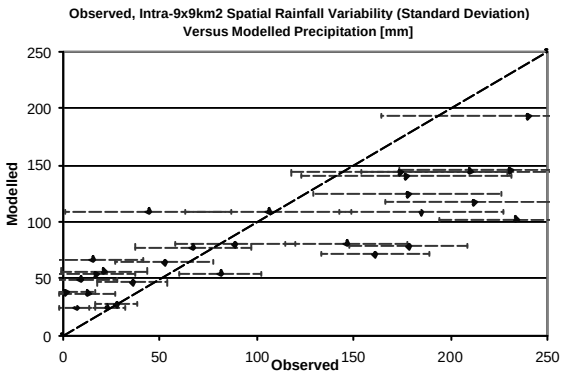

Fig. 2 Scatterplot simulated *vs* observed precipitation (in mm) and standard deviation of observed intra-9 x 9 km^2 spatial rainfall variability.

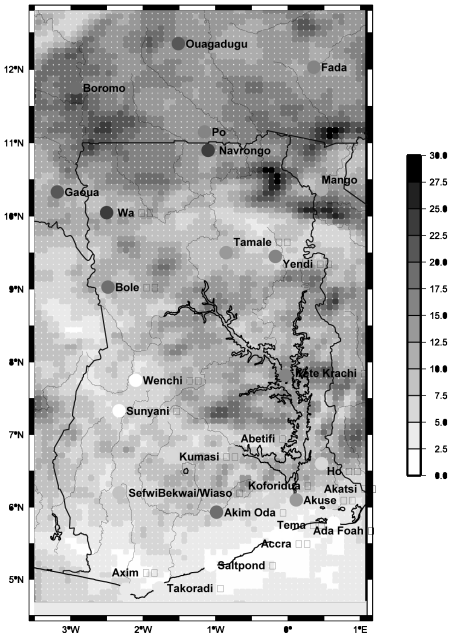

Fig. 3 Simulated precipitation [in cm] within the period 15 July to 14 August 1998. The circles around the stations indicate the observed precipitation value.

tendency in slightly overestimating precipitation, stations with high values of precipitation (mainly in the north) are underestimated. Altogether, the model's capability to simulate the observed rainfall pattern can be assumed to be satisfying. The intra-9 × 9 km^2-scale rainfall variability was investigated during a field campaign in summer 2001 and turned out to be around 39% (relative standard deviation). The resulting error bars for the observations are also indicated. It can be seen that most of the bars touch the diagonal, indicating a match of observed and simulated values.

Fig. 3 shows the simulated total precipitation for the simulation period under the deduced optimal model configuration. It demonstrates the high spatial variability of the rainfall that is of convective origin by more than 90%. Even if the exact value of precipitation is not met exactly at the observation location, the model is capable to reproduce precipitation values in the immediate surrounding, which are comparable to the observed value. Because of the chaotic nature of convectively induced precipitation, the model is only able to reproduce the approximate location of the rainfall events. The simple use of a GCM output for the analysis (e.g. NCEP reanalysis with 2.5° × 2.5° resolution as used for providing the boundary fluxes at the coarsest domain) would have not been sufficient to reproduce the observed small scale precipitation patterns that are created from convective precipitation events.

To check, whether not only simulated precipitation matches observations, but also vertical profiles of temperature, humidity, and wind, radiosonde data are applied. Within domain 3 only two radiosonde locations are available: Abidjan (Ivory Coast) and Ouagadougou (Burkina Faso). In domain 2 not more than 6 radiosonde profiles are usually available. Sounding data are extremely scarce in West Africa and are only performed irregularly. By applying bilinear horizontal and linear vertical interpolation of model results to the location and pressure levels of the radiosondes we compute the RMSE. Here, each pressure level is counted as one observation. Fig. 4 exemplary

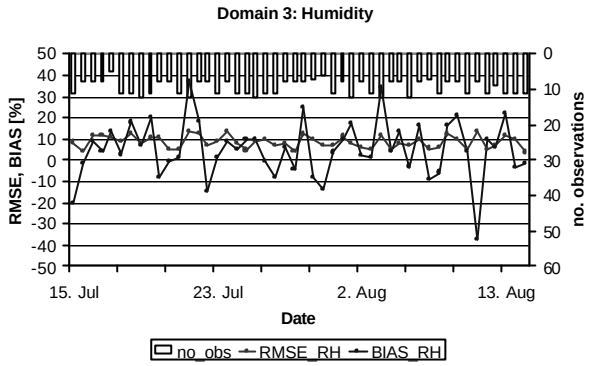

Fig. 4 RMSE and Bias of relative humidity (radiosonde profile *vs* model).

shows the RMSE of relative humidity, which is around 10%; the Root-Mean-Square-Vector-Error (RMSVE) of wind is around 2 ms^{-1}, the RMSE of temperature is around 1°C. This is seen as satisfying model performance. Similar magnitudes of the RMSE are obtained for domain 2 (up to 6 soundings available) and domain 1 (20 soundings).

SOIL MOISTURE-PRECIPITATION FEEDBACK MECHANISMS

The investigation of feedback mechanisms was performed according to the approach of Schär *et al.* (1996). It is based on atmospheric water balances over an analysis domain according to:

$$\Delta Q = I - O - P + ET \tag{1}$$

with ΔQ indicating change in storage, I inflowing and O outflowing water vapour, P precipitation, and ET evapotranspiration. The precipitation recycling ratio b can be deduced as:

$$\beta = \frac{ET}{I + ET} \tag{2}$$

The higher β, the higher the contribution of locally evapotranspirated water to precipitation in the interior of the analysis domain. Similarly, the precipitation efficiency c is defined as:

$$c = \frac{P}{I + ET} \tag{3}$$

describing the fraction of water that enters the domain, either by evapotranspiration or atmospheric transport, and subsequently falls as precipitation within it. The methodology applied assumes that the water molecules that derive from within and outside the analysis domain are well mixed. This assumption may be well justified in the vertical direction, since most of the precipitation in the analysis region is due to convective processes. In the horizontal direction, however, the assumption is weak, especially when orographic contrasts or land-sea mask effects are involved. For this reason the calculated precipitation recycling rates and precipitation efficiency rates later are compared to the recycling approach of Eltahir & Bras (1994).

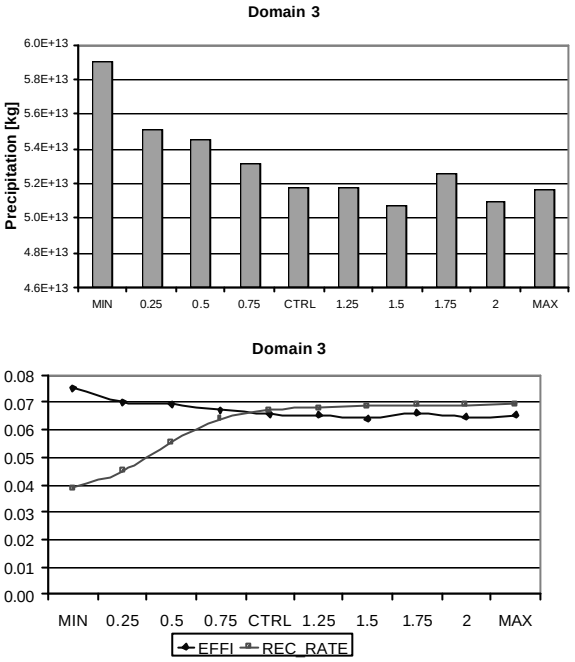

Fig. 5 Influence of initial soil moisture content on (a) total rainfall in domain 3 (Volta Basin) and (b) on precipitation recycling and -efficiency for the simulation period.

Figure 5(a) shows how different initial soil moisture contents at the beginning of the simulation period affect total rainfall in domain 3 (covering the Volta Basin). The initial soil moisture of the control-experiment (CTRL) was obtained from NCEP reanalysis data and successively decreased (by 25%, 50%, 75%) until minimum (MIN) physically possible soil moisture, and also increased (up to 125%, 150%, 175%, 200%) until maximum (MAX) physically possible soil moisture. The effect on precipitation recycling ratio and -efficiency can be seen in Fig. 5(b).While precipitation efficiency keeps more or less constant, recycling increases with increasing initial soil moisture. As can be seen, decreased initial soil moisture, however, lead to increased precipitation at moisture levels smaller than the CTRL-soil moisture (negative feedback). In case of initial soil moisture larger than that in the CTRL experiment, non-linear effects are observed. Here, the magnitude of changes in precipitation is smaller and can change its sign.

This result is contrary to similar investigations in Europe (Schär *et al.*, 1996) and especially to the explanation of feedback mechanisms according to (Eltahir, 1998), where an increase in soil moisture should lead to increased precipitation (positive feedback). According to the latter, decreased initial soil moisture leads to: (a) decreased latent heat fluxes; (b) increased sensible heat fluxes; (c) decreased total fluxes; (d) increased height of PBL; (e) decreased moist static energy in the PBL; and (f) increased stability (weaker gradient of equivalent potential temperature) and finally decreased precipitation. A detailed analysis showed that all of these six criteria were fulfilled when initial soil moisture was decreased in domain 3. Nevertheless, an increase in total precipitation was observed. Decreased initial soil moisture in the Volta region (domain 3) even led to increased total rainfall in entire West Africa (domain 2).

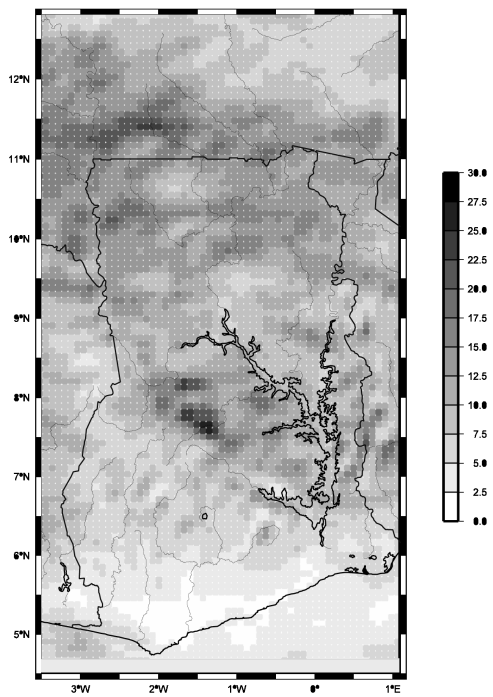

Fig. 6 Total precipitation [in cm] at decreased soil moisture (25% of control run).

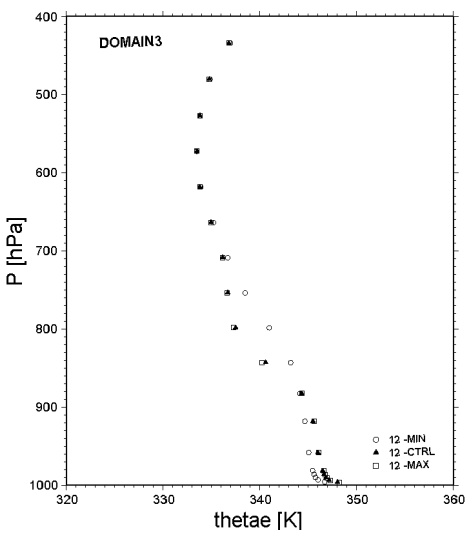

Fig. 7 Vertical profile of equivalent potential temperature at different initial soil moistures.

Moreover, decreased soil moisture in domain 3 even led to different major precipitation patterns (compare Fig. 6 to the control run in Fig. 3) Increased total precipitation for decreased initial soil moistures is observed in spite of increased stability as can be seen from the gradient of temporal and spatial horizontal averaged vertical profiles of equivalent potential temperature at 12:00 h (Fig. 7). The (positive) feedback mechanisms of Eltahir (1998) could only be verified at larger scales, i.e. in case of changing initial soil moisture for domain 2 and not for the Volta region alone.

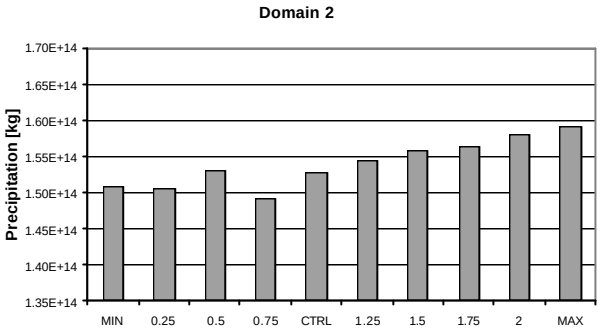

Fig. 8 Influence of initial soil moisture content on total rainfall in domain 2 (West Africa) for the simulation period.

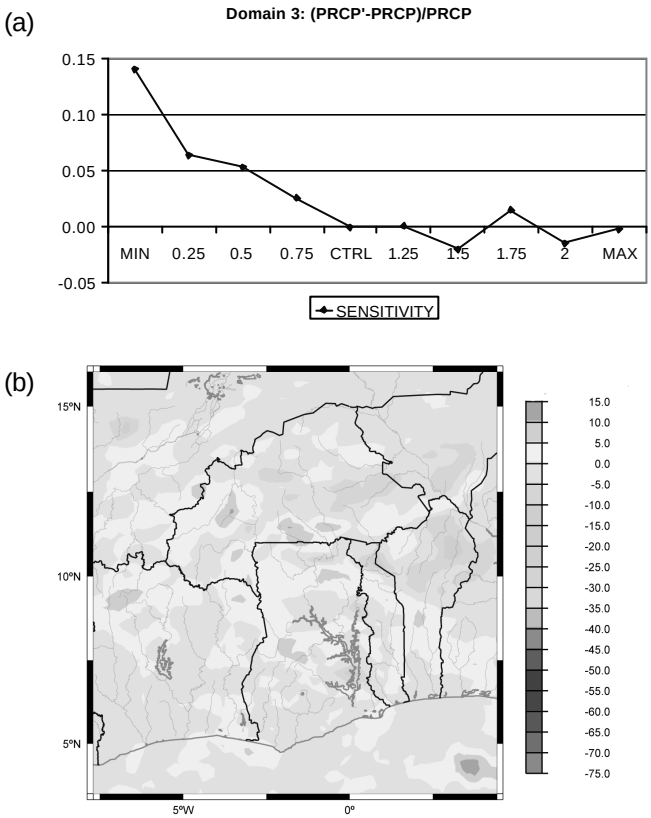

Fig. 9 (a) Normalized sensitivity of total precipitation with respect to initial soil moisture and (b) the spatial distribution of $\Delta P = P_{0.25} - P_{CTRL}$.

In this case, increased initial soil moisture indeed led to increased precipitation (Fig. 8). Sensitivity to initial soil moisture is higher at low soil moisture values (Fig. 9a). Altogether, this demonstrates that simple relations between soil moisture and precipitation in the region do not exist, justifying the CPU-time demanding simulations performed. It turns out that the sensitivity is very variable over space and takes on negative as well as positive values (Fig. 9(b)). Continued sensitivity analysis must be

undertaken to map not only those areas that are most affected by changes in land

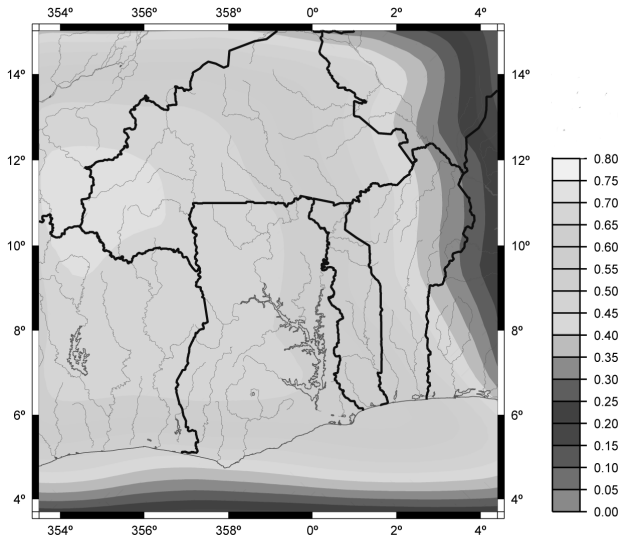

Fig. 10 Locally differentiated precipitation-recycling ratio for domain 2.

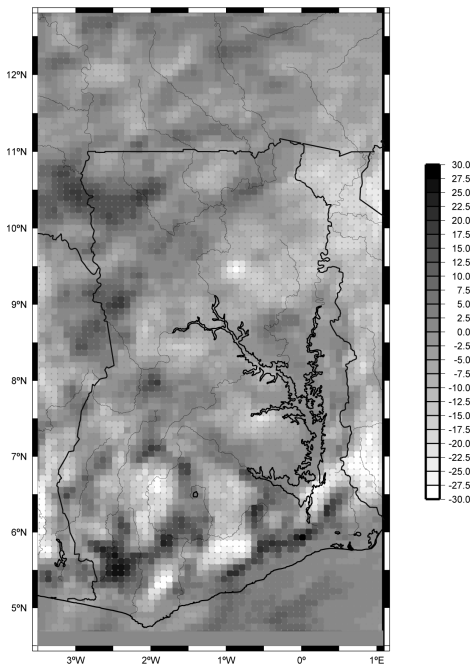

Fig. 11 Change in precipitation (in cm) in case of land use change (cropland woodland mosaic turns into shrub land).

surface characteristics but also those areas that, when changed, would have a large effect on weather and precipitation patterns.

Eltahir & Bras (1994) deduce an iterative algorithm allowing the calculation of a locally differentiating precipitation recycling ratio. This algorithm calculates the recycling ratio at each grid point, describing which fraction of precipitation water at this point originates from evapotranspiration of inside the analysis domain. We

adapted this method in MM5. Figure 10 shows the result for the simulation period. While the lumped recycling ratio according to Schär *et al.* (1996) approach yielded a recycling ratio of around 0.12 for domain 2, the approach of Eltahir & Bras (1994) yields values around a factor 4 larger. The reason for this big difference is under current investigation.

LAND USE CHANGE PRECIPITATION FEEDBACK MECHANISMS

First results of the GLOWA-Volta project show that land use change in the Volta Basin is basically characterised by a transition from cropland woodland mosaic into shrub land and finally into grassland. To investigate the effect of such a transition for the simulation period, we computed the total rainfall distribution under the assumption of the proposed land use substitution. The change of total rainfall with respect to this specific land use change scenario is seen in Fig. 11. Similar to initial soil moisture sensitivity (Fig. 9(b)), the response is very variable over space. As soon as more sophisticated, spatially resolved land use change data are available from satellite image interpretation (as recently compiled), more realistic scenarios and sensitivities can be computed.

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