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Modelling and observation of biosphere–atmosphere interactions in natural savannah in Burkina Faso, West Africa

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ABSTRACT

Savannahs are highly dynamic ecosystems but many of their properties and the related balances of energy, carbon, nitrogen, and water are still poorly understood. A particular scientific issue is the quantification of trace gases emitted from the soil of savannah ecosystems and their interaction with regional and global climate and air chemistry. Therefore it is important to develop and evaluate land-surface models that on the one hand represent vegetation and soil dynamics and on the other hand provide energy and water fluxes in a temporal resolution suitable for the application in climate/air chemistry models.

In this paper, we present a consistent coupling between a common land-surface model (OSU) and a widely used biogeochemical model (DNDC) that is a first step for a full coupling of climate/air chemistry and biogeochemical processes. For consistency reasons, both models are linked to a general physiologically based plant model to provide the physical boundary conditions as well as the carbon and nitrogen in- and output variables. Evaluation is carried out with measurements of soil temperature, latent heat flux, soil water content, and soil emission data from two vegetation periods collected at a natural grassland site in Bontioli Nature Reserve, Burkina Faso (Africa).

The results demonstrate that simulations of biogeochemical processes based on soil environmental conditions, calculated either with the land-surface model or with the unchanged biogeochemical model, do not differ significantly from each other. The OSU model simulates more realistic day-to-day variation of soil temperature as DNDC but the sensitivity of the biogeochemical simulation to this variation is small. In contrast, the sensitivity to differences in soil water content is high, but simulation results of both models are very similar on the daily scale and hardly depend on spatial soil resolution.

1. Introduction and objectives

Savannah is a woodland ecosystem characterised by the coexistence of grass and trees competing for water and light. Tropical savannahs cover an area of $17 \times 10^6\,km^2$ worldwide, which is approximately 20% of the continental surfaces (Scholes and Hall, 1996). The properties of this system are highly dynamic and influence the regional as well as the global climate. For regional climate simulations, this means that the exchange of water and energy between land and atmosphere has to be represented. In addition, global climate and air chemistry modelling is influenced by net carbon exchange and nitrous oxide emission (Mosier, 1998; Betts, 2007). Both have been shown to be of considerable amount and highly dynamic in savannah ecosystems (Castaldi et al., 2006). It is already known that these emission strongly depend on land cover, land use, and climate (Elberling et al., 2003; Tao and Jain, 2005; Tews et al., 2006). All of these impacts are currently subjected to fast changes in western Africa i.e. because of increasing human pressure on land use and regional hydrology (e.g. Ouattara et al., 2006; Kunstmann and Jung, 2007; Kunstmann et al., 2007) as well as accelerating climate change (Caminade et al., 2006). Thus, it is of utmost importance to understand and represent these mechanisms in regional models (see also Foley et al., 1998).

However, the dynamics of physical properties as well as carbon-, nitrogen-, and water exchange with the atmosphere in savannah ecosystems are still poorly understood. A major difficulty develops from the fact that hardly any field study captures all of the major processes influencing energy and matter exchange between biosphere and atmosphere. In contrast, process based models include a multitude of dependencies between physical conditions, water fluxes, plant development, and eventually carbon and nitrogen dynamics (Scholes and Archer, 1997). This information is hardly available for regional simulations which have to rely on the appropriate estimation of state variables. Therefore, extensive evaluations and sensitivity tests are required and

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improvements in process description might be needed before site models, i.e. biogeochemical process models, are applied on this scale.

How can fluxes that are related to biogeochemical processes be introduced in climate and air chemistry simulations? The problem is that models for the description of soil chemical and micro-biological processes (biogeochemical models, BGMs) are conceptually different from models that are designed to simulate exchanges of water and energy fluxes with climate models (land-surface models, LSMs). Due to the different temporal and spatial resolution, a simple coupling between the models is generally not possible without violating model inherent assumptions (Moorcroft, 2003). A flexible approach that separates physical-, water balance-, biogeochemical-, and plant development processes with the aim of new combinations that inherit advantages from different models has hardly been realized (for a specific solution on soil processes see Engel and Priesack, 1993). Such an approach has to cope with temporal and spatial resolutions and has to provide methods of integration and disintegration of exchange variables between functions. For this purpose, a modular biosphere simulation environment (MoBiLE, Grote et al., submitted for publication) has been developed and has been complemented with the functions of two different models, a typical BGM and a widely used LSM. The principal differences of the conventional approaches and the new concept are illustrated in Fig. 1.

The modelling results presented in this paper are compared with measurements obtained within the framework of the 'African Monsoon Multidisciplinary Analysis' (AMMA). This project has been developed in response on the dramatic decreases in rainfall over the whole of West Africa in the 70s to the 90s compared to period from 1950 to 1970 with devastating environmental and socio-economic impacts (Neumann et al., 2007). It is AMMAs aim to provide African decision makers with improved impact assessments of rainfall changes which are likely to occur during the 21st century due to natural fluctuations and as a result of anticipated global climate change. Progress in this area is critical for food security and the development of agronomic adaptation strategies at the longer time scale.

In this study, we try to simulate the soil–vegetation–atmosphere exchange processes for a grassland savannah in West Africa and also take a first step into the direction of a coupling of biogeochemical models with regional climate models. Additionally, we investigate weak points of biosphere process modelling that need adjustment to the specific environmental conditions at savannah regions. Simulations have been evaluated at a natural savannah site located in Burkina Faso that represents the vegetation type most important for regional analyses.

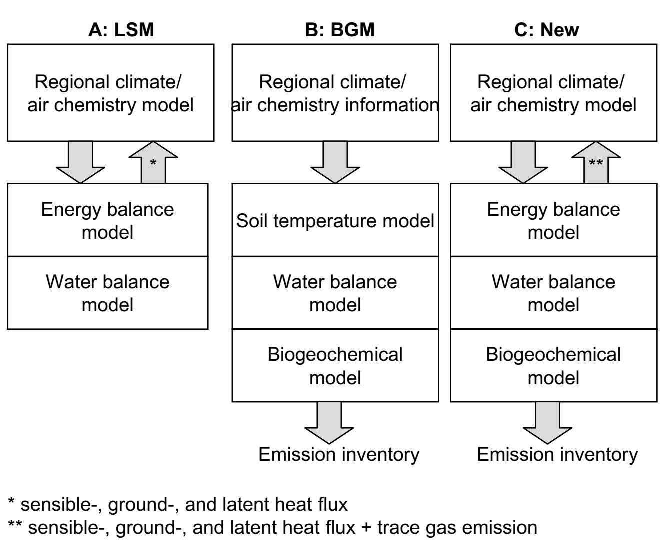

Fig. 1. Conceptual differences between land-surface models (A), biogeochemical models (B), and the new conceptual modelling system (C); *sensible-, ground-, and latent heatflux; **sensible-, ground-, and latent heatflux + trace gas emission.

2. Methods

2.1. Model selection and coupling

In order to simulate biogeochemical processes in savannah soils under West-African environmental conditions, the DNDC model (Li et al., 1992, 2000) had been chosen that considers aerobic as well as anaerobic soil fractions. DNDC has been applied to numerous studies of biogeochemical simulations worldwide, i.e. to investigate nitrous oxide emissions from soils (e.g. Cai et al., 2003; Grant et al., 2004; Saggar et al., 2007). This model has a basic time step of one day and is designed for the use of daily average weather data. Feedback to vegetation processes are realized by shading, litterfall, nutrient- and water uptake on the one hand and nutrient and water provision on the other. However, two major drawbacks with respect to application for grassland and crops in West Africa have been recognized. First, DNDC describes the development of grass and agricultural plants only in an empirical manner and is not parameterized for savannah grass and the species considered in this study. Second, some components of the energy balance that were available from measurements could not be represented. We are also aware from the literature that at least the hydrological processes employed in some versions of the DNDC model have found to be not suitable for tropical and sub-tropical conditions (Saggar et al., 2007).

As an example for a model that operates with temporal resolution suitable to exchange fluxes and energy with climate models, the OSU model (Ek and Mahrt, 1991; Chen and Dudhia, 2001) has been chosen. This model has already been applied in the AMMA integrated project for West Africa. Simulations are therefore consistent with water balance calculations carried out in other parts of the project. The exchange with the climate model typically runs on a 10–30 min time step and the soil is differentiated into four layers of different but pre-described depth. Soil temperature and water content is calculated for each soil layer and time step. Additional outputs are latent and sensible heat flux and net radiation balance. Leaf area, vegetation density and height are usually derived from tables that account roughly for seasonal dynamics.

In order to increase comparability between the two models, we replaced all descriptions of plant properties and their dynamics by the PSIM vegetation model (Grote, 2007). This model describes plant development based on carbon balance dynamics. It calculates respiration as a function of nitrogen uptake and plant growth (Thornley and Cannell, 2000). Carbon allocation is determined from the concept of sink-strength driven distribution (Grote, 1998). Phenology, which is a major driver for sink-strength disruption is calculated from temperature sum and day length (Lehning et al., 2001). The model is complemented by a physiologically based assimilation routine (Farquhar et al., 1980; Martin et al., 2000) which calculates photosynthesis from light and temperature conditions, considering restrictions from insufficient water and nitrogen availability (Jarvis, 1976).

The coupling of the different models that are further described as modules has been established by a new modelling framework (MoBiLE, Modular Biosphere simulation Environment, Grote et al., submitted for publication). In general, modules can be selected from six biosphere components: (1) physical environment, (2) water balance, (3) plant carbon and nitrogen dynamics, (4) soil carbon and nitrogen dynamics, (5) air chemistry, and (6) vegetation structure and dimensional development. Air chemistry processes and changes in vegetation structure are not considered here. This means that air concentration of trace gases, species composition, vegetation height, and ground coverage are assumed to be constant during the simulation period. The framework enables the exchange of a large number of ecosystem variables that are stored in arrays of above- and belowground biosphere layers. The exchange processes between the selected modules is presented in Fig. 2. MoBiLE structure provides a flexible 1D-initialization of biomass distribution within an ecosystem according to the simulation settings. Initial values of biosphere properties are read from tables or are estimated based on the information available. Driving forces such as weather data and air chemistry properties above the biosphere (field climate) can be read from tables in daily or a selected sub-daily resolution. The modelling system also provides a simple weather generator to produce idealized driving variables or to fill measurement gaps. The selected modules are called in sub-daily or daily time steps. Outputs from sub-daily called modules (such as OSU module) that are needed in modules that are called only once a day (such as DNDC and PSIM) are summed up or averaged, respectively, throughout the day.

2.2. Module implementation and model modification

The routines of all models used in this study are implemented into the appropriated biosphere components of the MoBiLE framework (see above). This ensures that each model can be applied with only its original routines (sub-daily call of physical environment and water balance modules for OSU, daily call of modules describing physical environment, water balance, and biogeochemical soil processes for DNDC) as well as in other combinations. Variables that represent linkages to vegetation processes (such as leaf area index, rooting depth, litter-fall, or nitrogen uptake from the soil) are either fixed or provided by a vegetation module selected by the model user. Our DNDC version was derived from the PnET-N-DNDC model (Li et al., 2000), which uses a modified version of the forest growth model PnET2 (Aber et al., 1995) for this purpose. This model is not suitable for savannah vegetation. Therefore, and considering future simulations of co-occurring grass- and tree species in savannah, we decided to employ the general physiologically based vegetation model PSIM that has just recently been published (Grote, 2007) to provide the necessary variables. PSIM runs in a daily time step.

Despite the use of original model routines, the implementation within the MoBiLE framework leads to slight differences to the original models. The definition of soil layer thickness and soil depth that was formerly fixed in DNDC (30 cm soil depth, 2 cm layer height) and OSU (4 layers of pre-defined extension representing as soil depth of 2 m) is now defined by the user according to field observations or expert assumptions. This flexibility allows accounting for small differences in the upper soil horizons and acknowledges that water extraction might be limited by a dynamically changing root depth. Nevertheless, for reasons of model stability, the original layer extensions used in the soil physics module of OSU are still kept within the module. Parameters relevant for energy flux calculations that characterise the soil layers (porosity), variables that influence the calculations but change dynamically (moisture), and produced variables (soil temperature) are therefore aggregated or disaggregated each time the module is entered or left. Equilibrium temperature is assumed to occur at a reference depth of 3 m and is equal to average annual air temperature. If not calculated explicitly, a linear development of temperature between the lowest initialized soil layer and reference depth is considered. Furthermore, we assume that water rise from below the profile is not possible. Additionally, we modified the OSU runoff scheme to allow for a certain amount of rain to be stored at the soil surface. This accounts for the fact that precipitation that is not infiltrating the soil immediately is partly retained due to the

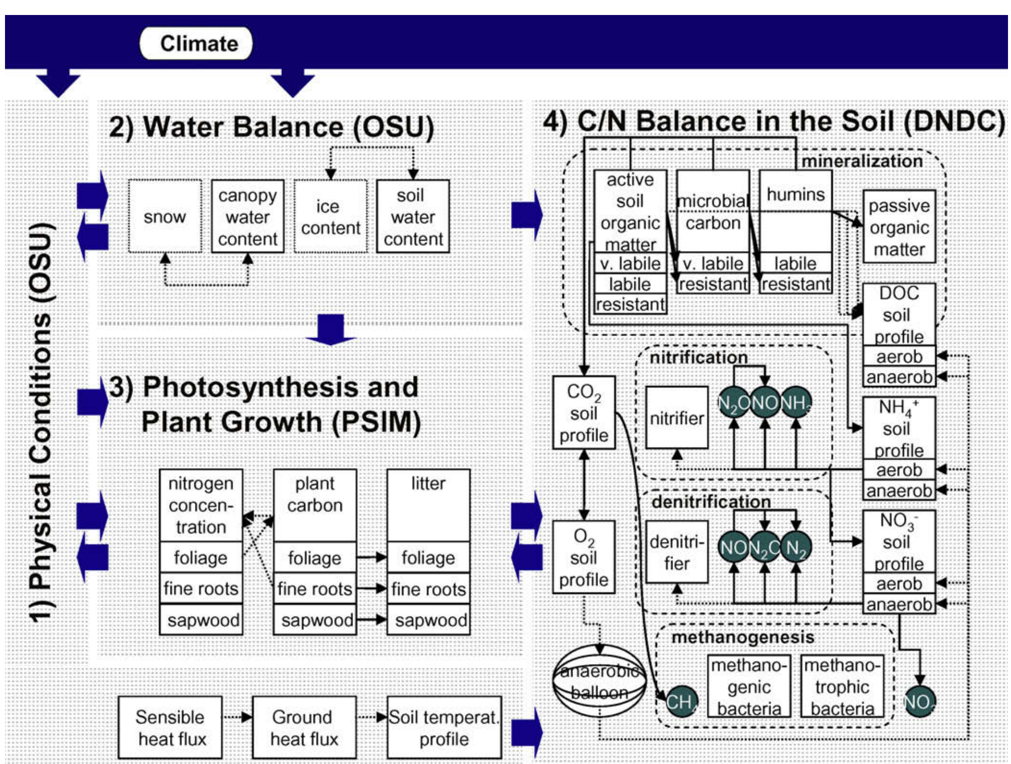

Fig. 2. Modular model framework. Relations between modules are presented as thick arrows between grey boxes. Within modules stocks are indicated as white boxes that are connected by matter flows.

roughness of the soil surface. Therefore, an upper limit of 10 mm is allowed to accumulate on the soil surface from where it is reduced by infiltration and evaporation during the following time steps.

2.3. Site information

2.3.1. General site characteristics

Mean annual air temperature in this region of Burkina Faso is 29.5 °C. Monthly averages ranged from the minimum of 24.7 °C in August 2006 to maximum values of 31.9 °C in May 2006. Long-term mean annual precipitation is 926 mm with a typical split-up into a wet (May–October) and a dry season (November–April). Eighty percent of the annual rainfall sum was recorded from June to September. Precipitation during this season is characterised by strong and short storms occurring mainly during the evening. During the very dry months from November to February the total amount of rainfall is only approx. 20 mm.

Our studies focus on a region in the Southwest of Burkina Faso, West Africa. The site is located within the Bontioli Nature Reserve, about 35 km south of Dano. It represents typical natural conditions dominated by grass (*Andropogon gayanus* and *Loudetiopsis kerstingii*). Soil type could be classified as sandy loam and can be considered as one homogenous layer of 35–50 cm thickness that stocks on laterite rocks. For more detailed information on soil parameters see Brümmer et al. (2008a,b) and Table 1.

2.3.2. Measurements

Data for driving the models and to evaluate the results were automatically collected by a weather station close by and during two intensive measuring campaigns in the years 2005 and 2006. Air temperature and relative humidity were measured with a HMP45C probe (Vaisala, Finland). Net radiation (R_n) was determined using a NR-Lite net radiometer as well as a CNR1 (Kipp & Zonen, The Netherlands) for the determination of incoming and outgoing solar and far-infrared radiation. Photosynthetically active radiation (PAR) was measured with a PAR-Lite sensor (Kipp & Zonen, The Netherlands). Rainfall was recorded with an ARG 100 rain gauge (Campbell Scientific, UK). All parameters were determined at a height of 2.0 m, except for rainfall that was recorded 1.0 m above ground.

The instrumental setup for automated continuous soil measurements consisted of a heat flux plate (HFT-3, Campbell Scientific, USA) in 0.08 m depth, three soil temperature probes (107 Thermistor, Campbell Scientific, UK) in 0.02 m, 0.1 m, and 0.3 m depth, respectively, and a theta probe soil moisture sensor (Delta-T, UK) in 0.2 m depth. Additionally, soil moisture and soil temperature were monitored manually at the locations of N_2O and CH_4 measurements with a handheld TDR probe (ML-2x, Delta-T, Cambridge, UK) and a cut-in thermometer (Novodirect, Kehl, Germany) in 5 cm depth simultaneously with trace gas flux measurements.

For determination of the soil–atmosphere exchange of N_2O and CO_2, the static chamber technique was used. Manual measurements (one to three flux rates per week) were conducted at all five experimental sites. At each site, four chambers were placed between the crop plants on plastic frames, which were anchored approx. 15 cm deep in the soil and were closed gas-tight with metal clamps. Four air samples were taken with gas-tight syringes every 10 min over a 30 min period. All gas samples were analyzed one day after sampling by a gas chromatography system. Flux rates were calculated via linear regression of the four sampling points for each chamber and by applying a temperature and pressure correction. For more detailed information see Brümmer et al. (2008a,b).

Table 1
Soil properties at the savannah grassland site at Bontioli National Reserve

Soil type	Sub-tropical brown soil
Soil density (kg dm^{-3})	1.431
Saturated hydraulic conductivity (cm min^{-1})	0.03
Saturated soil water tension (m)	−0.324
Organic carbon content (upper 10 cm)	0.00564
Sand content	0.65
Silt content	0.27
Clay content	0.07
Overall water content at field capacity (mm m^{-3})	500
Overall water content at wilting point (mm m^{-3})	140

2.4. Simulation setup

Simulations were carried out over the whole time period of 2005 and 2006. However, weather information for the period from June to December 2006 was not available at Bontioli and was therefore complemented by weather information from a similar station located approximately 25 km north of the National Park. Long-wave radiation was estimated from air temperature and vapour pressure, using the procedure suggested by Nagar et al. (2002).

Simulations were run on the basis of either sub-daily (10 min resolution) or daily weather data. In order to derive an alternative set of high resolution weather input from daily average data, we used literature derived algorithms for radiation and temperature distribution throughout the day. These were available from literature and are implemented in the MoBiLE framework to estimate the development of temperature (De Wit et al., 1978) and radiation (Berninger, 1994). Vapour pressure deficit and relative humidity are then calculated from temperature, assuming vapour saturation at the minimum temperature of the day. This method also serves well to overcome gaps in the measurement records. To test the suitability of this approach, we simulated soil temperature and energy fluxes from May to November 2005 with measured as well as with estimated high resolution weather data (10 min) and compared both simulation results with measurements.

The soil is initialised with measurements of field capacity, wilting point, bulk soil density, saturated conductivity, and carbon and nitrogen content. Water content at field capacity and wilting point for the upper soil horizon are derived from soil water measurements. Below 10 cm these two values are estimated from tables according to the texture type. For biogeochemical calculations, the amount of carbon and nitrogen in each layer has to be distributed into different fractions. This distribution is determined by a pre-run of two years using the weather data of 2005 and 2006 where an approximate equilibrium of these values could be reached. Without any modifications, the model tends to accumulate carbon to soil concentrations much higher than actually measured. Probably, the main reason for this behaviour is that fire effects have not been considered the simulation framework. Therefore, only nitrogen but not carbon from foliage litter is prevented from falling to the ground in the simulations, assuming it is released in the air. Soil- and rooting depth are set to 40 cm. Within this depth, the simulations are carried out with either 20 layers of equal thickness (high spatial resolution) or 2 layers of 10 and 30 cm dimension (low spatial resolution). No specific measurements were available with respect of the vegetation. However, sufficient information for the grass *Andropogon gayanum* could be found in literature to parameterize the vegetation model. The most important of the so derived vegetation properties for each species represented in the model are outlined in Table 2.

3. Results

First, it could be shown that the OSU model was able to generally represent soil temperatures as well as net radiation balance

Table 2
Basic properties of the vegetation types considered

Maximum rooting depth (m) (equivalent to initialized soil depth)	0.4	Indicated by measurements
Maximum leaf area index	3.0	Caylor et al. (2005)
Root/foliage ratio	4.0	Estimated from Monteny et al. (1997) and Jackson et al. (1997)
Fine root longevity (days)	791	Tjoelker et al. (2005)
Maximum RubP saturated rate of carboxylation at 25 °C ($\mu mol\ m^{-2}\ s^{-1}$)	55	Estimated from Simioni et al. (2004)
Maximum stomata conductivity ($mmol\ H_2O\ m^{-2}\ s^{-1}$)	273	Tjoelker et al. (2005)

Values reflect direct or indirectly parameterized values in the physiological submodel PSIM.

measured at the savannah site in Bontioli. Soil temperatures from May to December were slightly underestimated before the rainy season started and overestimated afterwards. There is also no major difference in the fit of simulation results that used 10-min weather data and those who are based on daily input values (Fig. 3A and B).

The difference between the use of real or estimated sub-daily weather data as simulation input is more visible when the net radiation balance calculated as the sum of ground heat, sensible, and latent heat flux (Fig. 4A and B). Simulation results are 10–16% below the measurements with more scattering when input data are estimated. More details about simulation fits of the single components of net radiation balance and the relation to total measured net radiation flux is given in Table 3.

Minor divergences in simulated soil temperature using either measured or estimated input values only appear on a sub-daily temporal scale, particularly during the rainy seasons, where occasional or long-lasting cloudiness leads to deviations between estimated and measured sub-daily weather variables (Fig. 5).

The DNDC model only calculates daily average soil temperature as input for biogeochemical computations. The calculation procedures provided by this model do capture the seasonal development of the soil temperature correctly (slope of simulation results against measurements: 0.97). However, the large day-to-day variation in the savannah soil, particularly during the dry periods could not be represented (R^2 = 0.26). This has been better represented with the OSU model (R^2 = 0.89, see Fig. 6).

Table 3
Slopes and squared indices of determination for the relationship of simulated to measured hourly values of sensible heat flux, ground heat flux, latent heat flux and net radiation balance

	Real data input		Estimated data input	
	Slope	R^2	Slope	R^2
Latent heat flux	0.86	0.77	0.94	0.73
Sensible heat flux	1.00	0.42	0.95	0.53
Ground heat flux	1.04	0.38	1.19	0.40
Net radiation balance	1.00	0.88	1.08	0.80

Simulations are carried out with the OSU physical module with weather input data in either 10-min (real data input) or daily resolution (estimated data input).

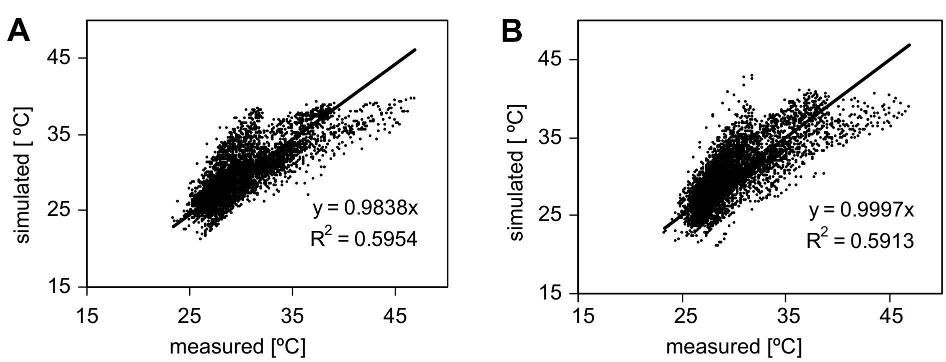

Fig. 3. Simulated vs. measured hourly soil temperature at 5 cm depth in the period May–December 2005 using either measured (A) or estimated (B) high resolution weather data as input for the simulations.

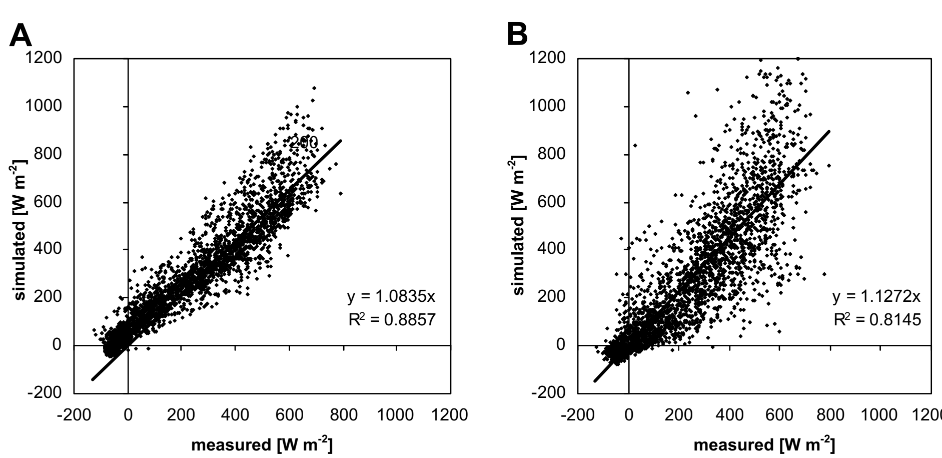

Fig. 4. Simulated vs. measured hourly sum of ground-, latent-, and sensible heat flux in the period May–December 2005 using either measured (A) or estimated (B) high resolution weather data as input for the simulations.

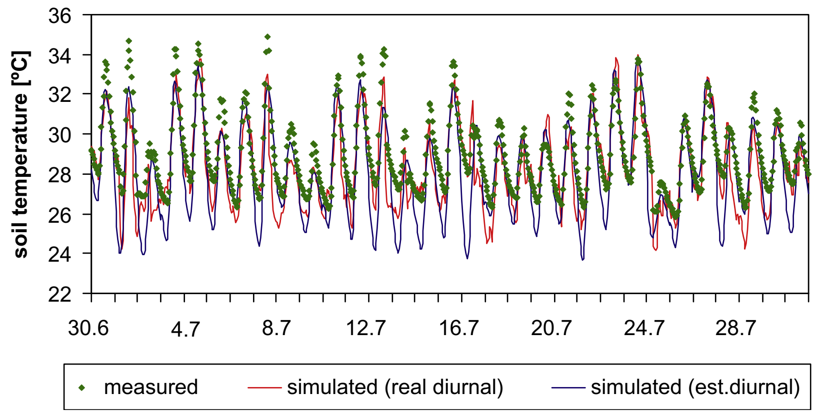

Fig. 5. Measured and simulated soil temperature during a July 2005 (within the rainy season). Simulations are based on either high or low-temporal resolution input.

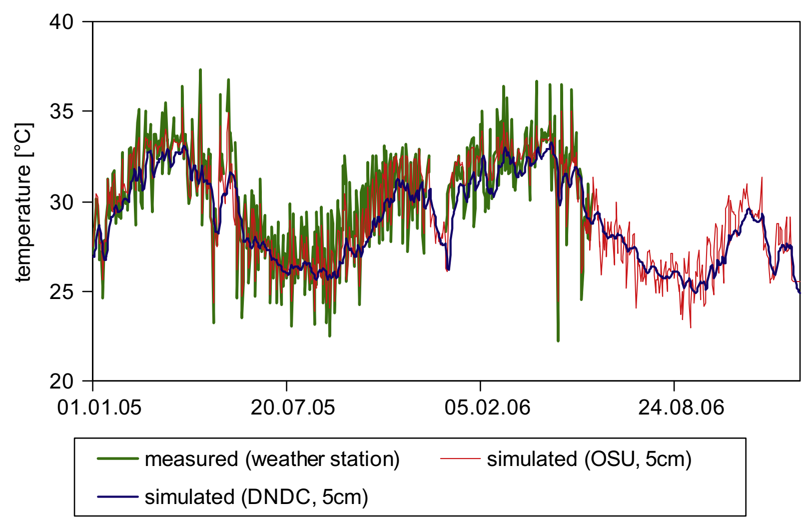

Fig. 6. Measured and simulated soil temperatures in approx. 5 cm depth in daily resolution throughout the years 2005 and 2006. Measurements are not available until the start of the rainy season in 2006. Simulations are carried out with the DNDC and the OSU model and are based on weather data in daily resolution (from which 10-min input data are derived for OSU calculations).

Soil water content in the upper layers could be well simulated with both, the DNDC model that only uses daily aggregated weather information and the OSU model which uses the 10-min input data directly (Fig. 7). The simulations with high or low spatial resolution of soil layers differ not substantially. OSU simulations are slightly closer to the measurements using the low resolution whereas DNDC performs a little better using the higher spatial resolution. Remarkably, the upper soil horizon seems to be almost totally dry outside the rainy season.

Since latent heat flux information was available from the Eddy-flux measurements, total evapotranspiration could be compared with simulation results obtained on the basis of OSU or DNDC simulations (Fig. 8). Measured latent heat flux was therefore transformed into mm units by dividing by latent heat of water evaporation (2272 J mm^{-1}). The simulation results produced with the two models were very similar although OSU results show a higher day-to-day variation that is consistent with the differences in soil temperature variation between DNDC and OSU (see Fig. 6). Both models tend to underestimate evaporation during the early phase of vegetation development and to overestimate it during the end of the rainy season. The overall result is an underestimation of latent heat flux by approx. 15%. These features probably indicate a mismatch in the simulation of phenological development that could not be evaluated in this study. The same dependence on soil layer thickness as observed with the simulations of soil water content is apparent. Again, the original resolutions used for the models perform best but the differences are relatively small.

Fig. 9A and B show measured soil respiration and N_2O emission, respectively, in comparison with DNDC simulation results based on the soil temperatures and water contents of either DNDC or OSU modules. Nitrogen emissions reached up to 20 µg N_2O–N m^{-2} h^{-1} after rain events (one measurement of 150 µg N_2O–N m^{-2} h^{-1} at the beginning of the rainy season in 2006 is not presented in the figure). Respiration rates are between approximately 10 and 350 mg CO_2 m^{-2} h^{-1}. Besides, large day-to-day variation for both fluxes is apparent in both years. This could not be well reproduced by the DNDC model. Both, respiration and nitrogen emissions were generally underestimated and represent approximately the lower limit of the measured fluxes in the rainy season.

Measurements in the dry season are not available and simulations indicate that emissions are either low or non-existent. The reason for the higher fluxes during this time as simulated on the basis of the DNDC physical and soil water modules compared to the OSU based simulations is the difference in soil water content in the deeper soil layers. Whereas these layers are quickly depleted down to the wilting point with the OSU modules, DNDC modules establish a certain amount of available moisture by early reduction

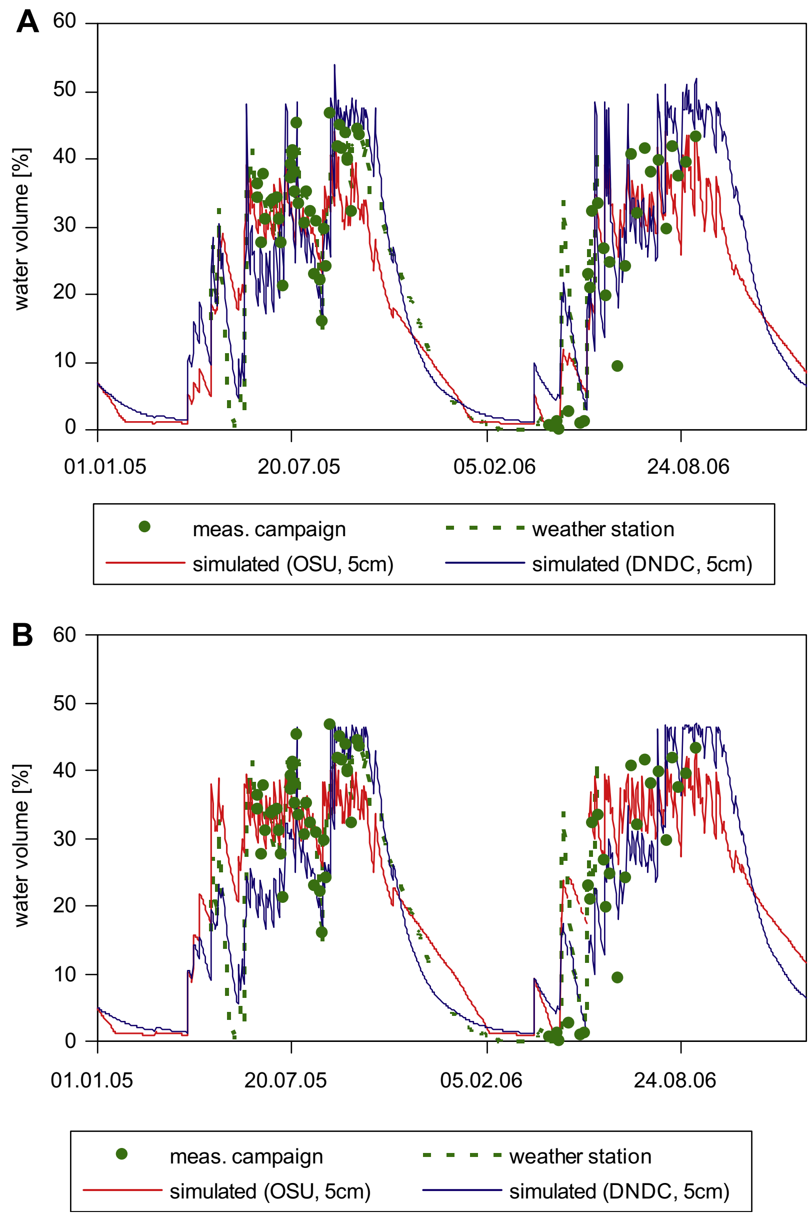

Fig. 7. Measured and simulated soil water content in 5 cm depth presented in daily resolution throughout the years 2005 and 2006. Simulations are carried out with the DNDC and the OSU model and are based on weather data in daily resolution (from which 10-min input data are derived for OSU calculations). Both models are either initialized with a high (A, 13 layers) or low (B, 2 layers) spatial resolution.

of soil evaporation. Also, the slight differences in N_2O emissions produced during the rainy seasons can be attributed to differences in the soil water because water filled pore space is somewhat higher with the DNDC water balance simulations.

4. Discussion

The simulation results with reference to physical and hydrological conditions at the investigated savannah site are well in accordance with measurements during this period. Soil temperature, soil water content, net radiation balance and single components of the radiation balance have been evaluated with measurements that overlap over long time periods. Soil temperature dynamics depend on vegetation cover as well as on soil water content – with lower temperatures and smaller temperature amplitudes during the rainy season. This dependency lead to some distinct deviations between OSU simulation results and measurements during short periods of leaf expansion and the start of foliage decline – where latent heat fluxes were under- or overestimated, respectively. Interestingly, there were only minor differences between simulations based on measured sub-daily weather data compared to those that are run with weather input that was estimated from daily resolution data.

Soil water content in the upper soil horizon could be traced well by both OSU and DNDC. The major difference between both models is that DNDC depletes deeper soil layers more slowly, leading to higher water contents in the total soil volume particularly during the transition from moist to dry periods. The sensitivity of model results to the number and thickness of soil layers has been of minor importance to the simulation of the average water content within one soil horizon. However, it should be recognized that water fluxes other than evaporation have not been evaluated. Thus, uncertainties remain, i.e. with respect to the calculation of runoff and deep percolation. Evapotranspiration is well simulated over

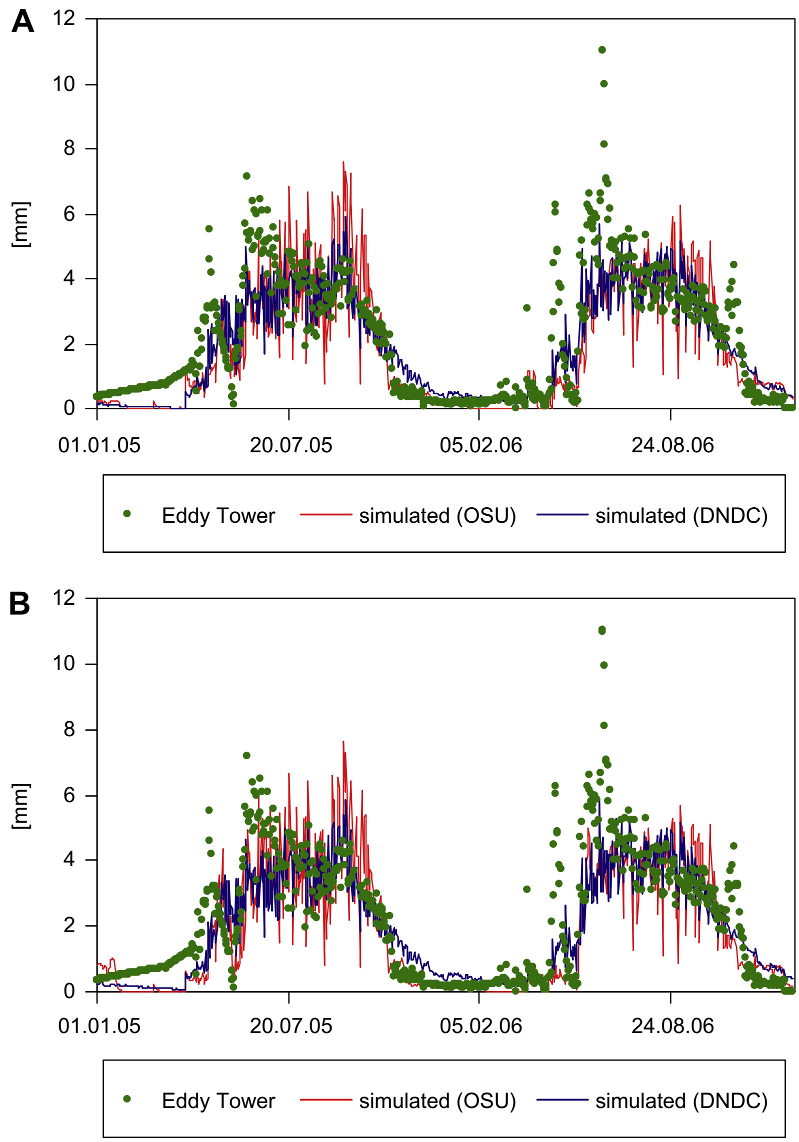

Fig. 8. Measured and simulated total evapotranspiration presented in daily resolution throughout the years 2005 and 2006. Simulations are carried out with the DNDC and the OSU model and are based on weather data in daily resolution (from which 10-min input data are derived for OSU calculations). Both models are either initialized with a high (A, 13 layers) or low (B, 2 layers) spatial resolution.

most of the year but – as already discusses with respect to the soil energy balance – has been underestimated during early foliage expansion and overestimated in the late vegetation season. To avoid this deviation, better physiological or phenological procedures should be tested, which could not be done in this investigation because foliage development and stomata conductance had not been observed.

Finally, simulated carbon and nitrogen emissions were independent of the module that has been used for calculating soil temperature and moisture. Small deviations between the simulations are mainly attributed to differences in soil water content. Soil temperature is considered as a daily average value in the biogeochemical calculations and model results are not sensitive to a higher (more realistic) day-to-day variation. However, biogeochemical processes could not be very well represented by DNDC simulations. In particular the common observation about N_2O emissions being very high at the beginning of the rainy season (e.g. Scholes et al., 1997; Rees et al., 2006) has not been shown up in the results. A similar deficit in reflecting fast soil water changes had been already recognized with respect to thawing events that also suddenly increase moisture availability under unfavourable starting conditions (Xu-Ri et al., 2003). It seems that either micro-biological activity is actually much faster initiated than expected or that substrate availability (e.g. carbon availability in the soil solution) after the release of one specific stress factor (i.e. drought) is not adequately represented. Just recently, Collins et al. (2008) made the same observations for arid soils and proposed a Threshold-Delay Nutrient Dynamics model to deal with problem.

A possible further source of errors is also the inherent daily time step in DNDC. This is particularly cumbersome in environments with high environmental fluctuations within a day such as savannah. With the new combination of models, a possibility emerges to calculate biochemical processes in a 'true' sub-daily time step using dynamically updated rather than daily average soil environmental conditions as drivers. However, this exercise could not be done within the frame of the present investigation. In any case, the result indicates that the effect of fast changes in soil water supply following prolonged periods of inactivity on biogeochemical processes are not yet well represented in DNDC and should be subject to further developments.

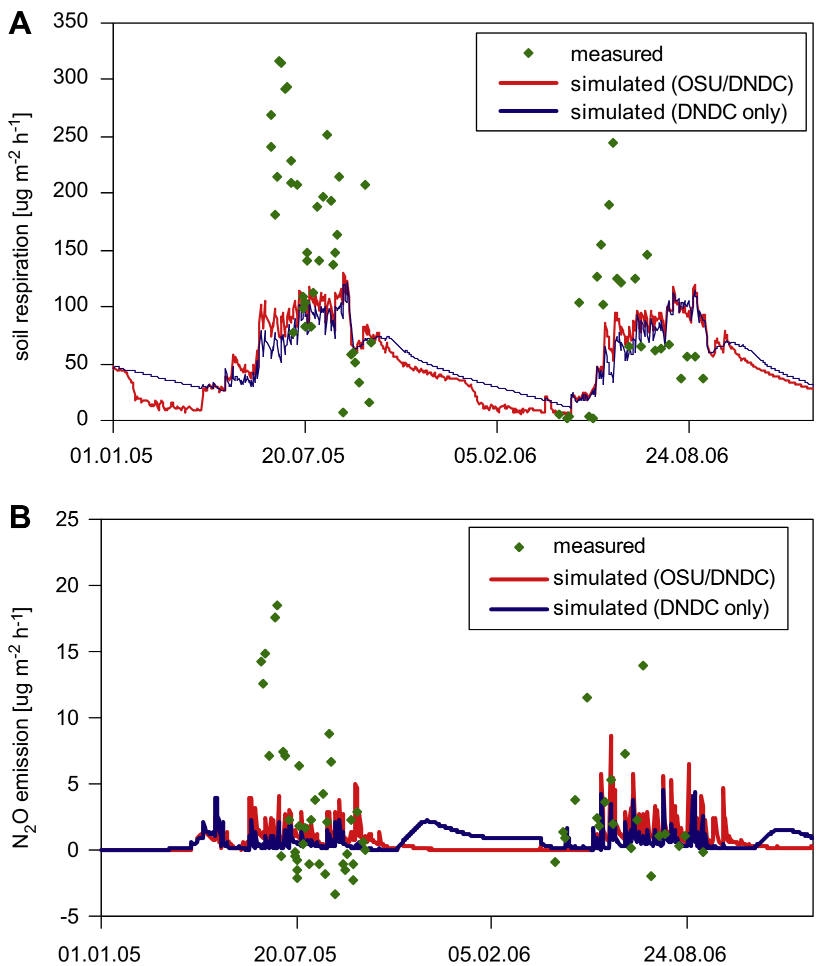

Fig. 9. Measured and simulated soil respiration (A) and N2O emission (B) throughout the years 2005 and 2006. To be comparable with measurements, daily simulation results are divided by 24. All simulations are carried out with the DNDC model using the physical and water balance calculations from either DNDC (DNDC only) or the OSU model (OSU/DNDC). Simulations are based on weather data in daily resolution (from which 10-min input data are derived for OSU calculations). Both models are initialized with high spatial resolution (13 layers).

Overall, simulation results demonstrate that it is possible to run the biogeochemical calculations with the soil temperature and water content values produced by OSU. The simulated soil conditions that drive biogeochemical processes are neither sensitive to the temporal resolution of energy balance calculations nor to the spatial resolution of vertical soil stratification. This means that the calculation of heat and water fluxes in a high temporal resolution as required for the coupling with regional climate models could be aggregated and applied to biogeochemical process models. It is also possible to apply a higher spatial resolution within the soil if this is required in order to account for a heterogeneous distribution of soil properties (e.g. carbon distribution with depth). The coupling of a physically based energy balance description with a biogeochemical model may be useful for future coupling of biogeochemical and regional climate models.

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