Boundary-Layer Meteorol (2006) 121: 153–174
DOI 10.1007/s10546-006-9066-4

ORIGINAL ARTICLE

Improved representation of land-surface heterogeneity in a non-hydrostatic numerical weather prediction model

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Received: 3 May 2005 / Accepted: 20 February 2006 / Published online: 27 May 2006

Abstract This study focuses on the relevance of accurate surface parameters, in particular soil moisture, and of parameterizations for heterogeneous land surfaces, for the prediction of sensible and latent heat fluxes by a mesoscale weather forecast model with horizontal grid resolution of 7 km. The analysis is based on model integrations for a 30-day period, which are compared both to flux measurements obtained from the LITFASS-2003 field experiment and to high-resolution-model (1-km grid spacing) results. At first, the relevance of improved parameter sets and input data compared to usual operational practice for an accurate prediction of near-surface fluxes is shown and discussed. It is demonstrated that an observation-based land-surface assimilation scheme leads to an improved soil moisture analysis, which is shown to be essential for the realistic simulation of surface fluxes. Secondly, the implementation of two efficient parameterization strategies for subgrid-scale variability of the surface, the mosaic and the tile approach, is presented. Using these methods, the simulations are in better agreement with measurements than simulations with simple aggregation methods that use effective surface parameters. Integrations with the mosaic approach reproduce high resolution simulations very well and more accurately than simulations with the tile method. Finally, the high resolution simulations are analyzed to justify and discuss the approximations underlying both methods.

Keywords Flux aggregation · Mosaic approach · Soil moisture · Surface fluxes · Surface heterogeneity · Tile approach

1 Introduction

The exchange between the land surface and atmosphere is an important source for water vapour and energy in the atmosphere. Turbulent latent and sensible heat fluxes affect directly near-surface temperature and humidity (e.g. Mahfouf 1990; Ronda et al. 2002), and frequently

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affect moist convection (e.g. Chen and Avissar 1994; Segal et al. 1995; Lynn et al. 1998; Findell and Eltahir 1999). Both aspects are of relevance for numerical weather prediction (NWP) and, consequently, an accurate representation of exchange processes is essential for NWP models. Although the horizontal resolution of these models has been dramatically reduced to the order of 10 km and below, land-surface heterogeneity has still considerably smaller spatial scales than the grid spacing and thus cannot be resolved explicitly.

Parameterizations of subgrid-scale land-surface heterogeneities have first been developed for larger scale ($\Delta x \sim 100$ km) global circulation models (GCM). Giorgi and Avissar (1997) present a comprehensive overview of those methods. At large scales, neglecting subgrid-scale land-surface heterogeneities may have two implications: at first, the relations between surface parameters and fluxes are non-linear and consequently calculations with averaged, effective parameters (e.g. Lhomme et al. 1994) may result in erroneous flux estimates (aggregation effect). Secondly, heterogeneous land surfaces may induce mesoscale circulations (dynamical effect) by differential surface heating similar to the well known land–sea circulations. Analyses of simulations with high-resolution models (Avissar and Schmidt 1998; Roy et al. 2003) indicate that land-surface contrasts with a spatial extent of at least 5–10 km are needed to generate mesoscale circulations. Since these structures can be resolved by most NWP models, parameterization of the dynamical effects is of minor importance for mesoscale weather forecasting models. This study will thus concentrate on the aggregation effect.

Studies with high resolution mesoscale models (Mölders and Raabe 1996a; Schlünzen and Katzfey 2003; Heinemann and Kerschgens 2005), as well as the evaluation of measurements (e.g. Mahrt 1996), have shown that, even with a grid spacing of only a few kilometres, considerable aggregation effects may occur and must be corrected for. Avissar and Pielke (1989) proposed the mosaic approach: the surface within a coarse scale atmospheric grid box is subdivided into patches with assumed homogeneous surface characteristics. Surface fluxes are calculated separately for each patch using local surface parameters but a uniform atmospheric state at the reference level. Averaging the resulting fluxes at the lowest model level provides a lower boundary condition for the atmospheric model.

Aggregation methods based on the mosaic approach, which differ only slightly in the selection criteria for patches and the treatment of soil processes, have successfully been applied in GCMs (e.g. Koster and Suarez 1992; Li and Avissar 1994; Seth et al. 1994; Giorgi 1997) and mesoscale models (e.g. Mölders et al. 1996b; Schlünzen and Katzfey 2003). While these studies concentrate either on large synoptic scales or on single case studies with high model resolution, our study focuses on the evaluation of these parameterizations in the framework of an operational numerical weather forecasting system under realistic conditions and for longer simulation times. Integrations using the operational, non-hydrostatic weather forecasting model ‘Lokal Modell’ (LM) (Steppeler et al. 2003) of the German Meteorological Service (‘Deutscher Wetterdienst’, DWD) are compared both to high-resolution-model results (1-km resolution) using the same model and measurements obtained from the LITFASS-2003 field experiment (Beyrich et al. 2006a) over a 30-day period.

The experiment, the mesoscale model LM, and the additionally implemented parameterization schemes for heterogeneous land surfaces are described in the next section. In Section “Improved explicit simulation of near surface fluxes” the relevance of improved parameter sets and input data of the land-surface scheme for the prediction of near-surface fluxes is discussed. We highlight in particular the importance of a precise soil moisture analysis (SMA). Various methods to parameterize the heterogeneous land surface are evaluated in Section “Evaluation of the parameterization methods” by comparisons to both measurements and high resolution simulations. The main findings are summarized and discussed in the last section.

2 Model and data description

2.1 Experimental data

We focus on the LITFASS-2003 experiment, which took place from 19 May to 17 June 2003 within the LITFASS domain 50 km south-east of Berlin (see Fig. 1). The LITFASS domain includes typical central European land-surface heterogeneities, especially land-use contrasts between forests in the western part and farmland in the east. Orographical effects are of minor importance because differences in elevation are below 100 m. During the experiment period 14 eddy covariance stations were deployed above different surface types. These observations were used to derive composite time series of latent heat flux, λE, and sensible heat flux, H, for all relevant land-use types (Beyrich et al. 2006b). These time series are area weighted to estimate the area-averaged fluxes for the whole LITFASS domain. These composite products are used for model evaluation. A detailed description of the experiment is given by Beyrich et al. (2006a).

Weather conditions during the experiment period were favourable for the investigation of heterogeneity effects, because fair weather situations with weak synoptical forcing and large net turbulent fluxes $\lambda E + H$ due to clear sky insolation were dominant. The first half of the campaign can be characterized as a dry-out phase with extreme dry soil conditions leading to limited plant transpiration. In the middle of the period (5 June 2003) significant convective rainfall increased the soil moisture storage locally. Afterwards the soil dried out again interrupted only by light stratiform rain on two occasions.

2.2 Model description

The LM is a fully compressible non-hydrostatic model that is currently operated by DWD with a horizontal resolution of 7 km. The time integration is implicit in the vertical direction and split-explicit in horizontal directions following the concept of Klemp and Wilhelmson

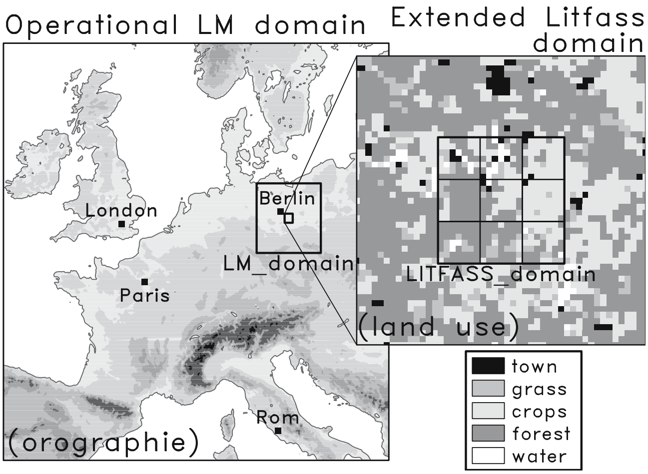

Fig. 1 Model domains: LM7_OP runs were performed on the operational LM domain covering Central Europe. All other simulations were performed on the LM domain (385 × 385 km^2). The soil moisture data obtained by MSMA is available for the Extended-LITFASS domain (49 × 49 km^2) and measurements are provided for the LITFASS domain (20 × 20 km^2)

(1978). The LM has a generalized terrain-following vertical coordinate with 35 layers reaching from the earth's surface up to 20 hPa. The vertical resolution is highest close to the surface with the lowest model level at 33 m above ground and increasing grid space with altitude. Prognostic model variables are the wind vector, temperature, pressure perturbation, specific humidity, and cloud water of grid-scale clouds. The LM comprises a state-of-the-art package of parameterizations of all subgrid-scale processes.

Subgrid-scale turbulence within the atmosphere is parameterized with a level-2.5 closure developed by Mellor and Yamada (1982). The exchange coefficients for momentum K_m and for heat and moisture K_h between surface and atmosphere calculated following Louis (1979). This scheme uses an approximation of the vertically integrated surface-layer profile functions derived by Businger et al. (1971), and the exchange coefficients depend on the roughness length z_0 and the bulk Richardson number Ri_b. Sensible heat flux H and latent heat flux λE can then be evaluated from the well-known bulk formulae:

$$H = -c_p \rho \, |v_h| \, K_h \, (\Theta_{\text{atm}} - \Theta_0) \, , \tag{1}$$

$$\lambda E = -\lambda \rho \, |v_h| \, K_h \, (q_{\text{atm}} - q_0) \tag{2}$$

with the air density ρ, heat capacity at constant pressure c_p, and latent heat of vaporization λ. Similar formulae are applied to calculate the exchange of momentum.

Surface temperature T_0 and soil moisture content S are predicted by the two-layer soil module TERRA, where the heat transfer equation is solved by the extended force restore method (Jacobsen and Heise 1982), and evaporation from bare soil and plants is parameterized using the BATS scheme of Dickinson (1984). A Davies (1976) relaxation technique is implemented to relax the prognostic values at the lateral boundary zone towards the boundary values. The model is especially designed for small-scale applications and has already been used successfully at grid spacings down to 1 km (Seuffert et al. 2002; Ament et al. 2004). More details about the model are given by Doms and Schättler (1999).

2.3 Model input parameters

Integrations for this study have been done on a $385 \times 385\,\text{km}^2$ area centred over the LITFASS domain (Fig. 1). Boundary and initial data were provided by the operational nudging scheme of DWD; they are calculated for the domain of the operational simulations (LM7_OP) at 7-km resolution. Since first comparisons of operational model results led to large differences with observations, we implemented for this area a new set of surface parameters. Surface parameters such as leaf area index LAI, roughness length z_0, are derived from the CORINE land-cover dataset CLC90 (EEA 2000) with 100-m horizontal resolution by assigning each land-use class typical parameter values according to Table 1. Surface elevation was derived from the global topography data GTOPO30 (USGS 1997) and the soil type classification was adopted from the operational LM settings. High resolution data were aggregated on coarse model grids by logarithmic averaging for z_0 and arithmetic averaging of all other continuous quantities. Categorized variables (land use and soil type) are aggregated by using the dominant class within each grid box. The annual development of vegetation is parameterized by a sinusoidal variation of LAI and plant cover between their minimum and maximum values during the vegetation period and using minimum values during the winter season. Simulations with the modified land-surface parameters are indicated by the notation LM7, in contrast to LM7_OP, which indicates simulations with the operational parameter settings.

Table 1 Surface parameters assigned to different land-use types

	Town	Grass	Crop	Shrub	Deciduous forest	Coniferous forest	Mixed forest	Water
Roughness length (m)	1.0	0.03	0.1	0.1	1.0	1.0	1.0	modified Charnock formula
Plant cover min/max	0.05/0.1	1/1	0.5/1	0.1/0.5	0/1	1/1	0.5/1	
LAI min/max	0.1/4	0.5/4	0.2/4	0.1/3	0/6	8/8	2.25/7	Constant surface temperature prescribed by initial data
Root depth (m)	0.3	0.15	0.3	0.4	0.8	0.8	0.8	
Vegetation Albedo	0.18	0.2	0.2	0.15	0.12	0.1	0.12	
Stomatal resistance min/max (sm^{-1})	100/3000	60/2000	100/3000	100/4000	200/5000	200/5000	200/5000	

2.4 New model extensions

Both LM7 and LM7_OP use effective surface parameters to account for land-surface heterogeneities. Two additional parameterizations, which simulate surface processes with a higher resolution than the atmospheric processes, have been implemented into the LM (Fig. 2). In the literature these approaches are often referred to as ‘mosaic’ and ‘tile’ methods, but with a partly ambiguous nomenclature. We adopt the definitions by Heinemann and Kerschgens (2005) and present a detailed description in the following.

2.4.1 Mosaic approach

In the mosaic approach (sometimes also referred to as the explicit subgrid approach, e.g. Seth et al. 1994) all surface processes including soil physics, the solution of the surface energy balance equation, and the calculation of fluxes are calculated at a finer grid than the atmospheric grid. Each atmospheric grid box contains N localized surface grid boxes. Surface and atmospheric grids are coupled by averaging the fluxes at the lowest model level, and by using the same atmospheric reference values ($\Theta_{\text{atm}}, q_{\text{atm}}, |v_h|$) in Eqs. (1) and (2), e.g. for calculation of sensible heat flux:

$$H = -{}^1\!/_N \sum_{i=1}^{N} c_p \rho_i \, |v_h| \, K_{h,i} \left(\Theta_{\text{atm}} - \Theta_{o,i}\right). \tag{3}$$

Local variables of the N sub-pixels are indicated by the subscript i. The local exchange coefficient $K_{h,i}$ is evaluated using the local roughness length $z_{0,i}$ and surface temperature $T_{0,i}$, but the coarse scale (atmosphere-scale) reference temperature T_{atm} and wind speed $|v_h|$. Latent heat and momentum fluxes are calculated in the same way.

The mosaic method implicitly makes an all-or-nothing assumption about subgrid-scale horizontal diffusion: at the reference height (in our case, 33 m above the ground) and above, this mixing is considered to be so effective as to remove all subgrid-scale variability. In contrast, horizontal exchange is totally suppressed in the surface layer and consequently the surface of each sub-pixel is coupled vertically with the atmosphere at the reference height according to constant-flux layer theory.

Radiative transfer is calculated at first for each atmospheric column using the surface albedo and infrared emission averaged over all sub-pixels (Hu et al. 1999). In a second step the average net radiation for each atmospheric grid box is disaggregated by using the local albedo and local surface temperature of each sub-pixel. In this study the mosaic approach is used with an atmospheric grid spacing of 7 km and with a resolution of 1 km for the surface (LM7_MOS1).

2.4.2 Tile approach

The tile method subdivides the surface within an atmospheric grid box into several classes — the ‘tiles’ e.g. according to the land-use type. For each class all surface processes are calculated separately, as for a sub-pixel of the mosaic method utilizing the similar all-or-nothing approximation of subgrid-scale horizontal mixing. Net fluxes at the lowest atmospheric level are determined, however, by a weighted average of the ‘tiles’ with fractional coverage of each class as weight, e.g. for the sensible heat flux:

$$H = -\sum_{i=1}^{N} f_i c_p \rho_i \, |v_h| \, K_{h,i} \left(\Theta_{\text{atm}} - \Theta_{o,i}\right) \tag{4}$$

with fractional coverage f_i of the surface class i. An analogous relation applies for λE and the flux of momentum. In this study the tile approach is applied with an atmospheric grid spacing of 7 km (LM7_TILE) and considers the eight land-use classes listed in Table 1.

The benefits of the tile method compared to the mosaic approach include an exact representation of the fractional coverage of various surface types and less computational demands for most applications, since in general fewer tiles than the sub-pixel are needed.

On the other hand, the tile method neglects all variability that is induced by other surface characteristics than the one used to define the tiles. Thus, the tile approach has (in our case) a maximum of eight different land-surface types, whereas the approach can have up to 49 different types.

2.4.3 Simplified mosaic and tile approaches

Both methods may be simplified by assuming homogeneous soil conditions within one atmospheric grid box. Consequently the same soil temperature and soil moisture values are used for all sub-pixels of the mosaic approach or all land-use classes of the tile approach; only different surface parameters such as roughness length or stomatal resistance are applied to calculate the individual fluxes. All processes within the soil, such as heat conduction or drainage, have to be calculated only once per atmospheric grid box. These simplifications with a homogeneous soil are indicated by LM7_MOS1_HSOIL and LM7_TILE_HSOIL.

3 Improved explicit simulation of near-surface fluxes

The LM with its operational configuration (LM7_OP) is not able to represent the observed turbulent fluxes during the LITFASS-2003 experiment, as the time series of domain-averaged latent heat flux (Fig. 3) clearly indicates. Evaporation is excessively overestimated by the model, which is mainly caused by inaccurate soil moisture data. The operational SMA provides very high values (Fig. 4), thus allowing plants to transpire at the maximum rate, whereas in reality transpiration was limited by soil moisture stress most of the time. Area-averaged soil moisture contents are hardly measurable and consequently any data assimilation system for soil moisture depends strongly on the background field, which is simply the model-predicted temporal evolution of soil moisture. Indirect observations are incorporated in the operational SMA of DWD by a variational algorithm (Hess 2001): errors in predicted temperature and humidity at 2-m height on the previous day are used to correct the soil moisture content in a Kalman filter approach. This method has two drawbacks, which may be the reasons for the observed deficiencies: if the soil moisture field is updated by the fully coupled atmospheric/soil model, all atmospheric variables influencing the soil moisture evolution, especially rain rate, are model variables with errors due to model shortcomings or limited predictability. Secondly, the variational soil moisture assimilation may introduce a bias in soil moisture because not all errors in the predicted variables at the 2-m level are caused by poor soil moisture data (see also Seuffert et al. (2004) for the potential for similar problems in the assimilation scheme of the European Centre for Medium Range Forecasts).

A measurement-forced soil moisture analysis (MSMA) turned out to be a more favourable alternative. Such concepts have recently been applied successfully at continental scales (Mitchell et al. 2004) as well as at the mesoscale (Trier et al. 2004). Our MSMA scheme

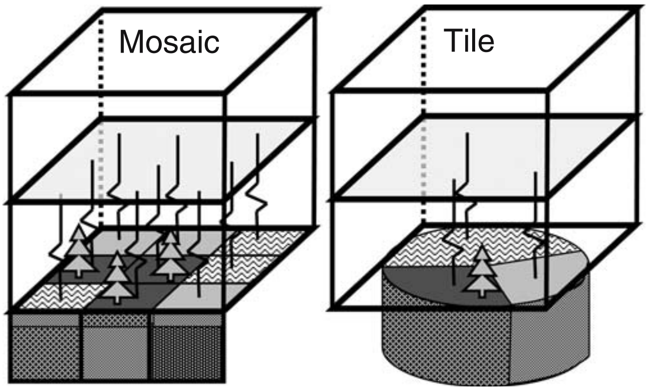

Fig. 2 Schemes of mosaic (left) and tile (right) approaches

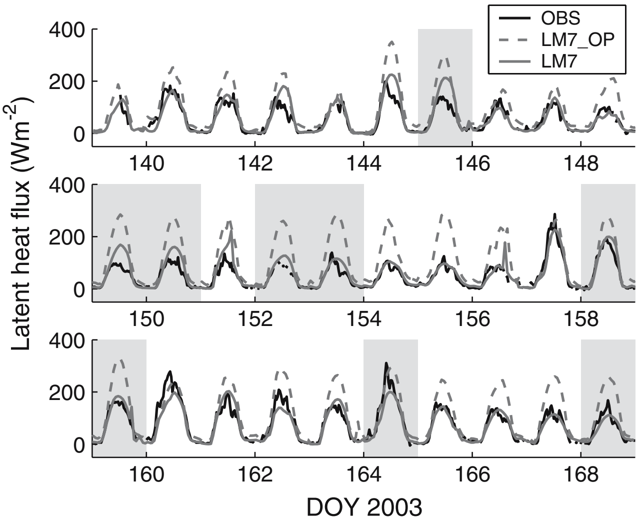

Fig. 3 Time series of LITFASS domain-averaged latent heat flux. Grey shaded areas indicate the nine selected days for which LM1 simulations have been performed

consists of a temporal integration of the soil module TERRA in a stand-alone version; all atmospheric forcing variables are provided by local or near-by measurements: temperature and humidity at 2-m height, downwelling radiation and the 10-m wind are prescribed homogeneously as measured at the central measuring facility of the LITFASS domain. Rain rates should not be prescribed homogeneously over the area because the spatio-temporal structure of rainfall determines largely also the spatio-temporal structure of soil moisture on short time scales (see results in Section "Summary and Conclusions"). During LITFASS-2003 radar-derived rain rates at 1-km resolution are assimilated; radar reflectivities are converted to rain rates by matching the cumulative frequency distribution of reflectivities and collocated rain gauges. Since radar data were not available in the time period before the campaign, spatially interpolated rain rates from a network of ten rain gauges were used instead. This method was not applied to the full model domain depicted in Fig. 1 but only to the extended LITFASS domain covering $49 \times 49\,\text{km}^2$ also indicated in Fig. 1. Outside this area it is

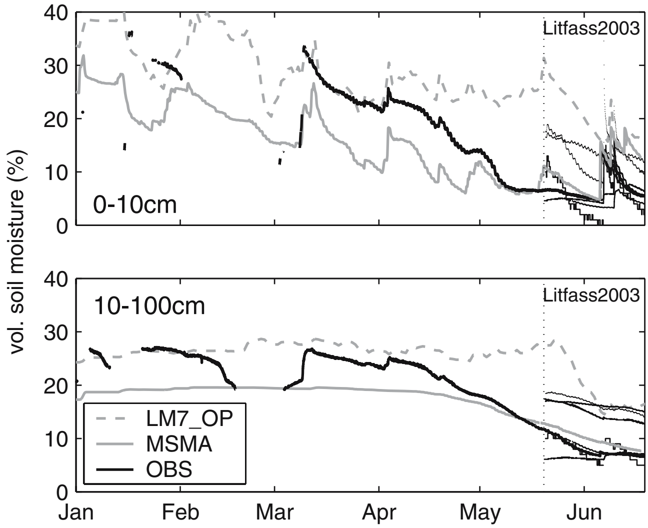

Fig. 4 Time series of modelled LITFASS domain averaged soil moisture content compared to point measurements at various sites

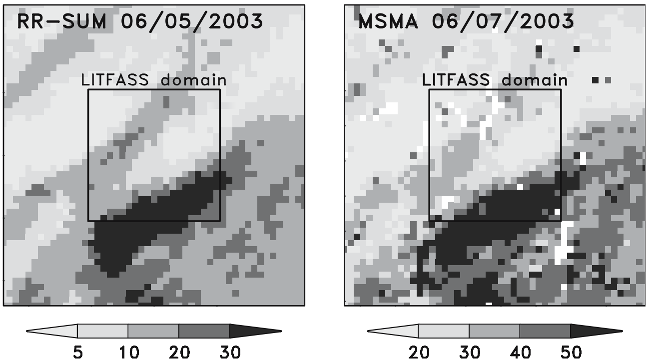

Fig. 5 Daily accumulated precipitation derived from radar measurements at the Extended-LITFASS domain (5 June 2003) and resulting soil moisture field (7 June 2003) given by MSMA

assumed that the operational SMA represents the correct spatial structure but might exhibit a bias. The bias is estimated by comparing the results of our MSMA with the operational SMA in the overlap area; the bias is then corrected for the whole external domain. Since any soil moisture variation in the generally densely vegetated model domain is dominated by plant transpiration, the soil moisture variable most appropriate for our bias correction is the relative plant available soil moisture. This variable is the volumetric soil moisture scaled by the field capacity and the permanent wilting point.

Figure 4 shows that the area-averaged soil moisture derived from the MSMA for the LITFASS domain is in much closer agreement with observations than the operational SMA. The observations are, however, only point measurements at different sites, thus these measurements can only indicate the order of magnitude of the true area average. One important advantage of our MSMA is its ability to reproduce in a most direct way the spatio-temporal response of the soil moisture distribution to rainfall (see Fig. 5).

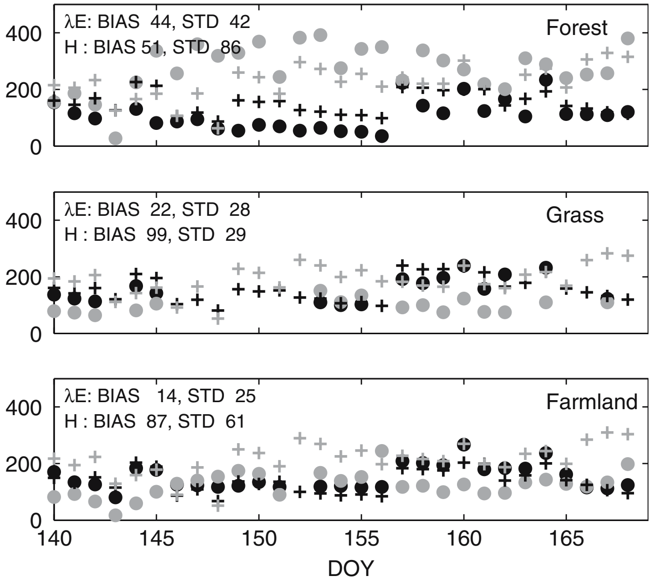

Fig. 6 Observed (•) and modelled (+) daytime (0800–1400 UTC) means of latent heat flux λE (black) and sensible heat flux H (grey) in W m^{-2} over different land-use types

The model simulations using the soil moisture contents from MSMA operate in the correct, soil-moisture-limited regime, but additional improvements were needed to reproduce the correct spatial flux distribution, in particular, the contrast between high H values over forests and moderate values over farmland. This deficiency in the operational model version was due to use of a constant stomatal resistance and albedo values for all types of vegetation. This problem was solved by introducing land-use-dependent stomatal resistance and albedo values according to Table 1. These changes have not only a direct and positive impact on modelled surface fluxes but also induce a long-term feedback mechanism due to the different temporal evolution of soil moisture.

The simulated fluxes by the LM7 integrations with MSMA and the now land-use-dependent parameters (Fig. 3) are in very good agreement with the measurements. Figure 6 shows a comparison between simulated (LM7_MOS1) and observed fluxes over different surfaces (LM7_MOS1 is used instead of LM7, since 7-km resolution is too coarse to analyse the spatial structure within the LITFASS domain); the model simulates successfully the overall differences between the land surfaces and their temporal evolution. Over farmland and especially over grass the simulated value of $\lambda E + H$ is, however, systematically higher than the observations, whereas the measured and modelled net radiation are in good agreement (not shown). This discrepancy is not necessarily caused by a model deficiency and is at least partly a result of the non-closure in the measured energy balance; according to Mauder et al. (2006) the energy balance cannot be closed by up to 20–30% of the available energy during LITFASS-2003. Over forest the model produces larger values of H compared to λE, but this difference is less pronounced than in the measured values. Since the forest time series is based only on one single eddy-covariance station a reliable tuning of model parameters is hardly possible. In essence, the modified model with MSMA and the improved parameterization is able to simulate the exchange between the atmosphere and heterogeneous land surfaces explicitly.

In the following the improved model will be applied to evaluate parameterization schemes for heterogeneous land surfaces. Such schemes are necessary because explicit representation of a heterogeneous land surface by grid refinement requires excessive computer time. The computational costs increase by the third power of the refinement factor since the number of grid points increases quadratically and a linear increase in timesteps is necessary to maintain numerical stability of explicit integration schemes.

4 Evaluation of the parameterization methods

Table 2 summarizes the settings of all model runs with the improved LM that will be evaluated in the next section. Weaver et al. (2002) demonstrated that a carefully chosen model configuration is necessary for any investigations of land-surface heterogeneity. Thus all runs are integrated for exactly the same spatial domain, because boundary conditions may introduce deviations that may have the same magnitude as the effects under investigation (Ament et al. 2004). The simulations are always terminated at 0000 UTC and reinitialized with atmospheric data from the operational analyses to ensure simulations close to real weather conditions. Soil moisture is also reinitialized at 0000 UTC and therefore errors in soil moisture due to wrong precipitation forecasts will not affect the simulations of the following days. In order to avoid spin-up effects concerning soil moisture, for each model configuration soil moisture was initialized separately by using the MSMA with the proper surface representation. In contrast to soil moisture, soil temperature was simulated continuously to ensure energy conservation in the soil and to guarantee a closed surface energy balance.

Our set of model variants is completed by reference simulations with a 1-km horizontal grid spacing for both soil and atmosphere (LM1). These integrations were, however, only performed for nine selected, so-called golden, days (grey shaded days in Fig. 3) because of the excessive computational demands of such high resolution simulations. LM7_MOS1 soil temperature forecasts of the previous day are used as initial values for the simulations of the golden days.

4.1 Comparison with flux measurements

Only slight differences between the area-averaged fluxes for the LITFASS domain (depicted in Fig. 7) occur for the different parameterizations methods. The coarse resolution of LM7 results in a higher percentage of forest area within the model domain (66% compared to a real value of 45%) and consequently the highest sensible heat fluxes and lowest latent heat fluxes compared to LM7_MOS1 and LM7_TILE. Again the sum of the turbulent fluxes in all runs is higher than in the observations, which is, as mentioned above, likely due to the non-closure of the observed surface energy balance. With the observational uncertainties in mind it is hardly possible to rank the different parameterization methods on the basis of Fig. 7 or the corresponding error measures summarized in the first two rows of Table 3. Independently from the employed parameterization scheme, there is a phase shift between modelled and observed fluxes: the modelled maximum of H is reached too early and the maximum of λE is modelled too late. This is unlikely to be caused by deficiencies in representing the soil heat flux in a two-layer soil module because simulations with a multi-layer version of TERRA, which is currently under development, revealed the same error. The measurements especially over forest hint at an, as yet, unknown (not modelled) process, which reduces evaporation in the afternoon. Further investigation is needed to clarify this issue.

Table 2 Set-up of LM integrations

	LM7_OP	LM7	LM1	LM7_mos1	LM7_ tile	LM7_ mos1_hsoil	LM7_ tile_ hsoil
Model domain, size (km^2)	Operational	LM_domain	LM_domain	LM_domain	LM_domain	LM_domain	LM_domain
	2275 × 2275	385 × 385	385 × 385	385 × 385	385 × 385	385 × 385	385 × 385
MSMA+ model improvements	No	Yes	Yes	Yes	Yes	Yes	Yes
Resolution of atmosphere	7 km	7 km	1 km	7 km	7 km	7 km	7 km
Resolution of surface fluxes	7 km	7 km	1 km	1 km	7 km, 8 classes	1 km	7 km, 8 classes
Resolution of soil	7 km	7 km	1 km	1 km	7 km, 8 classes	7 km	7 km

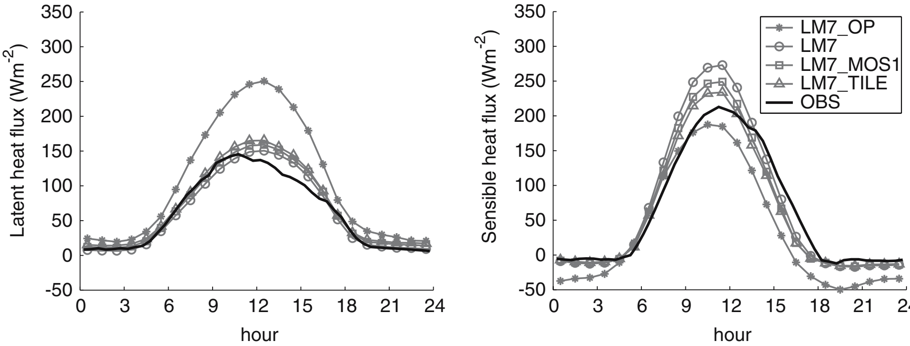

Fig. 7 Daily cycle of latent (left) and sensible (right) heat flux averaged over 30 days of LITFASS-2003

We hypothesize that LM simulations with improved parameterizations of the heterogeneous land surface will characterize the fluxes of individual model grid boxes more precisely. This hypothesis is tested by analysing the fluxes for the nine grid boxes within the LITFASS domain (Fig. 1). Synthetic measurement time series are generated by fractional weighting of the time series for different land-use classes, which have been derived from eddy-covariance measurements (Beyrich et al. 2006a). The accuracy of this approach is limited because spatial structure, which may be introduced by rainfall (Fig. 5), cannot be taken into account. To avoid discrepancies due to the non-closure of the energy balance only the anomalies of fluxes with respect to the LITFASS domain average are investigated. The bias and standard deviation of the modelled time series are listed in Table 3: all simulations with an improved parameterization of heterogeneous land surface lead to better results than LM7. A ranking between these methods, however, is not possible.

4.2 Comparison with high resolution simulations

Figures 8 and 9 show the bias and standard deviation of modelled fluxes with respect to LM1 simulations for every grid point estimated from 1200 UTC values of the nine golden days. Obviously LM7_MOS1 and LM1 agree very well, followed by the LM7_TILE and then LM7 results. The corresponding statistical numbers in Table 3 (average absolute value of bias and mean standard deviation) support these findings. Our ranking is in agreement with the model studies of Mölders and Raabe (1996a) and Mölders et al. (1996b) and of Heinemann and Kerschgens (2005). Bias and standard deviation fields are very patchy and no obvious larger scale structure exists. If the fluxes are averaged to the larger scale grid before computing the deviations, the errors are clearly reduced (Fig. 10). For the model-domain average all model versions give nearly the same result (Table 3). Figure 10 also shows that simulations with a non-homogeneous soil always give better results than a corresponding simulation with a homogeneous soil. Ranking the mosaic approach before the tile approach and at last the LM7 simulations is valid on all averaging scales but of minor importance on larger scales. LM7_MOS1 has more skill in reproducing LM1 results than LM7_TILE, because the surface representations of LM7_MOS1 and LM1 are identical and the variability induced by other quantities than land-use, in particular by soil moisture, has most likely a considerable impact (see also the analysis of LM1 simulations in the next section).

In addition to the magnitude of surface fluxes their variance is also important when used as a boundary condition in atmospheric models. The variance of fluxes is, e.g., needed as a

Table 3 Summary of the model evaluation. Values for λE and H ($\lambda E/H$) in W m^{-2}

		LM7	LM7_ mos1	LM7_ tile	LM7_ mos1_ hsoil	LM7_tile_hsoil
LITFASS mean	Bias	2/16	8/5	12/0	5/8	14/ − 1
	STD	28/57	27/52	26/49	26/52	29/49
Characterization of LM grid boxes (prediction of flux anomalies for nine LITFASS grid boxes)	Mean |Bias|	24/24	21/20	20/21	25/25	22/25
	STD	57/72	51/68	51/68	52/70	51/69
Consistency w.r.t. to LM1 (1200 UTC, nine ‘golden’ days)	Bias (domain average)	2/2	1/1	−3/0	7/ − 3	6/ − 5
	Mean |Bias|	27/31	3/4	16/15	10/17	18/17
	STD	19/20	8/13	15/17	15/17	17/17
Applicability	Computational costs (arbitrary units) (costs of LM1: 330)	1	2.1	1.2	1.9	1.15

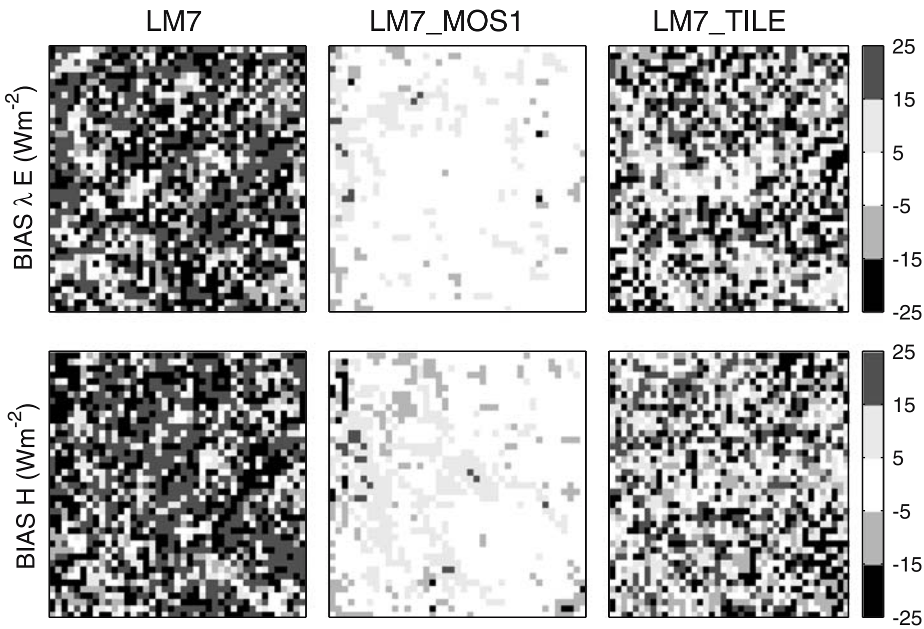

Fig. 8 Map of systematic error (BIAS) for the whole model domain with respect to LM1 simulations estimated at nine selected days at 1200 UTC

boundary condition for higher order turbulent closures and is an important triggering factor of convection. Figure 11 displays the standard deviation of fluxes at different averaging scales estimated from the high resolution LM1 simulation; it also illustrates the ability of the different parameterizations to reproduce this variability. Note that a considerable amount of variability in λE and H is caused by small spatial scales, which reflects the small-scale heterogeneity of the land-surface in the model domain and stresses the need to consider this land-surface heterogeneity for mesoscale modelling. LM7_MOS1 is in very good agreement with LM1 even at the smallest scale. The mosaic approach, as expected, slightly overestimates the flux variance because local adaptations of the atmospheric reference values to anomalies in the corresponding surface variables (see positive correlation in Fig. 12) are neglected. Again the model versions with differentiated soil physics lead to better results than those with homogeneous soil physics. The variance at averaging scales larger than the model resolution (in this case at scales of 21 km and 49 km) is reproduced correctly by all parameterization schemes.

Computational costs are an important issue for the operational implementation of improvements. The LM7_MOS1 simulations require twice the computational time than LM7 and the computational cost for LM7_TILE only increases by a factor 1.2. Both factors, which may be further reduced by optimized coding, make practical application of these methods feasible. In contrast a grid refinement to 1-km resolution would require 330 times more computational power, which makes this approach forbidding for operational runs.

4.3 Verification of parameterization assumptions

The high resolution simulations (LM1) are now analysed in order to verify the assumptions underlying the mosaic and tile approachs, and to elucidate why LM7_MOS1 and LM1 agree

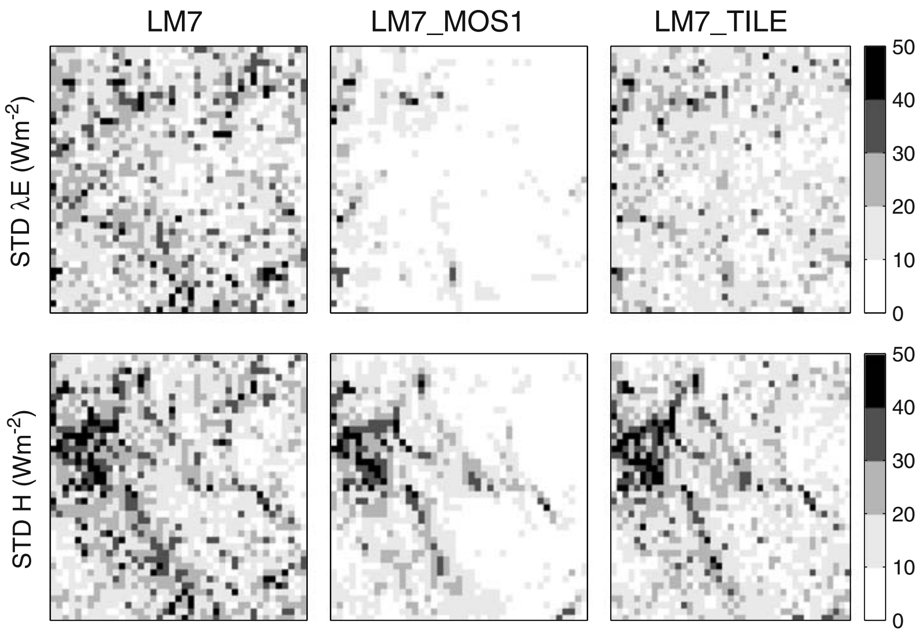

Fig. 9 same as Fig. 8, but maps of the stochastic errors (standard deviation, STD)

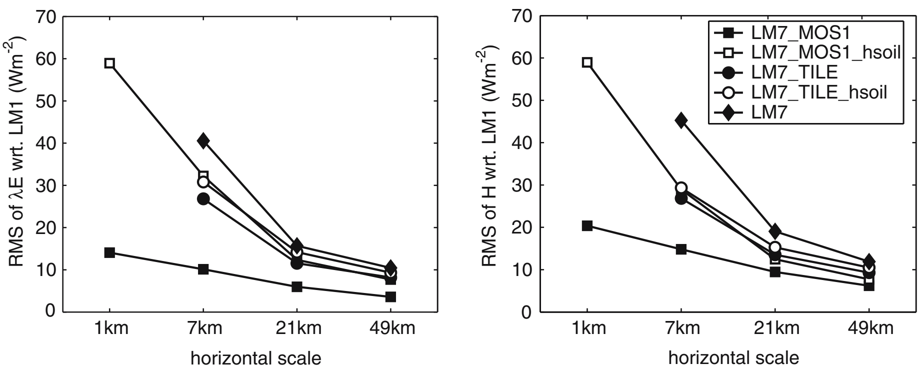

Fig. 10 Root mean square (rms) deviation of λE (left) and H (right) with respect to LM1 in dependence of the averaging scale

so well. Figure 12 shows that the surface values of potential temperature and specific humidity vary much more than the corresponding atmospheric values at scales smaller than 7 km. The standard deviations of T_s and q_s are by a factor 9 and 5, respectively, greater than the standard deviations of $T_{\rm atm}$ and $q_{\rm atm}$. Consequently the variability in surface quantities has a much larger impact on surface fluxes than the variability of the atmospheric reference values. Additionally the correlation between small-scale anomalies in surface quantities and atmospheric variables decreases quite rapidly with height. This means that the modelled atmosphere is very diffusive and very efficient in diminishing inhomogeneities introduced by the surface. In other words, the blending height for the considered cases and scales is very low. The dominant variability of the surface variables and the low blending height strongly

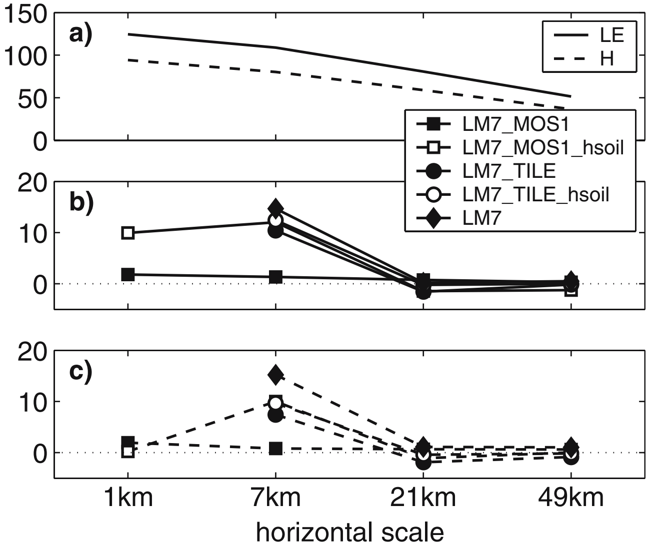

Fig. 11 **a** Standard deviation of turbulent fluxes in W m^{-2} estimated from LM1 simulations (nine 'golden' days at 1200 UTC). Deviation of simulated standard deviation in latent heat flux **b** and sensible heat flux **c** with respect to LM1 simulations

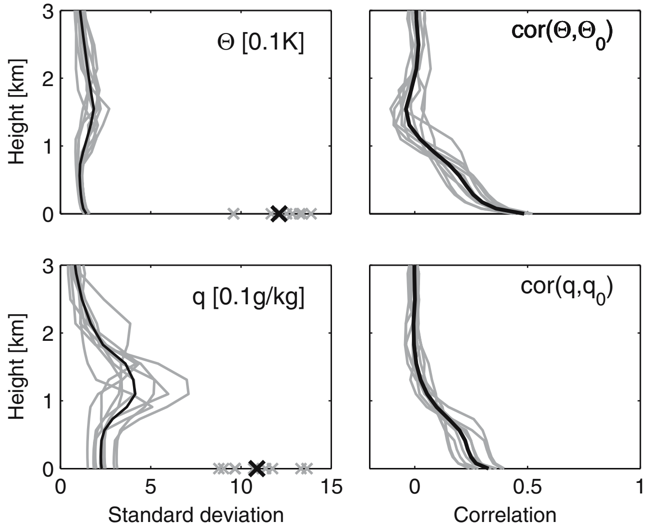

Fig. 12 Left: Standard deviation of potential temperature (top) and of specific humidity (bottom) at different altitudes and at the surface (crosses). Right: Correlation of atmospheric variables at different heights with surface values. Grey lines and crosses indicate results of individual LM1 simulations at 1200 UTC; black lines and crosses give the overall mean. All fields have been high-pass filtered with 7-km resolution to analyse only small-scale variability

support the validity of the approximation in both the mosaic and the tile approachs, namely to neglect subgrid-scale variability of atmospheric variables at the lowest model level. Experimental data analysed by Mahrt and Sun (1995) also support this approximation. Extensions of the mosaic or the tile approach by introducing blending height concepts (Claussen 1991) or by considering the vertical propagation of surface anomalies (Seth et al. 1994; Molod et al. 2003) seems to be of minor importance.

The importance of considering the variability of surface variables is also revealed by analysing the influence of various variables on the pattern of predicted fluxes by LM1. Figure 13 presents the explained spatial variance of all variables that may influence the surface fluxes with respect to H and λE. The analysis was confined to the extended LITFASS domain to ensure the best quality of all input fields, especially of soil moisture. For both cases the atmospheric reference values of temperature and humidity obviously have little impact. Concerning the importance of wind speed, exchange coefficient, soil moisture and land use the first case (30 May 2003) leads, however, to partly contrasting results. Wind speed during the first case was quite low and the soil was very dry. Consequently, wind speed and soil moisture of the upper soil layer (S_1) are of minor importance. Since plants can still provide some water from the lower soil layer, its soil moisture (S_2) controls plant transpiration. Land use influences the sensible heat flux due to its specific albedo. The second case (7 June 2003) is a situation after a strong convective rain event with high variations of rain rate in the extended LITFASS domain. Consequently the soil moisture of the upper layer S_1 explains a large part of the variance and land use is of minor importance. At this point the mosaic approach is superior to the tile approach, because the tile method cannot take into account the observed spatial soil moisture variations within an atmospheric grid box. For the second case the wind speed is relevant too, but strongly correlated ($\mathrm{cor}(|v_h|, S_1) = 0.54$) with the soil moisture, which initiated boundary-layer circulations on this day. Both mosaic and tile methods neglect such small-scale wind variations. Anyhow, this deficiency seems to have no large impact in this case because the comparison with respect to LM1 in the previous section revealed no great deviations.

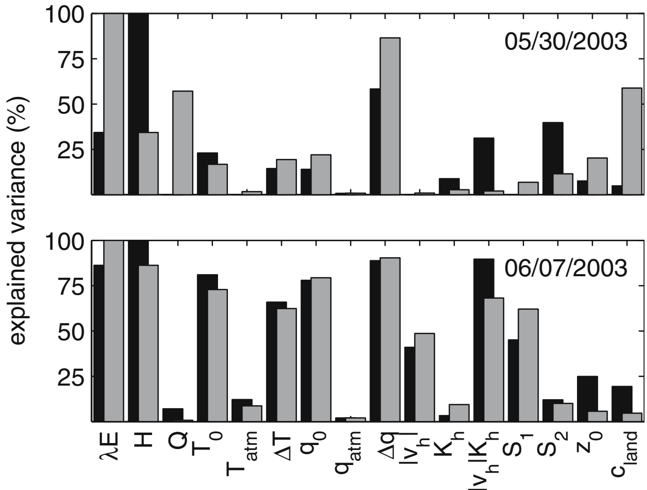

Fig. 13 Spatial explained variance of predicted λE (grey) and H (black) patterns by LM1 within the extended-LITFASS domain for various influencing fields: $\Delta T = T_{\mathrm{atm}} - T_0$, $\Delta q = q_{\mathrm{atm}} - q_0$, net radiation Q; see text for definition of other variables

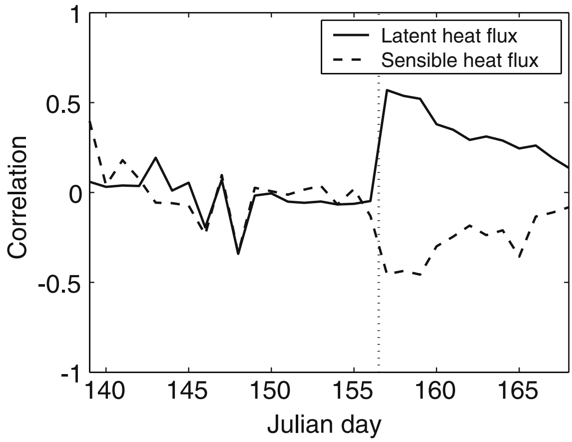

Fig. 14 Spatial correlation of rain sum pattern at 5 June 2003 (within the extended-LITFASS domain) and simulated latent and sensible heat flux patterns between 0800 and 1400 UTC at all days of LITFASS-2003

The importance of soil moisture under overall dry conditions was also stressed by an analytical study of Hu and Islam (1998). The previous analysis of explained spatial variance emphasised the relevance of soil moisture, especially after convective rain events. Figure 14 shows the spatial correlation of the rain rate observed on 5 June 2003 with the predicted daytime surface fluxes by LM7_MOS1. Using the MSMA the rainfall pattern and its influence on the soil moisture distribution is assimilated into the LM. No correlation exists before the rain event; but after the rain event a clear connection between rain pattern and surface fluxes exists, namely a positive correlation concerning latent heat flux (wet areas evaporate more) and a negative correlation concerning sensible heat flux. These correlations decrease with time but are significantly higher than the noise level until 9 days after the rain event. It can be concluded that under dry soil conditions, as experienced during LITFASS-2003, rainfall patterns influence surface fluxes on a temporal scale of up to a week. From this follows a forecast potential that can only be exploited if high resolution rainfall observations (usually radar data) are assimilated (e.g. by MSMA), and if the model is able to make use of localized high resolution surface information by e.g. using the mosaic method.

5 Summary and conclusions

Simulations with the non-hydrostatic, operational weather forecasting model LM of the German Meteorological Service with a horizontal grid spacing of 7 km for the 30 days of the field campaign LITFASS-2003 have been presented. The model with its operational configuration and input parameters was neither able to reproduce the observed flux contrasts between different land-use areas, in particular between farmland and forest, nor the measured temporal development of evapotranspiration, which was characterized by dry-out periods and limited transpiration due to soil moisture stress. Both problems could be solved by introducing land-use dependent vegetation albedo and stomatal resistance, as well as by providing more accurate soil moisture initial data by using a MSMA. The MSMA consists of a long term (2.5 years in this case) integration of a stand-alone version of the model soil module. All forcing variables are obtained from measurements. In particular assimilating radar derived rain rates yields a very good representation of the spatial soil moisture structure after convective rain events. It has been demonstrated that these structures explain a considerable amount of spatial variance in modelled surface fluxes even a week after the rain event. Assimilating radar derived rain rates consequently offers a new forecast potential of surface fluxes.

Subgrid-scale land-surface heterogeneity is considered in the operational LM only by using effective land-surface parameters. Two more advanced parameterization techniques, the mosaic and the tile approachs, have now been implemented, and which calculate surface processes with a higher spatial resolution than the atmospheric effects. Both methods have been tested with and without a differentiated simulation of soil physics for each sub-pixel or class. A comparison of the LITFASS domain-averaged flux revealed that the first step model improvements (i.e. land-use dependent vegetation parameters, MSMA) clearly result in more realistic simulations. The results using different parameterizations of land-surface heterogeneity are only slightly different. Looking more into details and comparing the flux prediction of individual grid box with measurements has given some indication that fluxes predicted using the mosaic and the tile methods are more realistic than those predicted by the operational effective parameter method.

Significant differences between the various parameterization methods occur if the results are compared to high resolution LM simulations with 1-km grid spacing (LM1): The average root mean square errors at 1200 UTC of latent (sensible) heat flux are 12 (16) $\mathrm{W\,m^{-2}}$ for the mosaic approach, 28 (27) $\mathrm{W\,m^{-2}}$ for the tile method, and 42 (45) $\mathrm{W\,m^{-2}}$ using effective parameters. The simulations using differentiated soil physics always give better results, especially as far as the mosaic approach is considered. Also the spatial variance of surface fluxes, which may be used as input variables for other parameterization schemes (turbulence and convection), is reproduced most accurately by the mosaic approach. In general the errors are largest at the smallest scale and strongly decrease when fluxes are averaged over larger domains. Although information on coarser scales than the grid scale might by sufficient for many practical applications, an accurate representation of fluxes at the pixel scale is vital for any model, because most parameterizations and resolved processes use input data at the pixel scale.

Mosaic and tile approaches are both based on the assumption that the variability of atmospheric variables, variables that are relevant for flux computation, is much smaller then the variability of the corresponding surface quantities, and consequently this variability is neglected. Analysis of high resolution simulations supports this approximation: the standard deviation in temperature and humidity is found to be much smaller at the lowest model level compared to the surface values. In addition, the correlation of small-scale anomalies in surface state variables with corresponding atmospheric values is low, mainly because the atmosphere is very diffusive. The pattern of surface state variables in contrast to atmospheric quantities explains a significant part of the spatial variability in surface fluxes, which is simulated by the high resolution LM. Temporally, in particular after rain events, the soil moisture pattern can be even more important than the land-use structure. Such conditions cannot be modelled accurately by the tile approach because no variability in addition to the classification criteria can be considered. On the other hand the tile approach requires less computational effort than the mosaic method because the number of surface classes is usually much smaller than the number of sub-grid pixels in a mosaic approach.

In summary, mosaic and tile approaches are very efficient methods to improve small-scale simulations of surface fluxes in mesoscale weather forecasting methods. It is not possible to rank both methods using the measurements of LITFASS-2003. The tile approach requires less computational power, but the mosaic method is more consistent with high resolution modelling results and more flexible, because multiple and even time dependent factors (e.g. land use, soil types, soil moisture) influencing surface factors can be considered simultaneously. Since sub-pixels of the mosaic approach are localized, this method has the potential to make use of high resolution land-surface assimilation data and may be applied in combination with sophisticated hydrological models that e.g., consider ground water flow. It is recommended to use both approaches with differentiated soil physics. Accurate surface parameters and in particular high resolution soil moisture analysis, which can be derived by the MSMA method, are essential to simulate surface heterogeneities.

Acknowledgements This research was performed in framework of the German EVA_GRIPS-DEKLIM project, which was funded by the Federal Ministry of Education and Research (FKZ 01 LD 0103). The German Meteorological Service kindly provided the model, operational analysis data and the computing facilities for the model integrations. The whole LITFASS-2003 team made available a very useful comprehensive dataset. Special thanks go to F. Beyrich, J.-P. Leps, T. Foken and M. Mauder for the quality controlled eddy-covariance measurements and composite time series.

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