Disaggregation of screen-level variables in a numerical weather prediction model with an explicit simulation of subgrid-scale land-surface heterogeneity

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A. Schomburg V. Venema F. Ament C. Simmer

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Abstract

The earth's surface is characterised by small-scale heterogeneity attributable to variability in land cover, soil characteristics and orography. In atmospheric models, this small-scale variability can be partially accounted for by the so-called mosaic approach, i.e. by computing the land surface processes on a grid with an explicit higher horizontal resolution than the atmosphere. The mosaic approach does, however, not account for the subgrid-scale variability in the screen-level atmospheric parameters, part of which might be related to land surface heterogeneity itself. In this study, simulations with the numerical weather prediction model COSMO are shown, employing the mosaic approach together with a spatial disaggregation of the atmospheric forcing by the screen-level variables to the subgrid-scale. The atmospheric model is run with a 2.8 km horizontal grid resolution while the land surface processes are computed on a 400 m horizontal grid. The disaggregation of the driving atmospheric variables at screen-level is achieved by a 3-step statistical downscaling with rules learnt from high-resolution fully coupled COSMO simulations, where both, atmosphere and surface, were simulated on a 400 m grid. The steps encompass spline interpolation of the grid scale variables, conditional regression based on the high-resolution runs, and an optional stochastic noise generator which restores the variability of the downscaled variables. Simulations for a number of case studies have been carried out, either with or without mosaic surface representation and with or without atmospheric disaggregation, and evaluated with respect to the surface state variables and the turbulent surface exchange fluxes of sensible and latent heat. The results are compared with the high-resolution fully coupled COSMO simulations. The results clearly demonstrate the high importance of accounting for subgrid-scale surface heterogeneity. It is shown that the atmospheric disaggregation leads to clear additional improvements in the structures of the two-dimensional surface state variable fields, but to only marginally impacts on the simulation of the turbulent surface exchange fluxes. A detailed analysis of these results identifies strongly correlated errors in atmospheric and surface variables in the mosaic approach as the main reason for the latter. The effects of these errors largely cancel out in the flux parameterization, and thus explain the comparably good results for the fluxes in the mosaic approach without atmospheric disaggregation despite inferior performance for the surface state variables themselves. Inserting noise in the disaggregation scheme leads to a deterioration of the results.

1 Introduction

The turbulent exchange of sensible and latent heat at the earth's surface plays a crucial role for the energy and moisture budget of the atmosphere. The partitioning of the incoming radiation into sensible and latent heat has a large impact on the development of the atmospheric boundary layer, on cloud formation and on the initiation of convective processes. These processes influence the hydrological cycle via precipitation and ensuing runoff, infiltration and feedback on the fluxes e.g. through soil moisture changes and hence on the atmospheric state. The accurate representation of these surface fluxes in atmospheric models, however, is challenging, because they are the result of a long, interacting chain of parameterizations, above and below the earth's surface.

In practice, almost all Soil-Vegetation-Atmosphere-Transfer (SVAT) models are column-models, which assume horizontal homogeneity. Horizontal exchanges in the soil and/or via groundwater have so far only been considered in experimental setups (e.g. Seuffert et al, 2002; Rihani et al, 2010). The coupling of the soil to the atmosphere is usually parameterized according to Monin-Obukhov similarity theory (Stull, 1988), which describes the near-surface layer above homogeneous terrain. Turbulent transport of energy or matter is parameterized proportional to the vertical gradient of the related variables between surface and lower atmosphere employing a turbulent diffusion coefficient K.

Processes in the sub-systems of the climate system, especially processes in the soil and vegetation on the one hand and in the atmosphere on the other hand, act, however, on highly different spatial and temporal scales. In the atmosphere small-scale spatial heterogeneities are often smoothed out quickly by turbulence, whereas the variability of the soil-vegetation subsystem is comparatively persistent. The different spatial scales of processes in the atmosphere and at the earth's surface make a consistent coupling of land surface and atmosphere difficult; and they are usually not accounted for explicitly in operational weather forecast and climate models.

Fluxes and surface temperature usually vary considerably between different surfaces; which was shown in simulations by e.g. Avissar and Pielke (1989) and Avissar (1992). Large differences in the turbulent fluxes over different land use classes were also found in flux measurement campaigns, e.g. the LITFASS[1] campaign (Beyrich and Mengelkamp, 2006) and in the framework of the EVAGRIPS project (Mengelkamp et al, 2006). Beyrich et al (2006), e.g., found differences of a factor of four for the sensible heat flux over forest versus farmland. Considerable differences were also found between different types of farmland.

These differences between different surfaces play a crucial role, because for nonlinear processes the aggregation of subgrid-scale heterogeneity effects up to the scale of the meteorological model is hampered; averaging of the subgrid-scale properties and computing the flux based on these mean parameters can from a fundamental point of view lead to systematic errors. Instead, the turbulent fluxes themselves are to be averaged. In several studies effects of nonlinear processes on the simulation of the turbulent fluxes have been investigated. Górska et al (2008) e.g. analysed the effect of horizontal variability of surface characteristics on the mean and variability of fluxes by aircraft and large-eddy simulations. Gao et al (2008), assessed the impact of the improvement in land surface information data sets on atmospheric modelling by substituting land surface information from coarse global data sets by high-resolution remote-sensing information in atmospheric simulations on a 3 km grid resolution over the Heihe river basin in China. Representing the heterogeneity more adequately by the new data sets decreased the local circulations and thus the simulated precipitation sums and helped to decrease a formerly wet bias considerably. Seth et al (1994) showed that neglected subgrid-scale heterogeneity can lead to errors in the Bowen ratio, i.e. the ratio of sensible to latent heat, of about 20%, this can have a significant influence on climate simulations. Avissar (1998) and Bonan et al (1993) studied the effects of subgrid-scale variability in surface properties on the grid scale fluxes by comparing energy fluxes computed based either on parameter-averaging, or on flux-averaging. They found only small differences for reflected solar radiation and emitted infrared radiation, but large differences for sensible and latent heat flux. Henderson-Sellers and Pitman (1992) demonstrated that small changes in input parameters for a land surface model can change the results considerably in a nonlinear way, illustrated exemplary for fractions of a rough surface in an otherwise smooth grid box. Generally most studies do not account for heterogeneities in the boundary layer induced (or reduced) by surface heterogeneities, and thus neglect small-scale feedback processes between surface and lower boundary layer.

Two approaches have been developed, which treat subgrid-scale land surface heterogeneities explicitly. These are the so-called discrete approaches including *tile approach* – first described in Avissar and Schmidt (1998) – and the *mosaic approach* – first presented by Seth et al (1994) – and continuous approaches describing heterogeneities by probability density functions (PDFs). In the latter approach the relevant processes are then integrated over PDFs for the different parameters (Avissar, 1991). Unfortunately, the nomenclature in use for the two discrete methods is ambiguous; in this study the definition also used in Heinemann and Kerschgens (2005) and Ament and Simmer (2006) will be used: In the tile approach, the soil processes are modelled separately for each of the different land cover classes, which are available at the subgrid-scale; and subsequently the resulting fluxes are averaged according to the fractional coverage of these land use classes. In the mosaic approach, the coarse atmospheric column is subdivided into an explicit number of sub-pixels, for which only the soil processes are computed separately. This is computationally more demanding, but it has the advantage that effects of different surface characteristics such as land use, orography, soil texture, soil moisture and soil temperature can be considered in a consistent way, as each sub-pixel has its own characteristics. Therefore this approach is sometimes also

[1] Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface - a long-term study

called “explicit subgrid approach”. One or more of these techniques have been applied by Avissar (1991, 1992); Koster and Suarez (1992); Schlünzen and Katzfey (2003); Essery et al (2003); Molod et al (2003); Ament and Simmer (2006). In all studies flux aggregating outperformed the common dominant type or parameter averaging methods, the largest improvements are achieved if water bodies are part of the subgrid-scale heterogeneity. Heinemann and Kerschgens (2005, 2006) found differences for the approaches on different averaging scales from 20 down to 2 km and thus confirmed the necessity of taking subgrid-scale variability into account even on very small scales.

Techniques are needed to realise the coupling between the two different scales of land surface and atmosphere. In the upward direction, the high-resolution turbulent fluxes at the interface are averaged to the coarser (atmospheric) scale, before passing them over to the atmospheric model. For the downward direction, i.e. for the coupling of the coarse atmosphere with the high-resolution surface, the standard approach assumes a constant atmospheric forcing for all sub-pixels belonging to one atmospheric column to drive the SVAT model. However, especially over heterogeneous land surfaces, also the lower part of the atmospheric boundary layer is heterogeneous. Atmospheric heterogeneity can induce or reduce surface heterogeneity; by assuming homogeneous atmospheric forcing these effects are neglected. A spatially distributed atmospheric forcing should lead to a more realistic input for the SVAT module and can thus lead to improvements for the fluxes. Such a spatially distributed atmospheric forcing in combination with the mosaic approach was first tested by Seth et al (1994). In their study temperature, humidity, convective precipitation and clouds were disaggregated to the high surface resolution. The method was tested for a stand-alone SVAT scheme and evaluated with respect to surface fluxes and hydrology (soil moisture and runoff). The horizontal resolution in their study was 3.0° for the atmosphere with 0.5° mosaic resolution; simulations were carried over a time period of 20 years. The authors found that due to the downscaling of atmospheric variables the heat fluxes changed by up to 15% and the runoff up to 33%. In studies by Arola (1999), Giorgi et al (2003) and Dimri (2009) simulations with very similar or slightly modified versions of this disaggregation scheme were tested. Especially the near-surface temperature in complex terrain could be improved, and therefore a more realistic snow cover distribution for mountain tops and valleys was obtained.

The cited studies show that considerable improvements can be achieved by taking variable atmospheric forcing into account for driving small-scale soil models. The studies addressed, however, scales of the order of 100 km in long-time climate simulations. In this study we evaluate the impact, which can be achieved by disaggregating atmospheric input in combination with the mosaic approach in a numerical weather prediction model on the meso-γ-scale.

In Schomburg et al (2010) we presented already a statistical downscaling system for disaggregating the atmospheric variables needed to drive a SVAT model from a 2.8 km resolution down to a 400 m grid.

We showed that the system was able to reproduce the small-scale anomalies accurately, compared to reference high-resolution model simulations from a fully-coupled atmospheric model on the 400 m scale.

In this study we now implemented the downscaling scheme into the numerical weather prediction model COSMO (Steppeler et al, 2003) and evaluate its performance in combination with the classical mosaic approach. The objective is to analyse the effect of disaggregating the atmospheric forcing variables driving the higher resolved SVAT model in model simulations for several case studies.

In the following sections we briefly describe the COSMO model and the atmospheric downscaling scheme (section 2) and the experimental setup (section 3). In section 4 results for model simulations with and without mosaic and with or without atmospheric disaggregation are compared, followed by a detailed analysis of the results. Section 5 provides a discussion of the results and concludes with implications.

2 Model description and experimental design

2.1 The COSMO model

The COSMO-model is part of the numerical weather prediction system of the German Meteorological Service (DWD). It has been developed and is maintained and operated by the members of the *COnsortium of Small-scale MOdeling*, which is an association of several European national weather services. In this work the operational COSMO-DE model configuration (based on a horizontal resolution of 2.8 km and 51 vertical levels), which is run for the daily weather forecasts by the DWD, is adopted, and briefly described in this section.

A model simulation is based on the integration of the set of primitive non-hydrostatic hydro-thermodynamic equations by a two-time-level Runge-Kutta integration scheme, which is third order in time (Baldauf et al, 2011). The mode splitting approach (Klemp and Wilhelmson, 1978), is used to split the equations up in a longer model time step of 25 seconds for the processes on larger time scales such as advection and the tendencies from the physical parameterizations and a short time step for the fast sound wave processes.

The radiation scheme in the COSMO model (Ritter and Geleyn, 1992) is based on the one-dimensional *δ-two-stream approximation* of the radiative transfer equation. Clouds arise from condensation of cloud water by saturation adjustment. The treatment of grid-scale precipitation is based on a simplified one-moment version of a scheme by Seifert and Beheng (2001). Subgrid-scale cloudiness is considered by means of an empirical function depending on relative humidity, height, and convective activity. It is assumed that deep convection (showers and thunderstorms) is a grid scale process at the COSMO-DE scale of 2.8 km. Only shallow convection is parameterized by a mass flux scheme of Tiedtke (1989) with a closure based on moisture convergence. The turbulence parameterization is based on K-theory, which relates the subgrid-scale flux to the gradient of a variable and a diffusion coefficient. The operational scheme is a prognostic Turbulent Kinetic Energy (TKE) scheme based on a closure of order 2.5. The exchange coefficients are calculated depending on the thermal stratification and vertical wind shear (Doms et al, 2011). The scheme has been extended by an additional TKE source term, which avoids the TKE getting close to zero under stable conditions. The surface flux transfer scheme computes the flux density of model variables at the lower model boundary, acting as the interface between surface and atmosphere. The operational COSMO transfer scheme is based on the diagnostic TKE equation, which provides the stability functions, which are in turn needed for calculating the turbulent length scale for the diffusion coefficients.

The lower boundary condition of the atmospheric model is simulated by the multilayer soil and vegetation model TERRA (Doms et al, 2011), providing the temperature and humidity at the land surface. In TERRA all processes are modelled one-dimensionally on eight (six) vertical layers for the heat (moisture) processes; no lateral interactions between adjacent soil columns are considered. The atmospheric driving variables for TERRA are the temperature, specific humidity and wind speed at the lowest atmospheric model layer, and the radiation fluxes, pressure and precipitation at the surface.

The water budget at the surface can be written as

$$E_b + E_i + E_{snow} + \sum_{k=1}^{ke_{soil,hy}} Tr_k = -(F_{q^v})_{sfc} \tag{1}$$

with E_b evaporation of bare soil, E_i, E_{snow} evaporation from interception and snow store, respectively, and Tr_k water extraction by roots. $ke_{soil,hy}$ is the number of active layers of the hydrological part of TERRA. The energy budget at the upper boundary of TERRA, i.e. the forcing at the surface can be written as

$$G_{sfc} = (F_h)_{sfc} + L(F_{q^v})_{sfc} + Q_{rad,net} + G_P + G_{snow,melt}, \tag{2}$$

the sum of sensible heat flux $(F_h)_{sfc}$, latent heat flux $L(F_{q^v})_{sfc}$, net radiation $Q_{rad,net}$, which is taken from the radiation parameterization, G_P, which considers effects of freezing rain and melting snowfall, and $G_{snow,melt}$ models the influence of surface melting processes on soil temperature. The sensible and latent heat flux is parameterized by the gradient between the centre of the lowest atmospheric layer (in 10 m height) and the surface value:

$$(F_h)_{sfc} = -c_p \rho K_h |\mathbf{v}_h| (\Theta - \Theta_{sfc}) \tag{3}$$

$$(F_{q^v})_{sfc} = -L \rho K_h |\mathbf{v}_h| (q^v - q^v_{sfc}) \tag{4}$$

with q^v specific humidity, Θ potential temperature, $|\mathbf{v_h}|$ wind speed, ρ air density and K_h the transfer coefficient of heat computed in the transfer parameterization as described above. c_p denotes the specific heat of dry air at constant pressure, and L_h the latent heat of vapourization.

2.2 The atmospheric disaggregation scheme

The atmospheric downscaling scheme employed here including its development, training and an offline evaluation is described in detail in Schomburg et al (2010); here we restrict ourselves to a short description.

Table 1: Relationships exploited in the deterministic downscaling step. T: temperature, Q^v: specific humidity, FF: wind speed, $S\uparrow$: shortwave upwelling radiation, L_{net}: longwave net radiation, $PREC$: precipitation, P_{sfc}: surface pressure. For coefficients refer to Schomburg et al (2010).

Downscaling variable	Predictor	Condition
T	relief height	negative T-gradient
Q^v	-	-
FF	-	-
$S\uparrow$	albedo	always
L_{net}	surface temperature	cloud-free
$PREC$	-	-
P_{sfc}	relief height	always

For the training of the scheme a database comprising model output of 400 m-horizontal resolution COSMO model simulations for very different weather situations was exploited.

The disaggregation system comprises three steps, which can be applied individually or subsequently, depending on the variable and the application under consideration. As a first step, a bi-quadratic spline interpolation from the coarse grid to the fine resolution is applied, which conserves the mean and the gradients of the coarse field.

The second step exploits empirical relations between atmospheric variables and surface characteristics using high-resolution surface information ("deterministic" downscaling rules). For these rules high-resolution surface information is used as predictor in a linear regression based on physical relationships. By this means the surface pressure anomaly can be downscaled by using the relief height anomaly Δz in the hydrostatic equation. The downscaled diffuse upwelling shortwave radiation is computed explicitly from the high-resolution surface albedo for direct and diffuse radiation, whereas the downwelling direct and diffuse radiation are not correlated with surface variables. Both have little subgrid heterogeneity in cloud-free cases, whereas in cloudy situations their subgrid-scale variability relates to cloud cover variability on the subgrid-scale. Thus, in rather homogeneous cloud-free conditions the shortwave net radiation can be disaggregated with near perfect correlation because all subgrid variability is associated with surface (albedo) variability. Under cloudy conditions the variability has to be induced by stochastic methods (in step 3).

For the remaining variables (temperature, humidity, wind speed, precipitation and longwave radiation) the situation is less intuitive. Thus the high-resolution data base was statistically evaluated for possible correlations between atmospheric and surface variables. Such correlations are, however, not generally valid, but depend on the prevailing weather conditions. To find the most suitable predictors and indicators of specific atmospheric conditions, an automatic rule detection system was set up. In this system the correlations between all possible predictors and the desired downscaled variables were calculated and conditioned on indicator thresholds. With this approach we found that the near-surface temperature can be disaggregated using the high-resolution relief height as a predictor for most cases except situations with a very stable lower boundary layer, which is indicated by a positive temperature-gradient. Moreover, the ground temperature can be used to disaggregate the longwave net radiation in cloud-free cases, because in cloud-free situations the longwave emission from the surface is the only source of heterogeneity, whereas in cloudy cases the longwave downwelling radiation anomalies are mainly determined by clouds and less by the emitted radiation from the surface. Table 1 contains the disaggregation rules for all atmospheric forcing variables of TERRA. For some variables no relationships with surface variables (for the scale under consideration) could be found, i.e. no deterministic downscaling step is applied for those quantities. The first downscaling step, however, is applied for all variables under all circumstances.

Except for surface pressure the downscaling steps 1 and 2 alone do not reproduce the small-scale variability (in the statistical sense) contained in the simulated high-resolution fields. The full variance can, however, be very important for modelling the nonlinear processes at the surface. Lower variabilities can lead to biases in the computed fluxes when averaged over larger spatial and temporal scales. To avoid these biases, the yet unresolved variance can be added as noise in the last step, at the expense of a higher error at the smallest scale. The missing variability first needs to be assessed, as it may vary considerably for different synoptic conditions and also for different variables. For this purpose, a stepwise multiple linear regression with different predictors for the different atmospheric variables is employed, which estimates the small-scale standard deviation based on the coarse-scale standard deviation of the surrounding 3x3 coarse pixels, and other variables, which serve as a measure for the prevailing conditions, see Schomburg et al (2010). The noise is modelled based on an auto-regressive process, to account for its temporally correlated nature

$$x_{new} = \phi x_{old} + \epsilon \tag{5}$$

where ϵ is a Gaussian noise term. The precipitation anomalies, were not modelled as additive, but as multiplicative noise. Cross-correlations between shortwave and longwave radiation and wind speed and specific humidity, respectively, which were found for the small-scale anomalies, were also emulated in the noise-generating process; for details refer again to Schomburg et al (2010).

For all downscaling steps the coarse mean of the grid cell is conserved, ensuring the conservation of energy and mass.

2.3 Model setup

In section 4 we compare the results of the mosaic and the disaggregation simulations to model output of high-resolution COSMO model with 400 m horizontal grid spacing. Since this resolution is much higher than the highest operationally used resolution of 2.8 km at DWD, an appropriate setup and a set of external parameters containing information on the surface characteristics had to be prepared.

For the grid scale of 400 m some model default settings had to be altered. The time step is adjusted from 25 to 4 seconds to obey the Courant-Friedrich-Levy (CFL) stability criterion for the slow dynamical processes. This high time-stepping frequency in combination with the high horizontal resolution leads to a considerable increase in computation time, therefore a small model domain of 168x168 km^2 in western Germany has been chosen (see Figure 1). This region has been chosen because it is the main investigation area of the Transregio Collaborative Research Centre 32 (Vereecken et al, 2010), in the framework of which this work has been carried out. Parts of Luxembourg, the Netherlands and Belgium are also included in the model domain, which covers both mountainous regions as well as flat agricultural and urban areas, hence a broad range of landscape characteristics is present (see Fig. 2). For initialisation and boundary forcing COSMO-DE analyses are used. The vertical resolution of the model has not been altered, the 51 layers with increasing thickness with height as in the standard configuration are used for all simulations. The lowest layer has a vertical extent of 20 m, thus for the flux computations the atmospheric screen-level variables at the centre of the layer in 10 m height are used.

The model needs a preprocessed data set of surface parameters giving information on land fraction, relief height, plant cover, leaf area index, root depth, and soiltype. These were derived from three primary data sets for topography, land use and soil texture (for details see Schomburg et al, 2010).

In turbulence parameterizations a common simplification is to neglect the horizontal exchange coefficients, which is reasonable if the horizontal grid spacing Δx is much larger than the vertical grid spacing Δz. However, this approach becomes questionable at horizontal scales of some hundred metres. Thus, for the evaluation of the downscaling implemented in the COSMO model, all model runs - low and high resolution - have been carried out with the TKE turbulence scheme described in section 2.1, however with an additional simple horizontal turbulent exchange parameterization in the high-resolution model runs, where the horizontal exchange coefficients are a simple function of the vertical coefficients.

Clouds can cross several 400 m grid boxes in a few minutes, thus a high temporal frequency of radiation calculations is necessary. In the 400 m simulations radiation computations were carried out every 3 minutes. To avoid the effect that the radiation updates do not keep track of the cloud movement and development (see e.g. Schomburg et al, 2012), in the 2.8 km runs the radiation update frequency has also been increased (to 4 minutes) and is computed on each atmospheric column in all COSMO simulations.

The downscaling of atmospheric variables has been implemented into the numerical weather prediction model COSMO, as further enhancement of the mosaic approach. For this purpose, a modified model version COSMO-SUBS (Ament and Simmer, 2006, based on COSMO model version 4.0) has been used, which includes the mosaic subgrid surface representation.

3 Experimental setup

Ament and Simmer (2006) found the effect of improved soil/surface heterogeneity representation by the mosaic approach to be too small to be verified with flux measurements. The quantitative comparison

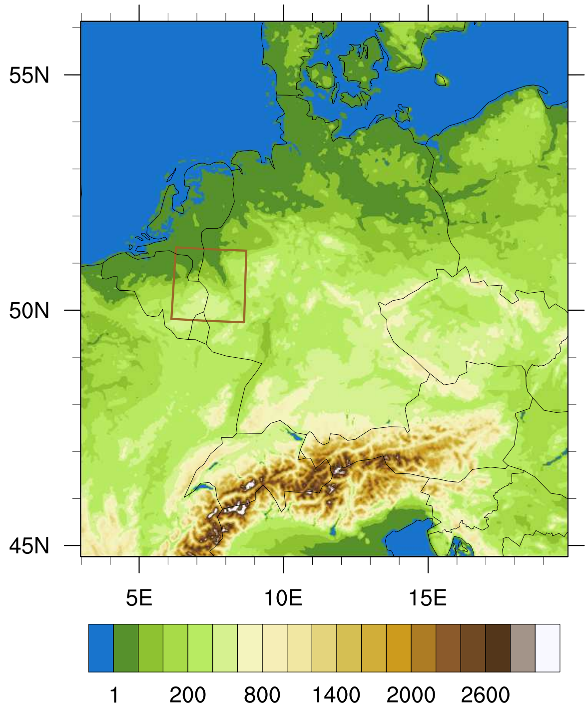

Figure 1: Model domain of the standard COSMO-DE model configuration with 2.8 km grid spacing and the smaller model domain used for the case studies indicated by the square. The colouring indicates the orogrographic relief height [m].

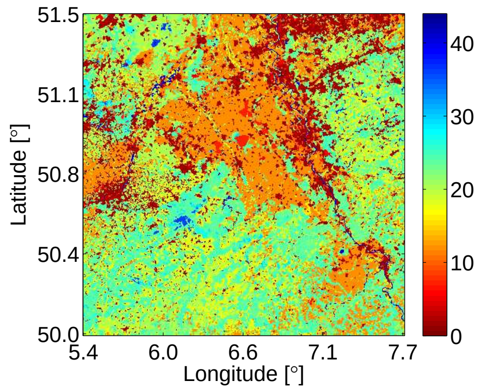

Figure 2: Land cover distribution of the model domain (on the 400 m resolution). The numbers correspond to the 44 different CORINE (EEA, 2000) land cover classes. These are discontinuous urban fabric (dark red), non-irrigated arable land (orange), pastures and complex cultivation patterns (light green), different kinds of forests (turquoise green) and water (dark blue).

Table 2: Overview of simulated days including prevailing weather situation.

Date	**Weather situation**
12 May 2008	calm, only sparse cloud cover
15 May 2008	convective clouds, showers and thunderstorms
16 July 2008	stratiform rain
20 October 2009	cirrus clouds, no rain
21 October 2009	some clouds
26 January 2010	fog in the morning, clear sky later

with measurements is hampered by several factors. First, the model boundary conditions (atmospheric forcing, surface characteristics, soil state etc.) have to match the reality very closely, which is difficult due to imperfect knowledge of initial conditions (e.g. for soil moisture), availability of measurements covering larger areas, and other model related errors. Besides, also flux measurements do not reflect reality either, since they are subject to measurement errors and non-closure of the energy-budget inherent in flux measurement techniques (see e.g. Foken, 2008; Hendricks Franssen et al, 2010). In this study, a comparison with observations is even more difficult, because the additional effect of atmospheric downscaling is expected to be smaller than the improvement gained with the mosaic versus coarse-resolution standard model runs. The difference between measurements and model results is much larger than between model runs with and without the different downscaling configurations. Therefore, high-resolution model runs (400 m horizontal grid size) have been used as reference for the fully coupled online validation simulations. This procedure, however, has the disadvantage that model runs with different configurations will inevitably diverge from each other. Thus, a one-to-one comparison of turbulent fluxes and other variables might be misleading because the differences can also be attributable to, e.g., different positions of the clouds. Nevertheless, the comparison with high-resolution model runs as reference can be considered as sort of a consistency check.

Six case studies have been carried out. Surface heterogeneity representation is expected to be most important in calm weather situations. In synoptically driven weather conditions with strong advection, or large-scale rainfall or cloud cover, the surface characteristics will have less impact on the surface fluxes and on the lower boundary layer. Thus, four days with calm, fair weather, have been simulated, only one day characterised by convective clouds, showers and thunderstorms and another day with stratiform rainfall and homogeneous cloud cover attributed to a cold front crossing the model domain were simulated (see Table 2).

Model simulations with in total five different configurations (see Table 3) have been conducted: 1) the 400 m high-resolution "reference" simulations; 2) coarse-scale simulations without any subgrid heterogeneity representation; 3) coarse-scale mosaic simulations without downscaling; 4) coarse-scale mosaic simulations with atmospheric downscaling steps 1 and 2; and 5) coarse-scale mosaic simulations with the full downscaling thus including also the third, stochastic downscaling step. To exclude boundary effects a 22 km broad zone at the edges has been omitted in the analysis of the results (hence the Figures in the result section show only the inner part of the model domain).

4 Results

4.1 Surface energy budget

The quantitative errors measures shown in this section are obtained by averaging the results of the six validation case studies, in order to obtain robust results with respect to the effects of the downscaling procedure and to alleviate effects of divergence of single model runs.

Table 4 summarises the root mean square differences (RMSD) for the turbulent surface fluxes of sensible and latent heat, averaged over all six case studies. These errors have been computed on the coarse scale for all configurations, because only the coarse-scale fluxes eventually force the atmospheric model. Using the mosaic approach, a considerable improvement in RMSD compared to the standard coarse configuration is achieved; the errors are reduced by 40-60%. The differences between the three mosaic configurations, however, are very small; in particular the improvements by the simulations with atmospheric downscaling are marginal. This holds also if only the results for the fair weather days are considered (see lower part of table 4), when maximum positive impact is expected. The relative

Table 3: Model configurations for comparisons.

Name	Atmospheric information	Surface information
Reference	fine	fine
Coarse	coarse	coarse
Mosaic	coarse	fine
No noise	downscaled without noise generation	fine
With noise	downscaled with noise generation	fine

Table 4: Root mean square differences of the turbulent heat fluxes on the 2.8 km scale, for coarse surface and atmosphere ("coarse"), mosaic ("mosaic") and mosaic plus downscaling steps 1 and 2 ("no noise") and full downscaling ("with noise"). Upper part: averaged over all six case studies; below: Averaged over the four calm days.

	RMSD [W/m^2]			
	coarse	mosaic	no noise	with noise
Sensible heat	19.31	11.02	10.98	10.97
Latent heat	20.72	7.96	7.91	7.94
	only calm days			
Sensible heat	19.65	10.06	9.99	9.96
Latent heat	19.84	5.60	5.52	5.52

Table 5: Mean subgrid-scale standard deviations [Wm^{-2}], averaged over all six validation case studies.

	coarse	mosaic	no noise	with noise	ref
Sensible heat	0	12.50	13.30	16.11	13.44
Latent heat	0	14.97	14.81	15.65	14.68

improvement gained by all fine-surface configurations versus the coarse simulation is even larger than averaged over all cases, but the additional improvement by the atmospheric disaggregation remains small. Systematic differences, i.e. biases, are low and strongly varying in time and from day to day for all configurations, thus averaging them over time leads to values close to zero (not shown).

Table 5 lists the mean subgrid-scale standard deviations per coarse pixel. For the sensible heat flux the subgrid-scale variability of the mosaic alone is too small compared to the reference. Variability is increased to a value closer to the reference if atmospheric downscaling without noise is applied. The heterogeneity of the latent heat flux is too large for the standard mosaic, and can be reduced by the downscaling steps 1 and 2. Thus, the atmospheric disaggregation "pulls" the variability of the fluxes into the right direction. The full downscaling, however, leads to excessive variabilities for both fluxes, probably due to inter-variable relationships not accounted for adequately by the current stochastic noise generation.

4.1.1 Error analysis

In this section the results are analysed in more detail, for a better understanding why the effect of the atmospheric downscaling is rather small although the subgrid-scale standard deviations are simulated better and the downscaling for the single atmospheric variables yields good results, as shown in Schomburg et al (2010). Figure 4 depicts the root mean square errors for the atmospheric and surface temperature and specific humidity respectively, computed on the 400 m scale. Errors are small for all simulations at timestep zero due to spinup processes, because the reference high-resolution simulations are initialized with interpolated 2.8 km analyses, however in forecast hour one this effect has vanished. Downscaling clearly leads to improved atmospheric temperatures of the lowest atmospheric layer (keep in mind that these disaggregated temperatures are only used as input for the SVAT module and for the flux computations, not in the dynamics of the model). Improvements are also visible for the surface temperature (note the different ordinate scale); these improvements are obtained through indirect effects, because no downscaling is applied to the surface temperatures, as they are explicitly calculated on the small scale. Hence, by forcing the soil model with disaggregated atmospheric quantities instead of the coarse values as in the standard mosaic approach a clear beneficial effect on the soil variables can be achieved, the average daily error reduction is about 5% versus the mosaic simulations. No large impact can be expected from the disaggregated wind speed, because only downscaling step 1 is applied, which has only little additional skill. For the full downscaling the stochastic noise leads as expected to an increase of errors on the 400 m scale (Only in spatial averages a beneficial effect could be expected due to a more realistic subgrid-scale variability. But even this is not the case for the fluxes, as the addition of noise to the different variables increases the variance of the fluxes by a too high amount as seen in Table 5.) For specific humidity hardly any difference is visible for downscaling without noise, because no deterministic downscaling step is ap-

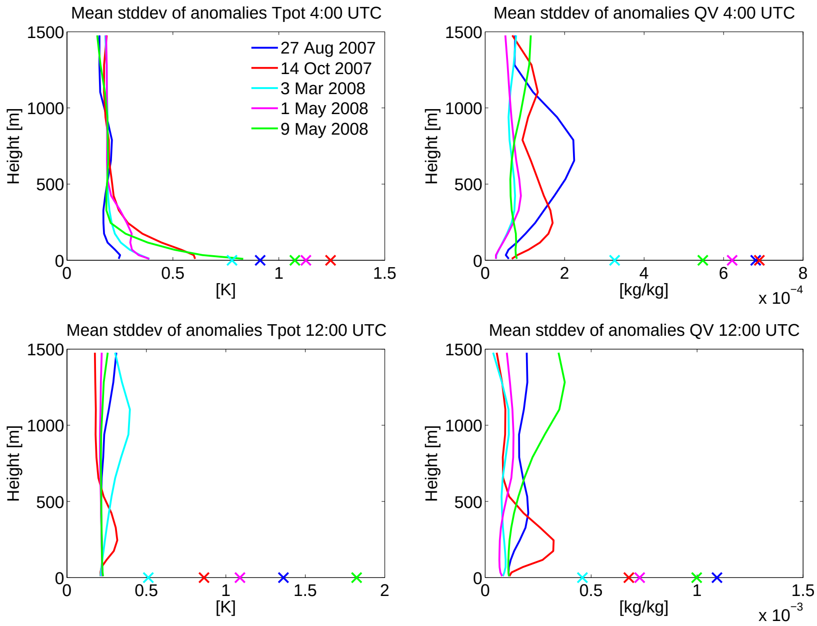

Figure 3: Mean subgrid-scale (400 m) standard deviations per coarse pixel (2.8 km) for potential temperature (left) and specific humidity (right) for 4:00 (top) and 12:00 UTC (bottom) in the atmosphere (lines) and at the surface (marked by crosses).

plied for this state variable. The effect of the mosaic versus no subgrid surface heterogeneity is expected to be more pronounced than the additional effect of atmospheric disaggregation, because heterogeneities at the surface are much larger than in the atmosphere due to missing turbulent mixing. In Figure 3 mean subgrid variability of 400 m anomalies with respect to 2.8 km pixels are depicted for several cases from the training data base for the downscaling scheme. Especially during day the atmosphere is well mixed, and the mean variability per coarse grid box is small. During night the mixing is weaker, in particular in anticyclonic conditions, which holds for 14 October 2007 (red line) and 9 May 2008 (green line). Thus, the largest possible improvements due to downscaling are smaller than the maximal improvement from applying the mosaic approach. However, some improvement, at least for the sensible heat flux, is expected due to the clearly improved surface- and near-surface temperatures. Thus, the results for the sensible heat flux are analysed in more detail in the following.

Despite improvements of downscaling steps 1+2 for the temperature at the surface and at the lowest atmospheric model layer, which enter the turbulent flux computations as vertical gradient, obviously no improvements for the temperature gradient itself can be achieved (Figure 5). The explanation can be found in the correlations between the errors of atmospheric and surface values, this is depicted exemplary in Figure 6 for temperature. The largest correlations are obtained for the standard mosaic without downscaling. Obviously the positive correlation of the errors for the surface and atmospheric variables largely cancels the errors for the gradient (see Equation 3) and thus also for the fluxes.

The question arises, why the errors in the flux-influencing variables of the standard mosaic are that strongly correlated. Figure 7 depicts an exemplary two-dimensional field of the errors for screen-level and surface temperature of the standard mosaic and the mosaic with atmospheric downscaling steps 1 and 2 with respect to the high-resolution reference simulation. Obviously the error structures of both fields resemble each other closely. They are both caused by the coarse atmospheric forcing in the standard mosaic approach, which also leads to the block-like structure of the error field. Moreover, over- or underestimations due to unresolved valleys, gradients, or other characteristics are visible in the screen-level and in the surface temperature field. This effect is also visible when the errors are averaged over all cases and all times of the validation data set (Figure 8) for each grid point because the over- or respectively underestimations in the mosaic runs usually occur at the same geographical locations due to unresolved topography for the temperature forcing from the atmosphere. Thus, differences arising from slightly shifted large-scale phenomena as in Figure 7 for atmospheric temperature are not visible any more. Again, the error fields for the simulations with atmospheric disaggregation show smaller and less

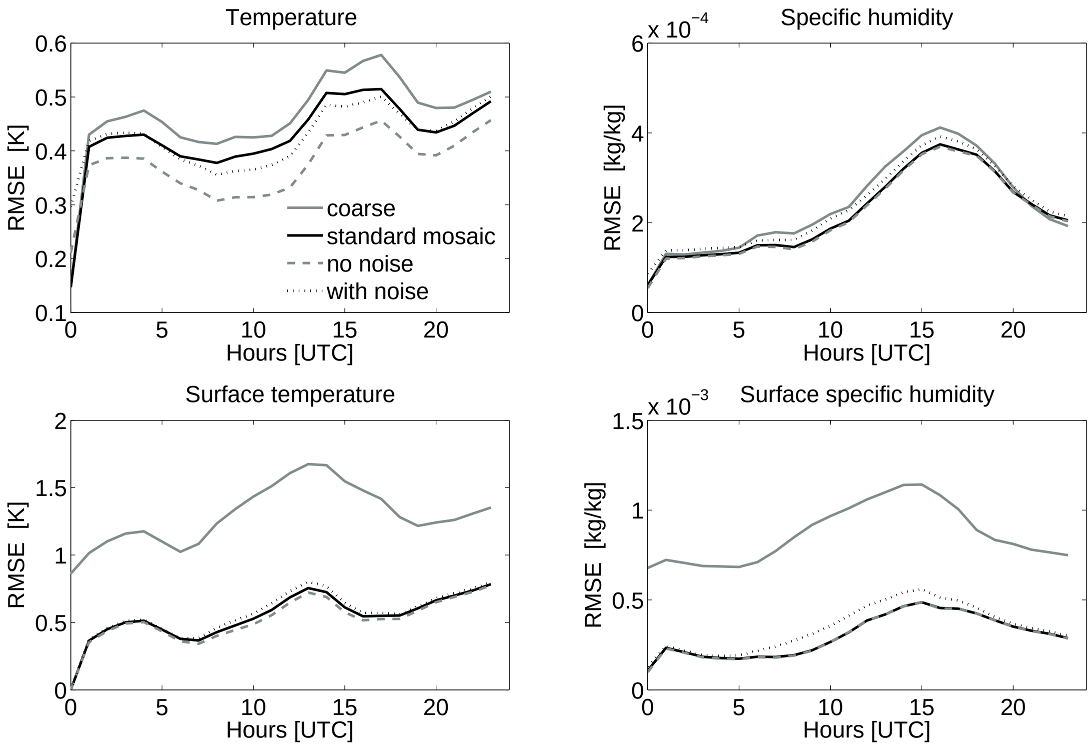

Figure 4: Root mean square differences for atmospheric (top) and surface (bottom) temperature (left) and specific humidity (right), averaged over all case studies for the model configurations as listed in Table 3.

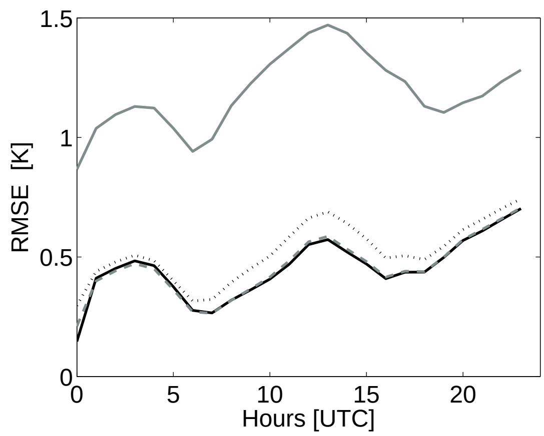

Figure 5: Root mean square differences for the temperature difference $T - T_s$ between lower atmosphere (lowest model level) and surface with respect to the high-resolution reference. Lines indicate the model configuration as in Figure 4, i.e. light grey solid: coarse, black solid: mosaic, dashed: no noise, dotted: with noise.

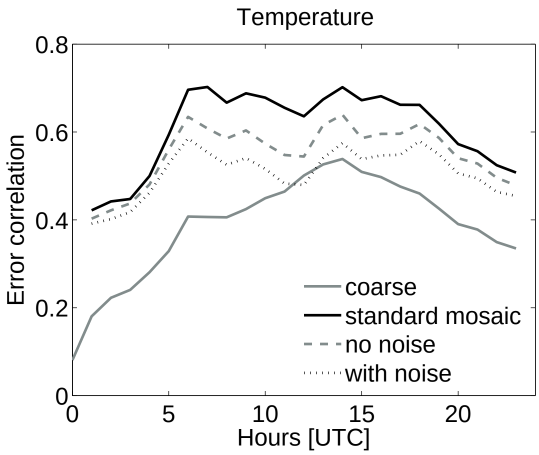

Figure 6: Correlations of errors of surface and atmospheric temperature, averaged over six case studies.

structured errors, whereas without atmospheric disaggregation the valleys are clearly discernable as too cold, the ridges as too warm, which is not the case in the model simulations with disaggregation of the atmospheric forcing variables. If atmospheric and surface temperatures are too high by about the same degree, the gradient will still have about the correct value. Thus, despite the lower and less structured errors obtained by application of the downscaling, this beneficial behaviour does not necessarily lead to improvements in the gradients, and thus obviously only a marginally better performance is obtained for the fluxes.

These differences in surface and near-surface temperature, however, have impact on snow cover. On one of the simulated case studies, on 26 January 2010, large parts of the model domain were covered by snow, but no fresh snow fell on that day. Thus, at the beginning of the simulation the snow cover was identical for all simulations, but during the simulation some snow melted or sublimated, to a different degree for the different simulations. The melting for the simulations with atmospheric disaggregation showed a more distinct dependence on the relief height. However, as during the day only about 0.12 cm melted and the average snow depth was about 8 cm, this effect is very small. To draw reliable conclusions, simulations over more complex terrain and over longer time periods will have to be carried out in the future. However the small effects seen in this one winter case study already indicate that the snow cover distribution is affected by the atmospheric downscaling.

5 Discussion and Conclusion

The mosaic approach has been used in several studies in the literature to account for subgrid surface heterogeneity in atmospheric models. In this study the approach has been applied in a short-range numerical weather prediction model on the meso-γ-scale with a horizontal resolution of 2.8 km and 400 m in the atmosphere and at the surface, respectively. To account for boundary layer heterogeneity and spatially variable atmospheric forcing induced by surface heterogeneities for the SVAT model, a disaggregation scheme for the atmospheric driving variables has been implemented and applied in the framework of the mosaic approach. Comparisons of model output from simulations with and without mosaic, either with or without atmospheric downscaling have been carried out.

Summarising, the model simulations with mosaic approach gave overall notably better results than model simulations without any surface variability representation. Root mean square errors of sensible and latent heat fluxes were reduced by about 40% and 60%, respectively (averaged over six case studies). The new atmospheric downscaling scheme, which intents to account for the predictable subgrid variability caused by surface heterogeneity, leads to only marginal further improvements. The effects on the grid scale fluxes due to the disaggregation of the atmospheric forcing variables are much smaller than those of the mosaic approach compared to model simulations without surface heterogeneity representation. Since the surface is much more heterogeneous than the atmosphere, where turbulent processes usually lead to well-mixed conditions a smaller beneficial effect of the additional downscaling was expected. A further impact reduction is caused by cancelling of the correlated errors in the screen-level and surface variables

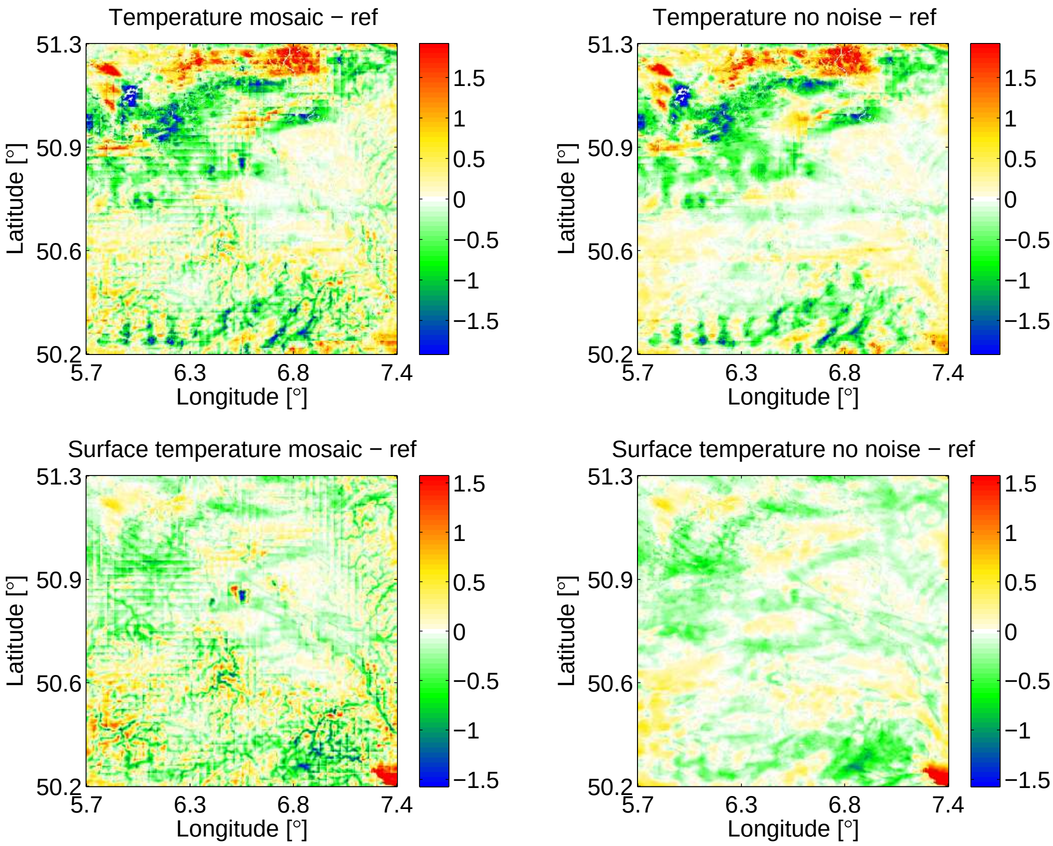

Figure 7: Temperature [K] (top) and surface temperature [K] (bottom) difference field (with respect to the high resolution reference) for 12:00 UTC on 16 July 2008 for model run with pure mosaic (left) and mosaic plus downscaling step 1 and 2 (right).

when computing fluxes in the standard mosaic approach, which mainly depend on gradients and not so much on the absolute values. Thus, if the screen-level temperature is too high, in general also the surface temperature is too high as a result of the coarse atmospheric forcing. Hence, although the spatial structure of the surface variables is more realistic due to the distributed atmospheric forcing, the overall benefits for numerical weather prediction are marginal. It is important to note, however, that part of the low impact of atmospheric disaggregation can be attributed to the rather simple parameterization of the exchange fluxes in current atmospheric models. In future applications, especially on smaller scales, non-local effects will become more important, and thus the fluxes will likely be parameterized by other, less simple concepts than according to Monin-Obukhov theory, which assumes horizontal homogeneity. Thus we expect that a more realistic representation of the flux-driving surface variable fields become much more important. A general drawback of the mosaic approach is the neglect of horizontal fluxes and advective effects between patches within a grid box. If for example a cool water body is situated upwind of an agricultural sub-pixel, in reality the atmospheric conditions at the downstream pixels would be affected by advection of cool or moist air, and thus also the turbulent fluxes.

The stochastic downscaling step leads to a deterioration of the simulated fluxes. Although the added small-scale variability restores - as it should - the variability in the disaggregated fields to the variability in the high-resolution simulations, the variability for the fluxes is too large, most probably due to not-captured cross-correlations between the relevant variables.

A few studies in the literature also apply an atmospheric disaggregation in combination with the mosaic approach (e.g. Seth et al, 1994; Giorgi et al, 2003; Dimri, 2009). In these studies positive effects due to, e.g., temperature downscaling have been demonstrated. Their simulations, however, were conducted on scales of about 50-100 km for several months or even years, and over highly structured terrain such as the Alps or the Himalaya. Positive effects were achieved for the hydrological cycle due to a better representation of snow cover in winter. In larger-scale simulations larger beneficial effects due the downscaling may be

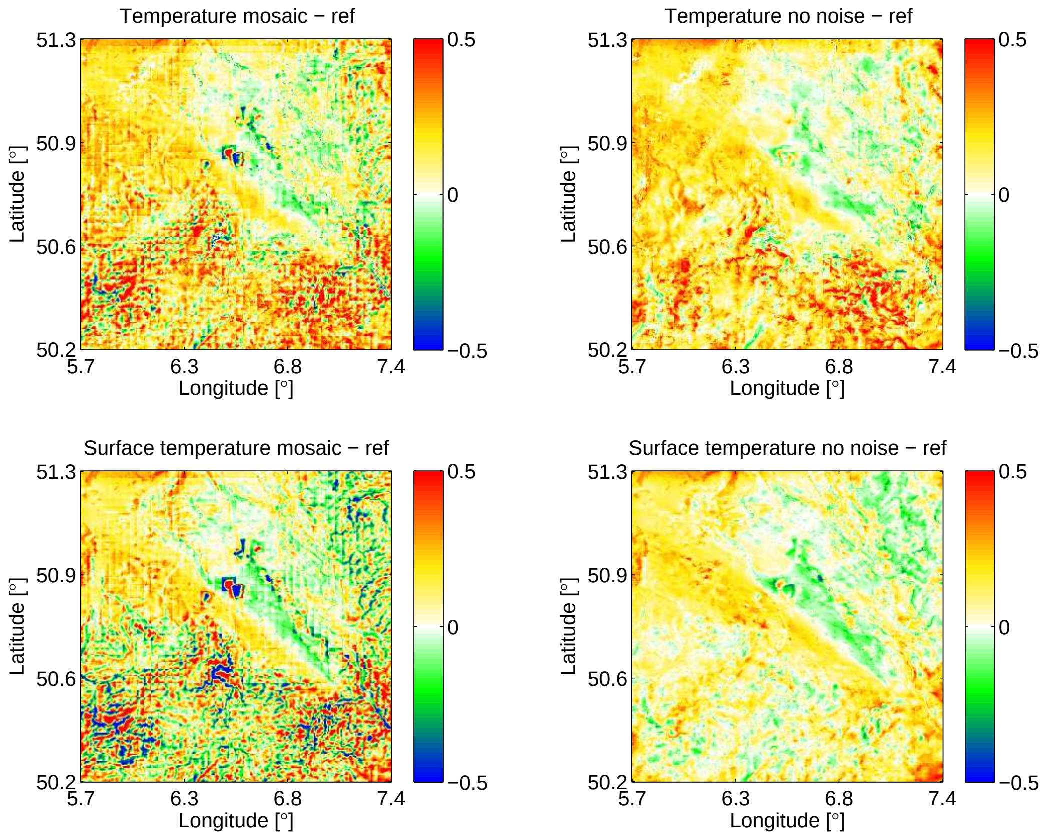

Figure 8: Same as Fig. 7, but now averaged over all days and all times.

expected, because more subgrid-scale variability in atmospheric quantities than on the meso-γ-scale is neglected. The accumulation of positive effects of a more realistic representation of precipitation, snow cover or runoff processes should lead to positive impacts on the simulation of the overall hydrological cycle in longer simulations or in continuous data assimilation - forecast cycles. Long-term climate simulations (global or regional) which include dynamical vegetation modules to incorporate the transient response of vegetation to changing climate conditions as e.g. by (Myoung et al, 2011) can also benefit from a realistic surface and boundary heterogeneity representation. A large beneficial effect of a mosaic in combination with atmospheric disaggregation should be expected for applications in highly structured terrain, for example in the Alpine region, due to a more realistic partitioning of precipitation into rain and snow dependent on elevation leading to indirect positive impacts due to more realistic patterns of high and low surface albedo over snow-covered and snow-free sub-pixels.

The downscaling system used here has been trained for atmospheric variables based on 400 m grid spacing as the smaller scale and 2.8 km. First tests, however, of the system for a downscaling from 14 km data down to 2.8 km have been conducted to analyse whether the system can also be used for regional climate simulations with the COSMO model on a 14 km grid, with surface information on a 2.8 km mosaic subgrid. Although the downscaling steps have been optimised for smaller scales, the results obtained by the disaggregation scheme are similar in terms of root mean square error reduction and subgrid-scale variance reconstruction for the atmospheric variables as for the development scale. These results indicate that the approach could also be employed for climate modelling without changes to the scheme or parameters, an application within model simulations at this scale will be carried out as a next step to test this hypothesis. Also tests with a different vertical layer configurations will be carried out, to investigate the performance of the scheme for different heights of the atmospheric reference level than the 20 m level as used in the training and validation. This result can also be understood from the way the downscaling method is constructed. Step 1 naturally does not depend on the resolution. The physical relations modelled by the rules in step 2 will also not change at similar scales. Only at very different scales other relations may have to be added. The variance added in step 3 is in many cases mainly proportional to the resolved variance of 3x3 columns around the candidate column.As the atmosphere is approximately fractal, these coefficients should also not drastically change for moderately different resolutions.

In an operational use of the mosaic approach, high-resolution soil initialisation information would be available, and stored on the subgrid surface representation from the previous model runs. In a continuous data-assimilation-forecast system spin-up effects, which influence the results for our short-term case studies, due to the coarse-scale soil-initialisation would cease to exist. In such a system, effects of more realistic atmospheric forcing patterns would accumulate over time in the surface and subsurface fields, for example for the soil moisture. This effect should prove even more beneficial when applied to a model, which also accounts for ground-water and lateral surface- and sub-surface routing, which, in combination with the highly resolved relief height, would lead to a more realistic ground-water and soil moisture field. Many studies show the strong dependence of simulated fluxes on the soil moisture representation (e.g. Chow et al, 2006; Maxwell et al, 2007; Schmidli et al, 2009), at least under calm weather conditions, and of ground-water distribution in regions where the ground-water level is within a critical depth (Kollet and Maxwell, 2008). In this work the soil moisture has been initialized by interpolating soil moisture from COSMO-DE analyses, also for the 400 m model simulations.

Abramowitz et al (2008) compared three state-of-the-art land surface models (LSMs) and two simple empirical-statistical models with flux measurements; they could show that the simple statistical models outperform the LMSs because the latter seem to under-utilise the atmospheric input information. Provided that this finding is generally valid, a spatially distributed atmospheric forcing in current LSMs may have less impact as it should have. Belušić and Güttler (2010) found that the artificial numerical diffusion contained in many atmospheric models to suppress numerical instabilities leads to a too strong damping of spatial and temporal variability as compared to measurements. Thus, besides adding variability at the sub-grid scale it can be useful to analyze whether the variability at the grid-scale is realistic.

A general issue in studies like the present one is the evaluation of the model simulations. In this work validation was limited to comparisons with higher resolution model simulations as a consistency check. For a stronger validation, a large number of simulations, ideally in a continuous data-assimilation-forecast-cycle should be carried out and detailed comparisons should be made in an operational verification framework based on observations, to be able to draw final conclusions about the performance in operational numerical weather prediction systems. A validation of the 400 m COSMO simulations versus dense surface and boundary layer observations (e.g. as by Lengfeld and Ament, 2011), as from e.g. measurement campaigns, would also give further insight to which extent the high-resolution simulations can be regarded as "pseudo-observations" in statistical evaluations as in this study.

Concluding, the adequate representation of surface heterogeneities is more important than the heterogeneities in the lower atmosphere, where the variability is smoothed out to a large degree by turbulent motions. In numerical weather prediction larger beneficial effects can be expected by improving the turbulence and transfer parameterizations itself, which still have deficiencies especially in very stable situations. For climate simulations, on longer time scales, at coarser resolutions, or more structured terrain, however further investigations of the disaggregation of atmospheric screen-level variables may prove valuable.

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