9.3 EFFECTS OF LAND SURFACE HETEROGENEITIES ON THE BOUNDARY LAYER STRUCTURE AND TURBULENCE DURING LITFASS-2003: LARGE-EDDY SIMULATIONS IN COMPARISON WITH TURBULENCE MEASUREMENTS.

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1 Introduction

Orography and differences in landuse represent inhomogeneities of the land surface, which range from continental scale to micro scale. In operational weather forecast models, the orography of the land surface is already well-implemented, being a crucial factor for success of the forecast. Despite of the effects of large-scale heterogeneities like land and sea (e.g. land-see breeze), it is still an open question if the heterogeneous landuse of meso- to micro- scale produce significant effects on local weather (e.g. convectively-induced rainshowers). Therefore, several experiments have been brought out in the last decades, e.g. Mahrt et al. (1994); Yates et al. (2001); Isaac et al. (2004). Until now, a "heterogeneous effect" of landuse on the CBL could not be clearly captured in any of these experiments. Reasons for this are e.g. a coarse instrumentation, synoptic-driven events like frontal clouding and rainfall, or high wind speeds during the campains. Simulations with mesoscale models suffer from the coarse grid resolution of a few kilometers (Lynn et al., 1995; Arola, 1999), while turbulence resolving large eddy simulation (LES) models were mostly used to investigate the effects of idealized inhomogeneites on the convective boundary layer (CBL), e.g. Albertson et al. (2001); Avissar and Schmidt (1998); Raasch and Harbusch (2001); Letzel and Raasch (2003).

The EVA-GRIPS project (for an overview see talk **9.1**) investigates the evaporation at the scale of about 0.1 - 20 km over the heterogeneous area around Lindenberg near Berlin/Germany, continuously recorded with 13 energy balance stations in May/June 2003. Orography plays only a minor role in this area, whereas differences in landuse represent strong heterogeneities. The main goal of EVA-GRIPS is the determination of mean surface sensible and latent heat fluxes for the whole 20 x 20 km^2 domain (A_i) and the detection of heterogeneity-induced effects in the CBL through analysis of flight-data (talk **9.4**) and atmospheric model data.

As a part of EVA-GRIPS, the LES model PALM (Raasch and Schröter, 2001) is used for the simulation of the CBL over the LITFASS-2003 area for several days of the experiment (currently two days, but in the talk we hope to show the results of three or four days). Because both the small-scale heterogeneity at the surface and the significant turbulent eddy-structures are explicitely resolved, it is possible to investigate the heterogeneous CBL. This gives also the opportunity to compare the LES results with soundings from a Lidar and with the measurements of a helicopter-airborne probe (HELIPOD).

2 Model setup

As model domain, it was not sufficient to choose A_i, because PALM uses cyclic boundary conditions in the horizontal direction even for irregular heterogeneous surfaces. This leads to a boundary-influenced unrealistic flow field near the inflow area, which is not suitable for analysis. To exclude these influences, we ran several test simulations and finally extended the LITFASS-domain to 32 x 40 km^2 (see Fig. 1 for simulations with easterly background wind). The horizontal grid resolution was $\Delta x, \Delta y = 100\,\mathrm{m}$, and the vertical grid resolution was set to $\Delta z = 50\,\mathrm{m}$, resulting in a computational grid of 320 x 400 x 70 gridpoints for the 2003/05/30 (day1) and 320 x 400 x 84 gridpoints for the 2003/06/02 (day2). In the simulation of day1, Δz was stretched by a factor of 1.08 above 2600 m and above 3300 m for day2, respectively. Simulation time was 5-17 UTC.

For the adaption of the heterogeneous landuse, we used the CORINE-dataset of the European Environment Agency with a resolution of 100 m and a more detailed dataset (w.r.t. vegetation classes) of the german weather service for A_i itself. The heterogeneity

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was then represented by 7 classes of landuse: water bodies, grass, maize, triticale, rape, barley and forest (including villages).

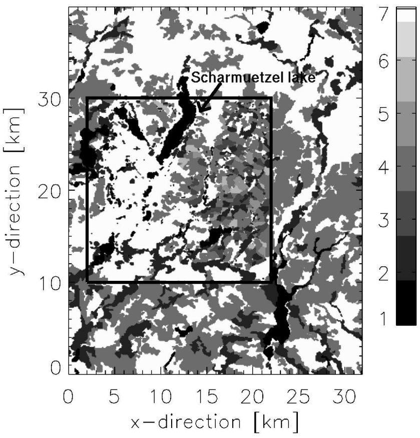

Figure 1: Surface heterogeneity in the simulations for 2003/05/30 and 2003/06/02: 1=water bodies, 2=grass, 3=maize, 4=triticale, 5=rape, 6=barley, 7=forest and villages. The LITFASS area A_i is marked by a square.

At the lower boundary, the temporal development of the surface sensible and latent heat flux was prescribed for the different classes as given by representative measurements from the respective energy balance stations. Additionally, the roughness length, the initial heterogeneous surface temperature and specific humidity were set up in the same manner. The initial profiles of potential temperature and humidity were derived from a radiosonde, whereas the wind profile was calculated by a 1D pre-run of the model with the appropriate geostrophic wind speed and direction gathered from a wind profiler. On day1 (day2), geostrophic wind speed was approx. $2\ \mathrm{m\ s^{-1}}$ ($4\ \mathrm{m\ s^{-1}}$) and wind direction was approx. 90° (113°). Both day1 and day2 showed nearly no synoptic influences and a relatively dry boundary layer and free atmosphere. Consequently, day1 was cloud-free, whereas on day2 only 2/8 cumulus humilis was observed after 10 UTC. The maximum CBL height was 2000 m for day1 and 2900 m for day2.

Heterogeneity induced secondary circulations have been determined by averaging 8 identical LES runs (ensemble runs), each started with different initial random perturbations in order to filter out the randomly distributed turbulent up- and downdrafts. With this method, we could extract the effect of the heterogeneity on the vertical sensible and latent heat flux (in A_i), following Chen and Avissar (1994) and thus dividing a variable ϕ into three parts ($\overline{\phi}$ indicates an average over all $x, y \in A_i$):

$$\phi(x,y,z,t) = \overline{\phi}(z,t) + \phi'(x,y,z,t) + \phi''(x,y,z,t), \quad (1)$$

where $\overline{\phi}(z,t)$, $\phi'(x,y,z,t)$, $\phi''(x,y,z,t)$ represent the large scale mean, the mesoscale pertuberation on $\overline{\phi}(z,t)$ and the turbulent (resolved + subscale) part, respectively. A time-average of our data over one hour did not totally filter out the turbulent part, so we can rewrite Eq. 1 as:

$$\phi(x,y,z) = \overline{\phi}(z) + \phi'(x,y,z) + \phi''(x,y,z). \quad (2)$$

$\langle\phi\rangle$ indicates an average over 8 ensemble runs. Note that $\langle\overline{\phi}(z)\rangle = \overline{\phi}(z)$, $\overline{\overline{\phi}}(z) = \overline{\phi}(z)$, $\langle\phi'(x,y,z)\rangle = \phi'(x,y,z)$, $\overline{\phi'(x,y,z)} = 0$, $\langle\phi''(x,y,z)\rangle \cong 0$. Using Eq. 2 the averaged total vertical flux can be expressed as:

$$\overline{w\phi}(z) = \overline{w}(z)\ \overline{\phi}(z) + \overline{w'\phi'}(z) + \overline{\langle w''\phi''\rangle}(z), \quad (3)$$

where we define $\overline{w\phi}(z)$ as the total flux, $\overline{w}(z)\ \overline{\phi}(z)$ as the large scale flux, $\overline{w'\phi'}(z)$ as the mesoscale flux and $\overline{\langle w''\phi''\rangle}(z)$ as the turbulent (resolved + subscale) flux. Note that $\overline{w}(z)\ \overline{\phi}(z) = 0$ for the average over the total domain. Concerning A_i, this large scale part generally contributes about 2% to the total flux.

All runs were performed on 8 processors of the NEC-SX6 vector machine of the DKRZ in Hamburg/Germany and each needed 12 hours of computation time.

3 Simulation Results

3.1 How reliable is the simulation data?

The temporal development and absolute values of the mean variables like mixed layer temperature, humidity, and boundary layer height (z_i) compare very well with the observations (for an example see Fig. 2). Hence, using the representative surface flux measure-

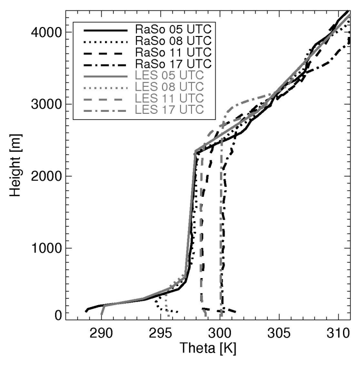

Figure 2: Profiles of pot. temperature for day2.

ments for the different landuse classes is a sufficient method for our model forcing in LITFASS-2003. Furthermore, these good agreements are the prerequisite for the validity of additional analysis and comparisons.

Due to the turbulence filtering of 3D-data using time- and ensemble averages, the standard deviation (w.r.t. the horizontal mean) of the flux (Fig. 3) is significantly reduced, but asymptotically approaches a limit value caused by the heterogeneous effects. In

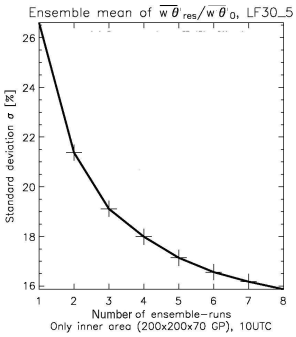

Figure 3: Effect of the ensemble averaging on the standard deviation of $\overline{w'\theta'}/\overline{w'\theta'}_0$, day1 10 UTC

order to ascertain the remaining amount of standard deviation caused by natural turbulence, we applied the same method on homogeneous control runs. Using 8 runs for this average, the remaining standard deviation of the turbulent sensible heat flux was only 1.9% of the prescribed surface flux. Thus, the mesoscale part of any variable is determined at high quality.

3.2 The mesoscale effect

With this background, we can investigate the daily cycle of the mesoscale part using Eq. 3, integrate from $0.0 - 1.0z_i$ and compare this value to the one of the total flux. Fig. 4 shows this time series for the sensible and latent heat flux of both simulated days. For day1,

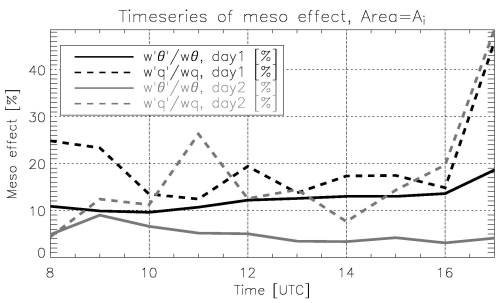

Figure 4: Mesoscale part of the height integrated total sensible and latent heat flux for day1 and day2. Remember that the values are representative for the preceding hour.

the mesoscale part of total sensible heat flux is significant throughout the whole day and rises to a maximum in the evening hours (17 UTC = 19 MEST). This evolution is related to the development of secondary circulations, which develop with the enforced heterogeneous forcing throughout the morning times (Fig. 5). They get stronger through the daytime and persist in contrast to the random turbulence even when the incoming solar radiation in the afternoon declines. Therefore, their effect is becoming more significant in the late afternoon period. For day2, the same variable is far less significant (most of the time below 5%) due to much weaker secondary circulations (not shown). Principle reasons for this are the stronger wind speed and the greater CBL height, which are both crucial for the generation of secondary circulations (Avissar and Schmidt, 1998). In contrast to the sensible heat flux, the mesoscale latent heat flux in Fig. 4 shows a significant signal for both days and rises strongly between 16-17 UTC. These behaviors may result from the spatial distribution of q', which consists of larger coherent structures than θ', but we are still investigating the cause.

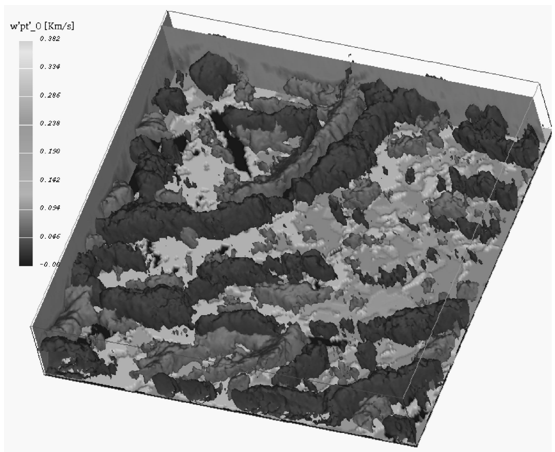

Figure 5: Mesoscale part of vertical velocity (secondary circulations) in A_i on day1 at 12 UTC. The shown isosurfaces represent $w' = 0.3ms^{-1}$ (dark grey) and $w' = -0.4ms^{-1}$ (light grey). At the bottom of the picture, the heterogeneous surface sensible heat flux is shown. Note the large circulation located at the so-called “Scharmuetzel lake” in the northern part of A_i.

3.3 Comparison to Lidar and HELIPOD measurements

Fig. 6 shows the latent heat flux profiles derived from LES data for A_i, the gridpoint of the Lidar location and for the “Scharmuetzel lake” as well as the flux measurements of Lidar and HELIPOD. The latter one flew at two different heights (100 m and 800 m agl) over four primary landuse classes. The standard deviation of the LES-Lidar profile was quite large (+/- 150 W m^{-2}), whereas horizontal averages over the lake and

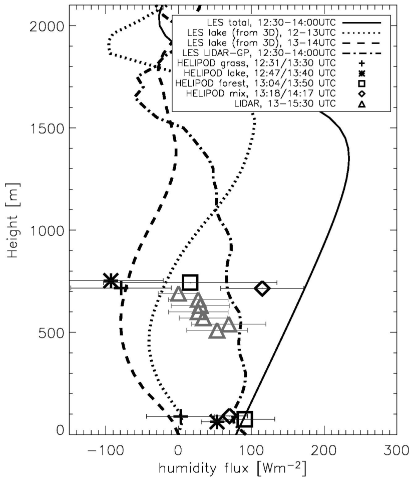

Figure 6: Vertical latent heat flux profiles of LES data, Lidar and HELIPOD measurements for the afternoon of day1.

A_i had only small standard deviation (+/- 20 W m^{-2}). Nevertheless, only the average over the different HELIPOD flight legs at the lower height nearly represents the area averaged flux, but not for 800 m. Regarding the temporal development of the LES lake profile, it becomes quite clear that a synchronous HELIPOD measurement at both heights would probably lead to a different flux for that area, due to the non-stationary CBL. The Lidar measurement similarly suffers from the impact of local turbulence and secondary circulations, which complicates the derivation of a representative flux profile from that data. For more details, see talk **9.4** and **6.1**. In contrast, comparisons with the sensible heat fluxes from the HELIPOD resulted in much better agreement (not shown).

4 Conclusions and outlook

We showed that our large eddy simulations compare well with the measurements of two days of the LITFASS-2003 experiment and that our method for the derivation of the mesocale effect delivers reliable data. This mesoscale effect is greater for the latent heat flux than for the sensible heat flux. Both fluxes increase towards late afternoon. Compared to homogeneous control runs, this does not affect the total flux profiles (not shown). Therefore, the mesoscale flux incorporates no additional transport, but reduces the turbulent transport. Responsible for the mesoscale effect are secondary circulations, whose generation strongly depends on boundary conditions like wind speed and CBL depth, but which have been identified for the LITFASS-area on two days. The first comparison to Lidar and HELIPOD data reveals a restricted representativeness of local and flight-leg averaged latent heat fluxes concerning the total domain, so that their interpretation in favor of a flux profile might be misleading. A comparison to large-aperature scintillometer measurements at 40 m height is currently carried out through a high-resoluted simulation.

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