9.4 FIRST ATTEMPTS OF AN LES-MODEL EVALUATION BY COMPARISON WITH EXPERIMENTAL DATA GAINED FROM ACOUSTIC TOMOGRAPHY

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1 INTRODUCTION

Large-Eddy Simulation (LES) has become a common tool to investigate various topics in micro-meteorology. However, an evaluation of LES models using adequate experimental data is still necessary. Wyngaard and Peltier (1996) mentioned that "except for the rare occasions when its predictions clearly disagree with experiment, as in the mean wind profile near the surface, systematic experimental evaluation of LES results in micro-meteorology has been conspicuously lacking". One reason is that the experimental data are normally measured at a fixed spatial point with in situ sensors and have to undergo a filter process before they can be compared with the simulated gridvolume-averaged three-dimensional data.

One possible method to avoid this difficulty is the use of acoustic travel time tomography (Wilson and Thomson, 1994), where travel time data are the starting point for a subsequent tomographic reconstruction of the temperature and wind field by an inversion method. Important advantages of this experimental and analysis technique are its remote-sensing capacity and its effect as a spatial filter for subgrid-scale turbulent elements. Therefore, the tomography data are directly comparable with the resolved-scale gridvolume-averaged LES data. The spatial resolution of the measurement field depends among others on the number of sound rays (number of transmitters and receivers) and the size of the tomographic array.

Within this project we tried to perform such a comparison between data from our **pa**rallelized **L**ES **m**odel **PALM** (Raasch and Schröter, 2001) and tomography data from a group at the University of Leipzig (Arnold et al., 1999). We tried to limit the comparison to those regions where the subgrid-scale turbulence within the model is small compared with the resolved-scale turbulence. We thus avoided influences by the known shortcomings of the subgrid-scale (SGS) model in the near-surface region on our results.

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2 PREREQUISITES FOR A COMPARISON

In order to carry out the comparison, our simulation had to meet some prerequisites, determined as follows:

- Since the technical equipment allowed only measurements at a height of about 2 m, we had to use a very small grid spacing to ensure that the subgrid-scale turbulence at this model level is small. This is typically the case at the fourth or fifth grid level above the surface. Therefore, we took a very small grid spacing of $\Delta = 0.5$ m both horizontally and vertically.

- The clearest signals in tomography data are found for convective boundary layer (CBL) conditions, actually because of the very large spatial temperature fluctuations occurring under these circumstances. Therefore, we chose such a CBL situation for our comparison.

- The tomographic array provided data for a horizontal domain size of 200 m $\times$ 240 m with a horizontal resolution of 50 m $\times$ 50 m. We chose the horizontal domain size of our model to 350 m $\times$ 350 m in order to be able to simulate the largest turbulent structures registered by the tomographic array. Since under CBL conditions the boundary layer height in the simulation should not exceed half of the horizontal domain size (about 100 - 200 m) in order to cover the biggest convective structures, we had to restrict the comparison to a situation of CBL development in the early morning hours with $100 < z_i < 200$ m.

- The LES model uses cyclic horizontal boundary conditions. Therefore, the area outside the tomographic array should be as homogeneous as possible so that effects of differential horizontal advection can be neglected.

Since all transmitters and receivers of the tomographic array were mounted at the same height, only two-dimensional-averaged data at one level were available. This somewhat limits the comparability of measured and modelled data.

After carrying out our first test runs, the insufficient quality of the data about initial and (surface) boundary conditions needed to drive the model turned out to be an even bigger problem for a quantitative comparison. The temporal development of turbulence quantities like the temperature variance is very sensitive e.g. to the initial temperature profile (which effects the subsequent evolution of z_i) or the surface temperature. Since we took the surface temperature as a boundary condition (instead of prescribing the surface heat flux) and calculated the temperature flux from the temperature difference between the surface and the first computational grid level using Monin-Obukhov relations, we also needed the surface roughness length z_0. Some of these informations were provided by additional measurements, while others (in particular z_0) could only be estimated. Since the parameter values describing the initial and surface boundaries have a direct impact on the simulated data, they have to be known more or less precisely before a quantitative comparison between simulated and measured data makes sense.

In order to quantify the influence of the initial and boundary conditions on the simulated results, we carried out appropriate parameter studies with our LES model. We performed various runs in which the values of the critical parameters like z_0 were gradually varied and analyzed the changes in the model results, especially the mean vertical profiles of the temperature variance (Weinbrecht et al., 2002). This sensitivity analysis allowed us to describe the fluctuations of the model output variables due to changes in the initial and boundary conditions as functions of their measured accuracy. We found, for example, that to reach a fluctuation rate of only 10 % in the simulated temperature variances, the roughness length has to be determined with an accuracy of 35-50 %. The smaller the roughness length the more precisely it must be provided. One main result of the sensitivity analysis was that most of the initial and boundary conditions during the measurement period were only known with insufficient accuracy so that quantitative comparisons between simulated and measured data were not very convincing.

Despite all these difficulties, we still tried to perform at least a qualitative comparison because we wanted to demonstrate that such a comparison between LES- and tomographic data is useful and possible in principle.

3 EXPERIMENTAL AND NUMERICAL SETUP

The tomography field experiment was carried out at the test site of the German Weather Service (DWD) in Lindenberg, 70 km south east of Berlin, in autumn 1999. The tomographic array was mainly situated on grassland with 3-5 cm vegetation height. Six acoustic sources and five receivers were positioned at the border of an array with horizontal dimensions of 200 m$\times$240 m at a height of 2 m.

The morning (0620 UTC - 0720 UTC) of September, 24th was selected for the comparison with the LES, because on this day the weather conditions (sunny with moderate wind speed of 3-4 ms^{-1}) met the requirements mentioned in Section 2. The temperature profile at the beginning of the comparison period was gained from measurements at a 100 m mast and from a radio sounding system. It showed a well mixed layer topped by an inversion of 0.6 K / 100 m at a height of 135 m. In order to create a quasi-stationary CBL with a minimum of computer time, which could be used as the initial state of the simulation, we performed a prerun with a weakly stably stratified layer up to 131 m, where the surface temperature is incremented by 1.14 K at the beginning. After 10 minutes, a quasi-stationary CBL developed which resembled the observations. During the main run of the model, the surface temperature was continuously adapted to surface temperature measurements observed by an infrared thermometer.

Because of the small grid spacing, the numerical grid consisted of 700$\times$700$\times$350 grid points. Runs with such a high resolution were only possible on a massively parallel computer. Nevertheless, simulating a period of 1 hour took about 860 hours of CPU-time on 350 processor elements of a Cray-T3E.

4 FIRST RESULTS

Figure 1 shows a horizontal cross section of the potential temperature field at 2 m height one hour after the beginning of the main run. Line shaped coherent structures are aligned along the direction of the near-surface mean wind, similar to previous LES studies (see e.g. Khanna and Brasseur, 1998), although they occur on a much smaller scale in our studies. However, since the horizontal resolution of the tomography data is 50 m, no direct comparison is possible. To allow a comparison, the simulated temperatures are averaged over areas of 50 m$\times$50 m. Figure 2(a)

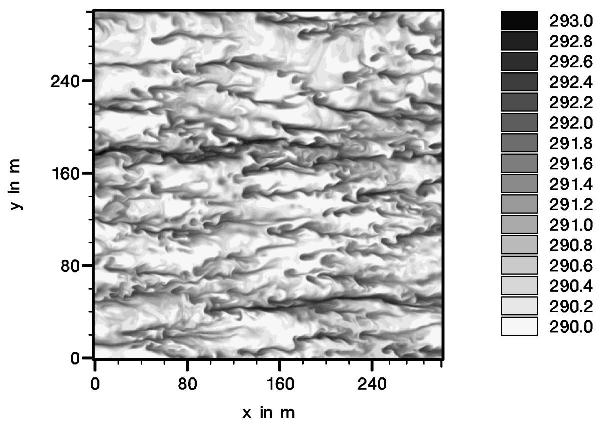

Figure 1: Horizontal cross section of the simulated potential temperature in K at 2 m height.

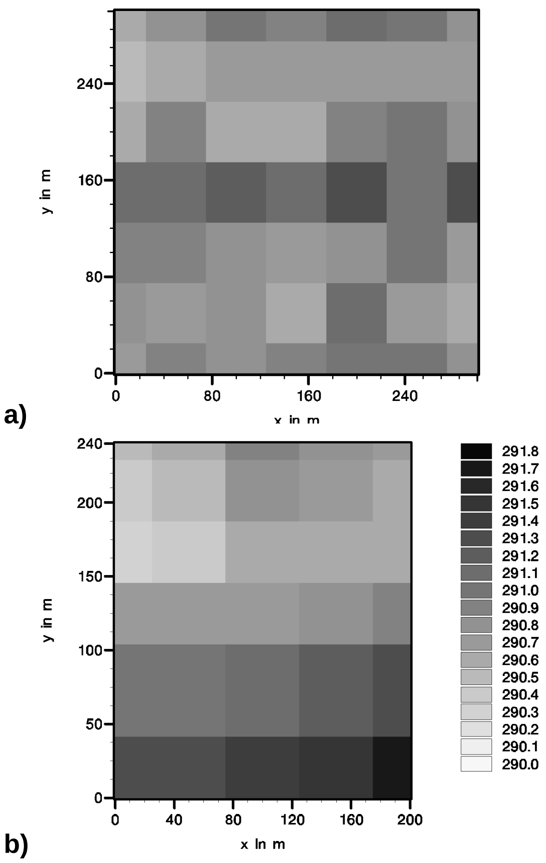

Figure 2: Horizontal cross section of potential temperature in K at 2 m height. (a) averaged LES data; (b) tomographic data.

shows the same but now averaged LES temperature field of Figure 1 in comparison with the corresponding temperature field derived from the tomographic array. The linear structures are almost completely eliminated from the LES field by the averaging process. Measured and simulated data do not show any direct correspondence.

However, this is not necessarily an indication for problems in the simulation or the experiment. Because of the sensitive dependence of turbulence on the initial conditions, one can only compare the statistics of the fields, not the instantaneous fields themselves. Instead of these fields, Figure 3 compares the time series of measured and simulated temperature variance σ_θ^2. The LES variance is calculated from the averaged data. The scatter bars indicate the uncertainty of the LES data due to the uncertainties in the initial and boundary condition parameters, as derived from our sensitivity analysis. In principle, there is a qualitative agreement between measured and simulated data, but it is impossible to use these data for an LES evaluation due to the extremely large uncertainty bars. Our sensitivity study even does not explain all of the differences. One additional reason which may account for them is an heterogeneous surface. Possibly, the surface at the experimental site or in its neighbourhood was not totally homogeneous. For example, an inhomogeneous surface heat flux can be caused by horizontal differences in the soil humidity. Large-eddy simulations showed that near-surface temperature variances are extremely sensitive to surface heat flux variations (Raasch and Harbusch, 2001). A further reason maybe given by technical limitations of the tomographic array. The acoustic tomography method directly provides only the effective sound speed, which depends on temperature as well as on the wind speed. From the effective sound speed values the temperature and wind field has to be derived by the inversion method. As the number of transmitters and receivers was limited in the experiment, these fields could not be specified both with the same resolution. To detect at least the temperature with a resolution of 50 m $\times$ 50 m, the horizontal wind vector was assumed to be constant on a much larger area. Because of this assumption all variations of the effective sound speed within the areas of assumed constant wind speeds were interpreted as variations of the temperature field. Therefore, the temperature variance can be assumed to be too large. In future experiments this shortcoming can be avoided by using a larger number of transmitters and receivers.

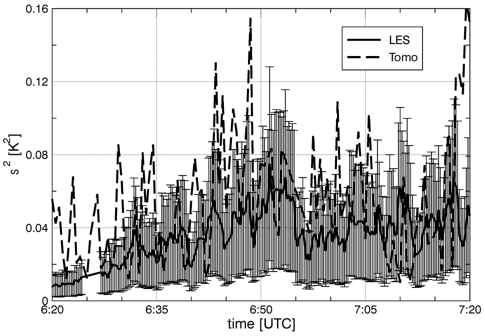

Figure 3: Spatial temperature variance σ^2 in K^2. The solid line represents the simulated data and the dashed line the data gained by acoustic tomography. The scatter bars indicate the uncertainty of the simulated variances according to the results of the sensitivity analysis.

5 CONCLUSIONS AND OUTLOOK

Although the acoustic tomography method generally provides data which can be directly compared with the volume-averaged LES data, an evaluation of LES will additionally require very precise knowledge of various initial and boundary parameters, which may be very hard to obtain during real field experiments.
Our results suggest that it might be more favourable to evaluate LES models with data from laboratory experiments, because initial and boundary conditions are known much better and are under much stricter control.

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