STINHO - micro-α scale measurements and LES modelling

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ABSTRACT

A micrometeorological field experiment within the scope of the **STINHO**-project (**ST**ructure of turbulent transport under **INHO**mogeneous conditions) was performed at the boundary layer research field of the Lindenberg Meteorological Observatory in the summer of 2002 to investigate the interaction of an inhomogeneously heated surface with the turbulent atmosphere. The data of this field experiment (STINHO-II, July 2002, RAABE ET AL., 2005) were used to initialize a large-eddy simulation model that has been adjusted to the area under investigation. The accuracy of the calculations is supported using analytical models. The LES initialization conditions are adapted to reach an agreement between observed as well as calculated parameters, e.g. the increase of the near surface air temperature or the time dependent rise of the height of the convective boundary layer (CBL) in the first hour after sun rise. A direct comparison between observed and calculated parameters of the CBL-development is possible for averaged data. The detailed spatial and temporal structure of the investigated morning heating process can only be compared using statistical parameter.

ZUSAMMENFASSUNG

Im Rahmen des **STINHO** Projektes (**St**ruktur des turbulenten Transportes über **inho**mogener Unterlage) wurde im Sommer 2002 auf dem Gelände des Grenzschichtmessfeldes des Meteorologischen Observatoriums Lindenberg ein mikrometeorologisches Feldexperiment durchgeführt, um die Wechselwirkung einer sich heterogen erwärmenden Erdoberfläche mit der turbulenten Atmosphäre zu untersuchen. Die Daten aus einem Experiment (STINHO-II, Juli 2002, RAABE ET AL., 2005) werden zur Initialisierung eines an die Bedingungen des Untersuchungsgebietes angepassten Large-Eddy Simulationsmodells verwendet und mit Beobachtungsdaten verglichen. Die Effizienz der numerischen Simulationen wird durch die Verwendung eines analytischen Modells unterstützt, um eine Konsistenz zwischen Initialisierungsbedingungen und den beobachteten als auch den berechneten Parametern (bodennaher Lufttemperaturanstieg oder die Zunahme der Höhe der konvektiven Grenzschicht) in der ersten Stunde nach Sonnenaufgang herzustellen. Ein Vergleich zwischen beobachteten und berechneten Parametern der konvektiven Grenzschichtentwicklung ist nur für gemittelte Daten möglich. Die räumliche und zeitliche Darstellung der Struktur eines solchen Erwärmungsprozesses kann nur geprüft werden, indem statistische Parameter verwendet werden.

1. INTRODUCTION

The **STINHO** project (s. RAABE ET AL., 2005, ARNOLD ET AL., 2004), which is a subproject of the **VERTICO** (**VERTI**cal transports of energy and trace gases at anchor stations under **CO**mplex natural conditions, s. BERNHOFER ET AL., 2005) research network, aims to study the effect of non-homogeneity in surface heating at the micro-α scale on the vertical turbulent heat exchange and there consequences for the resulting development of a CBL.
The results of the STINHO experiment (RAABE ET AL., 2005) have been used to initialise a Large-Eddy Simulation (LES) model with horizontally non-homogeneous surface heating conditions. The LES calculates the development of a CBL (Convective Boundary Layer) in the morning hours starting after sun rise and this LES output (temporal development of spatial distribution of wind and potential air temperature) will be compared with likewise spatially distributed observations (temporal development near surface horizontal wind and temperature fields, acoustic tomography).
In recent years, Large-Eddy Simulation (LES) has become a common method to investigate the atmospheric boundary-layer turbulence. LES is widely accepted as a compromise between direct numeric simulation (DNS) where all scales are explicitly resolved and Reynolds-averaged numerical simulations (RANS) which provide an ensemble averaged view of the boundary layer turbulence (s. SAGAUT, 2006).
Within an LES the energy containing eddies relevant for the characteristics of the simulated turbulent flow are explicitly resolved whereas only a small part, the so called subgrid or subfilter scales, has to be parameterised. Especially for the layers of the model close to the earth surface parameterisation schemes have to be used to describe the interaction of the turbulent air stream with the surface. LES under natural conditions must take into account that the surface properties are non-homogeneous and the LES must use a non-homogeneous forcing to predict the development of e.g. a convective boundary layer (CBL). Since the fundamental works of LILLY (1967) and DEARDORFF (1970), LES has been used frequently to study the structure and development of the atmospheric convective boundary layer under homogeneous (e.g. DEARDORFF, 1974, MASON, 1988, SCHMIDT and SCHUMANN, 1989) as well as under heterogeneous surface conditions (e.g. AVISSAR AND SCHMIDT, 1998; RAASCH AND HARBUSCH, 2001; LETZEL AND RAASCH, 2003).
The field experiment STINHO-II was especially designed to observe all relevant data for operating a LES model including a real, non-homogeneously heated surface, although finally the agricultural conditions during summer 2002 have prevented the desired symmetrically nested structure of the different observational systems (RAABE ET AL., 2005, Fig. 1). The measurement campaign was performed at and around the boundary layer research site of the Deutscher Wetterdienst (DWD, German Meteorological Service) near Lindenberg (Fig. 1). The experiment combined local energy balance measurements over two different types of surfaces with area-integrating and spatially resolving measurements. ***Inhomogeneity*** of the landscape is considered in STINHO-II as a pronounced thermal contrast of two neighbouring land use types (here: bare soil and grassland). It will be assumed, that such a contrast in surface temperature has a significant and visible influence (in the experimental data) on the turbulent heating of the lower atmospheric boundary layer (ABL).

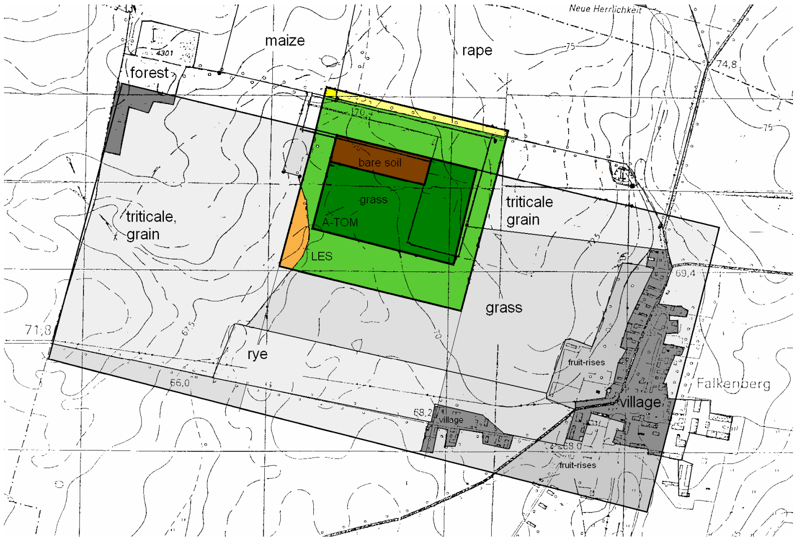

Fig. 1: View of the landscape around the Boundary Layer research site of the Meteorological Observatory Lindenberg of the DWD. The mutual arrangement of the observations and simulations are shown. The acoustical tomography system (A-TOM) spanned over an area of an extension of 300m x 450m and observes spatial and temporal air temperature and wind fields. The A-TOM area contains bare soil and grassland and divides this region into 35 grid cells for temperature (extension of 70m x 70m) and 9 grid cells for wind (extension of 145m x 100m). The LES-area covers 575m x 575m around the A-TOM area and uses a resolution of 0,75m x 0,75m for calculations. Further instruments like the IR camera covers an area of 900m x 2000m (grey colour) and the Helipod-legs partly covers an area of 5000m x 5000m. Within the LES- area further surface flux observational systems were distributed.

The STINHO-II observation period was carried out during the first ten days of July 2002. For the initialization of the LES a day with a strong heating of the surface in the morning hours, the July, 06th, was selected.

This day was the compromise between a complete available data base and the requirements of the simulations. All equipment worked very well, but the energy course was disturbed a short time after sun rise by some thin clouds. However, the LE- simulators decided to use this day for calculations with the aim to reproduce the observed CBL-development by simulation.

During the morning heating phase different observations were carried out: air temperature and wind field using acoustic tomography (ZIEMANN ET AL. 2002, TETZLAFF ET AL., 2002), surface temperature using an IR-camera and vertical profiles of wind and potential air temperature were observed using the Helicopter system HELIPOD (BANGE, ROTH, 1999). Further meteorological observations like mast and radio soundings as a part of the DWD - Lindenberg monitoring programme, were executed. Several systems are used for collecting turbulent heat fluxes (path-integrating laser scintillometer measurements, eddy covariance measurements) which are checked for representativeness regarding to the underlying surface type (bare soil, grassland) using foot print analysis technique (GÖCKEDE ET AL. , 2004, 2005; RAABE ET AL., 2005).

2. PREPARATION OF CALCULATIONS WITH LES-MODEL PALM

2.1 Basics

In the present study the numerical investigation of the development of the non-homogeneously heated ABL is performed using the LES model PALM (RAASCH AND SCHRÖTER, 2001). PALM (for Parallelized LES Model) is specially designed for the use on massively parallel computers. The governing equations and the parameterization basics have been described in detail by RAASCH and ETLING (1991, 1998). In its current parallelized version the model is described by RAASCH and SCHRÖTER (2001). PALM has meanwhile been used in several boundary layer studies with regard to inhomogeneous surface conditions (e.g., RAASCH and HARBUSCH, 2001, WEINBRECHT and RAASCH, 2001, LETZEL and RAASCH, 2003).

2.2 Model setup

2.2.1. General setup

To investigate the influence of surface (thermal) inhomogeneity on the structure and the evolution of the convective boundary layer a striking signal of the different types of land use must appear. The requirement would be an intensive developing CBL over dry bare soil (after sunrise developing high surface temperatures and high sensible heat fluxes), surrounded by grass (much more evaporation, after sunrise the development of surface temperature and the resulting heat fluxes are reduced in comparison to bare soil).
In order to avoid influences of the known shortcomings of the sub grid-scale model, which is used in PALM in the near surface region the comparison has to be limited to those regions where the sub grid-scale turbulence within the model is small compared with the resolved scale turbulence. This is the case at about the forth or fifth grid level and above (WEINBRECHT ET AL., 2003).

As for technical reasons and for comparison with point observations at standard height the measurement height of the acoustic tomography during the STINHO-II experiment was about 2 m above the surface. A very high model resolution was required to comply with the conditions of the simulation results at the investigation height being mostly independent of the subgrid-scale model. As a compromise between a model resolution as high as possible and available computational recourses, a grid spacing of 0.5 m in the vertical and 0.75 m in both horizontal direction has been used.

To simulate a CBL the model domain must include the complete boundary layer in the vertical and several convective structures in the horizontal directions. As a high model resolution will be necessary, the boundary layer height and the diameter of convective cells should be relatively small in order to save computational resources. Thus it was decided to restrict the simulation period to the early morning hours, when the CBL is only 50-300 m deep. The horizontal area has been set to 575 m x 575 m and the vertical direction uses a variable grid size above 360 m height. This results in 768^3 grid points.

2.2.2 Mean vertical profiles of temperature and velocity

The data, which should be used to initialize and to control the LES are taken from the STINHO-database (ARNOLD ET AL., 2002). The period between 5:30 UTC and 6:40 UTC of the July, 06th 2002 fulfils the prerequisites which had to be considered.
For the initialization the following parameters were used:

- Typical (spatially and temporally representative) vertical profile of potential temperature and wind speed before sunrise (Tab. 1) with a southerly geostrophic wind of 3.5 m/s.
- An adapted time dependent turbulent sensible heat flux over the two types of surface (Tab. 3, bare soil, grassland, fig. 4).

Tab. 1: The vertical profiles (sampling points) of potential temperature and wind speed used for LES initialization. The LES technique uses a linear interpolation between the layers.

Height	*Z (m)*	*0*	*50*	*75*	*100*	*150*	*200*	*300*	*500*
Pot.Temp.	$\theta(K)$	*288*	*288*	*289*	*290*	*291,5*	*293*	*293,5*	
Wind speed	$\boldsymbol{v}$*(m/s)*	*0*		*7*	*7*			*5*	*3,5*

The available measurements of wind and temperature profiles are used to initialise the LES under the restriction that these profiles represent the general vertical structure of the atmosphere during the entire simulation period. The vertical profile of the potential temperature at 5:00 UTC is characterized by a neutral layer of 50 m thickness near the ground a strongly stable stratified layer ($\gamma = 2.93$ K/100 m, Tab. 2) up to about 200 m and $\gamma = 1$ K/100 m above. As shown by RAABE, ET AL. (2005) the vertical wind profile is characterized by a low level jet with a maximum of about 7 m/s in 80-90 m height, an additional challenge for LES initialization. These profiles have been transferred as horizontally homogeneous to the LES simulation area at the starting time of the numerical calculation.

2.2.3 Estimation of the turbulent surface heat flux

For detailed investigations, e.g. to study the influence of surface non-homogeneities on the structure and the evolution of the CBL, the large eddy simulation must be provided in a way to ensure for a good correspondence between observed and the numerically calculated data.
The development of a CBL after sunrise is characterized by an time dependent increase of sensible surface heat flux $H_0(t)$. The result is an increase of the height if the CBL $z_i(t)$ accompanied by an increase of the potential air temperature $\theta_0(t)$ near the surface or averaged within the complete CBL $\overline{\theta}(t)$ influenced by a gradient (stable stratification) of the potential air temperature $\gamma = \frac{\partial\theta}{\partial z}$ above the height of the CBL. The first time of the development of a CBL after sun rise can approximated as an linear increase of (kinematic) heatflux $\gamma_H = \frac{\partial H_0}{\partial t}$, mixing height $\gamma_{z_i} = \frac{\partial z_i}{\partial t}$ and potential air temperature $\gamma_\theta = \frac{d\overline{\theta}}{dt}$. These

parameters characterize the averaged values for the CBL. The simplest model to describe the interaction of these 3 parameters is used here to control the plausibility of the observed data with the restriction to estimate the maximum of CBL heights (s. Stull, 1988):

$$\frac{\partial z_i}{\partial t} = \frac{H_0 - H_{z_i}}{\gamma \cdot z_i} \quad \text{and} \quad \frac{d\overline{\theta}}{dt} = \frac{H_0 - H_{z_i}}{z_i} \tag{1}$$

More detailed models, e.g. Deardorff (1974), include a parameterized entrainment at the top of the CBL H_{z_i} and the influence of coriolis force which only reduces the estimated boundary layer heights especially at times fare from sunrise. This simple linear concept (eq. (1)) is successfully used by J. BANGE ET AL. (2006) to generalize the results of different days of HELIPOD-observations.

If the variability of the surface heat fluxes after sun rise (t_0=0) is approximated as a linear function $H_0(t) - H_0(t_0) = \gamma_H \cdot t$ and if $H_{z_i} = 0$ the integration of eq. (1) is:

$$z_i - z_i(t_0) = \left(\frac{\gamma_H}{\gamma}\right)^{1/2} \cdot t \quad \text{and} \quad \gamma_{zi} = \left(\frac{\gamma_H}{\gamma}\right)^{1/2} \tag{2}$$

That means that the increase of CBL is forced by the heat flux and damped by the (stable) stratification outside of the CBL.

Further the change of the averaged potential air temperature inside the CBL can be described as: $\overline{\theta}(t) - \overline{\theta}(t_0) = \gamma_\theta \cdot t$ which leads to (using $z_i(t_0) = 0$ and $H_0(t_0) = 0$)

$$\gamma_\theta = \frac{d\overline{\theta}}{dt} = \frac{\gamma_H}{\gamma_{z_i}} \tag{3a}$$

and $\gamma_\theta = (\gamma \cdot \gamma_H)^{1/2}$. (3b)

The increase of the averaged potential temperature inside of the CBL depends on a large amount of heat flux enclosed in a flat CBL, or, if the stability of the air mass outside of the CBL is high and the heat flux as the near surface energy input is high, than the air temperature inside of the CBL increase very quickly.

These simple approximations (eq. 2, 3) could also be used to calculate the gradient γ from the observed values of, γ_H, γ_{z_i} and γ_θ:

$$\gamma = \gamma_H \cdot (\gamma_{z_i})^{-2} \qquad \gamma = \gamma_\theta^{\ 2} \cdot \gamma_H^{-1} \tag{4}$$

and vice versa the linear time-variability of the heat flux γ_H using observed values of $\gamma_\theta, \gamma_{z_i}, \gamma$:

$$\gamma_H = \gamma_\theta^{\ 2} \cdot \gamma^{-1} \qquad \gamma_H = \gamma \cdot \gamma_{z_i}^2 \qquad \gamma_H = \gamma_\theta \cdot \gamma_{z_i} \tag{5}$$

The experimentally determined values of these linear functions are shown in Tab. 2.

The relations (2)-(5) can be used to calculate the different values independently of the observed values. If the conception is closed in itself the observed and analytically determined values must agree. The variability of these calculations is marked in Fig. 2 to 4 in comparison with observations during STINHO-II (see RAABE ET AL. 2005). In addition table 2 contains the detailed results of the different sensible heat flux observations above grassland and bare soil.

Tab.2: Results of the vertical profiling (HELIPOD (HEL) and DWD radiosonde (RASO)) and the ground based observations during STINHO-II on July, 06^th^,2002: Development of the CBL-parameter after sunrise approximated as linear functions.

gradient of potential air temperature (K) up to 300 m	$\theta(z) = \theta(z=0) + \gamma \cdot z$		
	$\theta(z=0)$	$\gamma \quad (K \cdot m^{-1})$	Average
5:00-5:30 HELIPOD	287,8	0,0248	
4:30 RASO DWD	289,4	0,0236	0,024
Increase of CBL-Height (m) 5:00 – 9:00 UTC(0s – 14400s)	$z_i(t) = z_i(t=0) + \gamma_{z_i} \cdot t$		
	$z_i(t=0)$	$\gamma_{z_i} \quad (m \cdot s^{-1})$	
DWD	-15	0,0389	
HELIPOD	23	0,0518	
Increase of kinematic heat flux (K m/s) 5:00 – 12:00 UTC (0s – 25200s)	$\overline{H}(t) = \overline{H}(t=0) + \gamma_H \cdot t$,		
	$\overline{H}(t=0)$	$\gamma_H \quad (K \cdot m \cdot s^{-2})$	
bare soil	$2{,}08\ 10^{-2}$	$6{,}83\ 10^{-6}$	
grassland	$0{,}50\ 10^{-2}$	$3{,}92\ 10^{-6}$	
Increase of near surface temperature (K) 5:00 – 10:00 UTC (0s – 18000s)	$\overline{\theta}(t) = \overline{\theta}(t=0) + \gamma_\theta \cdot t$		
	$\overline{\theta}(t=0)$	$\gamma_\theta \quad (K \cdot s^{-1})$	
average $\overline{\theta}(t)$	288	0,0006	

The calculated and the observed courses do not agree very well. This inconsistency of the observed and calculated relations makes the following interpretation necessary:

Provide that this simple model describes partly the physics of the increasing CBL in the morning hours there is only one possibility to get an agreement between observed and calculated heights of CBL as well as the observed increase of air temperature: The turbulent heat fluxes must be much higher – that means the locally observed value of γ_H is to low (see Fig. 4). The influence of γ could not be the reason, because a decrease of γ is followed by an (observed) increase of γ_{z_i} but by a (not observed) decrease of γ_θ.

The consequence of this investigation is: The locally observed value of the turbulent heat flux is too low to explain the observed time-dependent increase of the boundary layer height using such an analytical model (Fig. 4). Also possible – the CBL-heights obtained using the observed data do not fit to the theory.

2.2.4 Sensible heat flux and the unclosed energy balance

However, it cannot be expected that the LES can reproduce the observations if using a false energy input. Hence, it is not easy to decide which near-surface sensible heat flux is necessary in order to reproduce the time-dependent increase of such a boundary layer height.

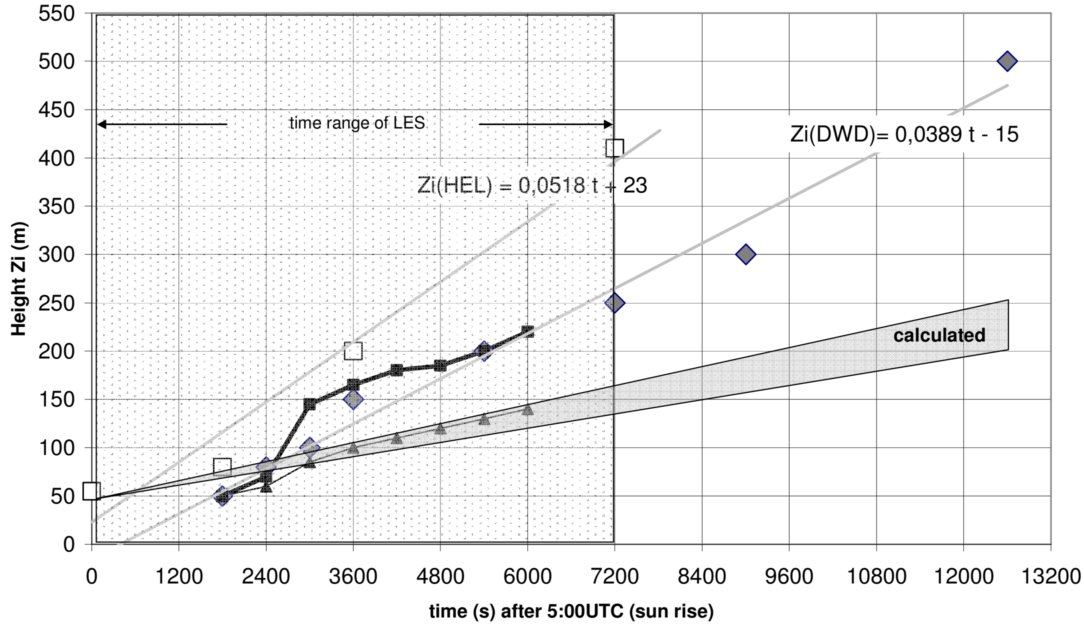

Fig. 2: Comparison of the observed and calculated CBL heights on July 06th, 2002 between 05:00 UTC (0 s) and 08:40 UTC (13200 s) resulting from the HELIPOD (HEL) and operational meteorological measurements (DWD). The range of calculations represents the resulting CBL-heights using the minimum and maximum values of the observed gradients γ_H and the average of γ (Tab. 1, eq. 5). The observed heights of CBL exceed the calculations (Eq. (2)) significant. Black triangles and black rectangles: CBL-heights taking from LES model using different methods (see. 3.1)

This difficulty is amplified because it is evidently not easy to measure the turbulent heat fluxes over the different surfaces with the necessary accuracy (MAUDER ET AL. 2006).

In the present case this can be shown analysing the experimentally observed energy balance. Theoretically, at a homogeneous surface the incoming flux of radiation (net radiation R_n) and the outgoing fluxes (ground heat flux G, turbulent sensible H and latent LE heat flux) must sum up to zero take into consideration the individual errors δ of measurement (eq. (6)). As a consequence of the non-homogeneous experimental conditions the observed sum of these components of the energy balance equation is not zero. Within a random error δ of the single components a gap (*D*), or residuum (FOKEN, 2006) or a so called imbalance is observed (see PANIN ET AL., 1998):

$$D \pm \delta = (R_n \pm \delta_{Rn}) + (G \pm \delta_G) + (H \pm \delta_H) + (LE \pm \delta_{LE}) \qquad (6)$$

However the amount of this residuum depends also on the used flux measurement method (FOKEN ET AL., 2006, BEYRICH ET AL., 2006). Independent of such difficulties in methodology in the case of the LES intialization it was necessary to use a larger amount of sensible heat flux as the observed one.

The time-dependent observed values of D are listed in tab. 3, in detail showed by RAABE ET AL. (2005). The accuracy of the imbalance D is calculated using the standard deviation of the sensible heat flux observations of the different systems and the standard deviation of the radiation flux measurements.

The non-homogeneous heating of the surface is reproduced by a horizontal variability of the vertical sensible heat flux (in the present case two types of surfaces). As a first assumption for the LES initialization the observed sensible heat fluxes over grassland as well as over bare soil were raised to the amount of such a part of the heat flux, corresponding to 50% of the gap of the current energy balance.

$$H_{cor} = H_{average} + 0.5 \cdot D \qquad (7)$$

The value of 50% is used here, in order to consider that the observed imbalance could also be an indication for difficulties to observe the true amount of latent heat flux, although MEIJNINGER ET AL. (2006) showed that the gap in the energy balance closure is connected much more with a lack in the latent heat observations. The values H_{cor} are in good agreement with the values used for LES initialization (tab. 3). The time-dependent heat flux for LES initialization follows results from the thoughts explained above.

Tab.3: The observed averaged data and the used time-depending variability of sensible heat flux for large eddy simulation.

LES heat flux time depending initialization								
	Sensible heat flux H – average - observed		Imbalance D observed		H_{cor}		**LES heat flux initialization**	
time (UTC)	bare soil W/m²	grass W/m²	bare soil W/m²	grass W/m²	bare soil W/m²	grass W/m²	**bare soil W/m²**	**grass W/m²**
05:00	18±3	7±4	49±9	40±11	43±12	27±15		
05:10	22±7	8±2	63±17		53±24			
05:20	30±5	11±2	59±14		90±19			
05:30	36±7	15±4	74±19	93±13	73±26	62±17	**77**	**55**
05:40	46±9	19±2	83±22		88±31		**98**	**71**
05:50	59±6	21±4	85±14		102±20		**114**	**75**
06:00	38±7	9±4	42±30	52±24	59±37	35±28	**69**	**40**
06:10	27±11	3±5	58±47		56±58		**54**	**30**
06:20	57±17	34±3	129±43		122±60		**106**	**82**
06:30	65±9	25±8	65±30	95±28	98±39	73±38	**143**	**103**
06:40	76±2	25±7	44±18		98±20		**150**	**100**
06:50	60±13	22±7	60±30		90±43		**150**	**100**
07:00	86±7	47±9	88±25	153±29	130±32	123±34	**(150)**	**(100)**

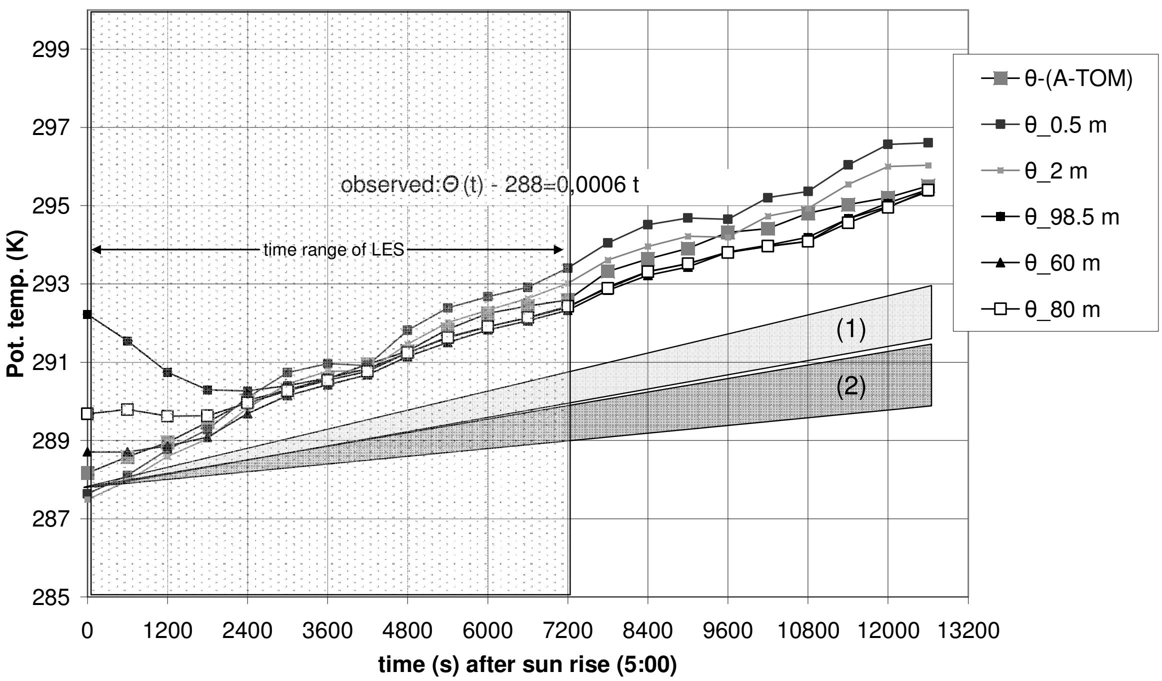

Fig. 3: Increase of the potential air temperature after sunrise on July 06th, 2002 (meteorological mast measurements from 0.5m up to 98.5m height and area-averaged near surface air temperature determined with the A-TOM). The range of analytical calculations results by using the minimum and maximum values of the observe, γ_H, γ_{z_i} and the average of γ (Tab. 2). The calculated time dependent increase of the averaged potential air temperature underestimates the observed one (1: eq. 3a, 2: eq. 3b).

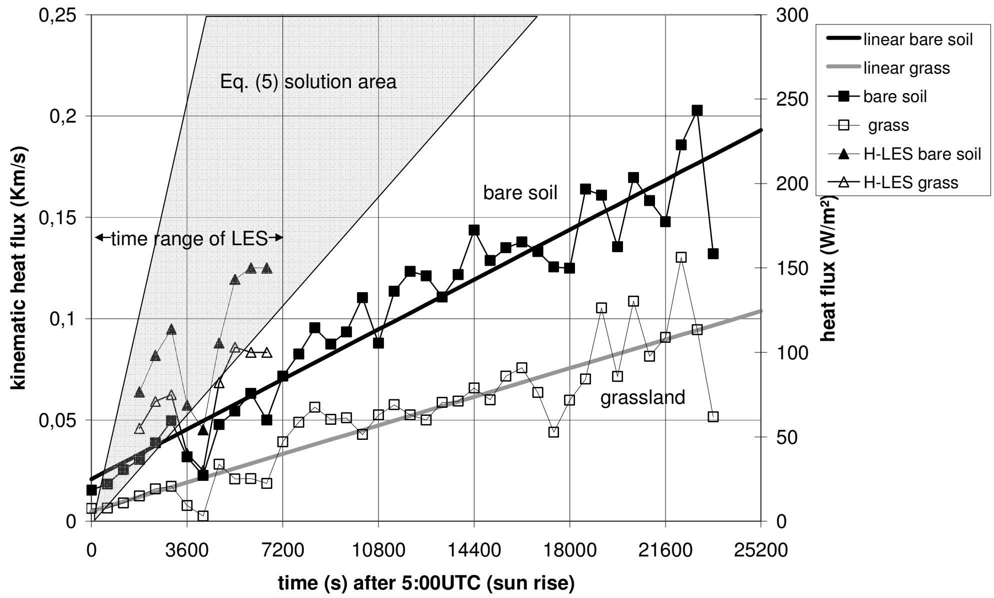

Fig. 4: The evolution of the sensible heat flux on July 06th, 2002 (arithmetic mean) observed with different systems. The linear approximation H(t) (see Tab. 1)is given. The range (grey area) is calculated using observed data and eq. (5). To explain the observed rise of the air temperature as well as the increase of the height of CBL significant higher heat fluxes are necessary. That's why the used values for LES are enlarged (see Tab. 3) by the amount of a partition of virtual heat flux. The resulting values fall into the grey-marked area covered by the relation eq. (5).

3. Comparisons between measurements and LES simulations

3.1. The vertical temperature profile

The LES calculations have been carried out at the IBM Regatta pSeries 690 of the ‚Norddeutscher Verbund für Hoch- und Höchstleistungsrechnen (HLRN)'. Using 128 parallel processes the simulations need 25 CPU days for one hour real time (the averaged time step was around 0.04 s). This explains a little bit, why it was not possible to extend the calculations to a longer time interval, which would be desirable for statistically more substantial conclusions.

A conventional proof of the agreement between LE-Simulation and measurements is the comparison of the observed and calculated development of the temperature profile (Fig. 5). The LES-profiles show the area averaged vertical variability of potential air temperature. The observed profiles represents averages over 10 min time (mast) or individual temperature measurement along a path through the atmosphere using the measurement platform HELIPOD. It is evident, that the simulation can reproduce the development of the vertical structure of the temperature in the morning hours. It is not surprising, that the variability of the measurements is much higher then those of the LES.

The calculated temporal increase of the height of CBL can be read off fig. 5. This height could be found by different points. For example the CBL-height can be defined as the intersection point of the initial profile and the new calculated profile some times later (see fig. 2 black triangles). Also possible: using the point where the new profile the first time deviates from the initial profile. The first method determines lower heights, the second method supplies to values of the CBL mostly identical with the observed values (fig.2 black rectangles).

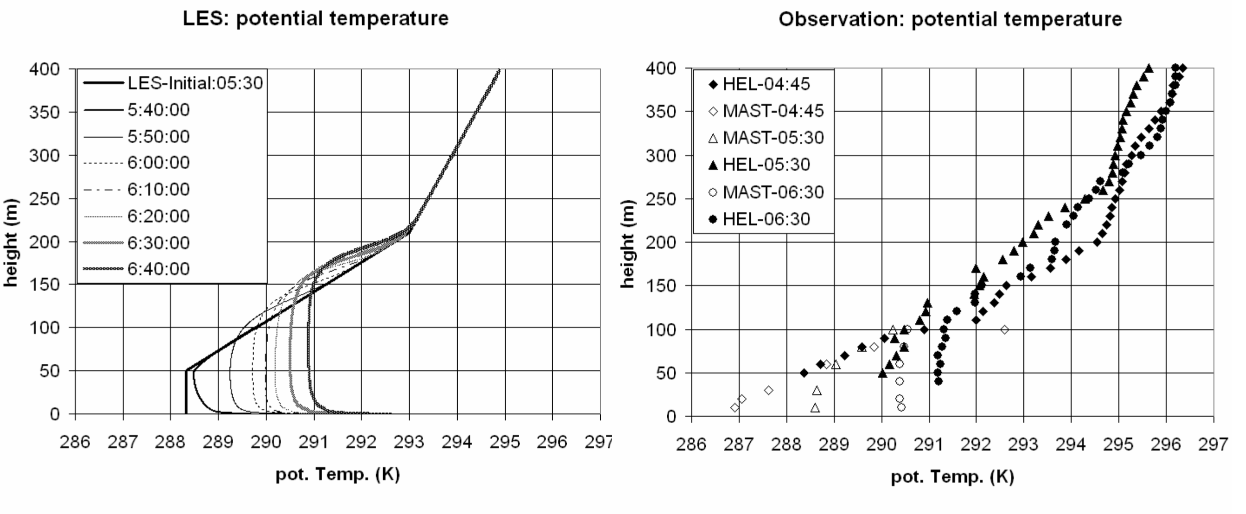

*Fig 5: Observed (DWD-**MAST** measurements and **HEL**IPOD measurements, see RAABE ET AL., 2005) and LES-calculated change of the potential temperature profile after sun rise.*

3.2 The temporal and spatial variable air temperature and wind field

The result of the LE-Simulation is a spatially and temporally variable distribution of wind and air temperature within the modeled area in a given height of the atmosphere. That's

why it was obvious to compare such a simulation with an experimental system which observes the wind and temperature field in a similar way.
Simulated and measured instantaneous wind and temperature fields can not be compared directly because the upwind and downwind areas are randomly distributed inside the homogeneous parts of the convective boundary layer (see WEINBRECHT ET AL., 2004). Therefore, statistical parameters of the meteorological fields were studied.

During STINHO-II the acoustic tomographic system (A-TOM) was used to observe the temperature and wind field within the experimental area. The resulting data sets are similar to the structure of the LES- data. The acoustic tomography observe, e.g. every minute one data set consisting of a record of time in flight of the acoustic signals (around 1s over a distance of around 300m). The A-TOM uses an iterative inverse reconstruction algorithm to conclude from the time in flight values to the data of temperature and wind (dividing the experimental area in single patches of 70m x 70m, means 35 temperature values and grid cells of 145m x 100m, 9 values of regional variable wind, s. RAABE ET AL., 2005). The LE-Simulation was carried out in a voxel grid of 0.75 m x 0.75 m x 0.5 m. This makes a time step for numerical calculations necessary of around 0.04s. To compare the LES with the measurements for every minute one numerically generated temperature or wind field is averaged using 93 x 93 single values for temperature and 196 x 133 values for velocity. From the PALM LES calculations one averaged temperature and wind distribution with the resolution of the A-TOM measurements was taken every 10 s. At least the A-TOM measurement and the LES data are aggregates to 10 min means.

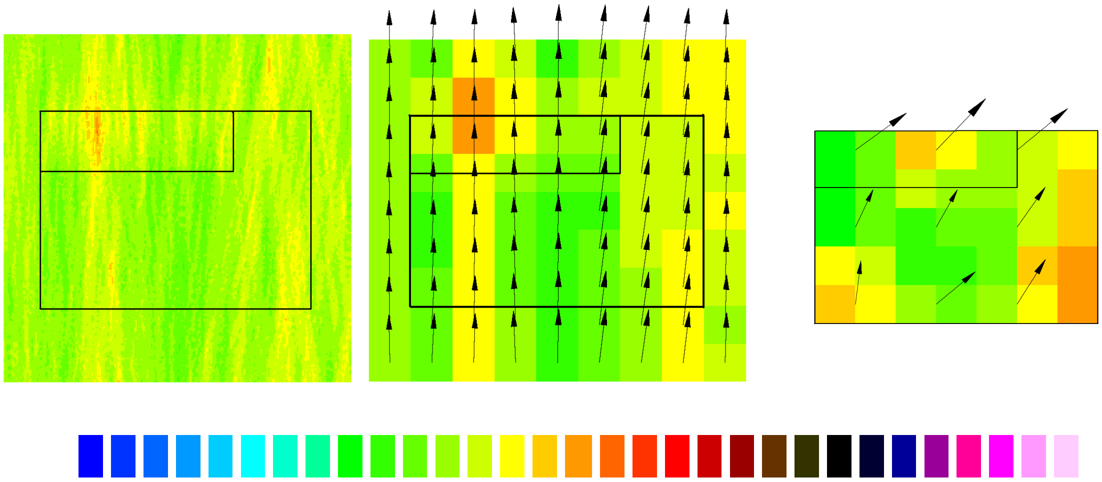

Fig. 6: Horizontal slices through the 10 min mean of the temperature field (instantaneous pictures in deg C, the colour steps are 0.1K, 290K blue - 293K pink) at a height of 2 m above ground on July 06^{th}, 2002 at 06:20-06:30 UTC, simulated with the model PALM (left: original model resolution, middle: model resolution according to tomographic measurements. right: observed in nature by acoustic tomography -10min mean (06:21 .- 06:30UTC).

Fig. 6 shows a 10 minutes average of a highly resolved LES-output. Also the aggregation algorithm is demonstrated. The observed picture obtains the impression of a similar spatial variability.
Due to the turbulent character of the air stream the single, instantaneous simulation and observation are not comparable. The LE-simulation use cyclic boundary conditions, means the landscape is covered with a sequence of similar changes between grass and

bare soil without any topography. Contrary to this behaviour the observations represent the air stream and temperature field above a real, non-reiterated landscape.
Comparing the averaged values for temperature and wind (fig. 7) the correspondence between simulation and experiment is satisfactory, much more for temperature then for wind. Evidently the selection of initialization data was successful.
Considering the variance of the temperature it can be seen, that the course of the calculated values follows closely to the course of the input data (see tab. 3). At the other side, the observed data do not show such a closed relation to the observed variability of the surface heat fluxes during the period of comparison (see fig. 4 and 7).
The LES-variance at the A-TOM- grid size is reduced to small values due to the averaging process, means the spatially variance of the highly resolve large eddy simulation can only be compared with the temporal variance of the A-TOM measurements. This comparison basically uses the Taylor hypothesis of frozen turbulence, which postulates an identity between spatial and temporal averaging.

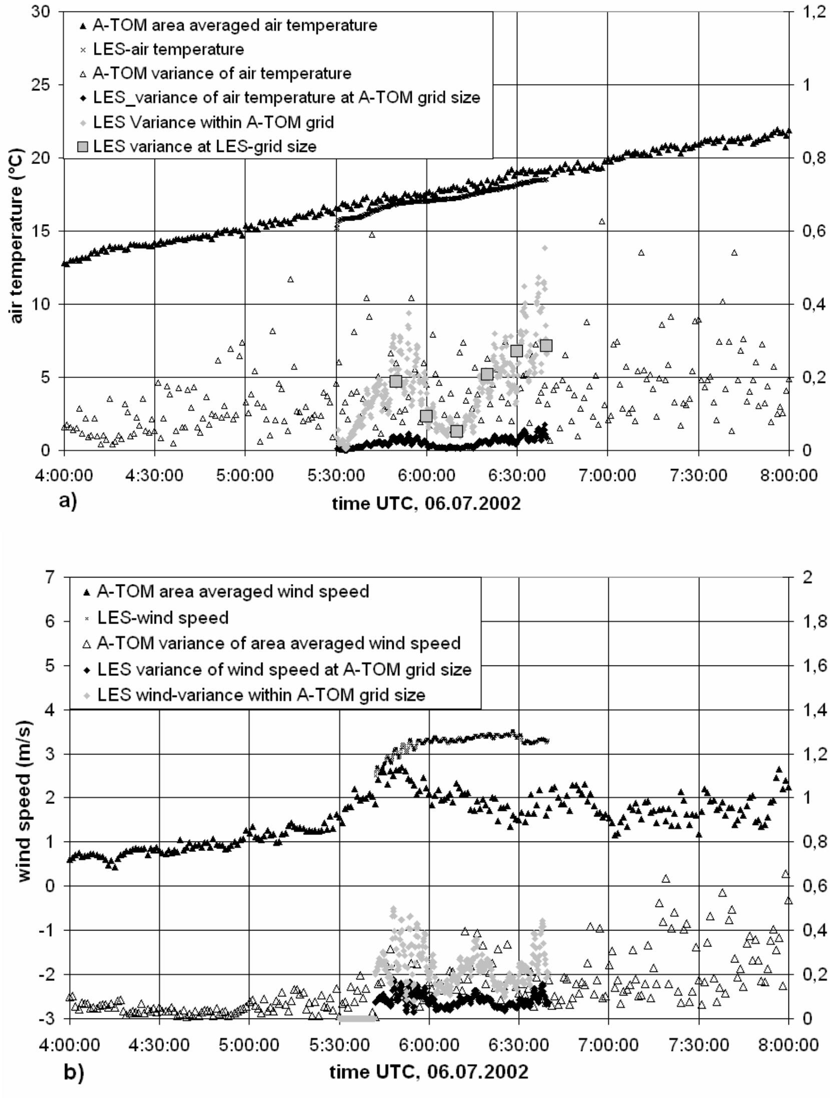

Fig.7: Comparison of averaged temperature (a) and wind speed (b) and their variances between the acoustic tomography (A-TOM) measurements and the LES. The grey symbols are calculated assuming a linear increase of the variance to compensate the numerical reduction of the values of variance by the spatial averaging effect.

4. Discussion

The STINHO project was performed to investigate the energy transfer within the atmospheric boundary layer under inhomogeneous surface conditions at the micro-α scale, especially to adapt a LES model to a real landscape.

In order to identify the signal from inhomogeneous heating clearly, the observations were performed close to the surface and around the borders between two fields of different surface properties. The resulting differences in the observed vertical turbulent heat fluxes between neighbouring surfaces are significant and much larger then measurement errors. At the other side, the observed differences in the air temperature field at a height of 2 m over different land uses are negligible, at least taking in account the accuracy of the measurements of wind speed and temperature. Significant 'inhomogeneous' signals are not visible neither in measurements nor in the simulations (RAABE ET AL., 2004).

The STINHO project has provide a data set to initialise a LES model. However, it was shown here which difficulties arise if experimental data are used for initialization. If one wishes to reproduce the increase of the observed temperature inside of the CBL as well as the increase of the convective boundary layer height correctly by the simulations, the observed values of the near-surface micro-scale sensible heat flux (necessary für LES initialization) are too small. The necessary larger amount of sensible heat for the LE simulations is taken here from the observed unclosed energy balance. Such deficiency in the energy balance observations mostly results from measurement techniques (FOKEN ET AL. 2006) or it is connected with the spatial and temporal structure to adapt point measurements to an area in a real landscape over flat, homogeneous surfaces and short vegetation (e.g., STANNARD ET AL., 1994; PANIN ET AL., 1998, MAHRT, 1998; TWINE ET AL., 2000; WILSON ET AL., 2002, BEYRICH ET AL. 2006,)

However, the 3D-LES model needs the total amount of available turbulent sensible heat to calculate a comparably structure of the CBL and not only this portion which was observed by small scale measurements. In general - the LES calculations follow nearby the time variable pre-determinations (especially for the temperature field).

Even with largest time and effort the comparison of the LES output with the described observations (acoustic tomography) is only qualitatively possible. This was already shown by WEINBRECHT,ET AL. (2004) for homogeneous surface conditions and this result must extended also to the present case of inhomogeneous heating.

The reason lies in the complex structure of a turbulent air stream and of the observation technique (acoustic tomography) as well as in the numerical technique (LES). Both techniques reproduce only a part (different parts) of the whole spectrum of turbulence. In the result a quantitative comparison of observations and calculations is impossible.

Subsequent projects, comparing turbulence structure simulations and area covering observations of turbulent fields must pay more attention to an adequate and adapted measurement and simulation algorithm – both methods must be able to reproduce the identical parts of the spectrum of turbulence.

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