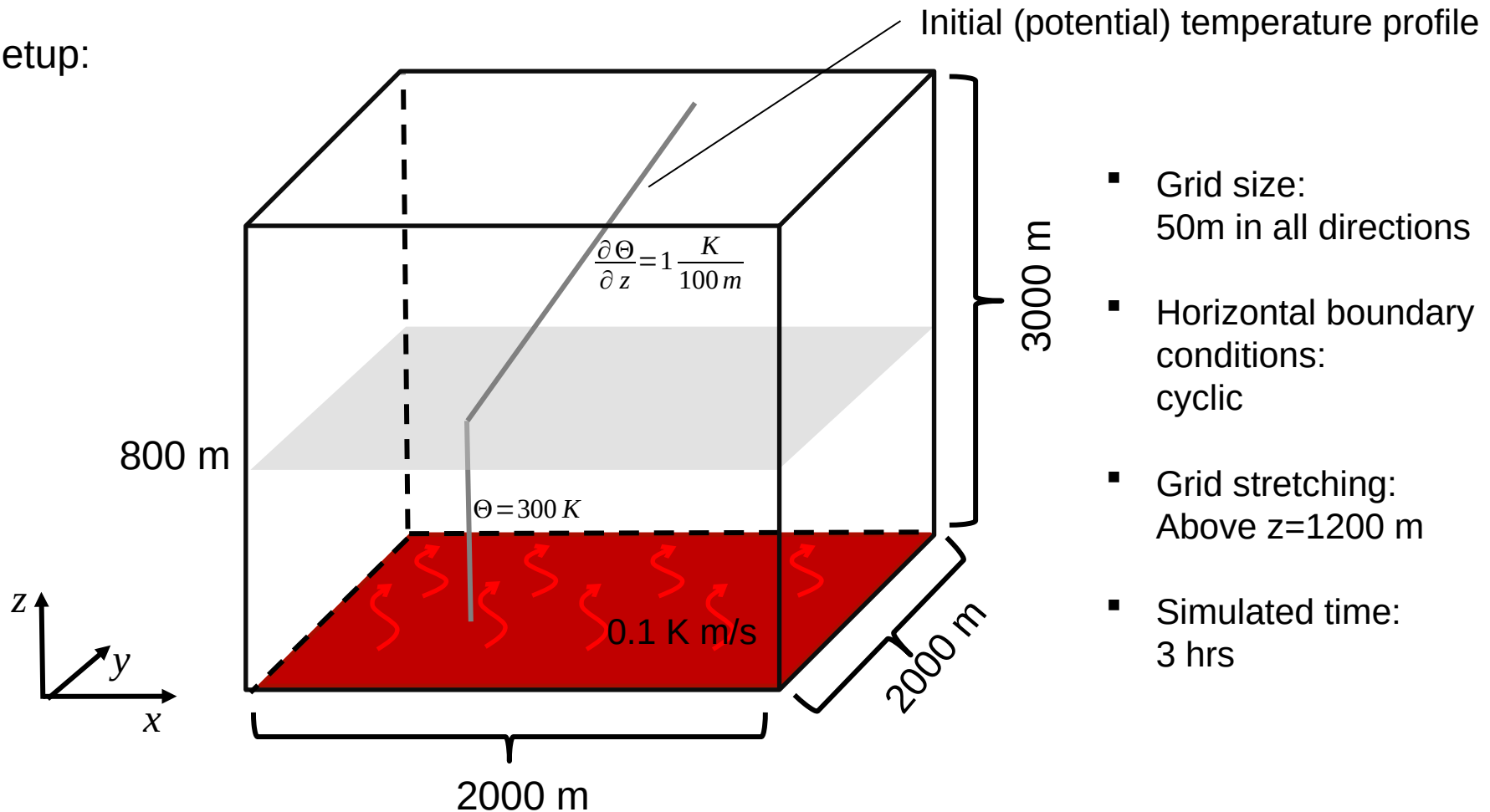# E1: Convective boundary layer

Institute of Meteorology and Climatology, Leibniz Universität Hannover

Task

In this exercise a convective boundary layer (CBL) above a homogeneously heated surface shall be simulated.

Setup:

Initial (potential) temperature profile

$$\frac{\partial \Theta}{\partial z} = 1 \frac{K}{100\,m}$$

3000 m

800 m

$\Theta = 300\,K$

0.1 K m/s

2000 m

2000 m

z

y

x

- Grid size:
  50m in all directions

- Horizontal boundary conditions:
  cyclic

- Grid stretching:
  Above z=1200 m

- Simulated time:
  3 hrs

palmgroup

Questions to be answered

- How would you characterize the 3d-temperature field after 3 hours of simulated time? And how does the 3d-flow field physically correlate to that?

- Explain the temporal evolution of the horizontally & temporally averaged vertical profiles of various quantities ($u, v, w, \Theta, \overline{u'^2}, \overline{v'^2}, \overline{w'^2}, \overline{w'^3}, \overline{\Theta'^2}, \overline{w'\Theta'}$), and how these quantities relate to each other.

- Is it really a large-eddy simulation, i.e., are the subgrid-scale fluxes much smaller than the resolved-scale fluxes? How long should the averaging time interval be?

- Explain the temporal evolution of the time-series of the total kinetic energy and how the maximum velocity components change in time? Has the flow become stationary? What happens during the first 30 minutes, and why?

- Has the domain size and grid size been chosen appropriately? Does the flow pattern changes if you double the horizontal domain size?

Hints – Model steering

Important PALM steering parameters for this exercise:

- **Domain size**
  - grid size **dx, dy, dz**
  - number of grid points **nx, ny, nz**
    Please note: **nx, ny, nz+1** define the index of the last grid point. Since numbering of grid points start with index 0, the total number of grid points used are actually **nx+1, ny+1, nz+2**. In case of cyclic boundary conditions, the domain size (along x) is **(nx+1)*dx**! The top boundary for u, v and scalar quantities is at k = **nz**+1 while at k = **nz** for w.

- **Initial profiles**
  - Use **pt_surface**, **pt_vertical_gradient** and **pt_vertical_gradient_level** to create the initial temperature profile.

- **Boundary conditions**
  - For heat flux, see **surface_heatflux**.
  - Prescribing of heat flux at bottom boundary requires a Neumann boundary condition for temperature, see **bc_pt_b**.

- **Simulation time**
  - See parameter **end_time**.

└─ **Hints – Data output**

- **Output Variables**

  - Choose the output variable with `data_output` for 3d-data, 2d-cross-sections and `data_output_pr` for profiles.

  - Positions of cross sections (grid points):
    `section_xy, section_xz, section_yz`

- **Output intervals**

  - `dt_data_output` effects all output quantities

  - Individual temporal intervals for the different output classes can be assigned by parameters `dt_do3d`, `dt_do2d_xy`, `dt_do2d_xz`, `dt_do2d_yz`, `dt_dopr`, etc.

- **Time averaging**

  - `averaging_interval`, `averaging_interval_pr`, `dt_averaging_input`, `dt_averaging_input_pr`.

- Visit: http://palm.muk.uni-hannover.de/trac/wiki/doc/app/
  Column "Model Setup" provides links to all Namelist parameters.

Please note: Most parameters exhibit standard (default) values which will be used, when the parameter is not given in the parameter file! However, the default value might not fit to the desired setup. So, be aware about the default values!

How to start?

- Choose an appropriate run identifier: **e1_cbl**

- Create a data folder for this new run:

    - **cd ~/palm/current_version**
    - **mkdir -p JOBS/e1_cbl/INPUT**

- Create the Namelist parameter file **e1_cbl_p3d** using a text editor of your choice, set the required parameters in this file, and place it under

    - **JOBS/e1_cbl/INPUT/**

- Start the run with palmrun-command (from directory ~/palm/current_version)

    - **palmrun -r e1_cbl –a "d3#" -X ...**

- After the run has finished, analyze the output files located in:

    - **JOBS/e1_cbl/OUTPUT**

The good news is:
We prepared already the parameter file for all exercises for you, but you still have to edit some positions marked with "?" ! You can find the file in the seafile system in the Monday "Exercises" folder in "E-1_Convective_boundary_layer_steering_files".

Hints – Data visualization

Example single-line commands for **palmplot** to create the plots for this exercise (see presentation „Data visualization" on how to use **palmplot**):

- **xy-cross-sections** (here from a 3D-data-file)

  - of temperature and vertical velocity:
    ```
    palmplot xy file_1=e1_cbl_3d.000.nc var='theta w' format_out=pdf
    file_out='e1_cbl_xy' start_time_step=3 end_time_step=3 zs=2 ze=10
    ```

  - or additionally with overlayed wind vectors over theta-field:
    ```
    palmplot xy file_1=e1_cbl_3d.000.nc var='theta w' format_out=pdf
    file_out='e1_cbl_xy_vec' start_time_step=3 end_time_step=3 zs=2 ze=10
    vector=1 plotvec='theta' vec1=u vec2=v ref_mag=1
    ```

- **profiles**

  - of temperature and heat flux:
    ```
    palmplot pr file_1=e1_cbl_pr.000.nc var='theta wtheta' format_out=pdf
    file_out='e1_cbl_pr' start_time_step=0 end_time_step=3
    ```

  - of resolved, subgrid-scale and total heat flux within one frame:
    ```
    palmplot pr file_1=e1_cbl_pr.000.nc format_out=pdf
    file_out='e1_cbl_pr_com' start_time_step=0 end_time_step=3 combine=1
    number_comb=3 var='wtheta w*theta* w"theta"' c_var='wtheta w*theta*
    w"theta"'
    ```

Hints – Data visualization

- **time series**
  ```
  palmplot ts file_1=e1_cbl_ts.000.nc format_out=pdf file_out='e1_cbl_ts'
  no_rows=6
  ```

Do not copy commands from files to the terminal. Otherwise, strange errors might occur.

The following figures (also of the upcoming exercises) might be generated with a different PALM version and/or better resolution. Therefore, do not wonder if your results will not look exactly the same. However, the following discussion must be applicable also to your results.
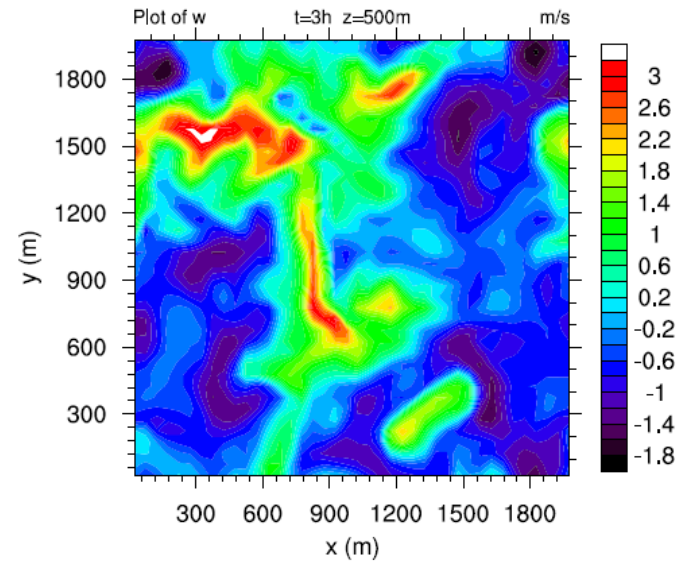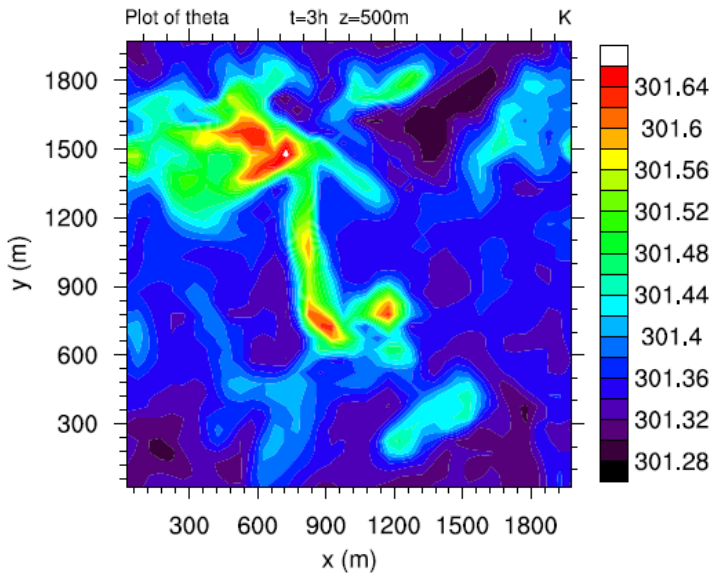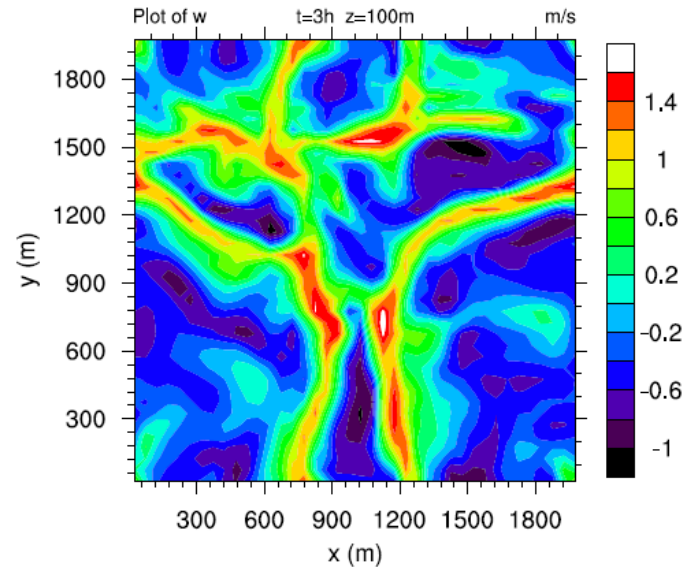
Documentation palmplot:
https://palm.muk.uni-hannover.de/trac/wiki/doc/app/nclparlist

GOOD LUCK!

Results – XY Cross Sections

palmgroup
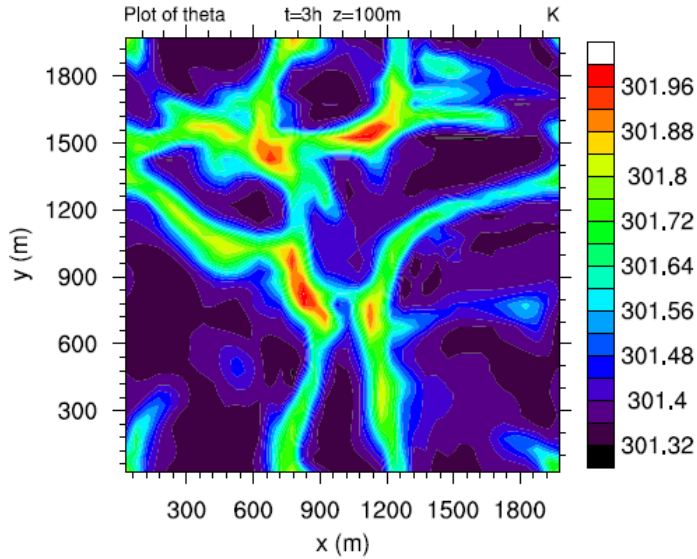
Answers to question (1)

How would you characterize the temperature field after 3 hours of simulated time? And how does the flow field physically correlate to that?

- Useful output: e.g. instantaneous cross-sections of potential temperature and vertical velocity, streamlines of horizontal wind field.

See slide 9:
- Temperature and w-velocity fields show a cellular pattern close to the heated surface; at larger heights, this pattern is less pronounced and disappears.

- Downdrafts in the inner part of the cell transport relatively cooler air from aloft towards the surface which then spreads towards the cell edges and heats up.

- Updrafts or warm air develop above the cell edges. Convective plumes rise from the edges up to the boundary-layer top.

- Strongest updrafts are found above the near-surface cell vertices in a height of about half of the boundary layer and above.

Results – Streamlines and XZ Cross Section
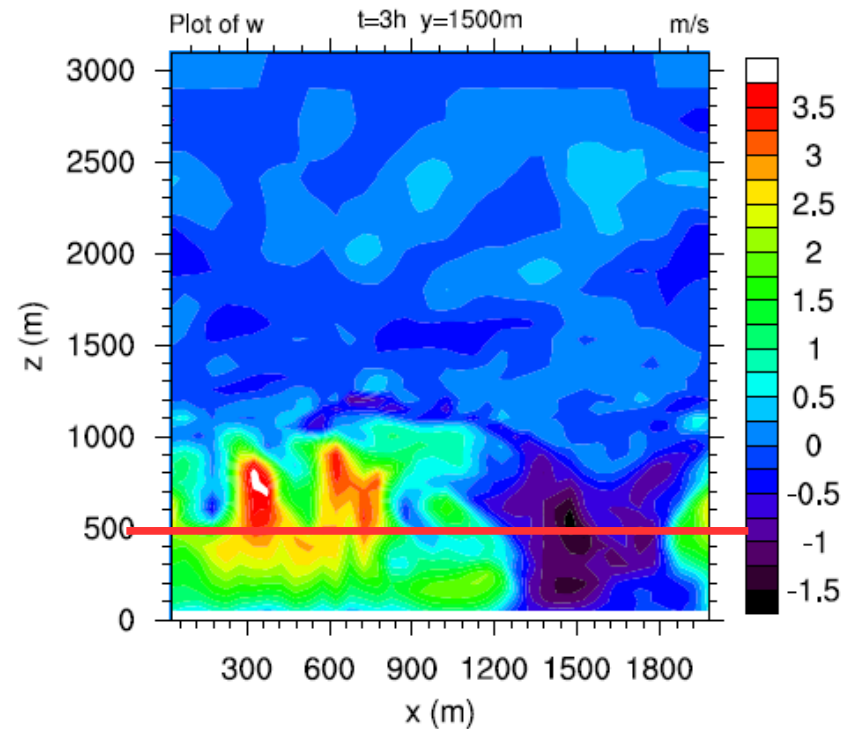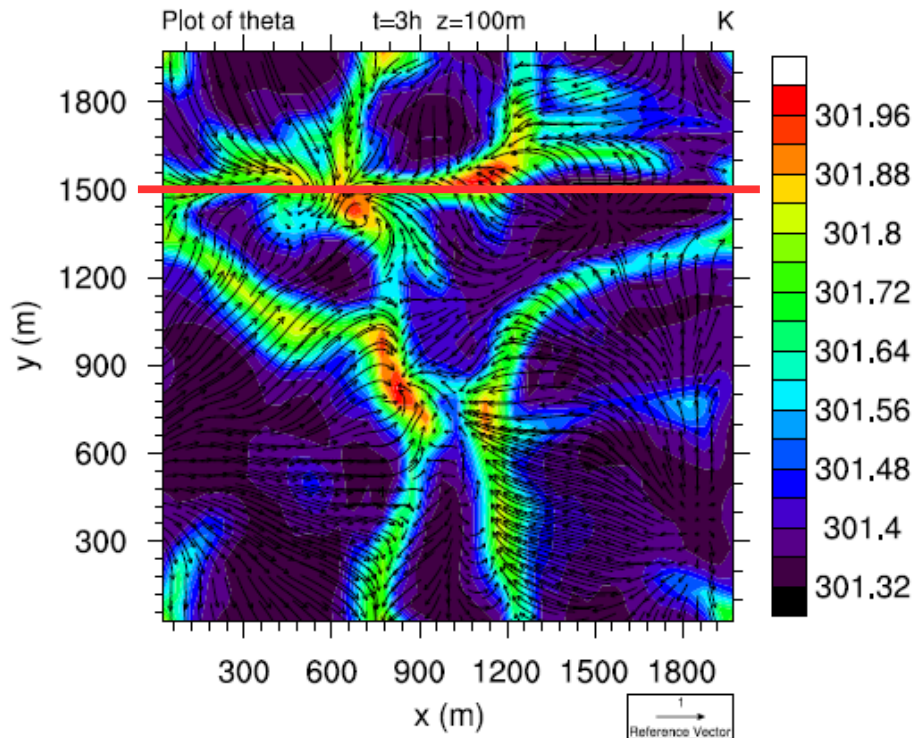
Answers to question (1)

See slide 11:

- Streamlines indicate horizontal flow convergence in regions with warmer air (cell edges), and even some vortices appear especially at cell vertices, where flow converges from the different directions into the nodal point. Furthermore, flow divergence appears from the cell centers towards the edges.

- Vertical cross-section of w shows convective plumes and downdrafts of cooler air; downdrafts are typically wider than updrafts, and updraft velocities are larger than downdraft velocities.

Results – Vertical Profiles I
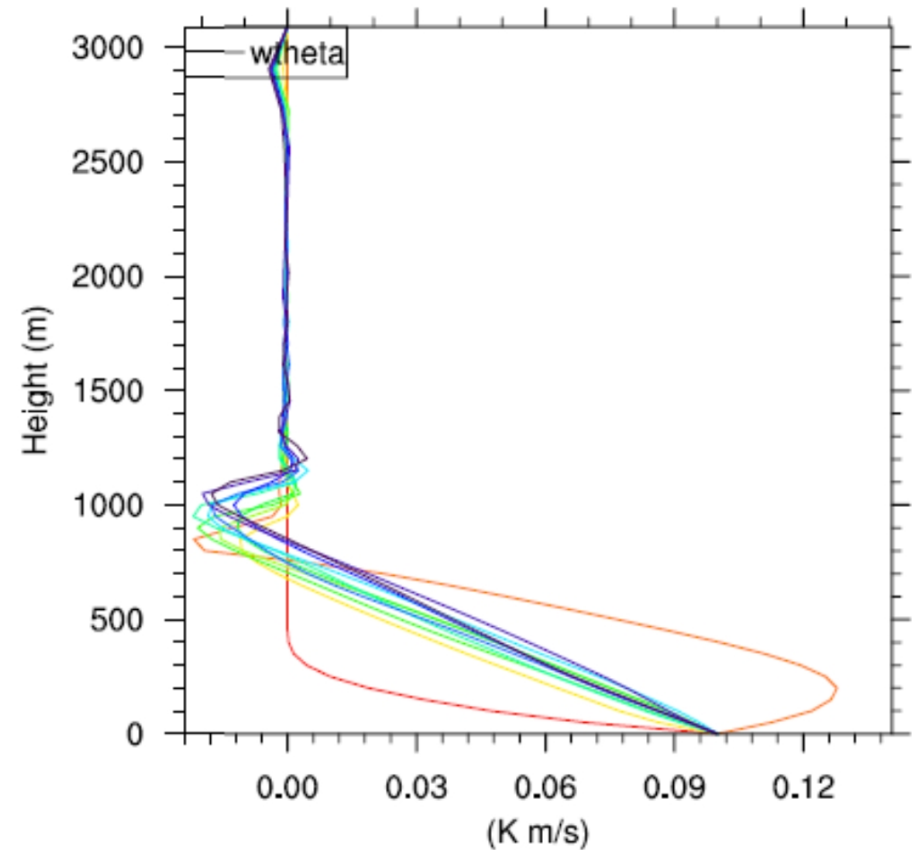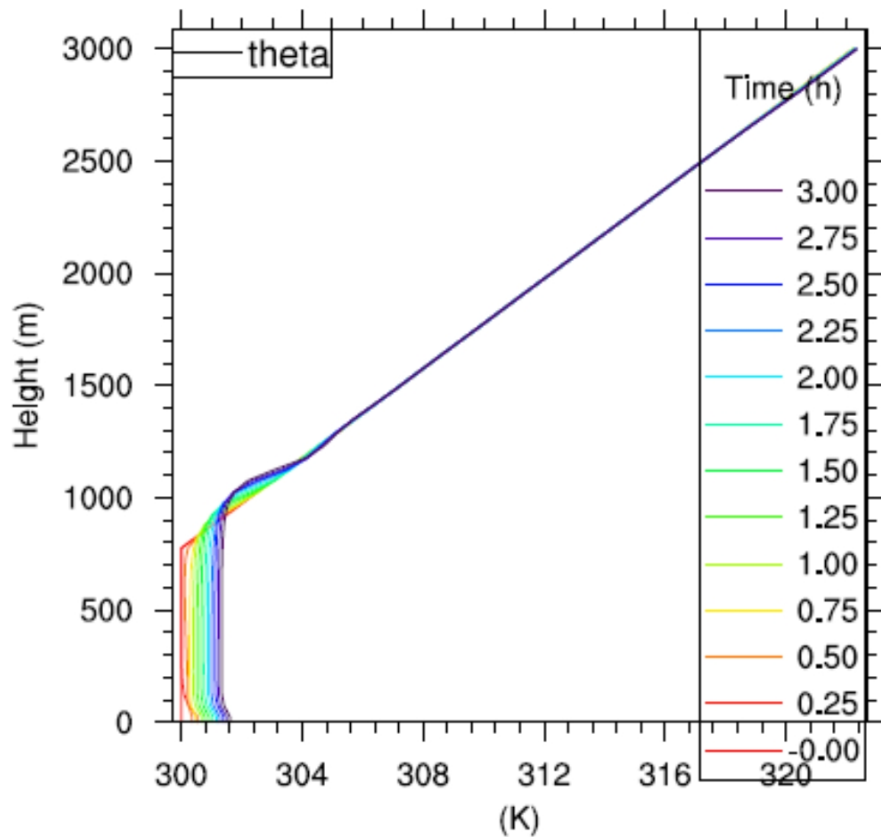
Answers to question (2)

Explain the temporal evolution of the horizontally & temporally averaged vertical profiles of various quantities ($u, v, w, \Theta, \overline{u'^2}, \overline{v'^2}, \overline{w'^2}, \overline{w'^3}, \overline{\Theta'^2}, \overline{w'\Theta'}$), and how these quantities relate to each other.

See slide 13 (left):

- Heating of the surface induces convection, resulting in a well-mixed boundary layer, where the potential temperature profile is constant with height throughout the bulk of the layer. Near the heated surface, vertical temperature gradients remain, since convective turbulence cannot remove them in the vicinity of the wall.

- During the temporal evolution, the boundary layer continuously warms up, hence the temperature profiles shift to the right, mainly maintaining the shape of the profile (quasi-stationary).

- At the boundary-layer top, the evolution of the profiles indicates that the inversion layer is cooled, which is due to mixing of cooler boundary-layer air into the inversion, and simultaneous mixing of warmer inversion air into the boundary layer. This process, called entrainment, promotes the growth of the boundary layer, in addition to the surface heating (encroachment).

Answers to question (2)

See slide 13 (right):

- The evolution of the temperature profiles can be explained by the heat-flux profiles:

  - Assuming horizontal homogeneity in the present case, the temperature equation reduces to

 $$\frac{\partial \theta}{\partial t} = -\frac{\partial \langle w\theta \rangle}{\partial z}$$

  - In a quasi-stationary state

    $$\frac{\partial \theta}{\partial t} \sim \text{const.}$$

    independent from z throughout the bulk of the boundary layer.

  - This explains the linearly-decreasing shape of the profile within the boundary layer.

  - The total turbulent vertical heat flux is positive within the boundary layer indicating upward transport of warmer air parcels and downward transport of colder air parcels.

  - In the inversion layer, where entrainment was identified by means of the temperature profile, the turbulent heat flux is negative, indicating upward transport of colder air parcels and downward transport of warmer air parcels. The different signs of the slope indicate heating of the lower part of the inversion and cooling of the upper part.

Results – Vertical Profiles II
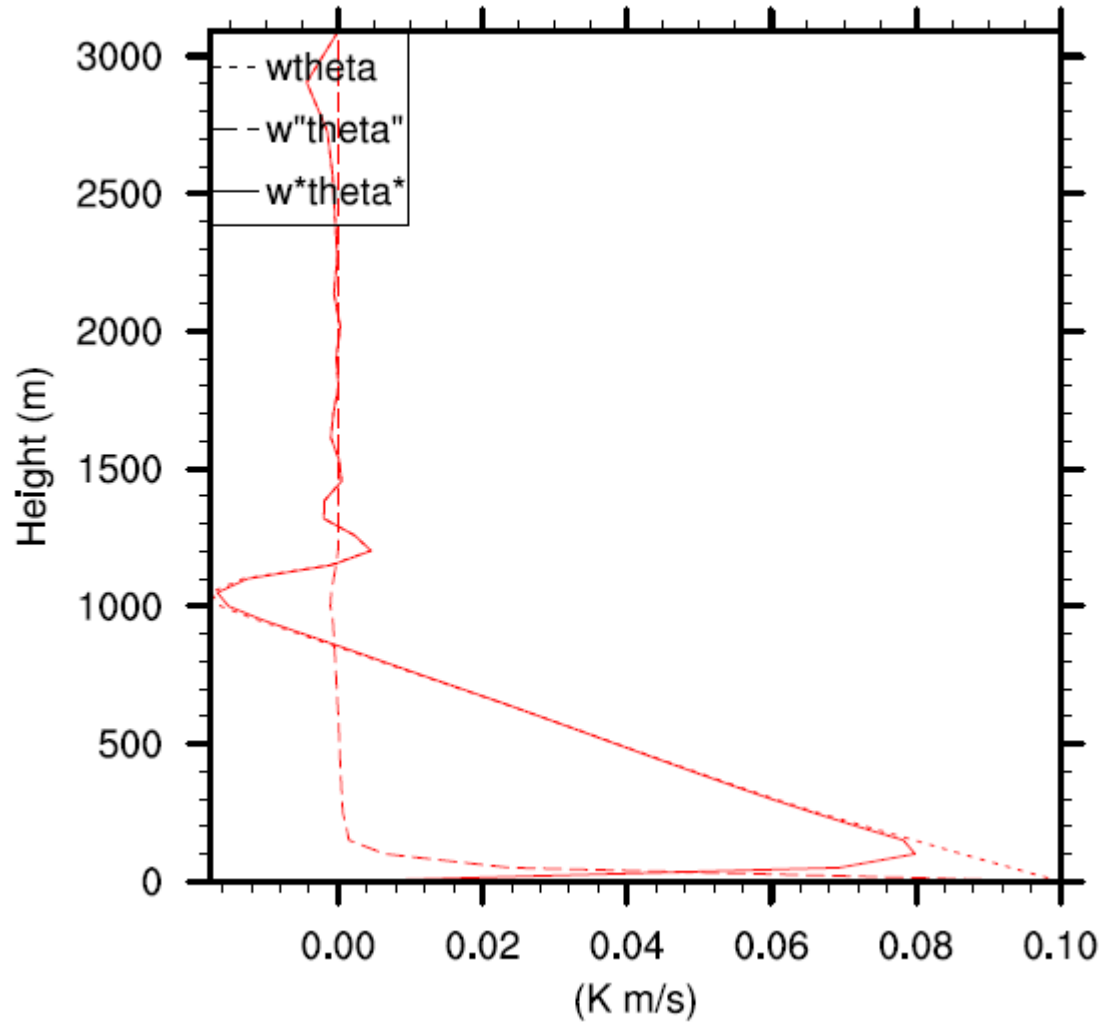
Answers to question (3)

Is it really a large-eddy simulation, i.e. are the subgrid-scale fluxes much smaller than the resolved-scale fluxes? How long should the averaging time interval be?

See slide 16:

- It is a large-eddy simulation because the sub-grid fluxes are negligibly small throughout the bulk of the mixed layer. There, the resolved turbulent flux is dominating the total flux, indicating a well-resolved turbulent flow. Sub-grid fluxes dominate close to the surface where the turbulent eddies cannot be resolved.

- Typically, the averaging time should contain several large-eddy turnover times. The large-eddy turnover time can be defined in a CBL as

$$\tau = \frac{L}{w_*} \quad \text{with} \quad w_* = \left(\frac{g\, z_i}{\theta_*} \overline{w'\theta'}_0 \right)^{1/3}$$

  where L is the length scale of the largest eddies in the flow and w_* is their typical velocity scale (Deardorff-Scale). τ can be interpreted as a typical time that an air parcel within an updraft needs to traverse the mixed layer. In our case, L is proportional to the boundary layer height ($z_i \approx 850m$) and w_* is about 1.4 ms^{-1} (see slide 18).
  $$\tau \approx 600s$$

- Thus, an averaging time of 900s as used here is barely appropriate. Increasing the horizontal domain size improves the statistics

Results - Time-series
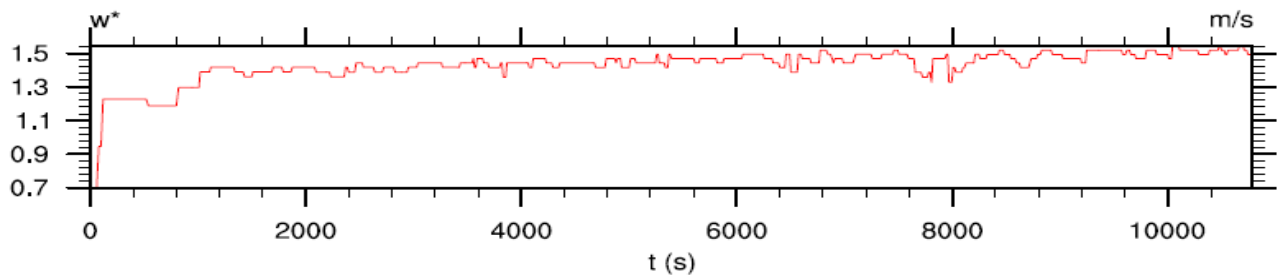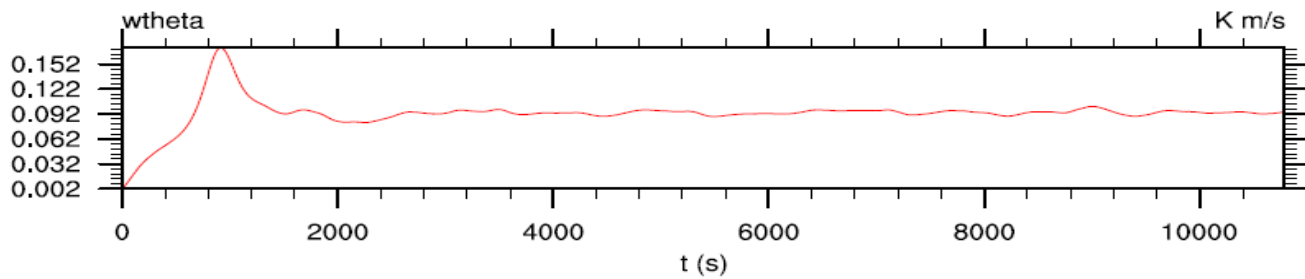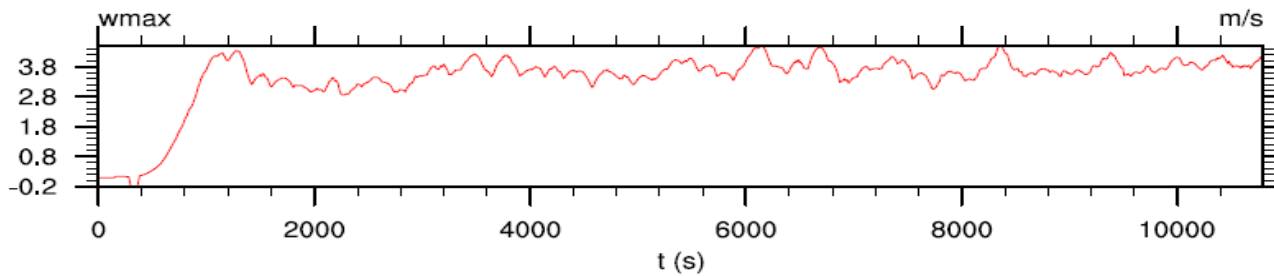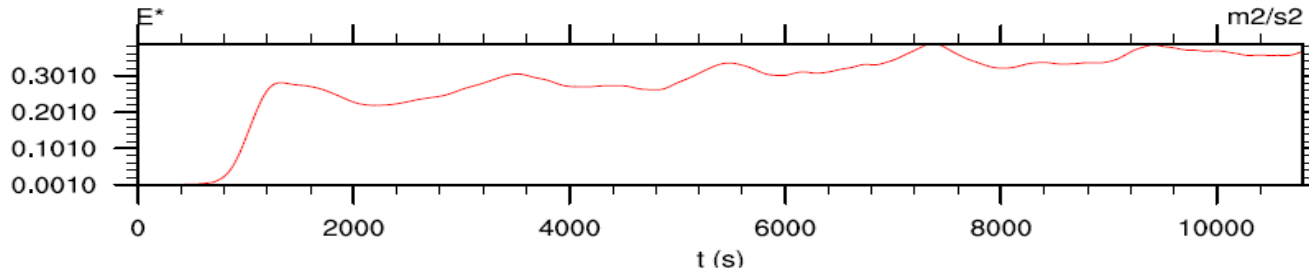
Answers to question (4)

Explain the temporal evolution of the time-series of the total kinetic energy and the maximum velocity components change in time? Has the flow become stationary? What happens during the first 30 minutes, and why?

See slide 19:

- The time series of the resolved-scale kinetic energy $E*$, the maximum vertical velocity *wmax* and the total vertical sensible heat flux close to the surface *wtheta* exhibit a spin-up phase of the model up to $t \approx 2000s$. During this spinup time, turbulence generation is triggered by adding artificial random perturbations until turbulence freely starts to develop.

- In the very beginning of the simulation, $E*$ remains zero although surface heating started at $t = 0s$. Resolved scale turbulence (convection) cannot develop at this time, because the convectively unstable layer is too shallow, so that turbulent eddies cannot be resolved by the numerical grid. At this time in the near-surface layer, heat is transported by subgrid-scale eddies only. Since transport by resolved eddies is missing, the total transport is too small and heat accumulates in this layer. Once this layer has grown large enough, so that resolved eddies can develop, convection is triggered, and plumes of warm air start to rise.

- Due to the initial „overheating" of the near-surface layer, the initial plumes carry a large amount of energy, explaining the overshooting at around $t \approx 1000s$.

- A stationary state can be seen by means of $E*$ which appears almost stationary in time. A fairly constant *wmax* also indicates stationarity of the flow.

Results – Larger Domain
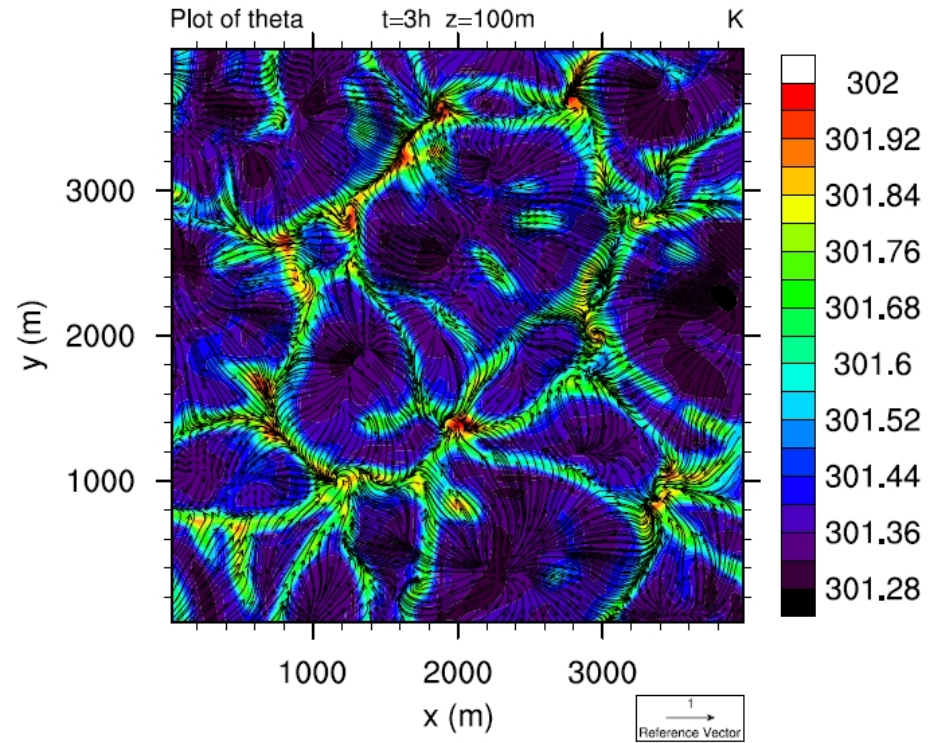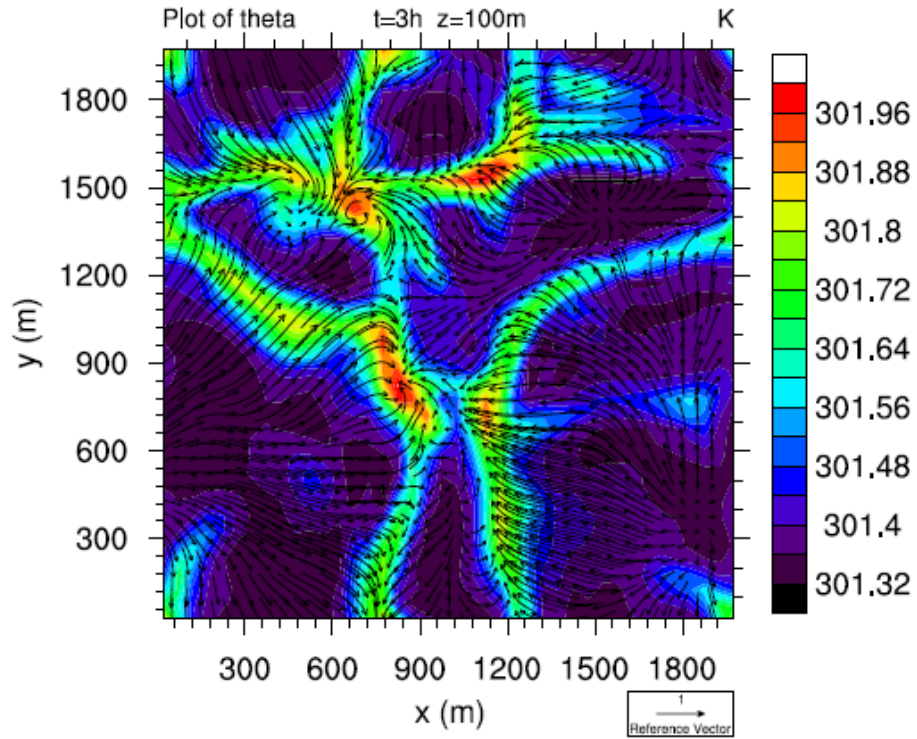
Answers to question (5)

Has the domain size and grid size been chosen appropriately? What happens to the flow field if you enlarge/reduce the domain size?

See slide 20:

- An appropriate domain size has generally been chosen, if several of the dominating flow structures fit into the modeling domain. From the left plot it becomes apparent that the typical hexagonal flow structures close to the surface can hardly be seen.

- On the right-hand side, where the domain size is doubled in both horizontal directions, several cells can be observed.

- The grid size should be chosen in a way that the dominating flow structures can be represented by at least several grid points (4-5). A grid spacing of 50 m as chosen in this exercise is appropriate since the dominant flow structures exhibit horizontal length scales of about 1 km. This length scale is of similar magnitude as the boundary-layer height.

PALM online:
https://palm.muk.uni-hannover.de

Our YouTube channel:
youtube.com/user/palmhannover