E2: Neutrally Stratified Boundary Layer

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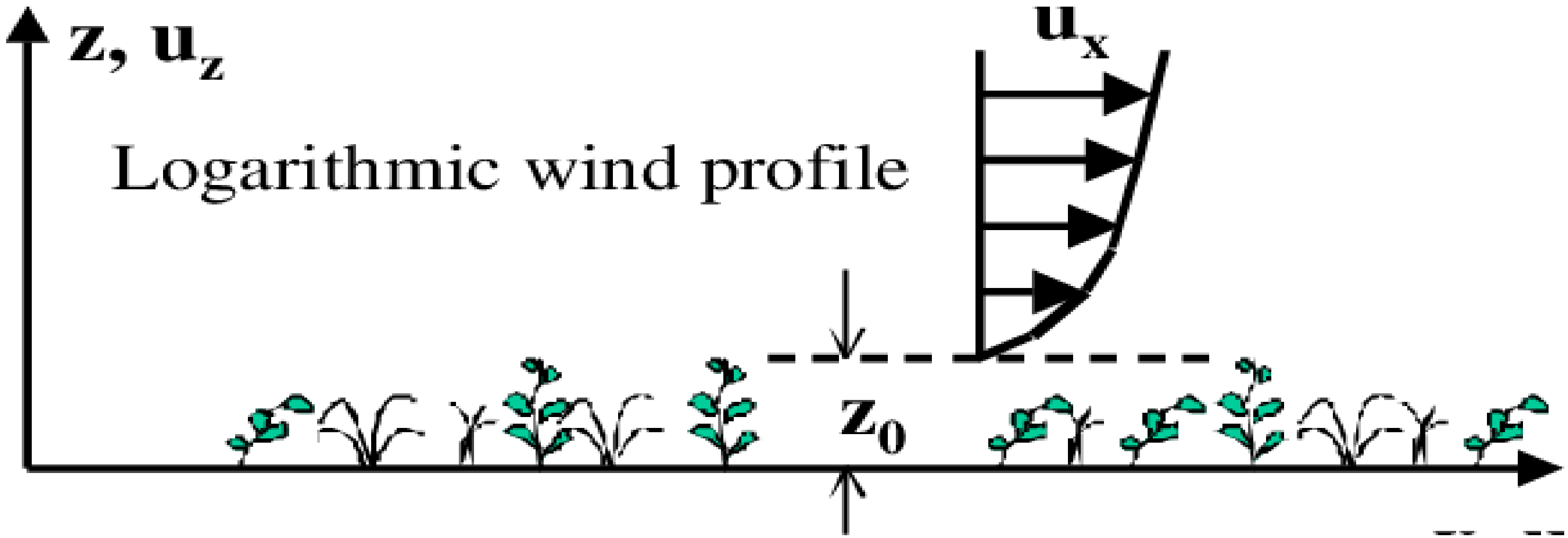
Introduction

- Neutral stratification : $\frac{\partial \theta}{\partial z} = 0$ or $\frac{\partial T}{\partial z} = -\frac{g}{c_p} \approx \frac{1\,K}{100\,m}$
- Flows are or can often be assumed to be stratified neutrally.
- Atmosphere: strict neutral stability conditions are rare. However, the ABL may be considered near-neutral especially during overcast skies and strong geostrophic winds.



- Simpler theoretical and semi-empirical approaches exist for neutral boundary layers (e.g., logarithmic wind profile in the surface layer).

- Turbulence is entirely of mechanical origin and depends on the surface friction and vertical distribution of wind shear.

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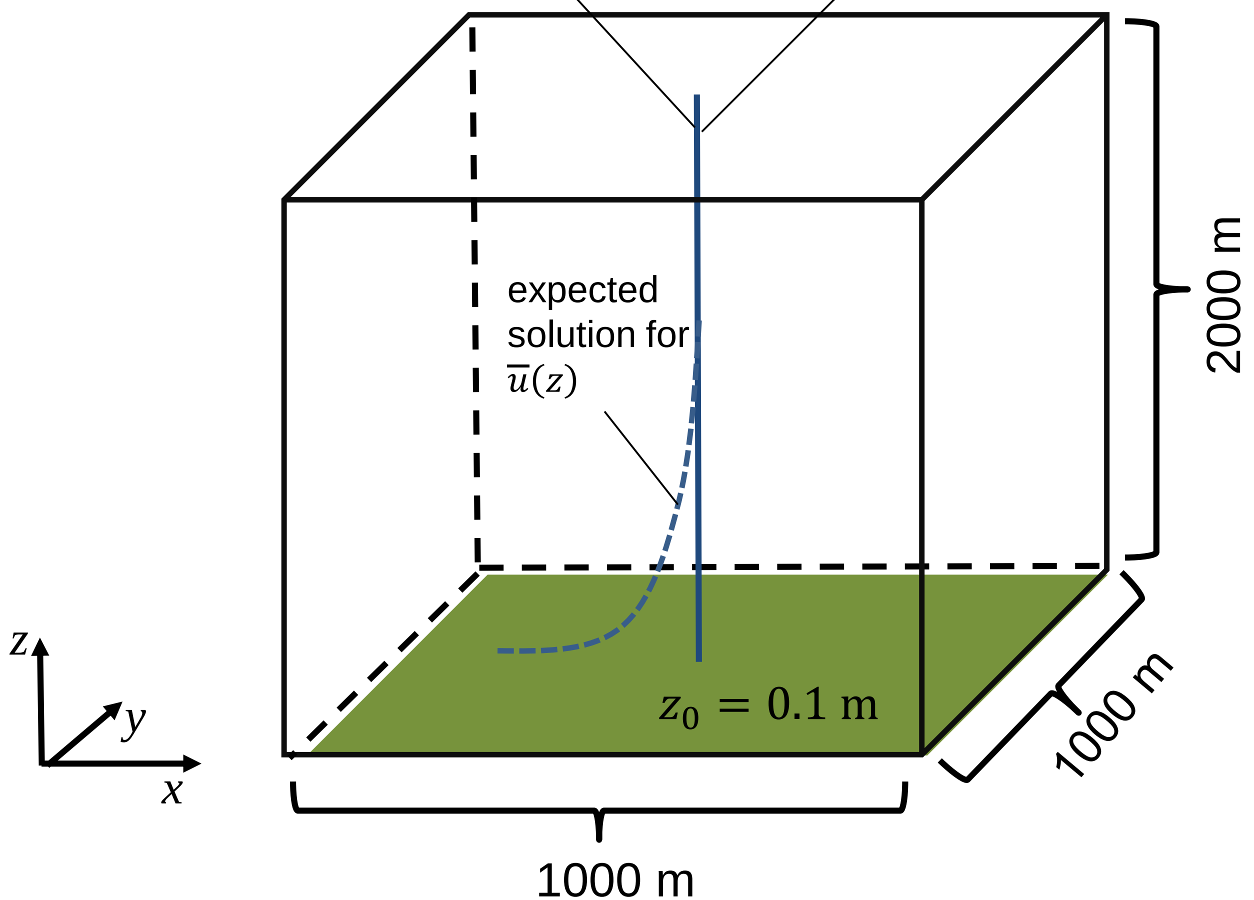
Setup:

Initial temperature profile:
$\theta(z) = const = 300\,\mathrm{K}$

Initial wind profile:
$u(z) = const = u_g = 5\,\frac{\mathrm{m}}{\mathrm{s}},\quad v(z) = v_g = 0$



- **Stratification:** Atmosphere is considered as neutrally stratified
- **Forcing:** Flow is driven by pressure gradient (geostrophic wind)
- **Grid size:** 20m in all directions
- **Horizontal boundary conditions:** cyclic
- **Simulation time:** 2 days

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Questions to be answered:

- After which time turbulence / mean flow becomes stationary?
- How do the horizontally and temporally averaged velocities and momentum flux profiles look like?
- Is it really a large-eddy simulation, i.e., are the subgrid-scale fluxes much smaller than the resolved-scale fluxes (except close to the surface)?
- How do the turbulence spectra of u, v, w along x and y look like?

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Hints (I)

- **Initial profiles/geostrophic wind**
  - Use **ug_surface**, **vg_surface**, **pt_surface** to prescribe the geostrophic wind & temperature.
  - With **initializing_actions = 'set_constant_profiles'** the initial wind profile will be constant with height with the geostrophic value.
- **Boundary conditions**
  - Between the bottom and the first grid level a constant flux layer (also called surface layer) shall be switched on, which corresponds to a no-slip condition at the surface. At the top, a Dirichlet condition with the geostrophic value shall be used. See **bc_uv_b** and **bc_uv_t** and **constant_flux_layer**.
- **Stationary state**
  - At the beginning of the simulation the mean wind in the boundary layer is not balanced with friction, Coriolis and pressure force → an inertial oscillation will appear. Due to friction the amplitude of the inertial oscillation becomes smaller with time till a stationary state is reached, but it would need very long time!
  - To prevent unnecessary long simulation time, a so-called Rayleigh damping can be applied, which damps the inertial oscillation. See parameters **rayleigh_damping_height** and **rayleigh_damping_factor**.

- **Saving CPU-time with Galilei transformation**
  - Switch on parameter **galilei_transformation** to save computing time.
  - Switch off the temperature equation to save CPU time by setting initialization parameter **neutral = .TRUE.**
- **Initial disturbances**
  - To initiate turbulence, it is necessary to impose artificial random perturbations to the horizontal velocity field (**create_disturbances, dt_disturb, disturbance_energy_limit**)
  - Otherwise, it would take quite a long time until turbulence develops under horizontally homogeneous conditions
- **Spectra**
  - Spectra output is controlled by parameters **data_output_sp**, **dt_dosp**, etc. These package-parameters have to be given in a separate NAMELIST block:

```
&runtime_parameters end_time = ... , /
&spectra_parameters data_output_sp = ... , /
```

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Hints (III)

- **Palmrun command**
  - `palmrun  -r e2_neutral -a "d3#" -X4`
- **Palmplot commands**
  - `palmplot pr file_1=e2_neutral_pr.000.nc format_out=pdf file_out=e2_pr time_stride=2 no_rows=2 no_columns=3 var=‘u v w wu wv w*2'`
  - `palmplot pr file_1=e2_neutral_pr.000.nc format_out=pdf file_out=e2_pr_2 time_stride=2 var='w"u" w"v" w*u* w*v*'`
  - `palmplot ts file_1=e2_neutral_ts.000.nc format_out=pdf file_out=e2_ts var='E E* umax' no_rows=3`
  - `palmplot sp file_1=e2_neutral_sp.000.nc format_out=pdf file_out=e2_sp start_time_step=48 no_rows=2 no_columns=2`

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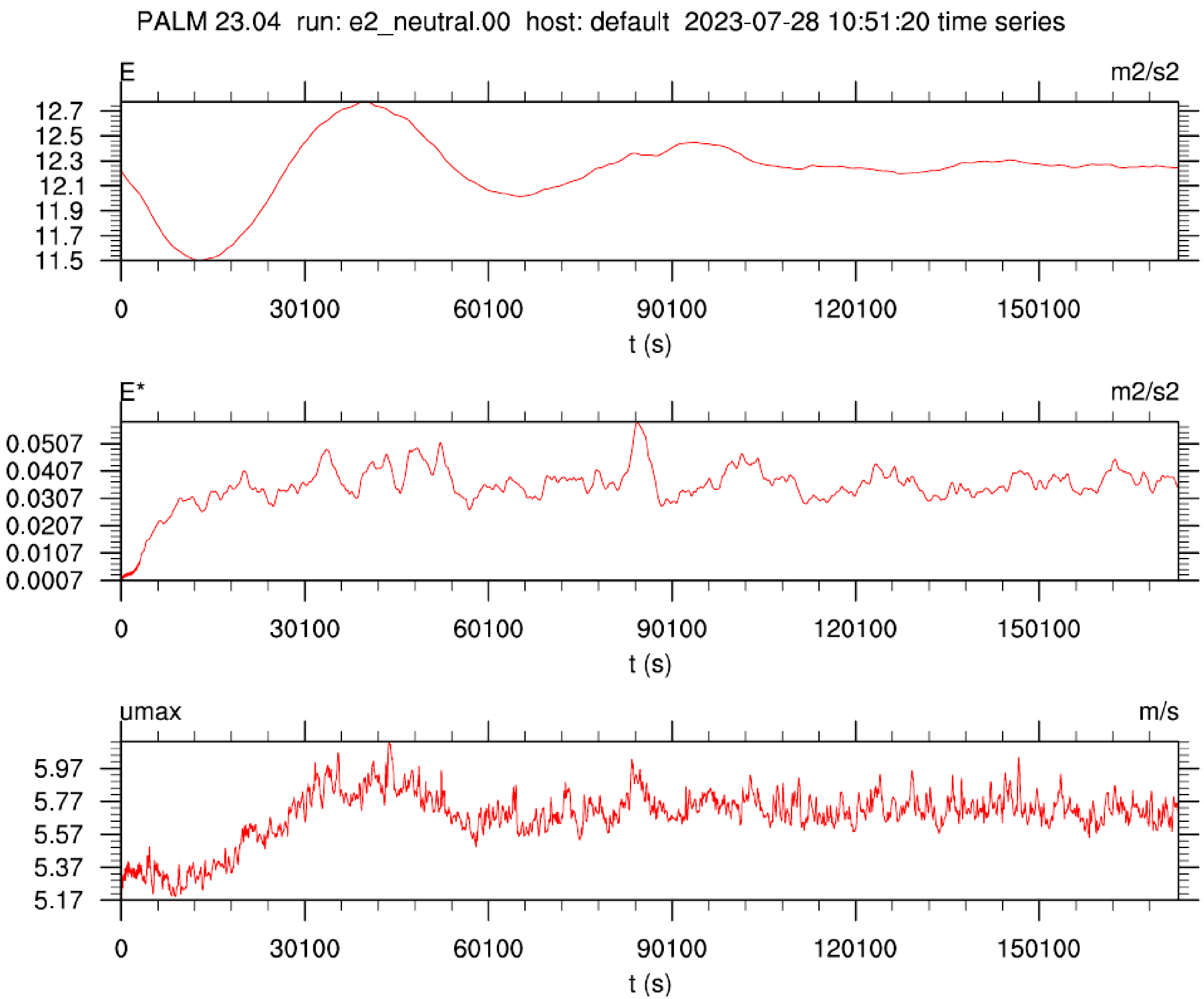
Time series of total kinetic energy, umax and wmax



How long do you have to simulate until turbulence / mean flow becomes stationary?

- As can be seen on previous slide, a simulation time of about 2 days (48 h, 172800 s) should be taken to obtain a roughly constant mean flow described by the total kinetic energy.
- The time series of E shows an oscillation with a period of roughly 14 h. This can be attributed to the inertial oscillation affecting the air parcels due to the Coriolis force. This oscillation is damped with time by the turbulent friction.
- However, the turbulent kinetic energy E* indicates that turbulence is fully developed from roughly 15000 s.
- umax also displays the inertial oscillation of the mean flow.

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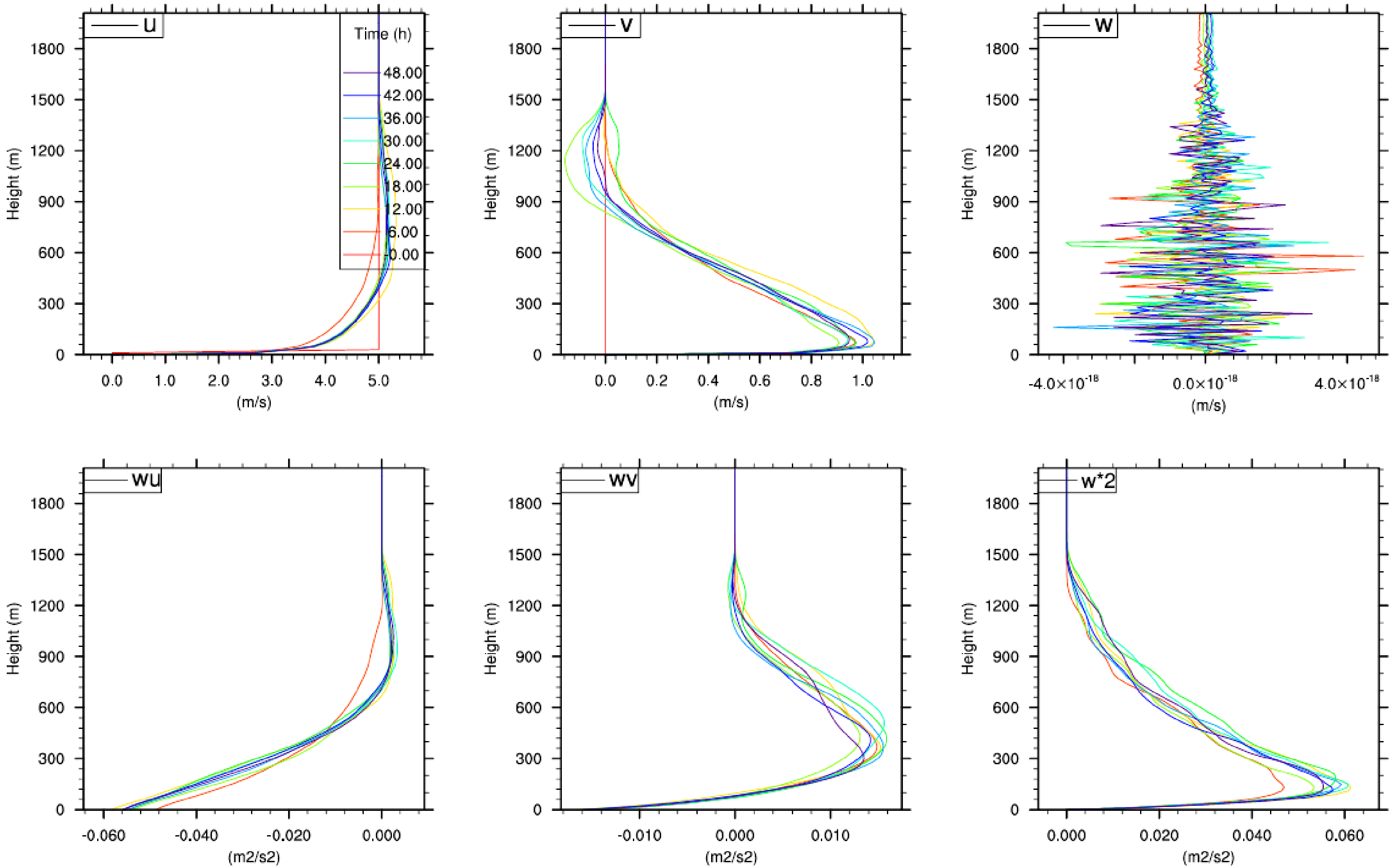
Vertical profiles of <u>, <v>, <w>, <wu>, <wv>,<w*2>

PALM 23.04 run: e2_neutral.00 host: default 2023-07-28 10:51:20



Answers to question II

How do the horizontally and temporally averaged velocity and momentum flux profiles look like?

- The horizontal mean velocities show the Ekman spiral. The mean vertical velocity is practically zero as the usage of incompressible equations together with cyclic boundary conditions (horizontal homogeneity) requires.

- Generally, the turbulent vertical flux of horizontal momentum in the boundary layer is oriented downward (as wind speed increases with height) and decreases with height due to decreasing vertical wind shear and additionally decreasing turbulence intensity from a certain height. Anyhow, looking at the components of the vertical momentum flux here, it looks more complex due to the Ekman-turning. In wu the mentioned features can be seen as it is the mean wind direction, but wv have a different behavior. -> See detailed discussion in lecture

- The non-convergence of the single profiles is mainly due to insufficient statistics. The averaging time of 3 h is still too small. Because of its smaller magnitude, the v-component shows larger fluctuations.

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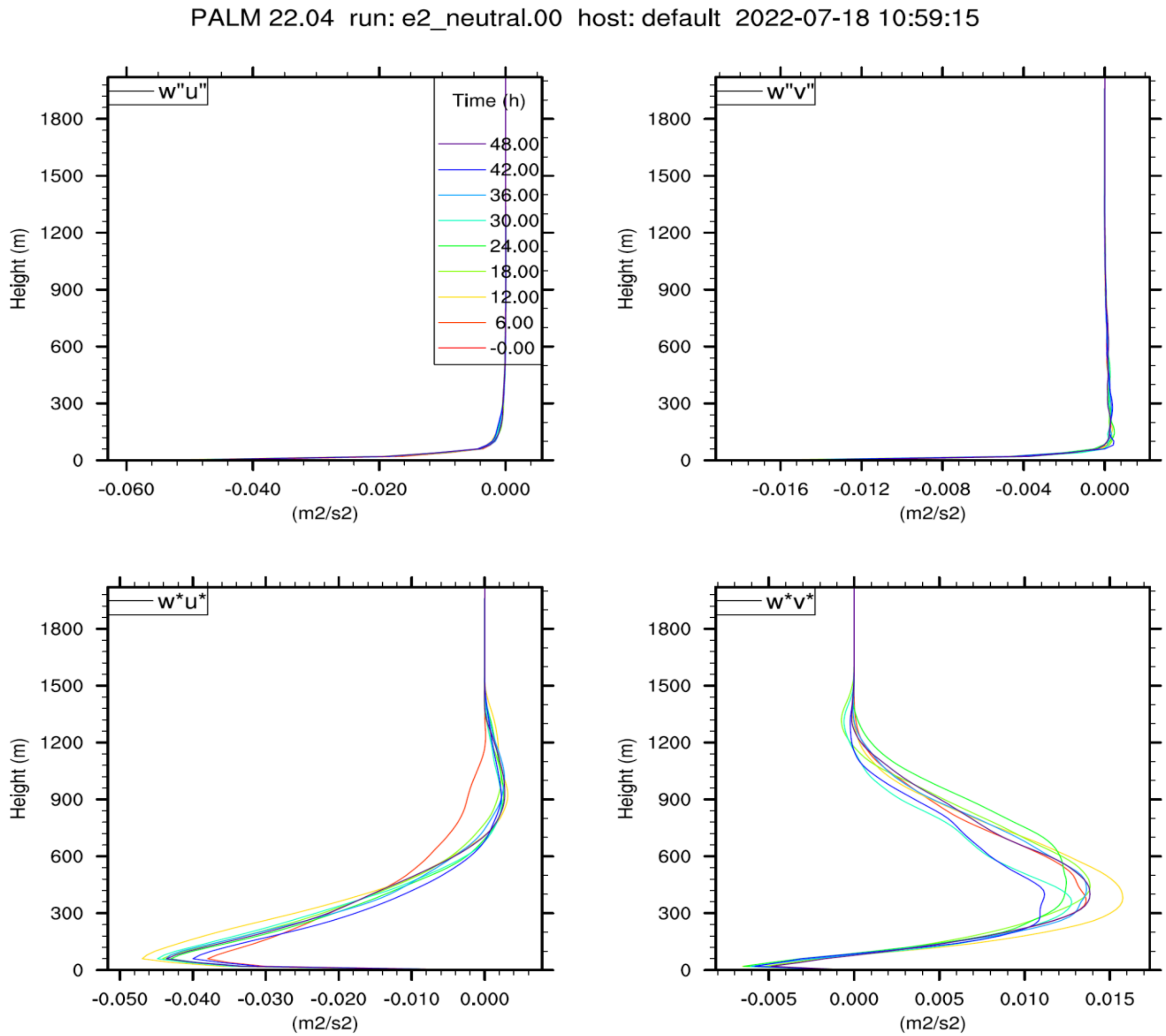
Vertical profiles of <*w''u''*>, <*w''v''*>, <*w*u**>, <*w*v**>



Answers to question III

Is it really a large-eddy simulation?

- The previous slide shows sub-grid and resolved-scale momentum flux profiles.
- The simulation is an LES since resolved momentum fluxes are the dominant components for the total flux (except for the near vicinity of the surface where the unresolved, sub-grid fluxes necessarily dominate).

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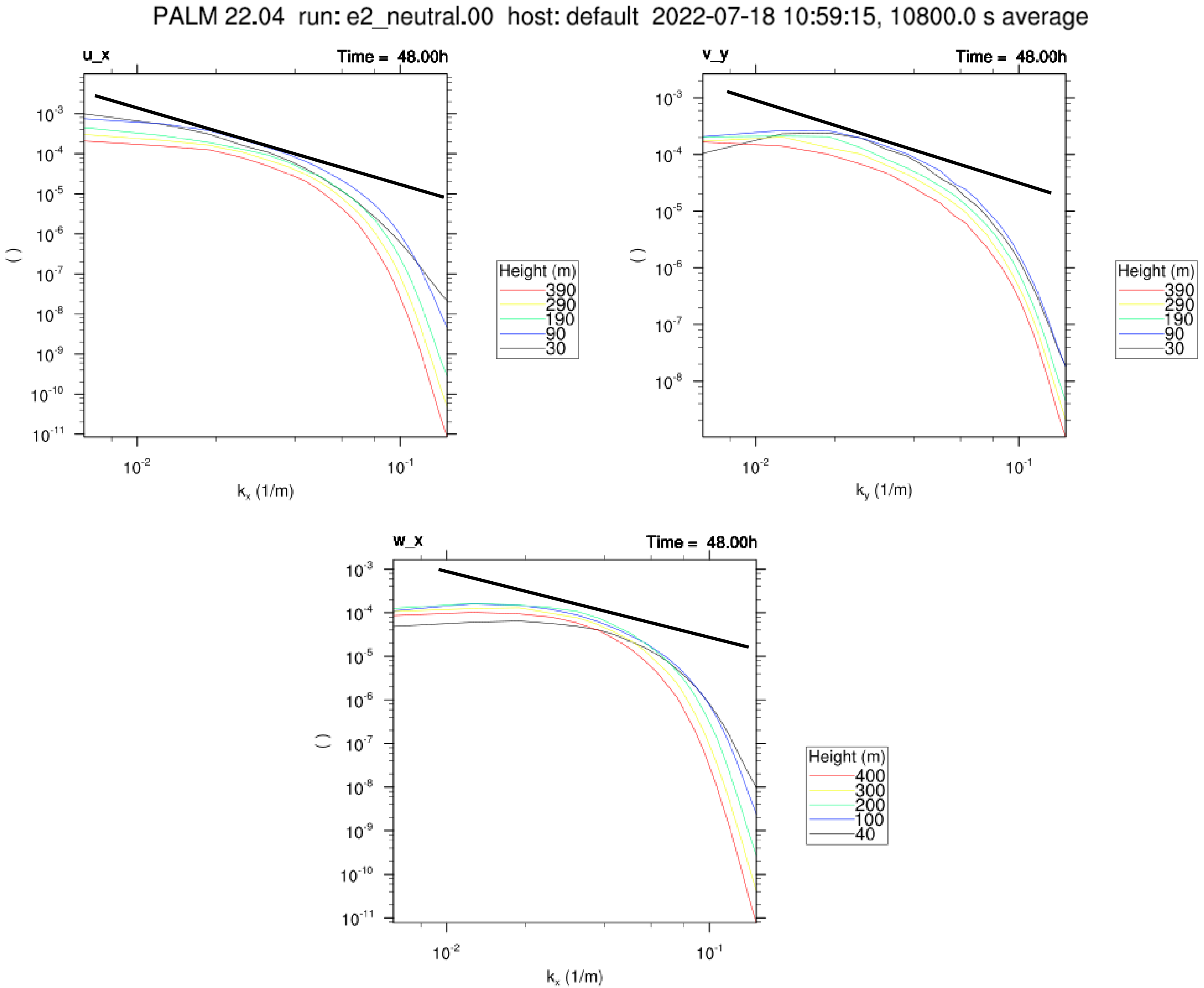
Spectra of *u*, *v* and *w*



Can you identify the inertial subrange?

- In PALM, the spectral density is normalized by means of the variance at the corresponding height level and additionally multiplied by the wave number. Thus, the spectral density appearing on the ordinate of the plots on the previous slide is dimensionless (otherwise it would be $\frac{m^3}{s^2}$).

- The spectra show a maximum spectral density for small wave numbers. Thus, the largest eddies contain the highest variance (or turbulence kinetic energy, TKE). For higher wave numbers the inertial subrange follows, where the spectra fulfill a -2/3 slope in the plot (indicated by a black line). There, the variance follows the energy cascade where larger eddies break up into smaller eddies. For the highest wave numbers, the spectra depart from the -2/3 slope indicating that dissipation takes place.

- The spectra also show that the production range is not well developed (very flat maxima). This suggests that the modeling domain might be too small to capture relevant larger scales. The inertial subrange could also be extended by decreasing the grid spacing.

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

Our YouTube channel:
youtube.com/user/palmhannover