The influence of small scale heterogeneities on the near surface turbulence structure and the energy balance closure

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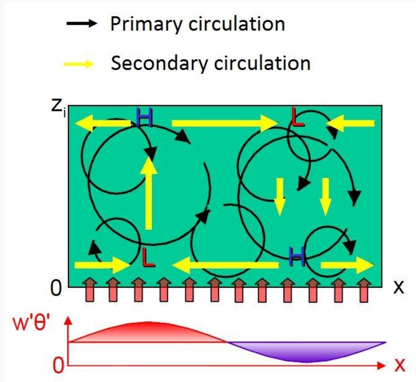
Motivation

- Heterogeneities due to differences in the surface structure may trigger secondary circulations in the convective boundary layer
- If the wavelength of the heterogeneity is in the order or larger than the boundary layer height, the secondary circulations reach the top of the boundary layer
- Because of their stationarity, turbulence measurements with the eddy-covariance method are not able to detect these fluxes
- The secondary circulations are suspected to be partly responsible for the non-closure of the energy balance in a height of 2 m (height of energy balance stations)



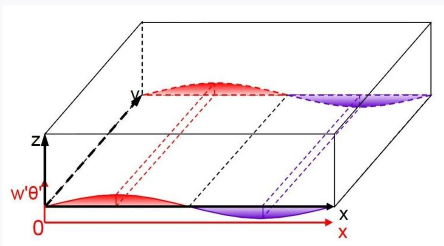
- Previous studies have shown that two mechanisms are responsible for the underestimation of the representative heat flux in eddy-covariance measurements: secondary circulations and turbulent organized structures
- They have also shown that the mentioned circulations can influence tower measurements but that they have nearly no influence in a height of 2 m
- Therefore heterogeneities with diameters of a few hundred meters are suspected to contribute to the observed non-closure
- As the fluxes cannot be measured in field experiments, they are simulated by Large-Eddy Simulation and virtual eddy-covariance measurements are performed

Simulations

- The LES model PALM (parallelized LES model) optimized for parallel computing was applied
- Runs were performed on the supercomputers of the HLRN (Norddeutscher Verbund für Hoch- und Höchstleistungsrechnen)

- Heterogeneities imposed as one-dimensional sinusoidal heat flux waves in x-direction
$\overline{w'\theta'}(x) = \overline{w'\theta'}_{av} + A_x \sin(\frac{2\pi}{\lambda}x)$

$\overline{w'\theta'}(x)$ heat flux
$\overline{w'\theta'}_{av}$ mean heat flux (0,16 K m/s)
A_x amplitude of the heterogeneity (0,15 K m/s)
λ wavelength of the heterogeneity



- Wind direction parallel to the x-axis
- Wind causes the turbulent organized structures to move faster through the model domain, thus their influence is reduced and the perceptibility of the secondary circulations is improved

- Horizontal boundary conditions are cyclic: infinitely often repeating model domain

- Simulation time of 8 h for all simulations, first 2 h with homogeneous surface heat flux for development of a convective boundary layer

- 2 h averaging period for the analysis of the circulations
- 1 h and 2 h averaging period for the determination of the imbalance of the virtual eddy-covariance measurements

Data processing

- The velocities in the circulations are low and superimposed by turbulent structures
- The results are phase- and time-averaged to make the circulations visible and to get representative data for each situation

- For a better comparability some mean characteristics are determined like the maximum vertical velocity, the position of the maximum/minimum and the height of the circulation

Eddy-covariance measurements:

- For a high statistical accuracy each grid point is used as a virtual measuring point
- Eddy-Covariance flux and imbalance are calculated from model output
  - Flux consists of a resolved part ($\overline{w'\theta'}_{res}$) and a parameterized, sub-grid scale part ($\overline{w'\theta'}_{SGS}$)

$$\overline{w'\theta'}_{res} = \overline{w\theta} - \bar{w}\bar{\theta} \qquad \overline{w'\theta'}_{SGS} = -K_h \frac{\partial\bar{\theta}}{\partial z}$$

  - Imbalance is calculated as local imbalance I and horizontally averaged imbalance [I]

$$I = \left(\overline{w'\theta'} - [\bar{F}]\right) / [\bar{F}] \qquad [I] = ([\overline{w'\theta'}] - [\bar{F}]) / [\bar{F}]$$

$\overline{w'\theta'}$ heat flux measured by virtual eddy-covariance measurements
$[\bar{F}]$ representative heat flux, horizontally and spatially averaged

Results

Model setup:

Wavelength λ = 100 m — Model domain 4000 m x 4000 m x 3750 m
Wind u_g = 1 m s^{-1} — Resolution Δ = 2,5 m

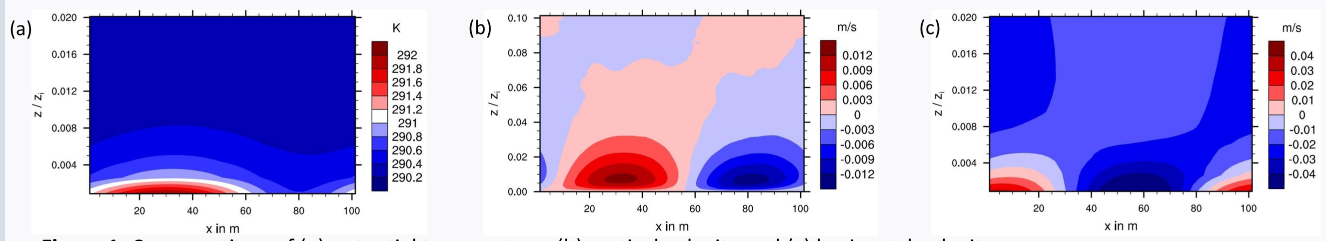


Figure 1: Cross-sections of (a) potential temperature, (b) vertical velocity and (c) horizontal velocity

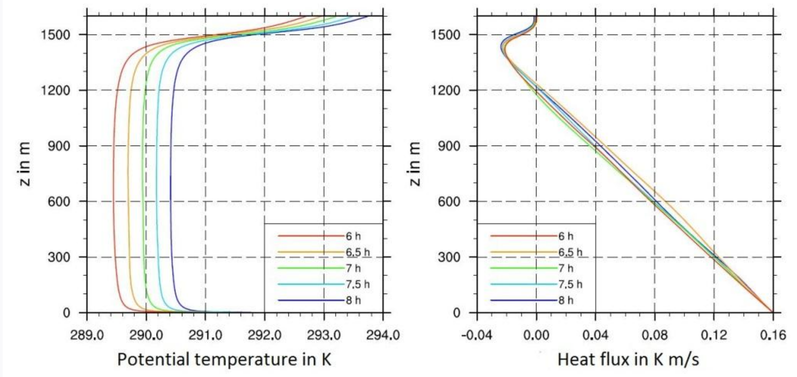


Figure 2: Vertical profiles averaged over 15 minutes

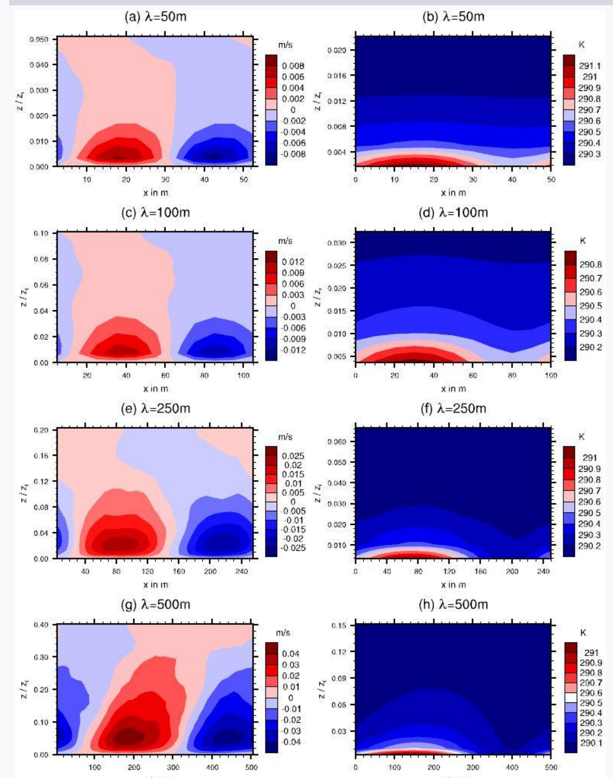
General effect of heat flux heterogeneities

- Profiles as expected in a convective boundary layer, no influence by heterogeneities
- Atmosphere in a quasi-stationary state over the averaging period
- Warmer air above the higher heat flux region than above the lower heat flux region
- Ascending air above the higher heat flux region, descending air above the lower heat flux region
- Near the surface: convergence of the horizontal wind above the heat flux maximum (updraft region) and divergence above the heat flux minimum (downdraft region)

Variation of wavelength and wind speed

Model setup:

Wavelength from 50 m to 500 m
Wind u_g = 1 m s^{-1}
Resolution Δ = 10 m (5 m for λ = 50 m)



Increasing wavelength:

- Strength of the circulation increases
- Influence of the heat flux variation is present up to larger heights
- Horizontal temperature difference increases, but horizontal gradient decreases
- Temperature gradient present up to greater heights
- Circulation reaches larger heights
- Absolute value of the vertical velocity in the up- and downdraft increases

Figure 3: Cross-sections of vertical velocity ((a), (c), (e), (g)) and potential temperature ((b), (d), (f), (h))

- Clear correlation between the height of the maximum vertical velocity and the wavelength and between the height of the circulation and the wavelength
- The maxima/minima can be found in nearly the same phase of the heat flux wave for all wavelengths
- The correlation between the maximum absolute value of the vertical velocity and the wavelength is almost linear

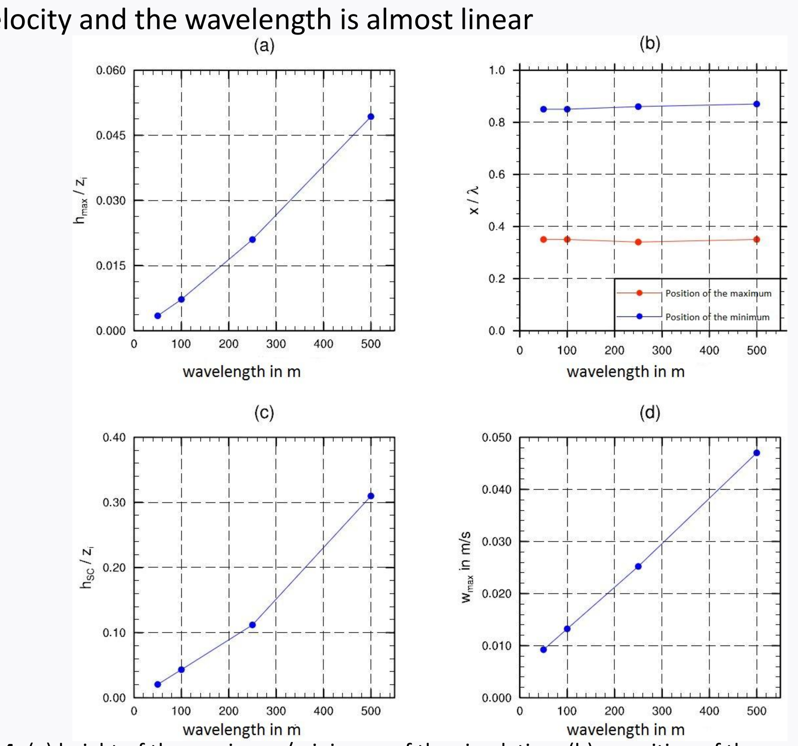


Figure 4: (a) height of the maximum/minimum of the circulation, (b) x-position of the maximum/minimum of the circulation, (c) height of the circulation and (d) maximum vertical velocity as a function of wavelength

Model setup:

Wavelength from 100 m to 500 m
Wind u_g from 1 m s^{-1} to 6 m s^{-1}
Resolution Δ = 10 m

Increasing wind speed:

- Surface information are smeared due to increased turbulent shear
- Horizontal temperature gradient decreases
- Strength of the circulation decreases for each wavelength
- Maximum/minimum moves with the wind to larger x-values

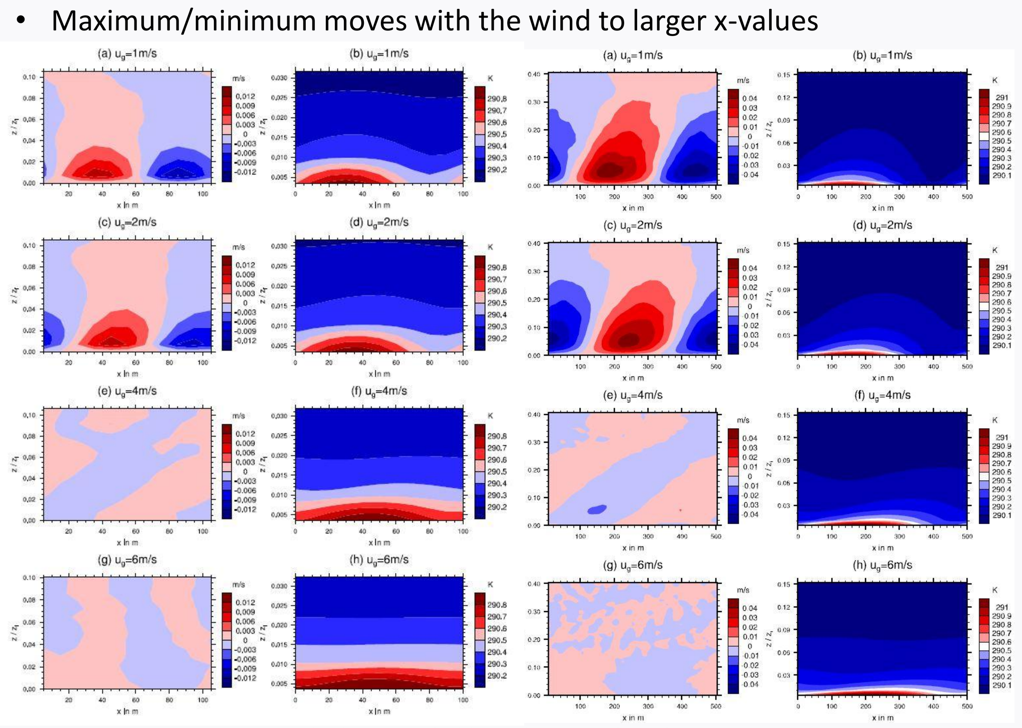


Figure 5: Same as in Figure 3 for λ=100 m (left) and λ=500 m (right)

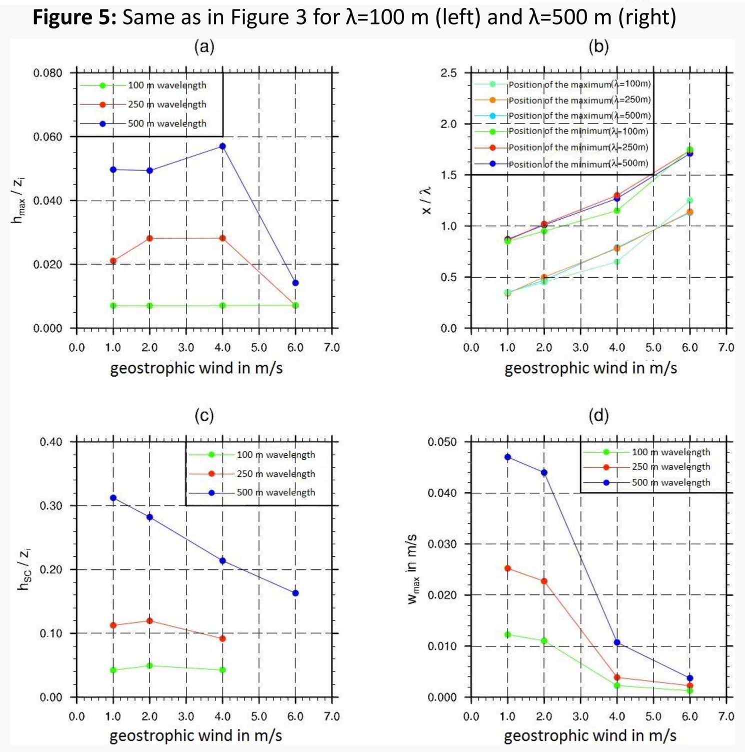


Figure 6: Same as in Figure 4 but as a function of geostrophic wind

- For wind speeds between 1 and 4 m s^{-1} the height of the maximum/minimum is nearly constant, for 6 m s^{-1} the height decreases
- With the chosen resolution no conclusion for λ=100 m possible
- Shifting of position of maximum/minimum of 0,8·λ between 1 and 6 m s^{-1}

- Nearly linear decrease of the height of the circulation with increasing wind speed for λ = 500 m
- The correlation of the maximum absolute value of the vertical velocity shows the same trend for all wavelengths

Energy balance closure

Model setup:

Wavelength from 0 m to 500 m — Model domain 8000 m x 8000 m x 3750 m
Wind u_g = 1 m s^{-1} — Resolution Δ = 10 m

The circulations bring warmer-than-surrounding air upwards and colder-than-surrounding air downwards. Both cases cause a positive heat flux that is not measured with the eddy-covariance technique, resulting in an underestimation of the real representative heat flux.

The measured imbalance consists of a part due to the circulations and a part due to turbulent organized structures.

Spatially averaged imbalance:

- Imbalance increases with height mainly because of the turbulent organized structures
- Influence of the wavelength:
  - Increasing the wavelength of the heterogeneity leads to just a small rise in the imbalance near the surface
  - In larger heights only the longest wavelengths have an influence on the imbalance
- For λ = 50 m and λ = 100 m the lowest measuring height is already above the height of the maximum/minimum of the circulation
- The influence of the wavelength becomes more apparent by increasing the averaging period from 1 h to 2 h

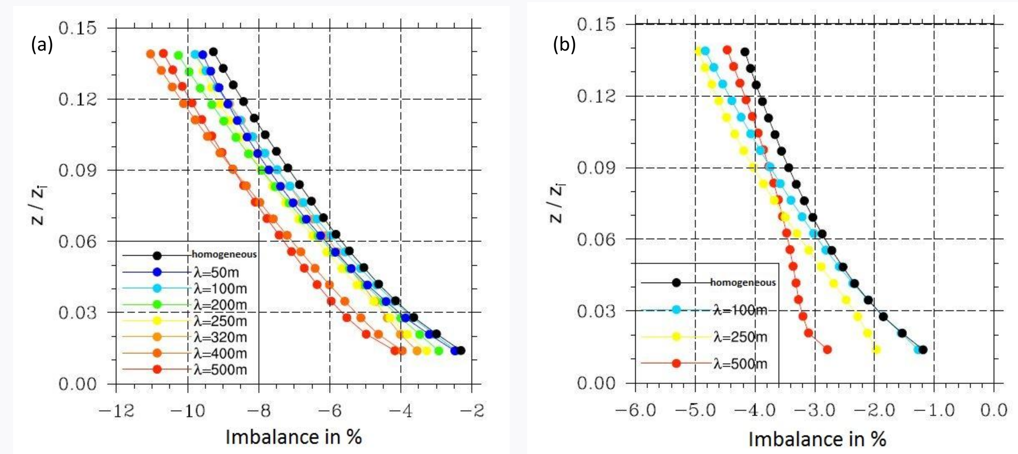


Figure 7: Vertical profiles of the imbalance with (a) 1 h and (b) 2 h averaging period

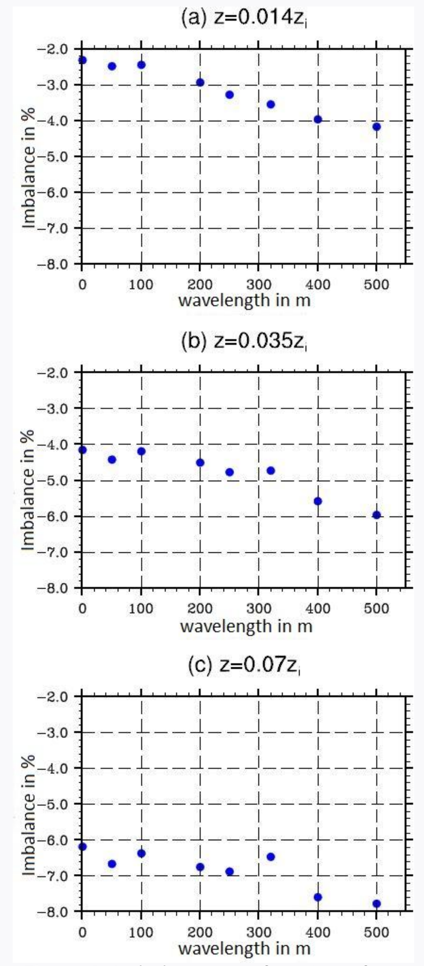


Figure 8: Imbalance as a function of wavelength

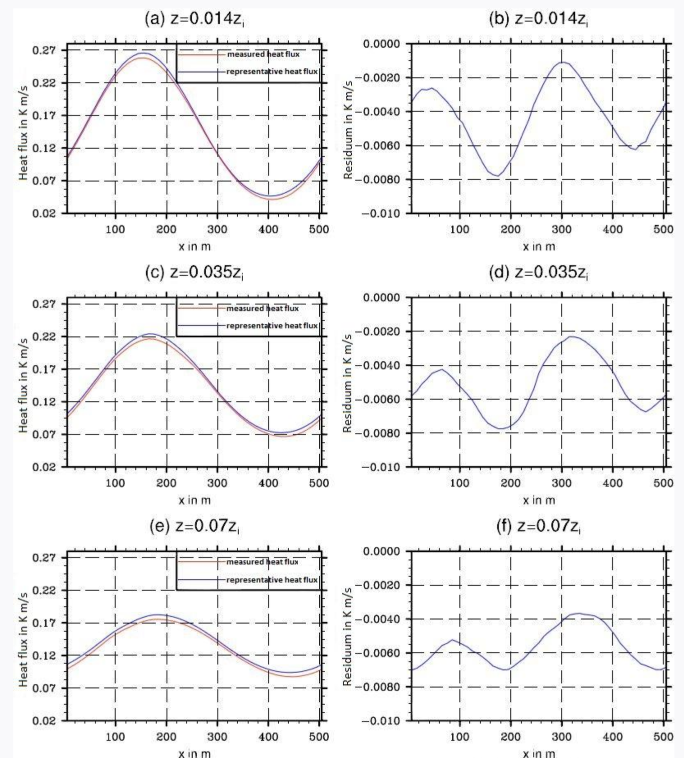


Figure 9: Progression in x-direction of heat flux ((a), (c), (e)) and residuum ((b), (d), (f)) for λ=500 m

Local imbalance:

- Analysis just shown for a wavelength of 500 m because of the strongest influence for this wavelength
- Influence of the position within a heat flux wave:
  - Nearly no imbalance in the part of the wave where the vertical velocity of the circulation is zero
  - Imbalance increases when the absolute value of the vertical velocity increases

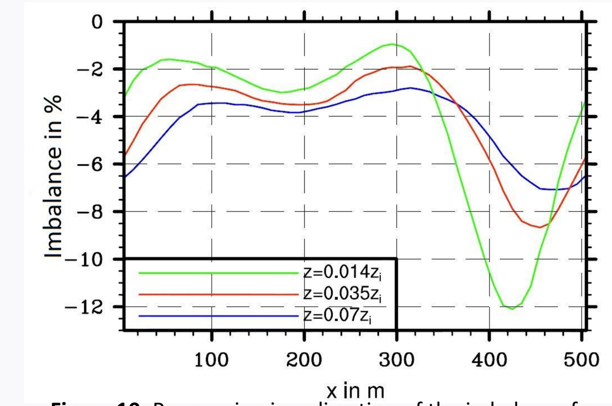


Figure 10: Progression in x-direction of the imbalance for λ=500 m

Conclusions

- The generated circulations are clearly weaker than circulations induced by heterogeneities with wavelengths in the order of the boundary layer height
- A variation of the wavelength of the heterogeneity has a significant effect on the strength and height of the circulation
- Increasing the background wind decreases the strength of the circulation for each wavelength
- Small scale heterogeneities cannot be responsible for the non-closure of the energy balance because only in small parts of the heat flux wave the circulations are producing an imbalance of over 10 %, which is observed in field experiments