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Spatial observations of large eddies and cross-canopy coupling with joint fiber-optic distributed sensing and eddy covariance flux measurements

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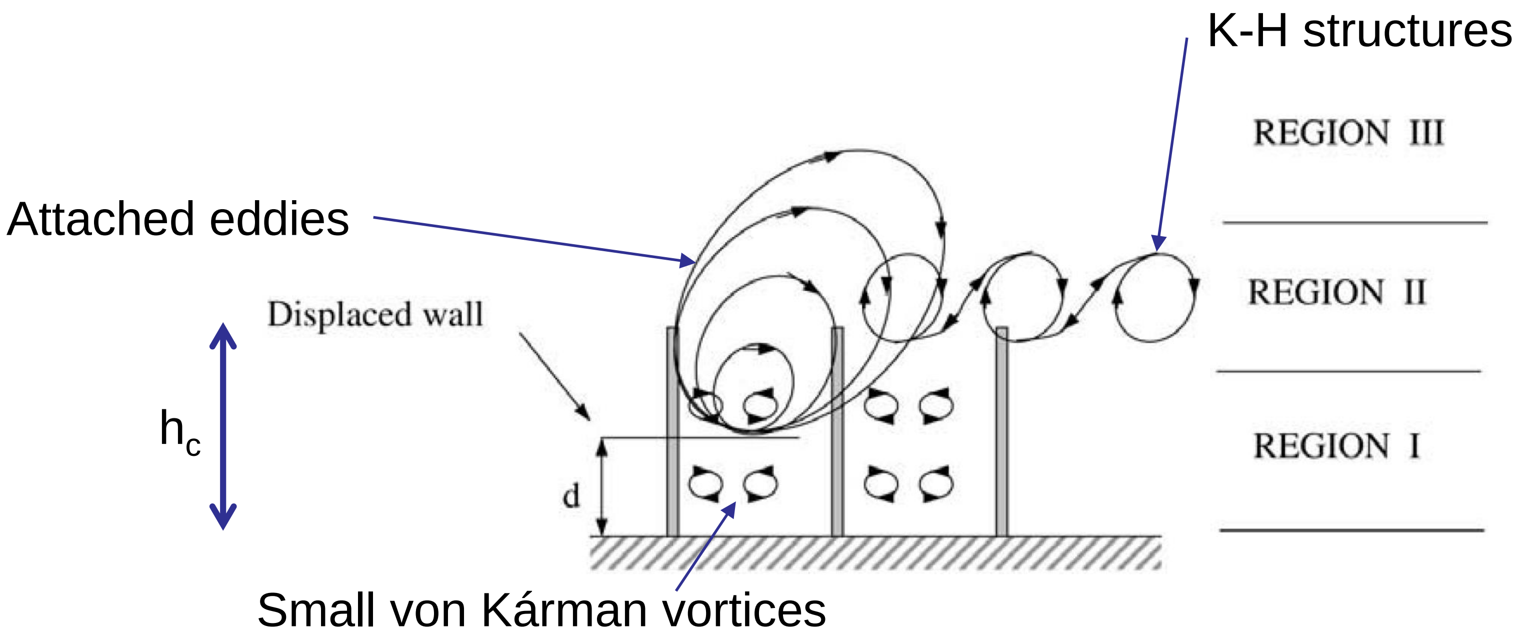
5/3/2020

Intro: Poggi et al. (2004)

Flows above canopies can be divided into three structures:
attached eddies (scale with z-d), K-H structures (scale with h_c) and von Kárman vortices
Three regions
Region I: subcanopy air space, von Kárman vortices
Region II: flows just above canopies, K-H structures dominate (roughness sublayer)
Region III: flows above canopies, attached eddies dominate (inertial sublayer)



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Poggi, D., Porporato, A., Ridolfi, L., Albertson, J. D., & Katul, G. G. (2004). The Effect of Vegetation Density on Canopy Sub-Layer Turbulence. *Boundary-Layer Meteorology*, *111*(3), 565–587. https://doi.org/10.1023/B:BOUN.0000016576.05621.73

Intro: Thomas and Foken (2007)

- Four scalar exchange regimes above forests were identified
  - Wa (wave)
    - Waves dominate the above canopy flow. Weak vertical transport
  - Dc (decoupled canopy)
    - Turbulence quiescent. Weak vertical transport
  - Ds (decoupled subcanopy)
    - Turbulent mixing above canopy, but not at subcanopy air space. Turbulent vertical transport misses the subcanopy signal (e.g. forest floor respiration)
  - Cs (Coupled subcanopy by sweeps)
    - Occasional downdrafts (i.e. sweeps) penetrate to the subcanopy air space. Turbulent vertical transport misses part of the subcanopy signal
  - C (fully coupled canopy)
    - Above canopy flow fully coupled with the subcanopy

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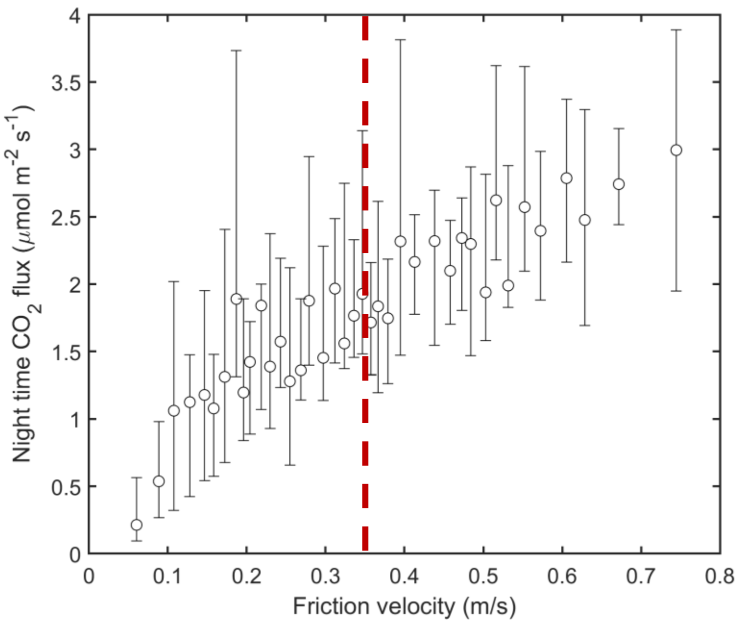
Thomas, C., & Foken, T. (2007). Flux contribution of coherent structures and its implications for the exchange of energy and matter in a tall spruce canopy. Boundary-Layer Meteorology, 123(2), 317–337. https://doi.org/10.1007/s10546-006-9144-7

Intro: CO_2 flux underestimation

- CO_2 fluxes measured above canopy are underestimated at night time when friction velocity (u_*) is low
- Introduces biases to ecosystem carbon balance estimates
  - ⇒measurements from periods with low u_* are typically discarded
- Clear friction velocity threshold is difficult to find at some sites

Dependence of night time CO_2 fluxes measured above canopy on friction velocity at Hyytiälä pine forest site



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Objective

- Objective of this study is twofold

1) Identify the height-time structure of coherent flow structures above forest canopy from detailed temperature profiles
2) Assess their role in cross-canopy coupling at night when CO_2 fluxes are underestimated

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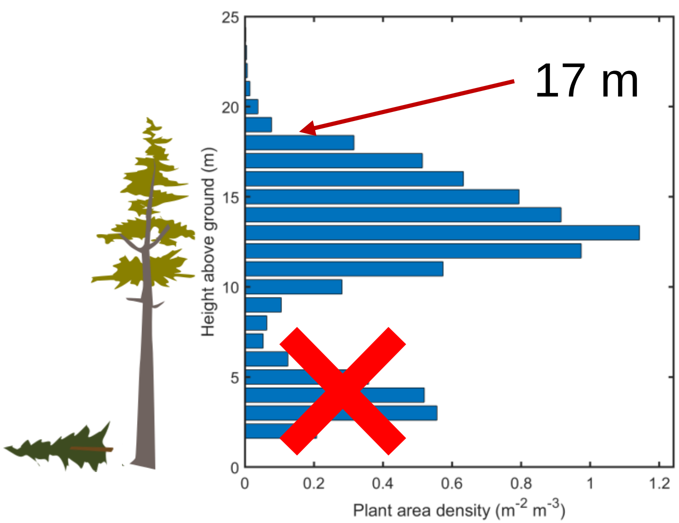
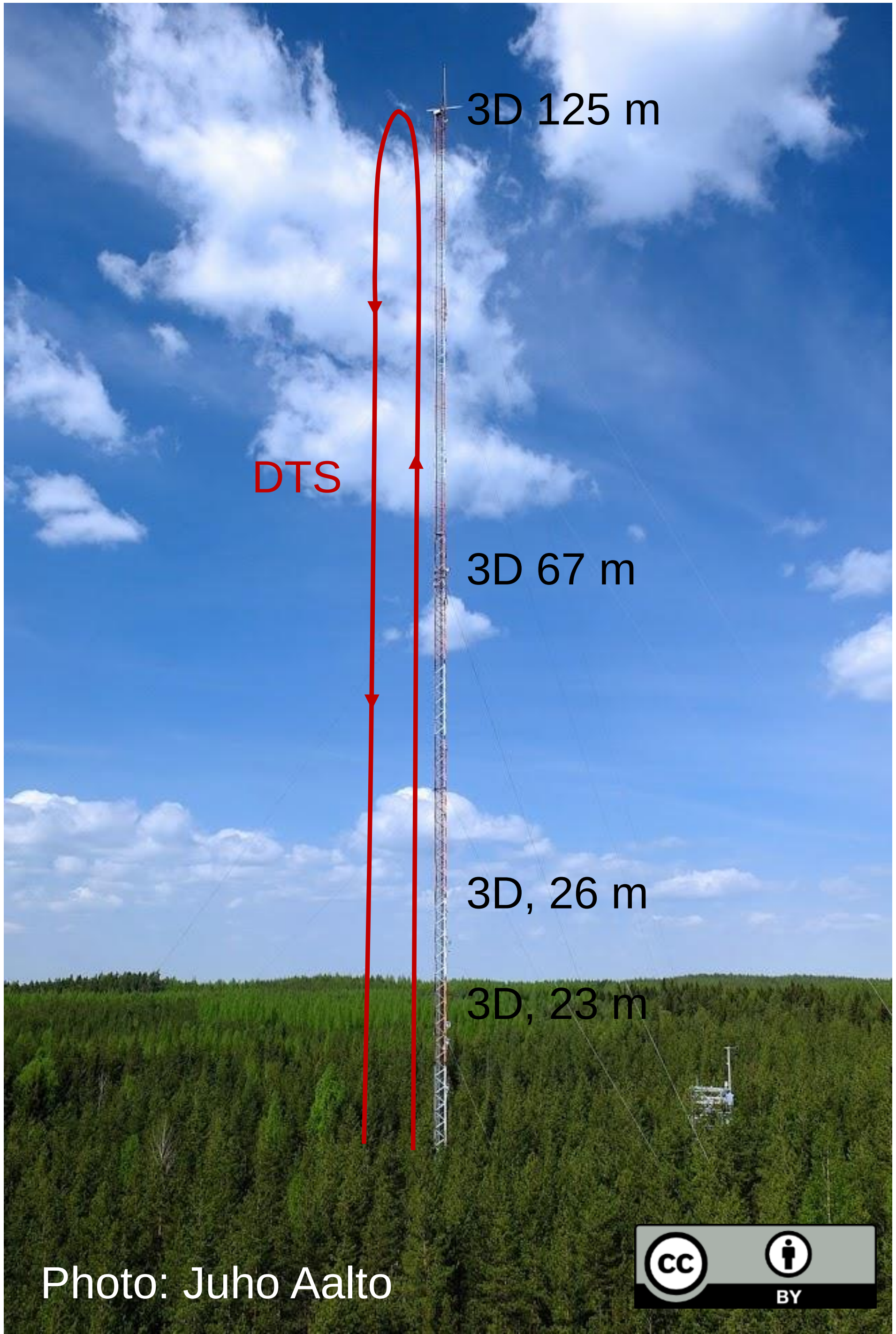
Hyytiälä, SMEAR II

- 125 m tall mast in a boreal pine forest in southern Finland
- Distributed temperature sensing (DTS)
  - Temperature data with 1 Hz and approx. 12 cm resolution along the fibre cable secured to the mast

    => continuous temperature profiles along the mast!
- 3D sonic anemometers at 1 m, 4 m, 23 m, 26 m 67 m and 125 m
- Measurements between 25.5. and 9.7.2019
- All-sided LAI 8 m^2 m^{-2} in year 2015





Data processing

- 3D sonic anemometers and EC:
  - Despiking
  - Coordinate rotation following Wilczak et al. (2001)
  - Detrending
  - Cross-covariance maximisation for gas fluxes
- DTS
  - Calibrating single-ended measurements (25.5.-3.6.) following Hausner et al. (2011) and double-ended (3.6.-9.7.) following van de Giesen et al. (2012)
  - DTS measurements contain significant noise component => denoising using proper orthogonal decomposition similarly as Epps and Krivitzky (2019)
- Throughout the study 10-min averaging period was used

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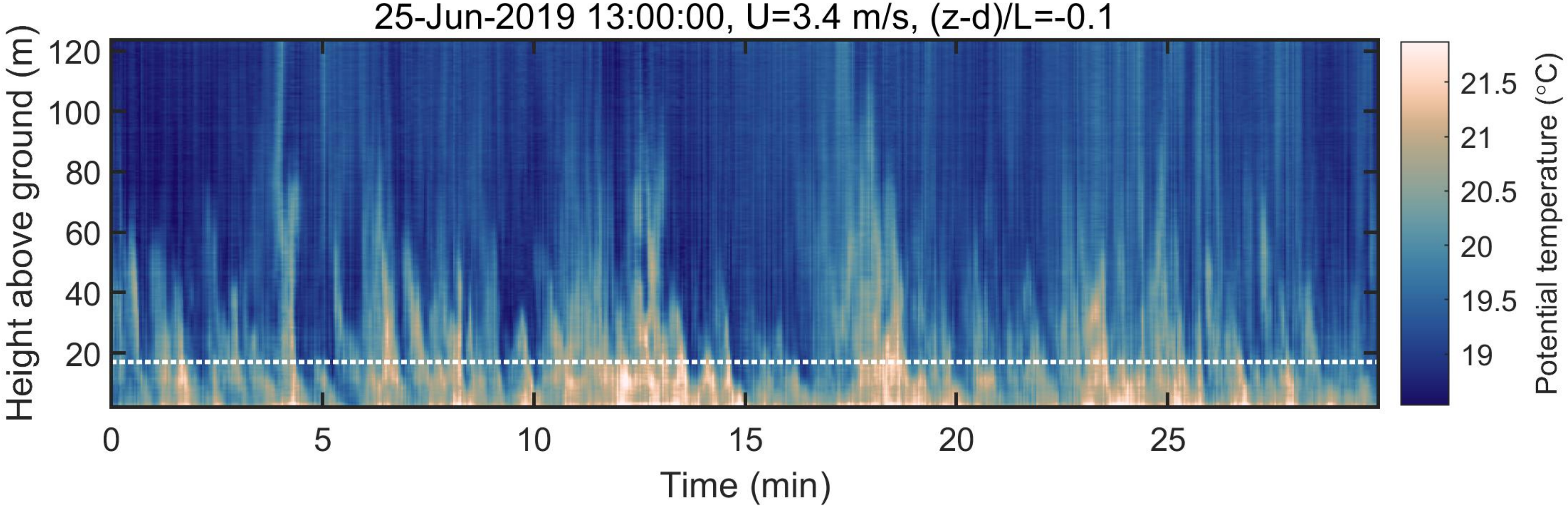
Epps, B. P., & Krivitzky, E. M. (2019). Singular value decomposition of noisy data: noise filtering. Experiments in Fluids, 60(8), 126. https://doi.org/10.1007/s00348-019-2768-4
van de Giesen, N., Steele-Dunne, S. C., Jansen, J., Hoes, O., Hausner, M. B., Tyler, S., & Selker, J. (2012). Double-ended calibration of fiber-optic Raman spectra distributed temperature sensing data. Sensors (Basel, Switzerland), 12(5), 5471–5485. https://doi.org/10.3390/s120505471
Hausner, M. B., Suárez, F., Glander, K. E., van de Giesen, N., Selker, J. S., & Tyler, S. W. (2011). Calibrating single-ended fiber-optic Raman spectra distributed temperature sensing data. Sensors (Basel, Switzerland), 11(11), 10859–10879. https://doi.org/10.3390/s111110859
Wilczak, J. M., Oncley, S. P., & Stage, S. A. (2001). Sonic Anemometer Tilt Correction Algorithms. Boundary-Layer Meteorology, 99(1), 127–150. https://doi.org/10.1023/A:1018966204465

Results: daytime example

- 30-min time series of potential temperature profile during weakly unstable period measured with the fibre-optic cable (DTS)



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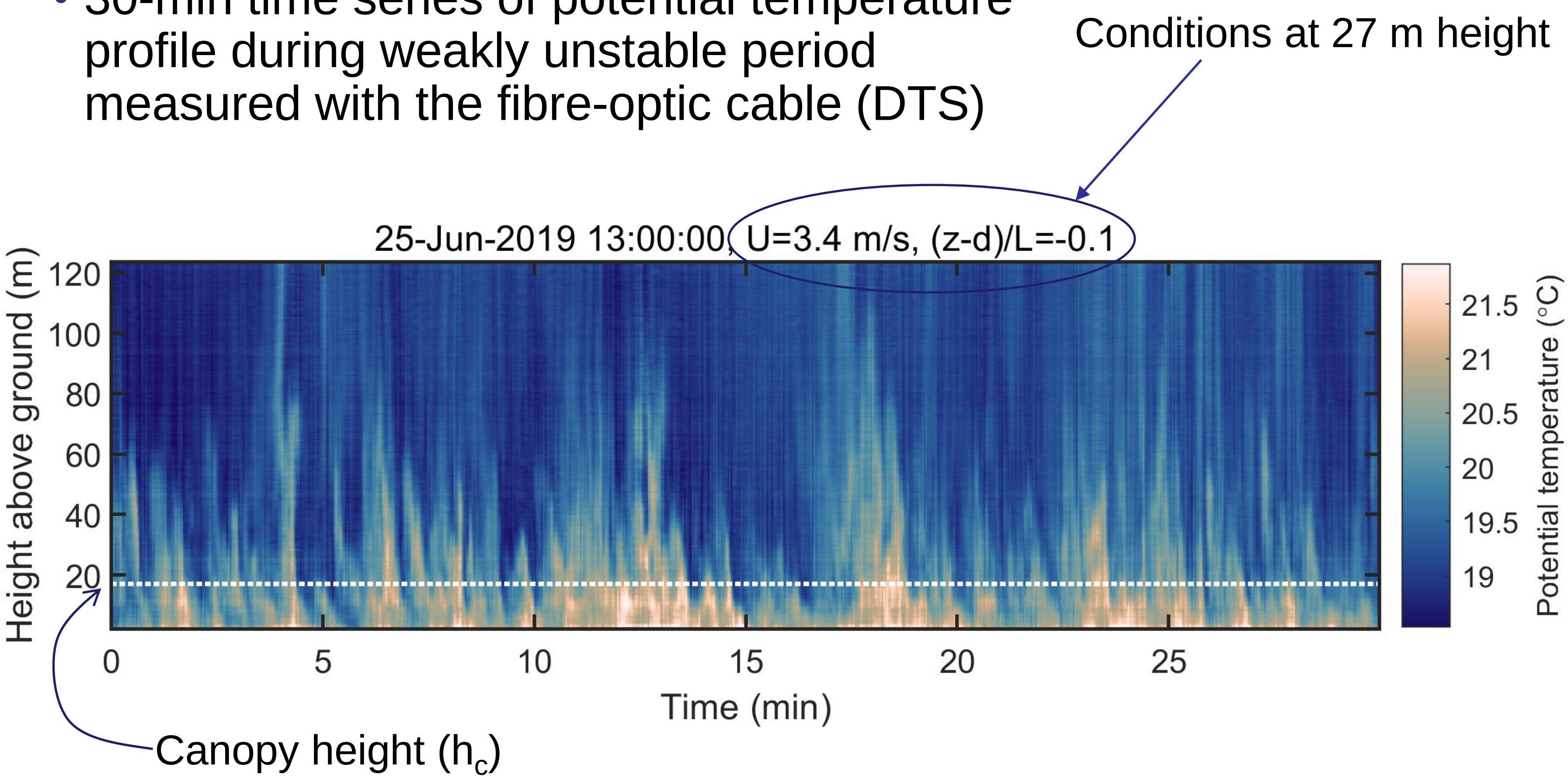

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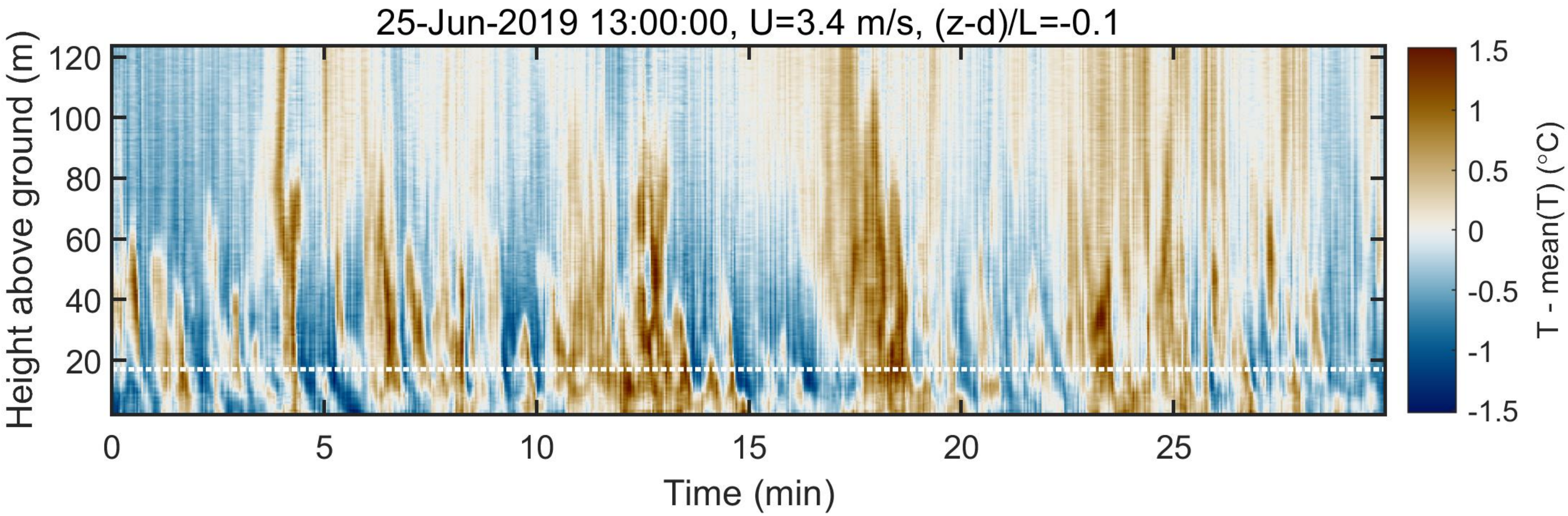
Results: daytime example

- Profile of temperature fluctuations around temporal mean at each height reveal turbulent structures better
- Negative excursions (blue) match with downward and positive (brown) with upward air movement (not shown)



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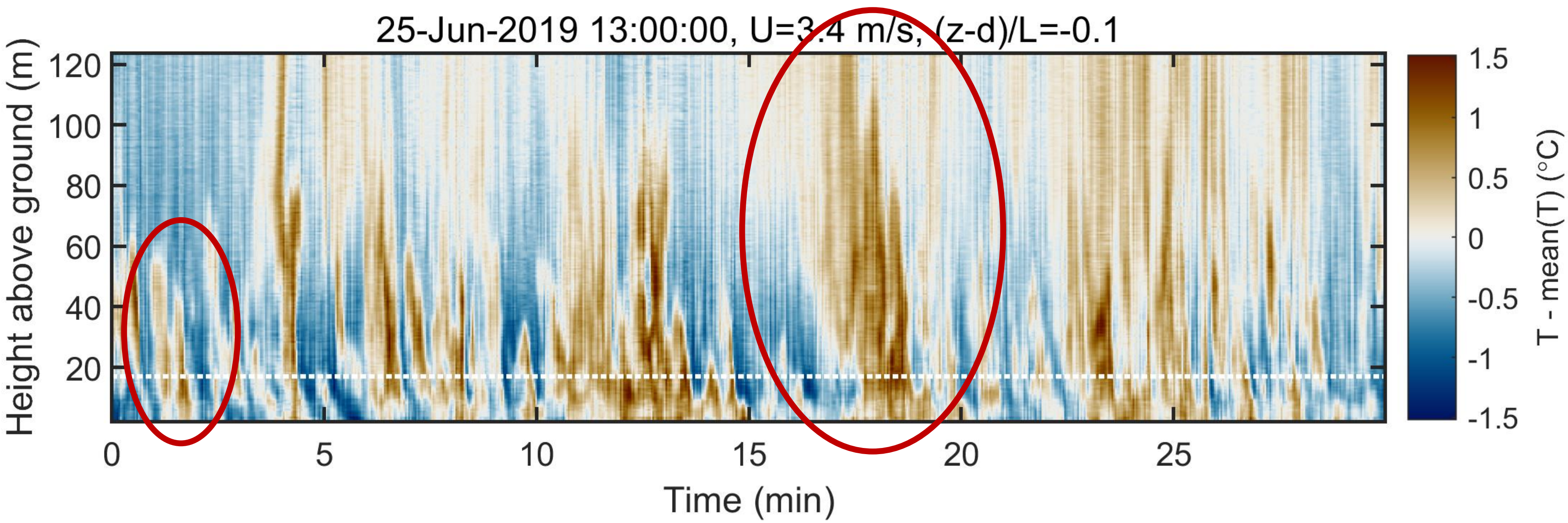
Results: daytime example

- Different sizes of structures can be identified
- By applying Taylor's frozen turbulence hypothesis time can be converted to horisontal distance and hence eddy size



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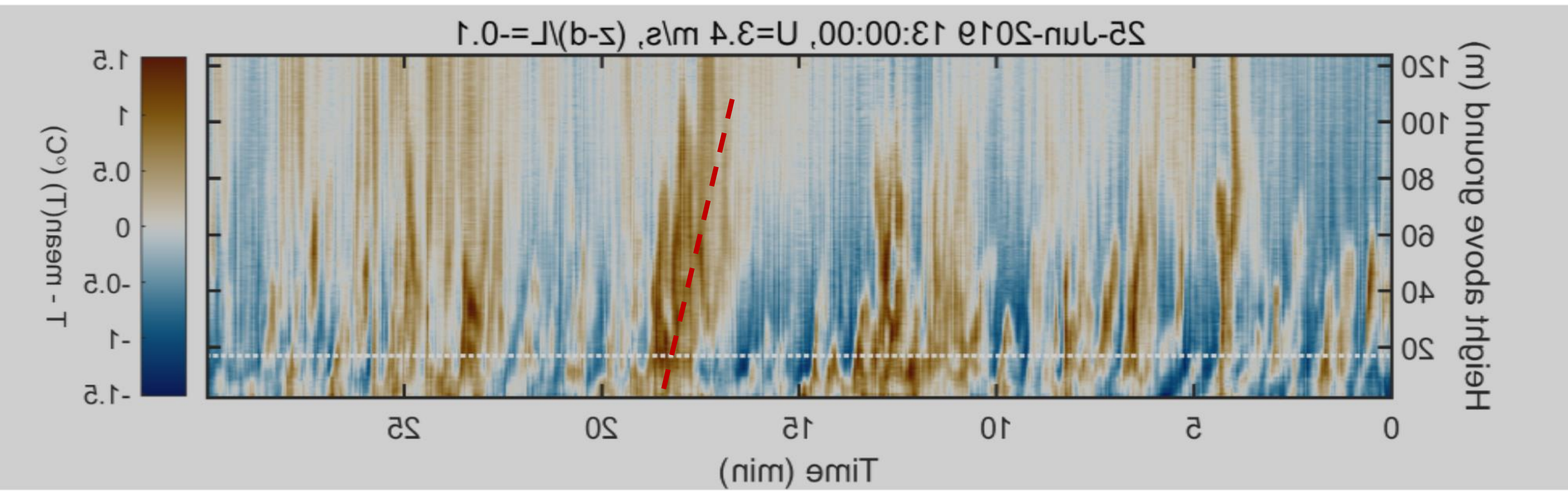
Results: daytime example

- By inverting the time axis we observe the eddies as they are advected past the measurement mast
- The eddies are inclined as they are advected by the mean flow and hence they are observed first at the highest levels



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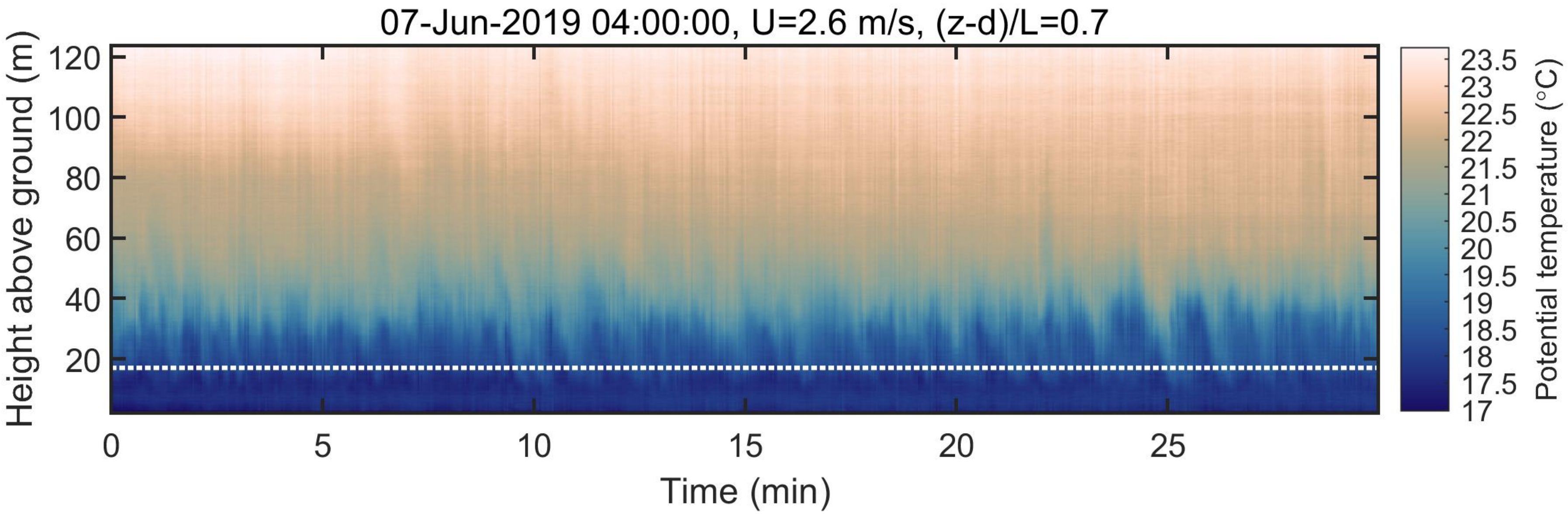
Results: night time example

- Stably stratified situation
- Coherent eddies between 10 m and 60 m
- No strong fluctuations above 60 m or below 10 m => negligible mixing



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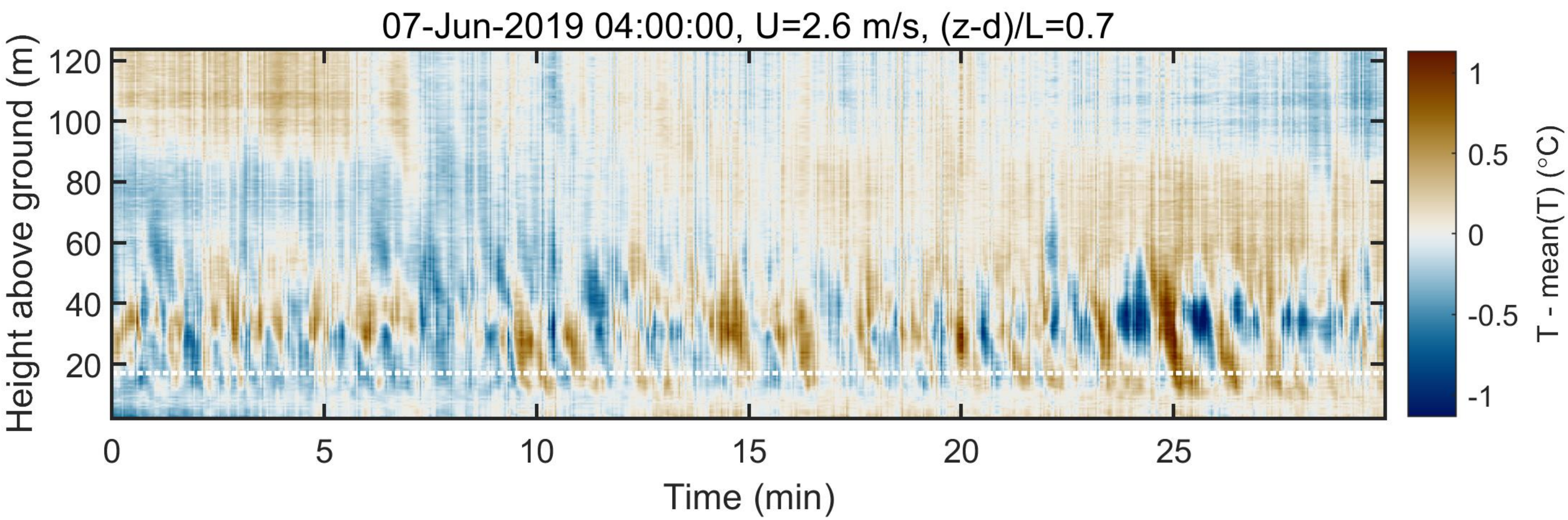

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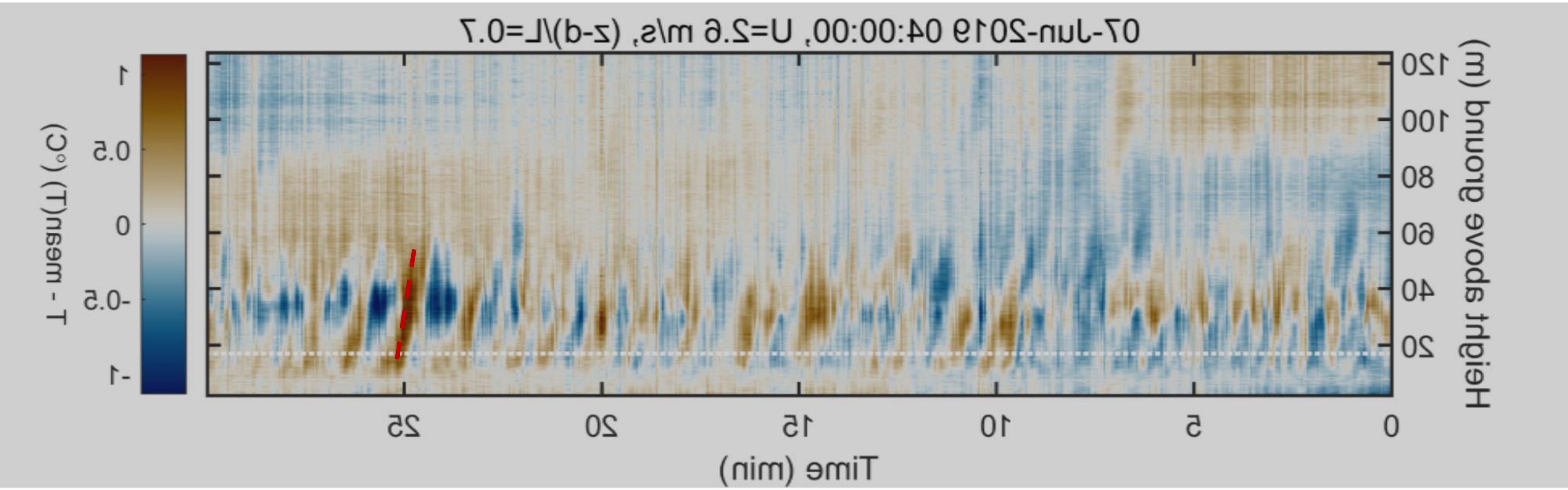

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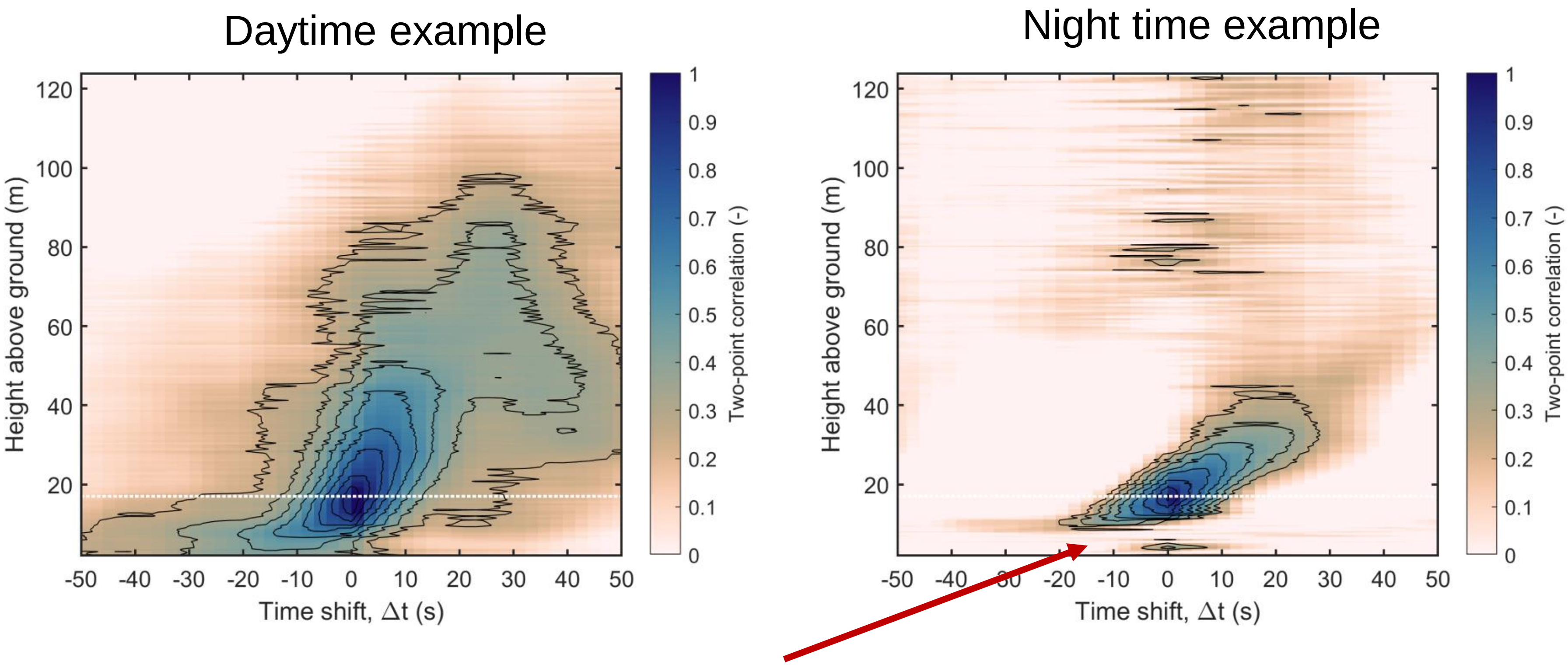
Two-point correlation

- Calculating two-point correlations for each averaging period with the following equation:

$$R(z,\Delta t) = \frac{\overline{T(h_c,t)T(z,t+\Delta t)}}{\sigma_T(h_c)\sigma_T(z)}$$



Note that the large eddies are decoupled from the forest floor

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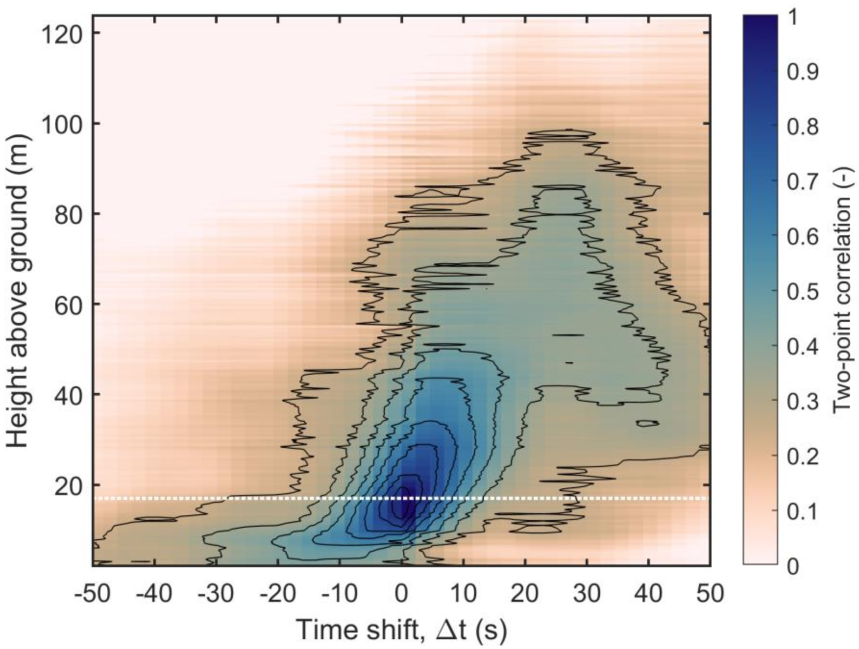
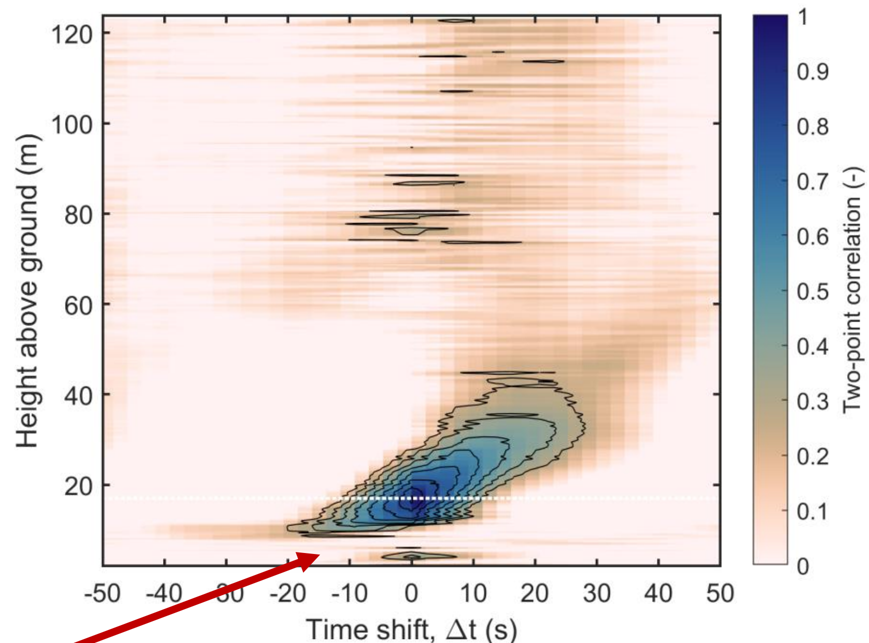
Two-point correlation

- Two-point correlations can be approximated to show the vertical and temporal extend of those flow structures that dominate the T variability at the reference height (here canopy height h_c)

Daytime example



Night time example



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Canopy eddies and decoupling

- Calculation of two-point correlations from the DTS data for each averaging period during the 1.5 month long measurement campaign
- Converting the x-axis from temporal (time shift) to spatial (distance) scale using Taylor's frozen turbulence hypothesis.
- Ensemble averaging the calculated two-point correlation matrices for different conditions

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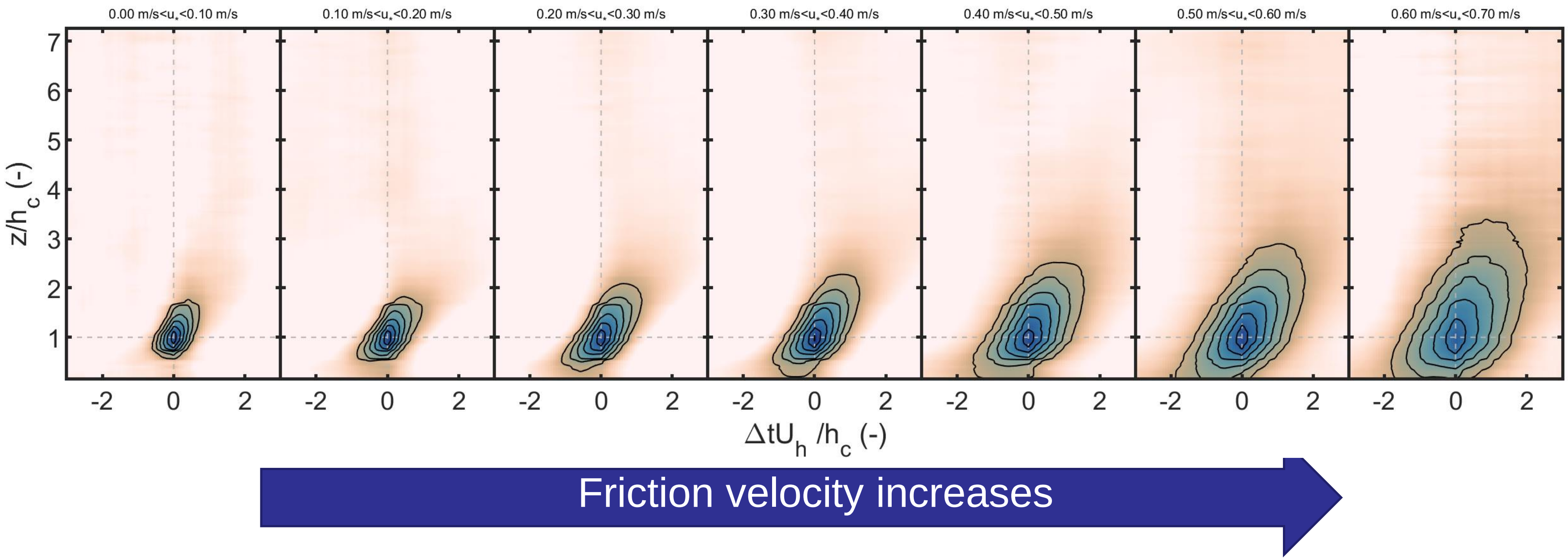
Canopy eddies and decoupling

- Ensemble averaged two-point correlations in friction velocity bins
- Only night time data



U_h=eddy advection velocity (wind speed at canopy height)

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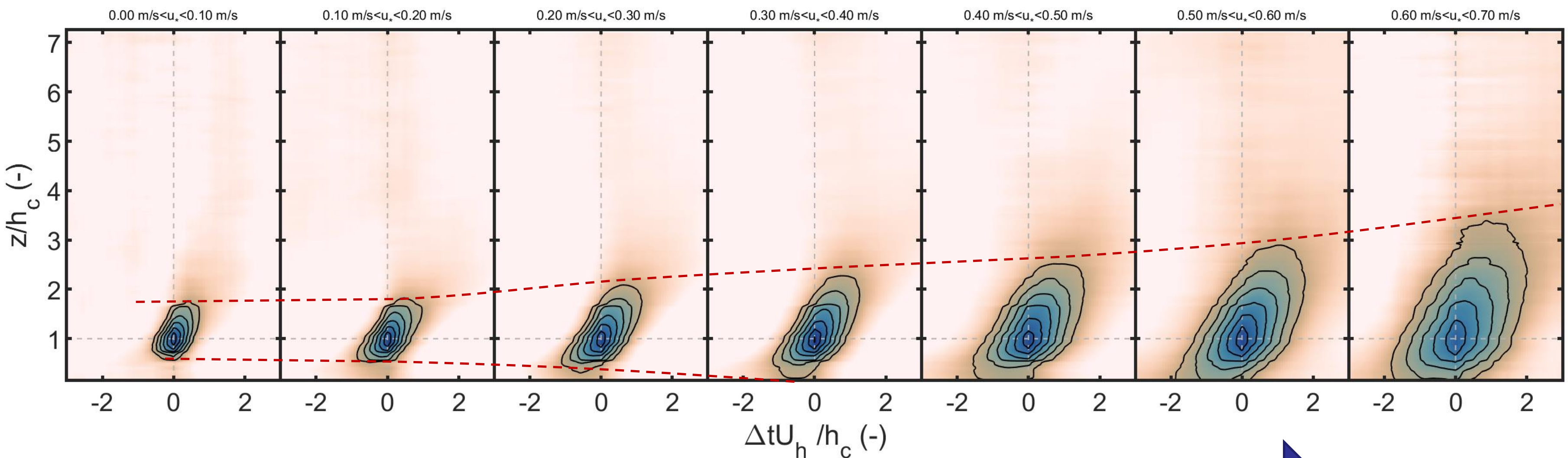
Canopy eddies and decoupling

- The height of the eddies dominating T variability at canopy height increase from $2h_c$ to $3h_c$ as u_* increases
- At low u_* the eddies are decoupled from the surface, but couple with the surface as u_* increases



Friction velocity increases

U_h=eddy advection velocity (wind speed at canopy height)

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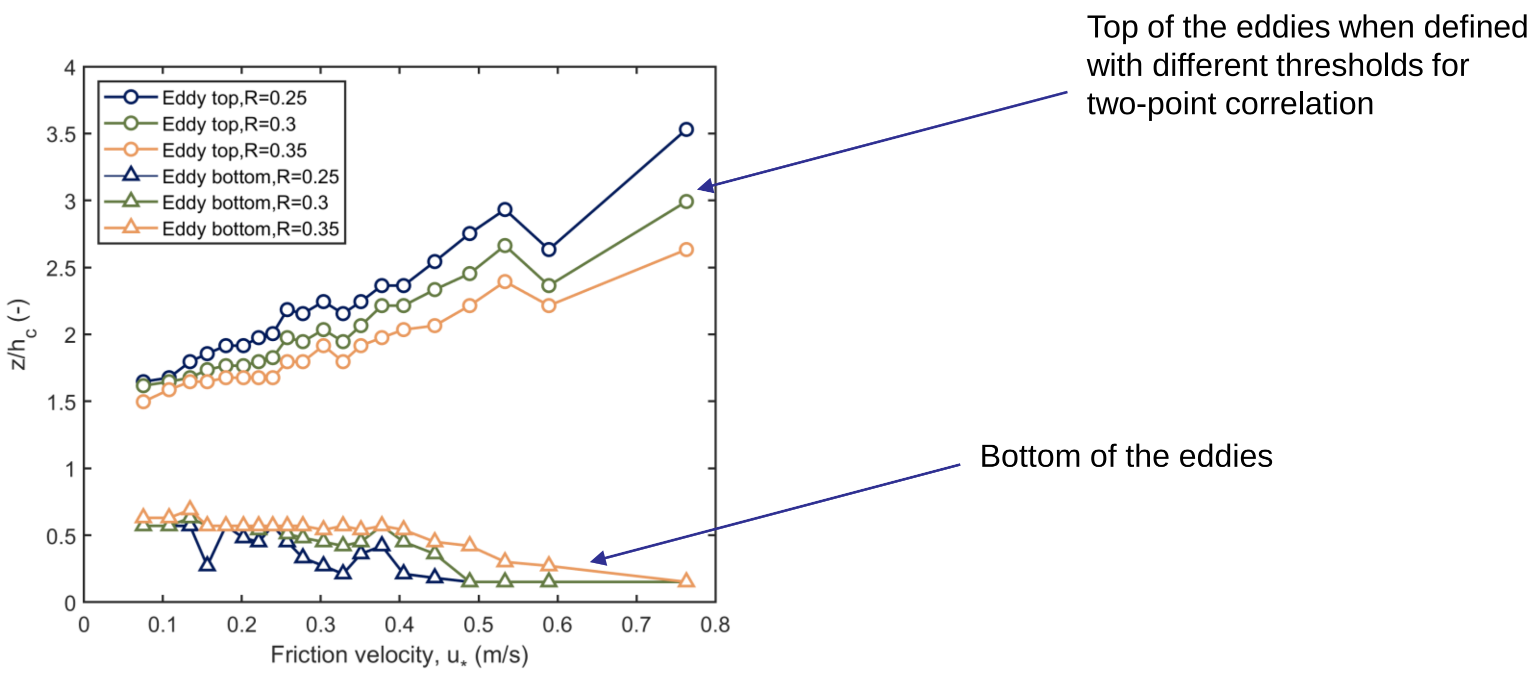
Canopy eddies and decoupling

- Analysing the bottom and top of the canopy eddies at night in different friction velocity bins
- Note that the eddies couple with the surface when u_* around 0.3…0.5 m/s



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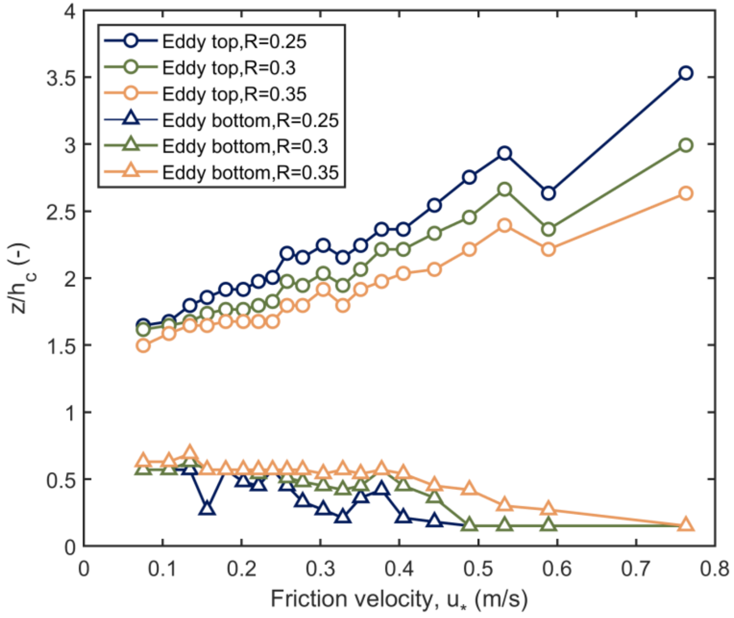
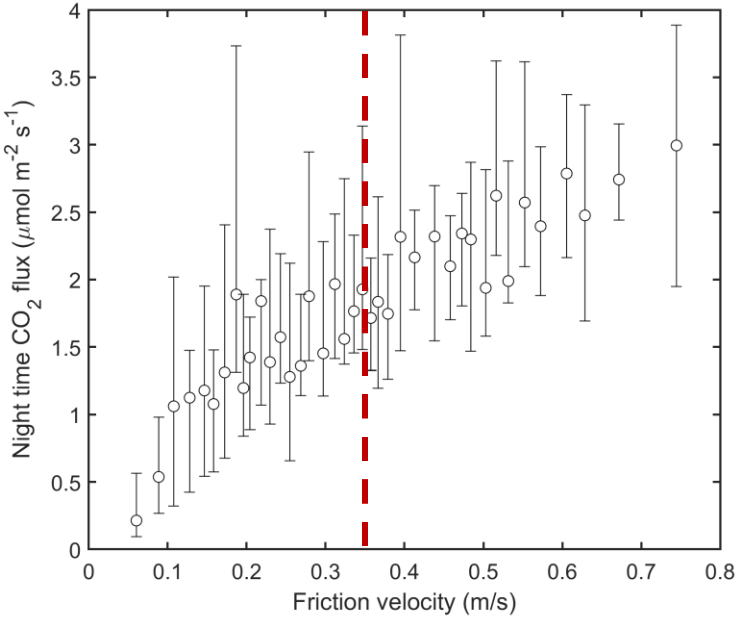
Canopy eddies and decoupling

- Note that when canopy eddies couple with the surface, CO_2 fluxes are almost independent of u_*





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Conclusions

- Coherent eddies were identified in the vertical DTS measurements
- Different eddy sizes were observed in different mixing conditions
  - Large thermal eddies in daytime unstable situation
  - Eddies that scale with h_c and produced by wind shear at the canopy top at night time
- At night time canopy eddies were decoupled from the forest floor in low u* conditions, but coupled with the surface once u* increased
- The u* limit at which the eddies coupled with the surface was similar to the u* threshold used in filtering CO_2 fluxes

  ⇒Is the coupling of large coherent eddies with the ground a necessary condition for observing unbiased CO_2 fluxes above canopies?
- Here fluctuations in T were used to estimate large canopy eddies and to study the cross-canopy coupling. This approach circumvents the critique of Freundorfer et al. (2019) on using above- and below-canopy σ_w on analyzing cross-canopy coupling
- This analysis will be complemented in the future with more in-depth analysis of coupling between below- and above-canopy wind data

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Freundorfer, A., Rehberg, I., Law, B. E., & Thomas, C. (2019). Forest wind regimes and their implications on cross-canopy coupling. Agricultural and Forest Meteorology, 279, 107696. https://doi.org/https://doi.org/10.1016/j.agrformet.2019.107696

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Thanks for reading!

OP is supported by the postdoctoral researcher project (decision 315424) funded by the Academy of Finland.

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