Correlations between thermal surface heterogeneities and secondary circulations during LITFASS-2003

An LES study

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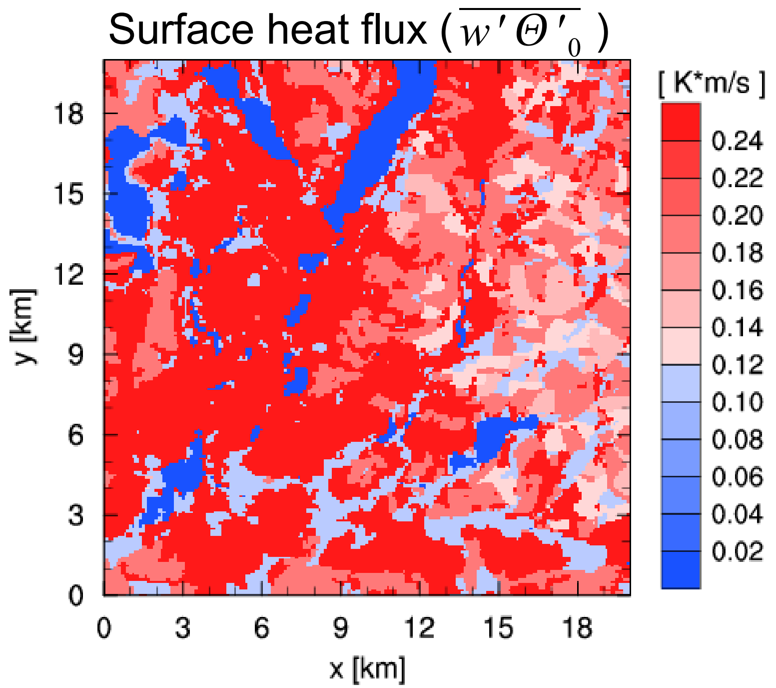
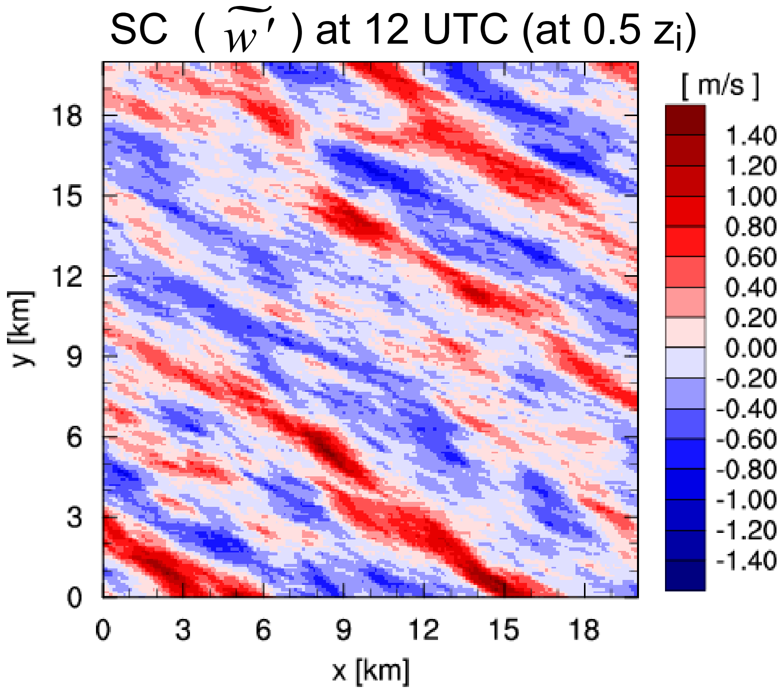
Introduction (I) : Secondary Circulations (**SCs**) and Heterogeneities

- Previous simulation results as starting point:





- Complex SC patterns appear above realistic surface heterogeneities

- Roll-like SC patterns develop in case of higher background winds

Introduction (II) : Motivation and Hypothesis

Main questions:

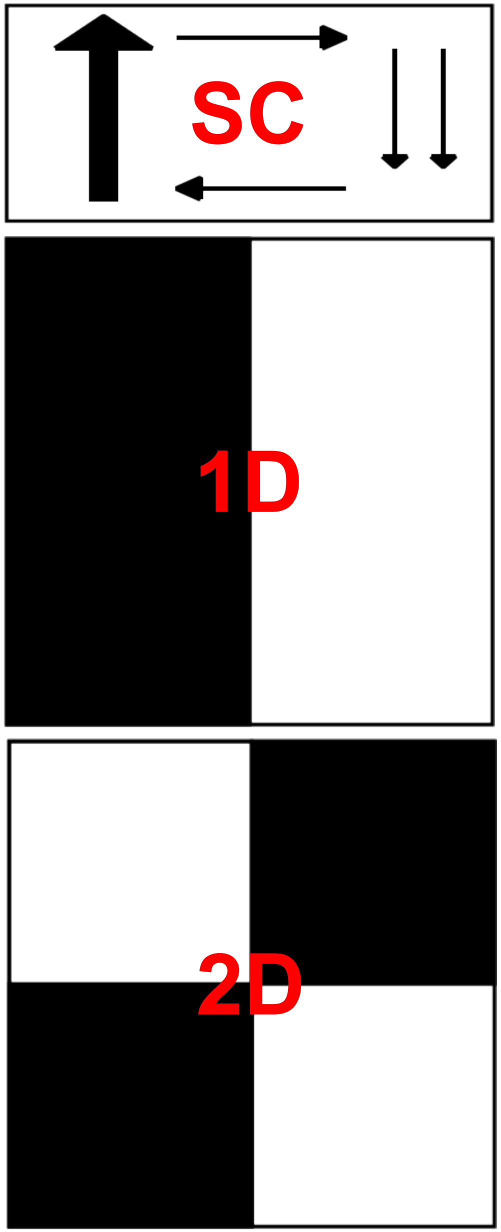
1. **Can the SCs be linked to the heterogeneities?**
2. **Is it possible to estimate the SC patterns in advance?**

Hypothesis (1): In case of roll patterns, there is a linear correlation between the streamwise-averaged underlying sensible surface heat flux and the vertical velocity of the SCs

Roughly speaking: the flow sees a "smeared" sensible surface heat flux and SCs develop according to this heat flux

Introduction (III) : Idealized Surface Heterogeneities

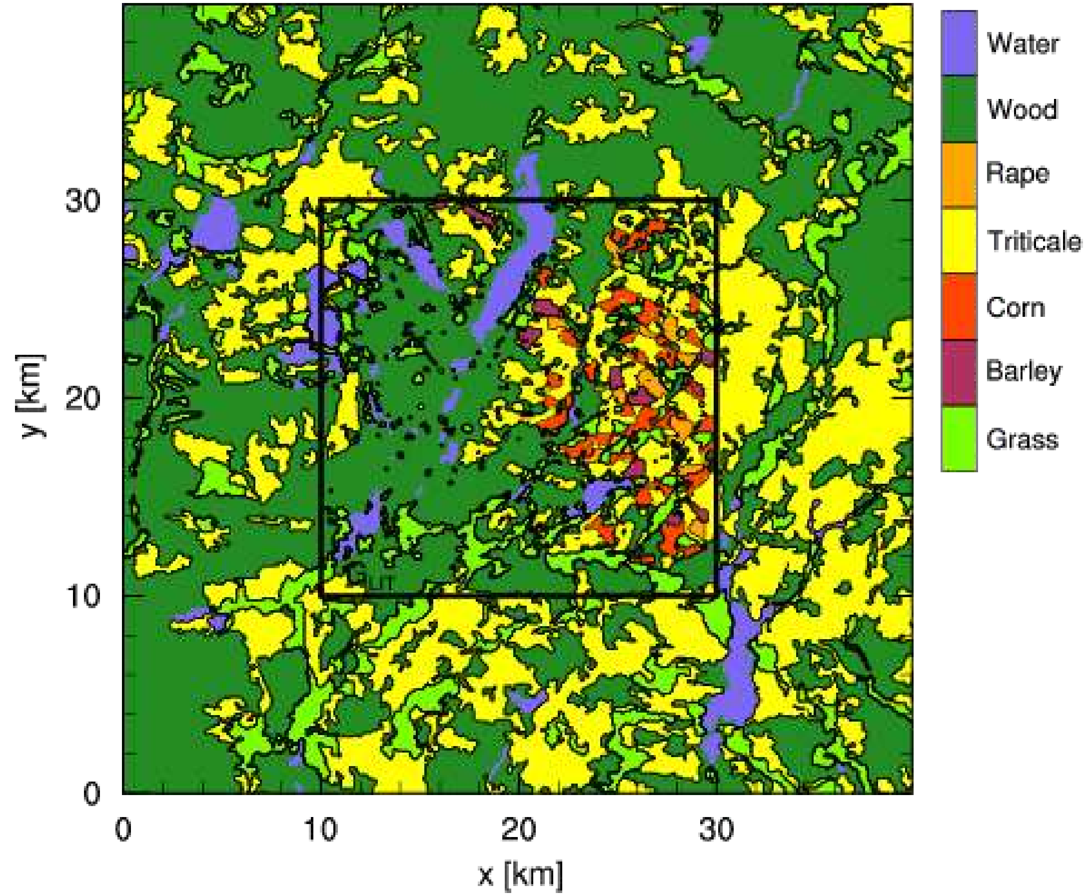
- Thermal heterogeneities: temperature or heat flux
- Past LES studies mainly investigated idealized heterogeneities
- **1D:** stripe-like or wave
  e.g. Avissar and Schmidt (1998), Patton et. al. (2005)
- **2D:** checkerboard
  e.g. Shen and Leclerc (1995), Raasch and Harbusch (2001), Courault et. al. (2007)
- SCs were obtained, depending on:
  - background wind speed and direction
  - amplitude of surface heating
  - size / wavelength of the patches
- Superimposed on the small-scale turbulent field



Idealized heterogeneities

Introduction (IV) : Real Heterogeneities during LITFASS-2003

- LITFASS Area (20km x 20km) in the south-east of Berlin, Germany
- LES with the aid of the model **PALM** (Raasch and Schröter, 1998)
- Follow-up study to Uhlenbrock (2006)
- Simulations require:
  - horizontal cyclic boundaries
  - special averaging (no phase average)

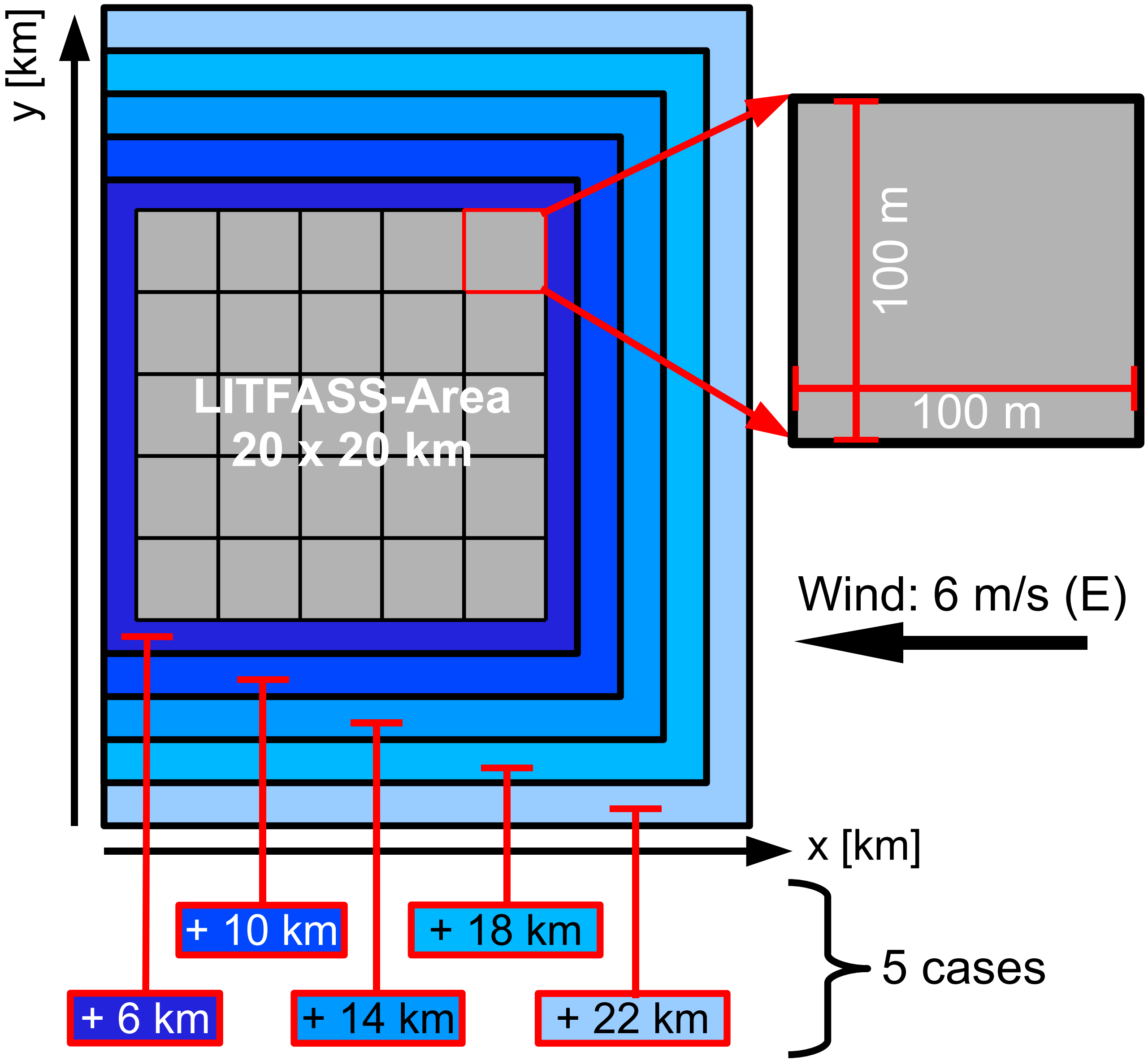


Land-use classes in the LITFASS area

- Ensemble-averaging:

$$\underbrace{w(x,y,z,t)}_{total} = \underbrace{\widetilde{w'}(x,y,z)}_{ensemble-average} + \underbrace{w''(x,y,z,t)}_{small-scale}$$

Model Setup and Driving Mechanism



- Setup:
  - Model domain up to **44 km x 56 km**
  - Vertical grid spacing: **50 m**
- Driving from measurements
  - $\overline{w'\Theta'}_0$ and $\overline{w'q'}_0$ (12 UTC)
  - Roughness length $\mathbf{z_0}$
- Initial profiles: neutral stratification with capping inversion ($z_i \sim z_i$ (12 UTC))
- Simulation over **6h**

Results (I) : Correlation Analysis

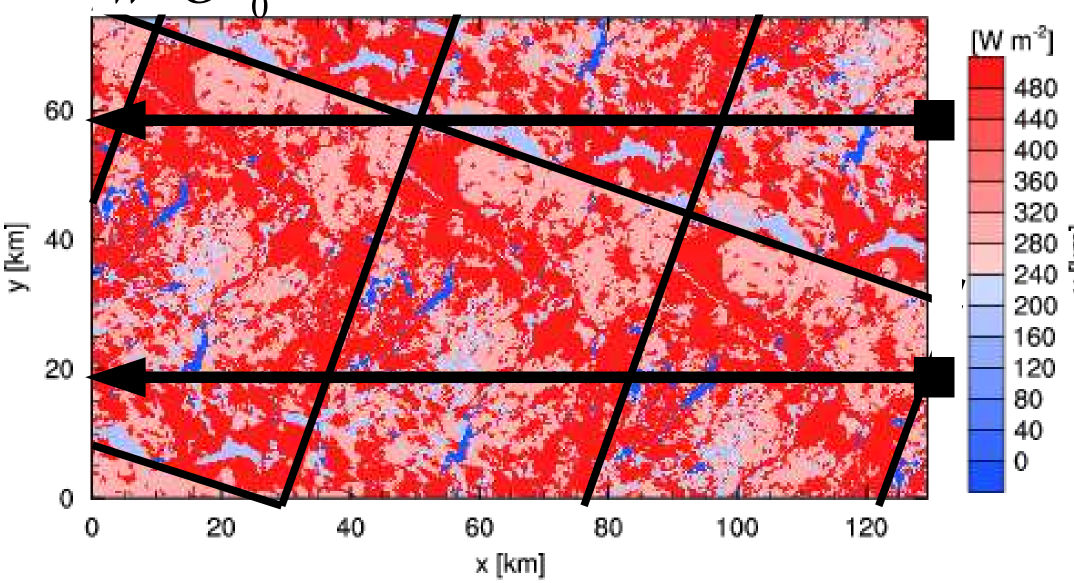
1. Averaging $\widetilde{w'}$ from 5h - 6h

2. Extending the fields to the distance a parcel of air passes during simulation time (here 126km in 6h), rotation

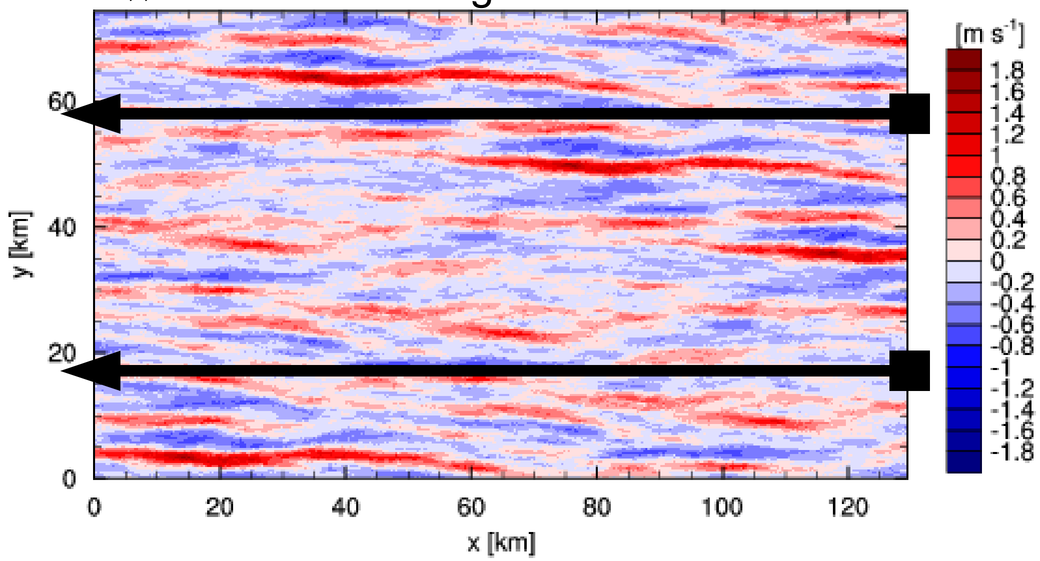
3. Streamwise averaging of $\overline{w'\Theta'_0}$ and $\widetilde{w'}$ at z = 0.4 * z_i (along the rolls' axes)

4. Calculating the cross-correlation $\rho_{\overline{w'\Theta'_0},\widetilde{w'}}$

$\overline{w'\Theta'_0}$

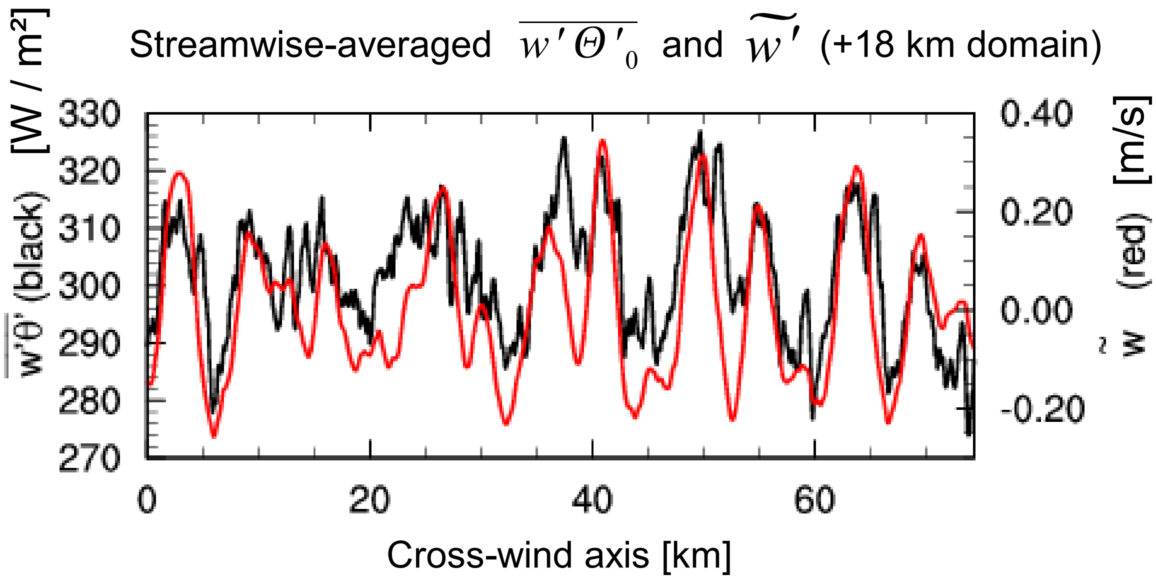


$\widetilde{w'}$ at 0.4 zi averaged from 5h - 6h



Results (II) : Constant forcing

Streamwise-averaged $\overline{w'\Theta'_0}$ and $\widetilde{w'}$ (+18 km domain)



Buffer	$\rho_{\overline{w'\Theta'_0},\, \widetilde{w'}}$
6 km	0.49
10 km	0.42
14 km	0.60
18 km	0.69
22 km	0.71

Correlations for different cases

- Slightly increasing with model domain
- Cross-correlations for all 5 cases:

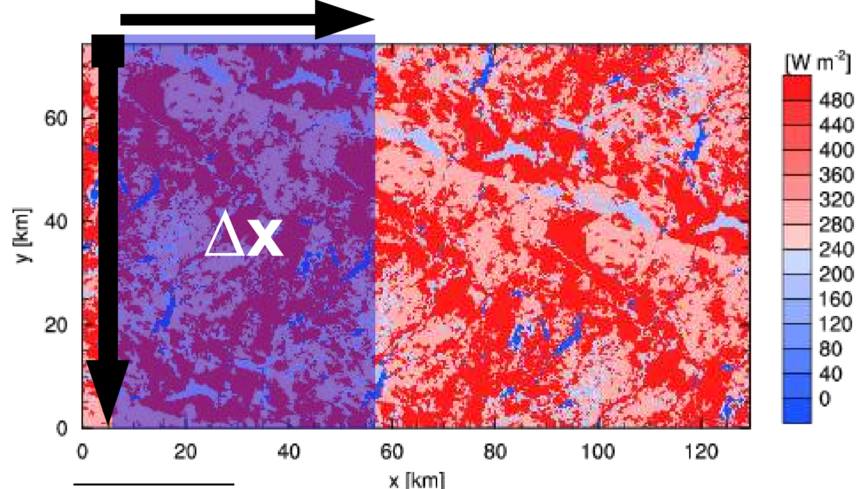
$$0.42 \leq \rho_{\overline{w'\Theta'_0},\, \widetilde{w'}} \leq 0.71$$

Results (III): Determination of the Fetch Length

Hypothesis (2): The contribution of $\overline{w'\Theta'}_0$ to the locally observed circulation should be large for the near upstream region and should decrease with distance.
A fetch length **FL**, which gives information about the upstream fetch, can be calculated.

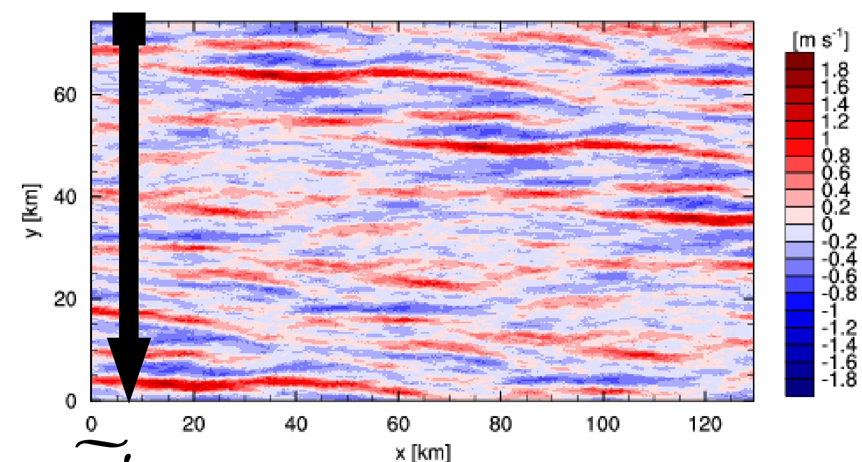
$$\bar{\rho}(\Delta x) = \frac{1}{N}\sum_{i=0}^{N} \rho\left(\widetilde{w}'(x_{i+1}, y), \overline{w'\Theta'}_0(\Delta x, y)\right) \quad \forall \quad \Delta x = 1, 2, \ldots, x_{max}$$

$\overline{w'\Theta'}_0(\Delta x = 50 \text{ km}, y)$



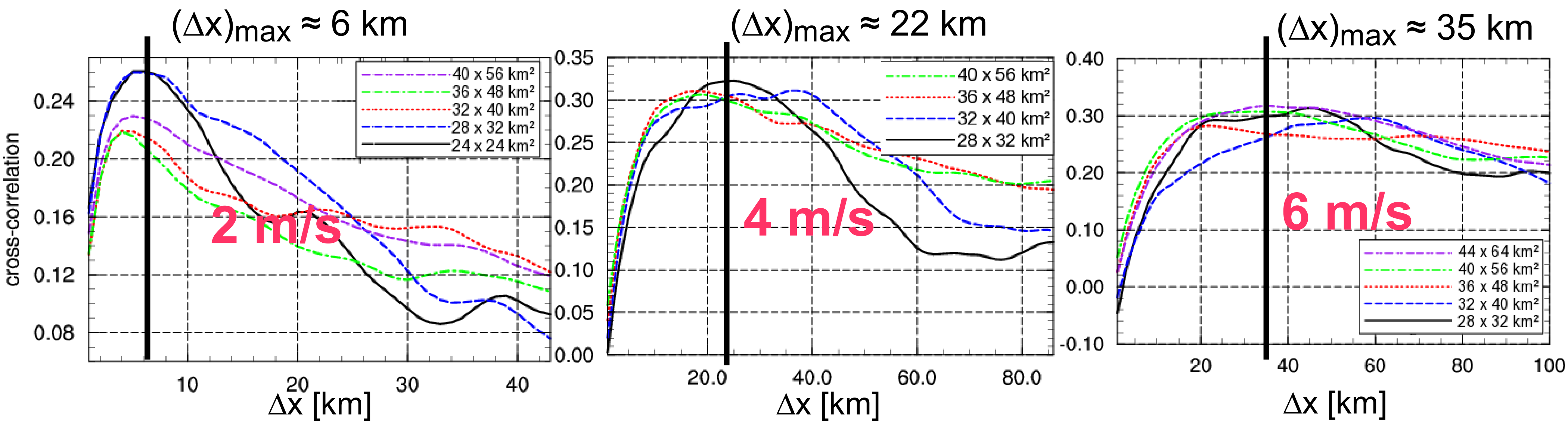
$\overline{w'\Theta'}_0$

$\widetilde{w}'(x = 7 \text{ km}, y)$



$\widetilde{w}'$ at 0.4 zi averaged from 5h - 6h

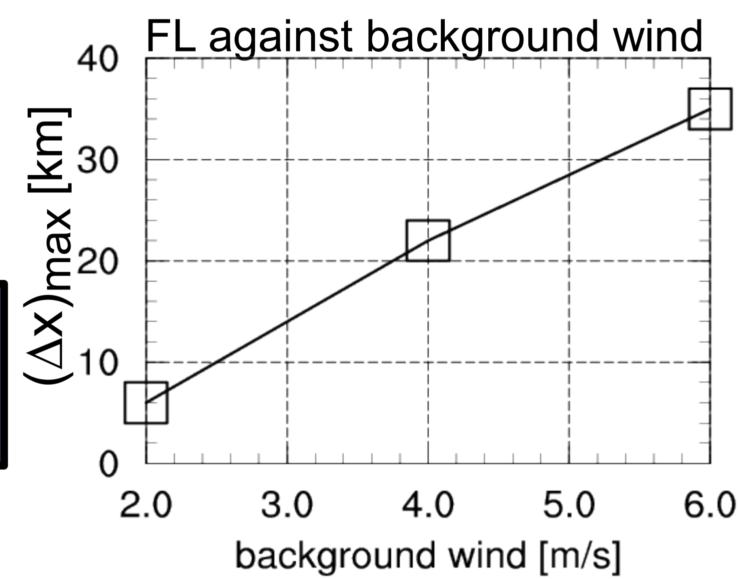
Results (IV): Determination of the Fetch Length



Cross-correlation against fetch lengths Δx for different background winds

- Simulations for **2 m/s**, **4 m/s** and **6 m/s** were carried out for comparison

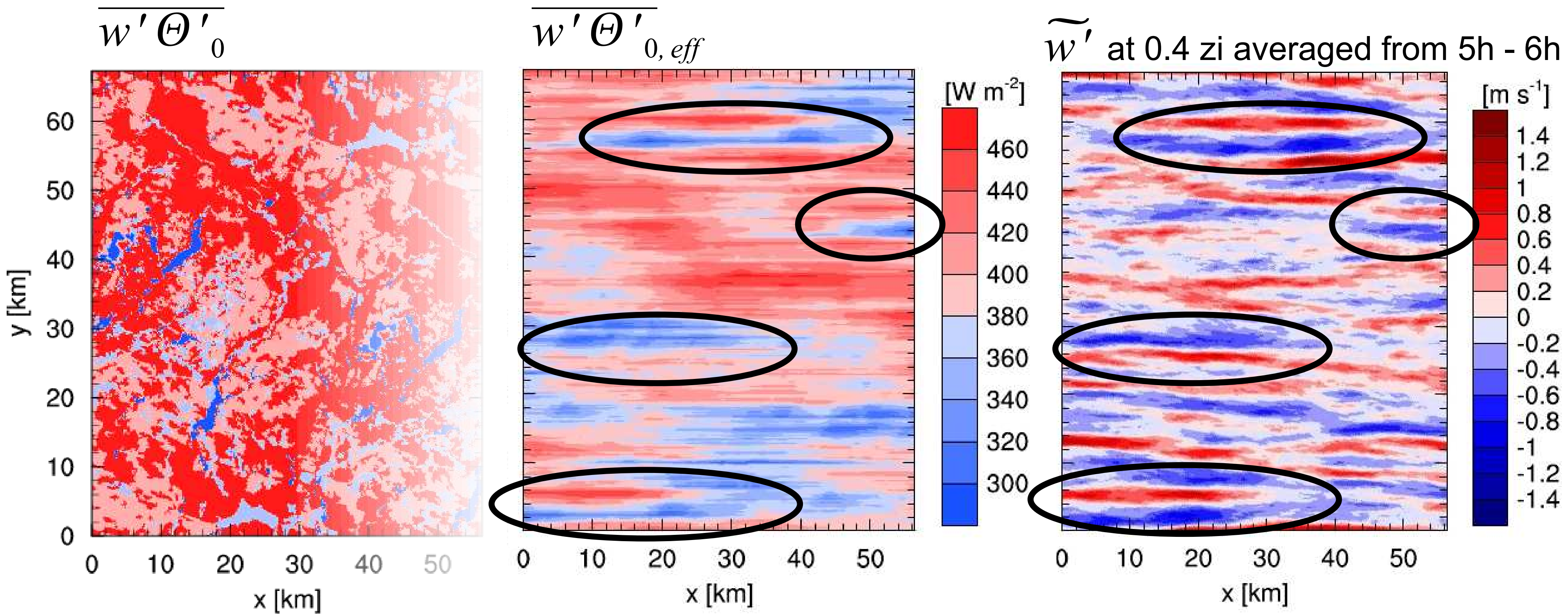
Result: FL ≡ $(\Delta x)_{max}$ increases with increasing background wind



Results (V) : Effective Surface Heat Flux

- **Definition:** "effective surface heat flux": $$\overline{w'\Theta'}_{0,\,eff}(i,j)=\frac{1}{FL}\sum_{k=0}^{FL-1}\overline{w'\Theta'}_0(i+k,j)$$

- Upstream moving average of the surface heat flux



Conclusions

- Cross-correlation of streamwise-averaged $\overline{w'\Theta'}_0$ and $\widetilde{w'}$ showed **high correlations (ρ ≤ 0.71)** and support the hypothesis that the flow sees a “smeared” surface heat flux which is causing the development of roll-like secondary circulations in case of higher wind speed
- Also valid for realistic simulations with a diurnal cycle **(ρ = 0.48 at 12 UTC, not shown)**
- The **upstream fetch length** (**FL**) of the flow due to the effect of advection could be determined. It is increasing with background wind
- The **“effective surface heat flux”** allows a rough *a priori* estimation of the secondary circulation patterns with the aid of the fetch length
- Further results from this study (not discussed here), e.g.:
  - Entrainment over heterogeneous surfaces is slightly decreased
  - Scalar quantities behave significantly different than $\widetilde{w'}$ and show larger scale structures