Large-Eddy Simulation of the Convective Atmospheric Boundary Layer over Heterogeneous Land Surfaces

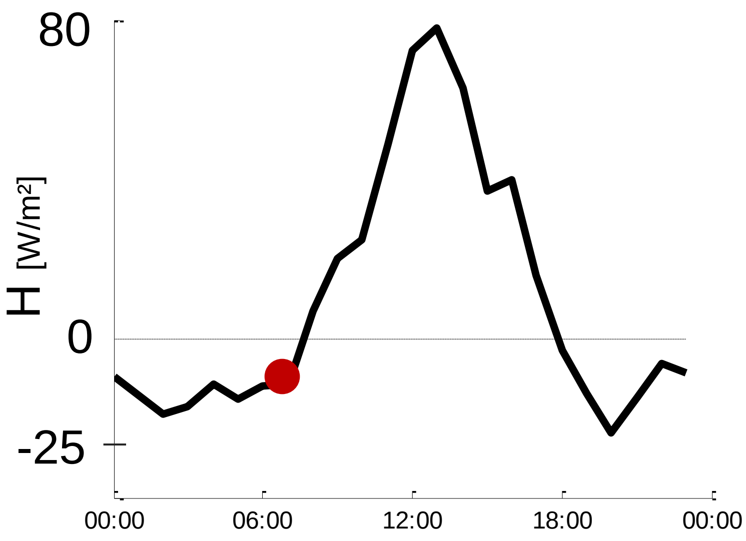
Daniel Nadeau

V. Kumar, C. Higgins, M. B. Parlange, E. Pardyjak

San Francisco, 17 December 2009

Motivations

Diurnal cycle of sensible heat flux



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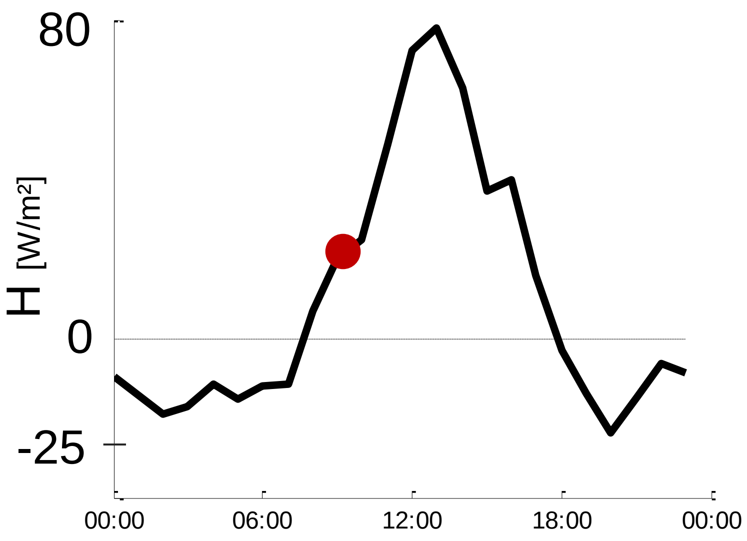
Motivations

Diurnal cycle of sensible heat flux



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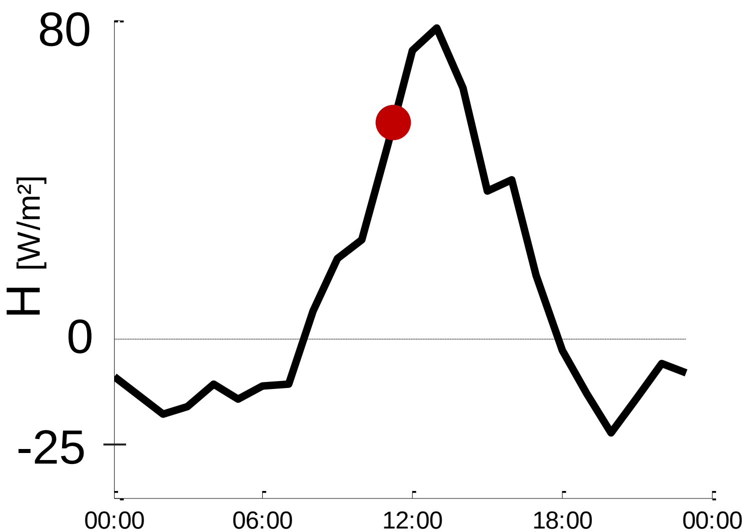
Motivations

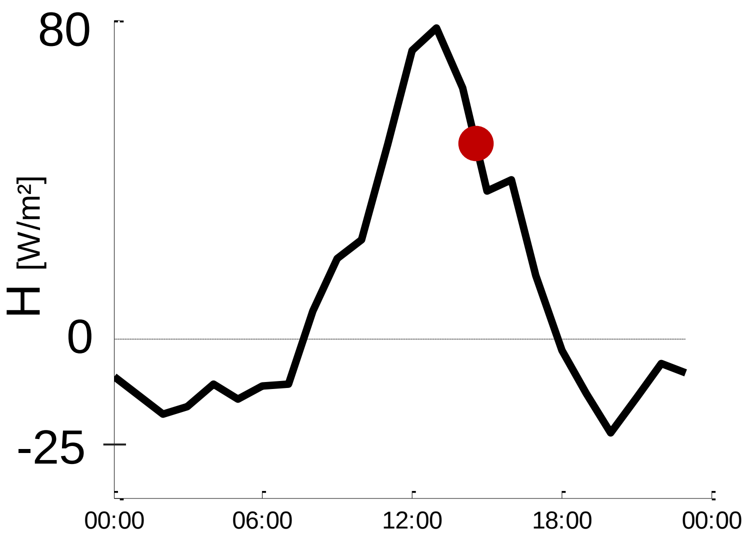
Diurnal cycle of sensible heat flux



11:30

Motivations

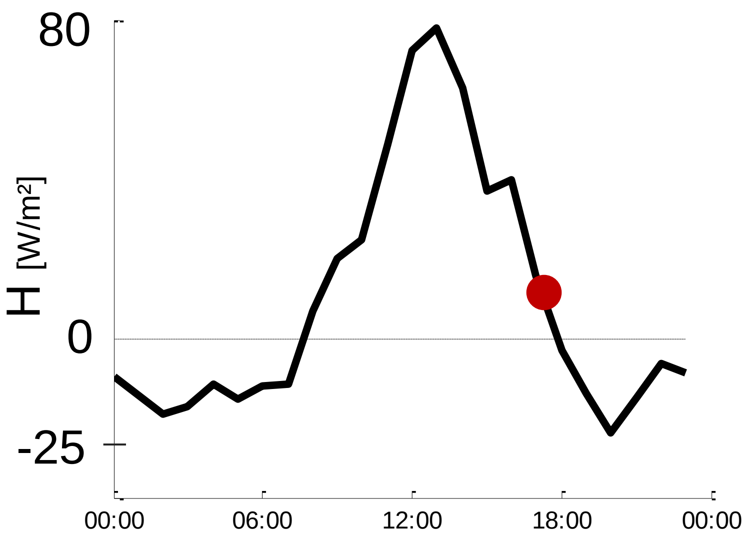
Diurnal cycle of sensible heat flux



14:30

Motivations

Diurnal cycle of sensible heat flux



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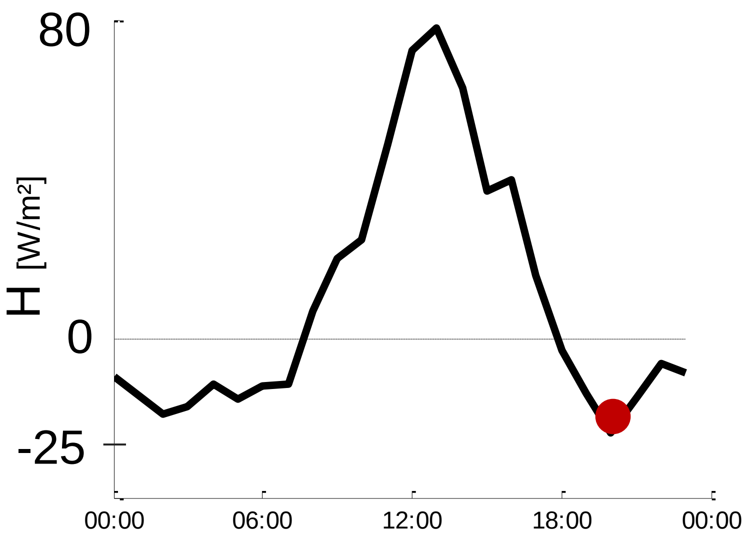
Motivations

Diurnal cycle of sensible heat flux



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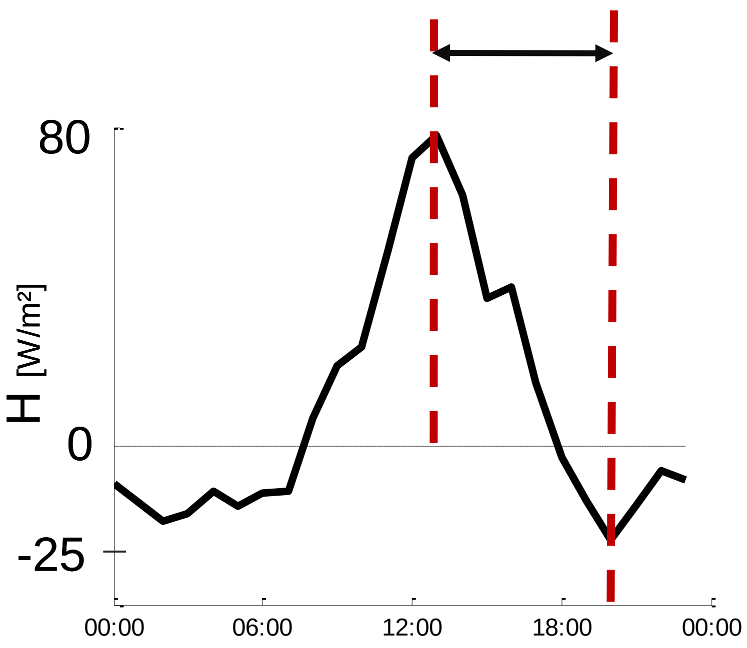
Motivations

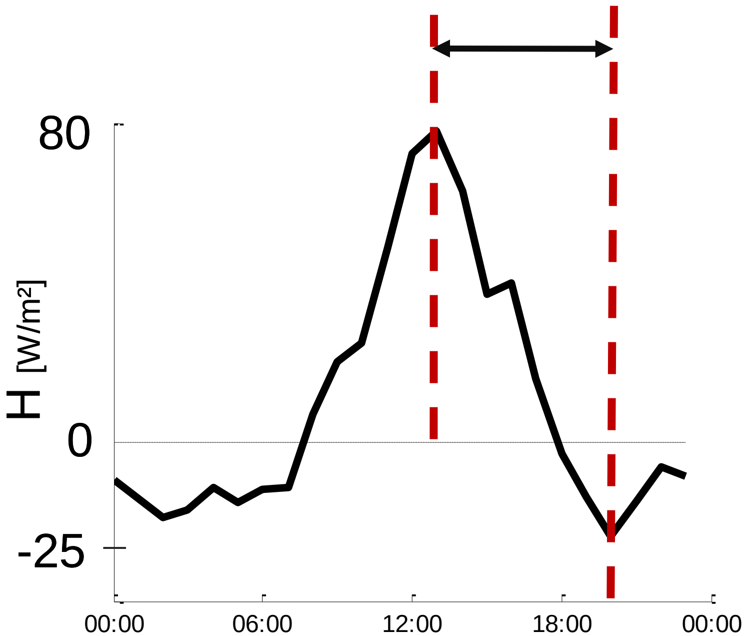
convective decay



Well studied for homogeneous conditions…

Motivations

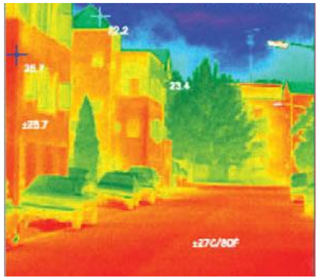
convective decay



Well studied for homogeneous conditions…

But in reality the surface is heterogeneous!

… in thermal properties



… in geometry

Impact of realistic heterogeneous surface conditions on afternoon convective decay?

Background

Scales of motion in the ABL

largest scales ~ 1 km

smallest scales ~ 1 mm

$\sim 10^6$

Background

Scales of motion in the ABL

largest scales ~ 1 km

$$\sim 10^6$$

smallest scales ~ 1 mm

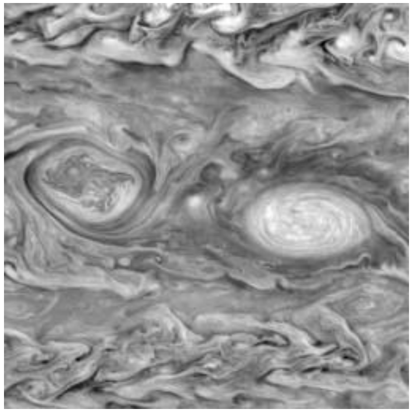
Impossible to resolve all these scales explicitly!

Background

Large-eddy simulation

Large scale motions:
- affected by the BCs
- carry the turbulent fluxes of momentum and heat

Small scale motions:
- more homogeneous and isotropic
- receive their energy from the larger scales



Background

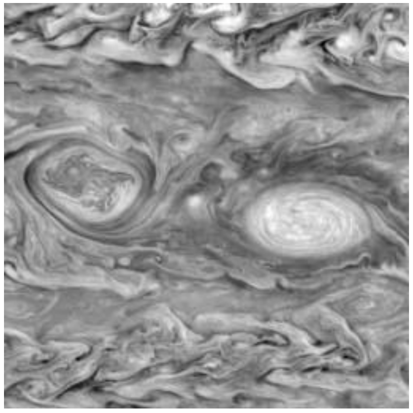
Large-eddy simulation

Large scale motions:
- affected by the BCs
- carry the turbulent fluxes of momentum and heat

solve them

Small scale motions:
- more homogeneous and isotropic
- receive their energy from the larger scales

parameterize them



Background

Set of governing equations

- Incompressible Navier-Stokes
- Boussinesq approximation
- Coriolis forcing

$\sim$	filtered variable
f	Coriolis parameter
U_g, V_g	geostrophic wind
τ_{ij}	SGS stress tensor
π_j	SGS flux of temperature

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i} \right) = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + g \left(\frac{\tilde{\theta} - \langle \tilde{\theta} \rangle}{\langle \tilde{\theta} \rangle} \right) \delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f \left(\tilde{u}_2 - V_g \right) \delta_{i1} - f \left(\tilde{u}_1 - U_g \right) \delta_{i2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j}$$

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A SGS model is needed!

Background

Sub-grid scale model

- Lagrangian scale-dependant dynamic model (Bou-Zeid et al., PF, 2005)
- Constant SGS Prandtl number

Smagorinsky model (Prandtl's mixing length hypothesis)

$$\nu_T = \underbrace{C_s}_{\text{Smagorinsky constant}} \cdot \underbrace{\Delta}_{\text{length scale}} \cdot \underbrace{\Delta\left|\tilde{S}\right|}_{\text{velocity scale}}$$

$$\tau_{ij}^{SMAG} = -2\left(C_{S,\Delta}\Delta\right)^2 \left|\tilde{S}\right| \tilde{S}_{ij}$$

$$\pi_{ij}^{SMAG} = -\frac{\left(C_{S,\Delta}\right)^2 \left|\tilde{S}\right|}{\Pr_{SGS}} \frac{\partial \tilde{\theta}}{\partial x_j}$$

ν_T	turbulent eddy viscosity
Δ	filter size
$\tilde{S}_{ij}$	resolved strain rate tensor
τ_{ij}^{SMAG}	modelled SGS stress
π_{ij}^{SMAG}	modelled SGS scalar flux

Model Setup

EPFL LES code details

- Spectral code in the horizontal directions
- Geostrophic forcing
- 2nd order centered finite differences in a staggered grid formulation in the vertical direction
- Monin-Obukhov Similarity applied at the first grid point
- Time integration: 2nd order Adams-Bashforth method
- Parallelization (MPI) using a domain decomposition with horizontal slices
- Dealiasing of nonlinear terms in Fourier space using the 3/2 rule

Used in several studies of the ABL:

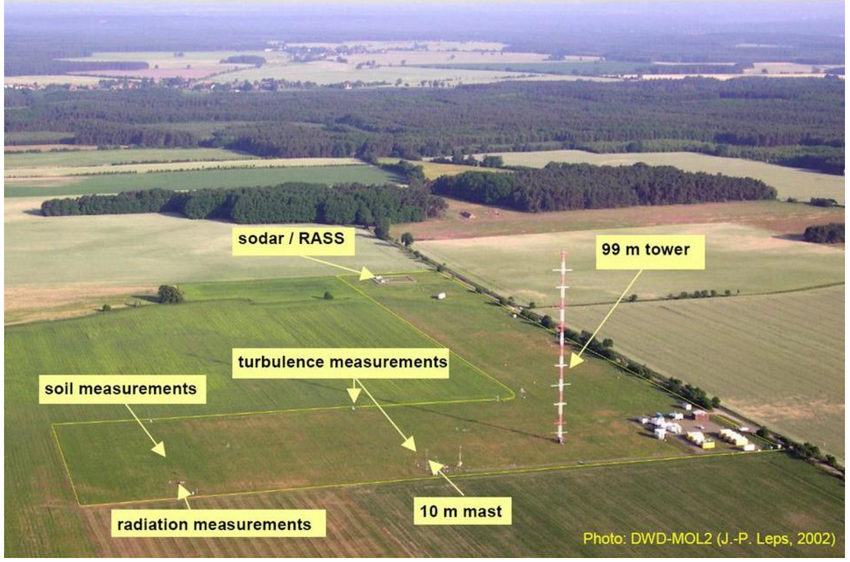
(Albertson & Parlange, AWR, 1999)
(Albertson & Parlange, WRR, 1999)
(Porté-Agel et al., JFM, 2000)
(Bou-Zeid et al., PF, 2005)
(Kumar et al., WRR, 2006)
(Yue et al., EFM, 2008)

Model Setup

Boundary conditions

LITFASS – 2003 (Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface: a long-term Study)

- Strong heterogeneities over flat terrain
- 20 x 20 km area
- 99-m meteorological mast
- Energy balance weather stations over different surface types
- Regular radiosonde launches
- SODAR/RASS system
- etc.



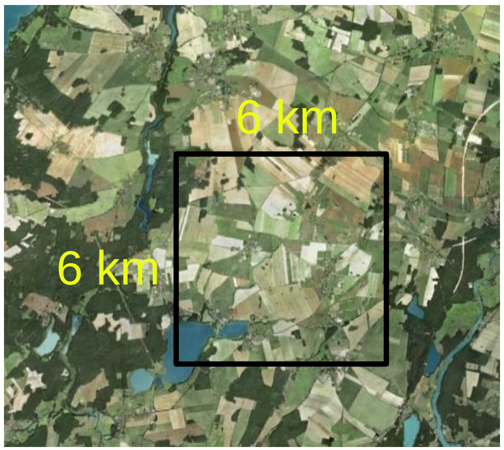
Model Setup

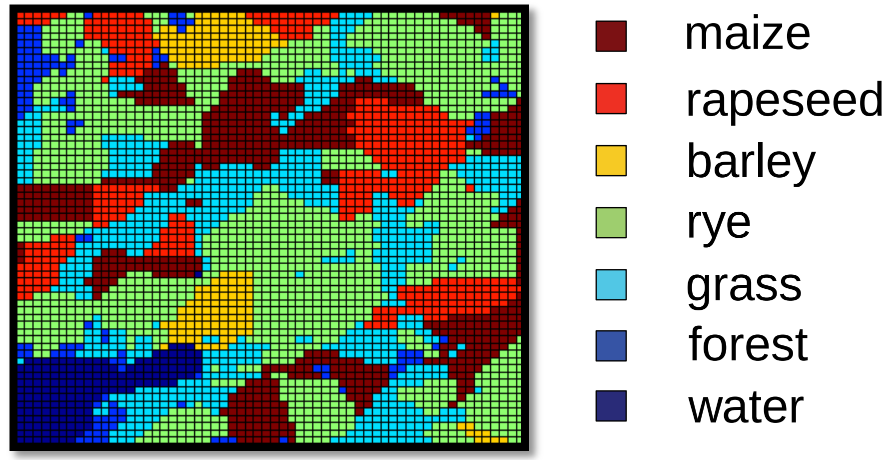
Simulation details

Number of grid points :	**64** x **64** x **64** (~ 262000)
Domain size – L_x , L_y ,L_z :	**6 km** x **6 km** x **3 km**
Horizontal mesh spacing – Δx, Δy :	93.75 m
Vertical mesh spacing – Δz :	46.88 m
Number of iterations :	180 000 with Δt = 0.2 sec (total of 10 h)
Number of processors:	**16 CPUs**
Geostrophic wind U_g :	-5 m/s

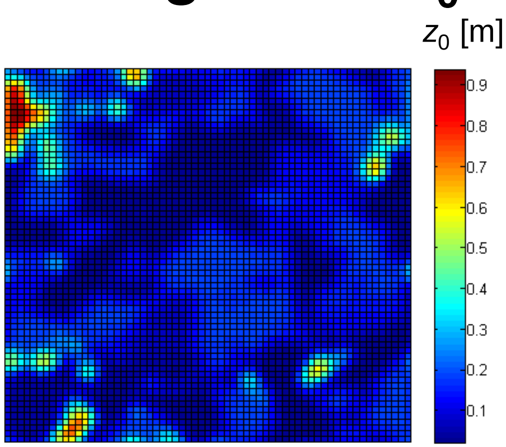
Model Setup

Surface type fields



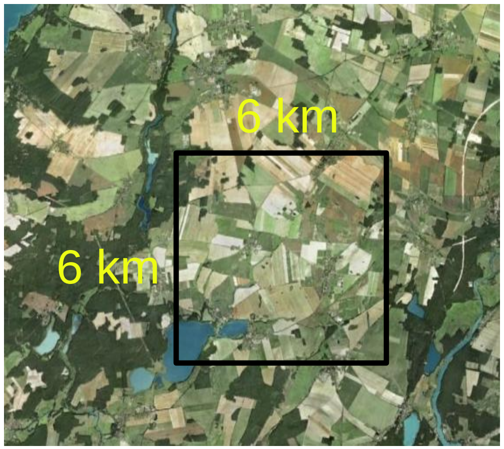


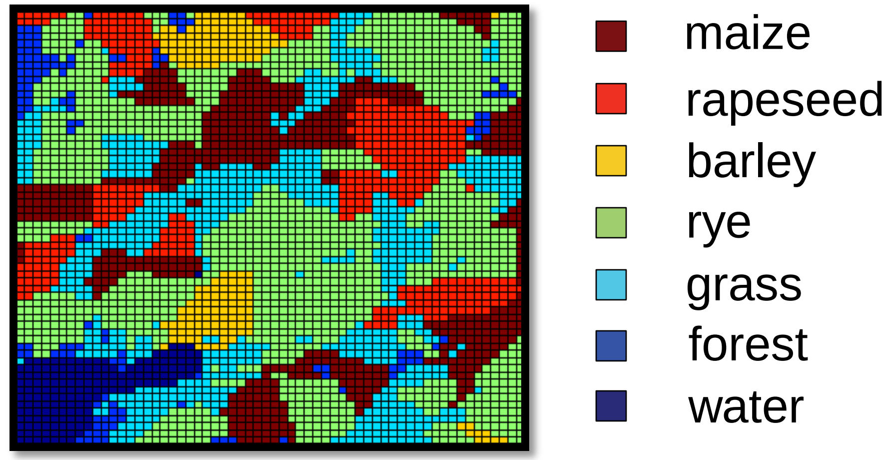
Surface roughness z_0



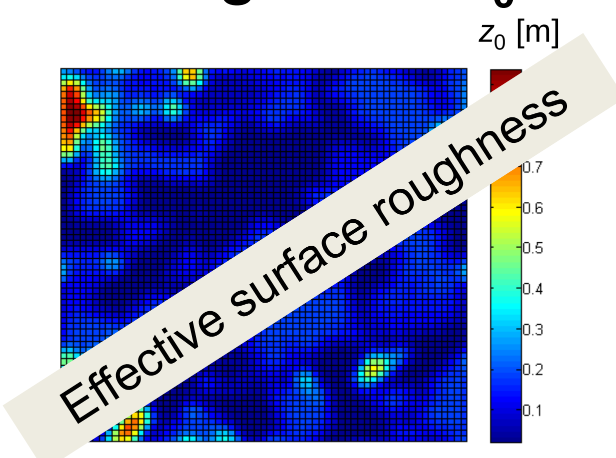
Model Setup

Surface type fields





Surface roughness z_0



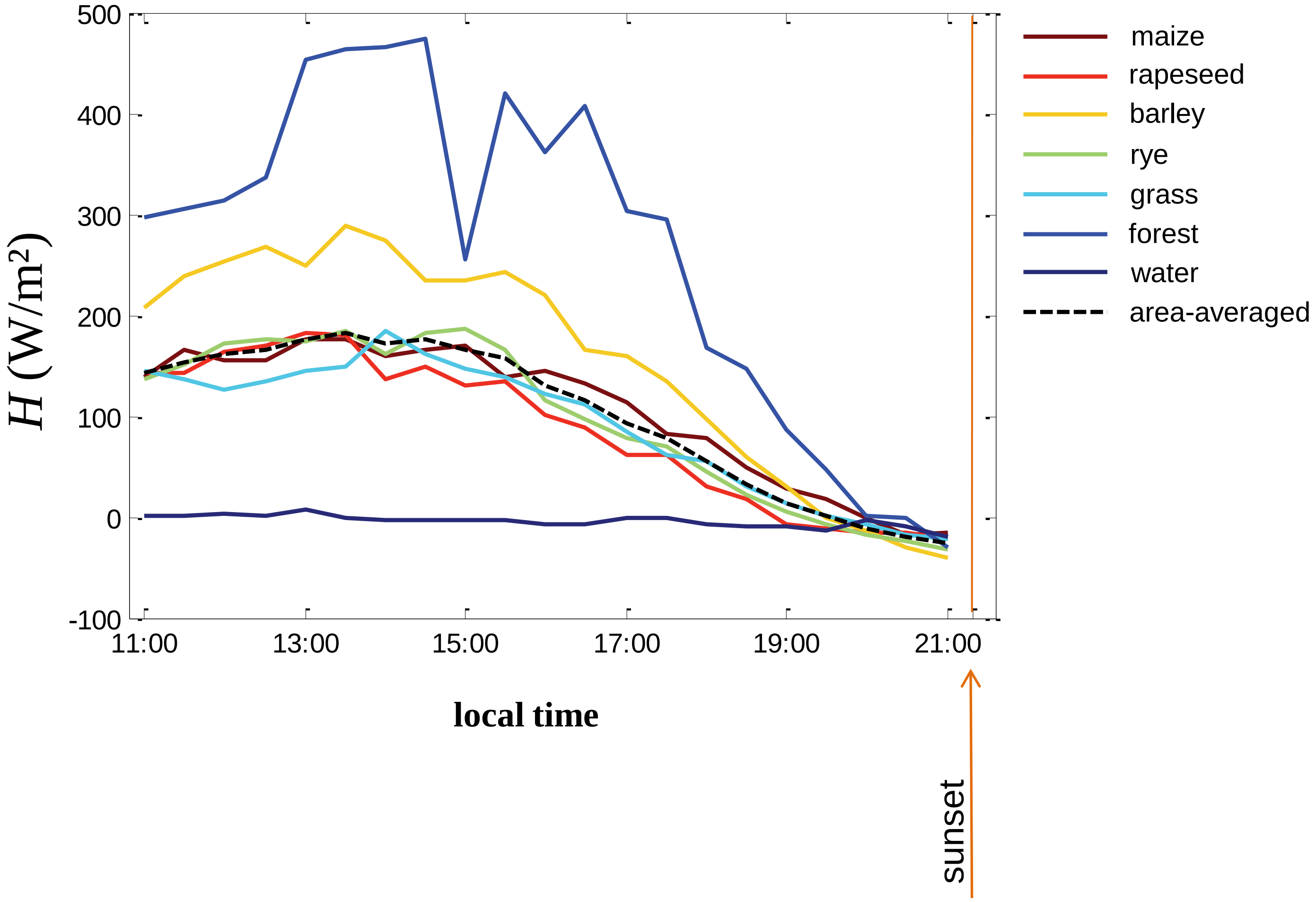
- Typical length patch length scale L_p= 1282 m
- Blending height h_b = 142.3 m

$z_{0,eff}$ = 0.11 m

See: Bou-Zeid et al., WRR, 2004
Bou-Zeid et al., JAS, 2007

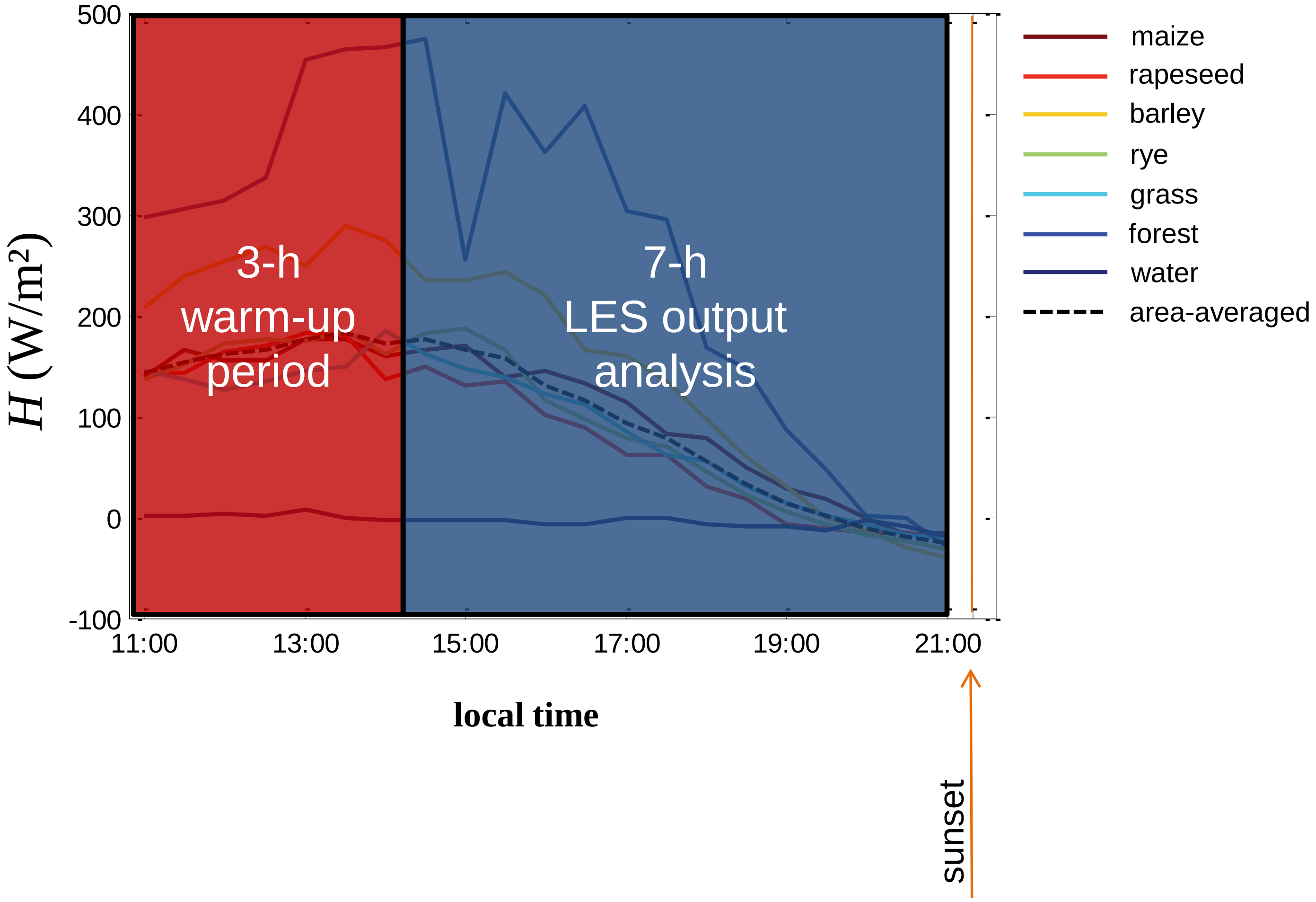
Model Setup

Boundary conditions – **Surface heating**



Model Setup

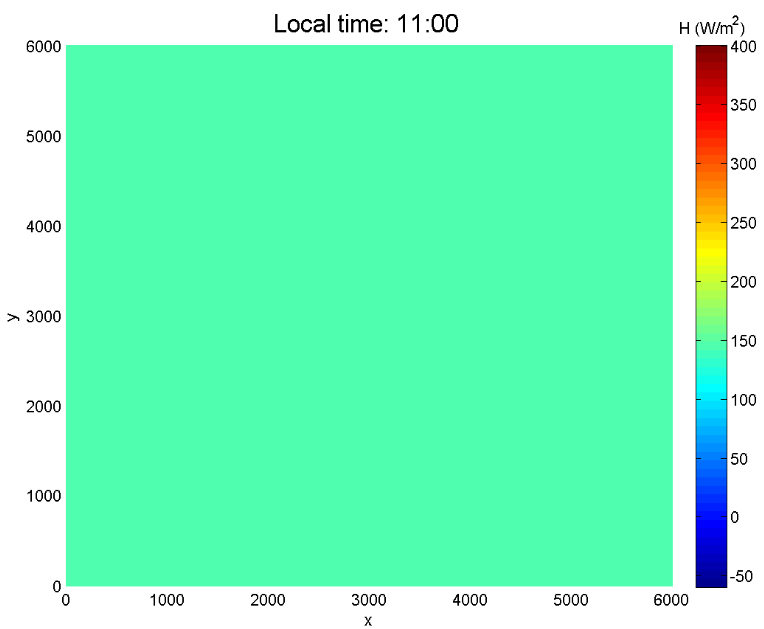
Boundary conditions **– Surface heating**



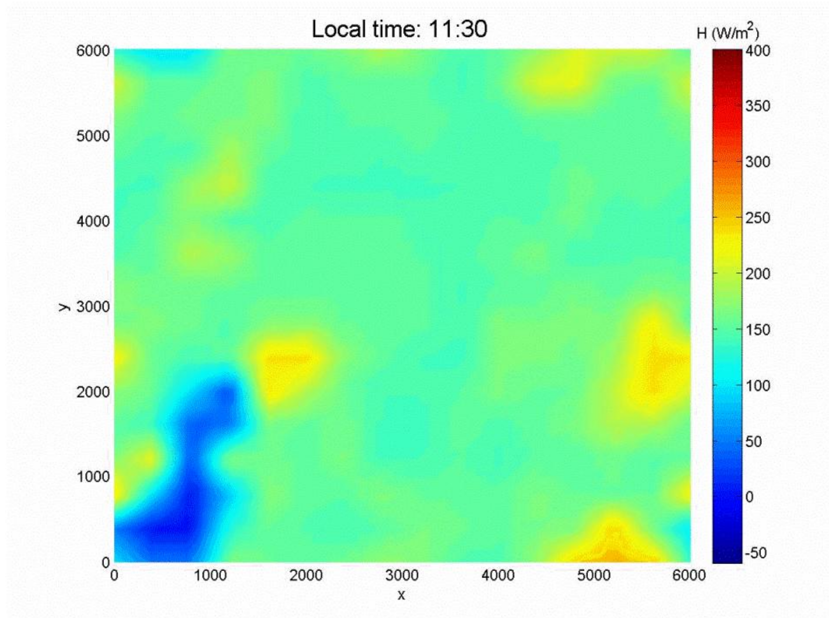
Model Setup

Boundary conditions **– Surface heating**

homogeneous test case



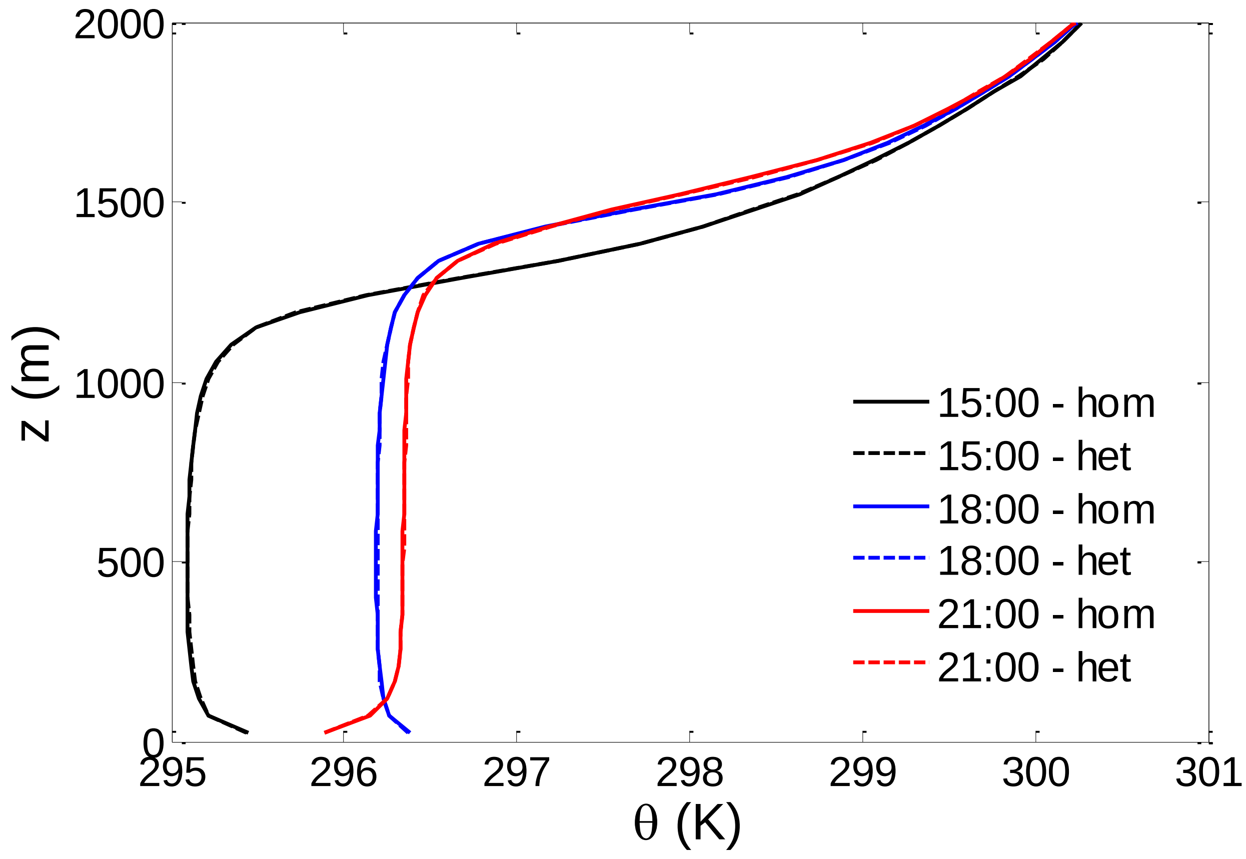
heterogeneous test case



Results

Potential temperature

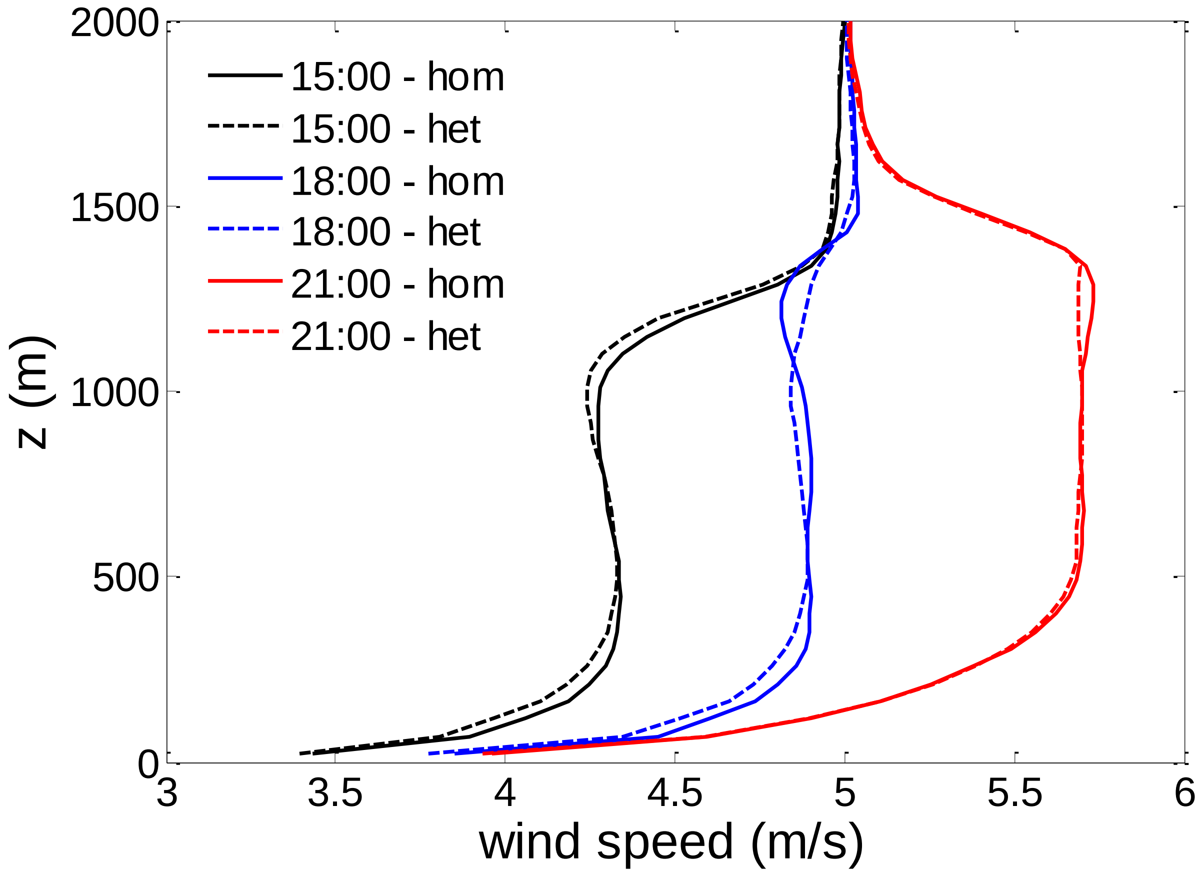
Hourly-averaged and horizontally averaged profiles



Results

Wind speed

Hourly-averaged and horizontally averaged profiles

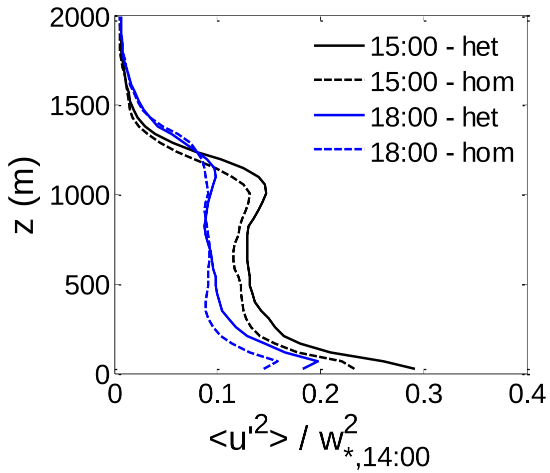


Results

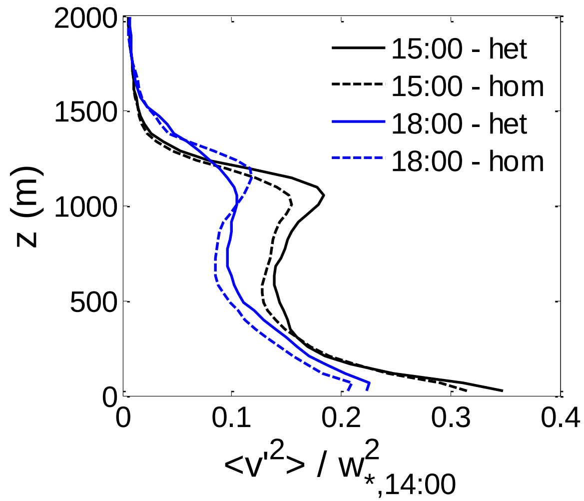
Velocity variances

Hourly-averaged and horizontally averaged vertical profiles

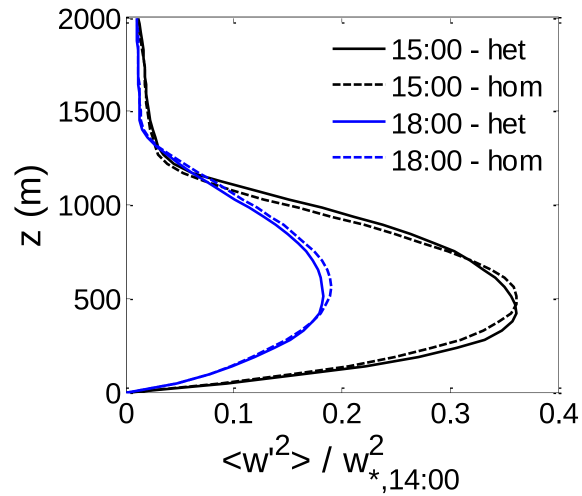
u velocity variance



v velocity variance



w velocity variance



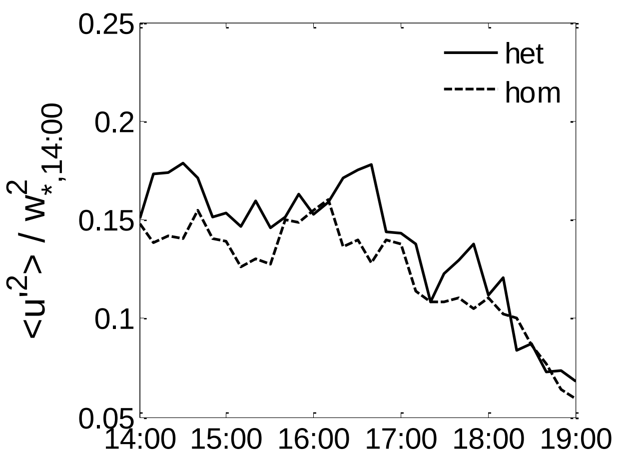
Convective velocity scale $w_{*,14:00} = \left(\frac{g}{T_0} \langle w'\theta' \rangle_0 \, z_i \right)^{1/3} \approx 1.7 \text{ m/s}$

Results

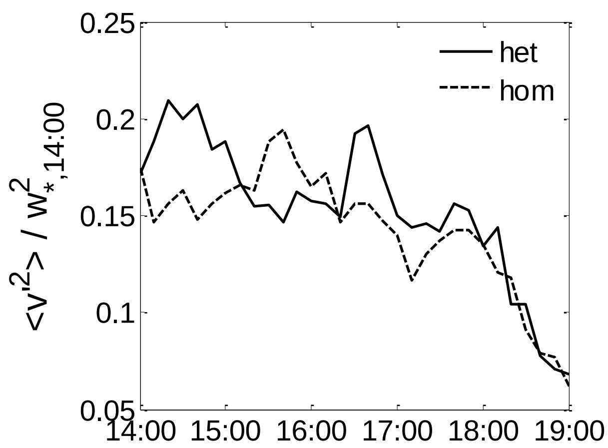
Velocity variances

Volume-averaged (over the ABL) time evolution

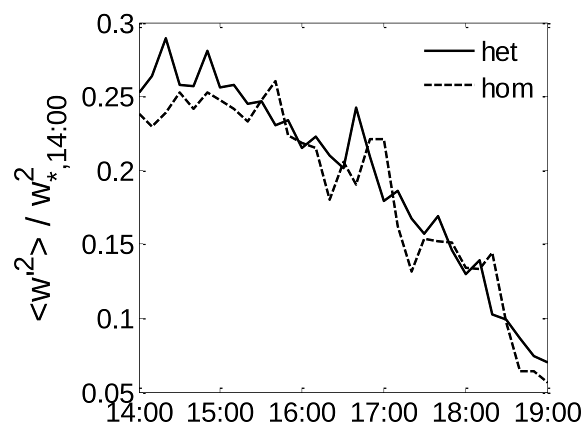
u velocity variance



v velocity variance



w velocity variance

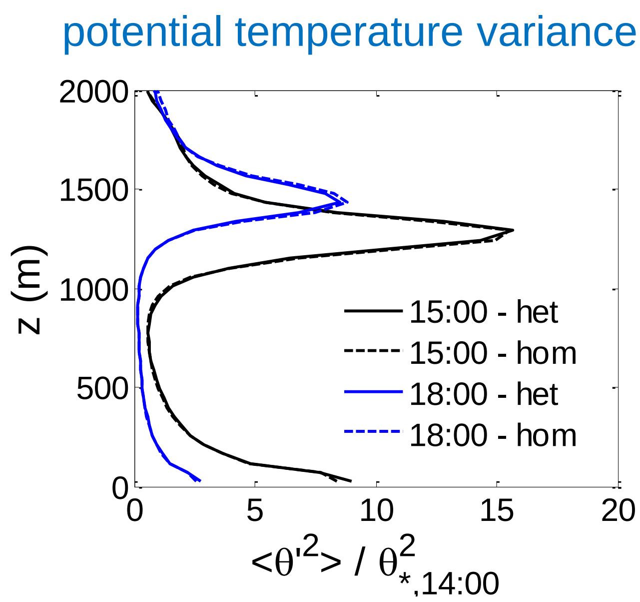


Convective velocity scale $w_{*,14:00} = \left(\frac{g}{T_0} \langle w'\theta' \rangle_0 \, z_i \right)^{1/3} \approx 1.7 \text{ m/s}$

Results

Temperature variance

Hourly-averaged and horizontally averaged vertical profiles



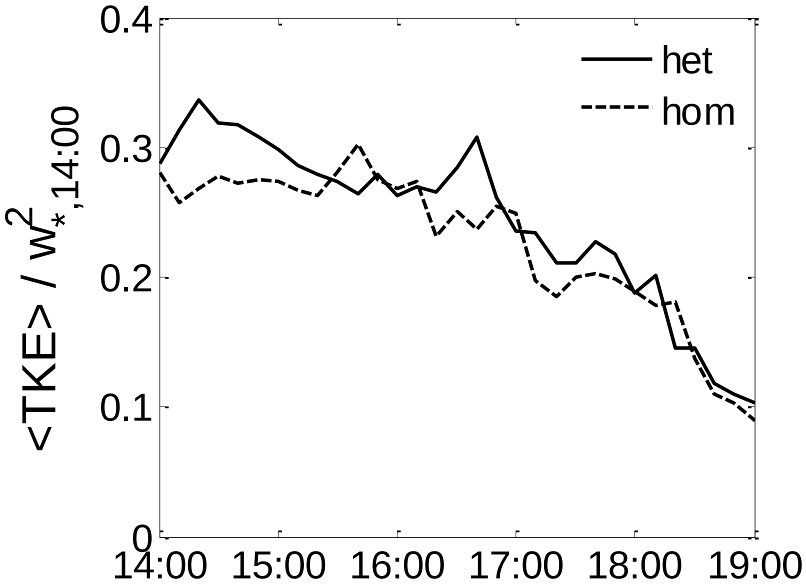
Convective velocity scale $$\theta_{*,14:00} = \frac{\langle w'\theta' \rangle_0}{w_*} \approx 0.08\,\mathrm{K}$$

Results

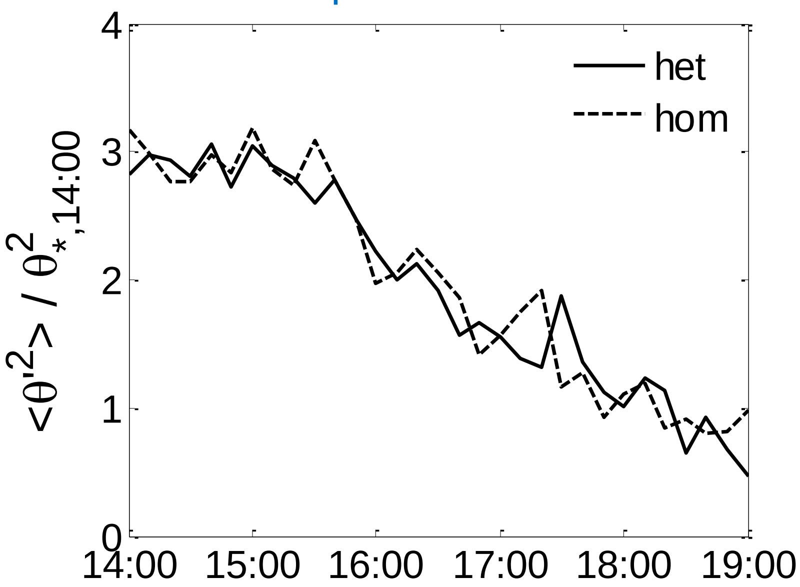
TKE vs. temperature variance

Volume-averaged (over the ABL) time evolution

TKE



Temperature variance

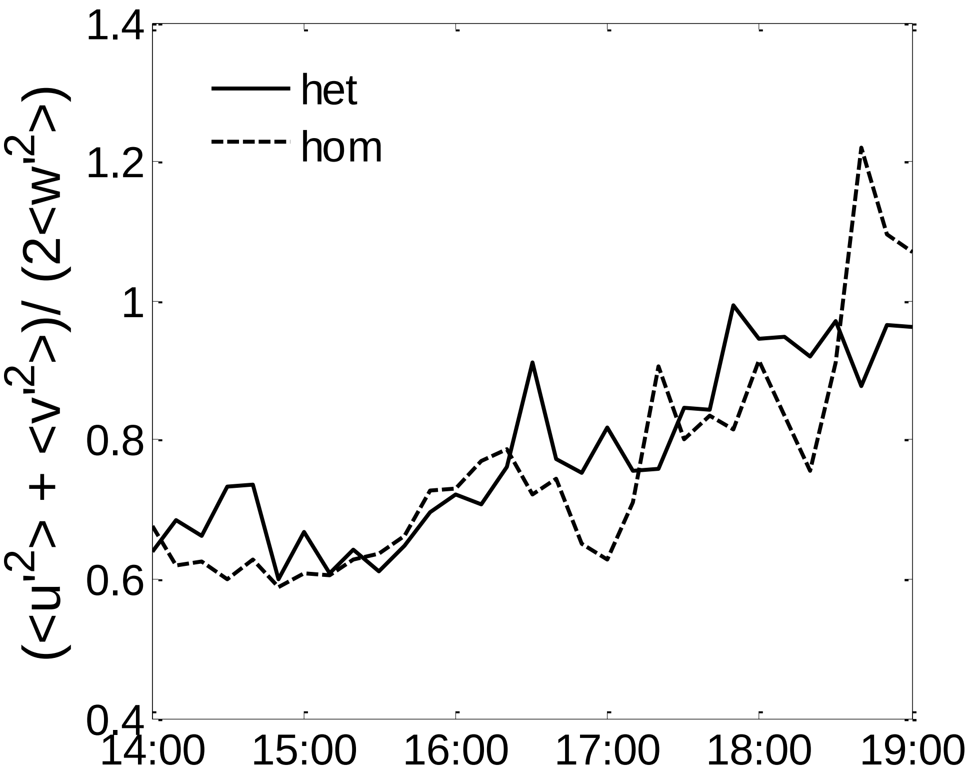


«Temperature fluctuations decay the fastest, while TKE decays more slowly.»

Results

Anisotropy

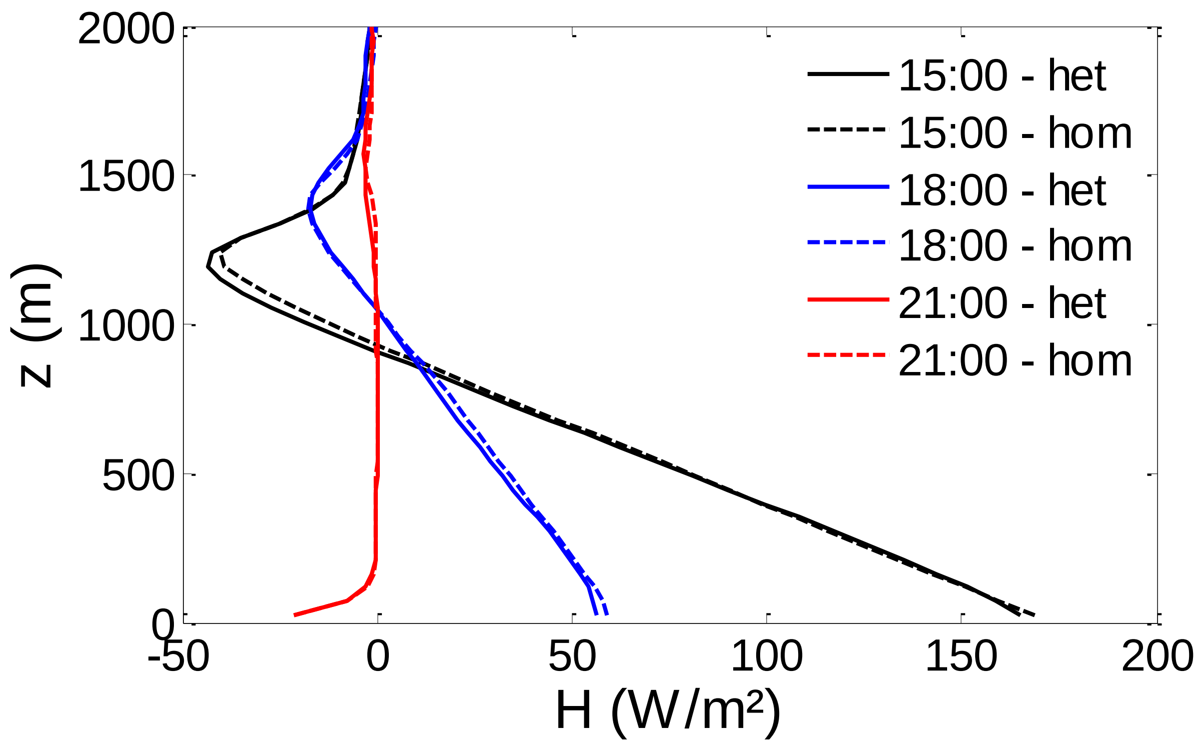
Volume-averaged (over the ABL) time evolution



Results

Heat flux profile

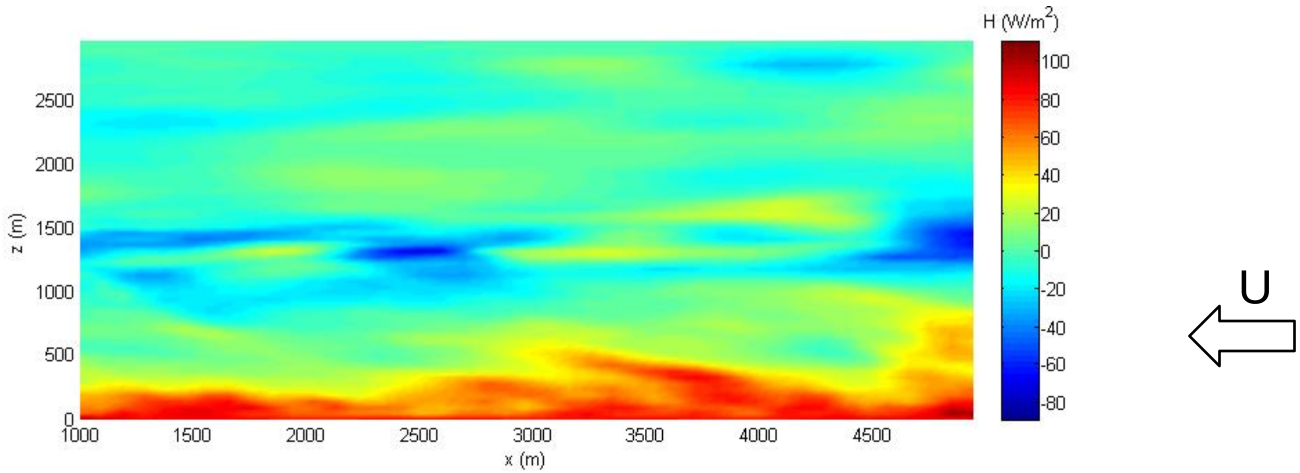
Hourly-averaged and horizontally averaged vertical profiles

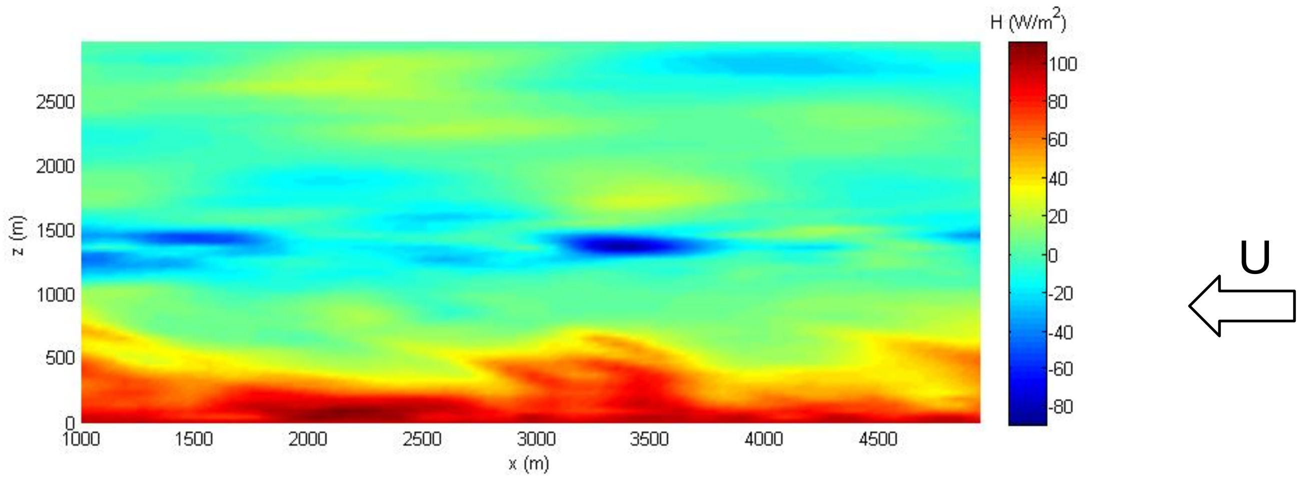


Results

Heat flux

30-min time average of a x-z slice in the middle of the domain



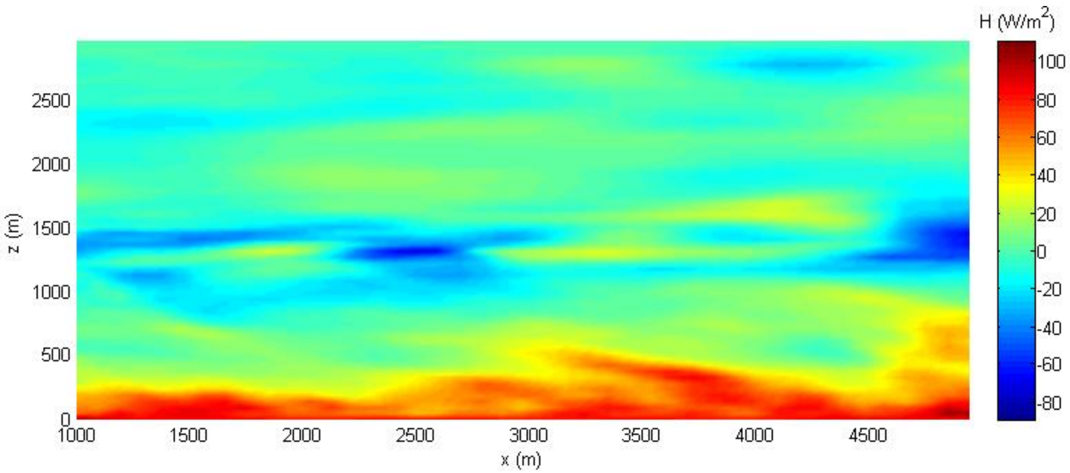


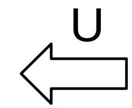
Results

Heat flux

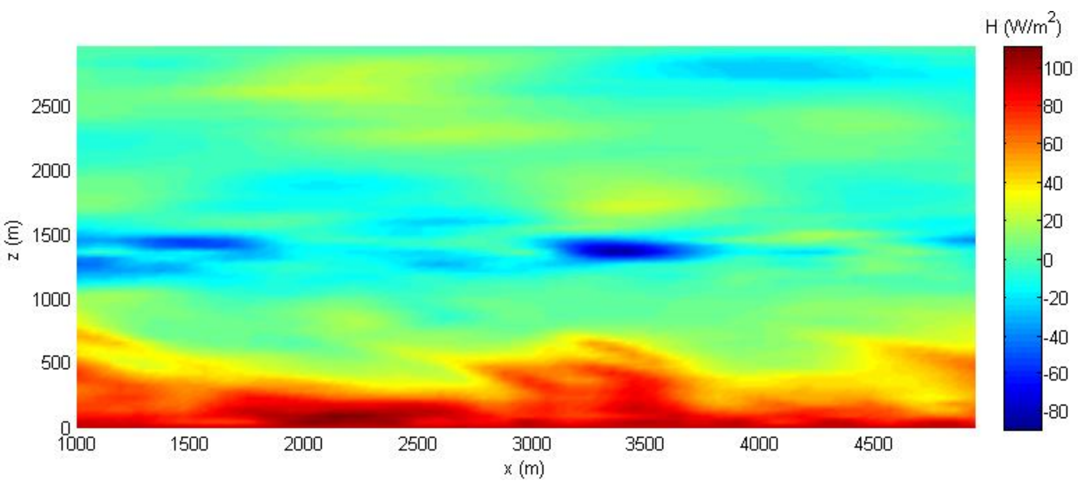
30-min time average of a x-z slice in the middle of the domain

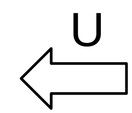
heterogeneous





homogeneous





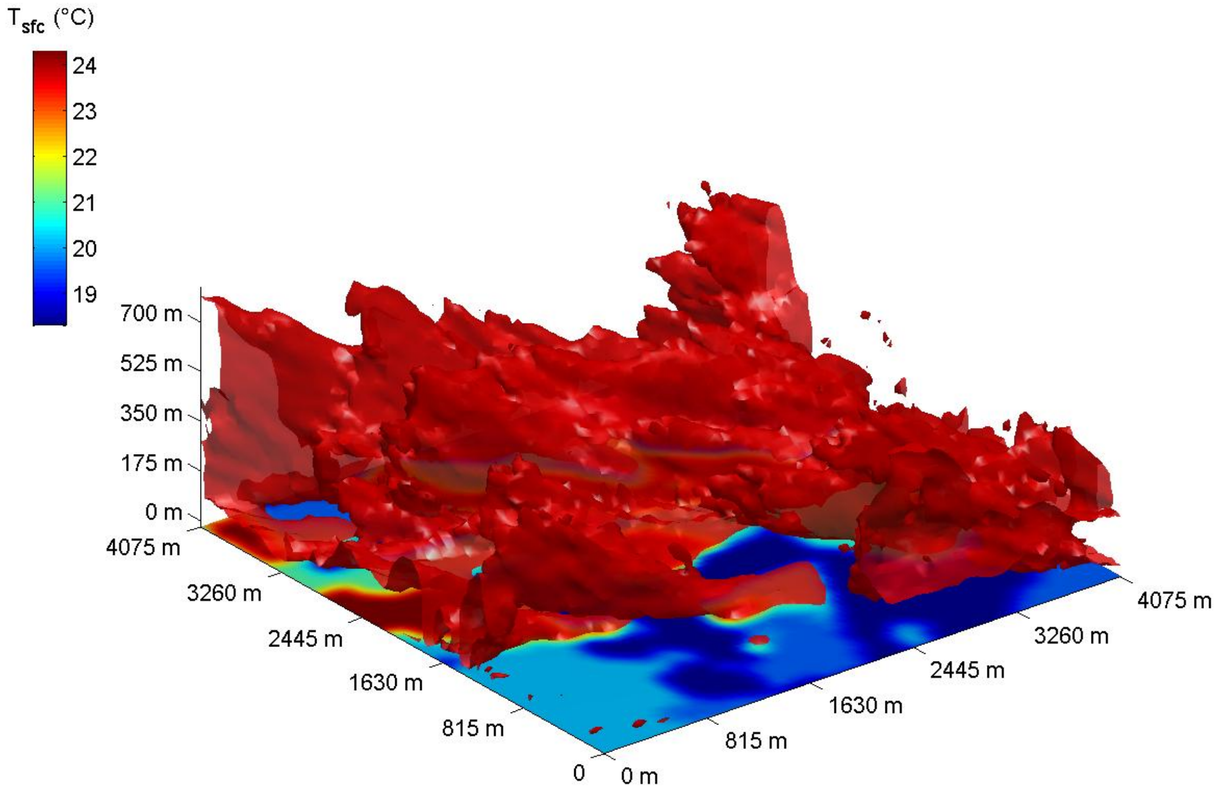
Preliminary Conclusions

- Profiles of velocity variances show greater values for the heterogeneous test case
- greater variability of the velocity variances during the decay for the heterogeneous test case
- 3 decay rates are observed for each velocity component
- signs of convective cells in the homogeneous test case

Future work

- Increase the spatial resolution (96^3 is currently running)
- Add surface roughness heterogeneities

Thank you!



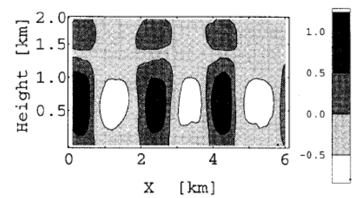
T_{sfc} (°C)
24
23
22
21
20
19
700 m
525 m
350 m
175 m
0 m
4075 m
3260 m
2445 m
1630 m
815 m
0
0 m
815 m
1630 m
2445 m
3260 m
4075 m

Background

Land-atmosphere interactions over heterogeneous terrain with LES

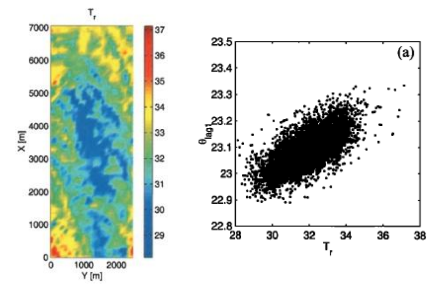
Avissar and Schmidt, JAS, 1998

- effects on the CBL of surface heterogeneities produced by H with waves of different means, amplitudes, etc.
- Idealized BCs



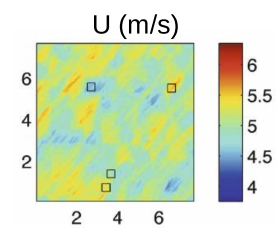
Albertson et al., WRR, 2001

- correlation between T_s and θ dependant on length scales of surface features
- scale-invariant SGS model, imposed pressure gradient



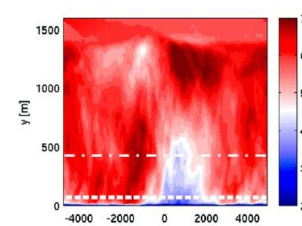
Bertholdi et al., JAMC, 2008

- surface-energy balance scheme coupled with LES
- Smagorinsky model



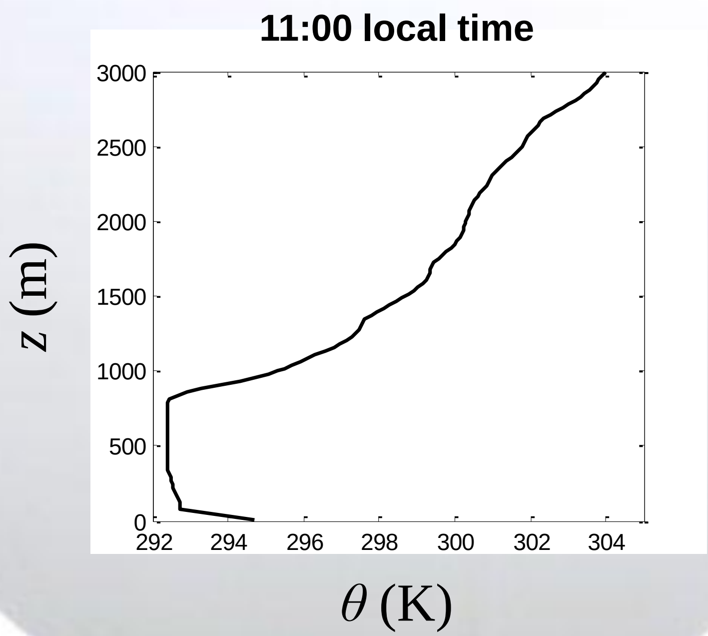
Huang and Margulis, WRR, 2009

- realistic surface BCs using SMACEX-2002 data
- Lagrangian dynamic scale-dependant SGS model



Model Setup

Initial potential temperature profile



Model Setup

30 May 2003

- anticyclonic conditions
- no clouds
- easterly winds