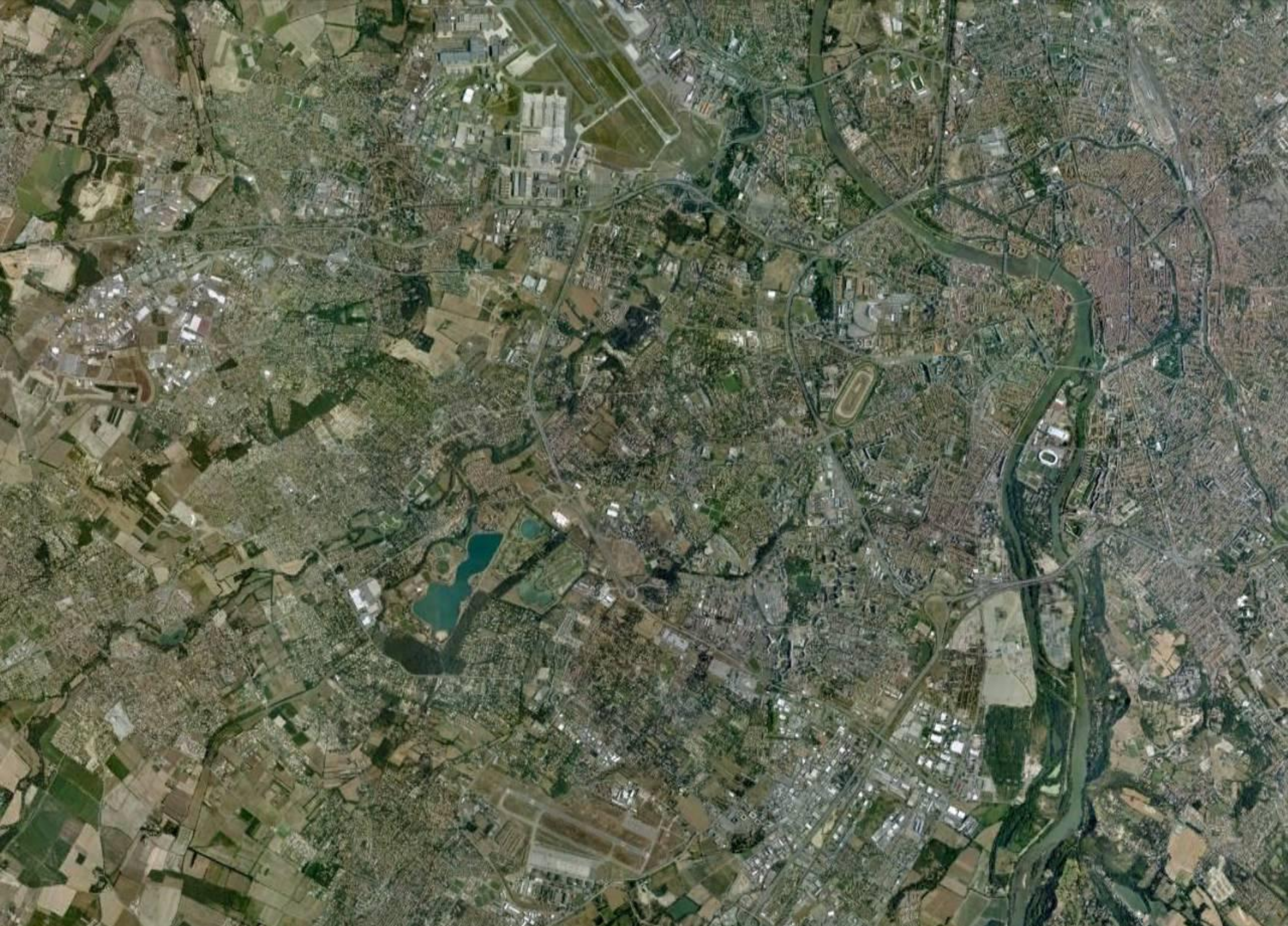
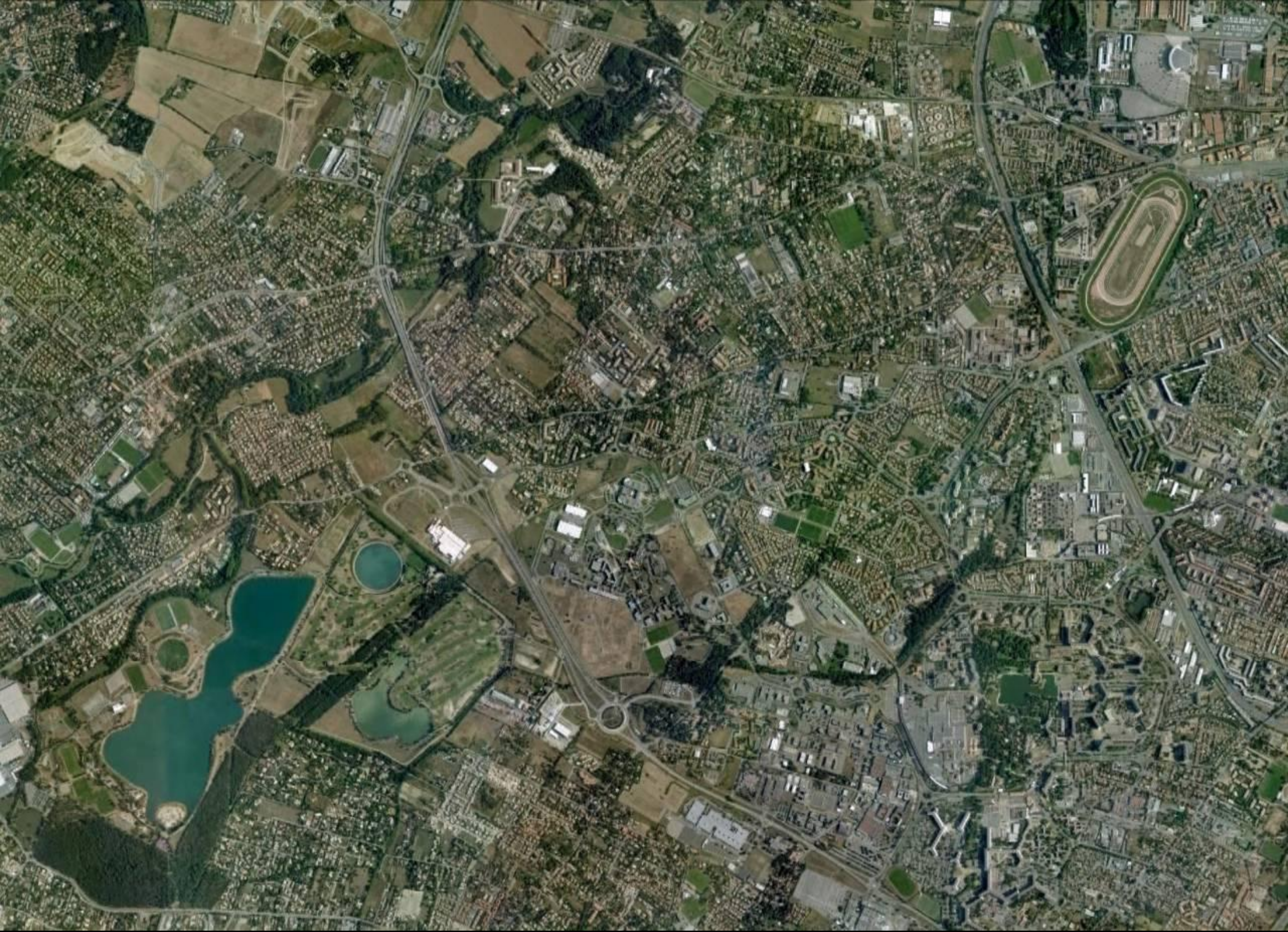
Large-Eddy Simulation of the Convective Atmospheric Boundary Layer over Heterogeneous Land Surfaces

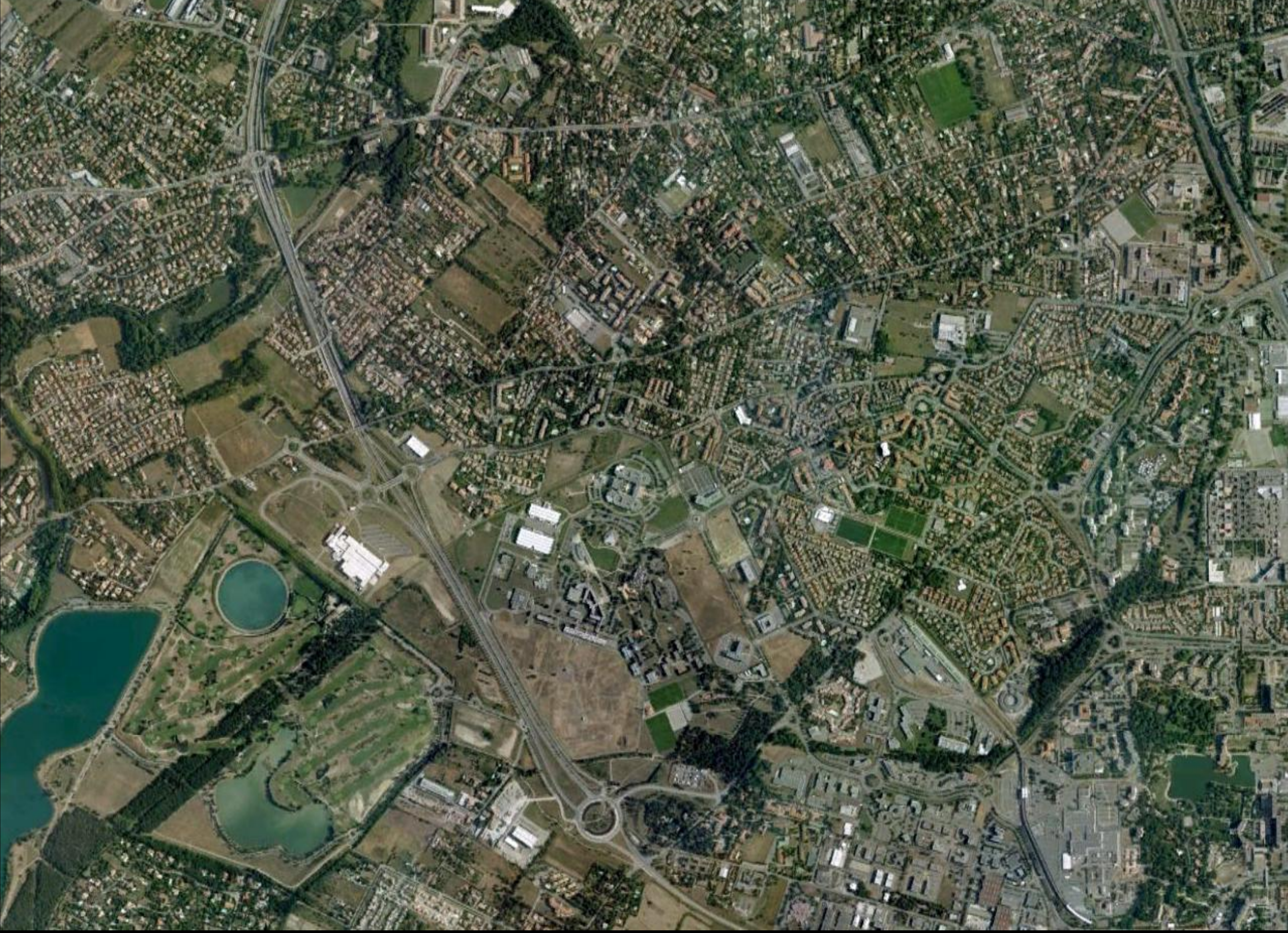
Daniel Nadeau

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

Toulouse, 2 October 2009



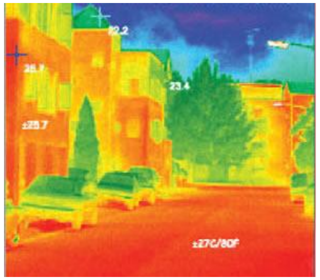




Motivations

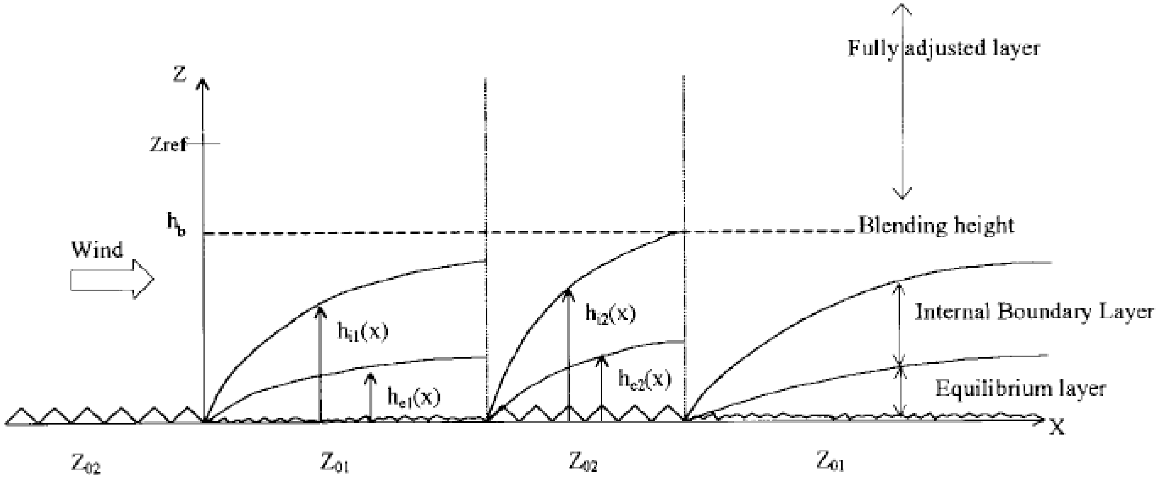
Surface heterogeneities

… in thermal properties (affects T_s)



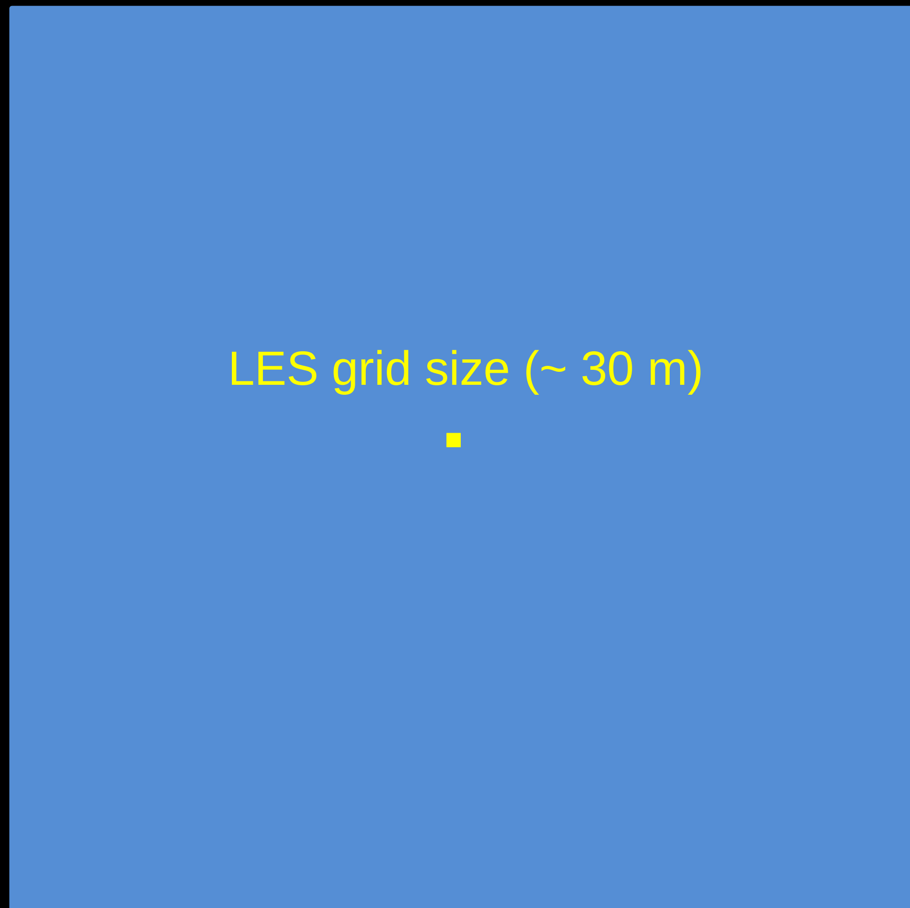
… in shape, geometry (affects z_0)

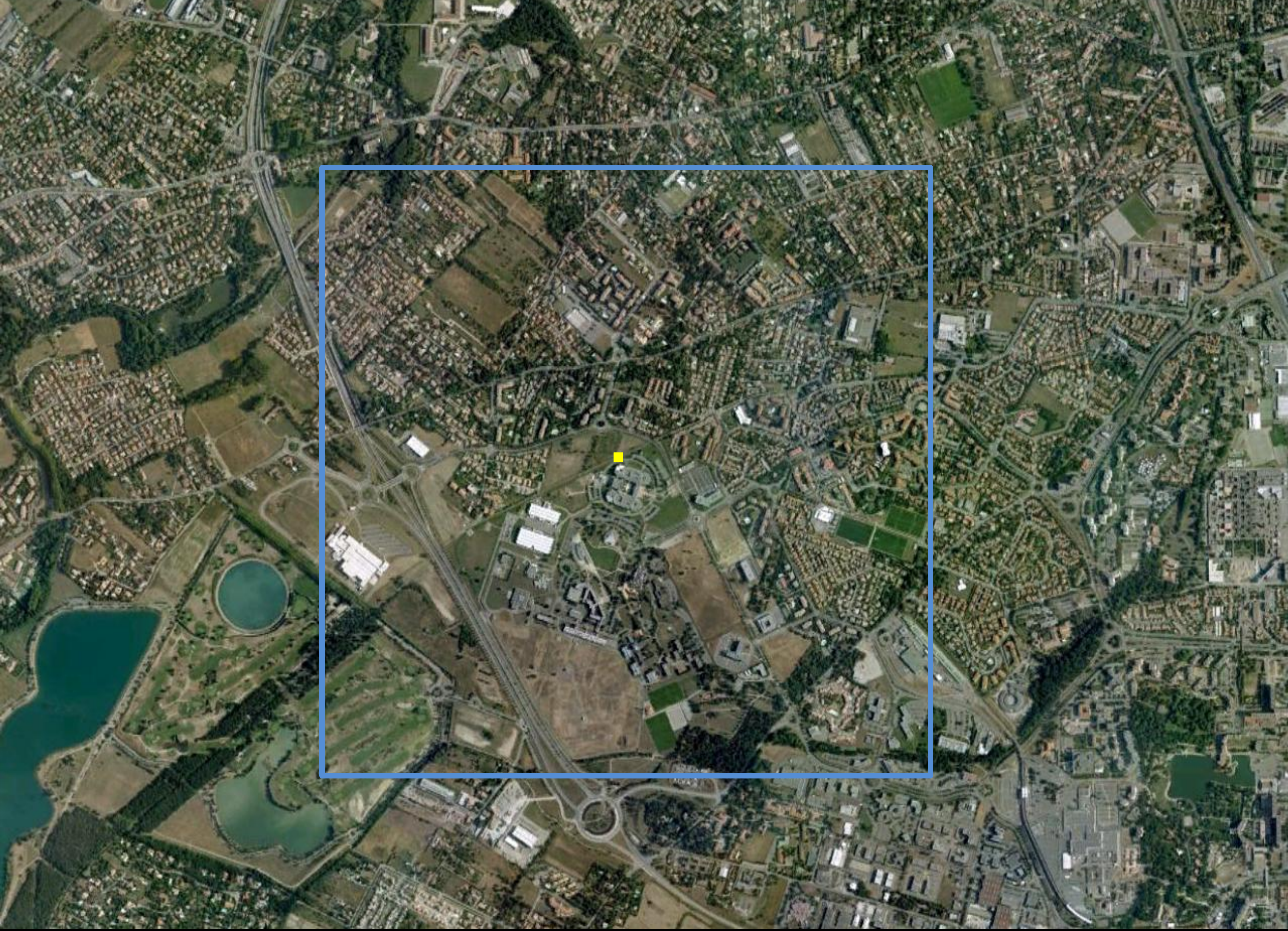
What is the impact of these heterogeneities on the **blending heights**?



Source: Goode and Belcher, BLM, 1999

Mesoscale model grid size (~ 2 km)





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

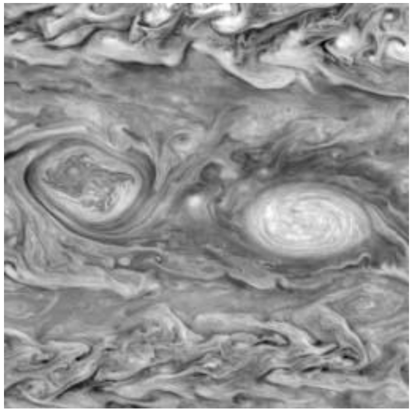
Impossible to resolve all these scales explicitly!

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

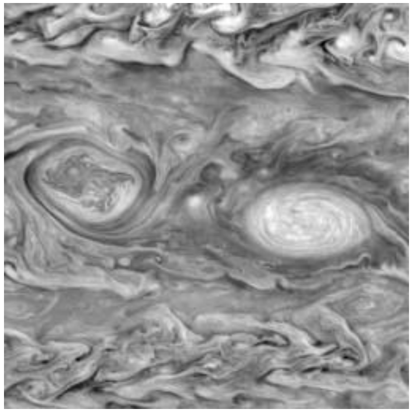
Large-eddy simulation

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

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial x_i} + u_j \left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + g \left(\frac{\theta - \langle \theta \rangle}{\langle \theta \rangle} \right) \delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f \left(u_2 - V_g \right) \delta_{i1} - f \left(u_1 - U_g \right) \delta_{i2}$$

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j}$$

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$$\frac{\partial \theta}{\partial t} + u_j\frac{\partial \theta}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j}$$

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)

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

velocity scale

length scale

Smagorinsky constant

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

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

ν_T	turbulent eddy viscosity
Δ	filter size
S_{ij}	resolved strain rate tensor
τ_{ij}^{SMAG}	modelled SGS stress
π_{ij}^{SMAG}	modelled SGS scalar flux

Model Setup

LES code details

- Geostrophic forcing → can vary with height and time (Kumar et al., JAMC, 2009, accepted)
- Temperature is implemented, but not humidity
- 2nd order centered finite differences in a staggered grid formulation in the vertical direction
- Spectral code in the horizontal directions
- 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

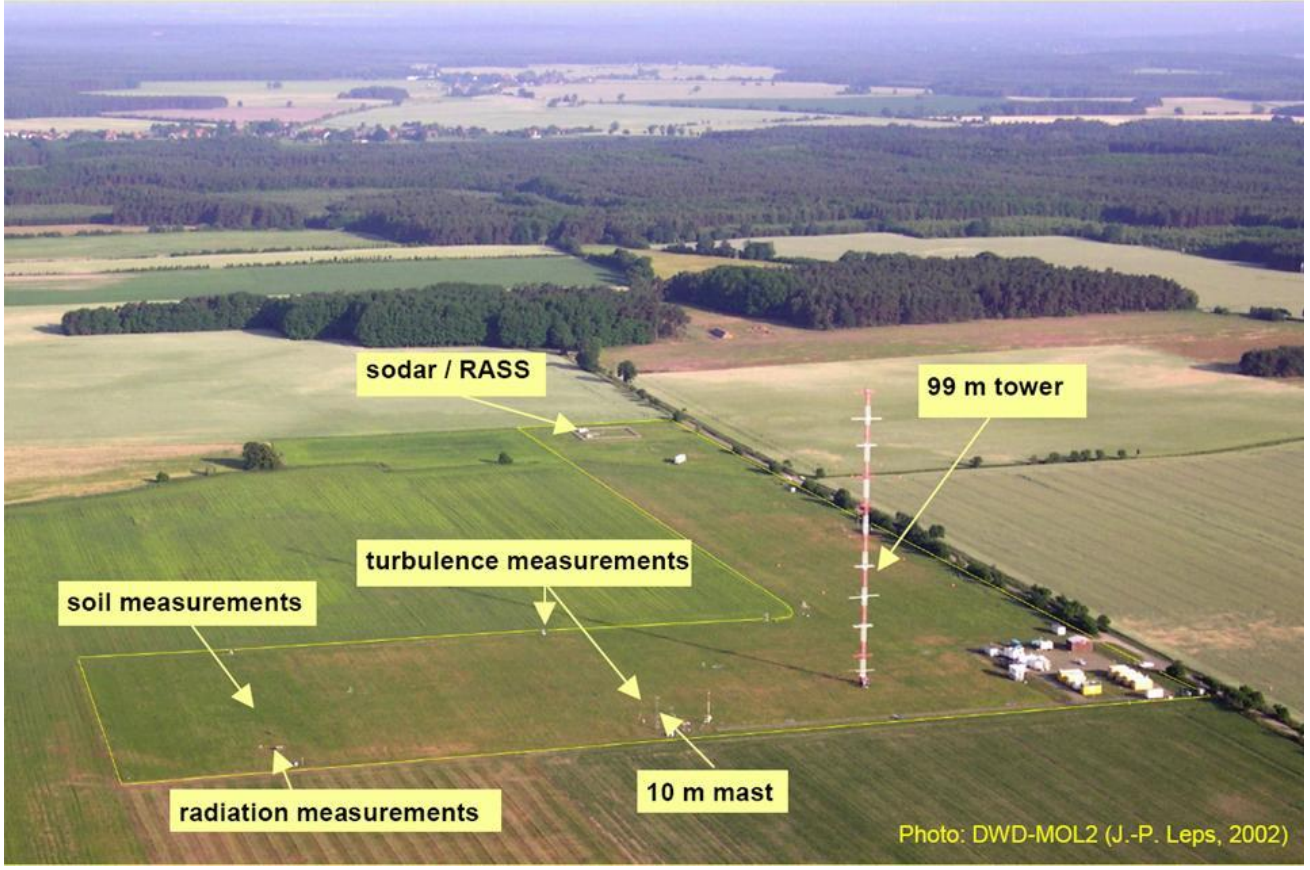
LITFASS – 2003 (Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface: a long-term Study)

- 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
- and much more…

Ideal for a LES validation over heterogeneous terrain!

Model Setup

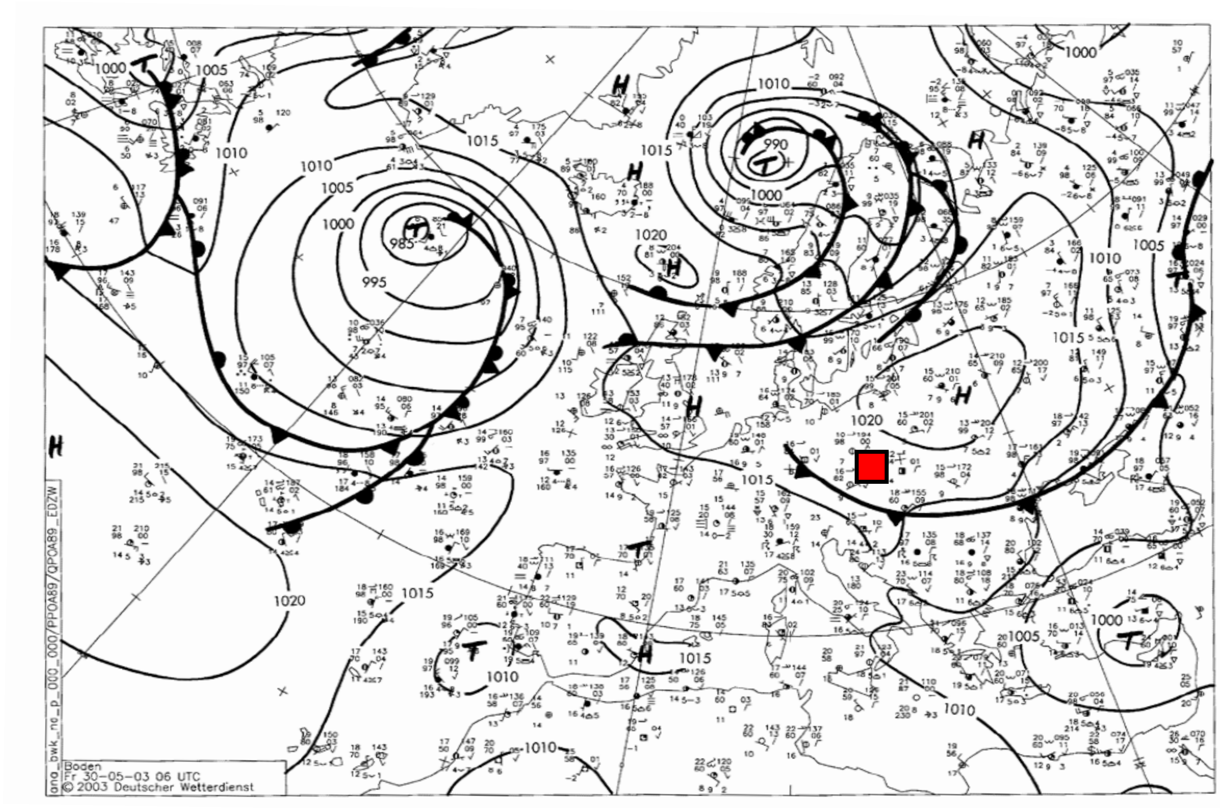
Center of the LES domain: the 99 m tower



Model Setup

30 May 2003

- anticyclonic conditions
- no clouds
- cold easterly winds



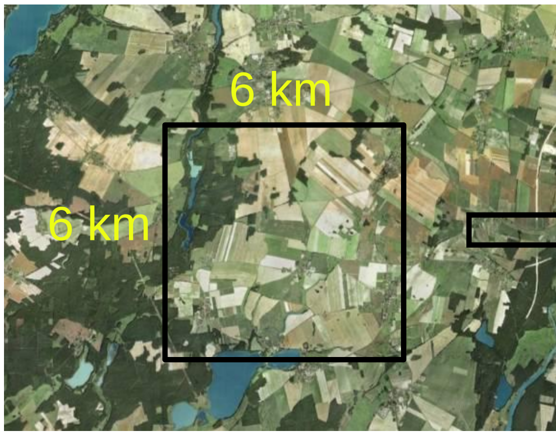
Model Setup

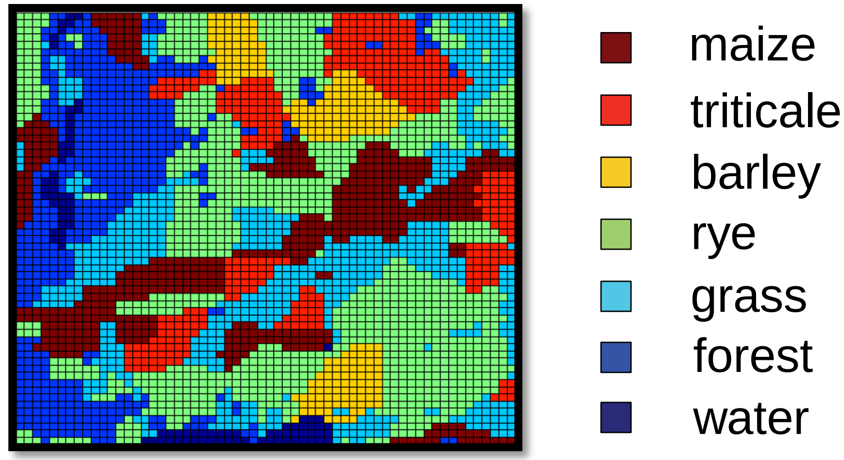
Simulation details

Number of grid points :	**128** x **128** x **128** (~ 2.1 million)
Domain size – L_x , L_y ,L_z :	**6 km** x **6 km** x **3 km**
Horizontal mesh spacing – Δx, Δy :	47.9 m
Vertical mesh spacing – Δz :	23.4 m
Number of iterations :	180 000 with Δt = 0.1 sec (total of 5 h)
Number of processors:	**16 CPUs**
Geostrophic wind U_g :	-5 m/s
Initial conditions for wind speed :	log-profile with randomly imposed TKE
Initial conditions for temperature :	convective profile with randomly imposed TKE
CBL inversion strength :	0.01 K/m
Top boundary condition :	stress-free
Warm-up period :	**first 4 h of simulation**

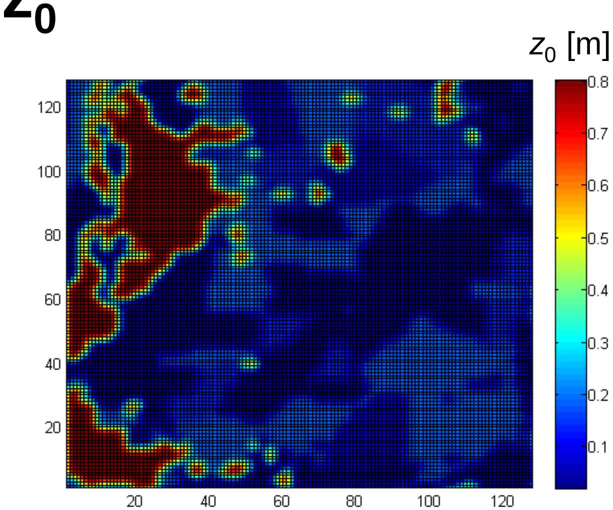
Model Setup

Surface type fields





Surface roughness z_0

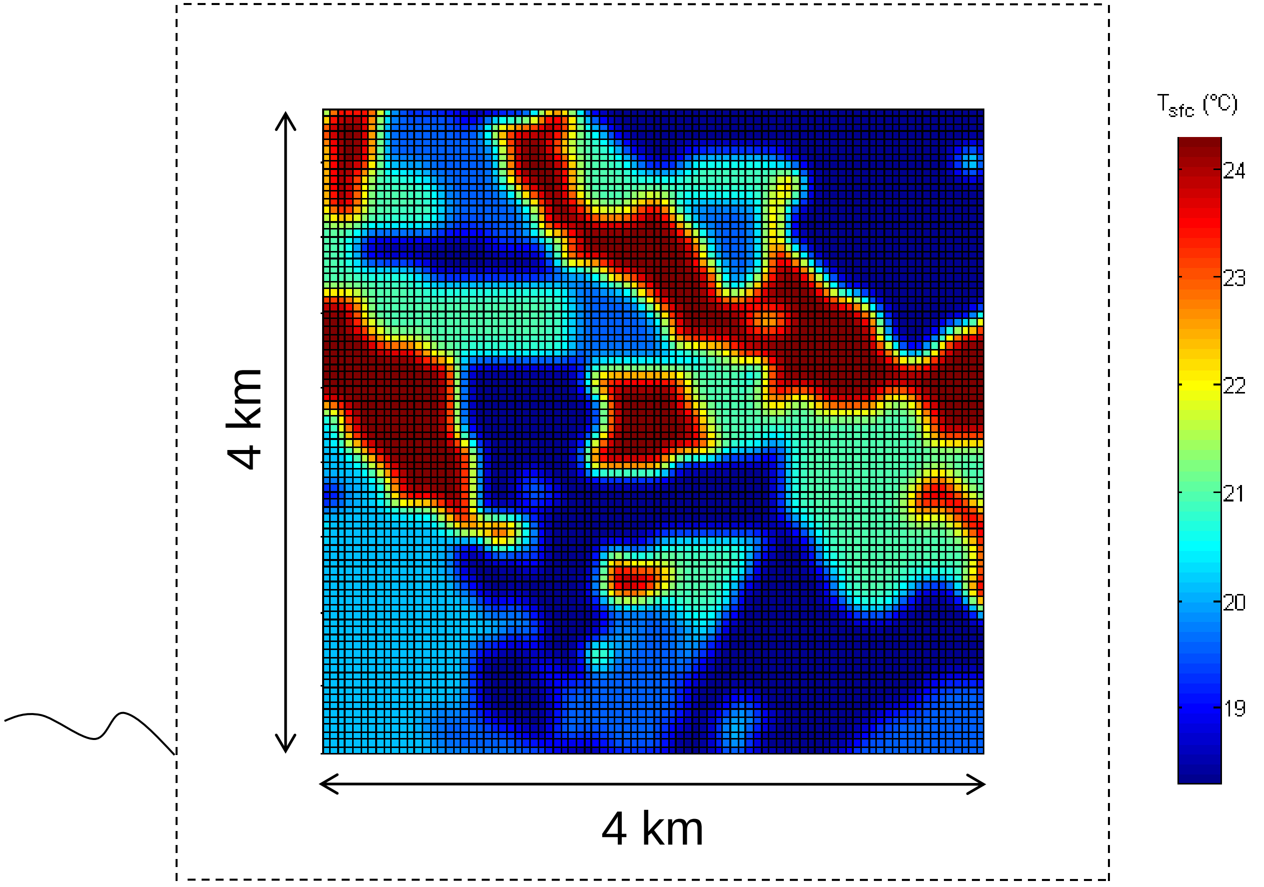


Results

Convective heterogeneous test case

- Uniform z_0 (≈ 0.2 m)
- Patches of surface temperature from 30 May 2003 at 7 UTC

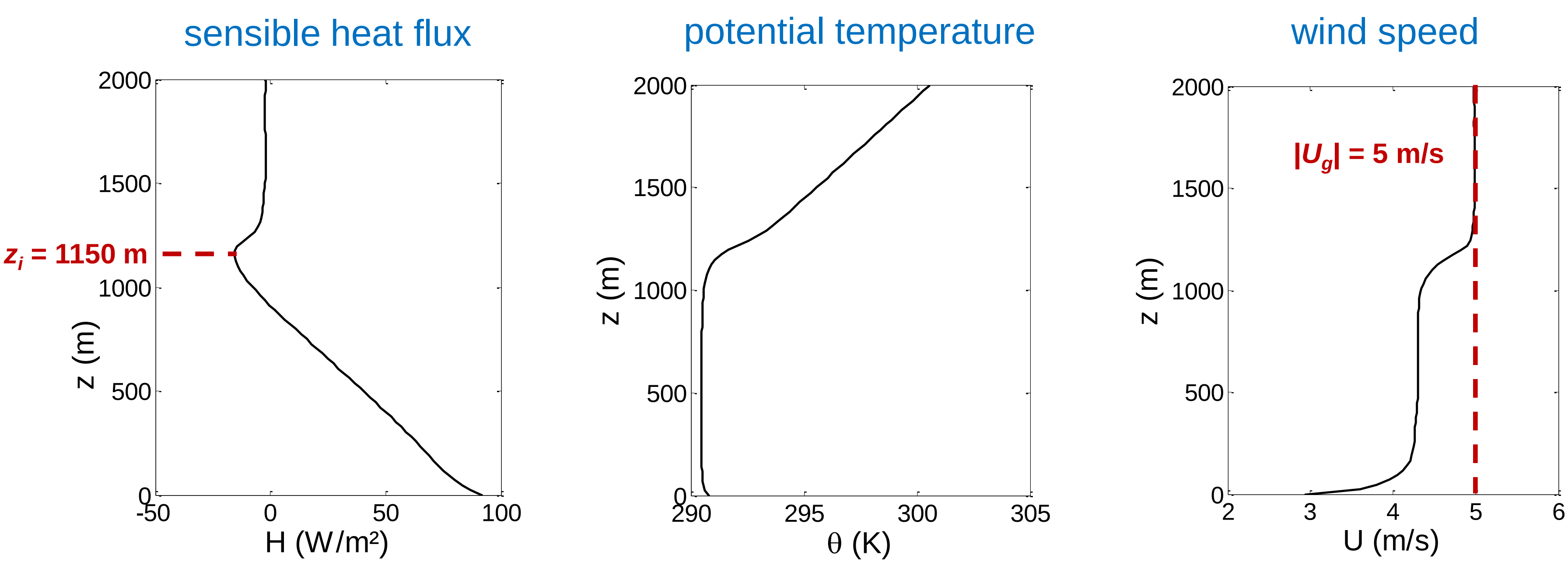
discard the first km of outputs



Results

Convective heterogeneous test case

Time-averaged and horizontally averaged vertical profiles

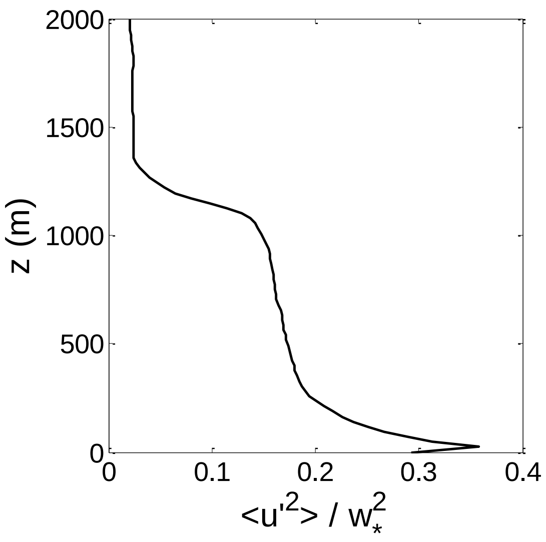


Results

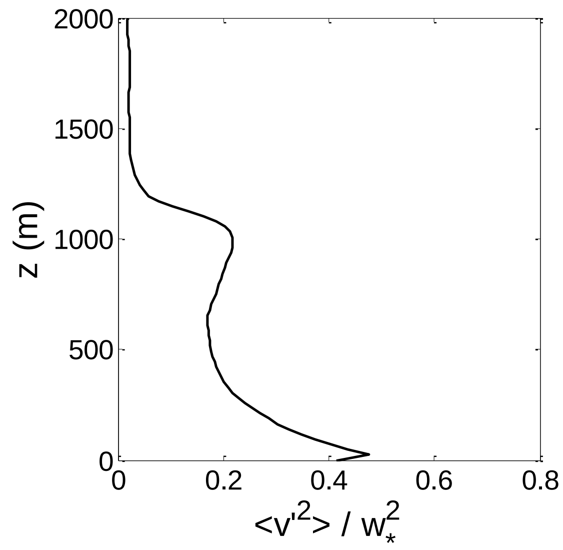
Convective heterogeneous test case

Time-averaged and horizontally averaged vertical profiles

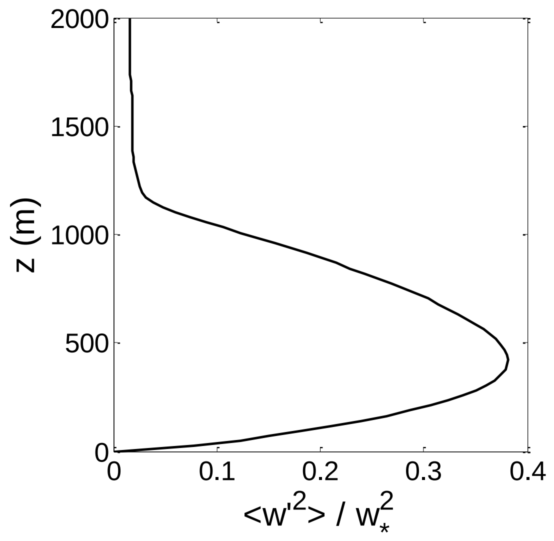
u velocity variance



v velocity variance



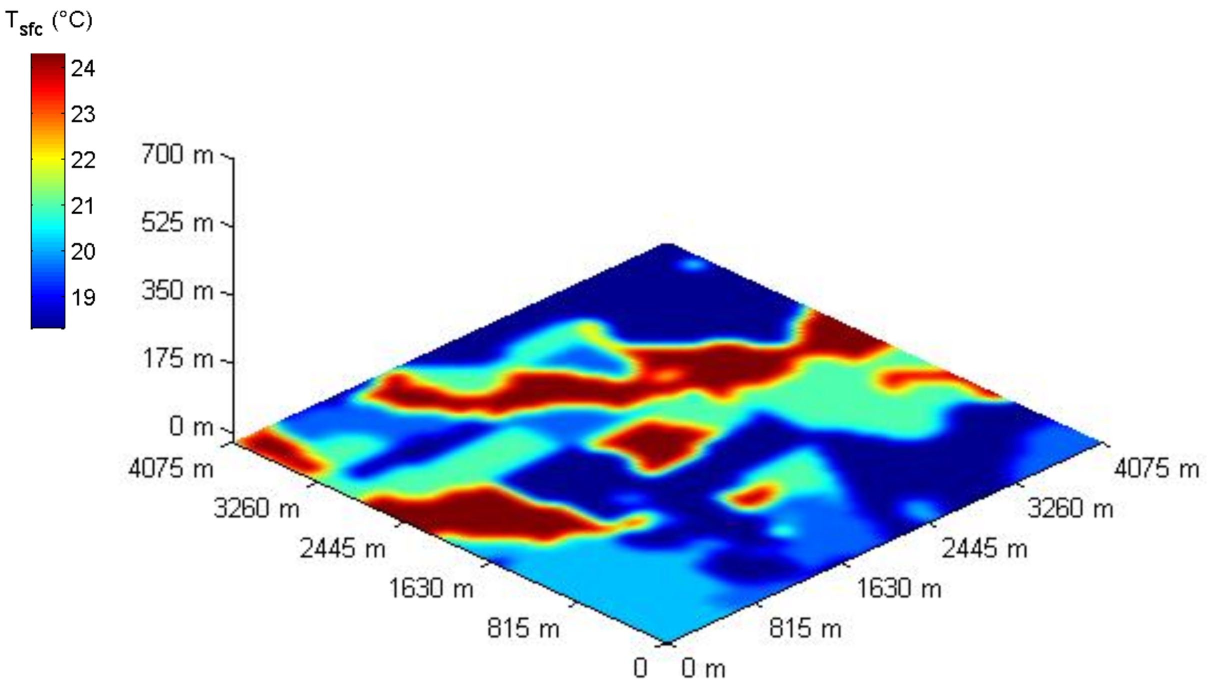
w velocity variance



Convective velocity scale $$w_* = \left(\frac{g}{T_0} \left\langle w'\theta' \right\rangle_0 z_i \right)^{1/3} \approx 1.42 \text{ m/s}$$

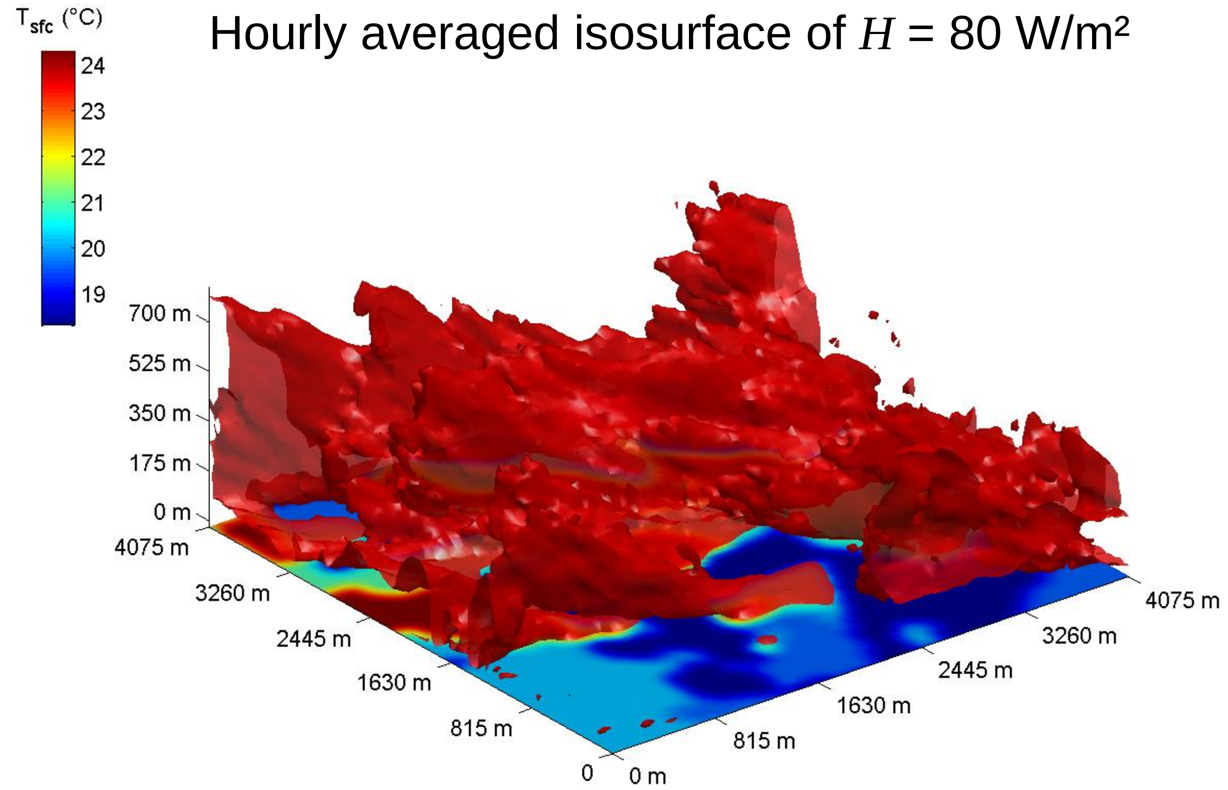
Results

Heat flux distribution



Results

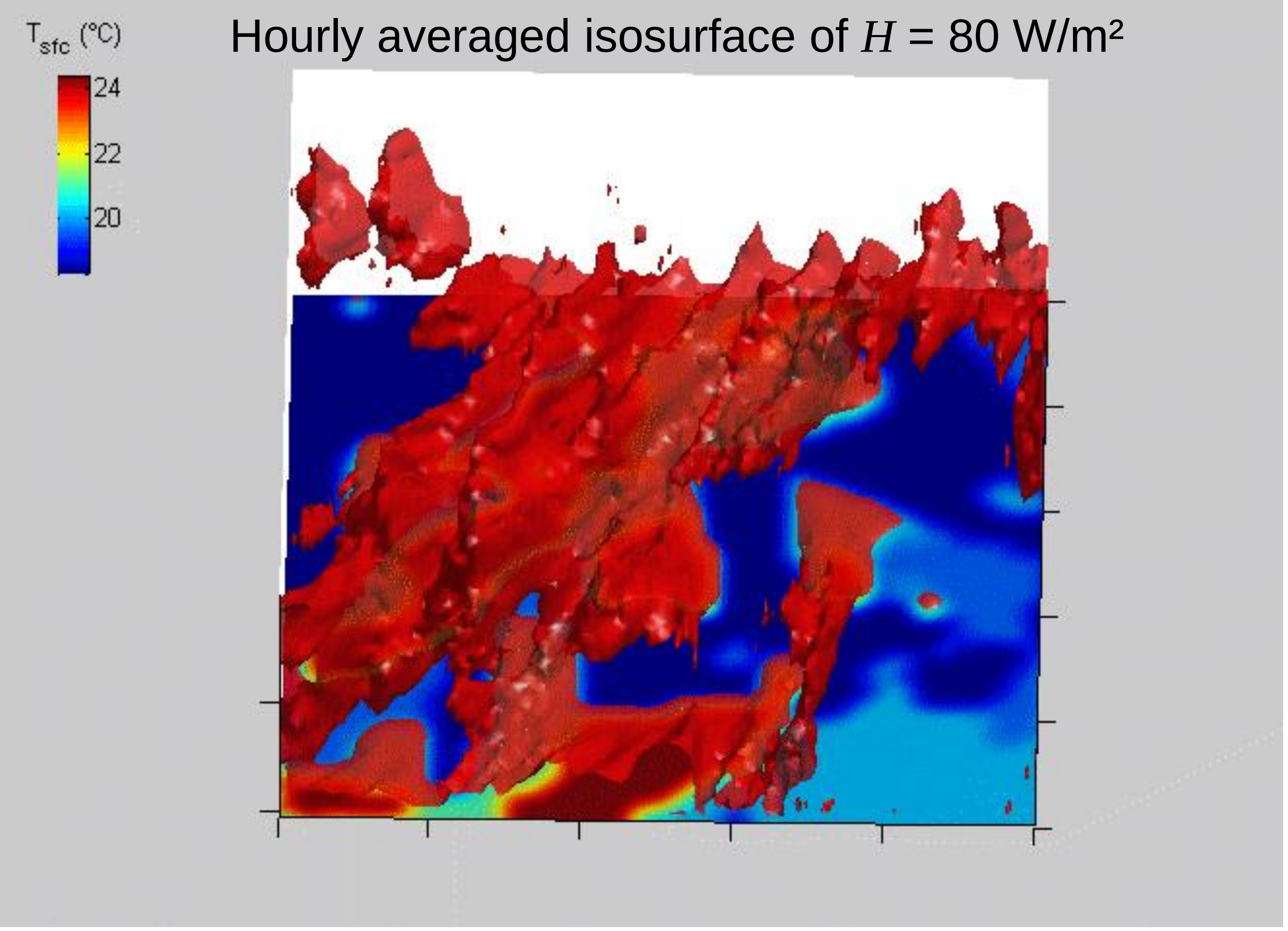
Heat flux distribution



Results

Heat flux distribution

Hourly averaged isosurface of H = 80 W/m²



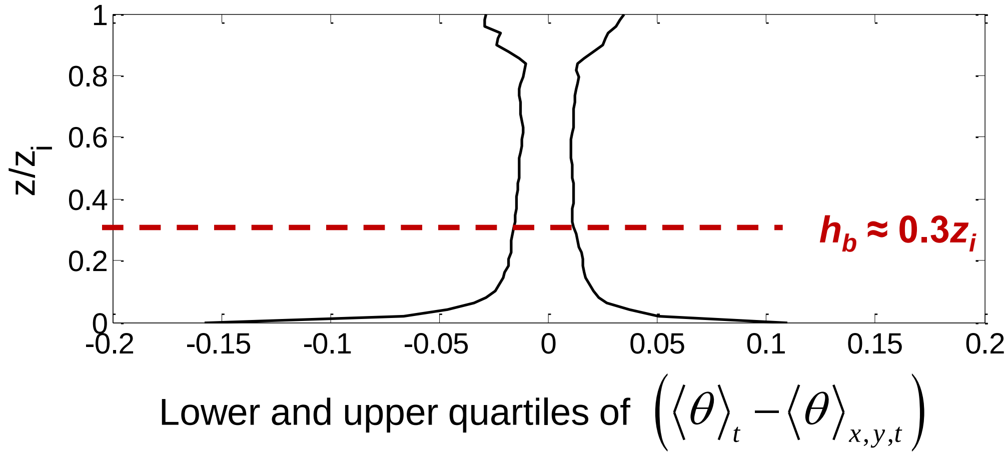
Results

Blending heights h_b

Height at which heterogeneities at the surface are completely blended due to turbulent mixing

Thermal h_b

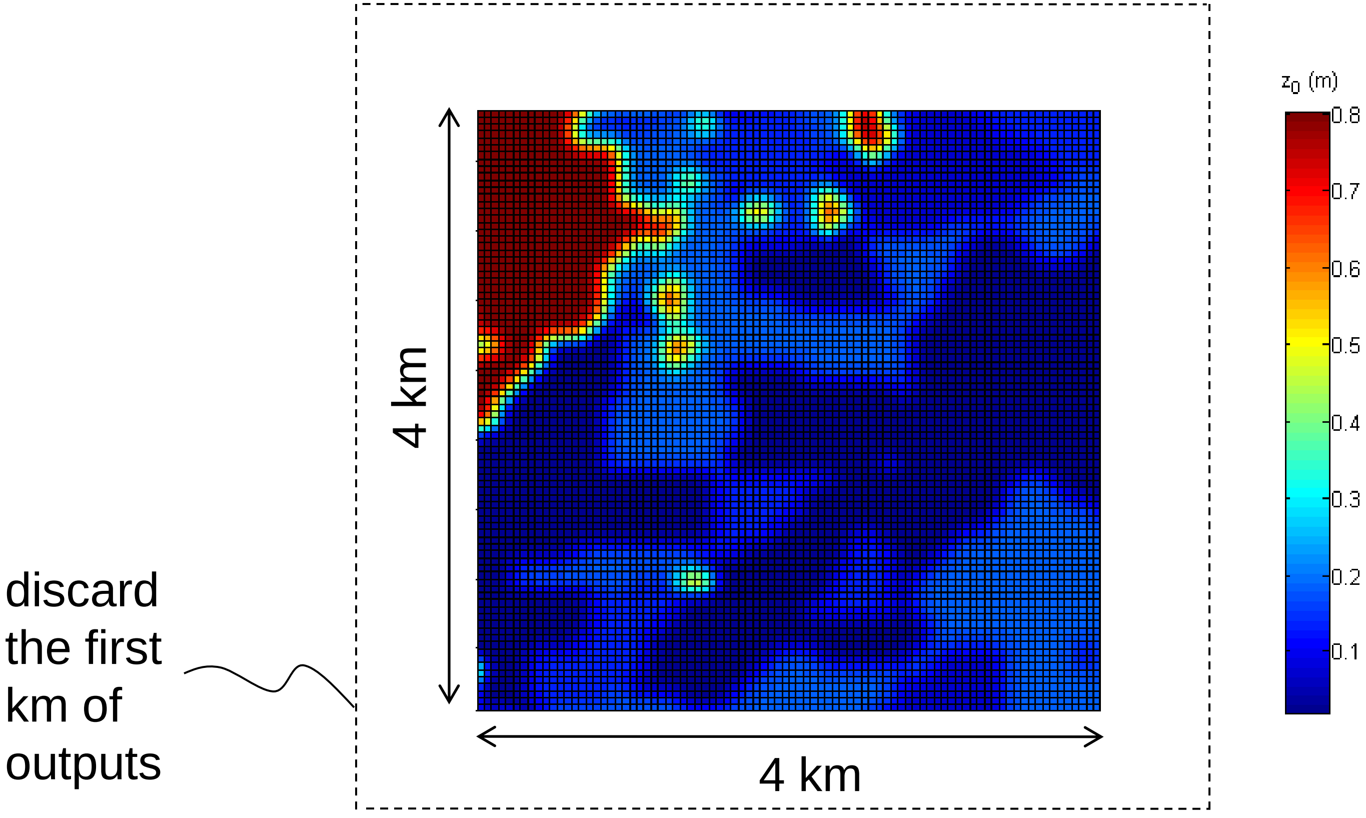
(convective run)



Results

Neutral heterogeneous test case

- Inhomogeneous surface roughnnes z_0
- Neutral conditions
- Assume z_i = 1000 m

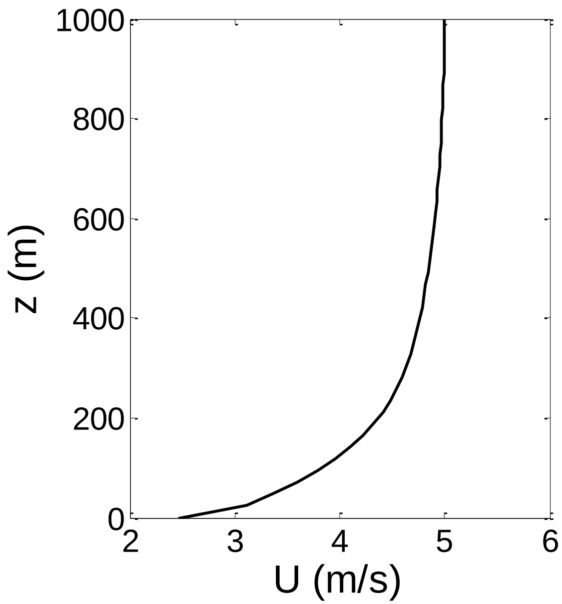


Results

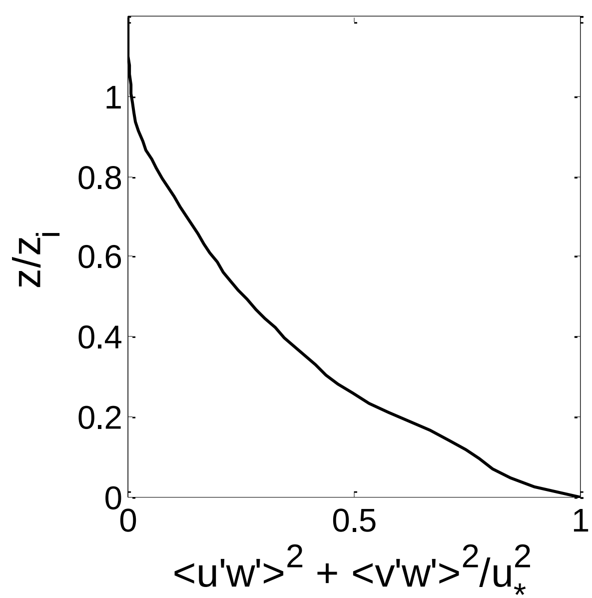
Neutral heterogeneous test case

Time-averaged and horizontally averaged vertical profiles

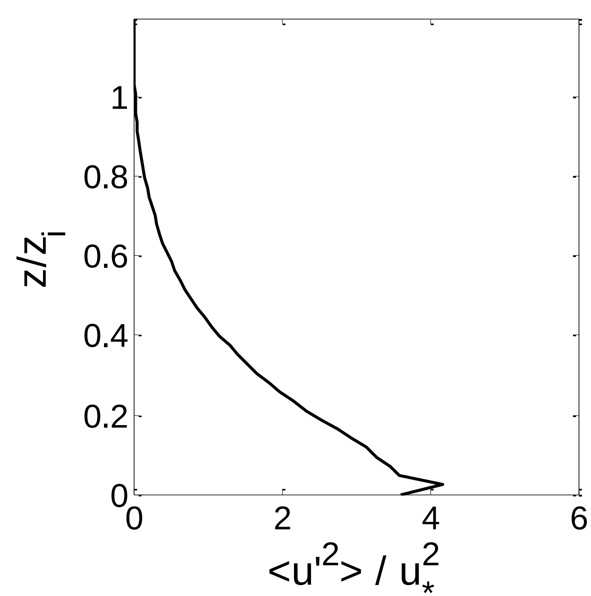
wind speed



Reynolds stress



u velocity variance



$$u_* \approx 0.22 \text{ m/s}$$

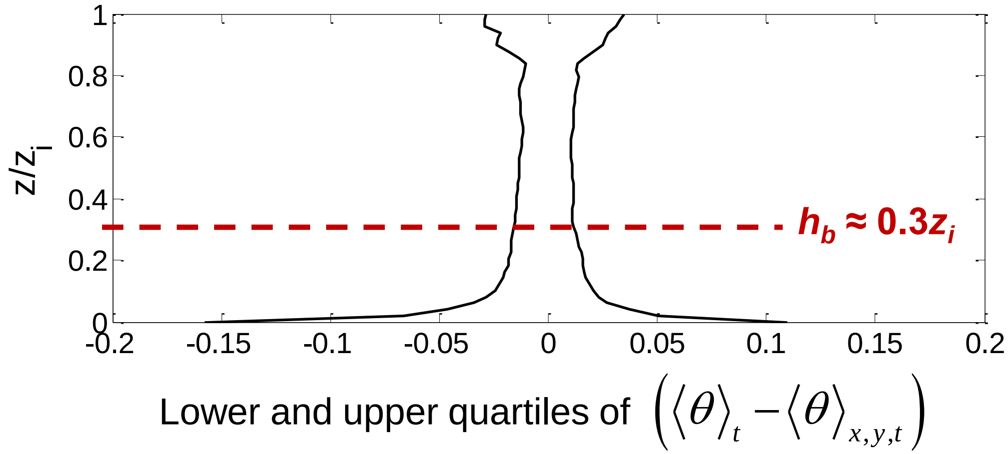
Results

Blending heights h_b

Height at which heterogeneities at the surface are completely blended due to turbulent mixing

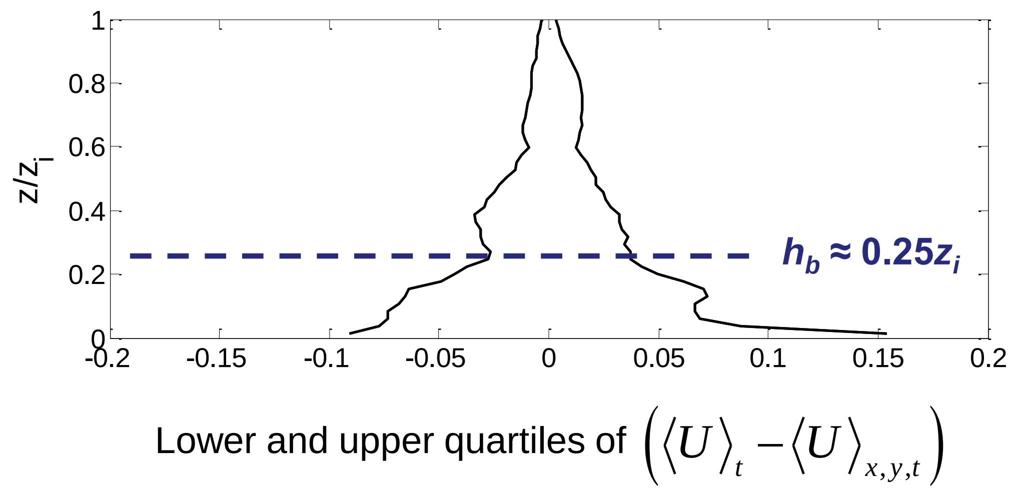
Thermal h_b

(convective run)



Momentum h_b

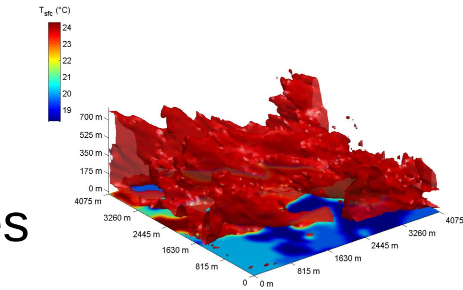
(neutral run)



Preliminary Conclusions

LES over heterogeneous terrain

- Successful to run with realistic BCs
- Can reproduce main ABL characteristics
- Found "periodic" turbulent structures in the heat plumes



Blending heights

- For the given LES domain and BCs: thermal h_b ~ momentum h_b

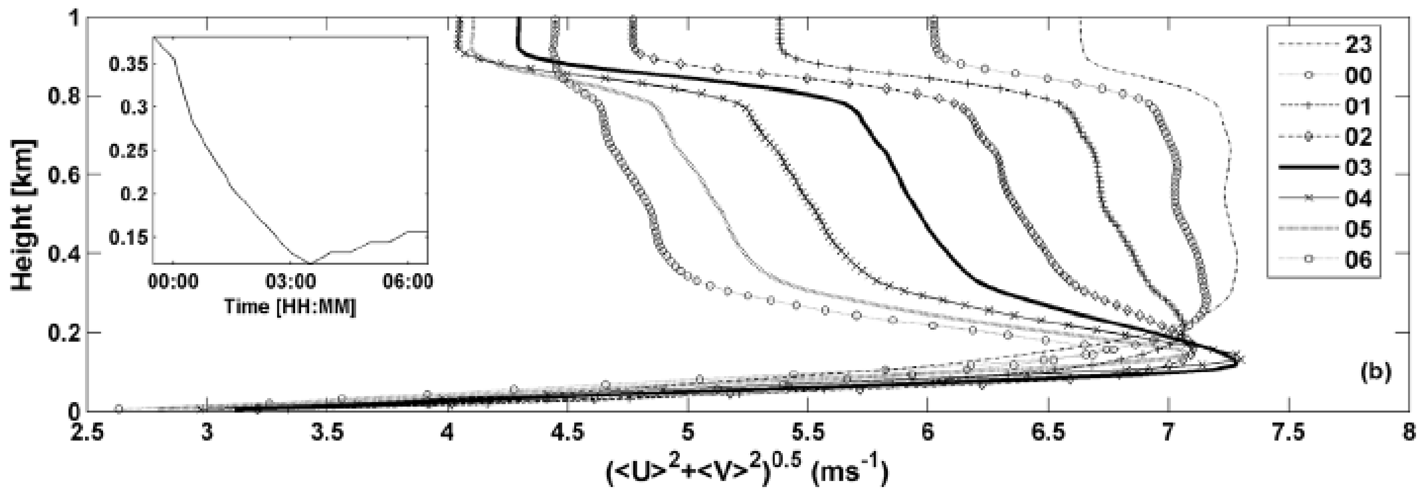
- Combining of the surface roughness and surface temperature fields…

Blending height – smaller or larger?

Future Work

LITFASS – 2003

- simulate over the entire diurnal cycle
    - compare with experimental data to validate the code



Source: Kumar et al., WRR, 2006

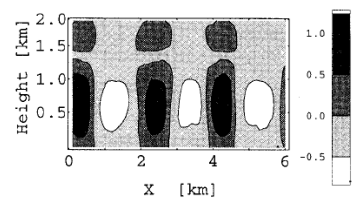
Thank you!

Background

Land-atmosphere interactions over heterogeneous terrain with LES

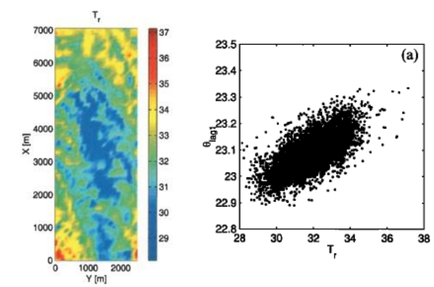
Avissar and Schmidt, JAS, 1998

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



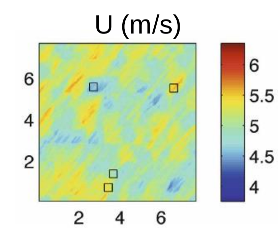
Albertson et al., WRR, 2001

- 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