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

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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)

LES grid size (~ 30 m)
Background

Scales of motion in the ABL

- largest scales ~ 1 km
- smallest scales ~ 1 mm

\[ \sim 10^6 \]
Scales of motion in the ABL

- largest scales $\sim 1$ km
- smallest scales $\sim 1$ 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
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
Set of governing equations

- Incompressible Navier-Stokes
- Boussinesq approximation
- Coriolis forcing

\[ \frac{\partial u_i}{\partial x_i} = 0 \]

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

\[ \frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j} \]
Background

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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)

\[ \nu_T = C_s \cdot \Delta \cdot \Delta |S| \]
- velocity scale
- length scale
- Smagorinsky constant

\[ \tau_{ij}^{SMAG} = -2 (C_{S, \Delta})^2 |S| S_{ij} \]
- modelled SGS stress

\[ \pi_{ij}^{SMAG} = - \frac{(C_{S, \Delta})^2 |S|}{\text{Pr}_{SGS}} \frac{\partial \theta}{\partial x_j} \]
- 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
- 2\textsuperscript{nd} 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: 2\textsuperscript{nd} 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)
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
30 May 2003
- anticyclonic conditions
- no clouds
- cold easterly winds
# Model Setup

## Simulation details

- **Number of grid points**: $128 \times 128 \times 128$ (~ 2.1 million)
- **Domain size** – $L_x, L_y, L_z$: $6 \text{ km} \times 6 \text{ km} \times 3 \text{ km}$
- **Horizontal mesh spacing** – $\Delta x, \Delta y$: 47.9 m
- **Vertical mesh spacing** – $\Delta z$: 23.4 m
- **Number of iterations**: 180 000 with $\Delta t = 0.1$ 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 $z_0$
Convective heterogeneous test case
- Uniform $z_0 \approx 0.2$ 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

sensible heat flux

potential temperature

wind speed

\[ z_i = 1150 \text{ m} \]

\[ |U_g| = 5 \text{ m/s} \]
Results

Convective heterogeneous test case

Time-averaged and horizontally averaged vertical profiles

$u$ velocity variance

$v$ velocity variance

$w$ velocity variance

Convective velocity scale

$$w_* = \left( \frac{g}{T_0} \langle w' \theta' \rangle \right)_0 z_i \right)^{1/3} \approx 1.42 \text{ m/s}$$
Results

Heat flux distribution
Heat flux distribution

Hourly averaged isosurface of $H = 80$ W/m²
Results

Heat flux distribution

Hourly averaged isosurface of $H = 80 \text{ W/m}^2$
Results

Blending heights $h_b$

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

Thermal $h_b$

(convective run)

![Graph showing the blending height $h_b \approx 0.3z_i$]
Neutral heterogeneous test case

- Inhomogeneous surface roughness $z_0$
- Neutral conditions
- Assume $z_i = 1000$ m

discard the first km of outputs
Results

Neutral heterogeneous test case

**Time-averaged and horizontally averaged vertical profiles**

- **wind speed**
- **Reynolds stress**
- **u velocity variance**

\[
\frac{\langle u'w' \rangle^2 + \langle v'w' \rangle^2}{u_*^2}
\]

\[
\frac{\langle u^2 \rangle}{u_*^2}
\]

\[
U (\text{m/s})
\]

\[
\frac{z}{z_*}
\]

\[
\frac{z}{z_*}
\]

\[
\frac{z}{z_*}
\]

\[
u_* \approx 0.22 \text{ m/s}
\]
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 $h_b \sim$ 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 $\theta$ 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