The effect of surface heterogeneity on fluxes in the stable boundary layer

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Land surface heterogeneity

Surface fluxes must be parameterized
Based on average $M$ and $\theta$ at the 1st level

$$\tau_s \sim f(M, z_o, \text{stability}, \ldots)$$

$$q_s \sim f(\theta, z_{o\theta}, \text{stability}, \ldots)$$
Land surface heterogeneity

During the daytime, strong convective eddies mix the boundary layer. This has the effect of blending out small scale heterogeneities (Claussen, 1990; Roy and Avissar, 2000, etc.)
Land surface heterogeneity

Surface fluxes must be parameterized based on average $M$ and $\theta$ at the 1st level

\[
\begin{align*}
\tau_s &\sim f(M, z_o, \text{stability}, \ldots) \\
q_s &\sim f(\theta, z_{o\theta}, \text{stability}, \ldots)
\end{align*}
\]

Large scale model: Night

1st grid point $\sim 10-50$ m

Troposphere

Internal boundary layer $\delta \sim 100$ m
Under stratified conditions, negative buoyancy inhibits mixing with the result that local heterogeneities can have an important impact on dynamics (e.g., Derbyshire, 1995; McCabe and Brown, 2007; Stoll and Porté-Agel, 2009)
Using LES to examine surface heterogeneity

- Based on GABLS I LES intercomparison (Beare et al. 2006)
- Domain size: $H = 400 \text{ m}$; $L_x = L_y = 800 \text{ m}$, Resolution: $\Delta = 5 \text{ m}$, $\Delta = 3.3 \text{ m}$
- Geostrophic: wind $U_g = 8 \text{ m/s}$, Coriolis: $f_c = 1.39 \times 10^{-4} \text{ s}^{-1}$ ($73^\circ \text{ N}$)
- Surface parameters: cooling = $0.25 \text{ K/hr}$, $z_o = 0.1 \text{ m}$
- periodic domain (patches repeat)
- 9 and 12 physical hr simulations (averaged over last hour)
- Scale dependent dynamic Lagrangian SGS model (Stoll and Porté-Agel, 2006)
  - ideal for heterogeneous flows with minimal grid resolution dependence for GABLS I case (Stoll and Porté-Agel, 2008)

- Heterogeneity from:
  - surface temperature transitions (Stoll and Porté-Agel, 2009)
  - aerodynamic surface roughness transitions (Stoll and Miller, 2012)
  - combined aerodynamic roughness and temperature transitions
Using LES to examine surface heterogeneity

Temperature transitions

rough

Δθ_s = 3K, 6K

cold

hot

roughness transitions

smooth

rough

Δθ_s = 6K

smooth

cold-rough to ‘hot’-smooth

‘hot’-rough to cold-smooth
Surface temperature heterogeneity

Temperature (02:25)

Z (m)

X (m)

Y (m)

K

263.8
263.6
263.4
263.2
263
262.8
262.6

$q_x$ (K/m/s)

0

0.2

-0.2

0

200

400

600

800

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Surface temperature heterogeneity

Surface heat flux

Surface stress

\[ \Delta \theta_s = 3K, 6K \]
Surface temperature heterogeneity

### Velocity Magnitude

<table>
<thead>
<tr>
<th>Case</th>
<th>δ (m)</th>
<th>$u_*$ (m/s)</th>
<th>$\theta_*$ (K)</th>
<th>L (m)</th>
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<tbody>
<tr>
<td>Hom</td>
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<td>0.260</td>
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<td>0.0422</td>
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<td>Het6-400</td>
<td>196</td>
<td>0.271</td>
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<td>Het6-200</td>
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<td>0.275</td>
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</table>
Surface roughness heterogeneity

- Surface stress
- Surface heat flux

- 
- 

- 400 m
- 200 m
- 100 m

- \( \tau_s \), \( u^+ \), \( u^+ \)
- \( \theta^+ \), \( \theta^+ \), \( \theta^+ \)

\( x/H \)
Surface roughness heterogeneity

**Velocity Magnitude**

**Temperature**

<table>
<thead>
<tr>
<th>Case</th>
<th>$L_c$ (m)</th>
<th>$R = \ln(z_{0,1}/z_{0,2})$</th>
<th>$\delta$ (m)</th>
<th>$u_*$ (m/s)</th>
<th>$\theta_*$ (K)</th>
<th>$L$ (m)</th>
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<td>A1</td>
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<td>2.3</td>
<td>174</td>
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<td>0.0421</td>
<td>107</td>
</tr>
<tr>
<td>A2</td>
<td>200</td>
<td>2.3</td>
<td>173</td>
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<td>A3</td>
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<td>2.3</td>
<td>175</td>
<td>0.262</td>
<td>0.0423</td>
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<td>0.259</td>
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<tr>
<td>C1</td>
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<tr>
<td>C3</td>
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<td>6.9</td>
<td>174</td>
<td>0.259</td>
<td>0.0420</td>
<td>107</td>
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</tbody>
</table>
Combined roughness-temperature

cold-rough to hot-smooth

hot-rough to cold-smooth

\[ \Delta \theta_s = 6K \]
Combined roughness-temperature

<table>
<thead>
<tr>
<th>Case</th>
<th>$\delta$ (m)</th>
<th>$u_*$ (m/s)</th>
<th>$\theta_*$ (K)</th>
<th>$L$ (m)</th>
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<tr>
<td>Hom $z_o=0.1$ m</td>
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<td>0.0316</td>
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<tr>
<td>Cold-Hot</td>
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<td>0.24</td>
<td>0.0371</td>
<td>105</td>
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</table>
Testing average models: bulk similarity

Temperature

Roughness

Combined

Similarity profiles

\{ \text{Businger et al. (1971)} \}

\{ \text{Beljaars and Holtslag (1991)} \}
Representing heterogeneity: blending

Blending height (Wieringa, 1986):

\[ l_b \left[ \ln \frac{l_b}{z_{o,e}} \right]^2 = 2\kappa^2 L_c \]

Mason, 1988:
• \( U_o(\partial u/\partial x) \sim \partial\Delta\tau/\partial z \)
• Height the mean follows M-O

Claussen, 1991:
• Diffusion height scale
• Everywhere homogeneous

\[ \frac{l_d}{L_c} \ln \frac{l_d}{z_{o,e}} = c_1 \kappa \]

• Can also be a function of stability (Wood and Mason, 1991)
• Mostly tested and developed for neutral or weak stability and is probably not valid under convective or strongly stable (Mahrt, 2000)
Representing heterogeneity: blending height

temperature

(a)

(b)

(c)
Representing heterogeneity: blending height

roughness

$\langle \Phi \rangle_{x,z} - \langle \Phi \rangle_z$
Representing heterogeneity: blending height

Combined roughness-temperature

cold-rough to hot-smooth

hot-rough to cold-smooth
Representing heterogeneity: tiles

- **Tile method (Avissar and Pielke, 1989):**
- **Use M-O locally between each ‘tile’ and the average temperature and velocity**

\[
\langle q_s \rangle = \sum_i^n f_i \left[ \ln \left( \frac{z_r}{z_0} \right) - \Psi_m \left( \frac{z_r}{L^i} \right) \right] \left[ \ln \left( \frac{z_r}{z_t^i} \right) - \Psi_h \left( \frac{z_r}{L^i} \right) \right]
\]

- **Modified tile method (e.g., Blyth, 1995):**
  - M-O should apply above \( I_b \) to the average
  - Below \( I_b \) apply the tile model with \( z_r = I_b \)
Testing average models: temperature

- Tile method (Avissar and Pielke, 1989):
  - Use M-O locally between each ‘tile’ and the average temperature and velocity
Testing average models: temperature

• Tile method (Avissar and Pielke, 1989):
  - Use M-O locally between each ‘tile’ and the average temperature and velocity
Examining cold patches

- patch flux \(>>\) mean flux
- decrease rapidly to some height

\[\Psi_m = -\beta_m \frac{z_r}{L}\]
\[\Psi_h = -\beta_h \frac{z_r}{L}\]

Typical similarity profiles are linear (or near linear)

\(\Rightarrow\) Patch fluxes decrease in magnitude rapidly with decreasing \(L\) at a given \(z_r\)
Linear flux assumption

- Alternative parameterization developed for temperature transitions (Stoll and Porté-Agel, 2009)
- Apply ‘local’ scaling (Nieuwstadt, 1984) over the cold patch at the ‘blending height’ $l_b$ (Wieringa, 1986).
- Assume linear $q_L$ and $u_{\cdot L}$:
  - $q_L = (q_i/q_s - 1)z/l_b + q_s$
  - $u_{\cdot L} = (u_{\cdot i}/u_{\cdot} - 1)z/l_b + u_{\cdot}$
- Using $q_L$ and $u_{\cdot L}$ define new $\Psi_M$ and $\Psi_H$.

\[
\begin{align*}
\Psi_M &= -Az - \frac{\beta}{L} \left[ \frac{B - A}{A^2(Az + 1)} - \frac{B - A}{A^2} + \frac{B}{A^2} \ln(Az + 1) \right] \\
\Psi_H &= \alpha \frac{B - A}{B} \ln(Az + 1) + \frac{\beta}{L} \left[ \frac{(3B^2z^2 + 3Bz + 1)A^2 + (3Bz + 1)BA + B^2}{3A^3(Az + 1)^3} - \frac{A^2 + BA + B^2}{3A^3} \right]
\end{align*}
\]

where $A = \left( \frac{u_{\cdot i}}{u_{\cdot}} - 1 \right) \frac{1}{l_b}$ and $B = \left( \frac{q_i}{q_s} - 1 \right) \frac{1}{l_b}$.
Testing average models: roughness

- All cases follow mean similarity ➔ just need to specify $z_{o,\text{eff}}$
- Many models, difference is mostly definition of what height scale to use:

$$\left[ \ln \left( \frac{l_b}{z_{o,e}} \right) \right]^{-1} = \sum_{i}^{n} f_i \left[ \ln \left( \frac{l_d}{z_{o,i}} \right) \right]^{-2}$$

<table>
<thead>
<tr>
<th>Case</th>
<th>$L_c$ (m)</th>
<th>$R$</th>
<th>LES</th>
<th>Taylor</th>
<th>Mason</th>
<th>Wood and Mason</th>
<th>Bou-Zeid et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>400</td>
<td>2.3</td>
<td>0.0329</td>
<td>0.0316</td>
<td>0.0435</td>
<td>0.0435</td>
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</tr>
<tr>
<td>A2</td>
<td>200</td>
<td>2.3</td>
<td>0.0344</td>
<td>0.0316</td>
<td>0.0458</td>
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<td>0.0371</td>
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<tr>
<td>A3</td>
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<td>B1</td>
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<td>C1</td>
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<td>0.0032</td>
<td>0.0338</td>
<td>0.0340</td>
<td>0.0199</td>
</tr>
</tbody>
</table>

- Can argue that $z_{o,e}$ is a property of the surface roughness (Bou-Zeid et al, 2004)
Testing average models: roughness

Taylor (1987)

Testing average models: combined

• Tile method (Avissar and Pielke, 1989):
  - Use M-O locally between each ‘tile’ and the average temperature and velocity

$$\langle q_s \rangle = \sum_i^n f_i \left[ \ln \left( \frac{z_r}{z_i} \right) - \Psi_m \left( \frac{z_r}{L_i} \right) \right] + \Psi_n \left( \frac{z_r}{L_i} \right)$$
Testing average models: combined

• Using Stoll and Porté-Agel (2009)
• With $z_{o,eff}$ for mean fluxes (to get blending height values)
Coupling to turbulence models

• Surface temperature heterogeneity test
• Simple single-column model:
  - 1st-order PBL turbulence model (Beljaars and Viterbo, 1998)
  - Coupled with bulk model
  - Coupled with basic tile model

<table>
<thead>
<tr>
<th>Case</th>
<th>$\langle \tau_s \rangle$</th>
<th>$\langle q_s \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homo</td>
<td>0.0676</td>
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<td>Het3</td>
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</tr>
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<td>Het6</td>
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<td><strong>1D Model</strong></td>
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<td>Homo</td>
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<tr>
<td>Het6</td>
<td>0.1196</td>
<td>-0.0077</td>
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</table>
Summary

• Models developed to represent the average effect of surface heterogeneity do not represent the fluxes correctly in the heterogeneous SBL over surface temperature transitions.

• It is possible to develop models that can mimic the effect of flux enhancement.

• Roughness transitions do appear to be represented well under wind conditions.

• Correlation between surface properties is especially important (and problematic) in the heterogeneous SBL.

• Flux boundary conditions and PBL turbulence models should be examined as a coupled systems in addition to ‘offline’
Future Directions

• Study weak wind conditions when stability will be higher and flow won’t be dominated by advection
• Larger range of patch sizes and impact of using the ‘wrong’ blending height
• Realistic surface heterogeneity patterns
• Impact of moisture on heterogeneity (more realistic local coupling)
• Examine a wider range of PBL schemes in SCM tests
Surface temperature heterogeneity

\[ \Phi_M = \frac{\kappa z}{u_*} \sqrt{\left( \frac{\partial \langle u \rangle}{\partial z} \right)^2 + \left( \frac{\partial \langle v \rangle}{\partial z} \right)^2} \]

\[ \Phi_H = \frac{\kappa z}{\theta_*} \frac{\partial \langle \theta \rangle}{\partial z} \]

similarity profiles

\{ \text{Businger et al. (1971)} \}

\{ \text{Beljaars and Holtslag (1991)} \}
Surface roughness heterogeneity

\[ \Phi_M = \frac{\kappa z}{u_*} \sqrt{\left( \frac{\partial \langle u \rangle}{\partial z} \right)^2 + \left( \frac{\partial \langle v \rangle}{\partial z} \right)^2} \]

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Similarity profiles

\{ \quad \text{Businger et al. (1971)} \quad \}

\{ \quad \text{Beljaars and Holtslag (1991)} \quad \}
Combined roughness-temperature

\[ \Phi_M = \frac{\kappa z}{u_*} \sqrt{\left( \frac{\partial \langle u \rangle}{\partial z} \right)^2 + \left( \frac{\partial \langle v \rangle}{\partial z} \right)^2} \]

\[ \Phi_H = \frac{\kappa z}{\theta_*} \frac{\partial \langle \theta \rangle}{\partial z} \]

Similarity profiles

Businger et al. (1971)
Beljaars and Holtslag (1991)