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

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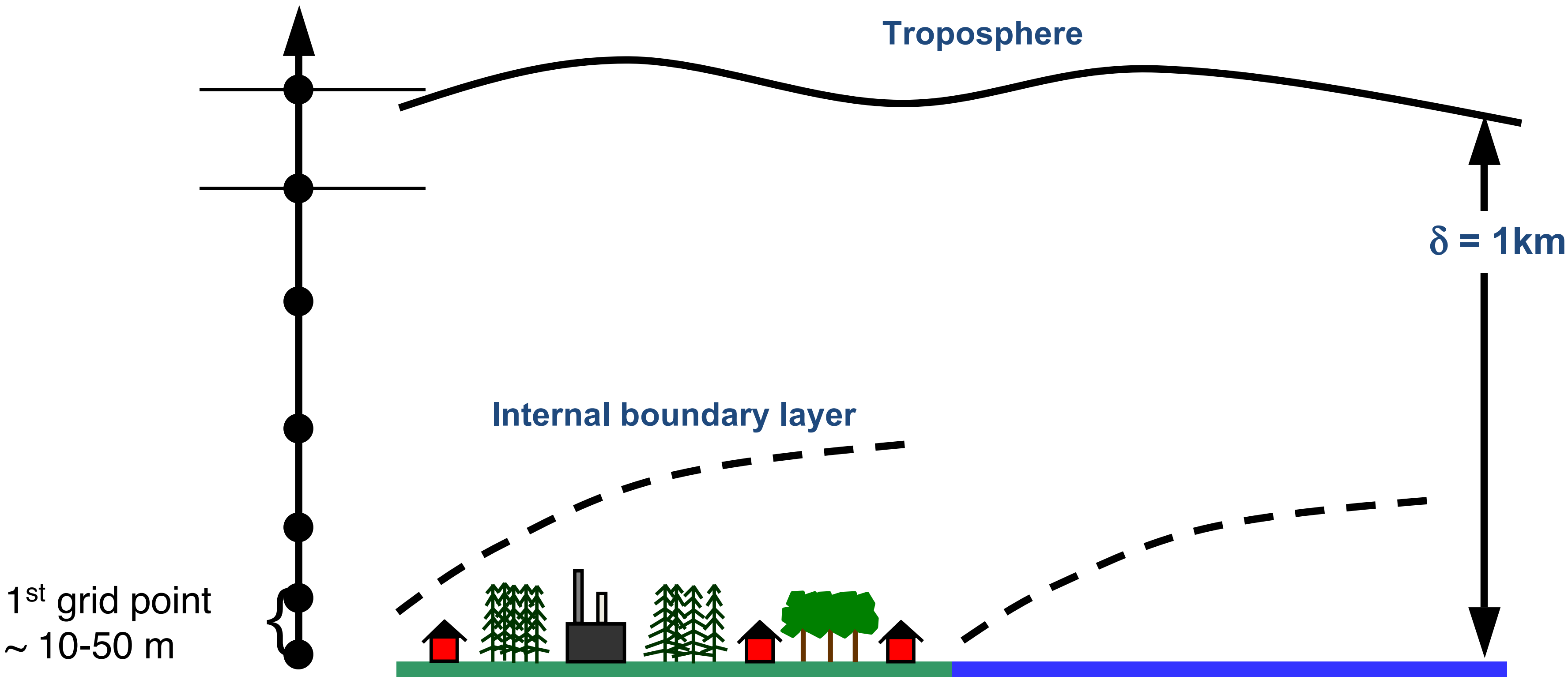
Land surface heterogeneity

Large scale model: Day

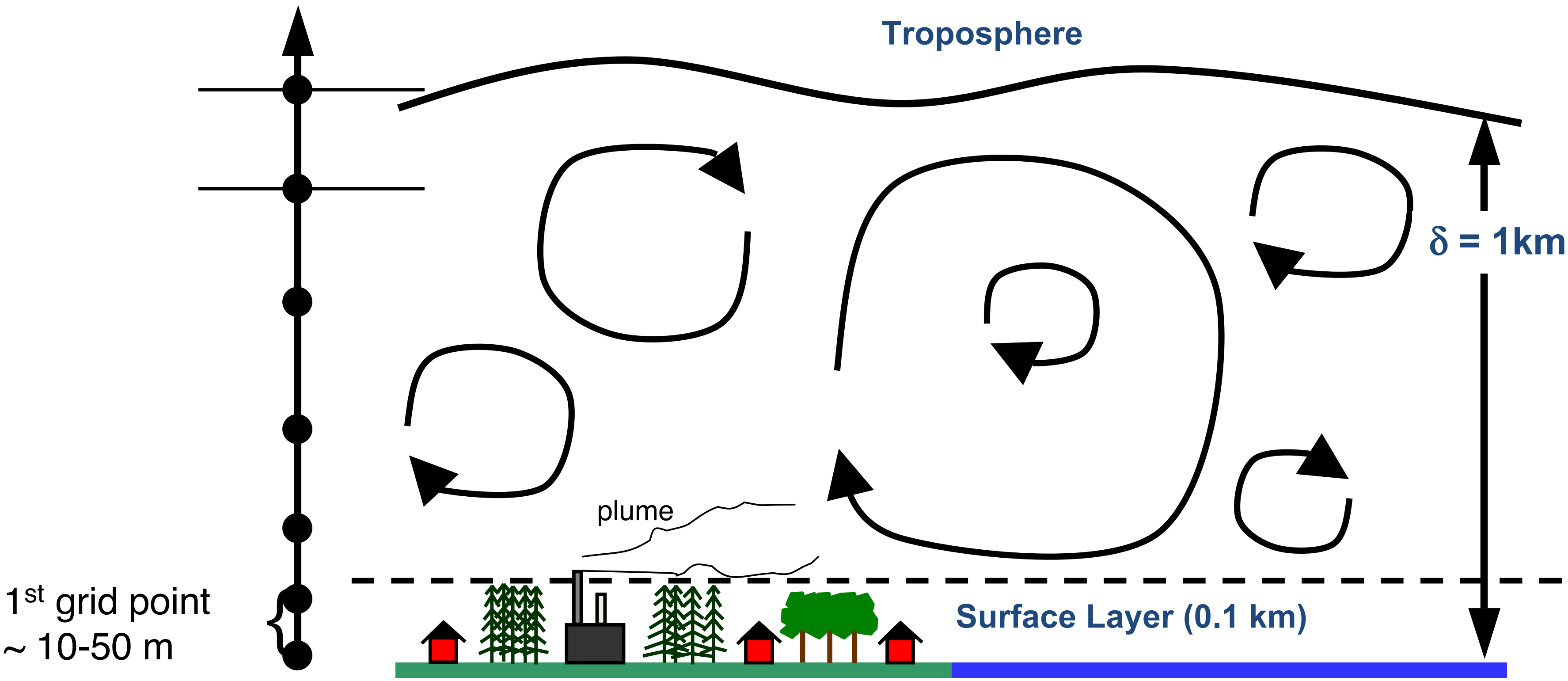


Surface fluxes must be parameterized
Based on average M and θ at the 1st level

$$\left\{ \begin{array}{l} \tau_s \sim f(M, z_o, \text{stability}, \ldots) \\ q_s \sim f(\theta, z_{o\theta}, \text{stability}, \ldots) \end{array} \right.$$

Land surface heterogeneity

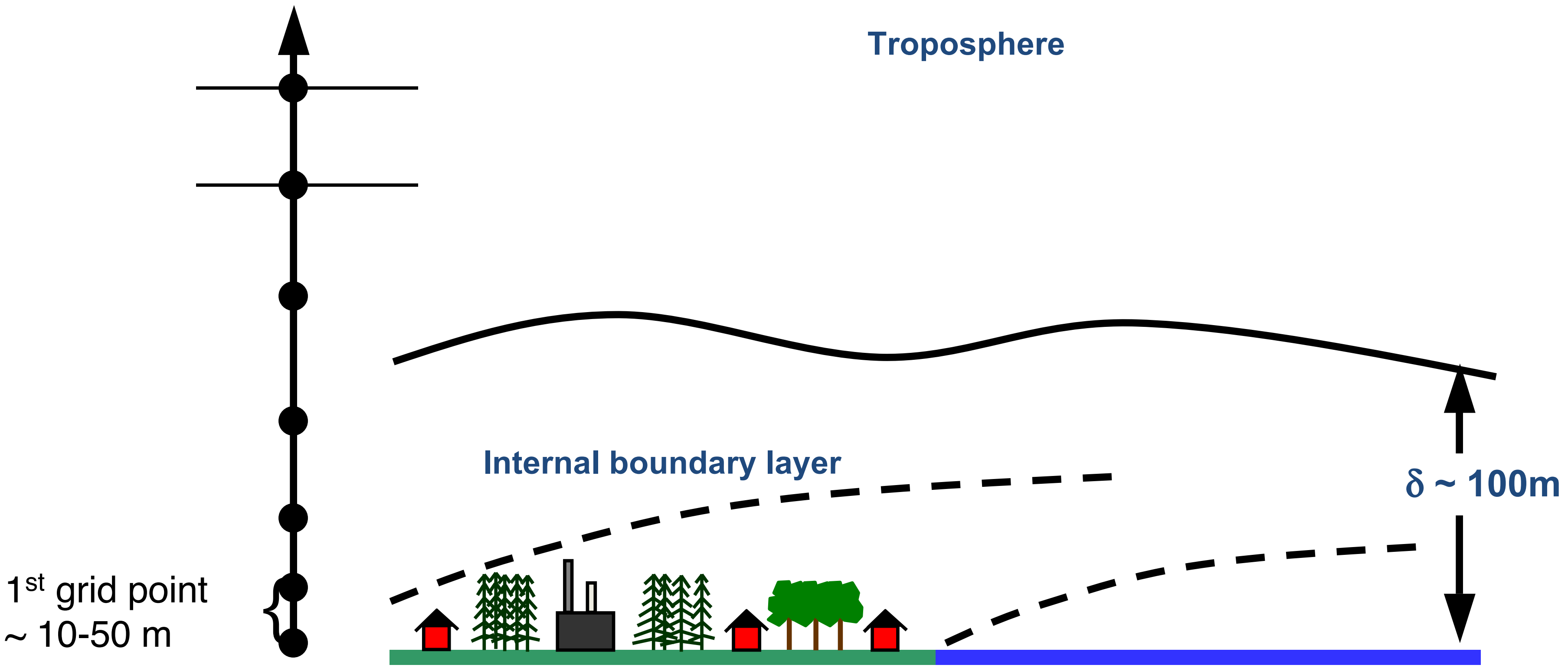
Large scale model: Day



• 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

Large scale model: Night

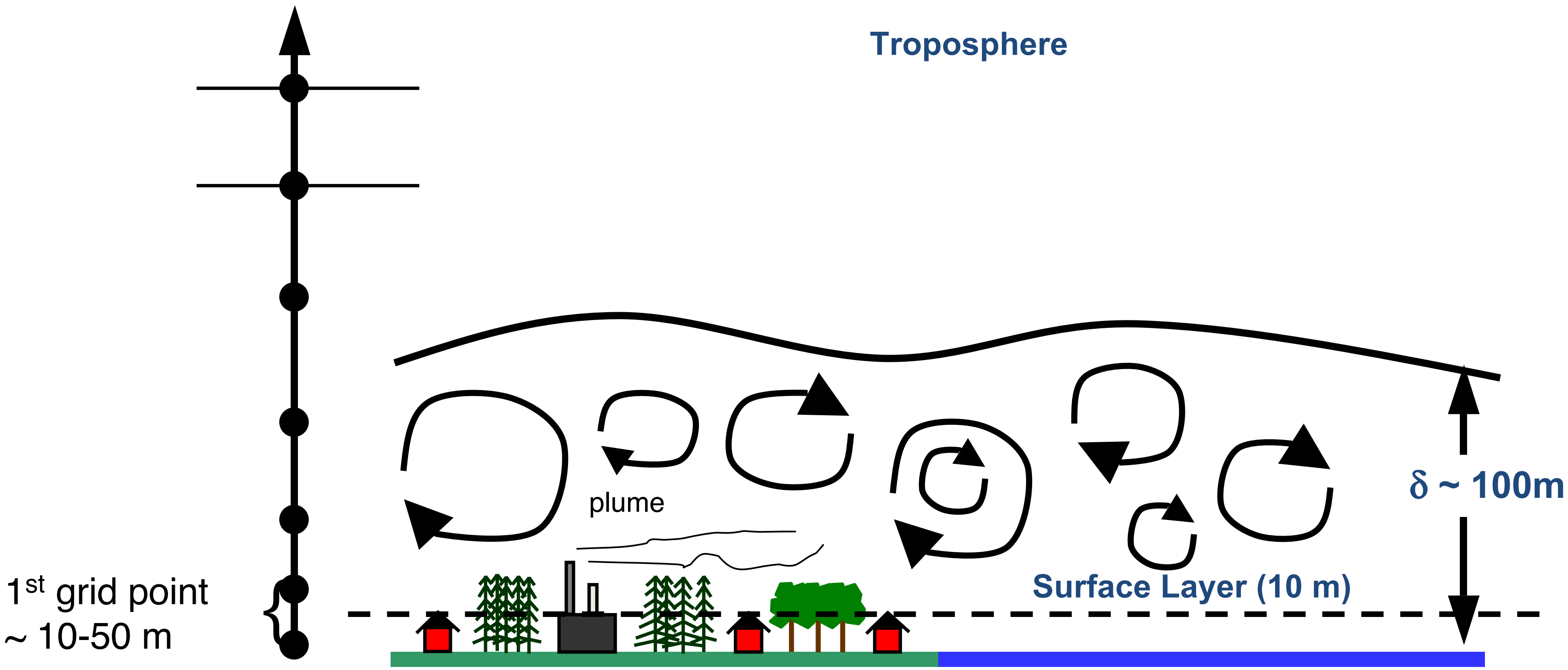


Surface fluxes must be parameterized
Based on average M and θ at the 1st level

$$\begin{cases} \tau_s \sim f(M, z_o, \text{stability}, \ldots) \\ q_s \sim f(\theta, z_{o\theta}, \text{stability}, \ldots) \end{cases}$$

Land surface heterogeneity

Large scale model: Night



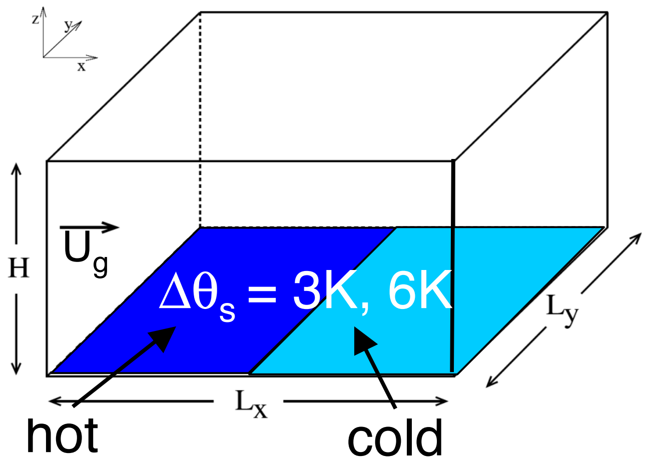
Under stratified conditions, negative buoyancy inhibits mixing with the result that local heterogeneities can have an important impact on dynamics (e.g., Derbyshire, 1995; McCabe and Brown, 2007; Stoll and Porté-Agel, 2009)

Using LES to examine surface heterogeneity

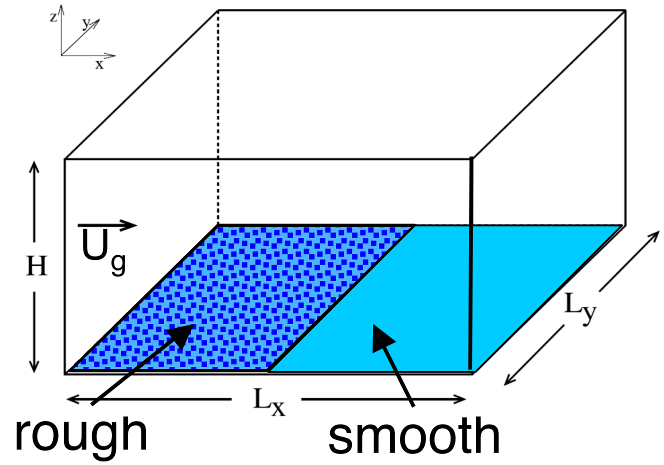
- Based on GABLS I LES intercomparison (Beare et al. 2006)
- Domain size: **H = 400 m; L_x = L_y = 800 m,** Resolution: **Δ=5 m, Δ=3.3 m**
- Geostrophic: wind U_g = 8 m/s, Coriolis: $f_c = 1.39 \times 10^{-4}\ s^{-1}$ (73^o N)
- Surface parameters: cooling = **0.25 K/hr**, **z_o = 0.1 m**
- periodic 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)
- **<u>Heterogeneity from</u>**:
  - 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

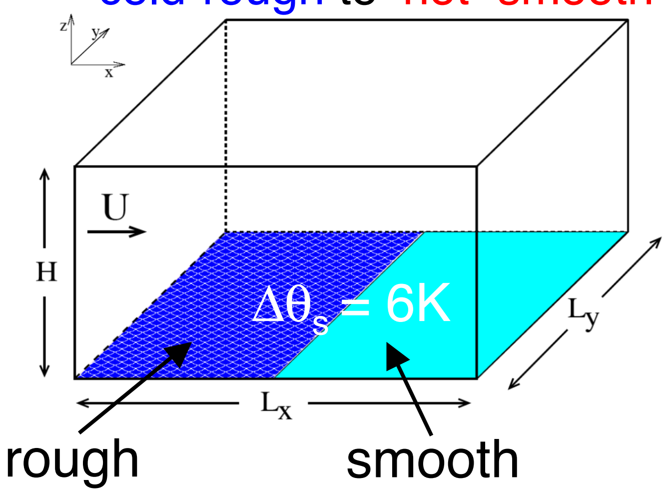
Temperature transitions



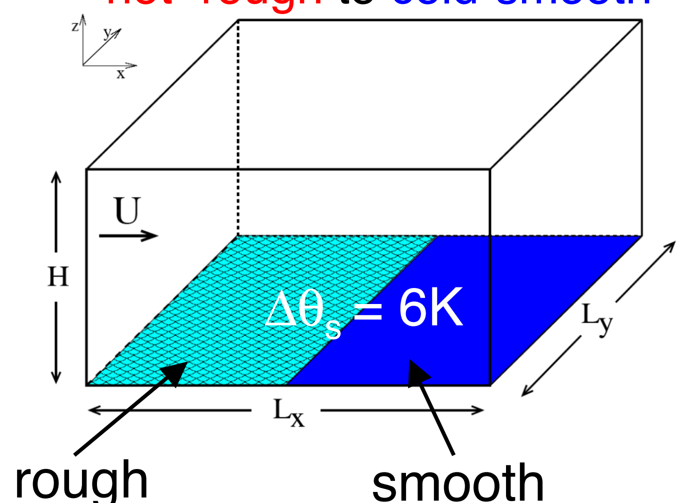
roughness transitions



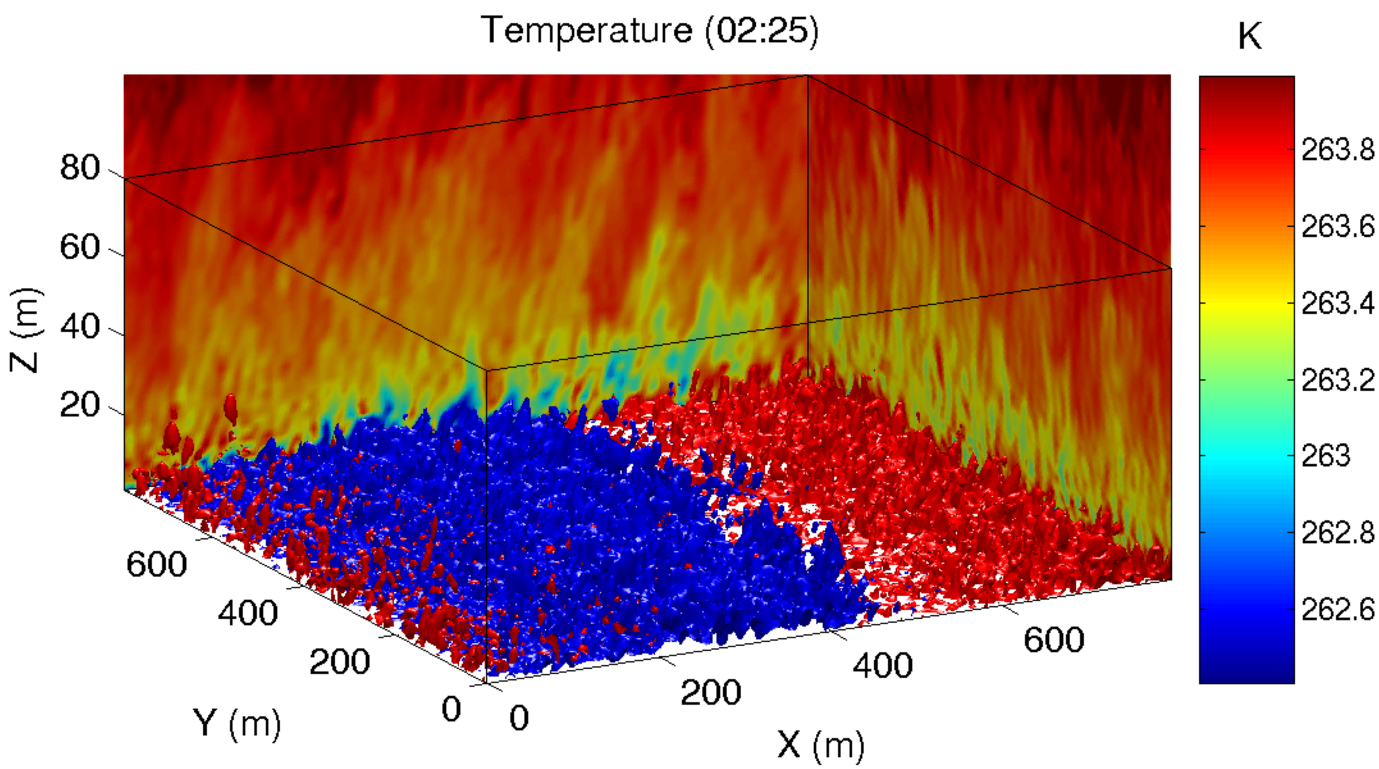
cold-rough to 'hot'-smooth

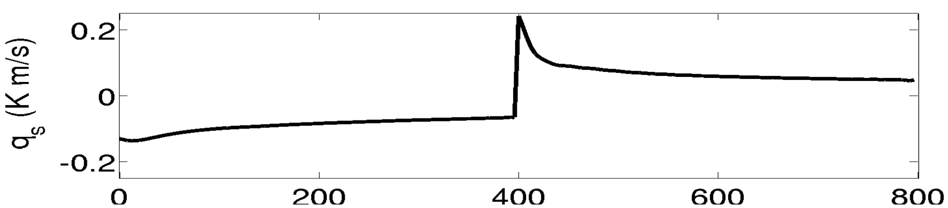


'hot'-rough to cold-smooth

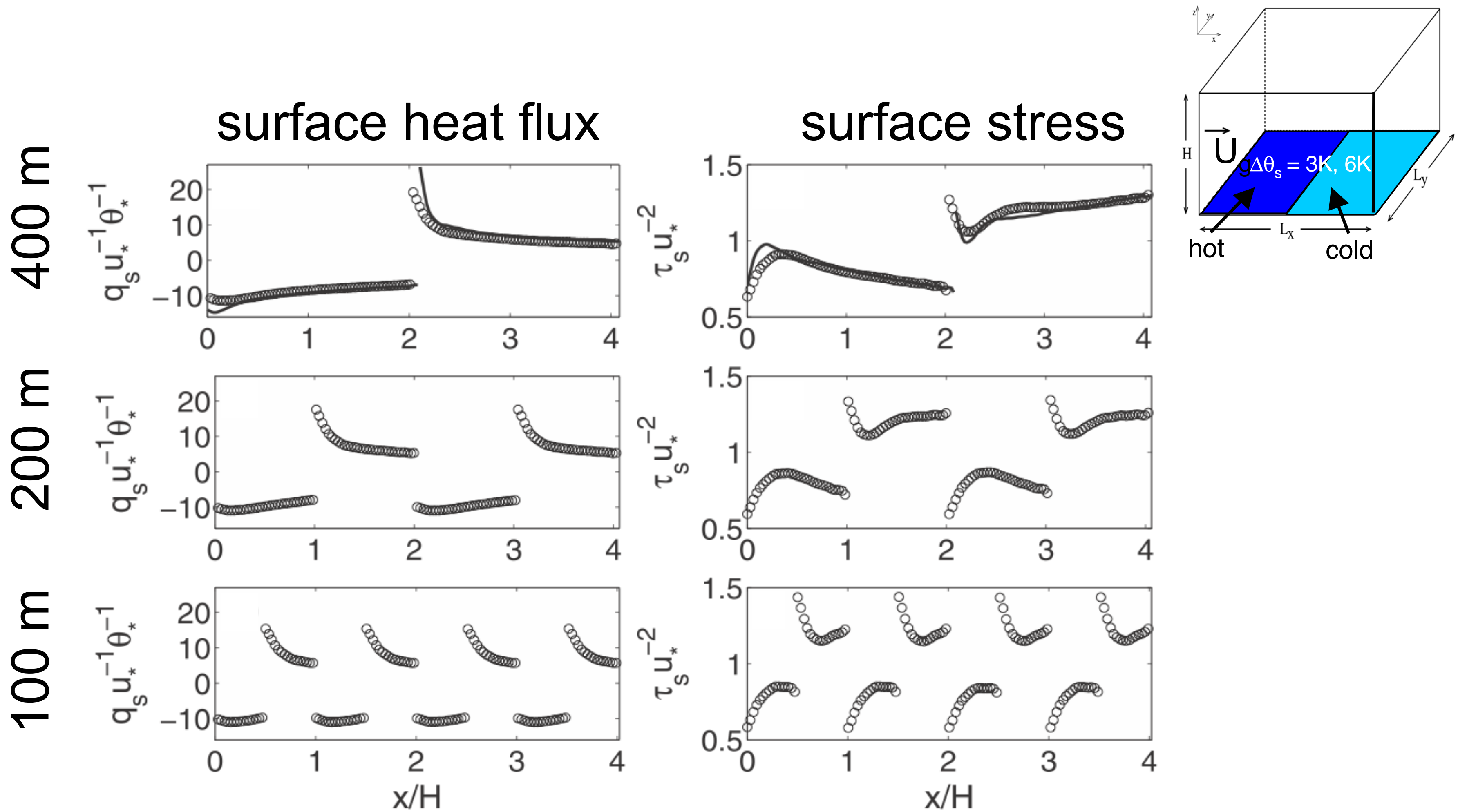


Surface temperature heterogeneity

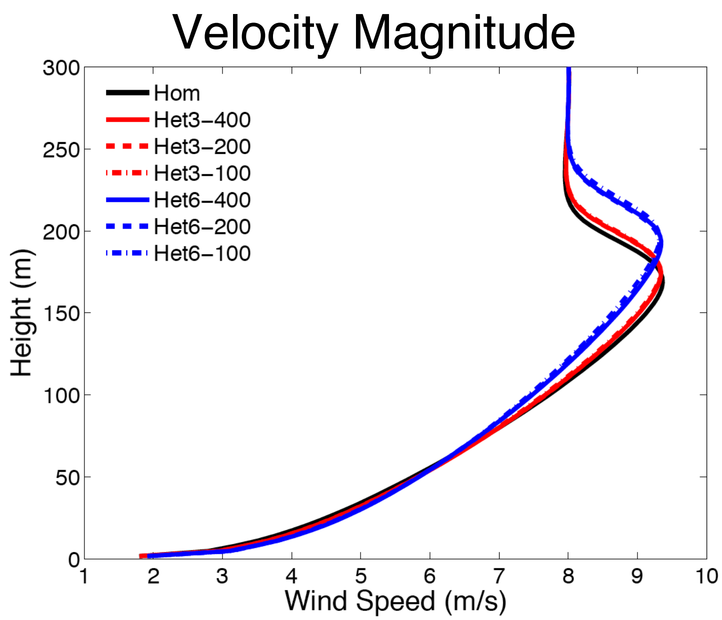




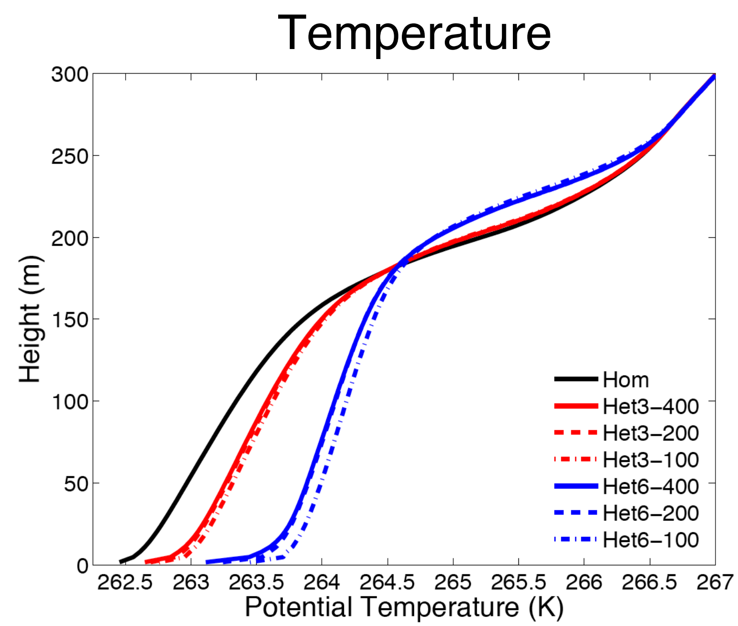
Surface temperature heterogeneity



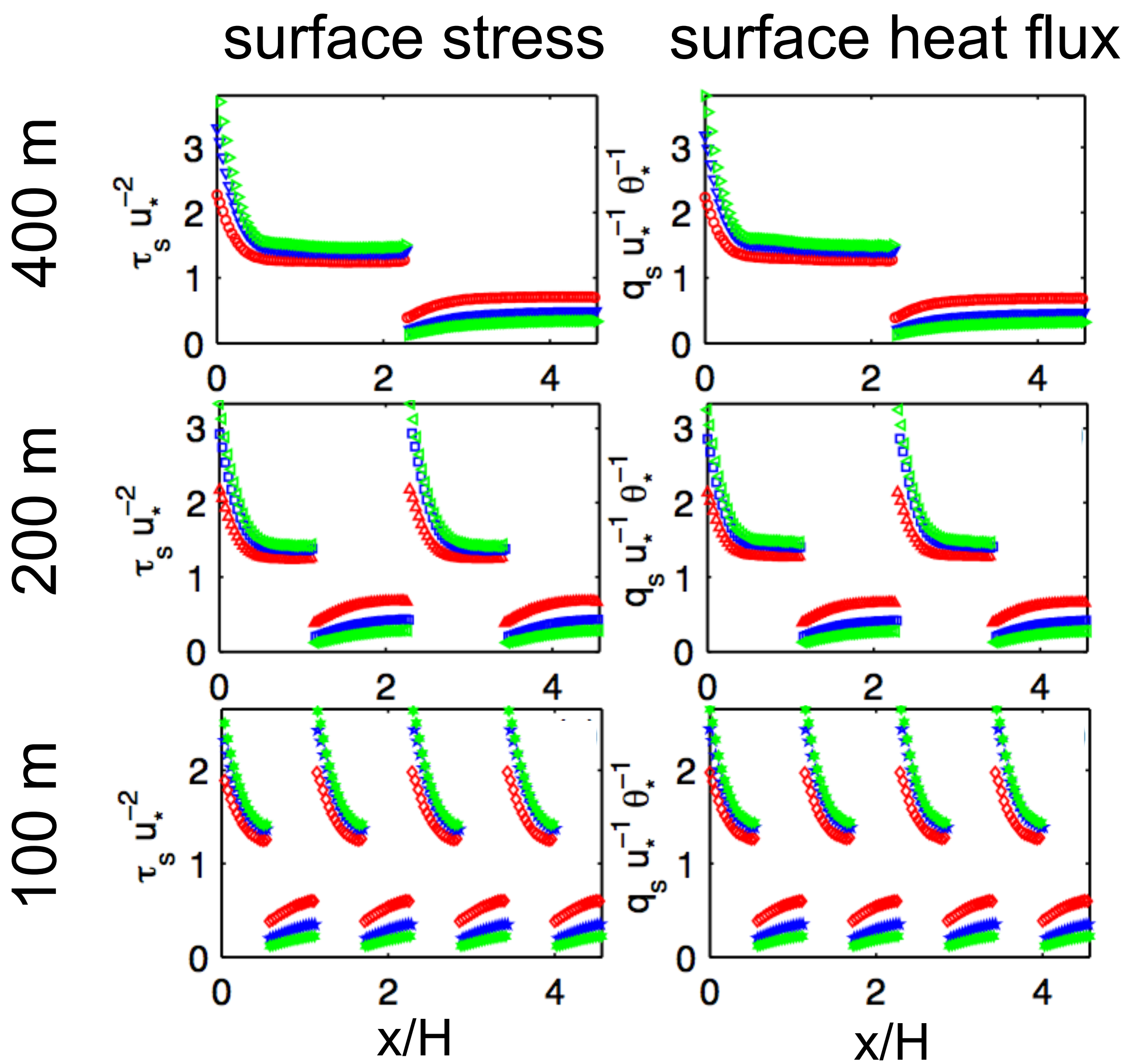
Surface temperature heterogeneity

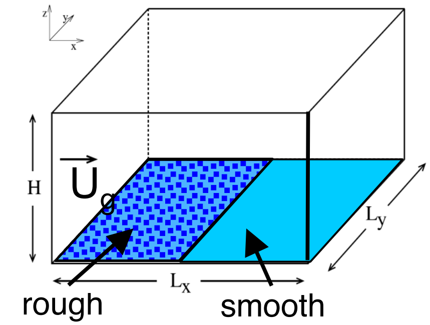


Case	δ (m)	u_* (m/s)	θ_* (K)	L (m)
Hom	175	0.260	0.0447	101
Het3-400	180	0.263	0.0425	109
Het3-200	180	0.263	0.0422	110
Het3-100	182	0.264	0.0421	111
Het6-400	196	0.271	0.0359	137
Het6-200	198	0.272	0.0362	137
Het6-100	200	0.275	0.0356	142



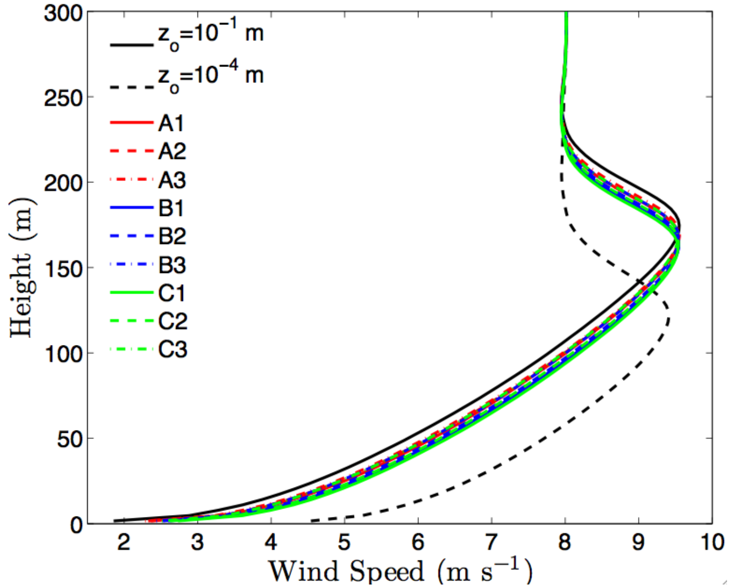
Surface roughness heterogeneity





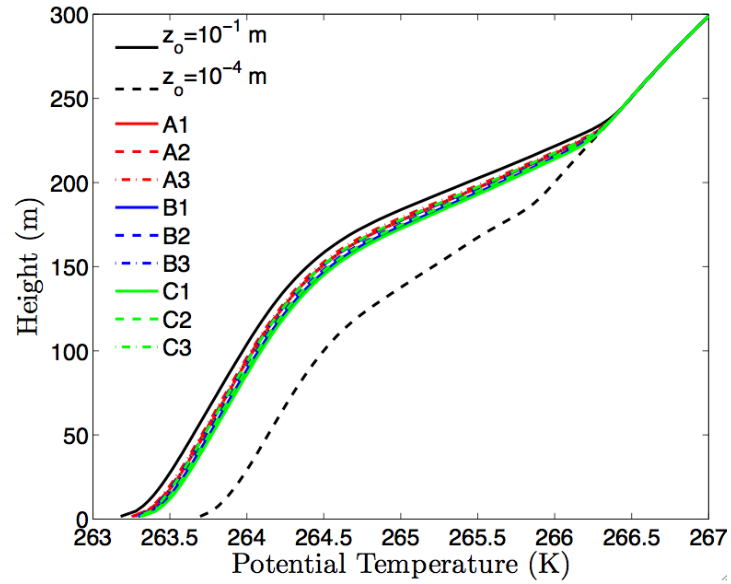
Surface roughness heterogeneity

Velocity Magnitude



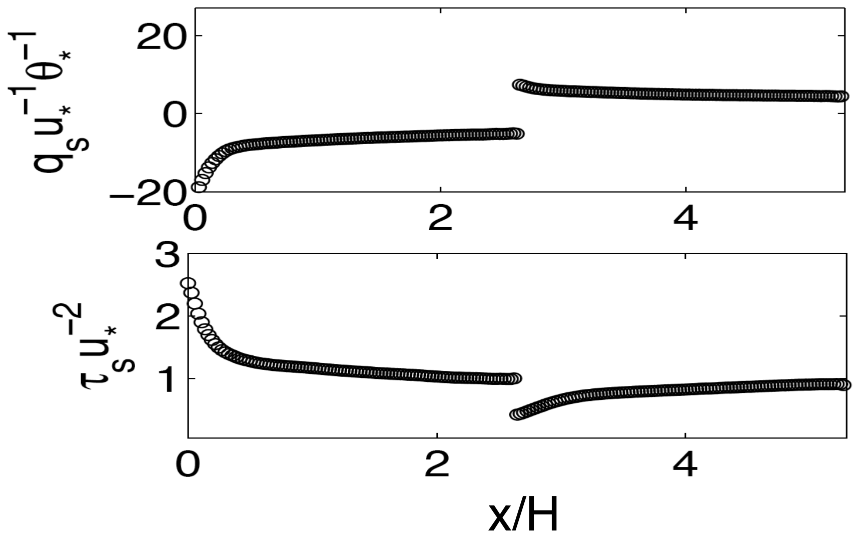
Case	L_c (m)	$R = ln(z_{o,1}/z_{o,2})$	δ (m)	u_* (m/s)	θ_* (K)	L (m)
A1	400	2.3	174	0.259	0.0421	107
A2	200	2.3	173	0.260	0.0420	108
A3	100	2.3	175	0.262	0.0423	109
B1	400	4.6	170	0.252	0.0413	103
B2	200	4.6	171	0.256	0.0417	106
B3	100	4.6	173	0.259	0.0420	108
C1	400	6.9	168	0.250	0.0412	102
C2	200	6.9	170	0.255	0.0417	105
C3	100	6.9	174	0.259	0.0420	107

Temperature

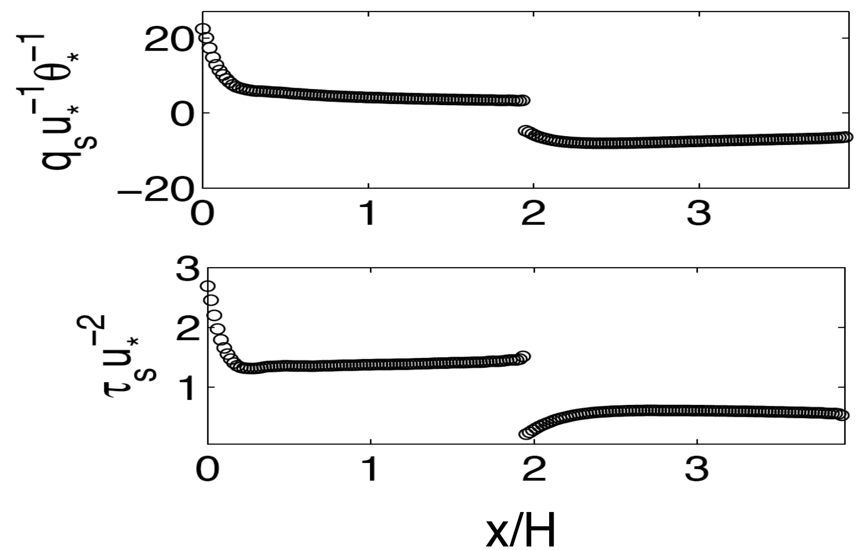


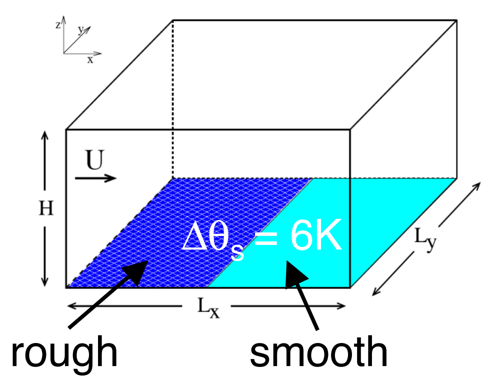
Combined roughness-temperature

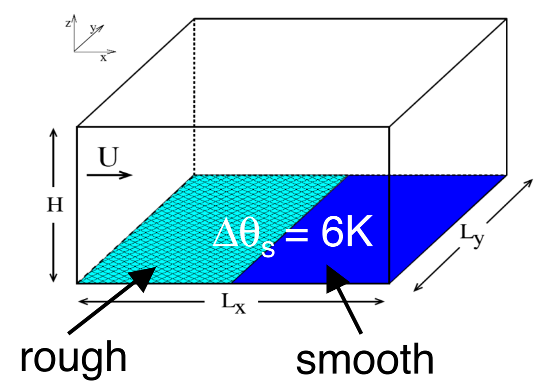
cold-rough to hot-smooth



hot-rough to cold-smooth







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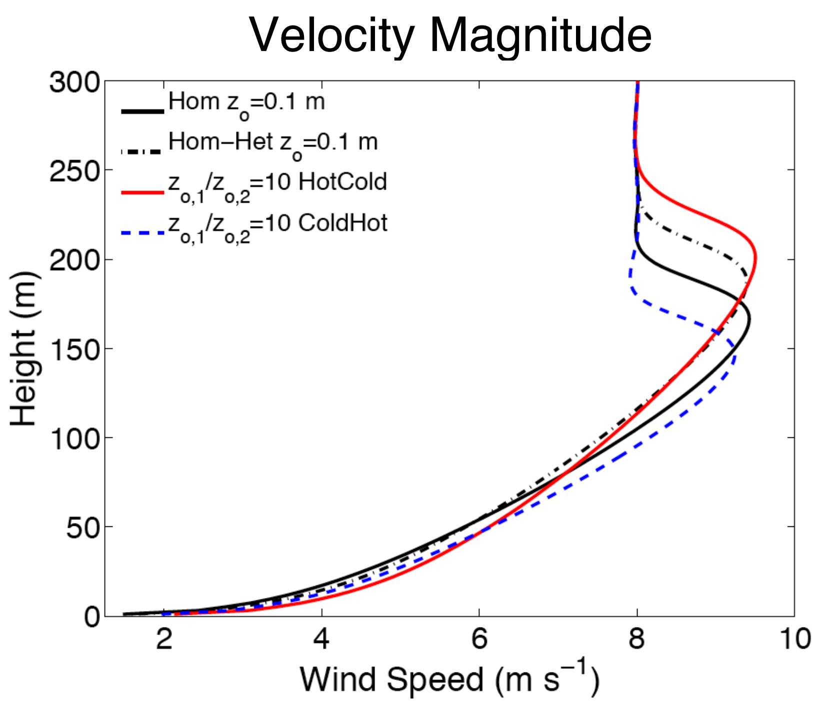
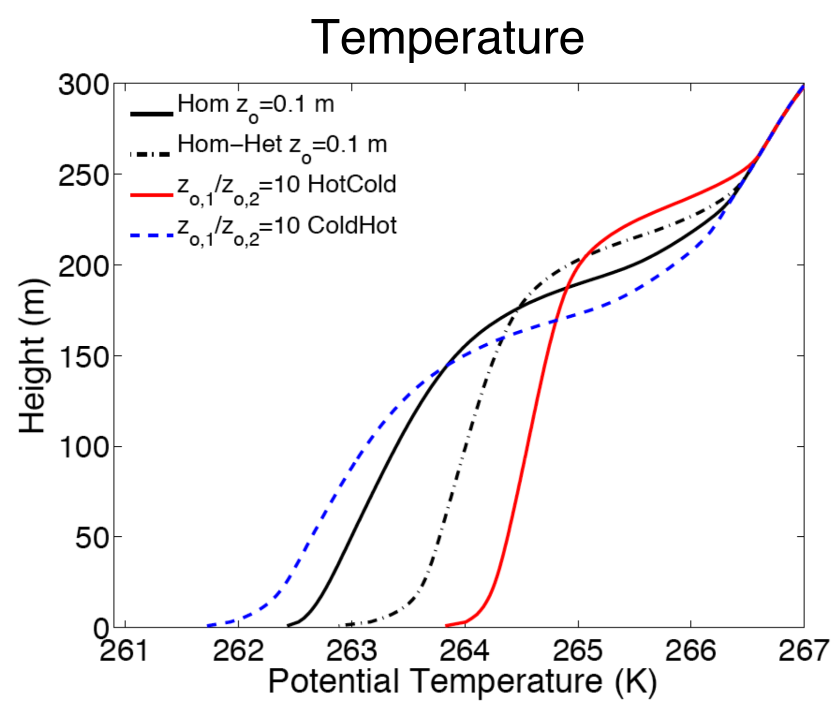
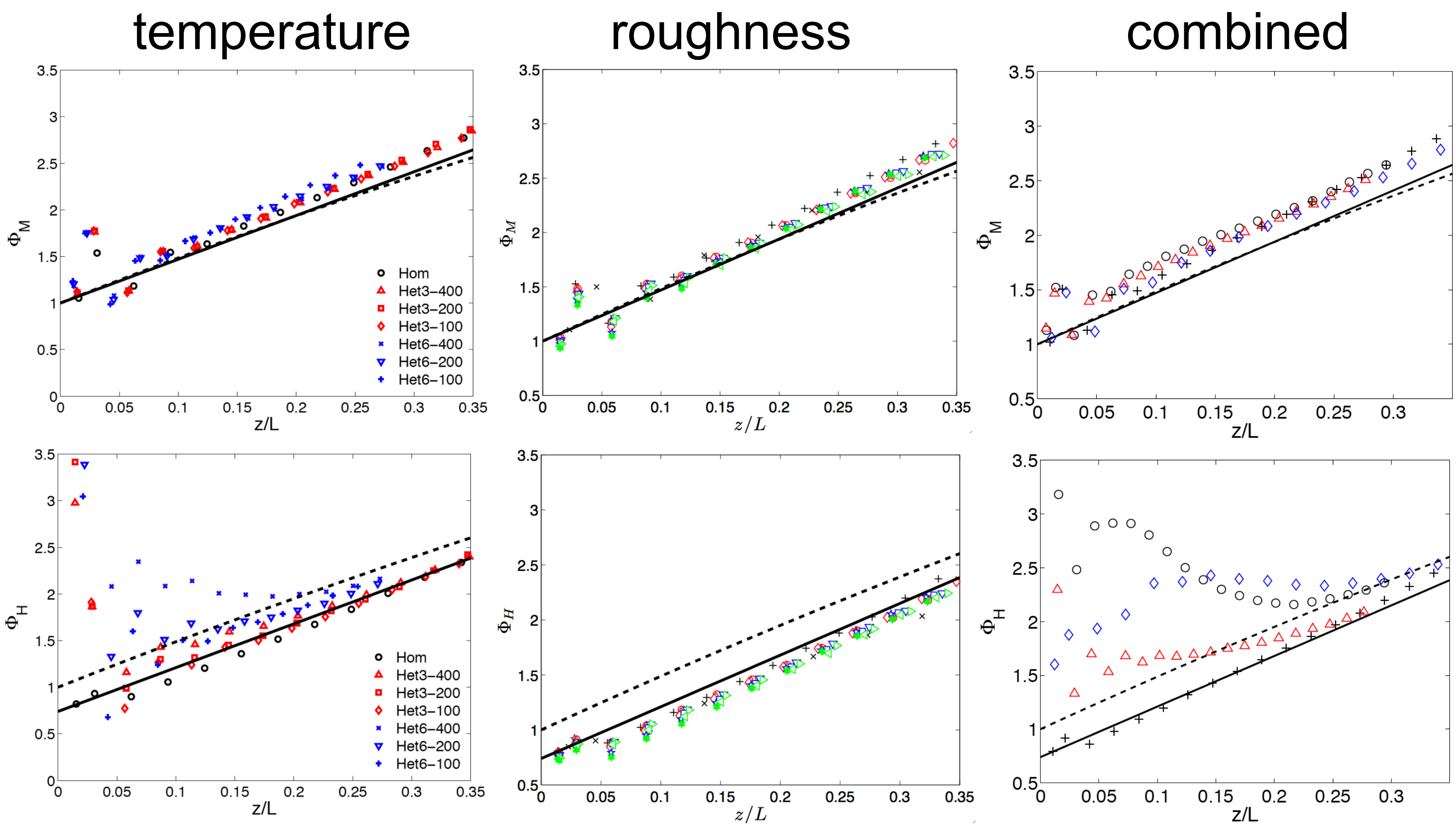


Case	δ (m)	u_* (m/s)	θ_* (K)	L (m)
Hom z_o=0.1m	169	0.254	0.0435	100
Het6-400	190	0.265	0.0348	135
Hot-Cold	205	0.26	0.0316	144
Cold-Hot	152	0.24	0.0371	105



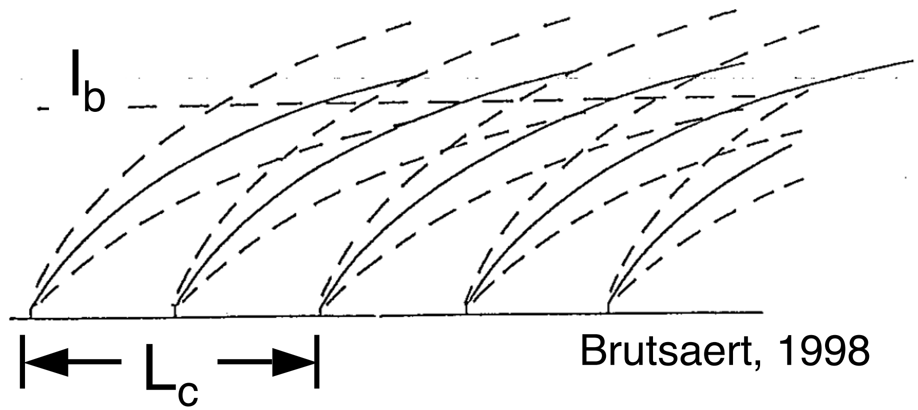
Testing average models: bulk similarity



similarity profiles { Businger et al. (1971)
Beljaars and Holtslag (1991)

Representing heterogeneity: blending

Blending height (Wieringa, 1986):



Brutsaert, 1998

Mason, 1988:

- $U_o(\partial u/\partial x) \sim \partial\Delta\tau/\partial z$
- Height the mean follows M-O

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

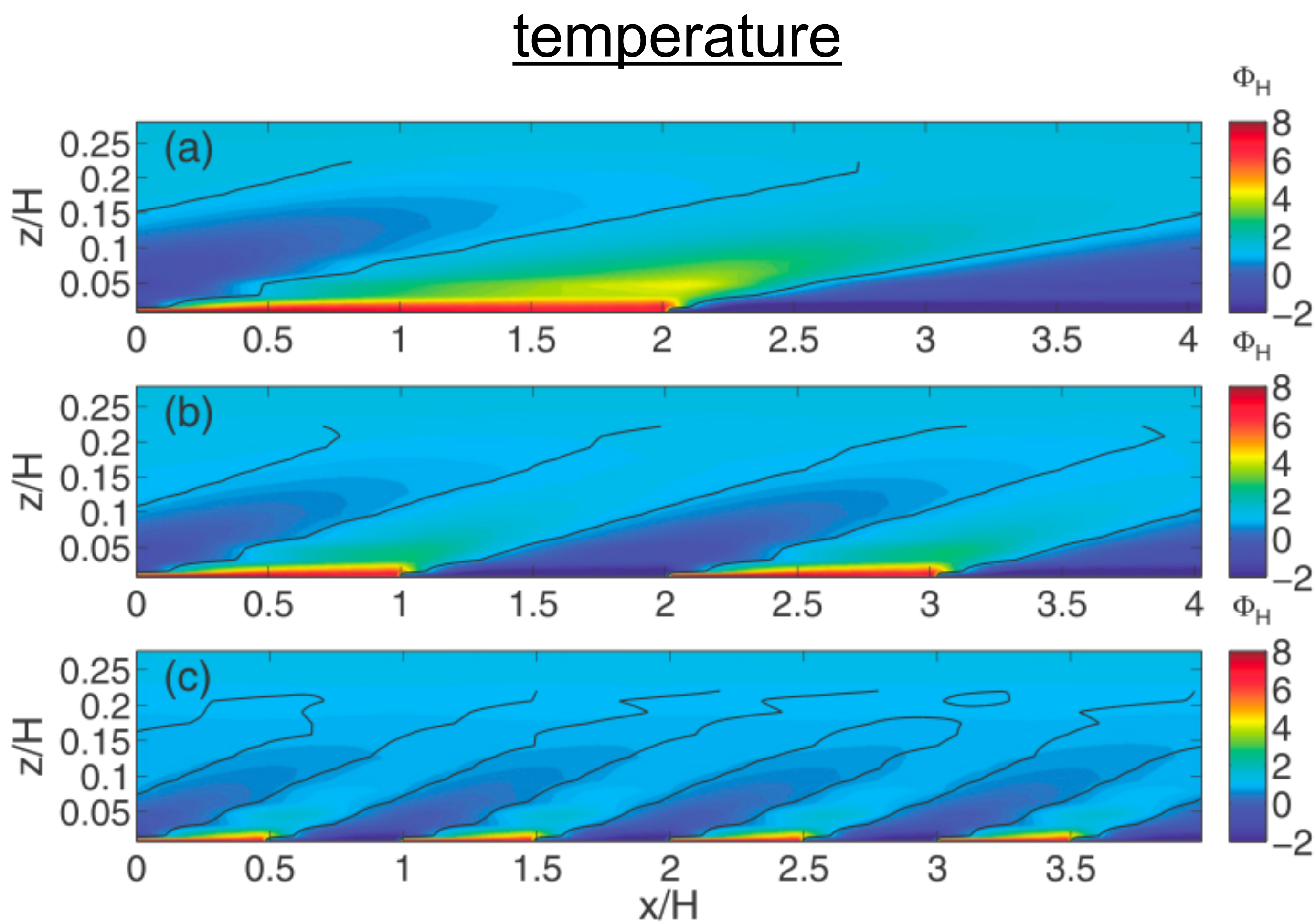
Claussen, 1991:

- Diffusion height scale
- Everywhere homogeneous

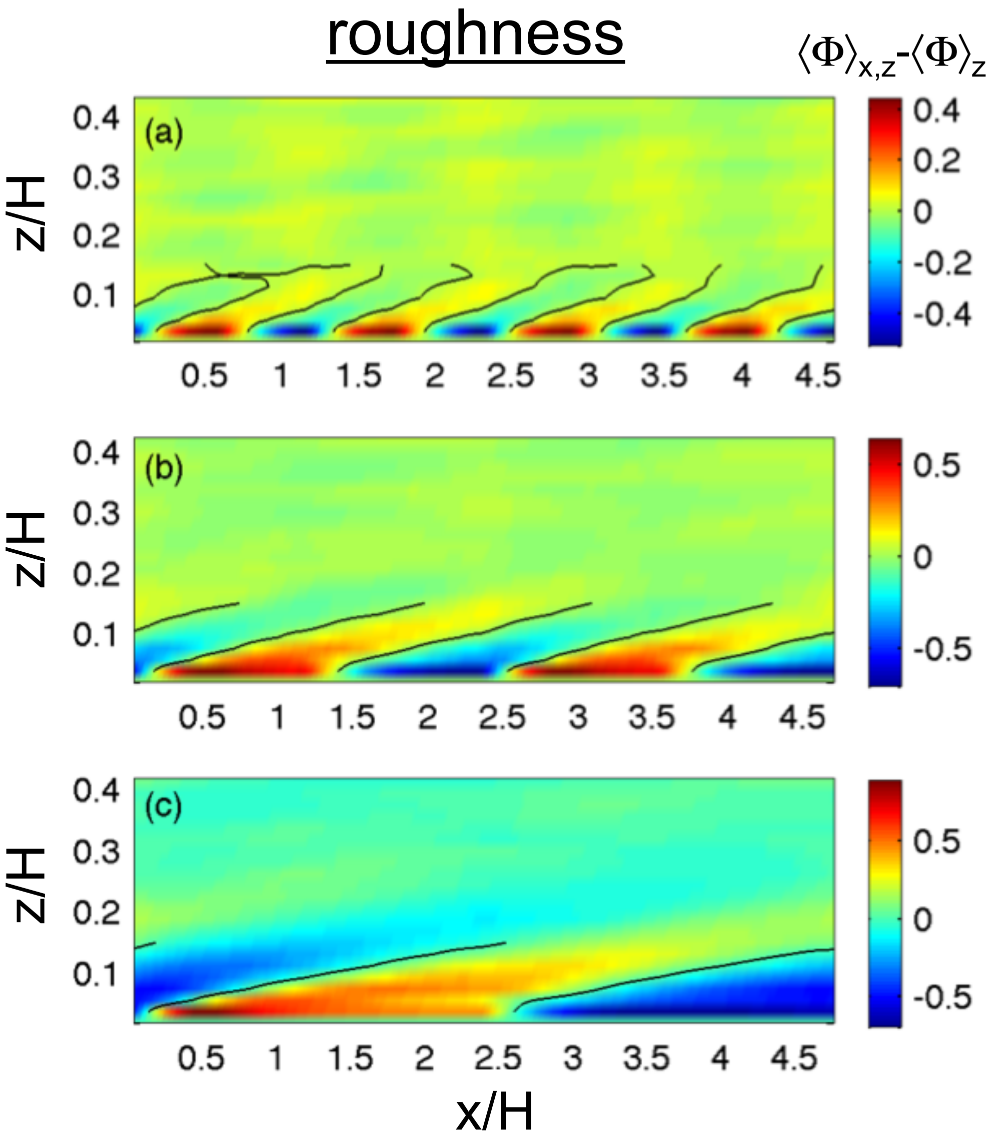
$$\frac{l_d}{L_c} ln \frac{l_d}{z_{o,e}} = c_1 \kappa$$

- Can also be a function of stability (Wood and Mason, 1991)
- Mostly tested and developed for neutral or weak stablility and is probably not valid under convective or strongly stable (Mahrt, 2000)

Representing heterogeneity: blending height



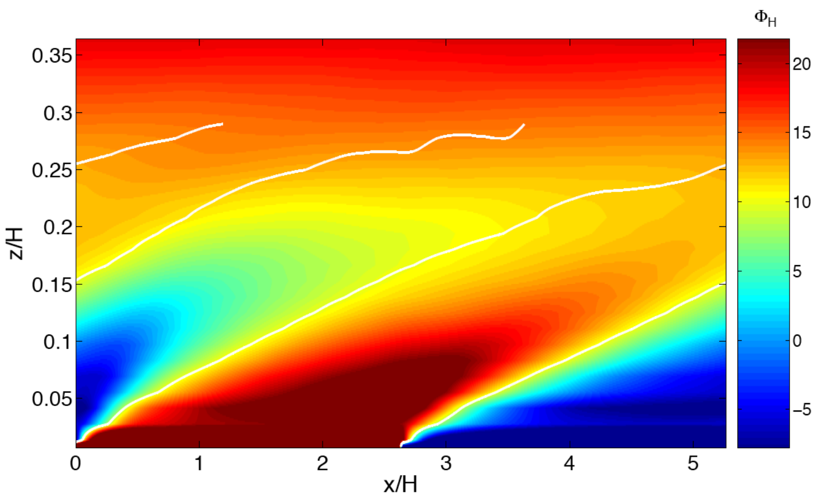
Representing heterogeneity: blending height



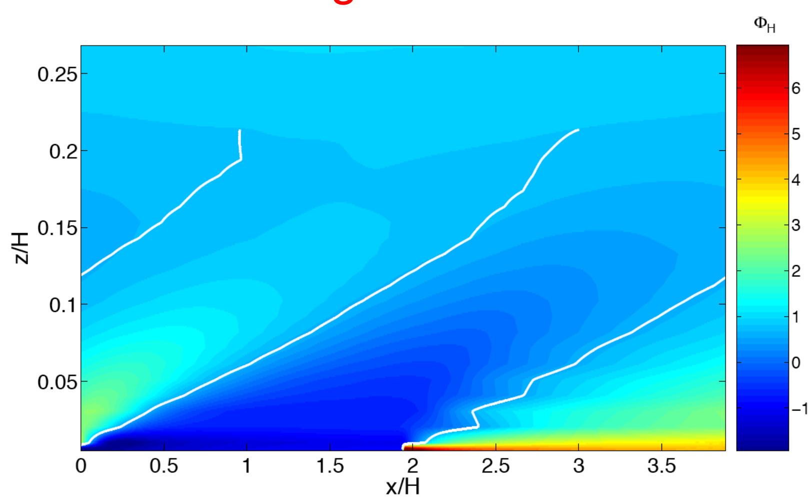
Representing heterogeneity: blending height

Combined roughness-temperature

cold-rough to hot-smooth



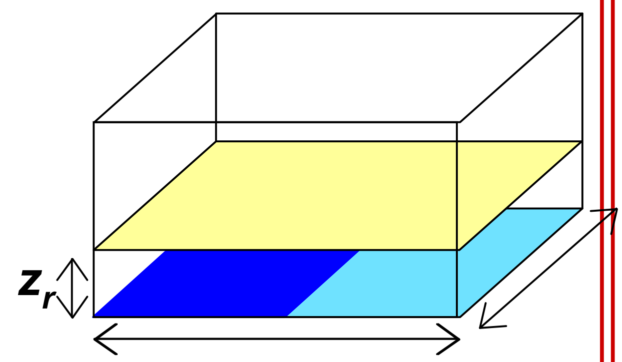
hot-rough to cold-smooth



Representing heterogeneity: tiles

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

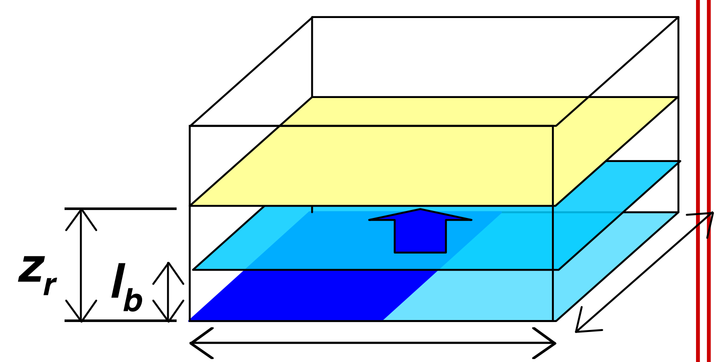
$$\langle q_s \rangle = \sum_i^n f_i \frac{\kappa \langle M(z_r) \rangle \left[\langle \theta(z_r) \rangle - \theta_s^i \right]}{\left[ln\left(z_r/z_o^i\right) - \Psi_m\left(z_r/L^i\right)\right] \left[ln\left(z_r/z_t^i\right) - \Psi_h\left(z_r/L^i\right)\right]}$$



- Modified tile method (e.g., Blyth, 1995):

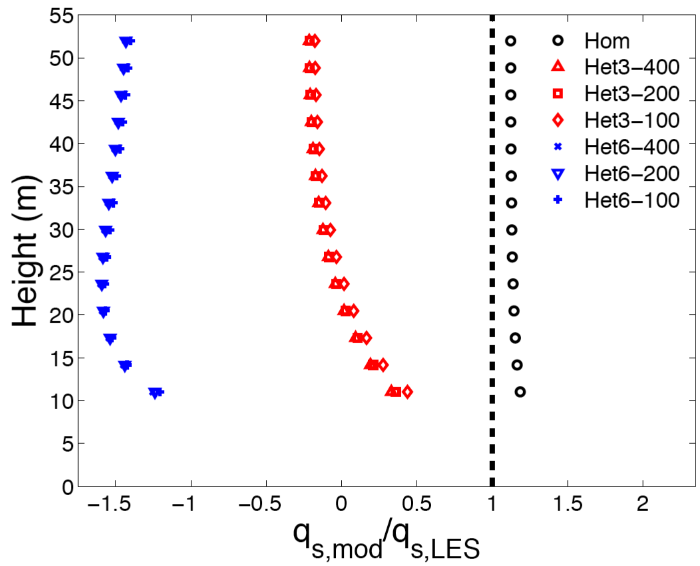
- M-O should apply above l_b to the average

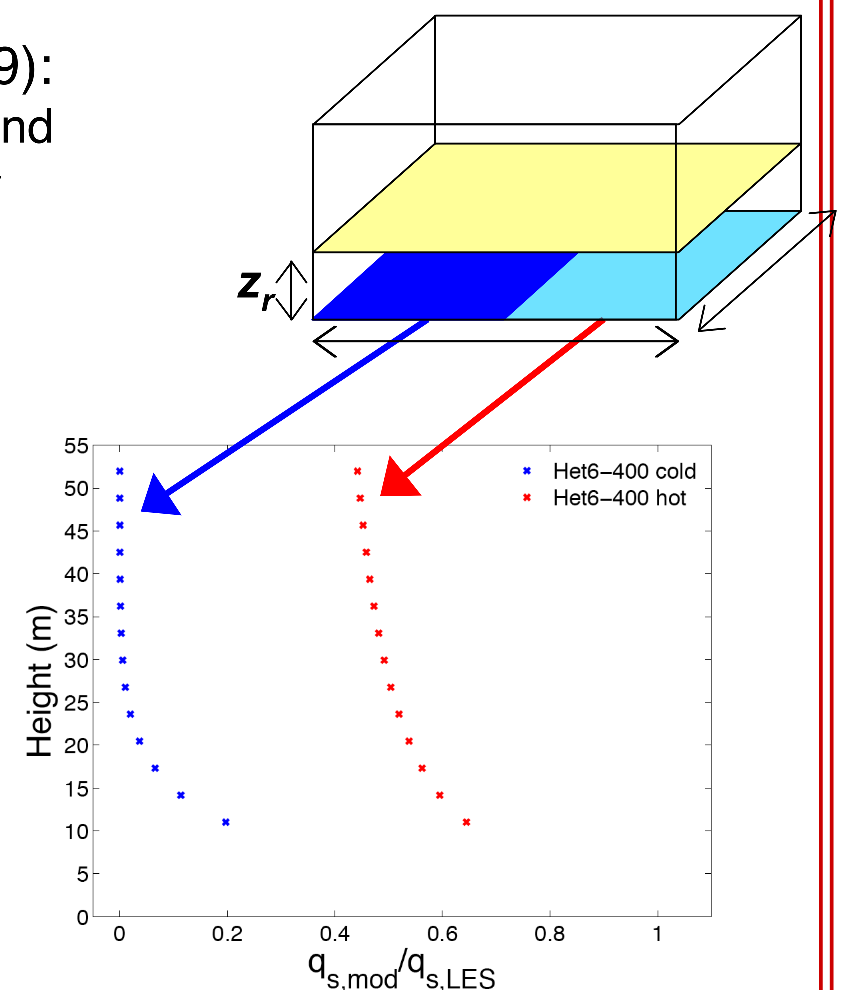
- Below l_b apply the tile model with $z_r = l_b$



Testing average models: temperature

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





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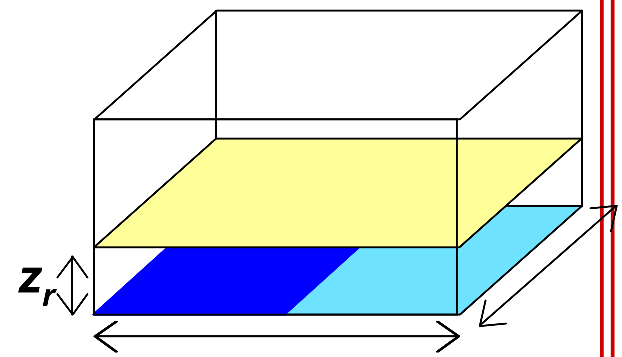
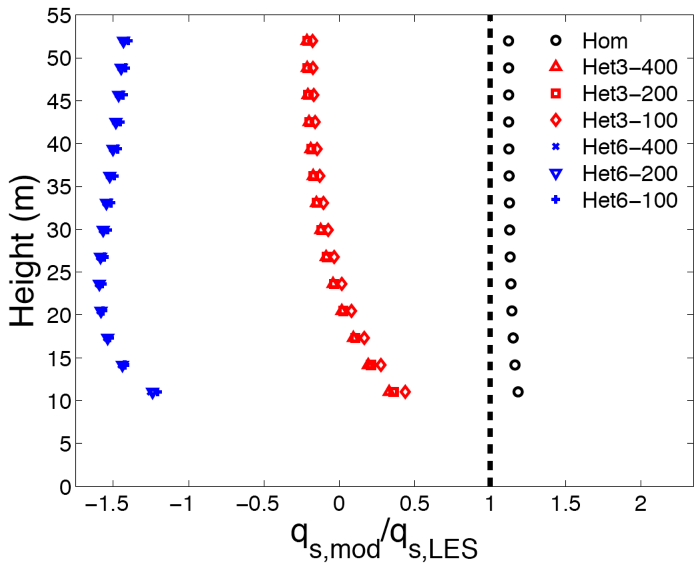
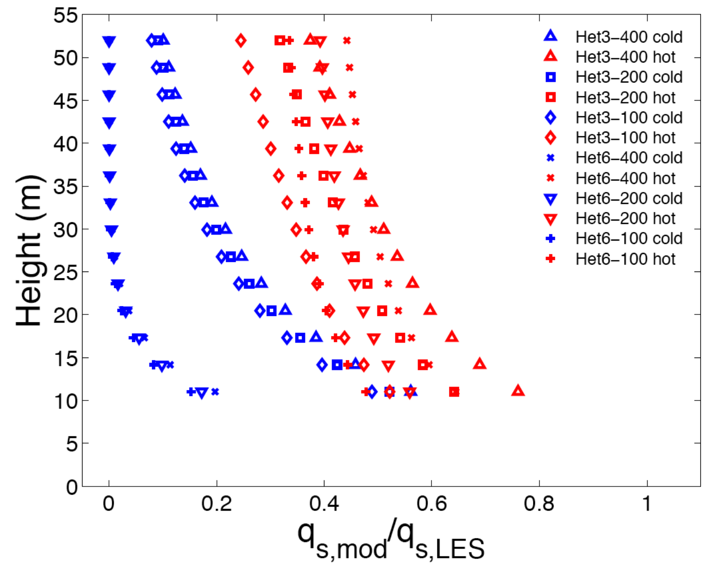


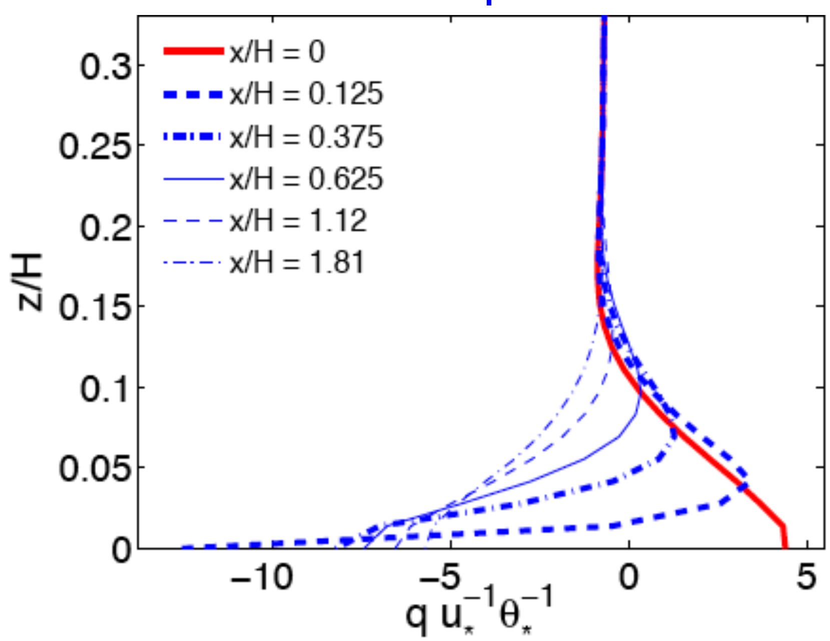




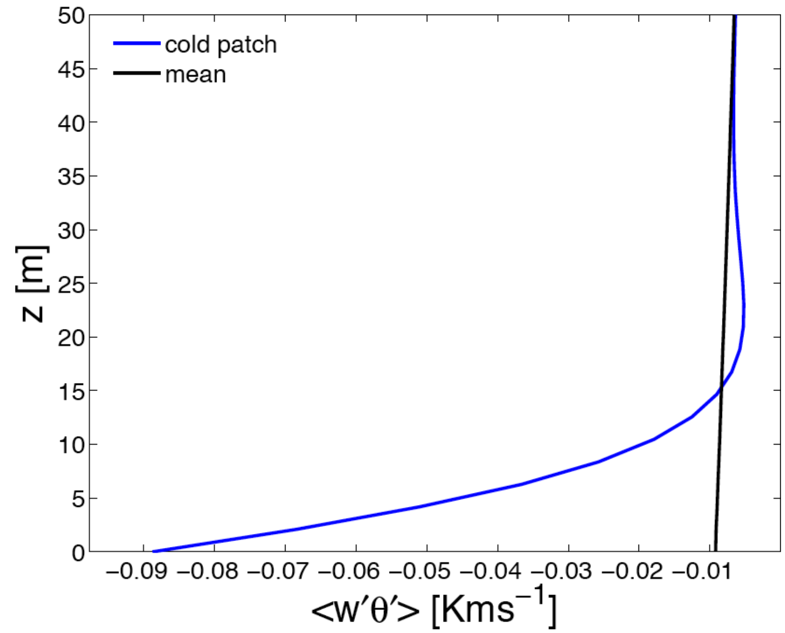
Examining cold patches

- patch flux >> mean flux
- decrease rapidly to some height

Local cold patch flux



Mean cold patch flux



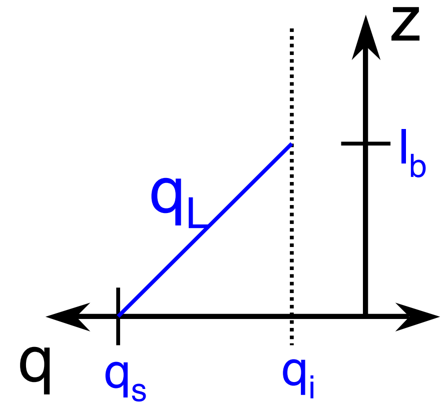
Typical similarity profiles are linear (or near linear)

$$\left.\begin{aligned}\Psi_m &= -\beta_m \frac{z_r}{L}\\ \Psi_h &= -\beta_h \frac{z_r}{L}\end{aligned}\right\} \Longrightarrow$$

Patch fluxes **decrease in magnitude rapidly** with decreasing L at a given z_r

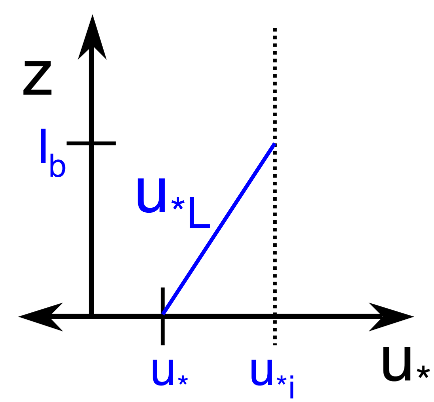
Linear flux assumption

- 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_{*L}:
  - $q_L = (q_i/q_s-1)z/l_b+q_s$
  - $u_{*L} = (u_{*i}/u_*-1)z/l_b+u_*$
- Using q_L and u_{*L} define new Ψ_M and Ψ_H.



$$\Psi_M = -Az - \frac{\beta}{L}\left[\frac{B-A}{A^2(Az+1)} - \frac{B-A}{A^2} + \frac{B}{A^2}ln(Az+1)\right]$$

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



where $A = \left(\frac{u_{*i}}{u_*} - 1\right)\frac{1}{l_b}$ and $B = \left(\frac{q_i}{q_s} - 1\right)\frac{1}{l_b}$

Testing average models: roughness

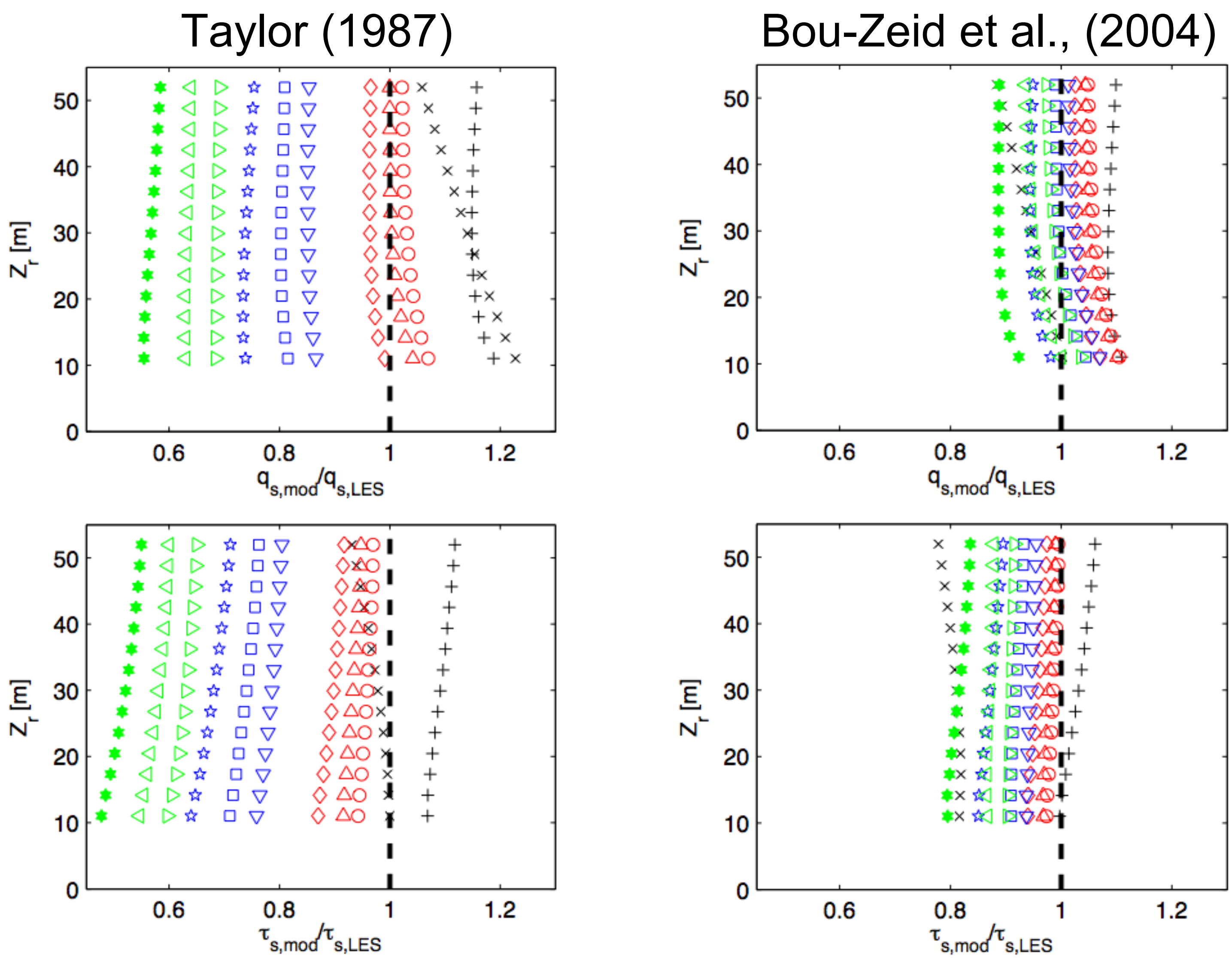
- All cases follow mean similarity ➔ just need to specify $z_{o,eff}$
- Many models, difference is mostly definition of what height scale to use:

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

Case	L_c (m)	R	LES	Taylor	Mason	Wood and Mason	Bou-Zeid et al.
A1	400	2.3	0.0329	0.0316	0.0435	0.0435	0.0348
A2	200	2.3	0.0344	0.0316	0.0458	0.0458	0.0371
A3	100	2.3	0.0379	0.0316	0.0482	0.0483	0.0395
B1	400	4.6	0.0172	0.0100	0.0308	0.0310	0.0202
B2	200	4.6	0.0192	0.0100	0.0340	0.0341	0.0227
B3	100	4.6	0.0233	0.0100	0.0376	0.0378	0.0253
C1	400	6.9	0.0109	0.0032	0.0260	0.0262	0.0146
C2	200	6.9	0.0130	0.0032	0.0297	0.0299	0.0170
C3	100	6.9	0.0173	0.0032	0.0338	0.0340	0.0199

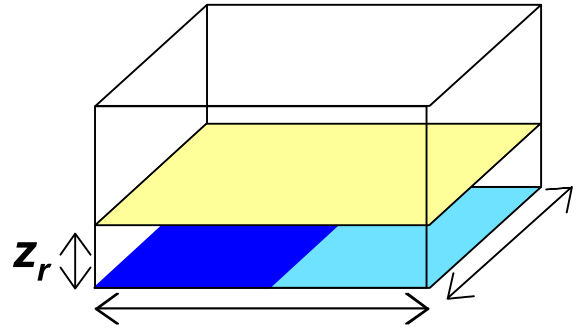
- Can argue that zo,e is a property of the surface roughness (Bou-Zeid et al, 2004)

Testing average models: roughness

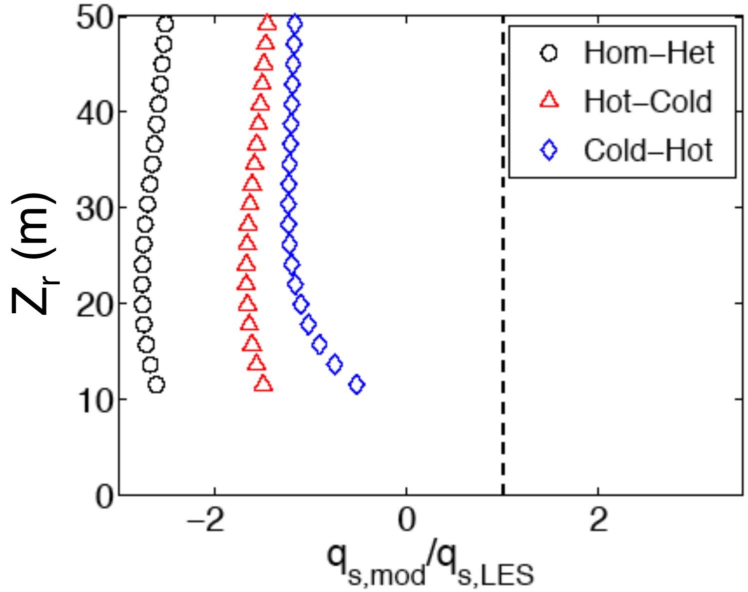


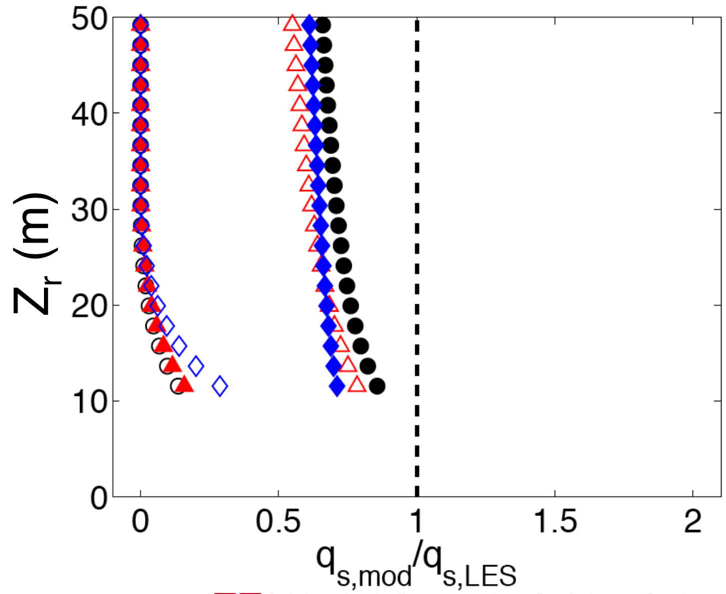
Testing average models: combined

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



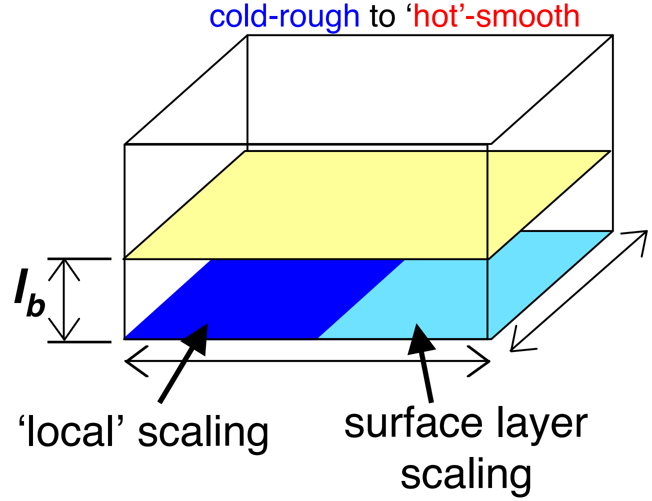
$$\langle q_s \rangle = \sum_i^n f_i \frac{\kappa \langle M(z_r) \rangle \left[\langle \theta(z_r) \rangle - \theta_s^i \right]}{\left[ln\left(z_r/z_o^i\right) - \Psi_m\left(z_r/L^i\right)\right]\left[ln\left(z_r/z_t^i\right) - \Psi_h\left(z_r/L^i\right)\right]}$$

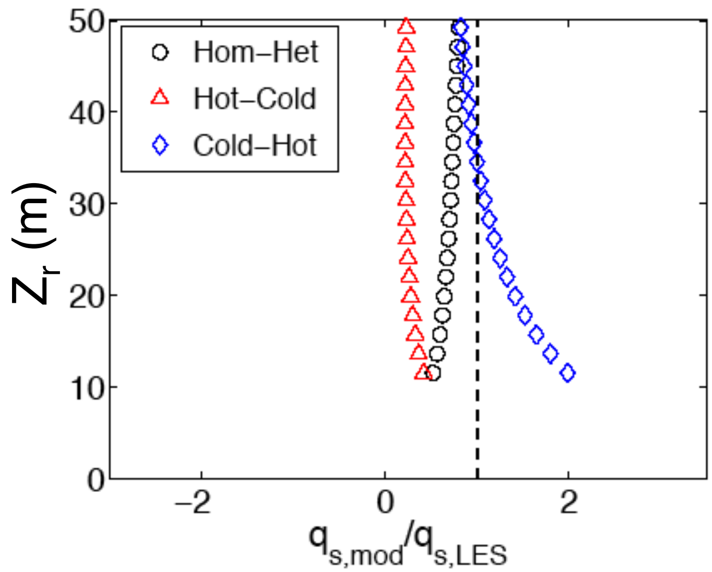


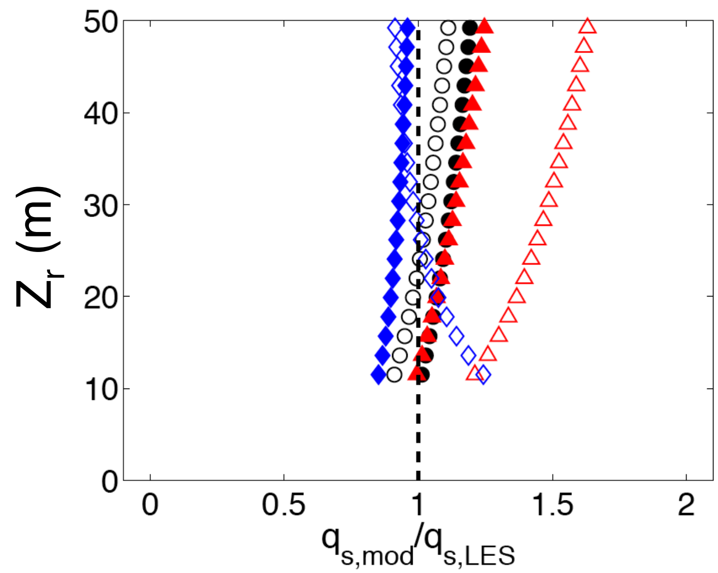


Testing average models: combined

• 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

Case	$\langle \tau_s \rangle$	$\langle q_s \rangle$
LES		
Homo	0.0676	-0.0117
Het3	0.0692	-0.0112
Het6	0.0734	-0.0098
1D Model		
Homo	0.1179	-0.0087
Het3	0.1179	-0.0084
Het6	0.1196	-0.0077

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’

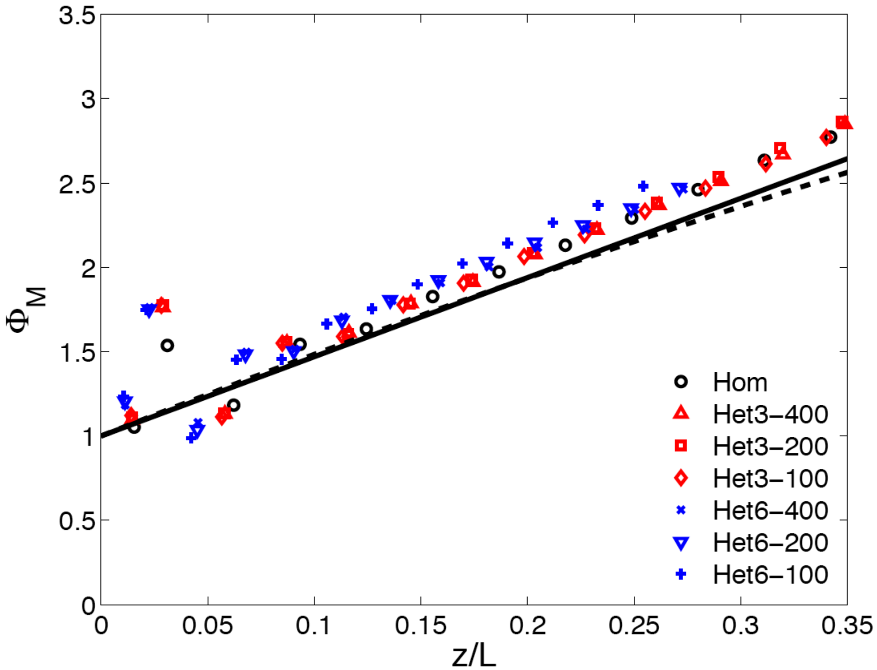
Future Directions

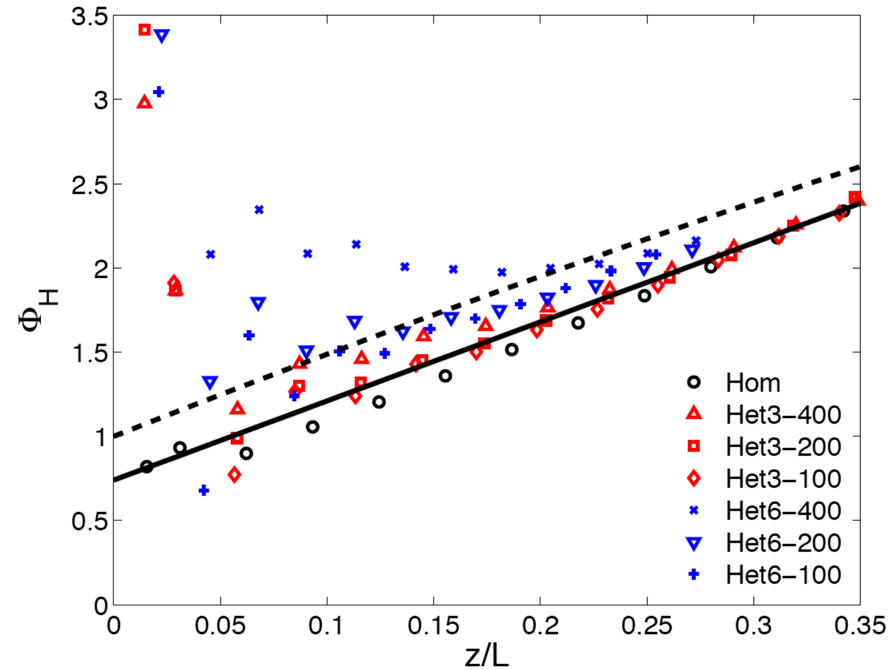
- Study weak wind conditions when stability will be higher and flow won't be dominated by advection
- Larger range of patch sizes and impact of using the 'wrong' blending height
- Realistic surface heterogeneity patterns
- Impact of moisture on heterogeneity (more realistic local coupling)
- Examine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

Surface temperature heterogeneity

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

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





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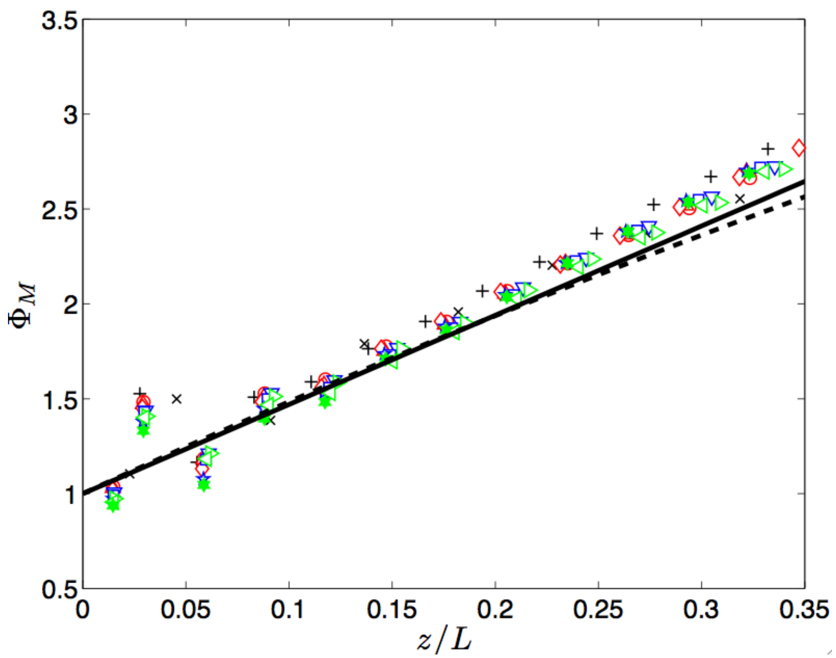

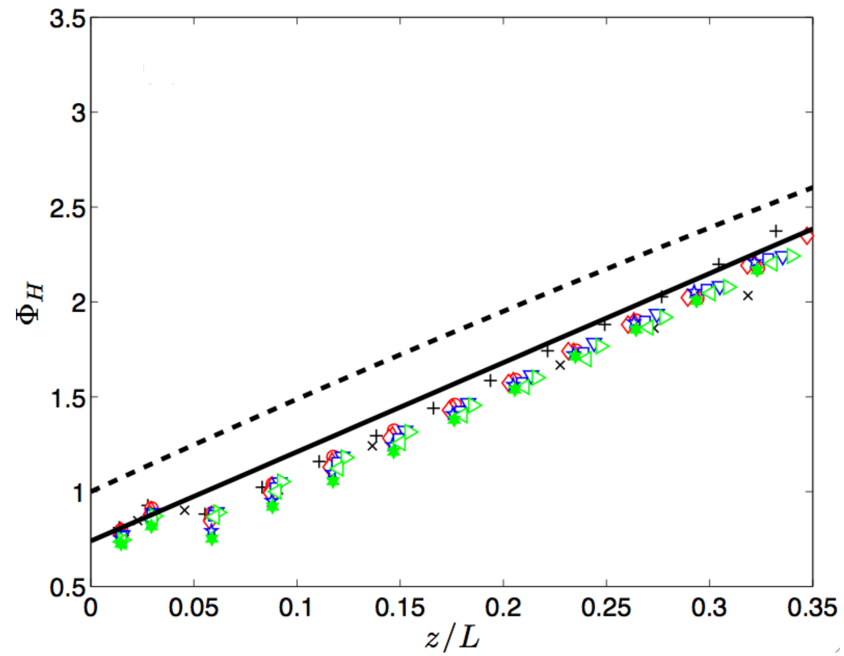

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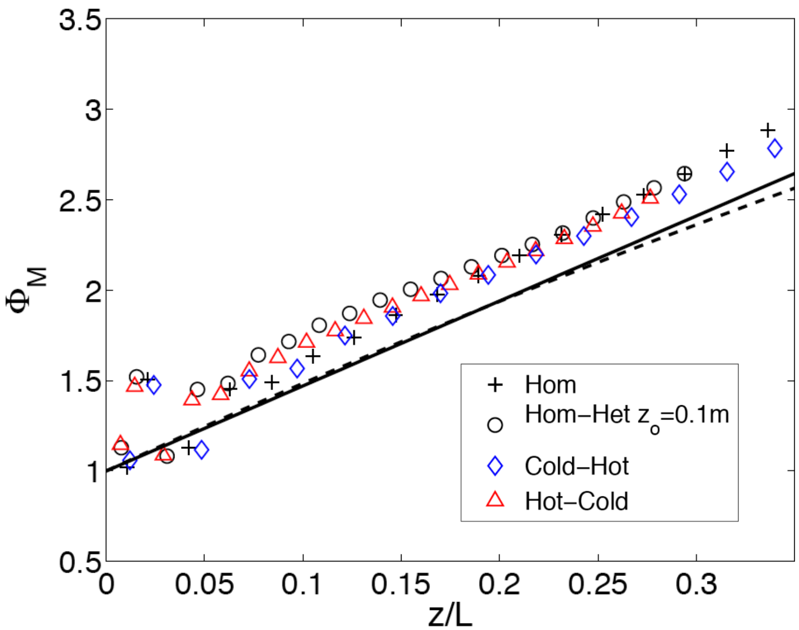
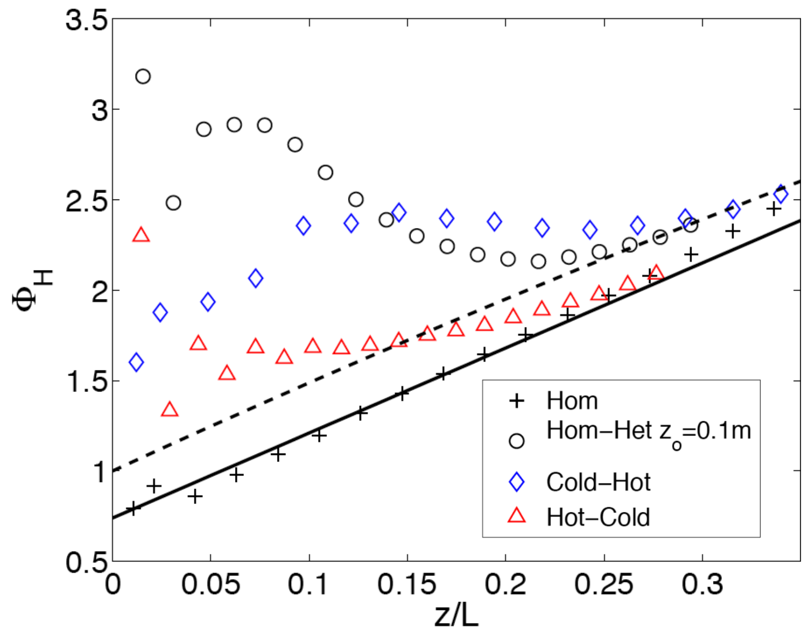
Combined roughness-temperature

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

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





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