Large-eddy simulation of the stable boundary layer

Revisiting GABLS with a linear algebraic subgrid-scale (LASS) turbulence model

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Talking Points

- How does LASS behave under different cooling fluxes?
- Can it provide appropriate SGS stress anisotropy?
- How does LASS performs in a moderately stable case (GABLS)?

Simulating the SBL:
Basic Difficulties

- Energetic eddies < 1 m
  - Computationally expensive
    - Need domains that are both large enough and resolved enough
- Stratification inhibits vertical motions
  - Subgrid-scale (SGS) turbulence is anisotropic

Simulating the SBL:
Desired Turbulence Model Qualities

- Predict Mean Flow
  - Velocities and Temperature
- Provide Turbulence Anisotropy
  - SGS turbulence are different magnitudes
- Provide Back Scatter of Energy
  - Move energy from small scales to large scales

The Linearized Algebraic Subgrid-Scale Turbulence Model (LASS): **Components**

$$\cancel{\frac{\partial}{\partial t}(\text{Turbulent Flux})} = \cancel{\text{Advection}} + \cancel{\text{Transport \& Diffusion}}$$

+ Production + Pressure Redistribution

+ Dissipation + Buoyancy Generation

~~+ Coriolis~~

LASS: Model Summary

SGS Stress $\left(\tilde{A}_{ij}\right)$ Model

$$0 = \underbrace{-\tilde{A}_{ik}\frac{\partial \tilde{u}_j}{\partial x_k} - \tilde{A}_{kj}\frac{\partial \tilde{u}_i}{\partial x_k}}_{\text{Production}} + \underbrace{\Pi_{ij}}_{\substack{\text{Pressure}\\ \text{Redistribution}}} \underbrace{-\frac{2}{3}\tilde{\varepsilon}\delta_{ij}}_{\text{Dissipation}} + \underbrace{\frac{g}{\theta_o}\left(\tilde{a}_i\delta_{j3} + \tilde{a}_j\delta_{i3}\right)}_{\text{Buoyancy Generation}}$$

SGS Heat Flux $\left(\tilde{a}_i\right)$ Model

$$0 = \underbrace{-\tilde{A}_{ik}\frac{\partial \tilde{\theta}}{\partial x_k} - \tilde{a}_k\frac{\partial \tilde{u}_i}{\partial x_k}}_{\text{Production}} + \underbrace{\Pi_{i\theta}}_{\substack{\text{Pressure}\\ \text{Redistribution}}}$$

Pressure Redistribution Model

SGS Stress Term

$$\Pi_{ij} = \underbrace{-c_1 \frac{\tilde{\varepsilon}}{\tilde{e}}\left(\tilde{A}_{ij} - \frac{2}{3}\tilde{e}\delta_{ij}\right)}_{\text{Slow Pressure-Strain}} \underbrace{- c_2\left(P_{ij} - \frac{2}{3}P\delta_{ij}\right) - c_3\tilde{e}\tilde{S}_{ij} - c_4\left(D_{ij} - \frac{2}{3}P\delta_{ij}\right)}_{\text{Rapid Pressure-Strain}}$$

$$\underbrace{-c_g \frac{g}{\theta_0}\left(\tilde{a}_i\delta_{j3} + \tilde{a}_j\delta_{i3} - \frac{2}{3}\tilde{a}_3\delta_{i3}\delta_{ij}\right)}_{\text{Buoyant Force}} + \underbrace{\left(c_5\frac{\tilde{\varepsilon}}{\tilde{e}}\left(\tilde{A}_{ij} - \frac{2}{3}\tilde{e}\delta_{ij}\right) + c_6 P_{ij} - c_7 D_{ij} + c_8\tilde{e}\tilde{S}_{ij}\right) f(z)}_{\text{Surface Reflection}}$$

SGS Heat Flux Term

$$\Pi_{i\theta} = - \underbrace{c_{1\theta}\frac{\tilde{\varepsilon}}{\tilde{e}}\tilde{a}_i}_{\substack{\text{Slow}\\ \text{Pressure-Strain}}} + \underbrace{c_{2\theta}\tilde{a}_k\frac{\partial \tilde{u}_i}{\partial x_k}}_{\substack{\text{Rapid}\\ \text{Pressure-Strain}}}$$

(Launder, Reece, and Rodi, 1975; Launder and Samaraweera, 1979)

LASS: Implementation

- Use Advanced Regional Prediction System (ARPS)
  - 3D
  - Non-hydrostatic
  - Compressible
  - Parallelized
  - Parameterizations for radiation, soil-vegetation models, and cloud microphysics
- Tested in idealized NBL and CBL

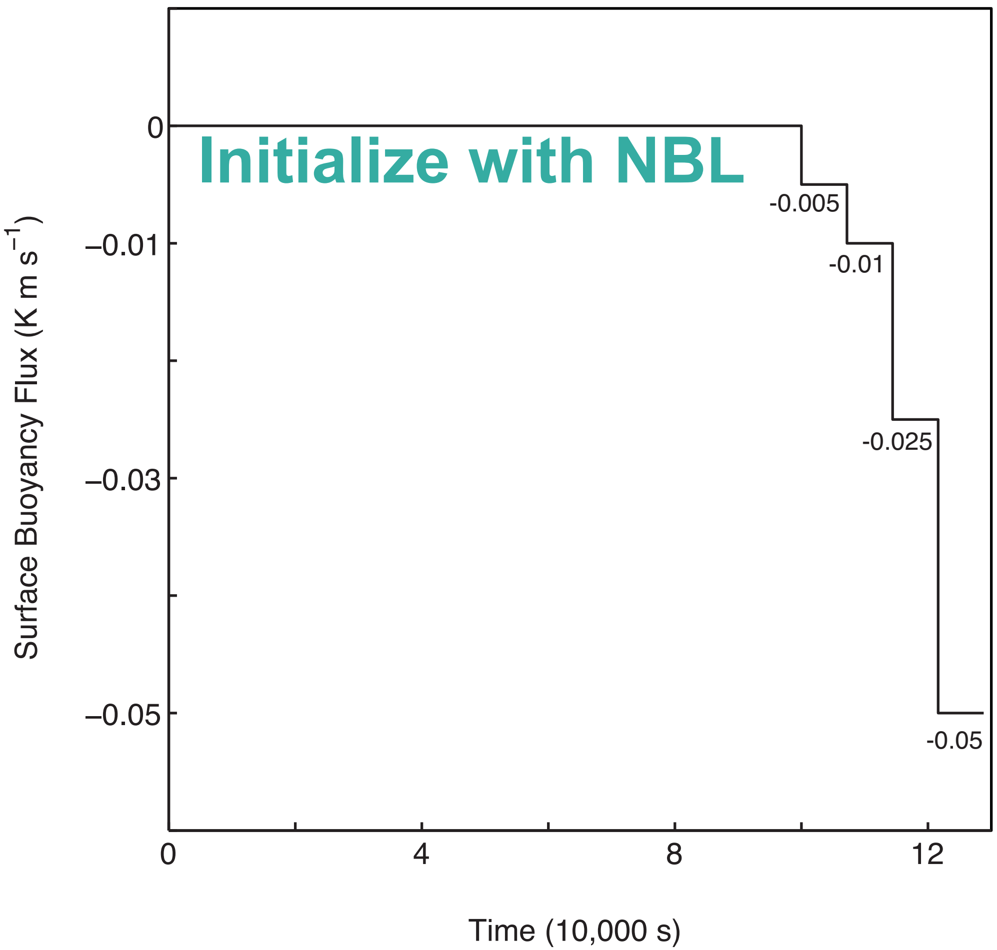
Simulating the SBL

&

LASS

Stable Boundary Layer:
Stepped Cooling

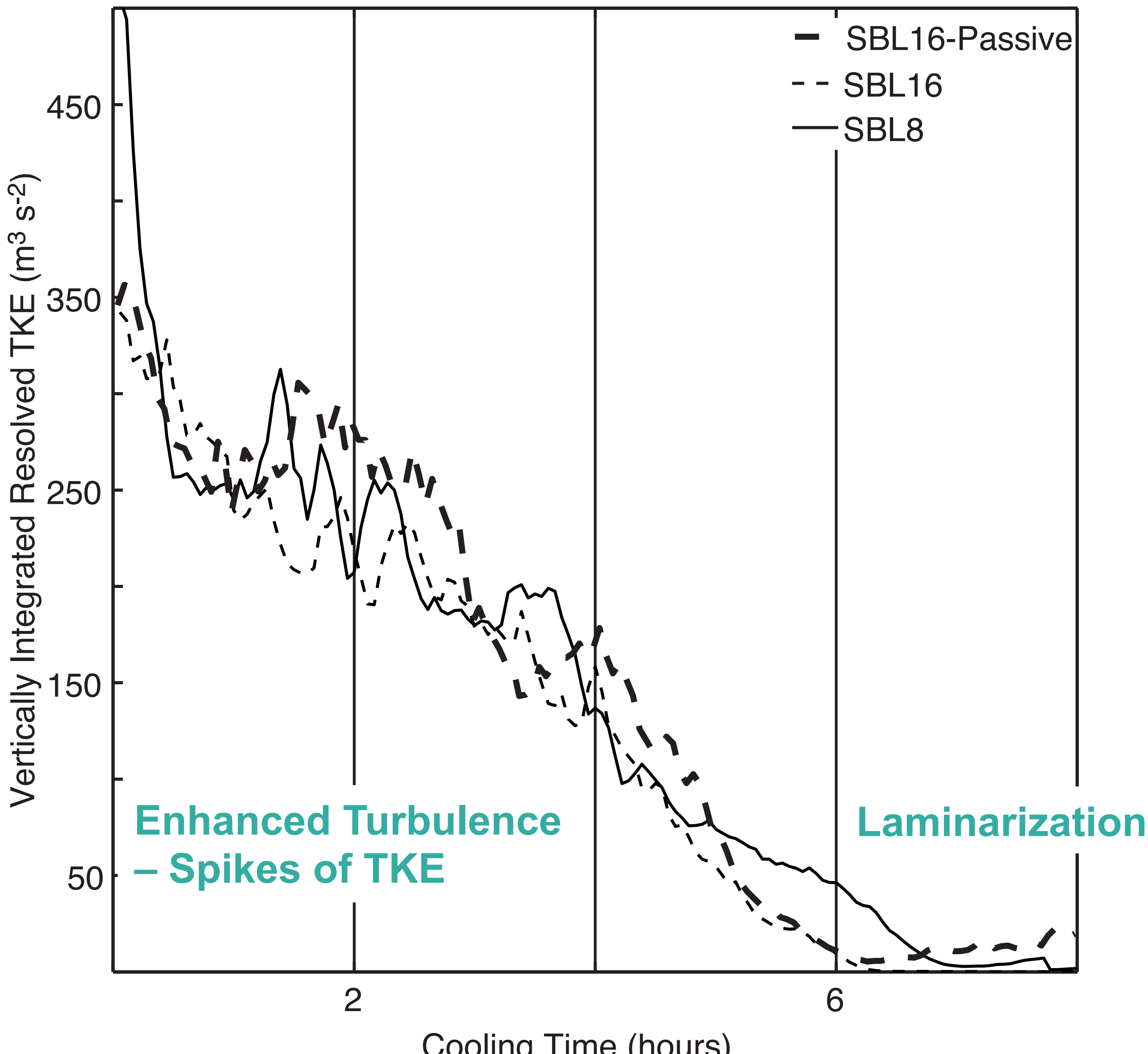
Simulations similar to Jiménez and Cuxart (2001)



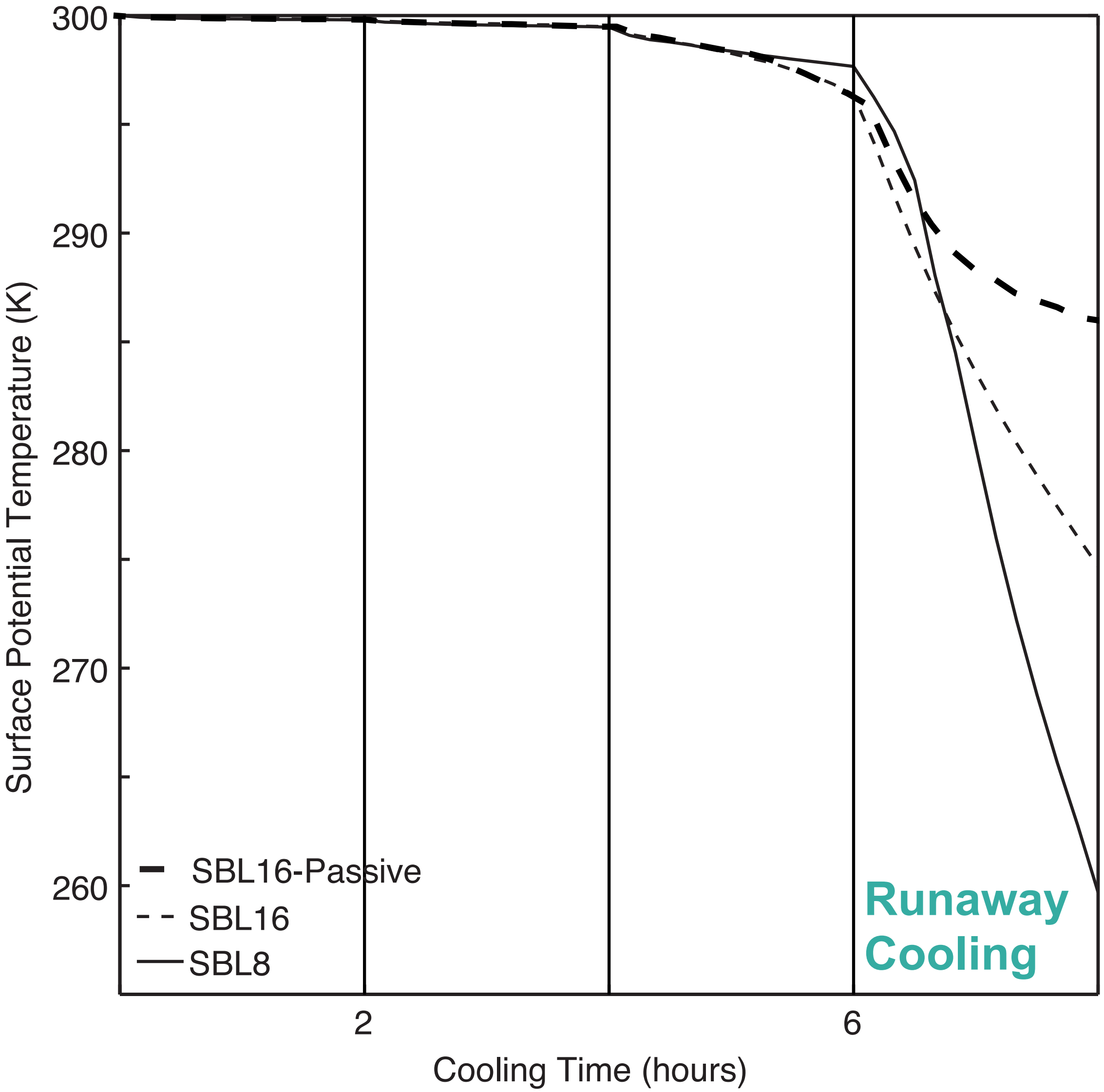
SBL8: 8 m (Δ_x), 2.5 (Δ_y)

SBL16: 16 m (Δ_x), 5 m (Δ_y)

Vertically Integrated TKE



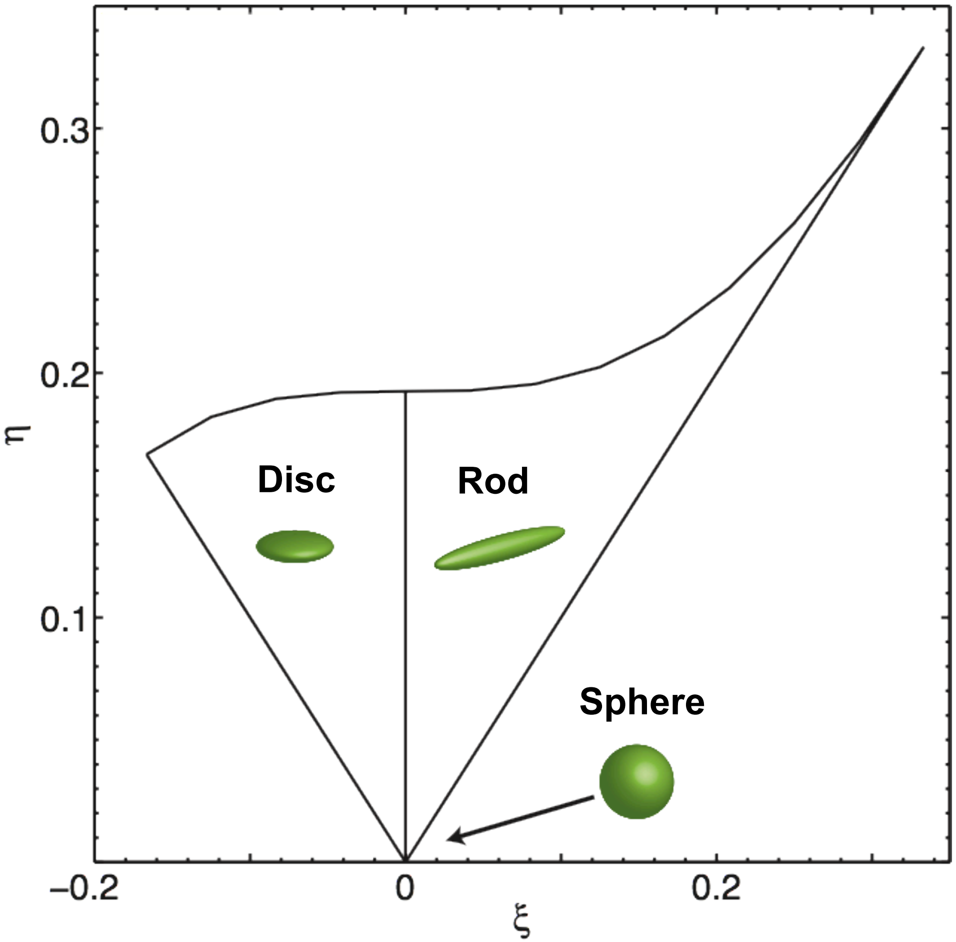
Surface Potential Temperature

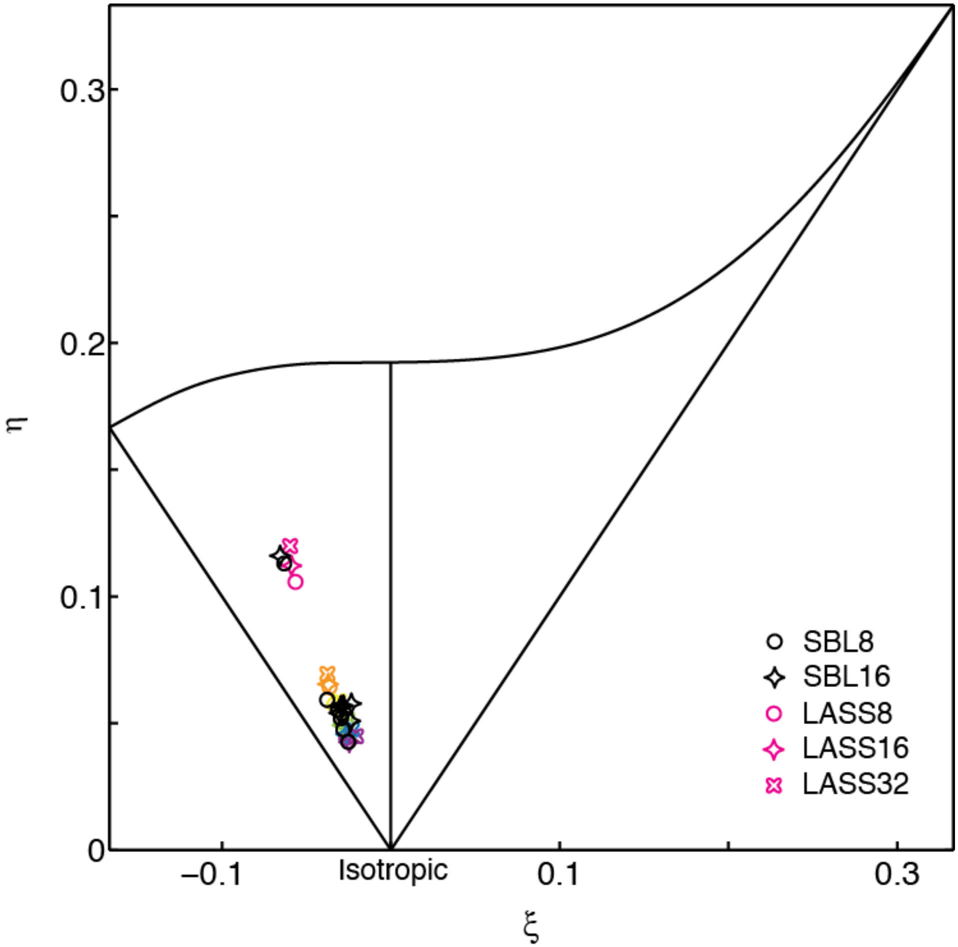


- Larger differences in surface PT with higher cooling flux
- Added buoyancy term (active cases) accelerates runaway cooling

SGS Anisotropy-Lumley Triangle

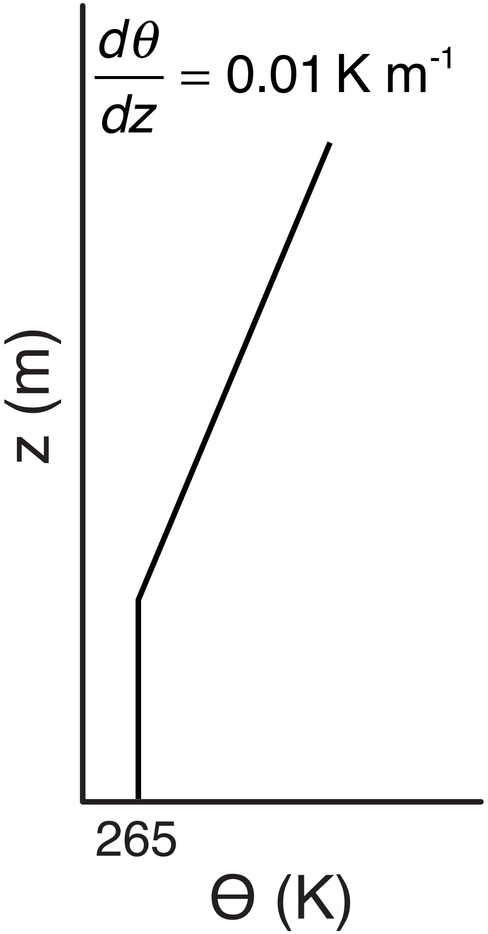
see Pope (2000)

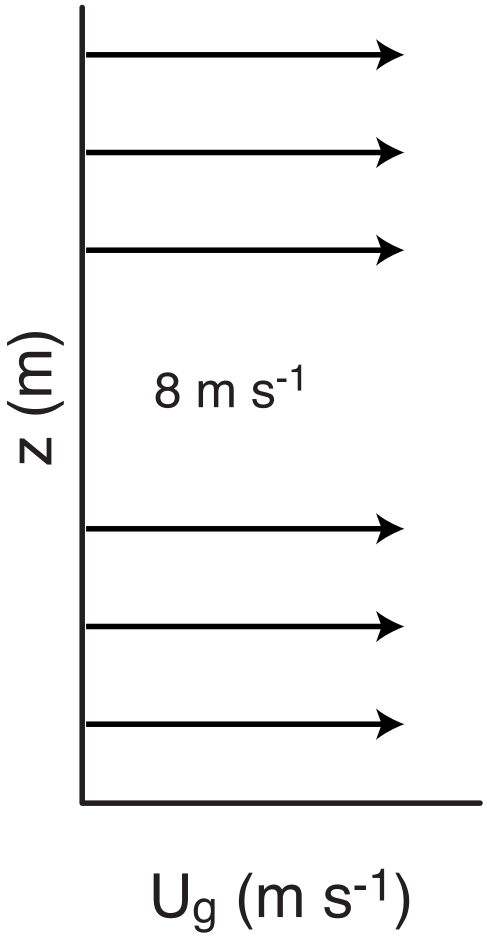




Decreasing anisotropy with height
Stress tensor shape is disc-like

GABLS Setup



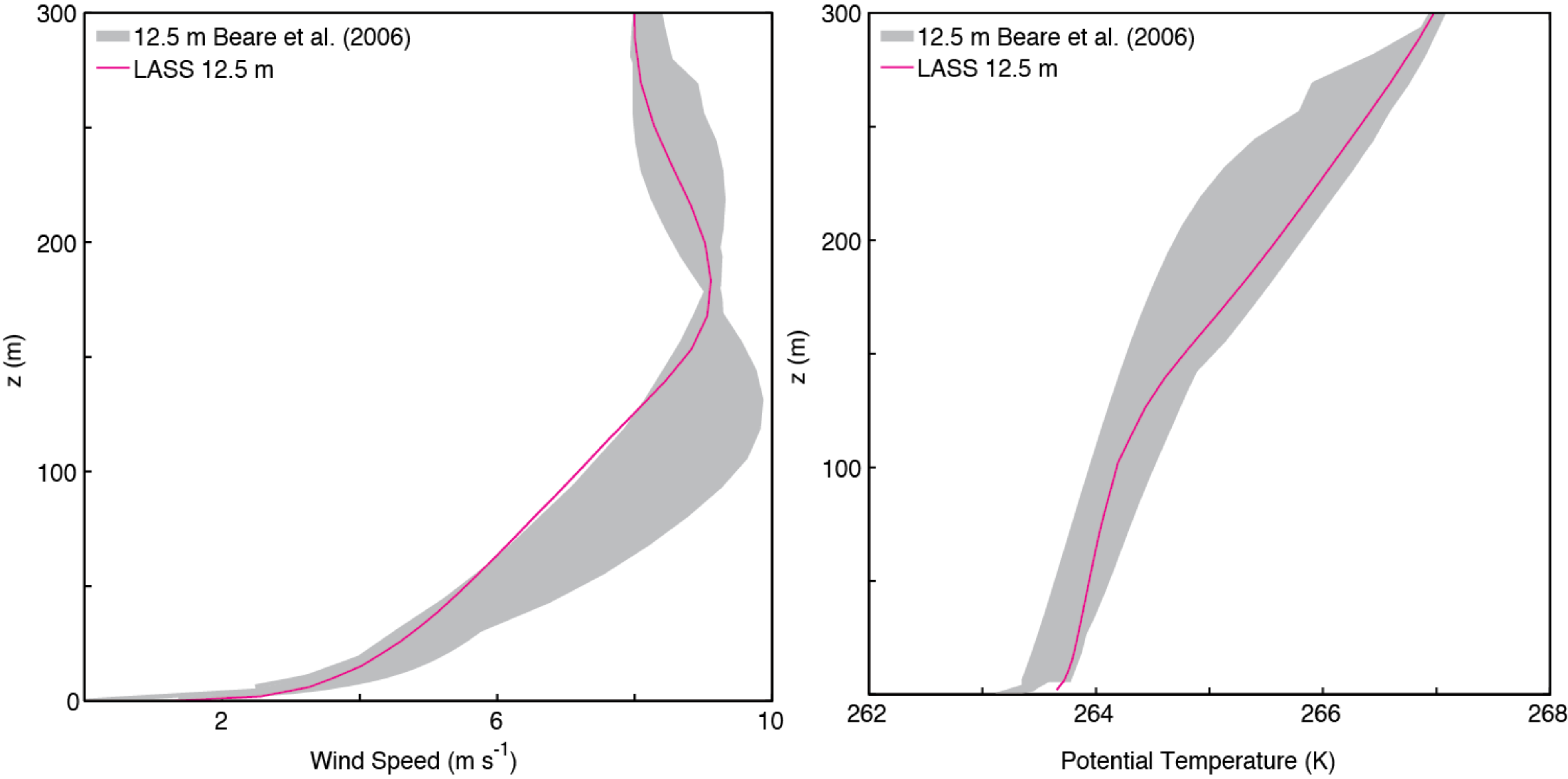


LASS 12.5: 12.5 m (Δ_x), 3.9 (Δ_y)

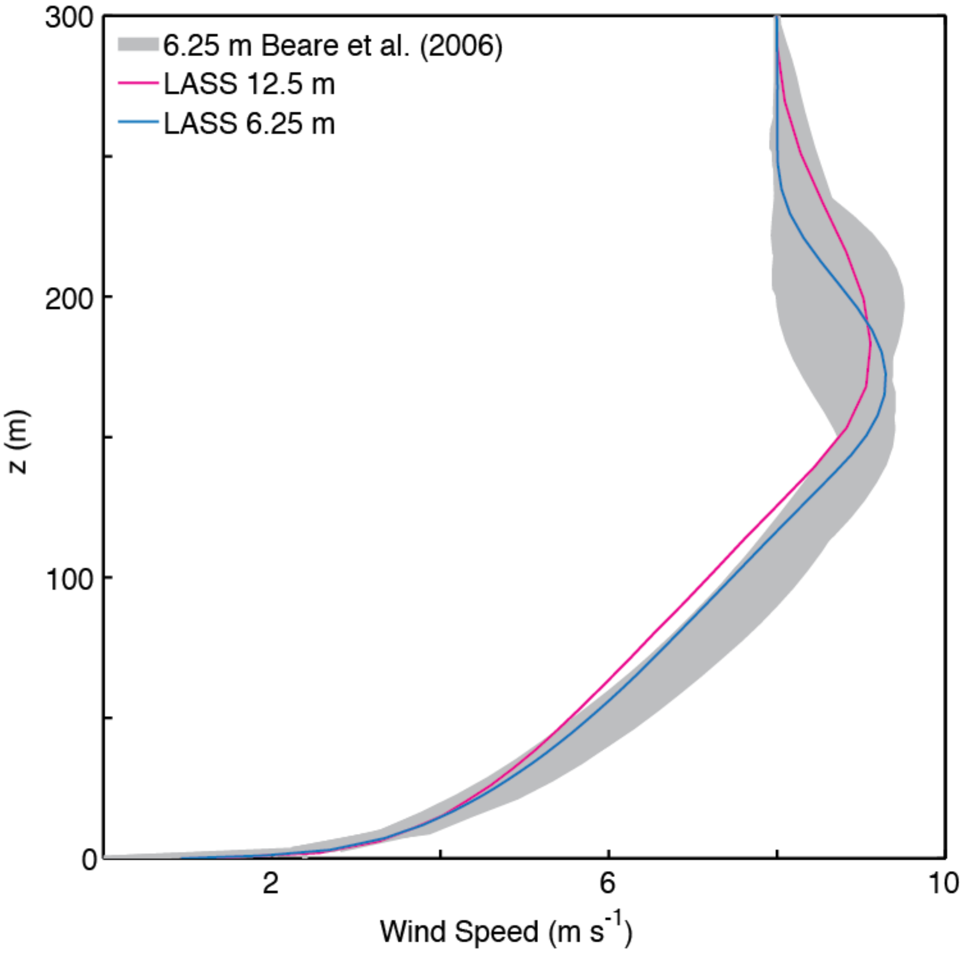
LASS 6.25: 6.25 m (Δ_x), 1.95 m (Δ_y)

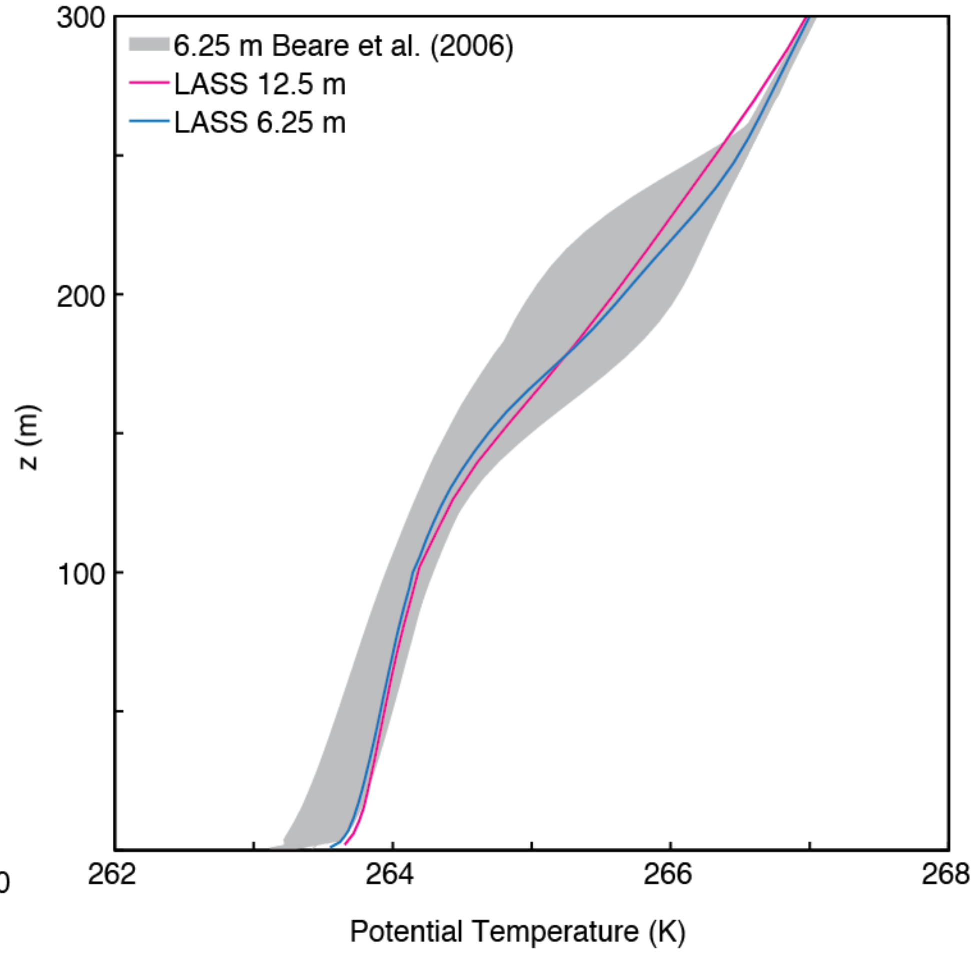
Simulations similar to Kosović and Curry (2000), Beare et al. (2006)

GABLS Δ_x = 12.5 m

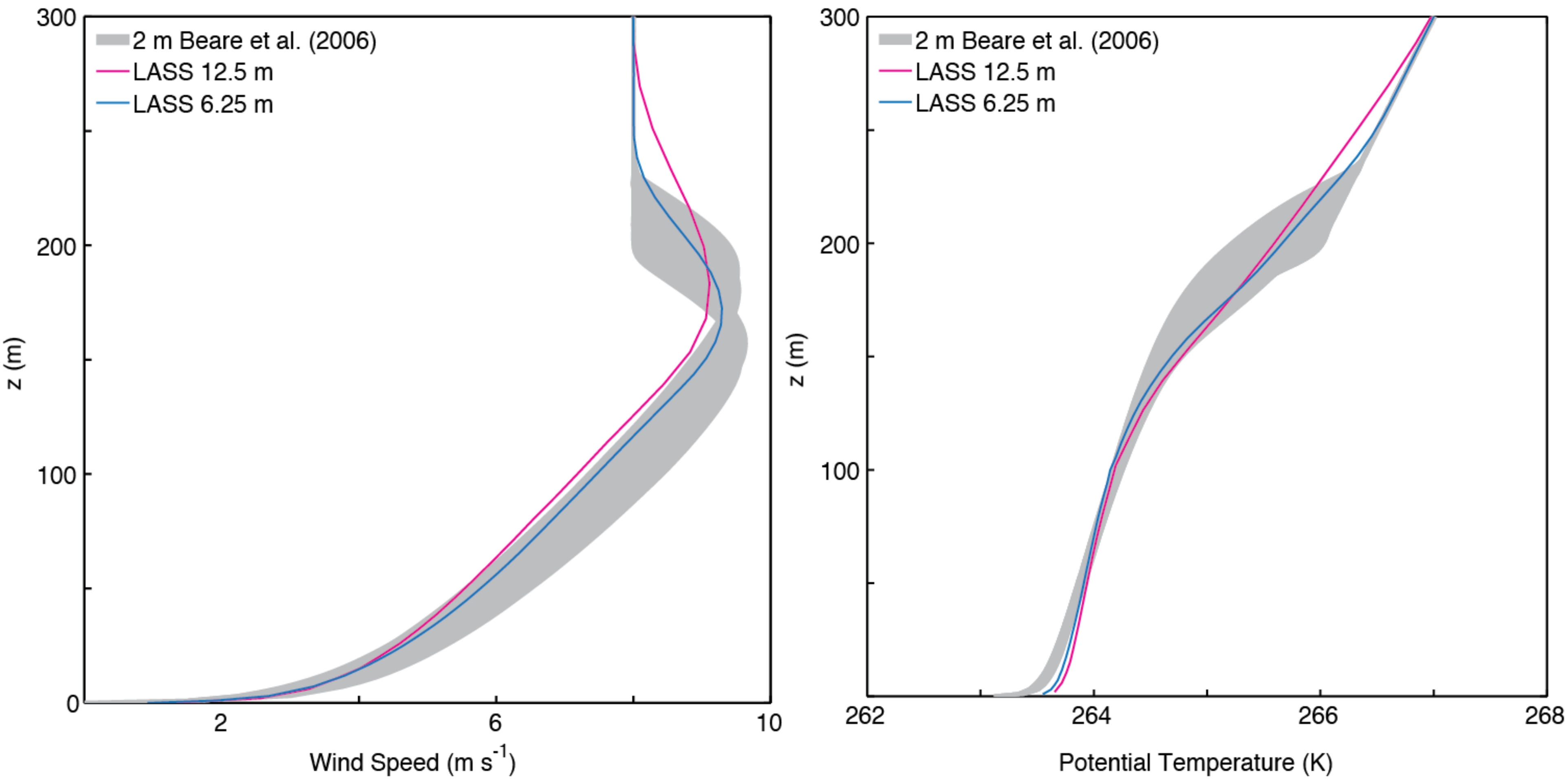


GABLS Δ_x = 6.25 m





GABLS $\Delta_x = 2$ m



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Stable Boundary Layer: Stepped Cooling

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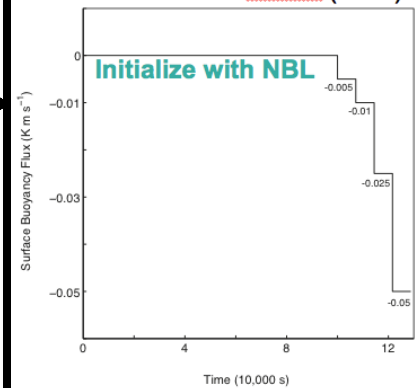

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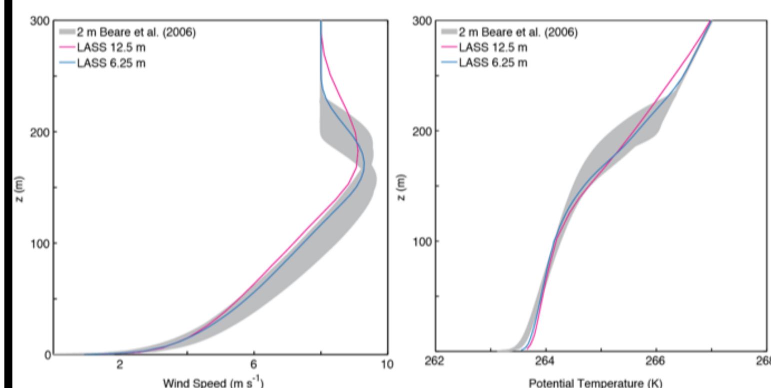

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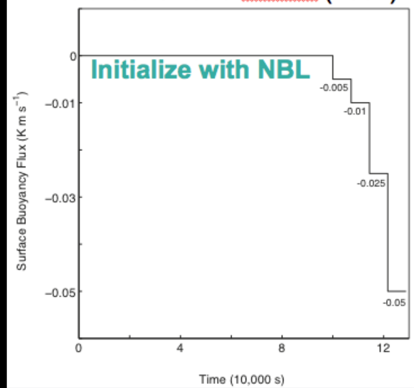

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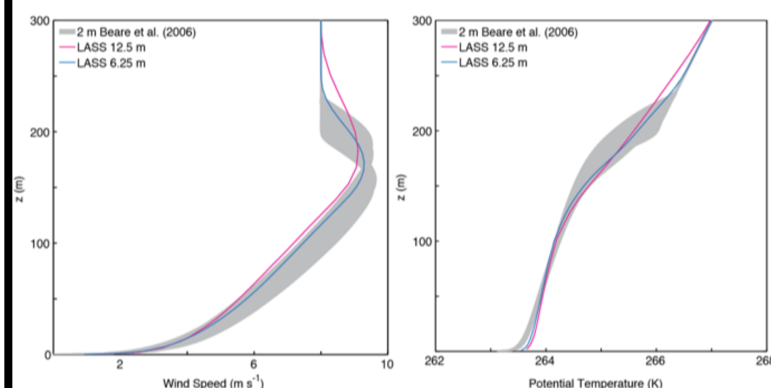


EXTRA SLIDES

Computational Time Cost Comparisons

Turbulence Model	Total Cost Factor
Smagorinsky	1.00
TKE	1.04
Dynamic Wong-Lilly	1.13
LASS	1.26

Bottom Boundary Conditions

$$U_s = \frac{u_*}{\kappa}\left[\ln\left(\frac{z+z_0}{z_0}\right) + \beta\frac{z}{L}\right], \quad L = -\frac{\theta_s}{g}\frac{u_*^3}{\kappa\overline{w\theta_s}},$$

$$u_1 = \frac{u_*}{\kappa}\ln\left(\frac{z_1+z_0}{z_0}\right)$$

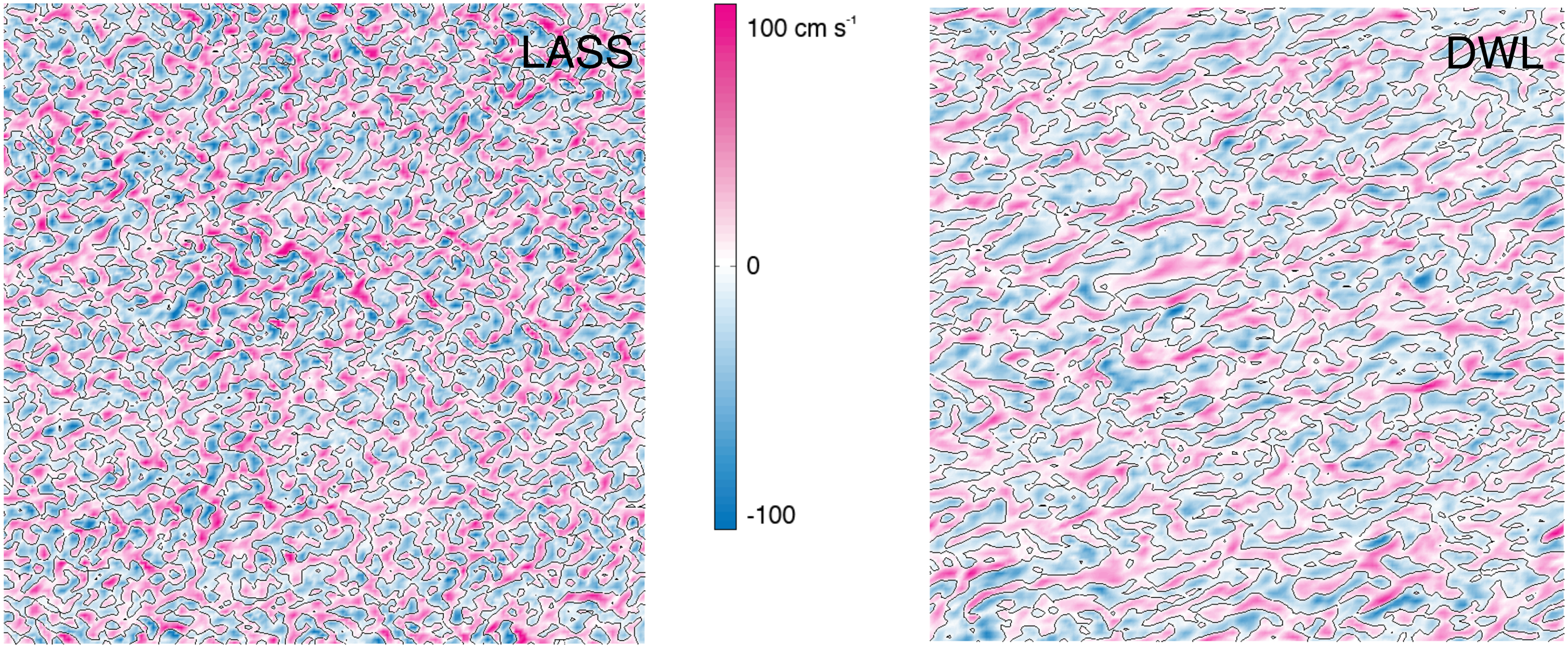
yields

$$C_D = \left[\frac{1}{\kappa}\ln\left(\frac{z_1+z_0}{z_0}\right)\right]^{-2} .$$

ch gives C_D given the grid spa
tant, typically set equal to 0.4

$$\tau_{wall} = C_D|u_1|u_1$$

Vertical Velocity z = 10 m



- Differences in the vertical velocity patterns are most distinct in the near-wall region
- Smaller resolved scales observed in GLASS