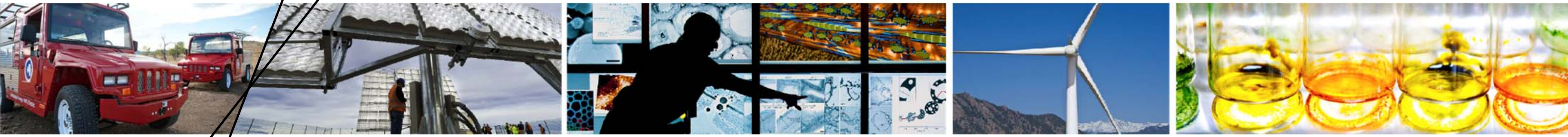
Adding Complex Terrain and Stable Atmospheric Condition Capability to the Simulator for On/Offshore Wind Farm Applications (SOWFA)



First Symposium on OpenFOAM in Wind Energy
Oldenburg, Germany

Matthew J. Churchfield

March 20, 2013

NREL/PR-5000-58397

Outline

I. What is SOWFA?

II. The Stably Stratified Atmospheric Boundary Layer

III. Terrain

IV. Conclusions

Outline

I. **What is SOWFA?**

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What is SOWFA?

- **The Simulator for On/Offshore Wind Farm Applications (SOWFA)**

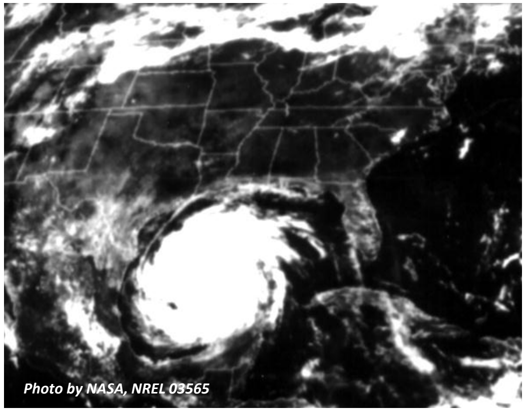


Photo by NASA, NREL 03565

Mesoscale weather modeling (WRF)

The focus of this talk is on this component of SOWFA


Photo by Iberdrola Renewables, Inc., NREL 15177

Microscale/wind plant scale large-eddy simulation (LES) (OpenFOAM)

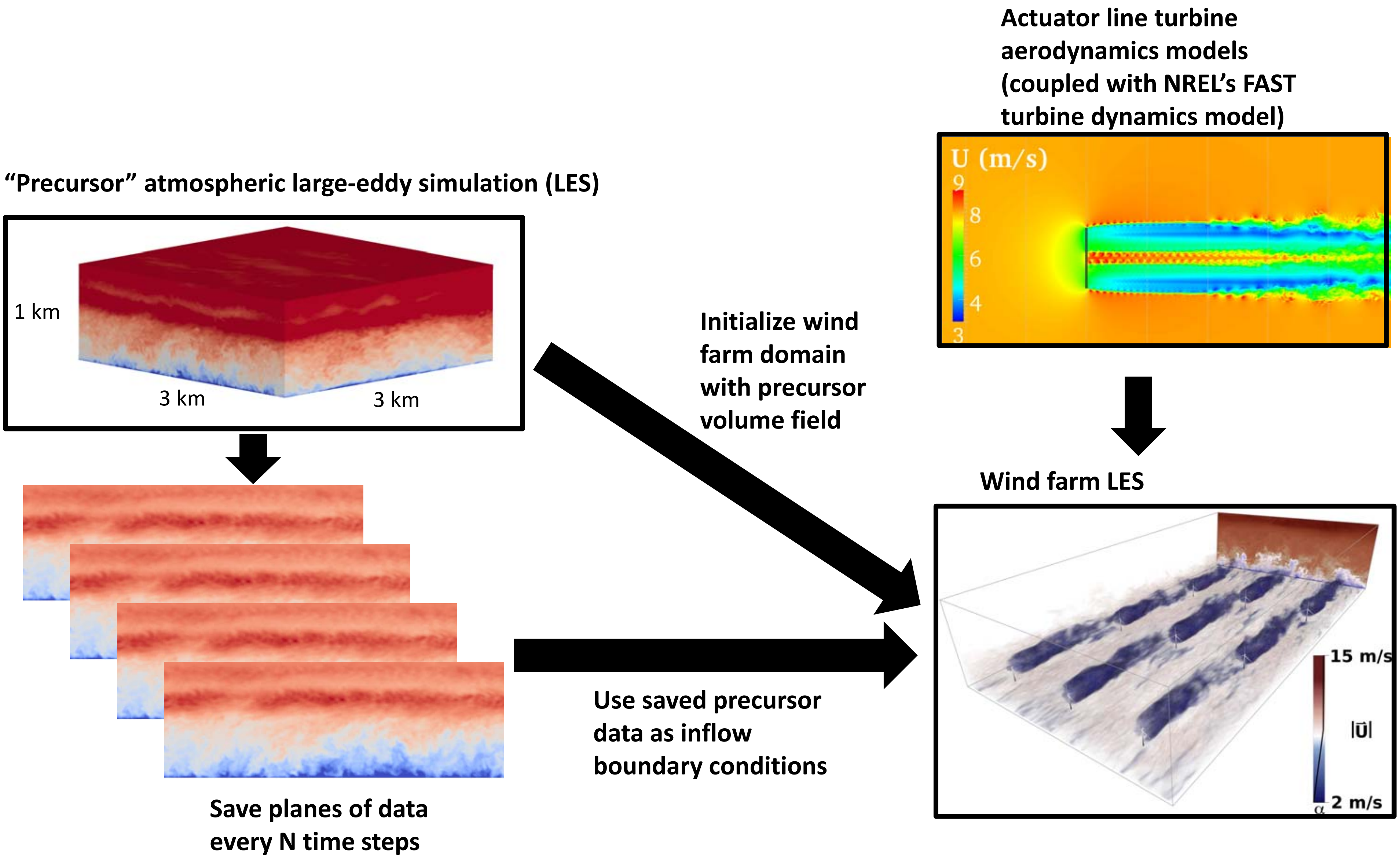

Photo by Dennis Schroeder, NREL 19075

Turbine system/structural dynamics (FAST)

- **Meant for understanding:**
  - Atmospheric stability affects on wakes, power production, and mechanical loads
  - Wake-wake interaction, wake meandering
  - Advanced control strategies

- **Available at http://wind.nrel.gov/designcodes/simulators/sowfa/**

What is SOWFA?



“Precursor” atmospheric large-eddy simulation (LES)

Save planes of data every N time steps

Initialize wind farm domain with precursor volume field

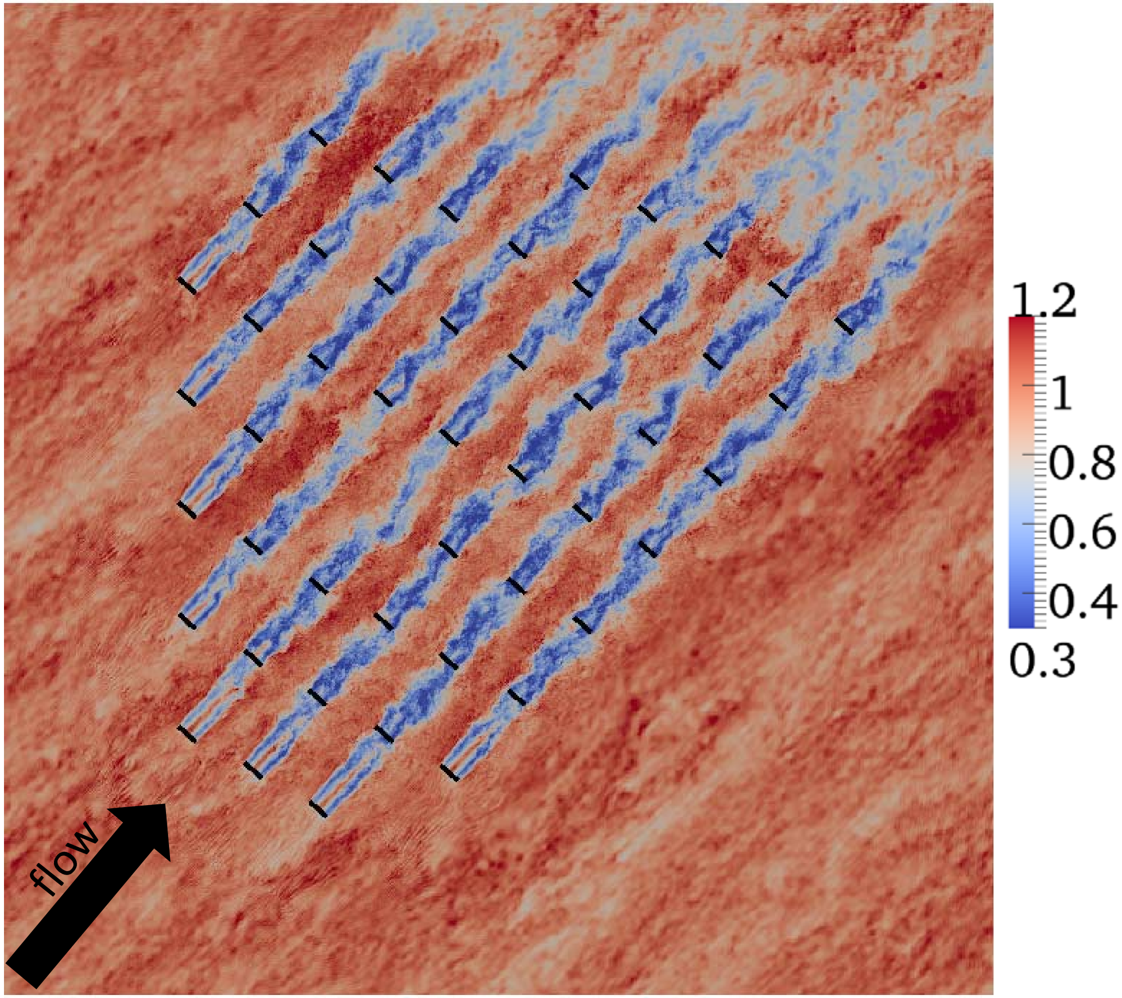
Use saved precursor data as inflow boundary conditions

Actuator line turbine aerodynamics models (coupled with NREL’s FAST turbine dynamics model)

Wind farm LES

Use of SOWFA: Power Production

Simulation of 48-turbine Lillgrund wind plant [1]

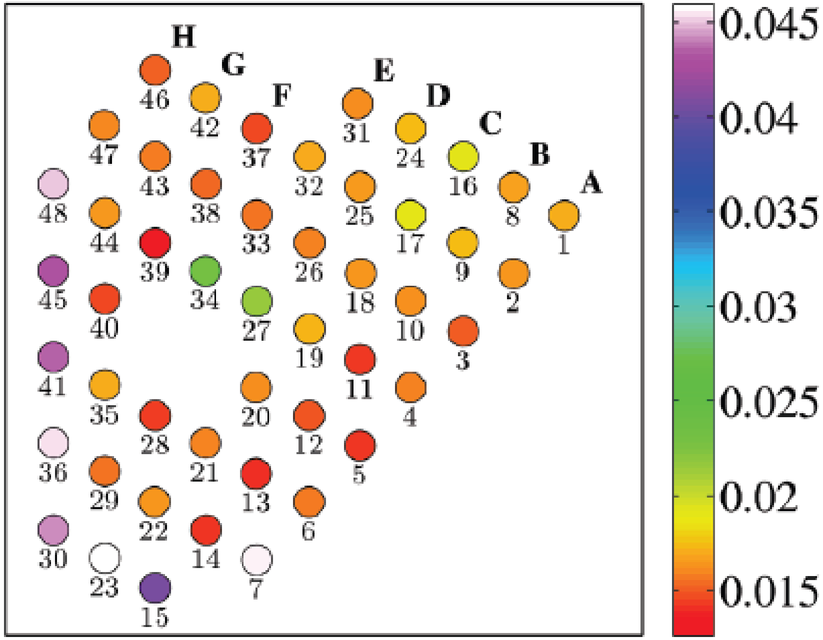


Top view of contours of instantaneous velocity normalized by freestream speed at hub height (black lines represent turbine rotors)

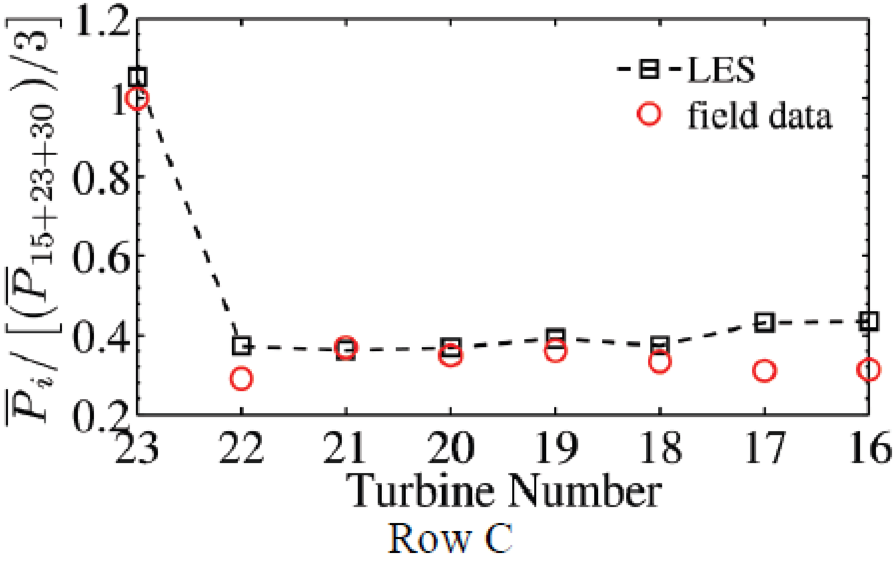
Use of SOWFA: Power Production

Simulation of 48-turbine Lillgrund wind plant [1]

Fractional contribution of each turbine's time-averaged power output to total power



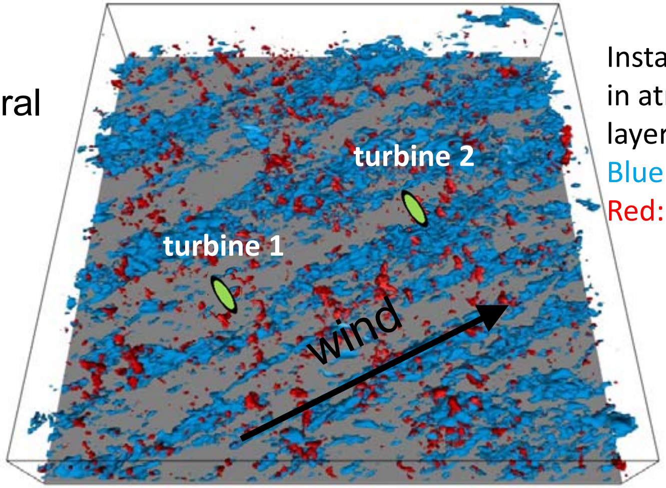
Average power along row C



Use of SOWFA: Mechanical Loads

Simulation of two turbines subject to four different atmospheric inflows: neutral and unstable, each with low and high surface roughness [2,3]

neutral

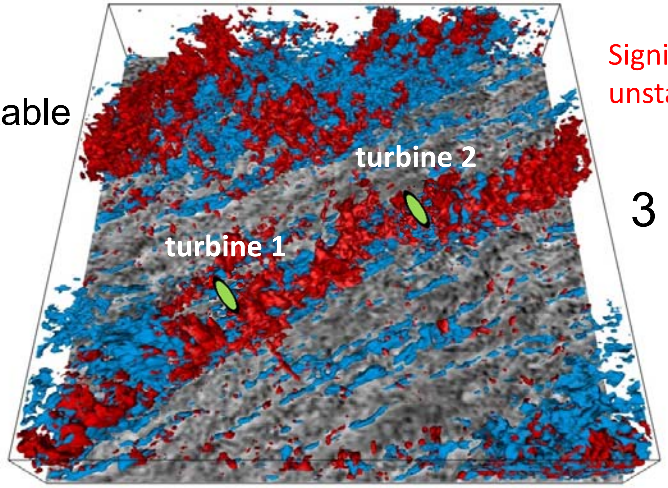


Instantaneous isosurfaces in atmospheric boundary layer viewed from above

Blue: low speed structures

Red: updrafts

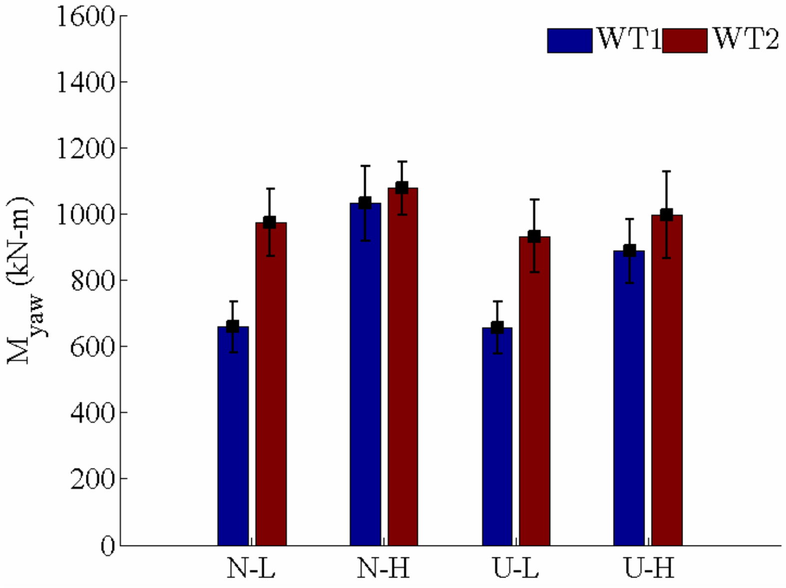
unstable



Significant updrafts in unstable case

3 km

3 km



Damage Equivalent Load (DEL)

Equivalent fatigue load under constant amplitude cycle that will produce the same amount of fatigue damage from actual loading history

Second turbine experiences more damaging yaw moments

Limitations of SOWFA

- **Could not handle complex terrain**
  - Wall shear stress model

- **Unsure about simulation of stable stratification**
  - Our custom subgrid-scale (SGS) model implementation limited solver to standard Smagorinsky model; could not use OpenFOAM standard SGS models

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Uniqueness of the Stable Atmospheric Boundary Layer

- **The stable atmospheric boundary layer (ABL)**
  - Cooling of air at lower surface
  - Positive vertical gradient of potential temperature
  - Common at night, warm air over cool water
  - Characterized by:
    - Low/intermittent turbulence
    - Strong vertical wind speed and direction shear
    - Formation of a low-level jet
  - Known to be particularly damaging to turbines
    - See the work of Neil Kelley of NREL [4]

Uniqueness of the Stable Atmospheric Boundary Layer

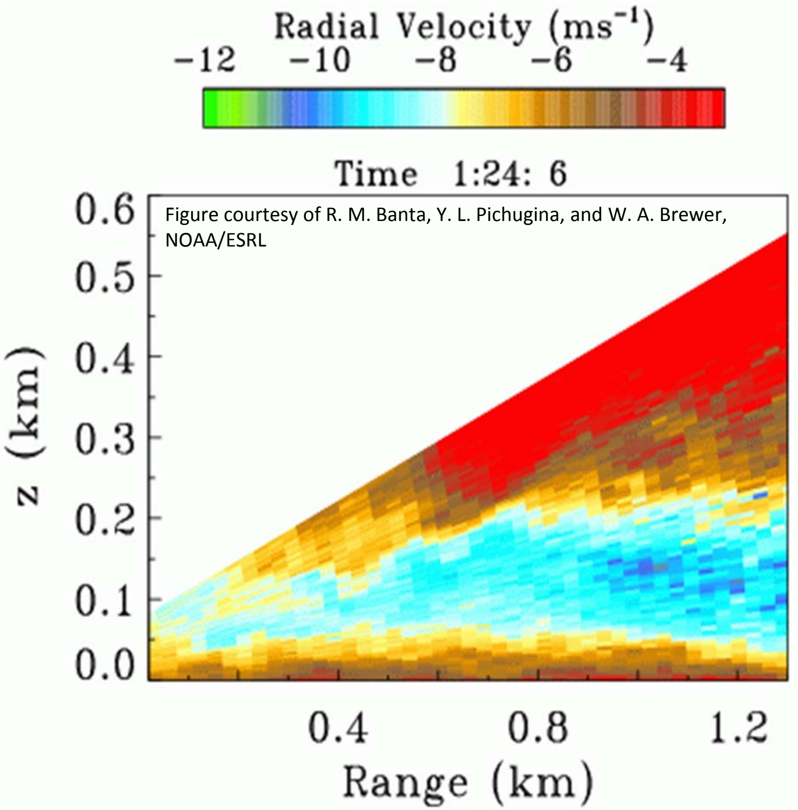


Figure courtesy of R. M. Banta, Y. L. Pichugina, and W. A. Brewer, NOAA/ESRL

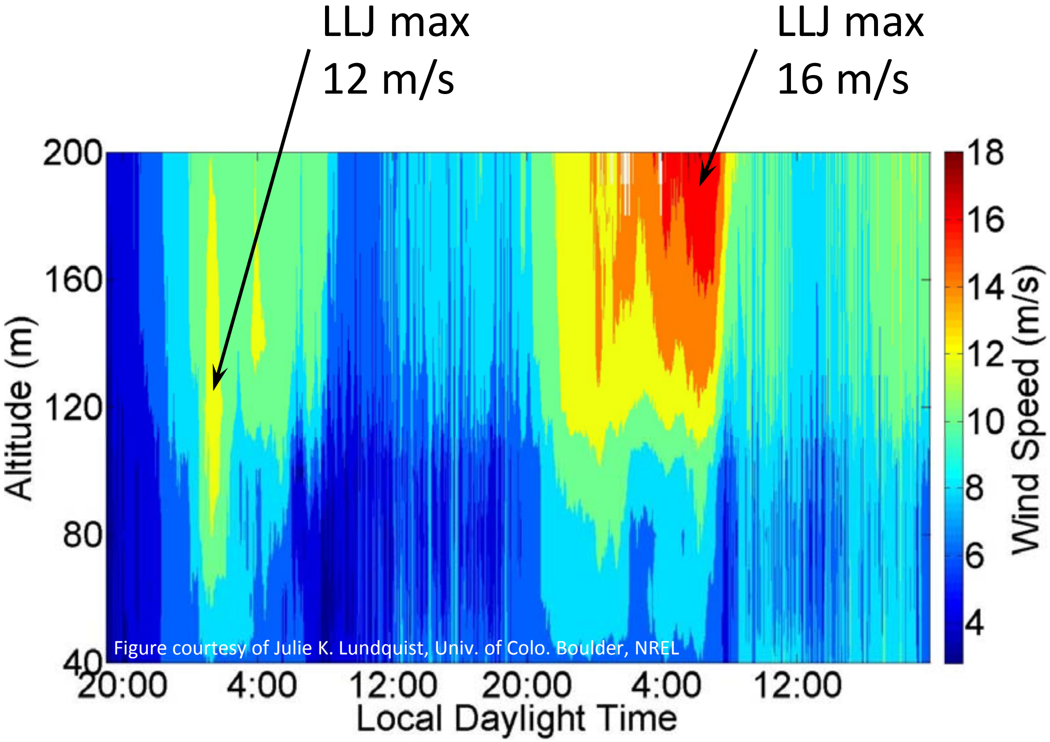


Figure courtesy of Julie K. Lundquist, Univ. of Colo. Boulder, NREL

Low-level jet (LLJ) formation after sunset observed with scanning light detection and ranging (LIDAR) (velocity along beam) [5]

Midwestern U.S. low-level jet observed with a Windcube LIDAR [6,7]

Subgrid-Scale Modeling

- **Smaller scales and low/intermittent turbulence make stable atmospheric boundary layer LES sensitive to SGS model**
    - SGS model has larger role than in neutral/unstable atmospheric boundary layer LES

- **Simpler models like standard Smagorinsky or one-equation SGS kinetic energy models:**
    - Are only dissipative (large- to small-scale energy flow)
    - Include an SGS stress linearly related strain
    - Contain “tunable” model constants

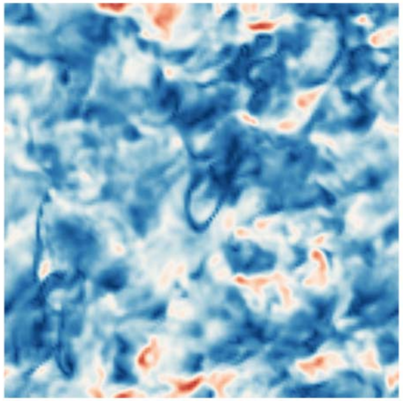
- **However, the following is true:**
    - Backscatter is important (small- to large-scale energy flow)
    - In regions of strong shear, SGS stresses become anisotropic
    - Ideal model constant value is problem-specific

Subgrid-Scale Modeling

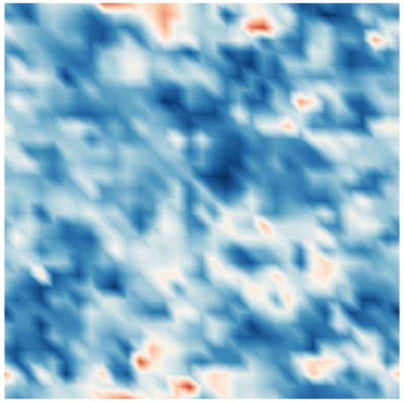
- **Modified SGS Models**
  - United Kingdom Met Office Smagorinsky model [8]
    - Sensitized to flux Richardson number
    - Backscatter through random number accelerations and fluxes
  - One-equation anisotropic [9]
    - Contains an “isotropy” factor
    - Reduces dissipation near surface in high shear
  - Nonlinear one-equation [10]
    - Anisotropy through nonlinear stress/strain relationship
    - Accounts for backscatter

Subgrid-Scale Modeling

- **Dynamic SGS Models**
  - Model determines model “constants” based on resolved and test-filtered flow
  - Model constants vary in space/time causing instability, so averaging is necessary
    - Over homogeneous directions (plane in flat ABL)
    - Backward along streamline (Lagrangian)
    - About cell/grid point of interest (local)



Resolved



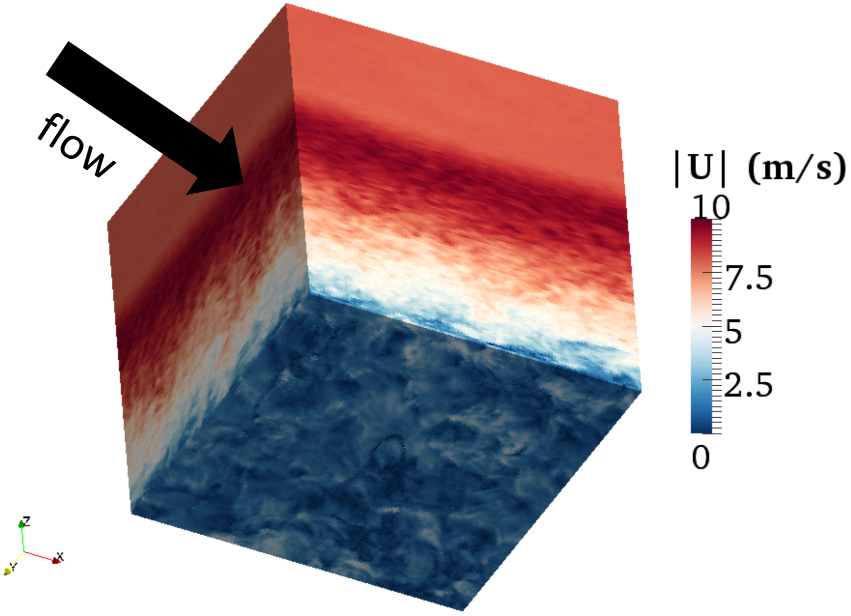
Test-filtered

Subgrid-Scale Modeling

- **Dynamic SGS Models**
  - Two variants:
    - Scale-invariant
      - Assumes the ideal model constant is the same at the resolved and test-filtered scale
      - Found to be under dissipative in ABL applications
    - Scale-dependent [11,12,13]
      - Assumes the ideal model constant is a function of filter width
      - Better level of dissipation
  - Lagrangian-averaged scale-independent (LASI) dynamic Smagorinsky model [14]
    - Included in OpenFOAM
    - Dynamically solves for model constant, C_s

Stable Stratification Test Case

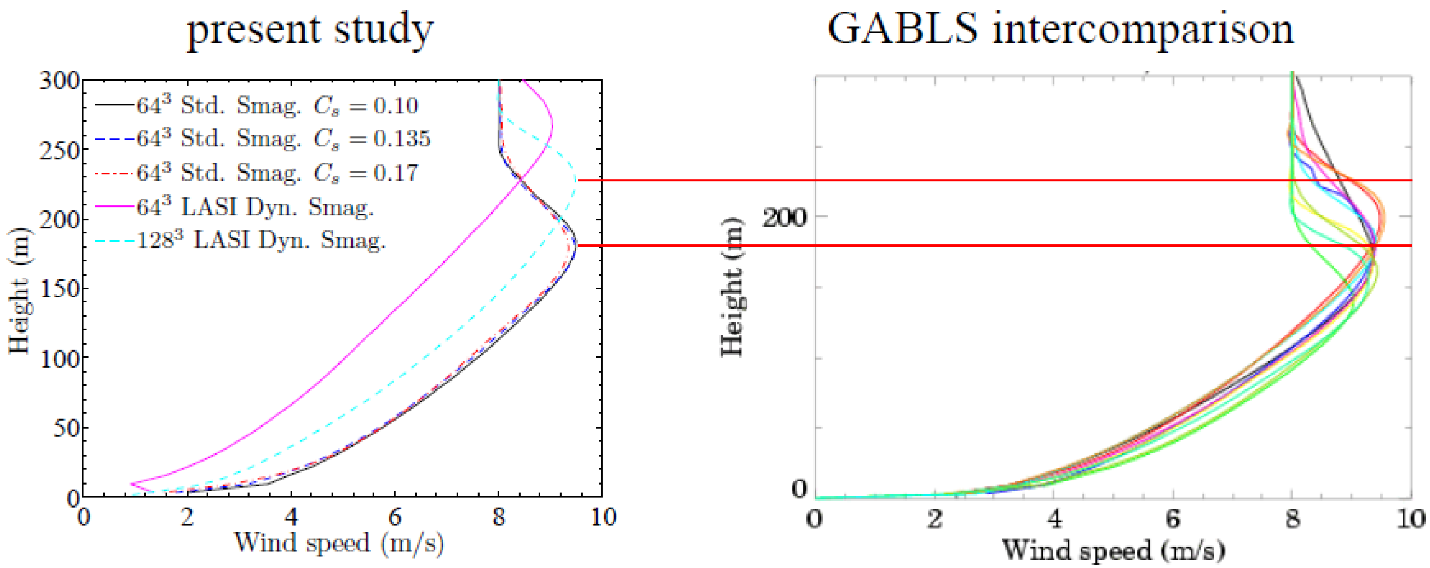
- **Global Energy and Water Cycle Experiment Atmospheric Boundary Layer Study (GABLS) model intercomparison case [15]**
- **Flat terrain**
- **400 m × 400 m × 400 m**
- **64^3 (6.25 m) and 128^3 (3.125 m) cells**
- **Initial temperature profile constant up to 100 m, capped by inversion**
- **Surface cooling rate 0.25 K/hr**
- **Periodic**
- **Geostrophic wind 8 m/s**
- **73° N latitude**
- **z_0 0.1 m**
- **SGS models**
    - Standard Smagorinsky
        - Used various values of model constant, C_s
    - LASI dynamic Smagorinsky
        - Model solves for model constant, C_s



Results

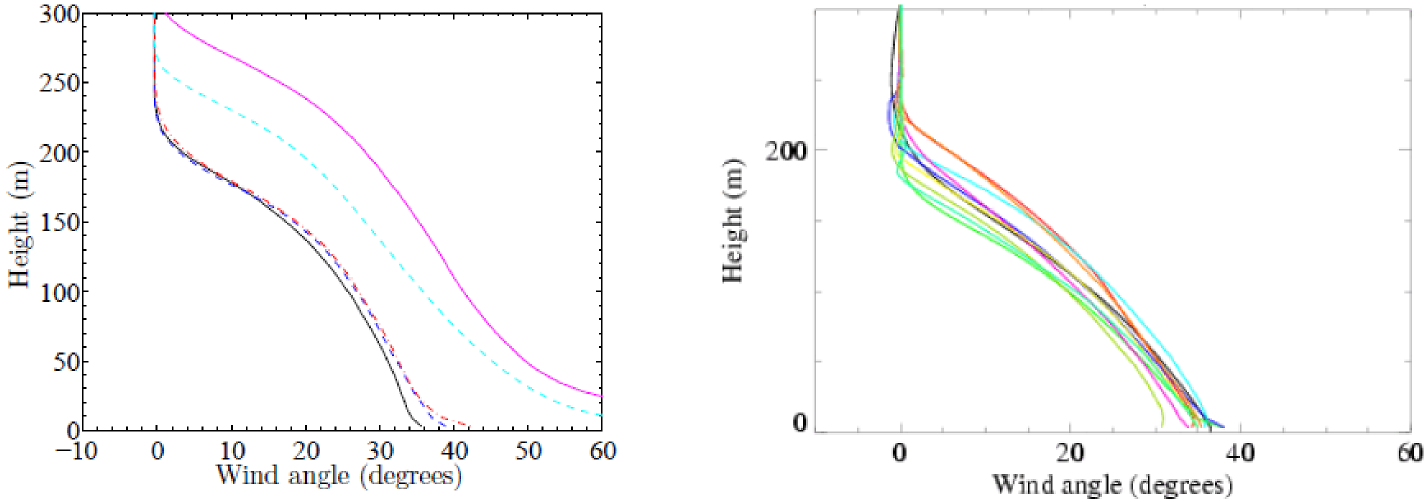
Standard Smagorinsky results in general agreement with GABLS intercomparison results

LASI dynamic Smagorinksy greatly overpredicts height of low-level jet—increasing resolution causes lower jet



Standard Smagorinsky results for total wind turning angle in agreement with GABLS intercomparison

LASI dynamic Smagorinsky overpredicts total turning angle

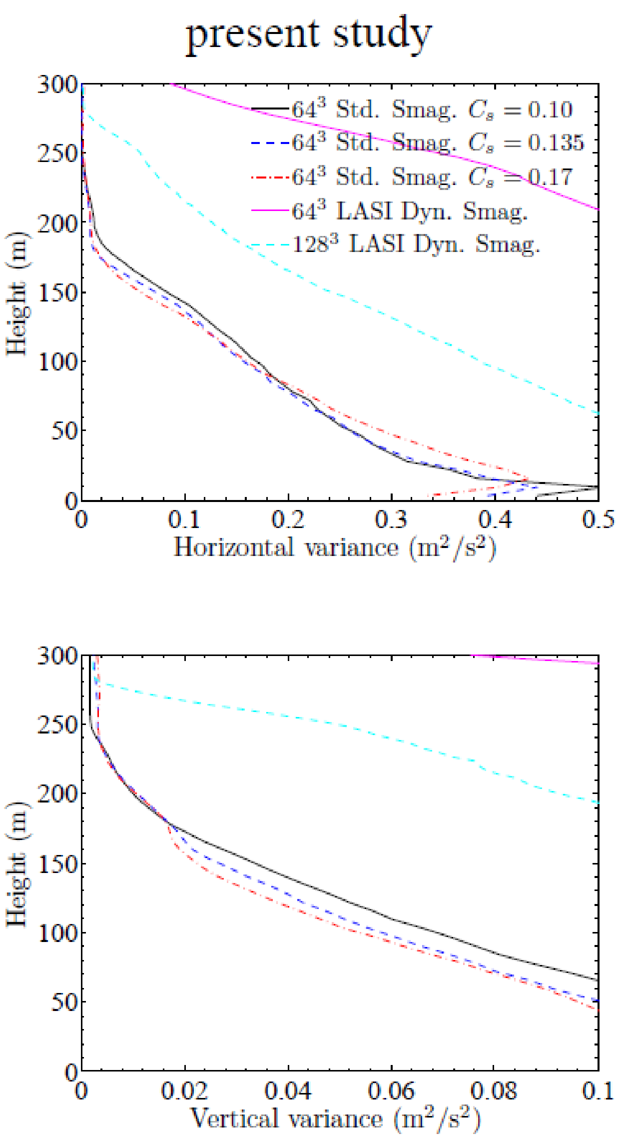


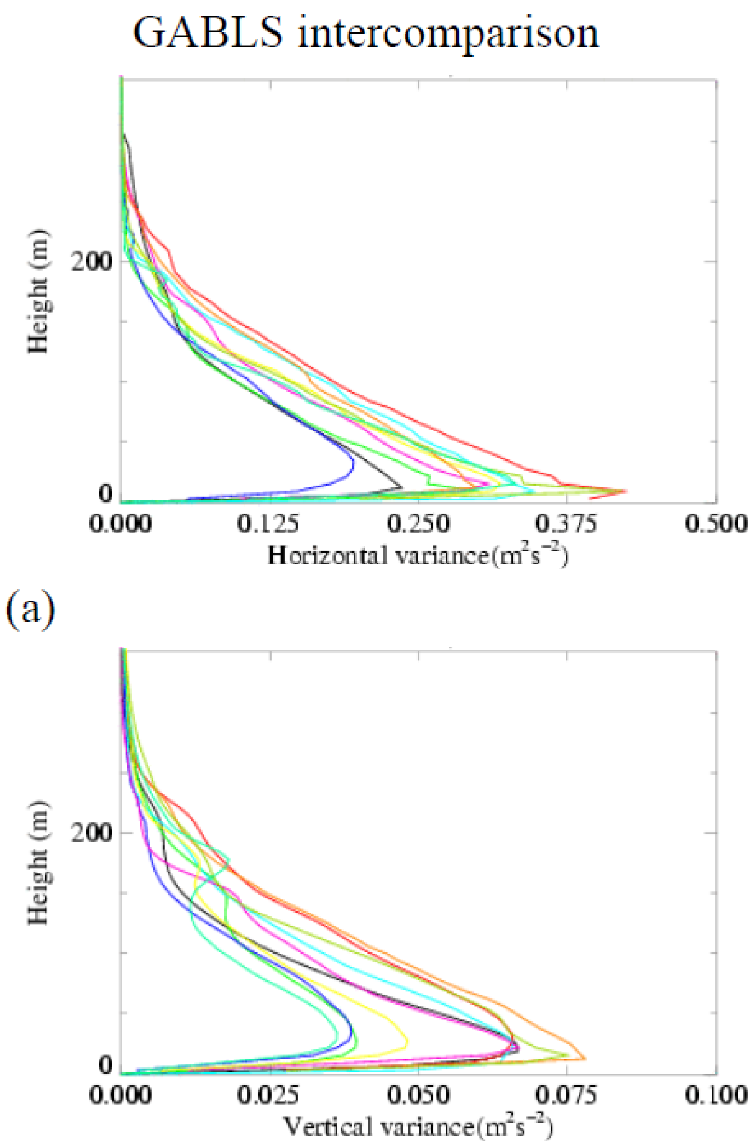
Results

Standard Smagorinsky generally overpredicts horizontal velocity variance and greatly overpredicts vertical

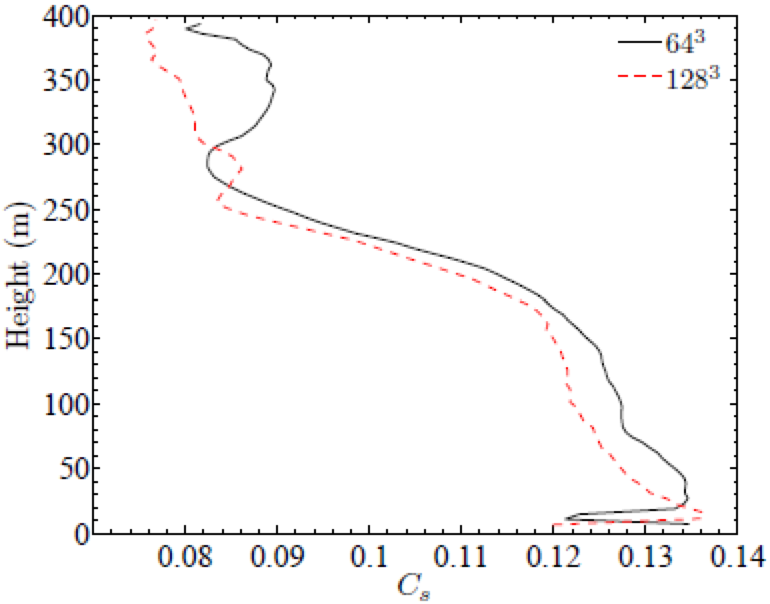
As model constant is increased, peak predicted variance is reduced

LASI dynamic Smagorinsky far overpredicts variances, hinting at not enough dissipation

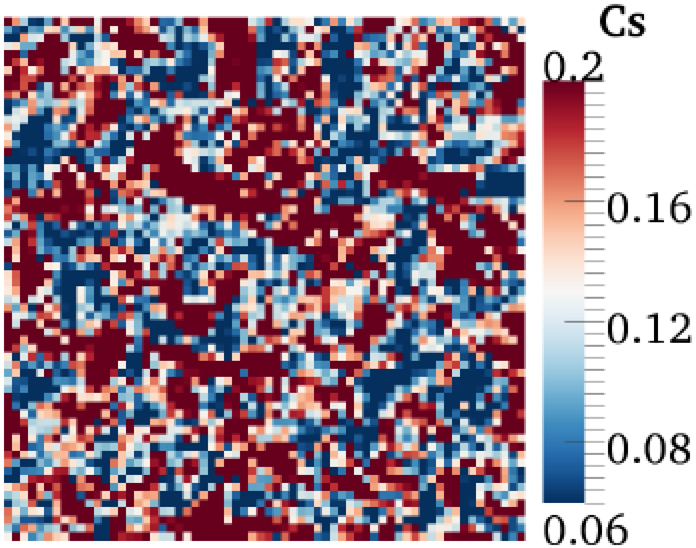

present study


GABLS intercomparison

Results



Vertical profiles of mean C_s from LASI dynamic Smagorinsky simulation



Instantaneous C_s in a plane at 3.125 m above surface from 64^3 LASI dynamic Smagorinsky simulation

- C_s increases as the surface is approached from low-level jet height, but then rapidly reduces near the surface
- Instantaneous C_s is very noisy (values range from 0.0035 to 4.6 in the plane above)
- The noise possibly acts like excessive backscatter

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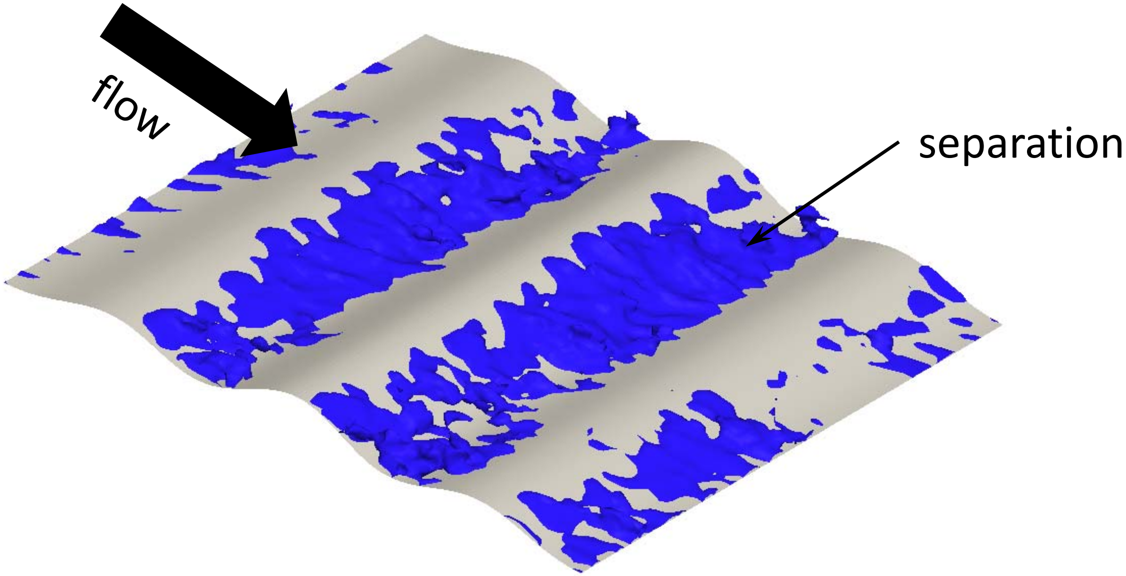
Issues with Modeling Flow Over Terrain

- **Difficult to model with computationally fast tools needed by wind plant designers**
- **Often unsteady effects, like separation on lee side of hills**



Wall-Modeled LES

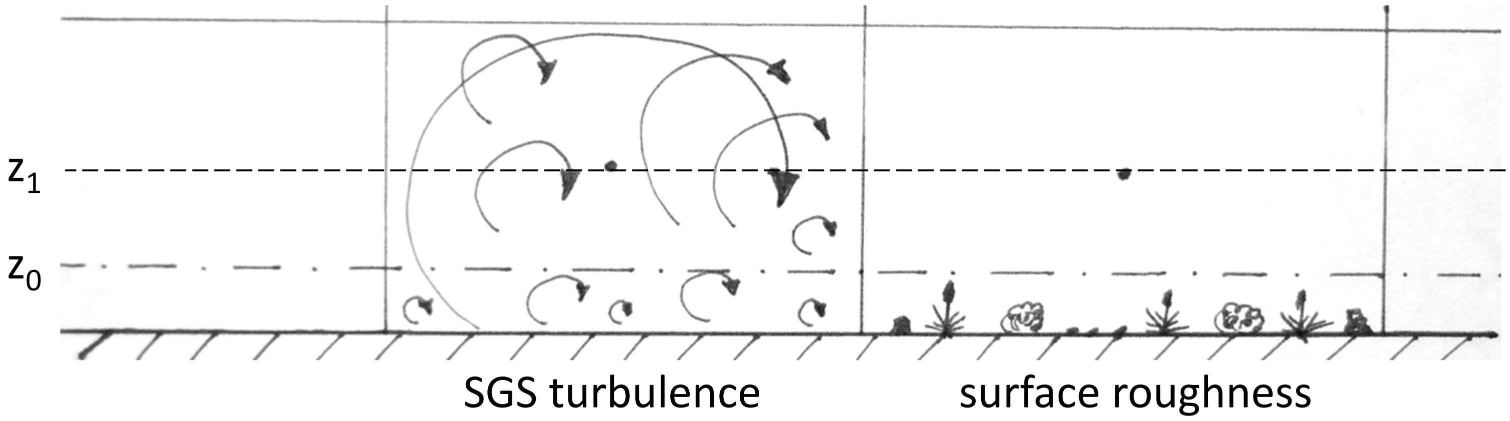
- **LES is meant to capture larger energy-containing scales**
- **As the wall is approached, energy-containing scales get smaller**
    - Requires increasingly higher resolution
- **There are roughness elements near the wall that affect the flow**
    - Grass, rock, shrubs, and so on

Commonly, the above effects are dealt with by using a surface shear stress and temperature flux model

Surface Shear Stress Model

- **At surface,** $\overline{\mathbf{U}}_s \cdot \mathbf{n}_s = 0$ $\quad$ $\boldsymbol{\tau} = \boldsymbol{\tau}_s = \begin{bmatrix} 0 & 0 & \tau_{13_s} \\ 0 & 0 & \tau_{23_s} \\ \tau_{13_s} & \tau_{23s} & 0 \end{bmatrix}$

- **Surface stress is caused by viscosity, roughness drag, and SGS turbulence**



Surface Shear Stress Model

With the following definitions/relationships:

- Friction velocity
- Monin-Obukhov ABL similarity laws (angle brackets denote planar average)
- Obukhov length

$$u_*^2 = \sqrt{\left\langle \tau_{13_s}(x,y) \right\rangle^2 + \left\langle \tau_{23_s}(x,y) \right\rangle^2}$$

$$\left| \left\langle \overline{\mathbf{U}}(z_1) \right\rangle \right| = \frac{u_*}{\kappa} \left[\log\left(\frac{z_1}{z_0} \right) - \psi_m\left(\frac{z_1}{L} \right) \right]$$

$$L = -u_*^3 \theta_0 / \kappa g q_s$$

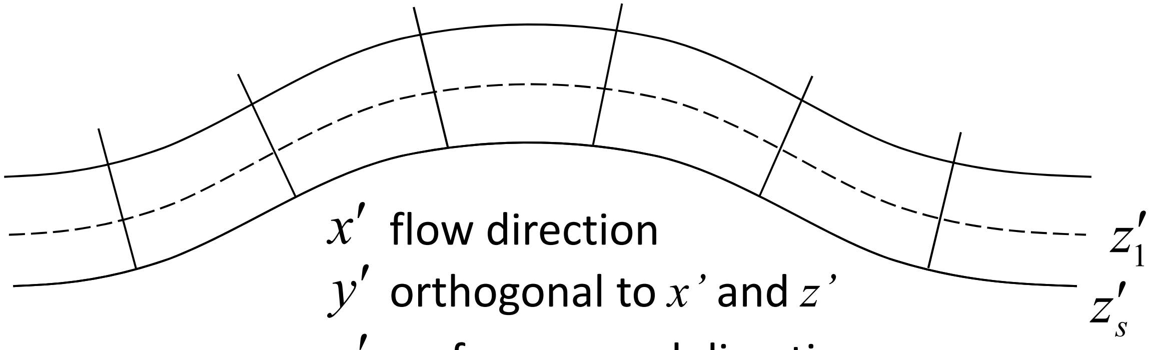
- **Implicitly solve (using an iterative technique) for friction velocity in the Monin-Obukhov similarity law using the known velocity information at the wall-adjacent cell centers (z_1)**
- **Then apply Schumann's surface stress model that uses friction velocity and velocity at surface-adjacent cell centers**

$$\tau_{i3_s}(x,y) = -u_*^2 \frac{\overline{U}_i(x,y,z_1)}{\left| \left\langle \overline{\mathbf{U}}(z_1) \right\rangle \right|}$$

- **Constraints**
  - Relies on planar averages (angle brackets)
  - Mathematically valid only for flow over flat terrain

Surface Shear Stress Model

- **Terrain**



x' flow direction
y' orthogonal to x' and z'
z' surface normal direction

  - Apply local Monin-Obukhov (no planar averages)
  - In a terrain-local coordinate system (primes denote local coordinates)

$$u_*^2(x,y) = \sqrt{\tau'_{13_s}(x,y)^2 + \tau'_{23_s}(x,y)^2}$$

$$\left|\mathbf{U}'(x,y,z'_1)\right| = \frac{u_*(x,y)}{\kappa}\left[\log\left(\frac{z'_1}{z_0}\right) - \psi_m\left(\frac{z'_1}{L}\right)\right] \qquad L = -\frac{u_*^3\theta_0}{\kappa g q_s}$$

$$\tau'_{i3_s}(x,y) = -u_*^2(x,y)\frac{\overline{U}'_i(x,y,z'_1)}{\left|\overline{\mathbf{U}}'(x,y,z'_1)\right|} \Longrightarrow \boxed{\boldsymbol{\tau}_s = \mathbf{T}\boldsymbol{\tau}'_s\mathbf{T}'}$$

transform back to Cartesian

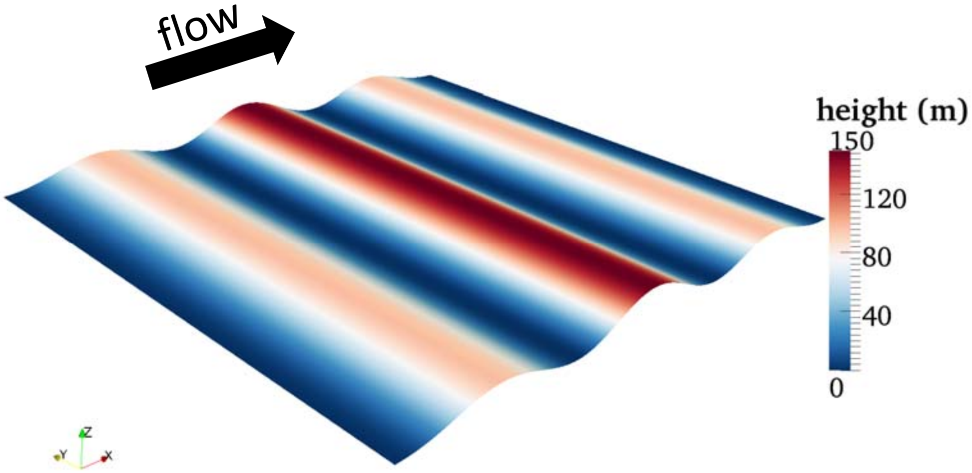
Surface Shear Stress Model

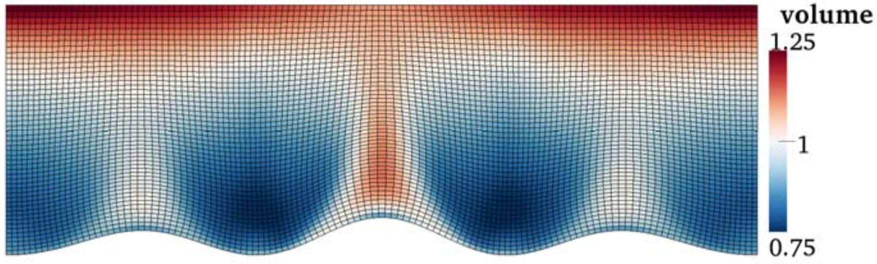
- **Does it make sense to apply Monin-Obukhov…**
    - Locally?
    - Over complex terrain?
- **Alternatives**
    - Include a Reynolds-averaged Navier-Stokes (RANS) layer to replace wall shear stress model
    - Include a curvature correction to Monin-Obukov

- **Surface temperature flux model faces analogous issues**

Terrain Test Case

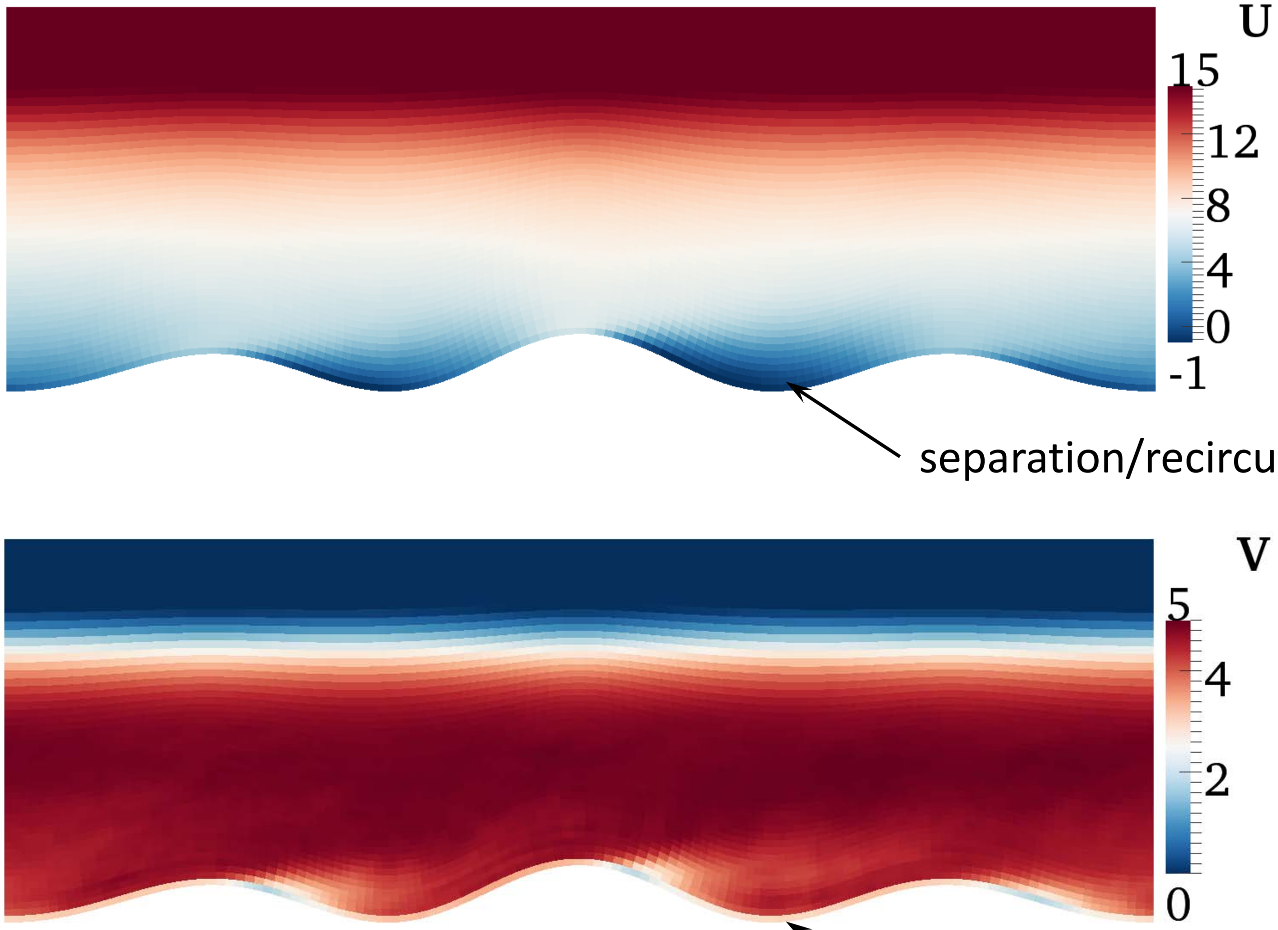
- Simple, hilly terrain
- 3 km × 3 km × 1 km
- 125 × 125 × 50 cells
- Neutral stability capped by inversion
- Periodic
- Geostrophic wind 15 m/s
- 45° N latitude
- z_0 0.16 m
- Mesh generated with `moveDynamicMesh`





Results

Mean resolved-scale velocity field

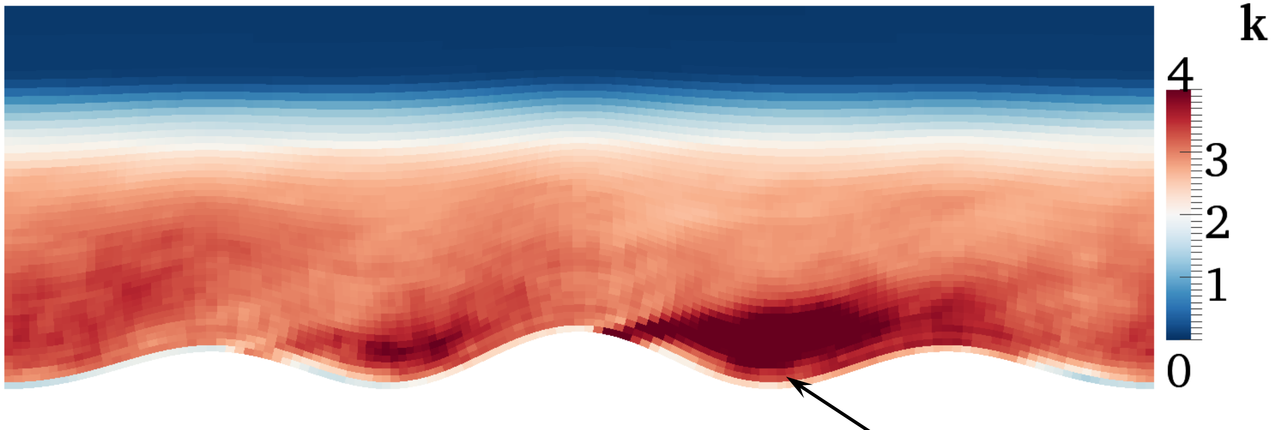


separation/recirculation

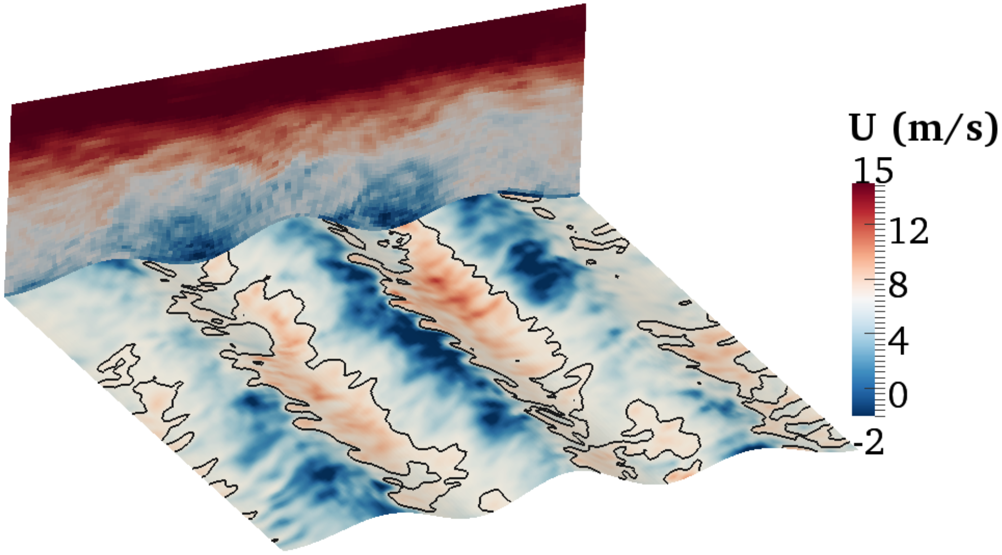
non-orthogonal correction needed?

Results

Mean resolved-scale turbulent kinetic energy field



separation/recirculation



View from above of instantaneous x-directed velocity in grid cells adjacent to surface

Black lines are contours of surface stress acting in x-direction

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Conclusions

- **LES of stably stratified ABL**
  - Standard Smagorinsky model within range of predictions of GABLS intercomparison for means, but overpredicts velocity variances
  - LASI dynamic Smagorinksy model significantly overpredicts the height of low-level jet and peak values of velocity variance
    - It appears not dissipative enough
  - Need to examine velocity/temperature spectra
    - Try LASD [13], Kosović nonlinear [10], and Sullivan et al. anisotropic model [9]
    - Remember, even the dynamic Smagorinsky model relies on linear stress/strain relationship
- **Terrain**
  - Terrain-local surface stress model using local Monin-Obukhov scaling seems to work qualitatively correctly
  - Does local Monin-Obukhov make sense?
  - Does Monin-Obukhov over complex terrain make sense?
  - An alternative is to have a near-surface RANS layer

- **The wind plant computational fluid dynamics part of SOWFA is now modularized**
  - Can use any OpenFOAM turbulence model
  - Although not tested, could run in RANS or detached-eddy simulation (DES) mode
  - ABL-specific boundary conditions now separated from solver code as classes

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