LES of Turbulent Flows: Lecture 18

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Overview

Evaluating Simulations and SGS Models

- How do we go about testing our models?
- How should models be validated and compared to each other?

Evaluating Simulations and SGS Models

Pope (2004) gives 5 criteria for evaluating SGS models

- Level of description in the SGS model
- Completeness of the model
- The cost and ease of use of the model
- The range and applicability of the model
- The accuracy of the model

Most of these criteria are related to the accuracy of simulation results

Evaluating Simulations and SGS Models

Accuracy

- Ability of the model to reproduce DNS, experimental, or theoretical statistical features of a given test flow (or the ability to converge to these values with increasing resolution)

Evaluating Simulations and SGS Models

Accuracy

- An important aspect of this is **grid convergence of simulation statistics**.
- This is not always done, but is an important aspect of simulation validation.
- Note that this convergence (especially in high-Re flows) may not be exact, we may only see approximate convergence.

Evaluating Simulations and SGS Models

Cost

- When examining the above, it is important to include the cost of each model (and comparisons between alternative models)
- One model may give better results at a lower grid resolution (larger Δ) but include costs that are excessive

Cost

- Example: Scale-dependent Lagrangian dynamic model (Stoll and Porté-Agel, 2006)
- 38% increase in cost over constant Smagorinsky model
- 15% increase over plane averaged scale-dependent model
- How much of a resolution increase can we get in each direction for a 30% cost increase?? Only a little more than 3% in each direction!

Evaluating Simulations and SGS Models

Completeness

- A "complete" LES and SGS model would be one that can handle different flows with simply different specification of BCs, initial conditions, and forcings
- In general LES models are not complete due to grid requirements and (possibly) ad hoc tuning for different flows

Completeness

- Example from RANS: mixing length models are incomplete (different flow different ℓ)
- Meanwhile, the k-ϵ model can be thought of as complete for RANS since it can be applied to any flow

Test Case: Turbulent Boundary Layers

An example from Guerts (2004) of the effect of different SGS models on boundary layer development

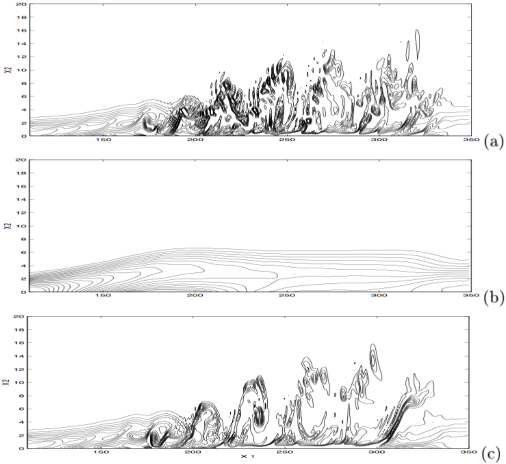
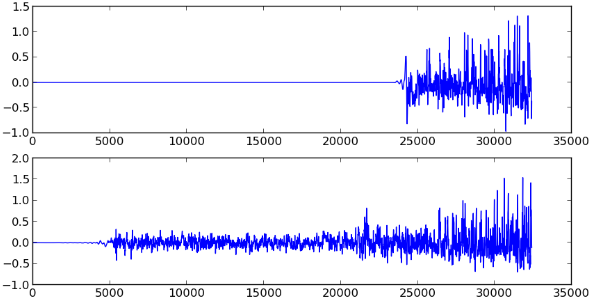


Fig. 8.15. Snapshot of the spanwise vorticity component: (a) DNS prediction, (b) LES with Smagorinsky's model and van Driest damping, (c) LES with dynamic eddy-viscosity model.

Test Case: Stable Boundary Layers

An example from GABLS3 (Gibbs, unpublished)



Near-surface vertical velocity fluctuations as produced by OULES with the Smagorinsky (top) and Deardorff (bottom) SGS models

Test Case: Backward Facing Step

An example from Cabot and Moin (1999)

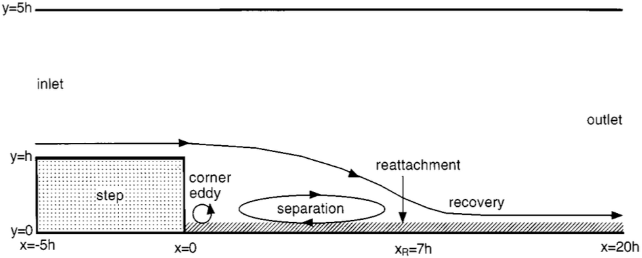


Figure 4. Sketch of the simulation domain for flow over a step of height h with an expansion ratio of 4 to 5. Wall stress models were used in the hatched region.

Test Case: Backward Facing Step

An example from Cabot and Moin (1999)

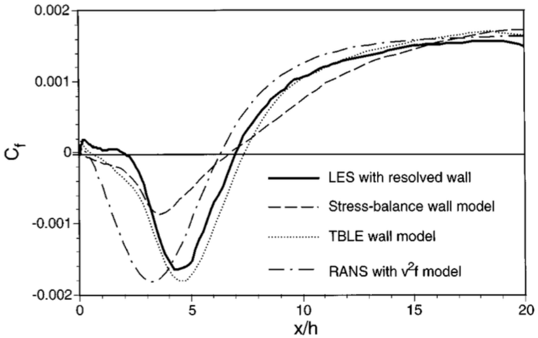


Figure 6. Friction coefficient on the bottom wall behind a step for the wall-resolved LES [2], wall stress models using stress balance and TBLE with a dynamic κ from Equation (12), and a global RANS $v^2 f$ model [18].

Test Case: Backward Facing Step

An example from Cabot and Moin (1999)

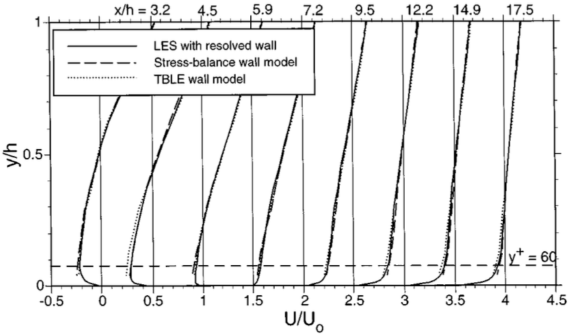


Figure 7. Mean streamwise velocity at different stations behind a step for the wall-resolved LES [2], and stress-balance and TBLE wall stress models. The dashed line is the height of the first computational cell, about 60 wall units near the exit.

Test Case: Mixing Layer

An example from Geurts (2004)

Name	**Model for $\tau_i j$**	**Plot legend**
M0	No model	$-$
M1	Smagorinsky	$\star$
M2	Similarity	$\times$
M3	Nonlinear	$+$
M4	Dynamic Smagorinsky	$--$
M5	Dynamic Mixed	$\ldots$
M6	Dynamic Nonlinear	$-\cdot$

Test Case: Mixing Layer

An example from Geurts (2004)

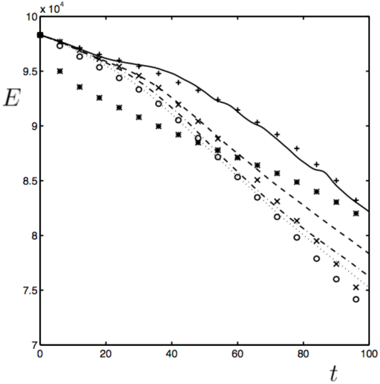


Fig. 8.5. Comparison of the total kinetic energy E obtained from the filtered DNS (marker o) and from LES using M0-6 (see table 8.2 for labels). From [221].

Test Case: Mixing Layer

An example from Geurts (2004)

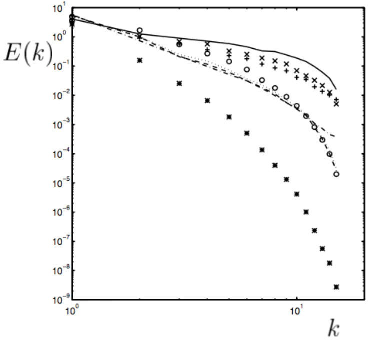


Fig. 8.6. Comparison of the streamwise energy spectrum $E(k)$ at $t = 80$ obtained from the filtered DNS (marker o) and from LES using M0-6 (see table 8.2 for labels). From [221].

An example from Geurts (2004)

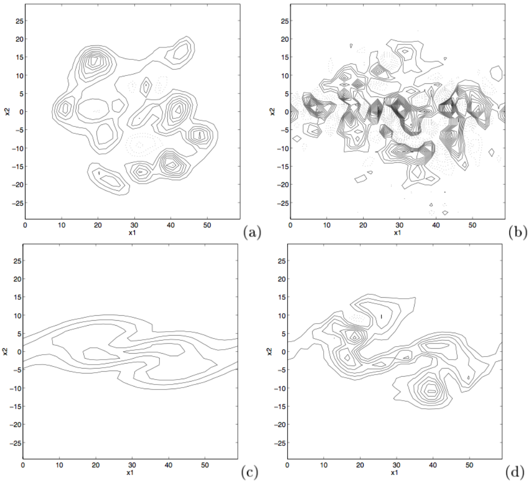
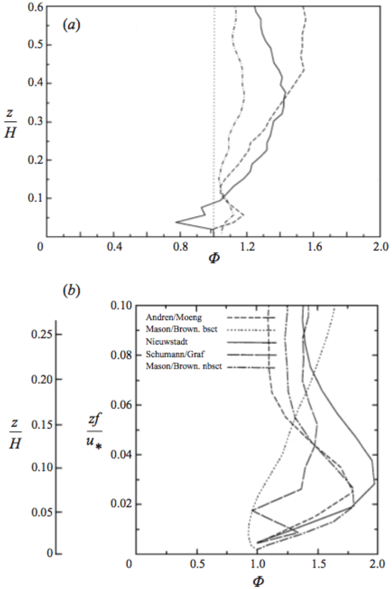


Fig. 8.7. Contours of spanwise vorticity for the plane $x_3 = 3\ell/4$ at t=80 obtained from (a) the filtered DNS, restricted to the 32^3-grid, and from LES using (b) M0, (c) M1 and (d) M4. Solid and dotted contours indicate negative and positive vorticity respectively. The contour increment is 0.05. From [221].

Accuracy of LES Models

- An example of the accuracy of LES models to predict flow statistics (from Porté-Agel et al 2000 and Andren et al. 1994)
- Φ is non-dimensional velocity gradient
- In panel (a), Dashed line: traditional Smagorinsky model with $C_0 = 0.1$ and $n = 2$; dot-dashed line: traditional Smagorinsky model with $C_0 = 0.17$ and $n = 1$; solid line: standard dynamic model



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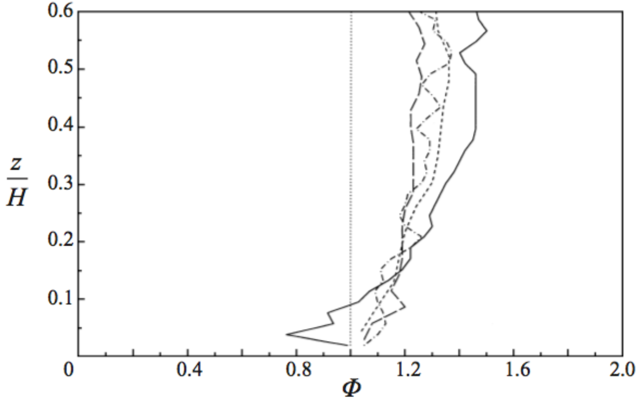

Non-dimensional velocity gradient

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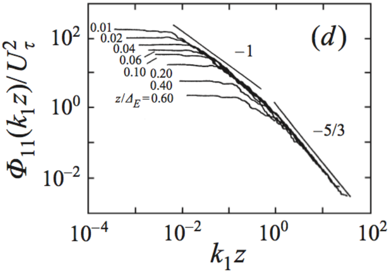
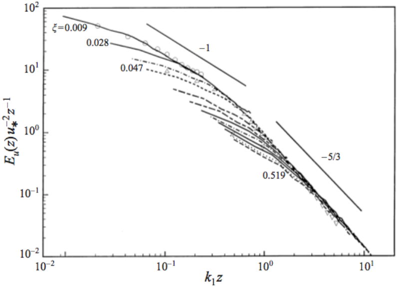
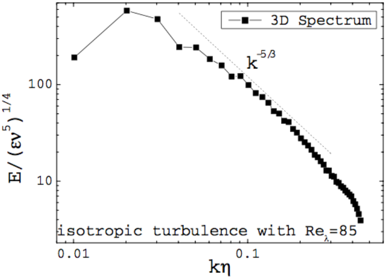


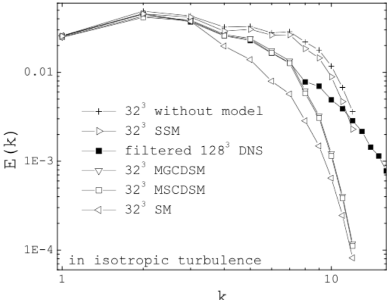


left: Streamwise velocity spectra from Perry et al (1986)
right: Streamwise velocity spectra at two different resolutions

Test Case: Isotropic Turbulence LES

An example from Lu et al (2008)





left: velocity spectra from DNS
right: velocity spectra from filtered DNS and LES

Test Case: Isotropic Turbulence LES

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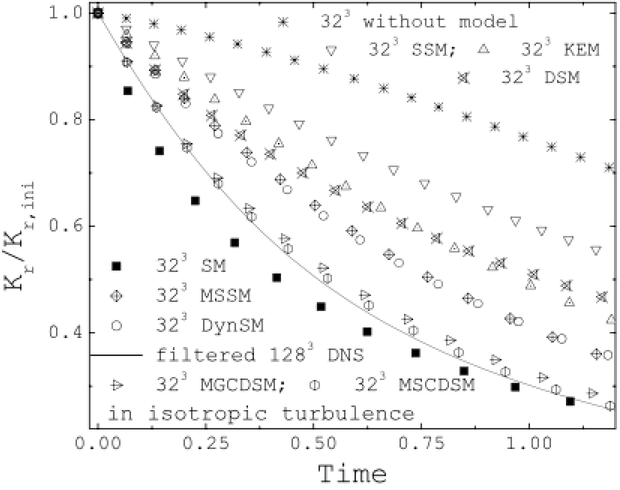
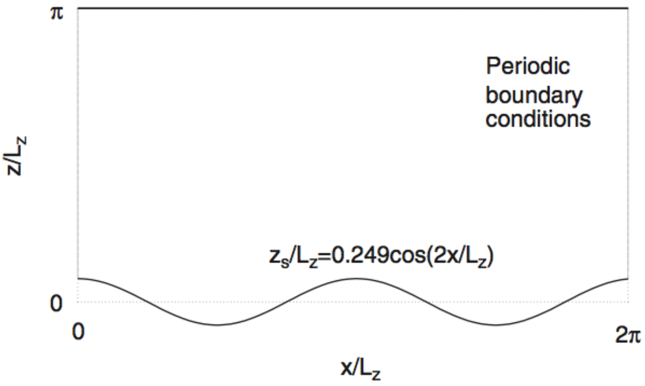


energy decay

Test Case: Flow Over a 2D Hill

An example from Wan et al (2007)



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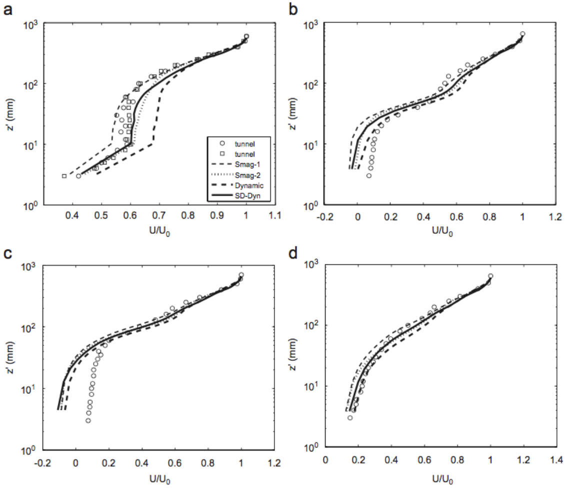

Velocity comparison with data and different models

Test Case: Flow Over a 2D Hill

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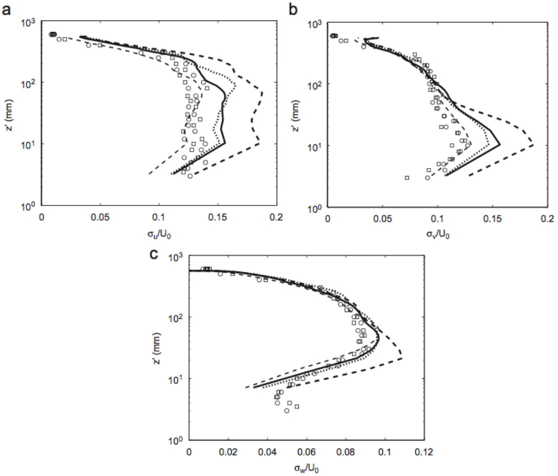


Velocity comparison with data and different models

Example: Grid Resolution

An example from Sullivan and Patton (2011)

- Re-examined a typical flow used in atmospheric simulations as an analog for daytime conditions (high-Re, weakly sheared convection)
- Goal: understand mesh dependence of a particular SGS model (Deardorff 1980 type, 1-equation)

Example: Grid Resolution

An example from Sullivan and Patton (2011)

- Domain: $5120 \times 5120 \times 2048$ m$^3 (x, y, z)$

Run	**Grid points**	$(\Delta x, \Delta y, \Delta z)[m]$	$\Delta_f[m]$
A	32^3	(160, 160, 64)	154
B	64^3	(80,80,32)	77.2
C	128^3	(40,40,16)	38.6
D	256^3	(20,20,8)	19.3
E	51263	(10,10,4)	9.6
F	1024^3	(5,5,2)	4.8

Example: Grid Resolution

An example from Sullivan and Patton (2011)

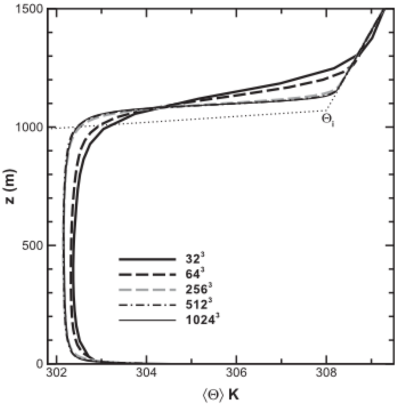


FIG. 2. Vertical profile of virtual potential temperature $\langle\overline{\theta}\rangle$ for varying mesh resolution. Note all simulations are started with the same three-layer structure for virtual potential temperature θ_i, indicated by the dotted line.

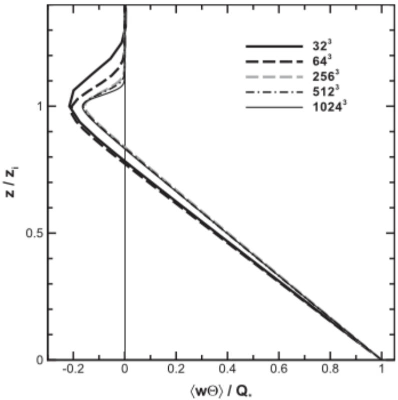


FIG. 3. Vertical profile of total temperature flux $\langle\overline{w''\theta''} + \mathbf{B}\cdot\hat{\mathbf{k}}\rangle/Q_*$ for varying mesh resolution.

Example: Grid Resolution

An example from Sullivan and Patton (2011)

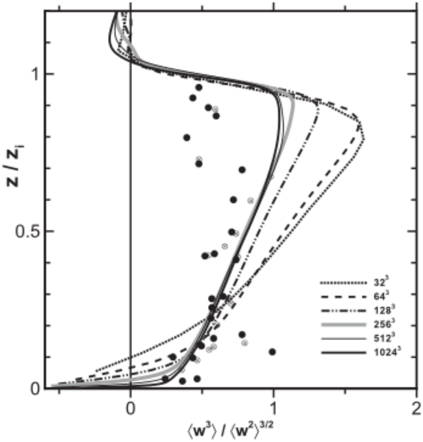


FIG. 9. Effect of mesh resolution on resolved vertical velocity skewness $S_{\overline{w}}$. The lines legend indicates the mesh size of the various simulations. The skewness is computed using the resolved (or filtered) vertical velocity field $\overline{w} = \overline{w}''$. The observations are taken from the results provided in Moeng and Rotunno (1990).

Example: Grid Resolution

An example from Sullivan and Patton (2011)

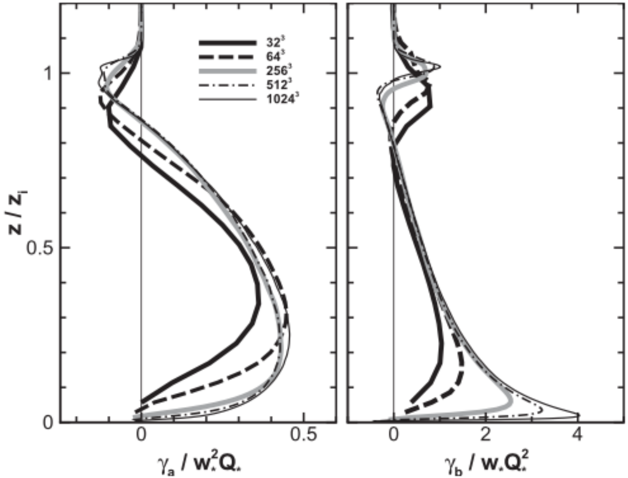
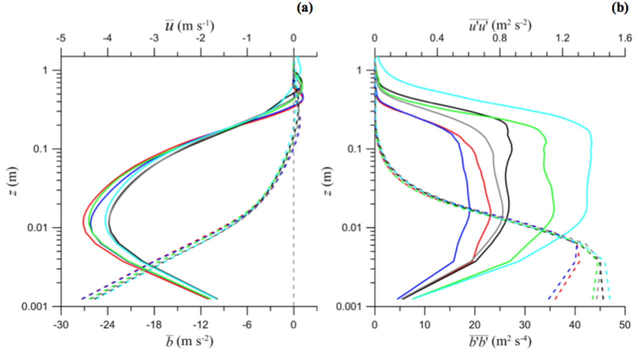


FIG. 12. Effect of mesh resolution on resolved third-order moments (left) $\gamma_a = \langle \overline{w}''^2 \overline{\theta}'' \rangle$ and (right) $\gamma_b = \langle \overline{w}'' \overline{\theta}''^2 \rangle$.

Example: Grid Size

An example from Gibbs, Fedorovich, van Heerwarden (unpublished)



Mean-flow (**a**) and variance (**b**) profiles of along-slope velocity and buoyancy in the katabatic flow with $B_s = -0.5\ \mathrm{m^2 s^{-3}}$, $\nu = \kappa = 10^{-4}\ \mathrm{m^2 s^{-1}}$, $N = 1$ rad s^{-1}, and 60° slope. Solid lines correspond to the lower-axis variable and dashed lines correspond to the upper-axis variables.

Red: $X \times Y \times Z = 0.32 \times 0.32 \times 1.5\ \mathrm{m^3}$; $n_x \times n_y \times n_z = 128 \times 128 \times 600$.

Black: $X \times Y \times Z = 0.64 \times 0.64 \times 1.5\ \mathrm{m^3}$; $n_x \times n_y \times n_z = 256 \times 256 \times 600$.

Blue: $X \times Y \times Z = 0.64 \times 0.32 \times 1.5\ \mathrm{m^3}$; $n_x \times n_y \times n_z = 256 \times 128 \times 600$.

Green: $X \times Y \times Z = 0.32 \times 0.64 \times 1.5\ \mathrm{m^3}$; $n_x \times n_y \times n_z = 128 \times 256 \times 600$.

Gray: $X \times Y \times Z = 1.28 \times 0.64 \times 1.5\ \mathrm{m^3}$; $n_x \times n_y \times n_z = 512 \times 256 \times 600$.

Cyan: $X \times Y \times Z = 0.64 \times 1.28 \times 1.5\ \mathrm{m^3}$; $n_x \times n_y \times n_z = 256 \times 512 \times 600$.

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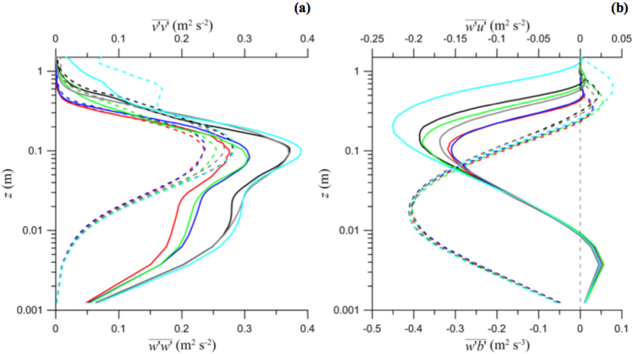

Slope-normal and cross-flow velocity variances (**a**) and kinematic slope-normal turbulent fluxes of momentum and buoyancy (**b**) in the katabatic flow with $B_s = -0.5\ \mathrm{m^2 s^{-3}}$, $\nu = \kappa = 10^{-4}\ \mathrm{m^2 s^{-1}}$, $N = 1\ \mathrm{rad\ s^{-1}}$, and 60° slope. Solid lines correspond to the lower-axis variable and dashed lines correspond to the upper-axis variables.

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