Assessment of a coupled momentum and passive* scalar flux subgrid-scale turbulence model for large-eddy simulation of flow in the planetary boundary layer

Poster #45

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Introduction

Turbulence significantly impacts momentum and scalar transport in the atmosphere and ocean. Our group develops turbulence parameterizations to improve the accuracy of fluid flow simulations. We extend our previous work to be applicable to a range of atmospheric stability conditions for the dry atmosphere by adding a passive algebraic subgrid-scale heat flux model. The SGS stresses are solved as a system of linear equations and are then coupled to the set of equations that model the SGS heat flux. We refer to the set of SGS stress-heat flux equations as the generalized linear algebraic subgrid-scale (GLASS) model.

*The active scalar version (SGS buoyant production term included) is being validated. For this paper, the "crossed-out" term below removes active two-way coupling. However, the SGS stresses used in the mean-gradient production term of the heat flux equation allow us to couple the SGS stress and heat flux equations. For undefined variables, see Enriquez et al. (2010).

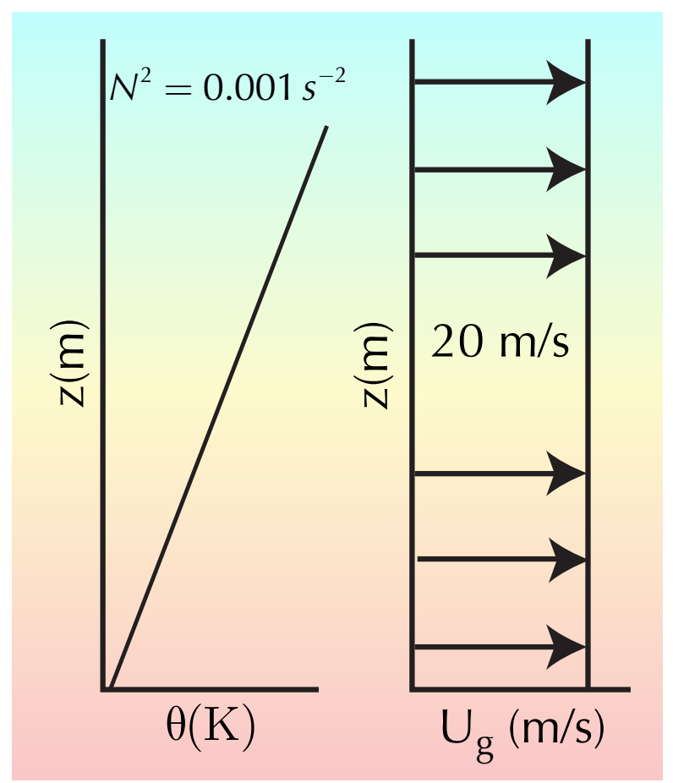
Large-eddy Simulations

The Advanced Regional Prediction System [ARPS] is 3D, compressible, non-hydrostatic, and parallelized. We simulate a convective (Fedorovich et al. 2004) and a stable (Zhou and Chow, 2011) boundary layer.

Convective Boundary Layer (CBL)

Resolution:	40 m x 40 m horizontal 20 m avg, 10 m min vertical
Domain Size:	10 km x 10 km x 2 km
Roughness Length:	0.01 m
Coriolis Parameter:	f [40° N] = 0.9 x 10^{-4} s^{-1}
Lateral Boundaries:	Periodic
Bottom Boundary:	Rigid wall, semi-slip
Reference Temperature:	300 K
Bottom heat flux:	0.1 K m s^{-1}

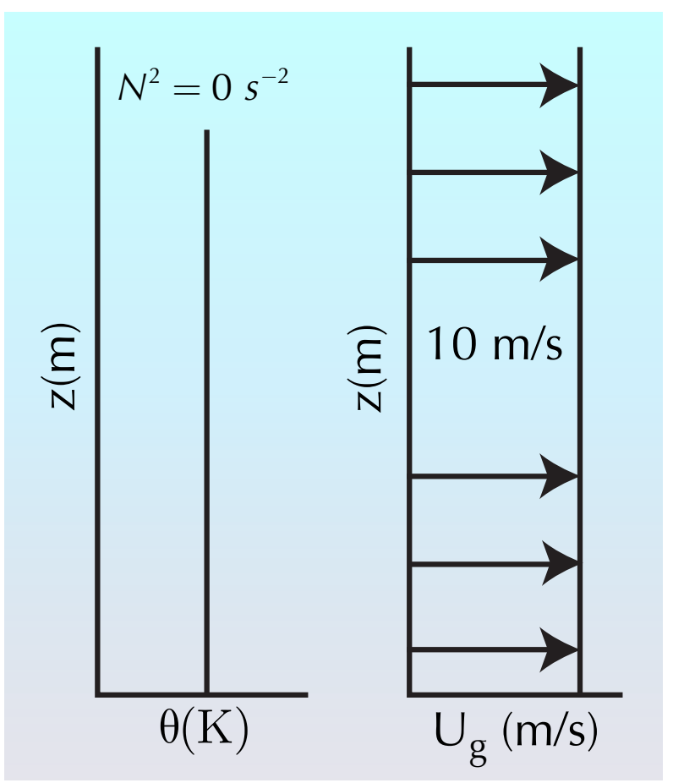
Initial Conditions



Stable Boundary Layer (SBL)

Resolution:	16 m x 16 m horizontal 16 m avg, 5 m min vertical
Domain Size:	640 m x 640 m x 640 m
Roughness Length:	0.1 m
Coriolis Parameter:	f [45° N] = 1 x 10^{-4} s^{-1}
Lateral Boundaries:	Periodic
Bottom Boundary:	Rigid wall, semi-slip
Initial Surface Temperature:	300 K
Heat Flux:	-0.02 K m s^{-1}

Initial Conditions



The Generalized Linear Algebraic Subgrid-Scale (GLASS) Model

SGS Stress (A_{ik}) Model

$$0 = \underbrace{-\bar{A}_{jk}\frac{\partial \bar{\tilde{u}}_i}{\partial x_k} - \bar{A}_{ik}\frac{\partial \bar{\tilde{u}}_j}{\partial x_k}}_{\text{Mean-Gradient Production}} \underbrace{-\tfrac{2}{3}\bar{\varepsilon}\delta_{ij}}_{\text{Viscous Dissipation}} \underbrace{\cancel{+\frac{g}{\theta_o}\left(a_j\delta_{i3} + a_i\delta_{j3}\right)}}_{\text{Buoyant Production}} \underbrace{+\Pi_{ij}}_{\text{Pressure Redistribution}}$$

$$\Pi_{ij} = \underbrace{-c_1\frac{\bar{\varepsilon}}{\bar{e}}\left(\bar{A}_{ij} - \tfrac{2}{3}\bar{e}\delta_{ij}\right)}_{\text{Slow Pressure Strain}} \underbrace{-c_2\left(P_{ij} - \tfrac{2}{3}P\delta_{ij}\right) - c_3\bar{e}\bar{\tilde{S}}_{ij} - c_4\left(D_{ij} - \tfrac{2}{3}P\delta_{ij}\right) \cancel{- c_g\frac{g}{\theta_o}\left(\bar{a}_j\delta_{i3} + \bar{a}_i\delta_{j3} - \tfrac{2}{3}\bar{a}_3\delta_{i3}\delta_{ij}\right)}}_{\text{Rapid Pressure Strain}} \underbrace{+ c_5\frac{\bar{\varepsilon}}{\bar{e}}\left(\bar{A}_{ij} - \tfrac{2}{3}\bar{e}\delta_{ij}\right) + c_6P_{ij} - c_7D_{ij} + c_8\bar{e}\bar{\tilde{S}}_{ij}\ f(h)}_{\text{Wall Effects}}$$

SGS Heat Flux (a_i)

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

$$\Pi_{i\theta} = \underbrace{-c_{1\theta}\frac{\bar{\varepsilon}}{\bar{e}}\bar{a}_i}_{\text{Slow Pressure Strain}} \underbrace{+c_{2\theta}\bar{a}_k\frac{\partial \bar{\tilde{u}}_i}{\partial x_k}}_{\text{Rapid Pressure Strain}} \underbrace{-c_{3\theta}\frac{\bar{\varepsilon}}{\bar{e}}\bar{a}_i\ f(h)}_{\text{Wall Effects}}$$

CBL Results

Turbulence occurs at various scales in the CBL. Small-scale turbulence dominates in the surface layer, while large thermals play a key role in the mixed layer.

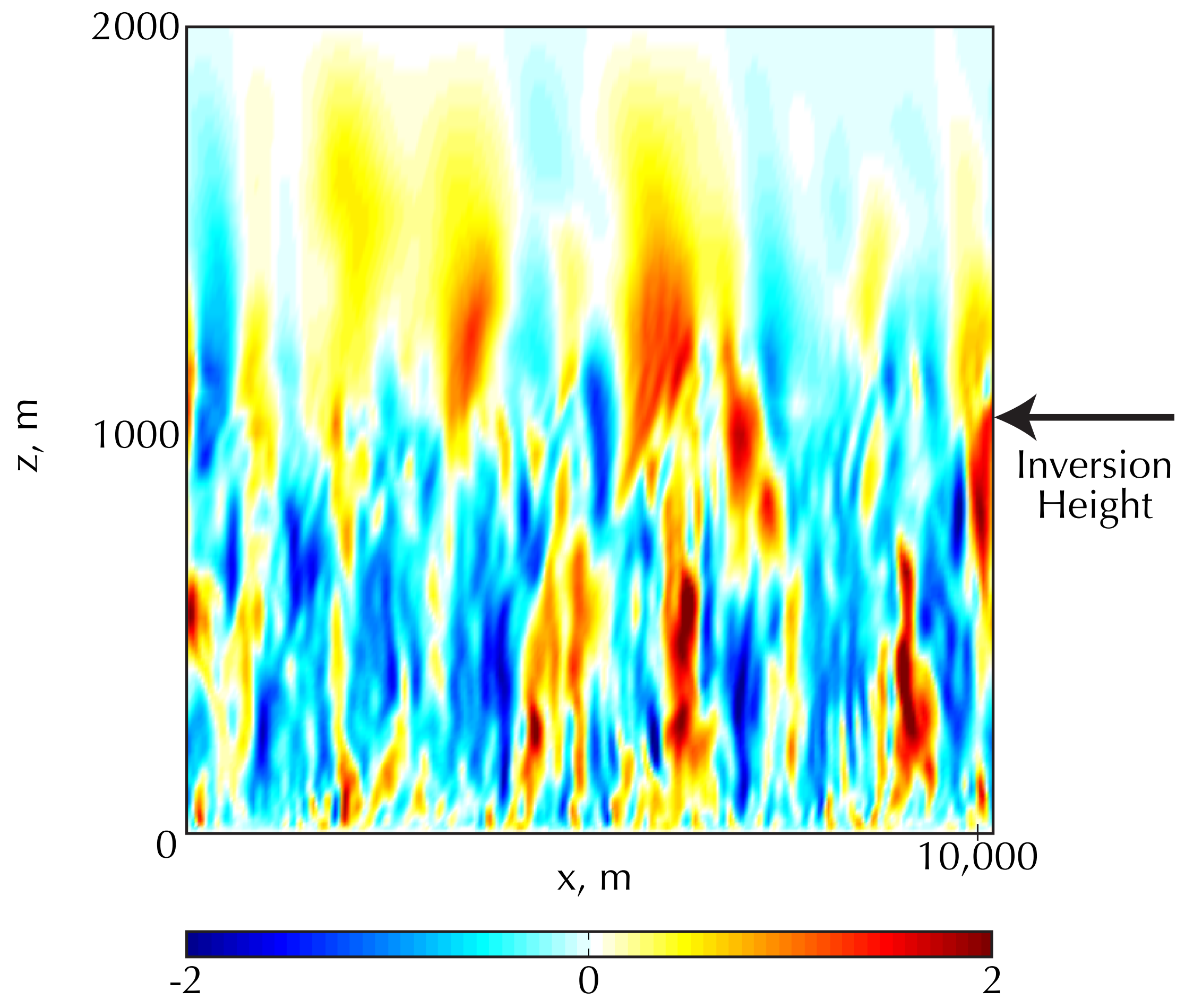


Figure 1. Instantaneous resolved vertical velocity x-z slice at 10,000 s. The varied length scales can be seen, from meters by the surface to hundreds of meters near and above the inversion.

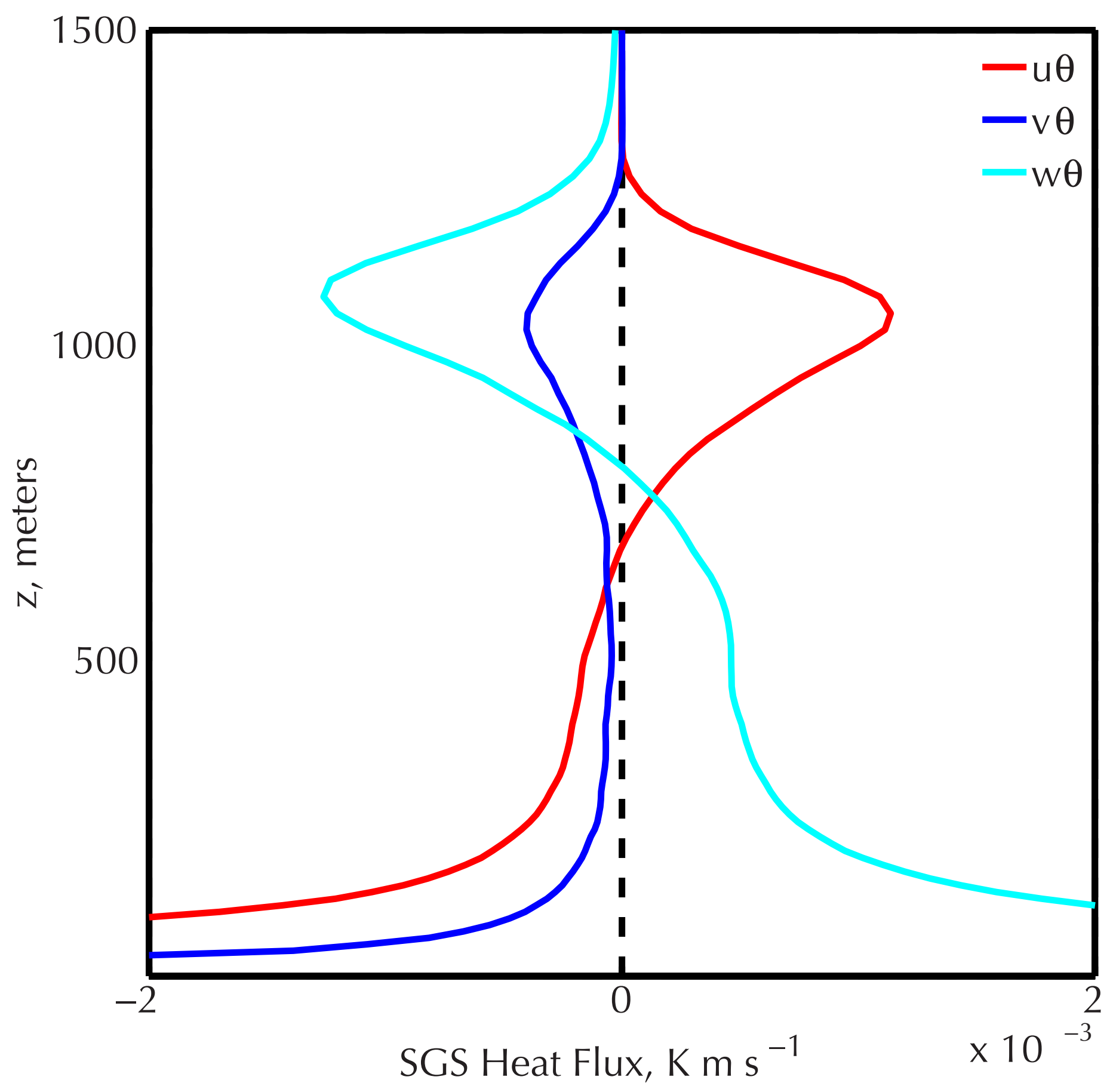


Figure 2. As a consequence of the SGS stress coupling, the SGS heat fluxes (at 10,000 s) are not, in general, aligned with the resolved scalar gradient.

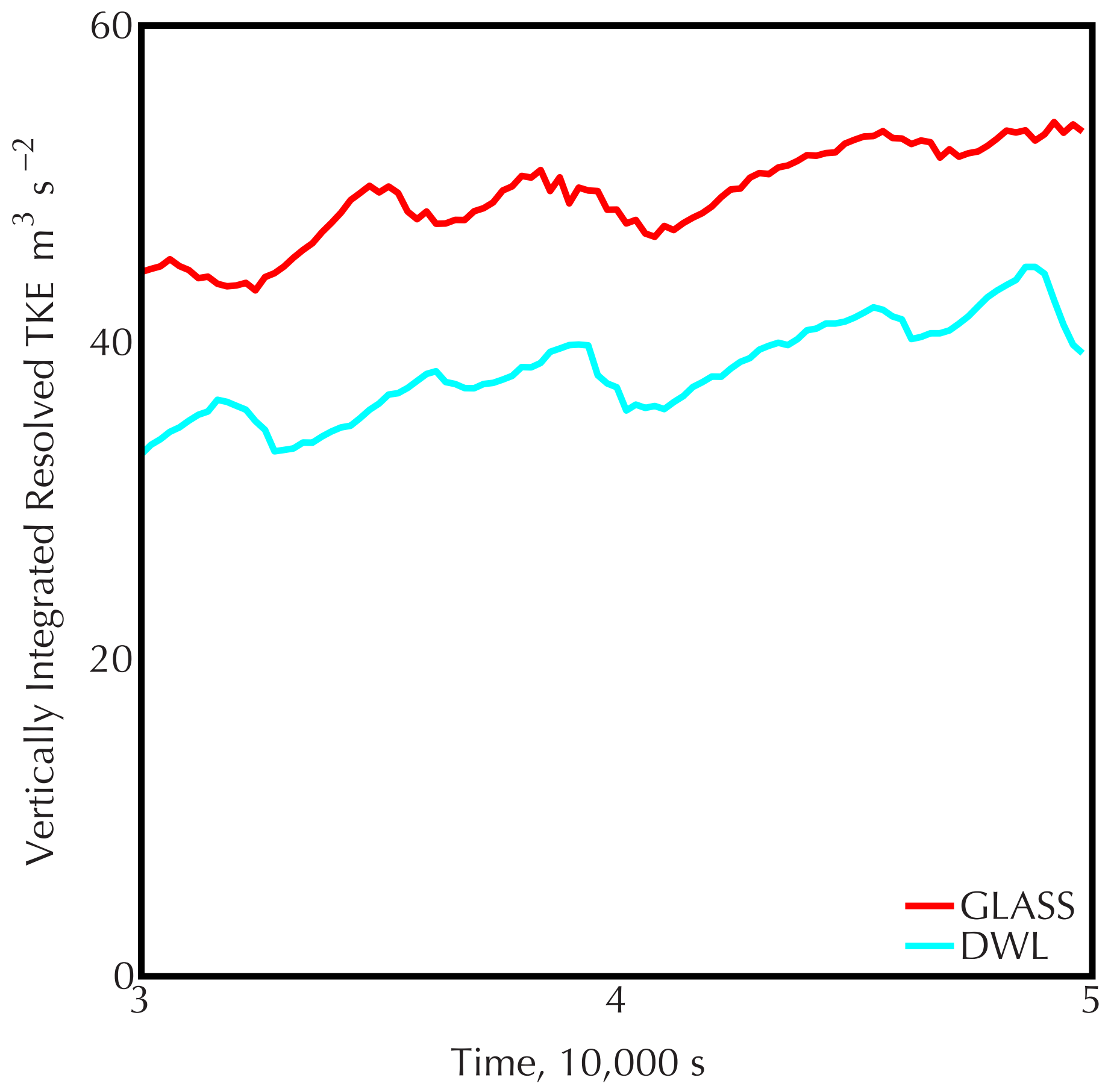
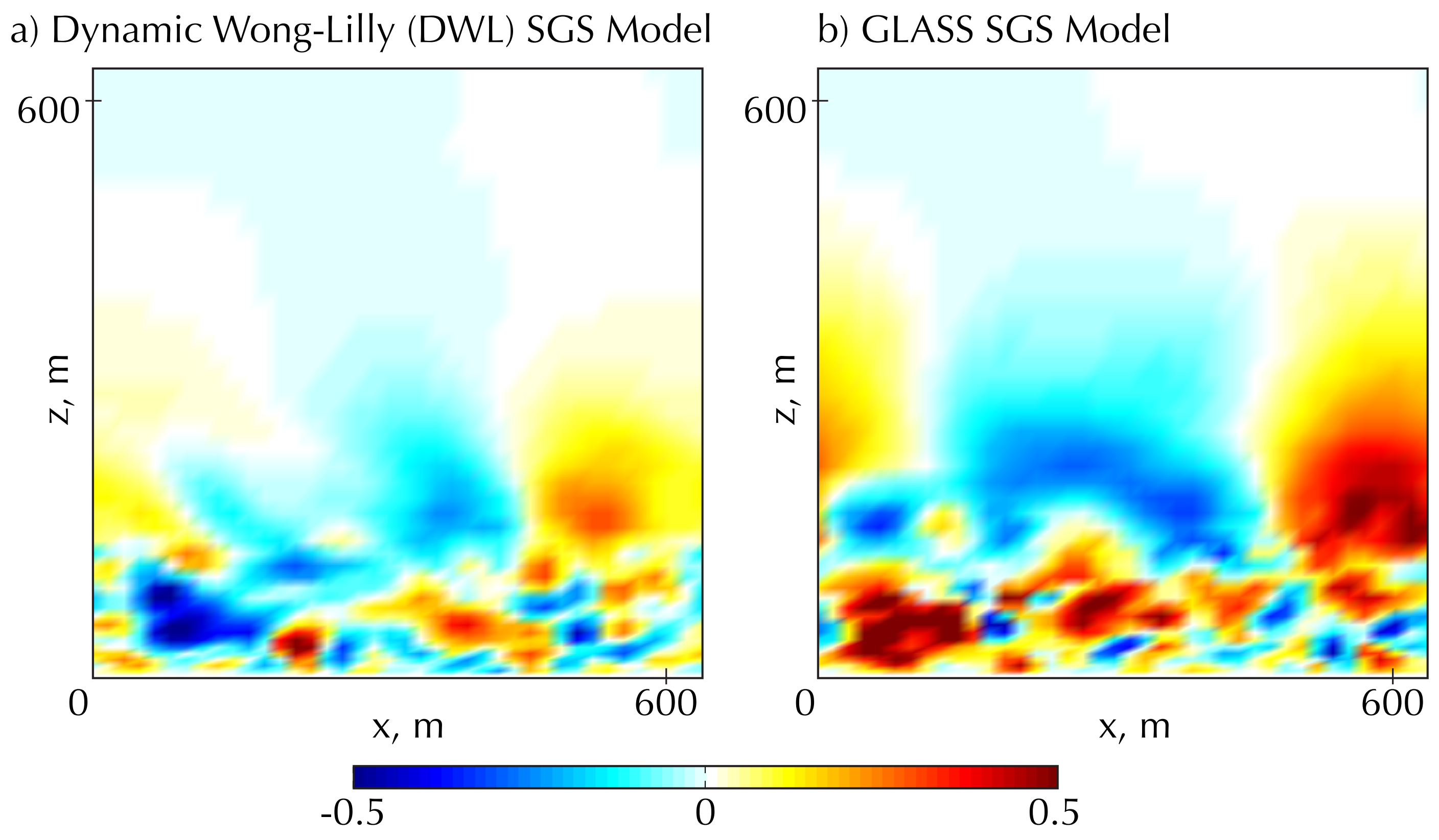


Figure 3. GLASS and Dynamic Wong-Lilly (DWL) simulations maintain a high level of vertically integrated SGS turbulent kinetic energy.

SBL Results

The SBL is typically thinner and less diffusive than the CBL. Turbulence in this regime is a delicate dynamical balance, and different SGS parameterizations can produce varying results.


a) Dynamic Wong-Lilly (DWL) SGS Model

b) GLASS SGS Model

Figure 4. Instantaneous resolved vertical velocity x-z slices of two different SGS turbulence models at 50,000 s. Both models show that the SBL has a narrower range of resolved vertical velocities and scales than the CBL. Smaller scale motions are observed at lower elevations. A low-level jet is produced ~ 200 m. Velocity profiles (not shown) reveal that the DWL predicts this jet at a slightly lower elevation than GLASS.

Conclusions

The CBL and SBL simulations demonstrate that GLASS can 1) perform at different stability regimes and 2) provide scalar and momentum flux anisotropies. Notably, GLASS overcomes the need to alter model coefficients for different positions in the flow, grid/filter aspect ratios, and atmospheric stabilities, etc. Future work includes adding the buoyancy production term for two-way coupling and simulating a diurnal cycle to study the transitions from one stability case to another.

References

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