1: Department of Meteorology, University of Reading | 2: Department of Mathematics, University of Exeter

University of Reading

A dynamic extension of the pragmatic blending scheme for scale-dependent sub-grid turbulent mixing in the boundary layer grey zone

Robert S. Plant[1] | George A. Efstathiou[2]

Overview

One approach to parameterized turbulent mixing in the boundary-layer grey zone is to blend between schemes for a mesoscale-model and a Smagorinsky LES formulation. We extend the approach to use a scale-dependent dynamic Smagorinsky scheme. This improves the simulation of the transition from the shallow morning to the deep afternoon boundary layer by better controlling the spin-up of resolved turbulence.

Boundary-layer grey zone

Numerical weather prediction is moving towards the boundary-layer grey zone where turbulence is neither fully parameterized or fully resolved (Fig. 1).

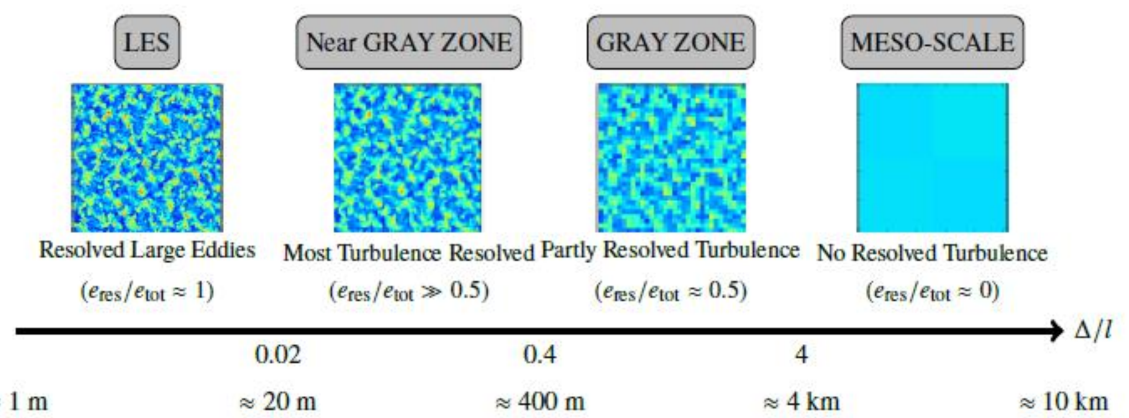

Figure 1. Example of a horizontal cross-section of vertical velocity in LES of the convective boundary layer, and coarse-grained onto larger scales (Honnert et al 2019).

Traditional NWP parameterizes all turbulence whereas LES parameterizes only the small scales. One approach in the grey zone (Boutle et al, 2014), as used operationally at the UK Met Office, is to blend between its NWP scheme and the Smagorinsky LES scheme.

An attractive approach for the near-grey zone is the dynamic Smagorinsky model. This is an LES approach where the mixing length is calculated by filtering the simulated flow field rather than being prescribed. We use a Lagrangian-averaged scale-dependent scheme (Bou Zeid et al 2005) which considers two filter scales.

Simulations in near-grey zone

Simulations of the evolving convective boundary layer are run with the Met Office LEM for the Wangara day 33 case. A reference LES is run at Δx =25m with Smagorinsky mixing.

Good results were also obtained using Smagorinsky at somewhat coarser resolutions but excessive diffusion and a delayed onset of resolved turbulence leads to errors in the mean temperature profile beyond $\Delta x \sim 100$m. The dynamic model is able to reproduce well the mean fields and the statistics of the filtered LES fields across the near-grey zone.

It achieves this by varying the Smagoririnsky coefficient C_S (Fig. 2). However, this has a usability limit in the grey zone, with difficulties at $\Delta x \sim 400$m when it does not produce sufficient mixing especially when the boundary layer is shallow.

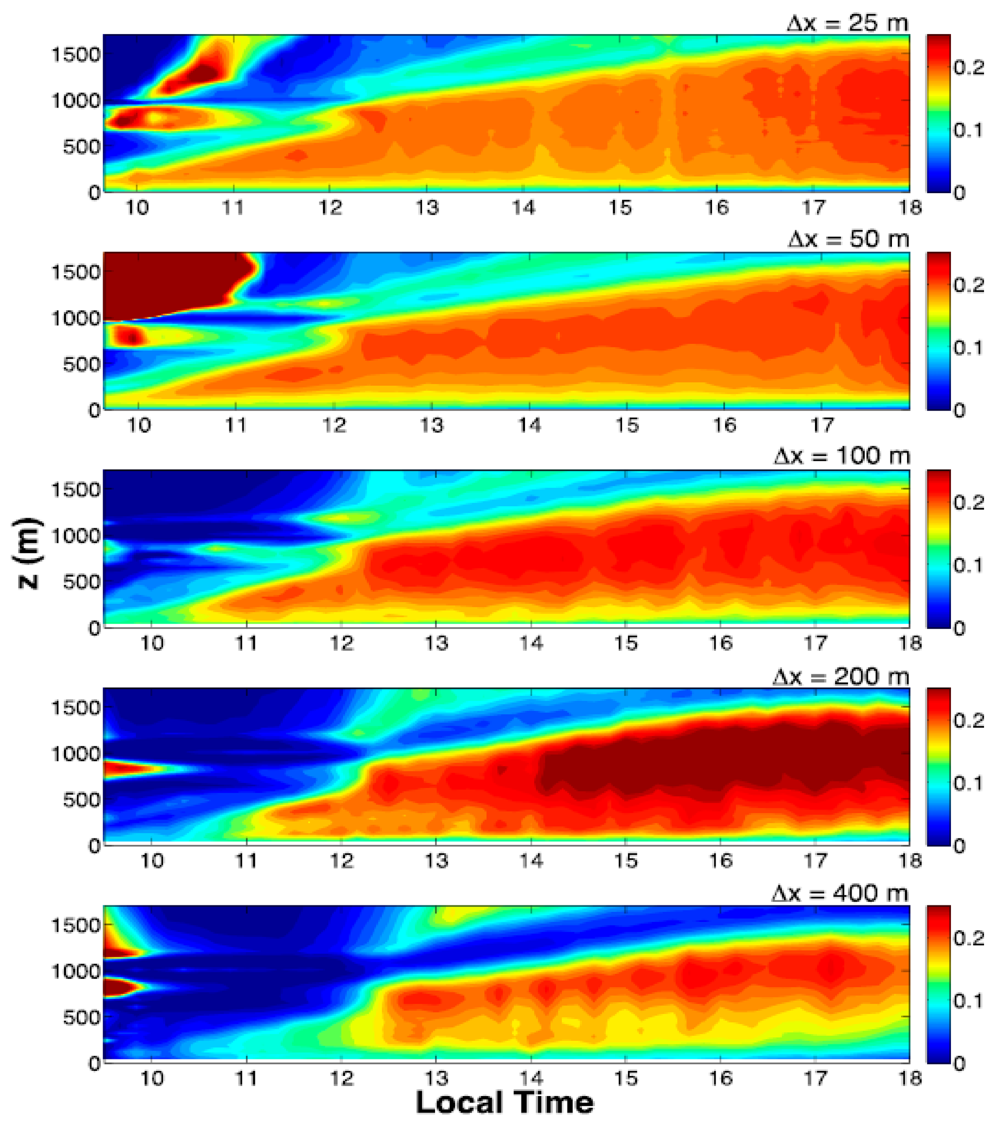

Figure 2. Variation of Cs in simulations with the dynamic Smagorinsky scheme, ranging from LES (top) through the near-grey zone (centre) and into the grey zone proper (bottom).

Blending scheme

The sub-grid sensible heat flux has local and weighted non-local contributions (based on Hong et al 2006)

$$\overline{u_j'\theta'} = -K_H \frac{\partial \bar{\theta}}{\partial x_j} + \delta_{3j} W \left(K_H \gamma + \overline{w'\theta'}|_{z_h} \left(\frac{z}{z_h}\right)^3 \right)$$

while momentum fluxes are treated locally:

$$\overline{u_i'u_j'} = -K_M \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)$$

The blending function is:

$$W = 1 - \tanh\left(b \frac{z_h}{\Delta x}\right) \max\left(0, 1 - \frac{\Delta x}{4 z_h}\right) \text{ with } b = 0.15$$

The eddy diffusivities K_H and K_M compare a weighted NWP profile from Lock (2000) and a Smagorinksy formulation with a blended mixing length

$$K_{M,H} = \max\left(W K_{M,H(NWP)}, l_{BLEND}^2 S f_{M,H}(Ri)\right)$$

$$l_{BLEND} = W l_{NWP} + (1 - W) l_{SMAG}$$

where l_{NWP} is from Lock (2000) and $l_{SMAG} = C_S \Delta x$ away from the surface. When blending with the dynamic model, $C_s = 0.23$ is no longer a constant but is computed, and there is no need to impose a wall damping.

Simulations in the grey zone

We focus on grey-zone simulations with $\Delta x = 400$m, using blending with either standard (PGB) or dynamic (DNB) Smagorinsky.

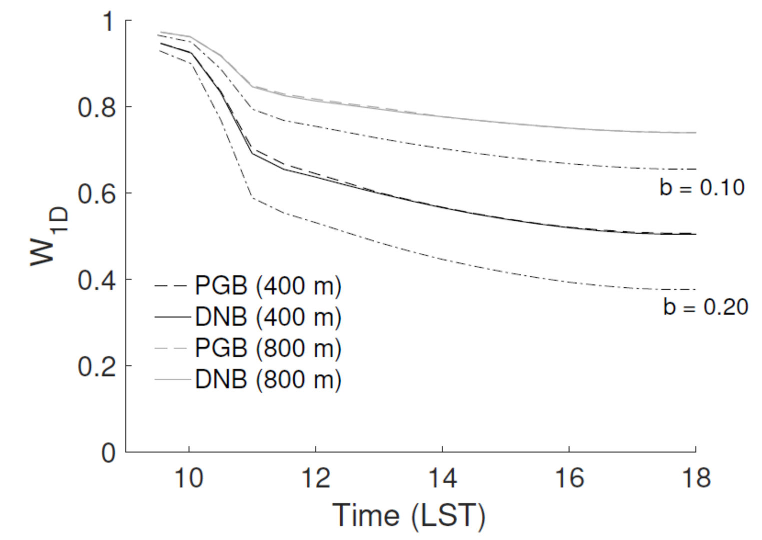

Figure 3. Time evolution of the weighting function W.

At early times, $W \approx 1$ and the NWP scheme captures the temperature profile well with little resolved motion. By 1140 both of the blended parts of the scheme become important. Using standard Smagorinsky, there is a delayed onset of resolved turbulence (Fig 4), despite the reduction in the NWP part of the eddy diffusion (Figs. 3,5) leading to a temperature profile that is slightly superadiabatic throughout the BL. There is insufficient non-local mixing at this time.

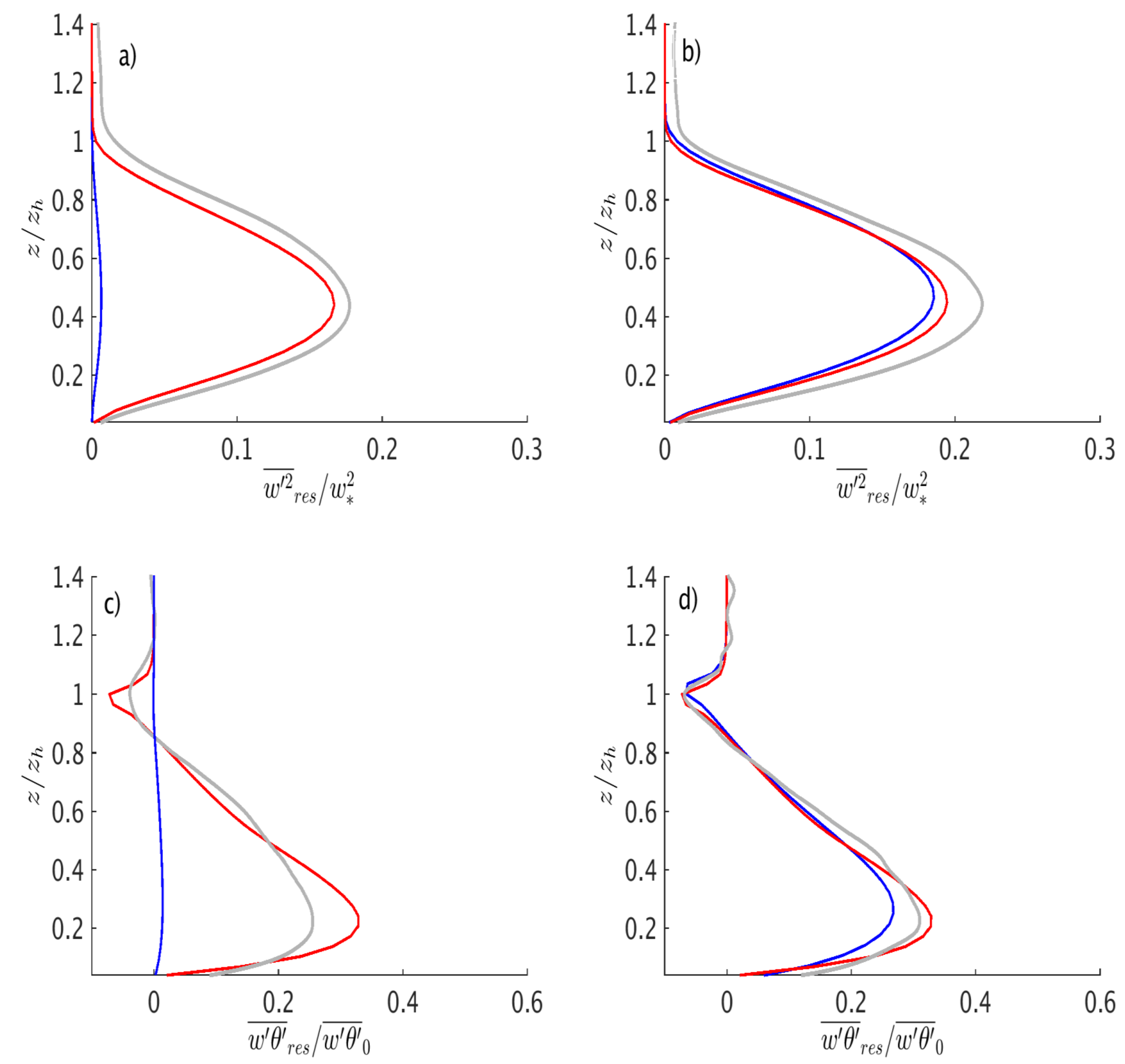

Figure 4. Normalized profiles of the resolved (a,b) vertical velocity variance and (c,d) turbulent heat flux in the 400m simulation with PGB (blue) and DNB (red). (a,c) at 1140 and (b,d) at 1240. The coarse-grained LES profiles is in grey,

Using the dynamic model, however, the boundary layer is well mixed and an appropriate level of resolved turbulence is enabled. The key point is that it produces significantly less mixing in the lower BL (Fig. 5a) from the Smagorinksy contribution (Fig. 5b). By 1240, explicit turbulence has developed in PGB producing a non-local heat flux that does produce a well-mixed BL with appropriate turbulent statistics.

For simulations with $\Delta x = 800$m, similar results occur but with turbulence initiated around 1 hr later.

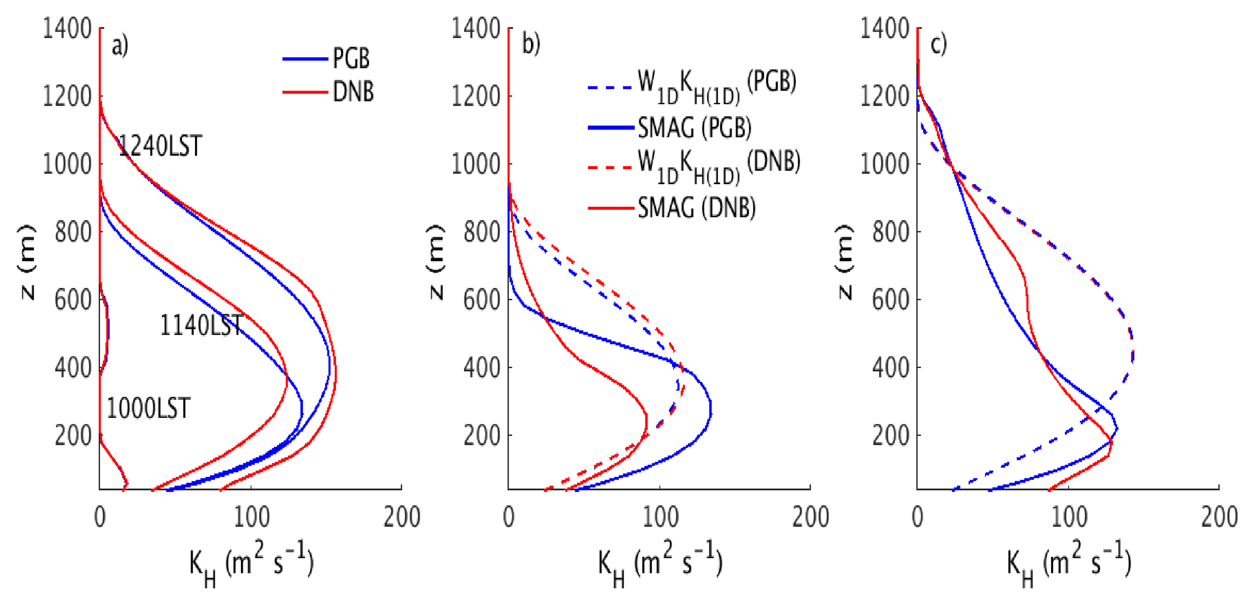

Figure 5. Profiles of the eddy diffusion K_H using PGB (blue) or DNB (red) for (a) three different times and (b,c) decomposed into NWP (dashed) and Smagorinksy (solid) contributions at (b) 1140 and (c) 1240.

Conclusions

- A new blending approach has been demonstrated for the turbulent grey zone, using a scale-dependent dynamic Smagorinsky model.
- There is little difference when the blending function is strongly weighted to the NWP scheme
- The dynamic approach improves mean profiles and turbulence statistics during handover from an NWP to a LES treatment.
- The main advantage is an earlier onset of resolved turbulence.
- The dynamic approach also alleviates the need for a specified functional form of the Smagorinsky mixing length or for well-chosen C_S.

References

1. I. A. Boutle *et al* (2014) Seamless stratocumulus simulation across the turbulent gray zone. Mon. Wea. Rev., **142**, 1655–1668.
2. E. Bou-Zeid *et al* (2005) A scale-dependent Lagrangian dynamic model for large-eddy simulation of complex turbulent flows. Physics of Fluids, **17**.
3. R. Honnert *et al* (2019). The atmospheric boundary layer and the "gray zone" of turbulence. Submitted to: Rev. Geophys.
4. S. Y. Hong *et al* (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. Mon. Wea. Rev., **134**, 2318–2341.
5. A. P. Lock *et al* (2000) A new boundary layer mixing scheme. Part I: scheme description and single-column model tests. Mon. Wea. Rev., **128**, 3187–3199.

Acknowledgements

This work has been funded by the NERC GREYBLS (Modelling Grey Zone Boundary Layers) project. We acknowledge use of Monsoon2 for high-performance computing.

Contact information

- Department of Meteorology University of Reading, RG6 6BB
- Email: **r.s.plant@reading.ac.uk**
- **www.met.reading.ac.uk/~sws00rsp/home**