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A Comparison of LES Sub-grid Turbulence Models at Different Grid Resolutions in a Convective BL

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Objectives

Coarse-grid Large-eddy simulations (LES) ($\Delta x > \sim 100$ m) and high-resolution mesoscale simulations ($\Delta x < \sim 1$ km) are both characterised by partially-resolved turbulence. Hence, in this regime the sub-grid model matters more than in well-resolved LES. This work explores the following questions:

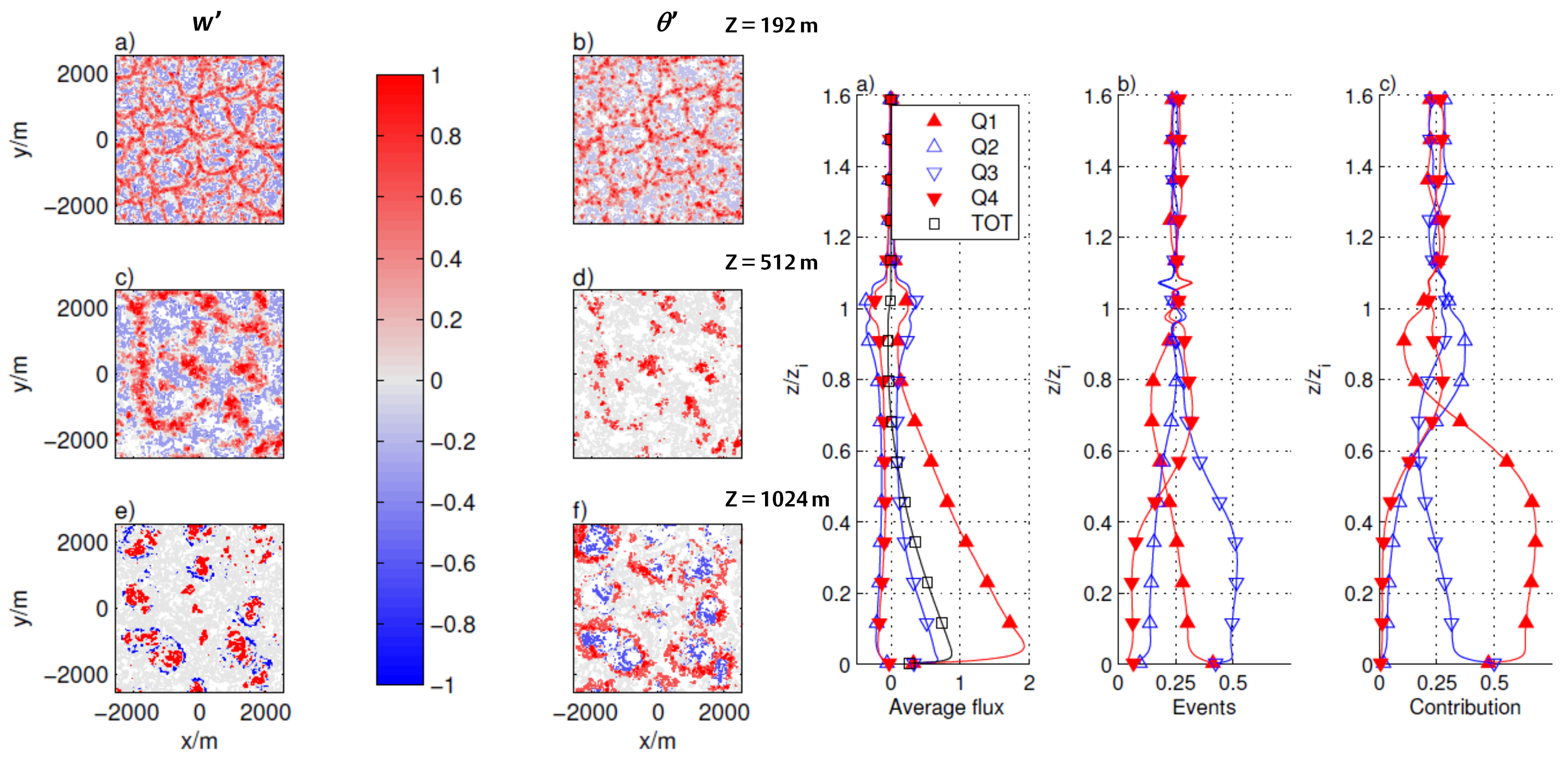
- **As the resolution of LES is coarsened, at what point does it start to matter what sub-grid model is used?**
- **What goes wrong as the resolution is degraded?**
- **Can this be fixed, e.g. with a better choice for the sub-grid model?**

High-resolution LES of a convective BL

Simulations using the UK Met Office LEM (MetLEM) with Smagorinsky sub-grid model.

Setup 1: Weak heat flux 30 Wm^{-2}; No mean wind;
Domain size 5120 m x 5120 m x 2048 m; Resolution $\Delta x = \Delta y = 10$ m, $\Delta z = 4$ m.

Setup 2: Strong heat flux 241 Wm^{-2}; Weak geostrophic wind $U_g = 1$ ms^{-1};
Domain size 9600 m x 9600 m x 2000 m; Resolution $\Delta x = \Delta y = 25$ m, $\Delta z = 10$ m.



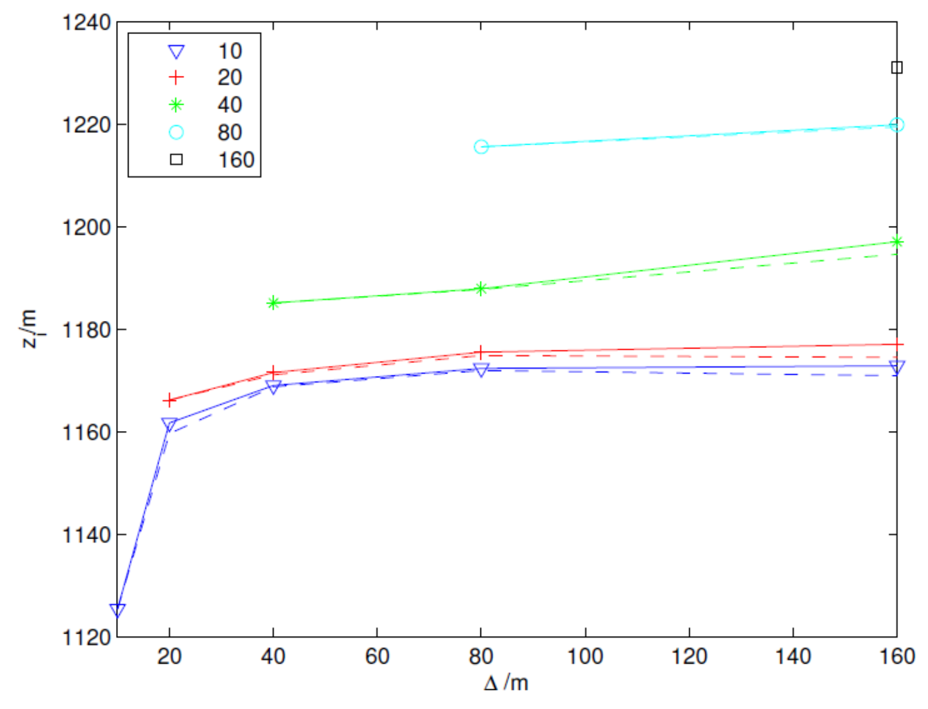
Instantaneous fields (left panel) and quadrant contributions to heat flux (right panel) for weak heat flux case (setup 1)

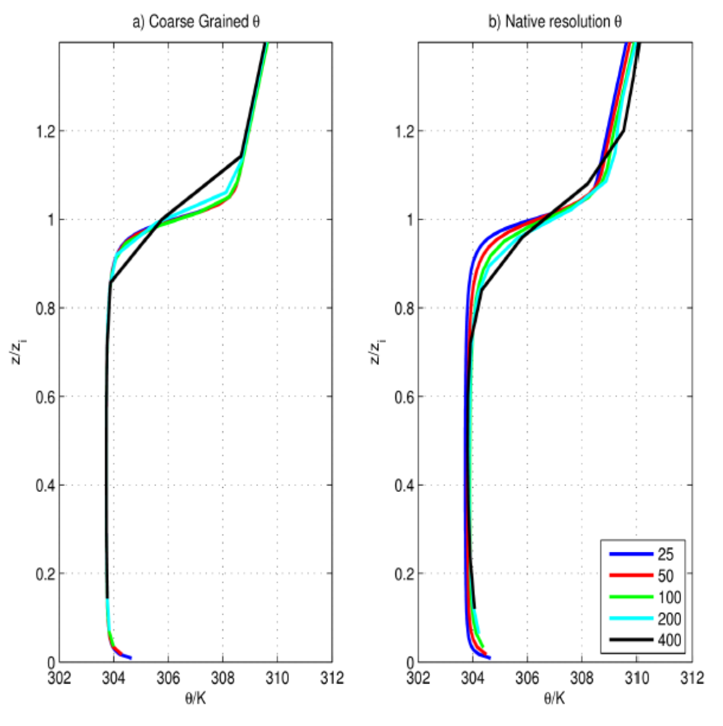
Left panel: Thermals rise and merge into larger structures; Temperature perturbations decrease due to mixing; Close to BL height θ′ coincides with positive w′, i.e. cooler air continues to rise due to residual momentum.

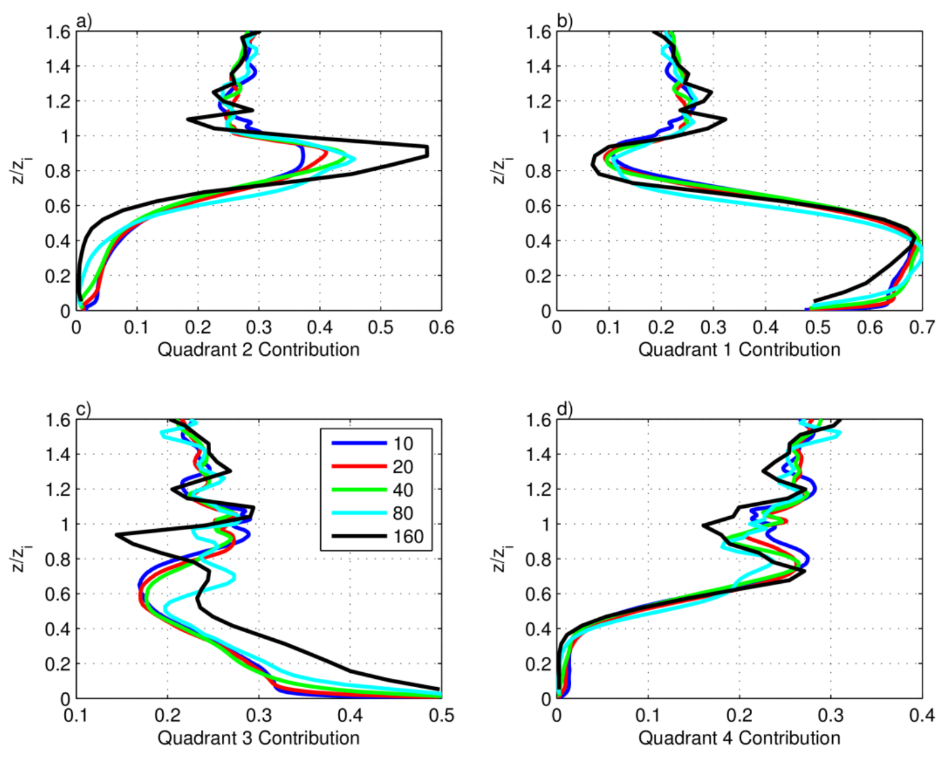
Right panel: More Q3 events but Q1 contributes more to heat flux; Thermals rise , mix with environment, get colder – hence Q1 can become Q2 as they rise; More Q4 events near inversion – due to entrainment; Q4 events turn into Q3.

Resolution-dependence

Lower resolution runs, Setup 1: $\Delta x = \Delta y = 20$ m, 40 m, 80 m, 160 m, $\Delta z = 0.4\Delta x$
Setup 2 : $\Delta x = \Delta y = 50$ m, 100 m, 200 m, 400 m, $\Delta z = 0.4\Delta x$







Lower resolutions give successively higher BL height, with a max difference of ~ 100 m. Coarse-graining gives higher values, but still short of native values, with a max difference of ~ 60 m.

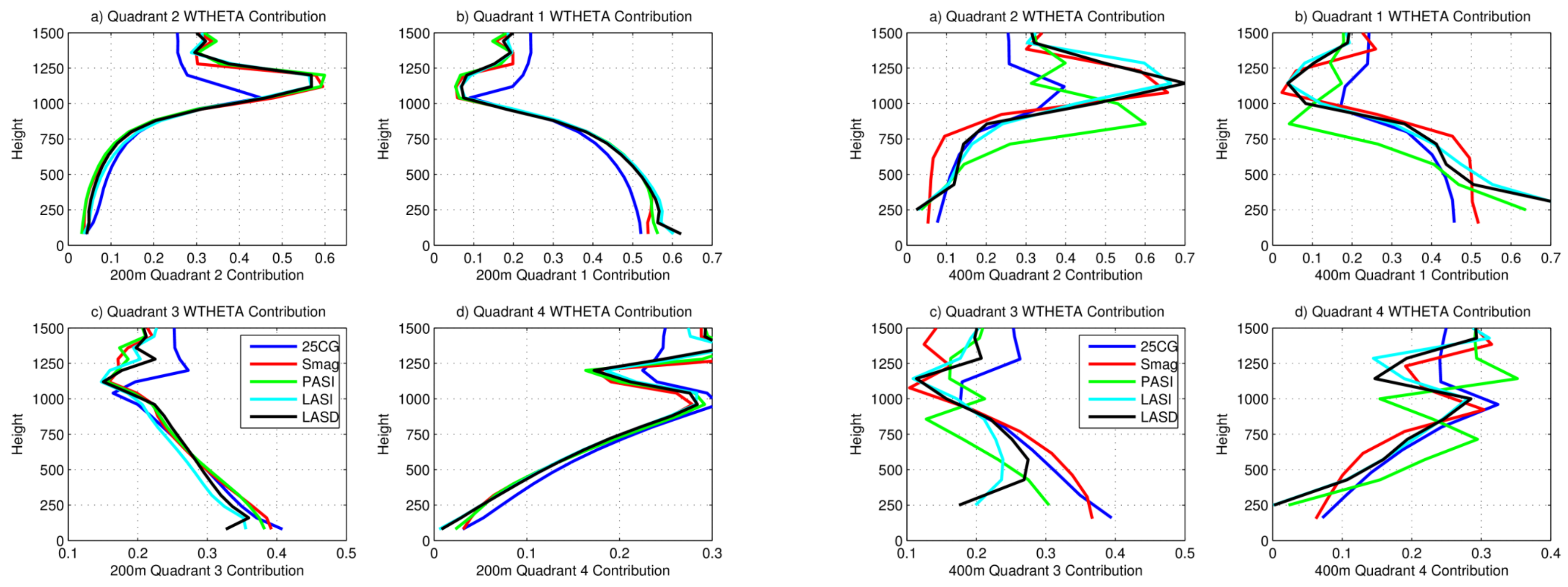
Lower resolution simulations give successively higher temperatures close to the surface and inversion layer.

At lower resolutions: Smaller Q1 contribution closer to surface; Smaller contribution from Q2 and larger from Q3 in lower BL; Larger contribution from Q2 in upper BL, due to less mixing and leading to higher BL; Smaller contribution from Q3 in upper BL.

Sub-grid model-dependence

Three variants of the dynamic model newly implemented in the MetLEM:

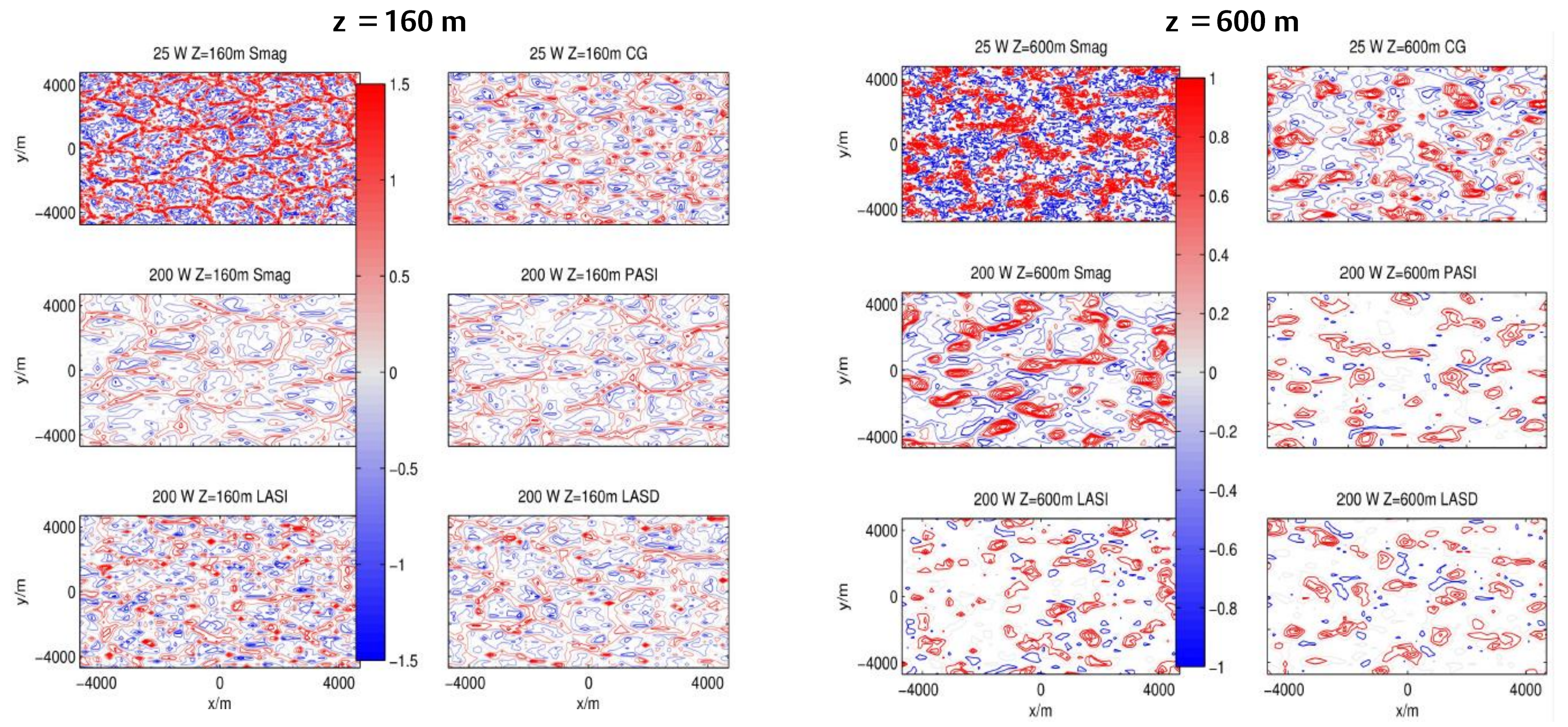
- Plane-averaged scale-invariant – PASI (Germano et al. 1991)
- Lagrangian-averaged scale-invariant – LASI (Meneveau et al. 1996)
- Lagrangian-averaged scale-dependent – LASD (Bou-Zeid et al. 2005)

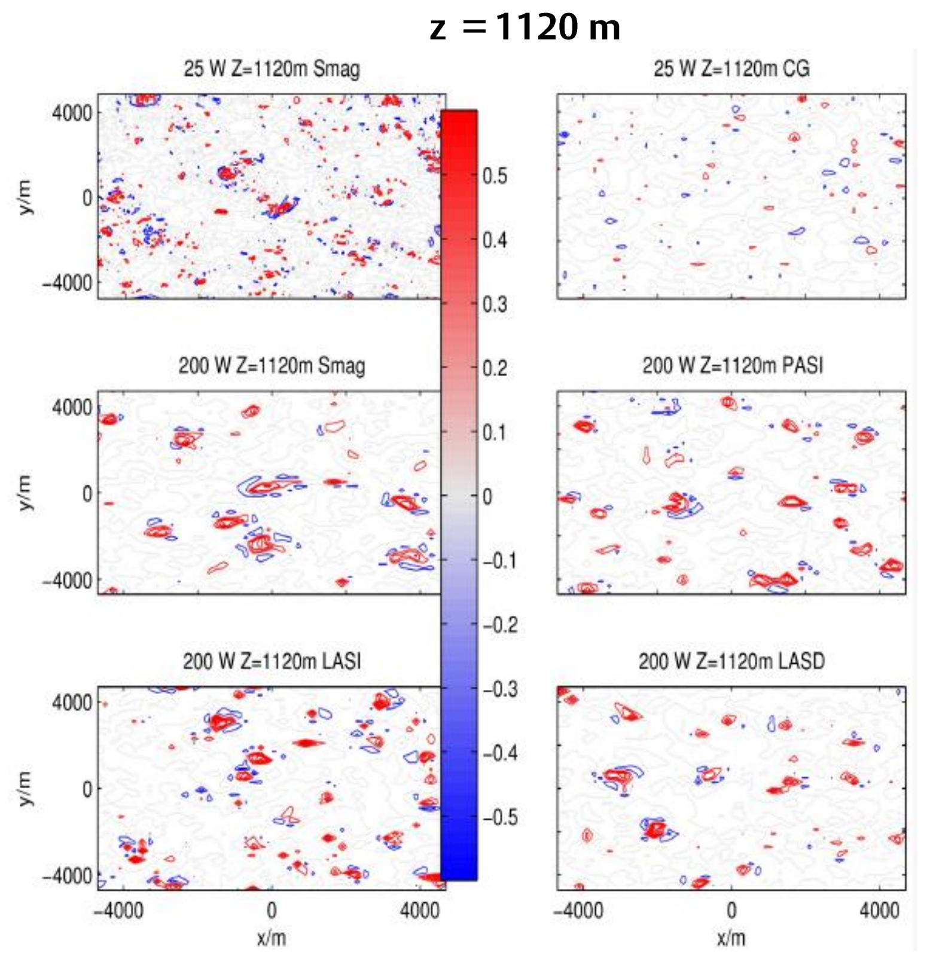


Quadrant contributions to heat flux for setup 2 for $\Delta x = 200$ m (left panel) and $\Delta x = 400$ m (right panel)

Differences between models appear from about $\Delta x = 200$ m and larger grid lengths.

Effect of sub-grid model on structures





Vertical velocity fields at different heights from simulations with different sub-grid models run at $\Delta x = 200$ m, compared with those from $\Delta x = 25$ m "truth run" coarse-grained to $\Delta x = 200$ m.

Close to the ground Lagrangian–averaged dynamic models seem to reproduce structures seen in higher-resolution runs slightly better.

In the middle of the boundary layer Smag looks slightly better.

Near the BL top all models have too strong w′. No improvement from Lagrangian dynamic models here.

Conclusions

- **Three variants of dynamic sub-grid model coded up in MetLEM; can be readily implemented in other codes.**
- **Compared with Smagorinsky model for convective BL simulations; sub-grid model makes a difference for a grid size of 200 m or larger.**
- **Dynamic models in general neither better nor worse than Smagorinsky for the convective cases considered; but improvements noticed for morning transition (work in progress).**

Acknowledgements

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