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

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Motivation and questions

- Coarse-grid LES (dx > ~100 m) and high-resolution NWP (dx < ~1 km) are both characterised by partially-resolved turbulence.

- Sub-grid model matters more than in well-resolved LES.

- As LES resolution 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 with a better choice for the sub-grid model?

LES: setups

- Convective BL simulations using the UK Met Office LEM (MetLEM)

- Setup 1: Weak heat flux of 30 Wm^{-2} ; No mean wind
  - Initial constant temp of 290.8 K up to 1 km, then stable stratification of 0.003 K/m
  - 1K amplitude perturbations, 2 hour simulations
  - Based on Brown et al. (1994) and Weinbrecht & Mason (2008)
  - Domain size: 5120 m x 5120 m x 2048 m
  - Highest resolution: $\Delta x = \Delta y = 10$ m, $\Delta z = 4$ m (512 x 512 x 512 grid points)
  - Lower resolution runs: : $\Delta x = \Delta y = 20$ m, 40 m, 80 m, 160 m, $\Delta z = 0.4\Delta x$

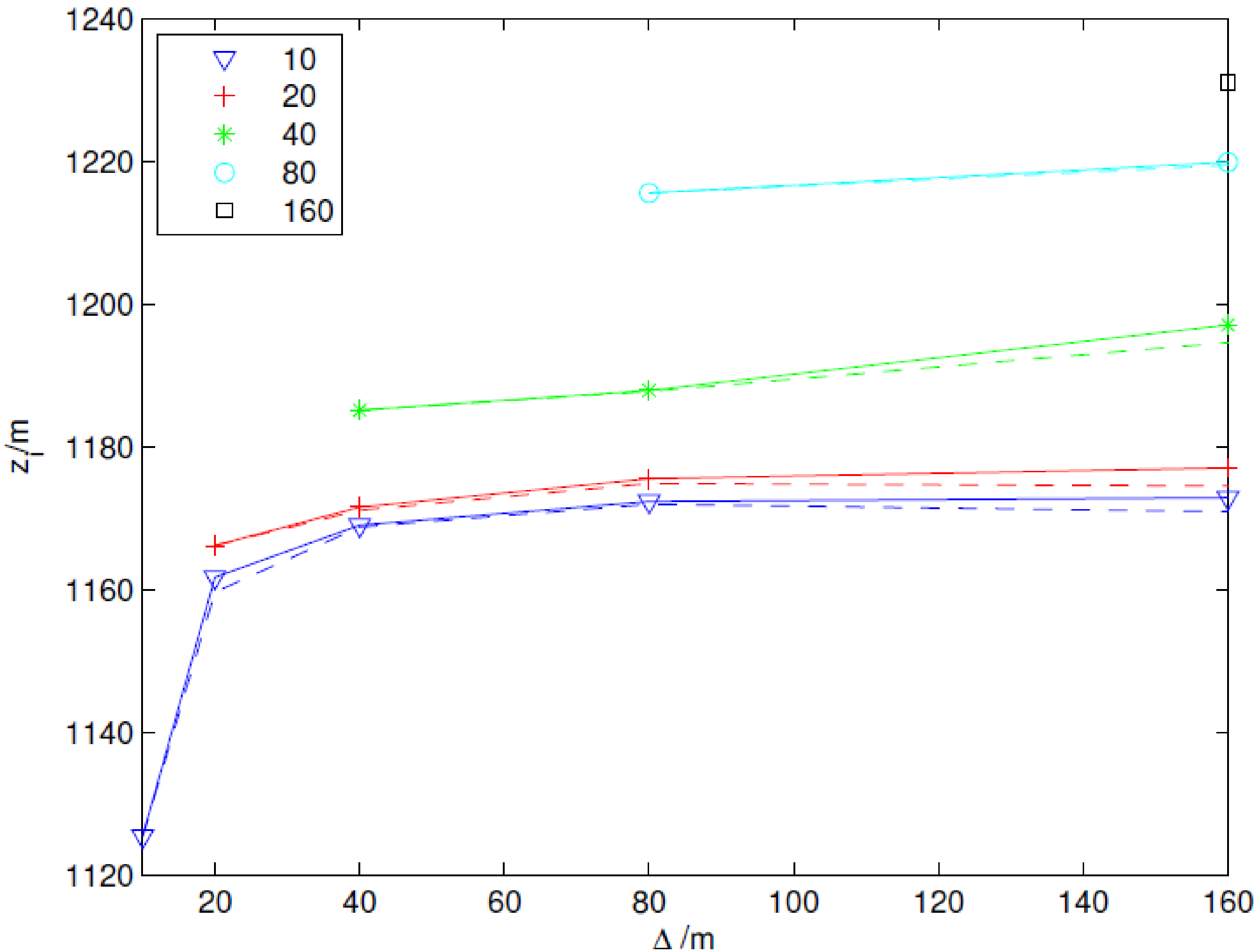
- Setup 2: Strong heat flux of 241 Wm^{-2}; Weak geostrophic wind $U_g = 1$ m/s
  - Initial constant temp of 300 K up to 1 km, then sharp jump of 8 K over 100 m near BL top
  - 1K amplitude perturbations, 4 hour simulations
  - Based on Sullivan & Patton (2011)
  - Domain size: 9600 m x 9600 m x 2000 m
  - Highest resolution: $\Delta x = \Delta y = 25$ m, $\Delta z = 10$ m (384 x 384 x 200 grid points)
  - Lower resolution runs: : $\Delta x = \Delta y = 50$ m, 100 m, 200 m, 400 m, $\Delta z = 0.4\Delta x$

LES: subgrid models

- Smagorinsky-Lilly as implemented in MetLEM
  - With Cs = 0.23
  - With different values of Cs
  - With stochastic backscatter

- Several 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)

Boundary layer height – weak flux



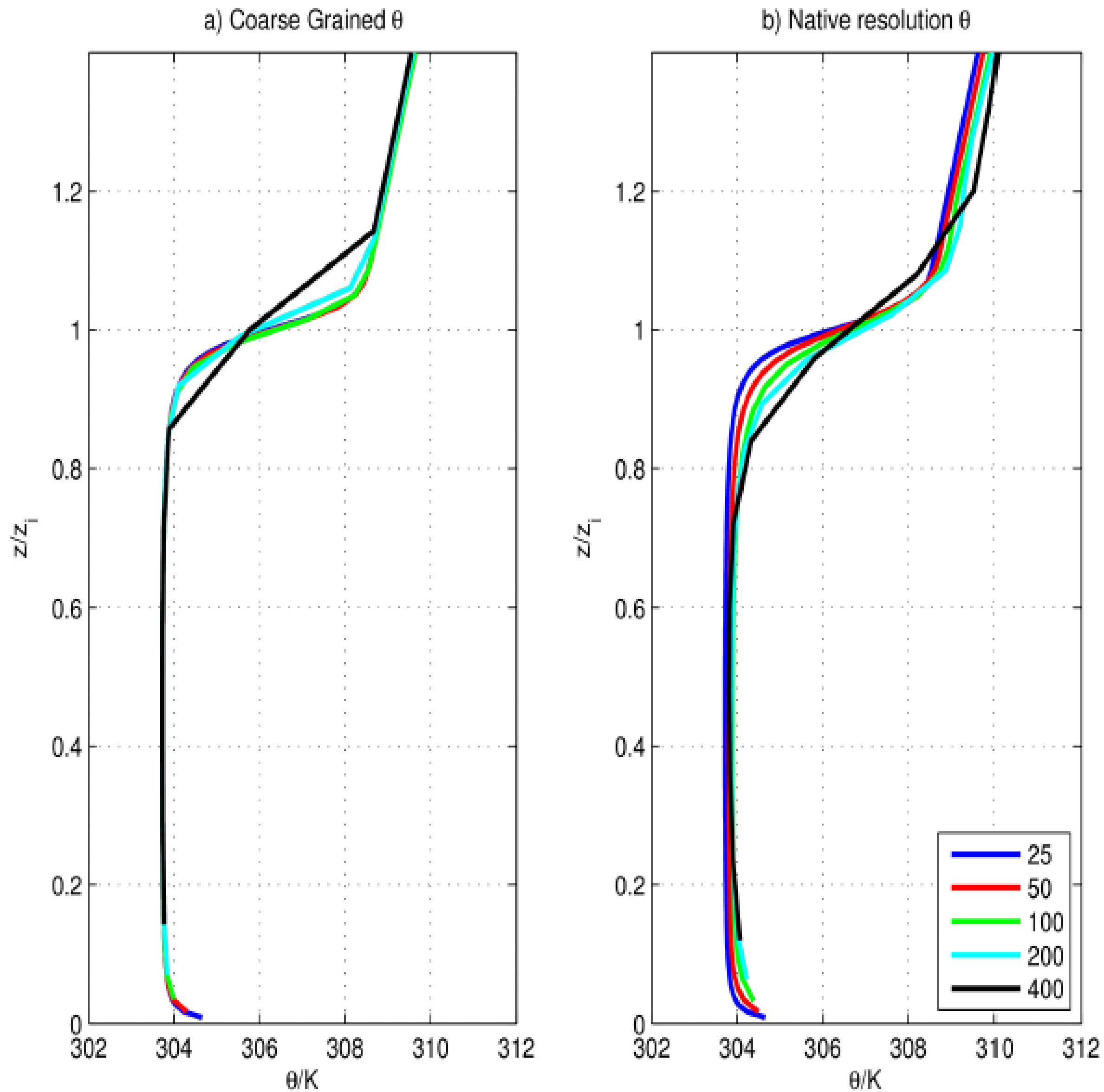
BL height diagnosed using gradient method

Lower resolutions give successively higher BL height – max difference of ~ 100 m

Coarse-graining gives higher values, but still short of native values – max difference of ~ 60 m

Only for 10m – 20m does coarse-graining account for most of the difference

Potential temperature profile – strong flux

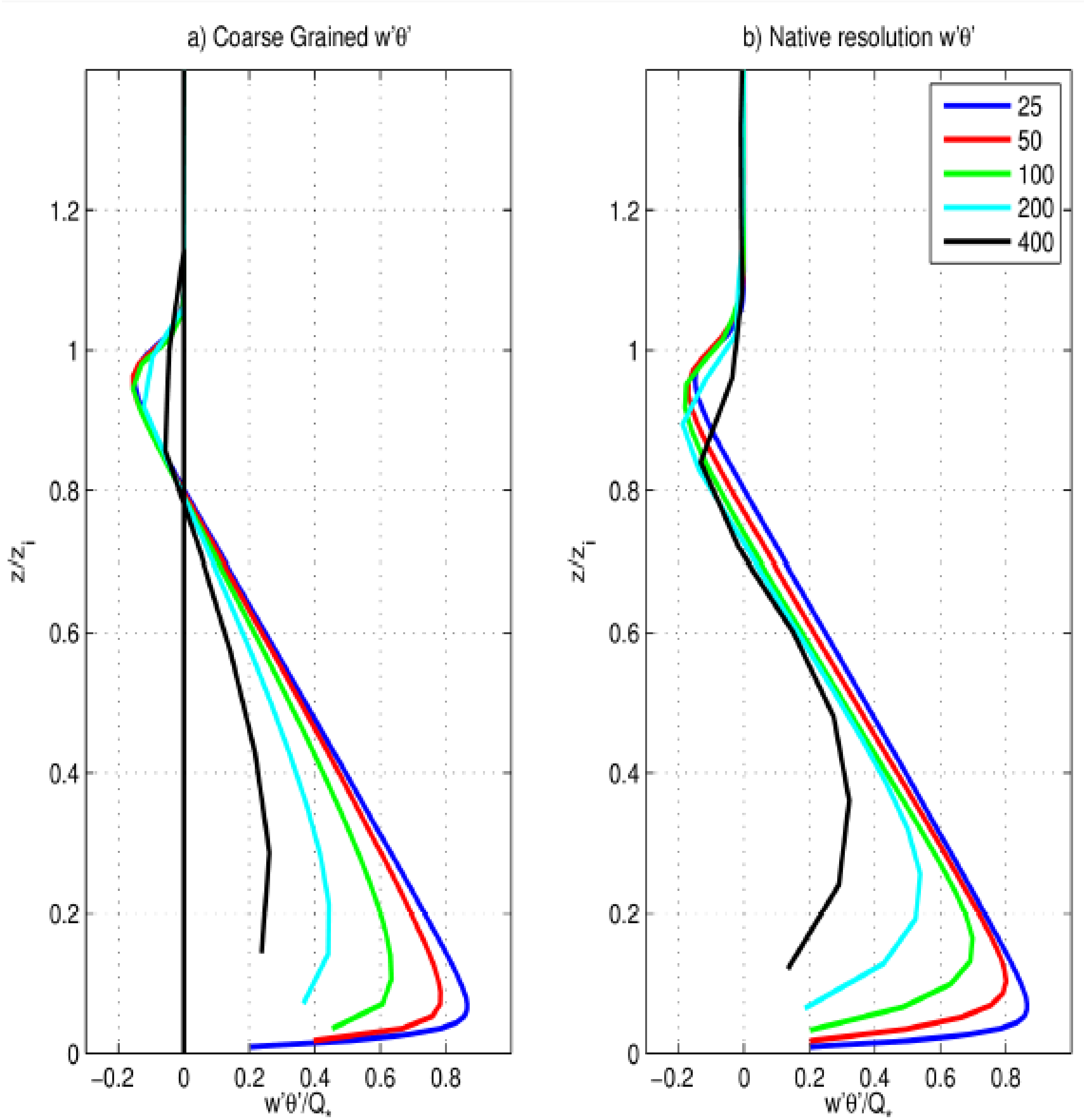


Typical convective BL potential temperature profile

Native resolution simulations warmer close to the surface and inversion layer

Low resolution runs show higher temperature at z = zi

Resolved heat flux profile – strong flux



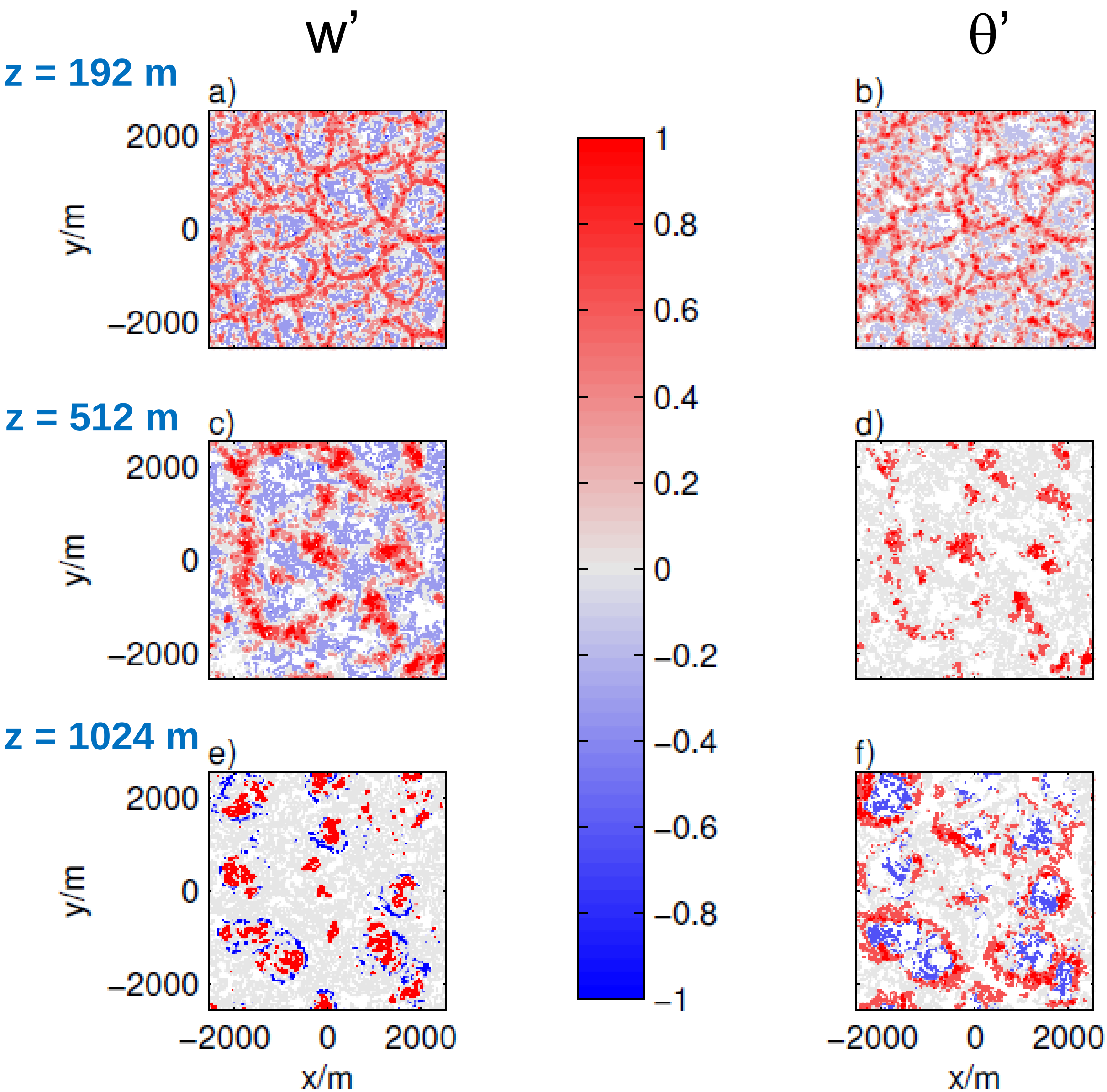
Decrease with height to a minimum

Negative region = entrainment zone

Minimum is lower at lower resolutions

CG data is more converged below zi

Structures: weak flux, dx = 10 m



Structures from "truth run"

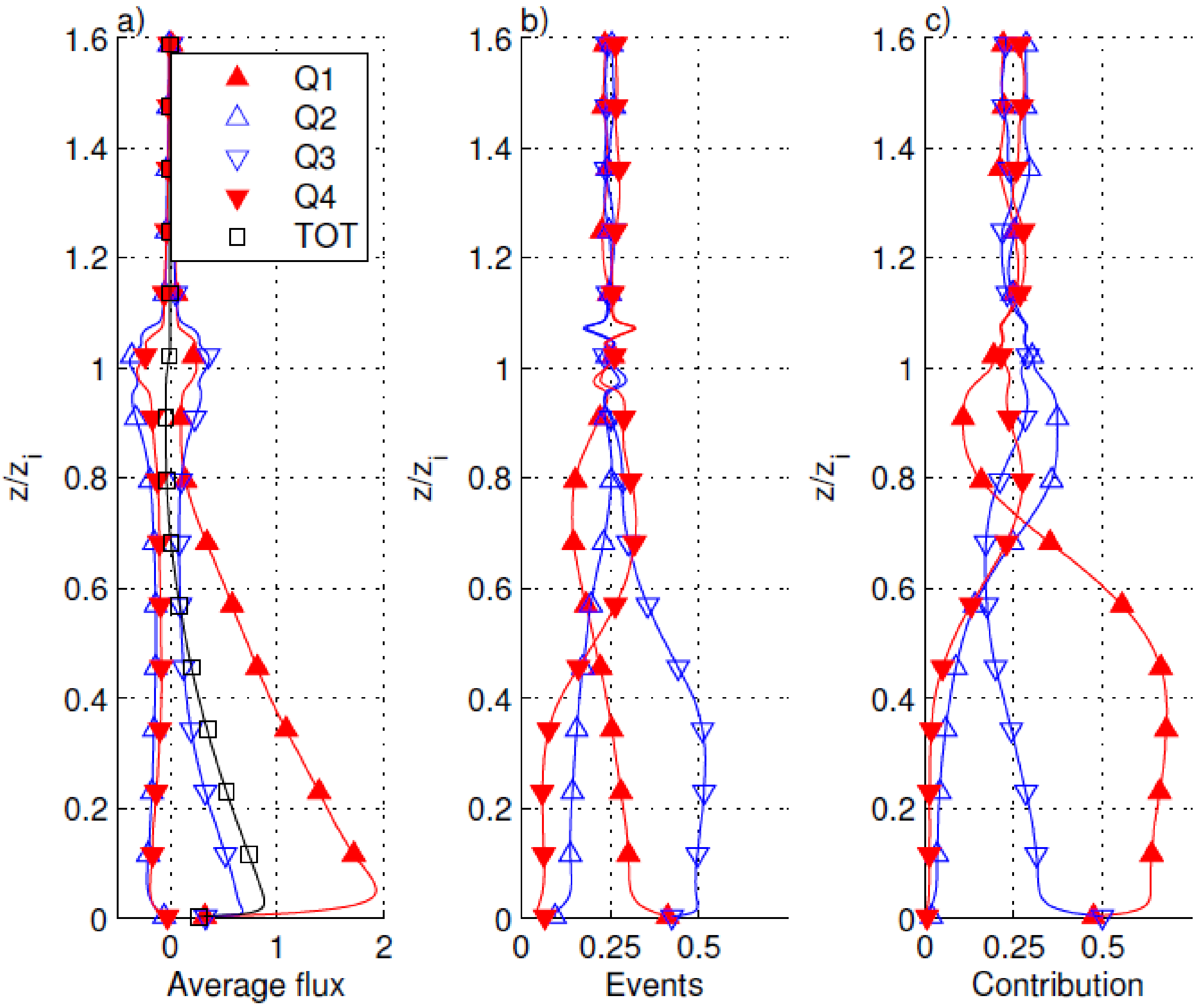
Thermals rise and merge into larger structures

Temperature perturbation decreases due to mixing

Closer to BL height, negative θ' coincide with positive w'

i.e. cooler air continues to rise due to residual momentum

Quadrant analysis: weak flux, dx = 10 m



More Q3 events but Q1 contributes more

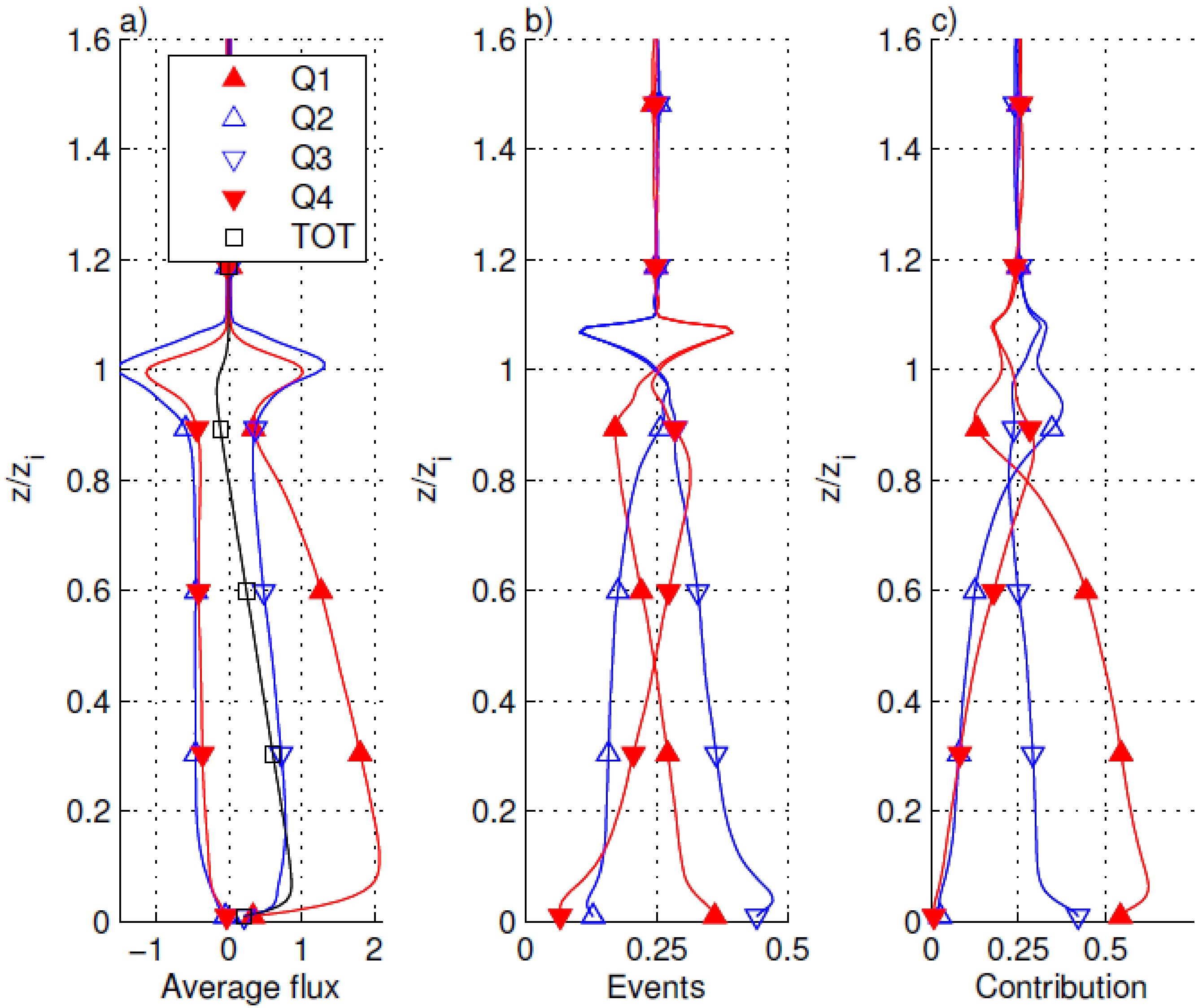
Thermals rise, mix with environment, get colder

Hence, Q1 can become Q2 as they rise

More Q4 events close to inversion layer – due to entrainment

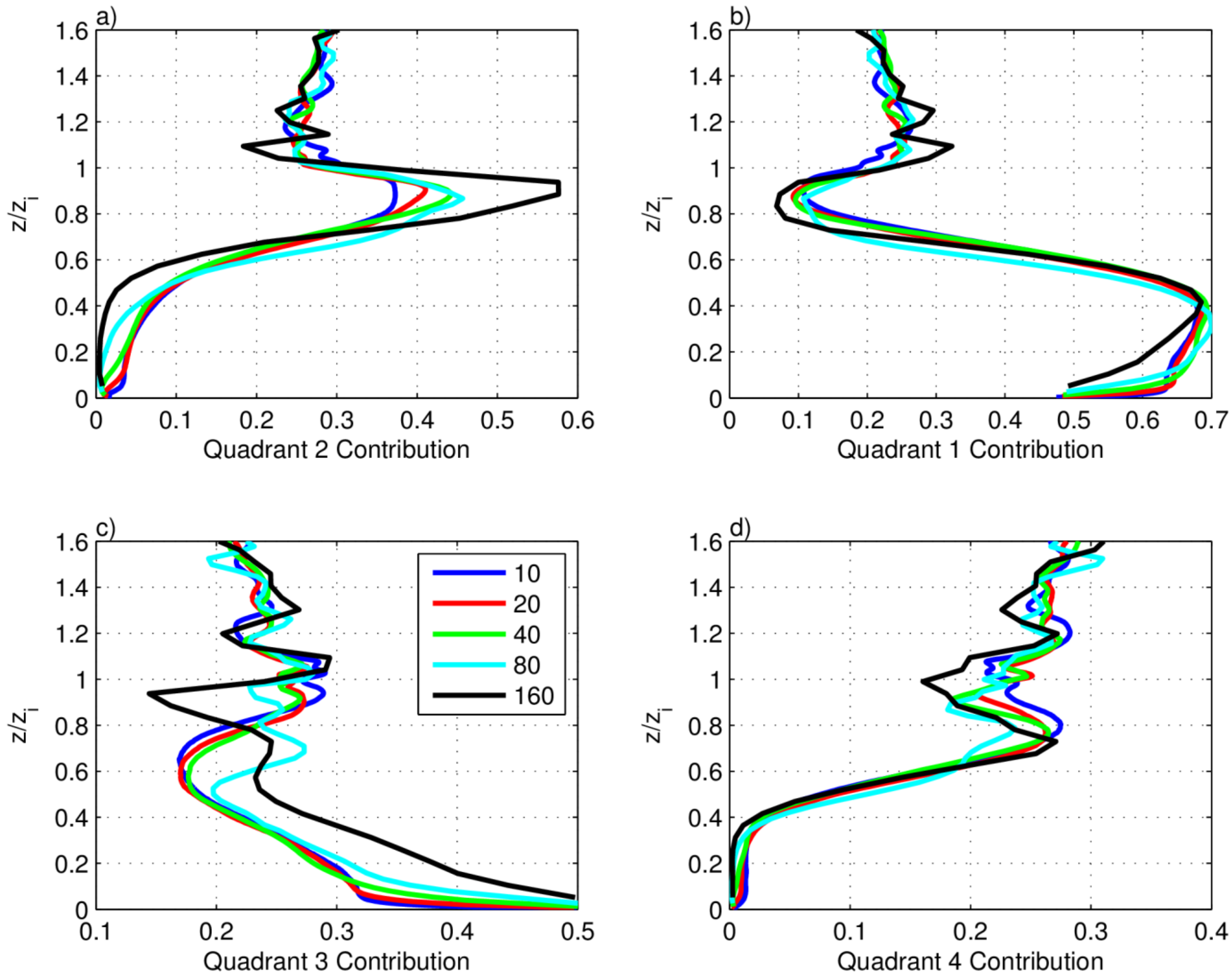
Q4 events mix with the environment and become cold, turning into Q3

Quadrant analysis: strong flux, dx = 25 m



Generally similar picture

Resolution-dependence : weak flux, Smag



At lower resolutions:

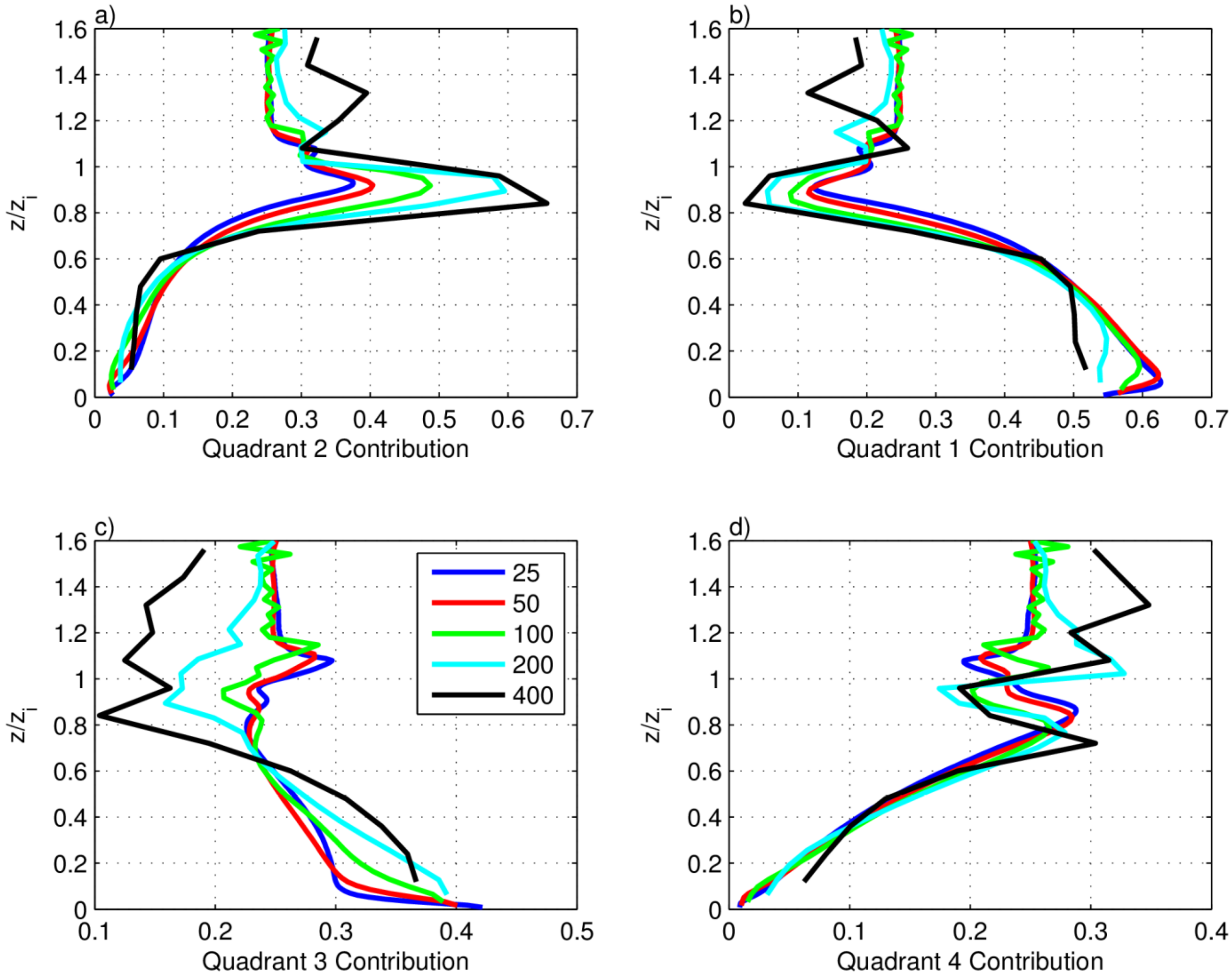
- Smaller Q1 contribution closer to surface

- Smaller contribution from Q2 and larger from Q3 in lower BL

- Larger contribution of Q2 in upper BL – less mixing – deeper into inversion – higher BL

- Smaller contribution from Q3 in upper BL

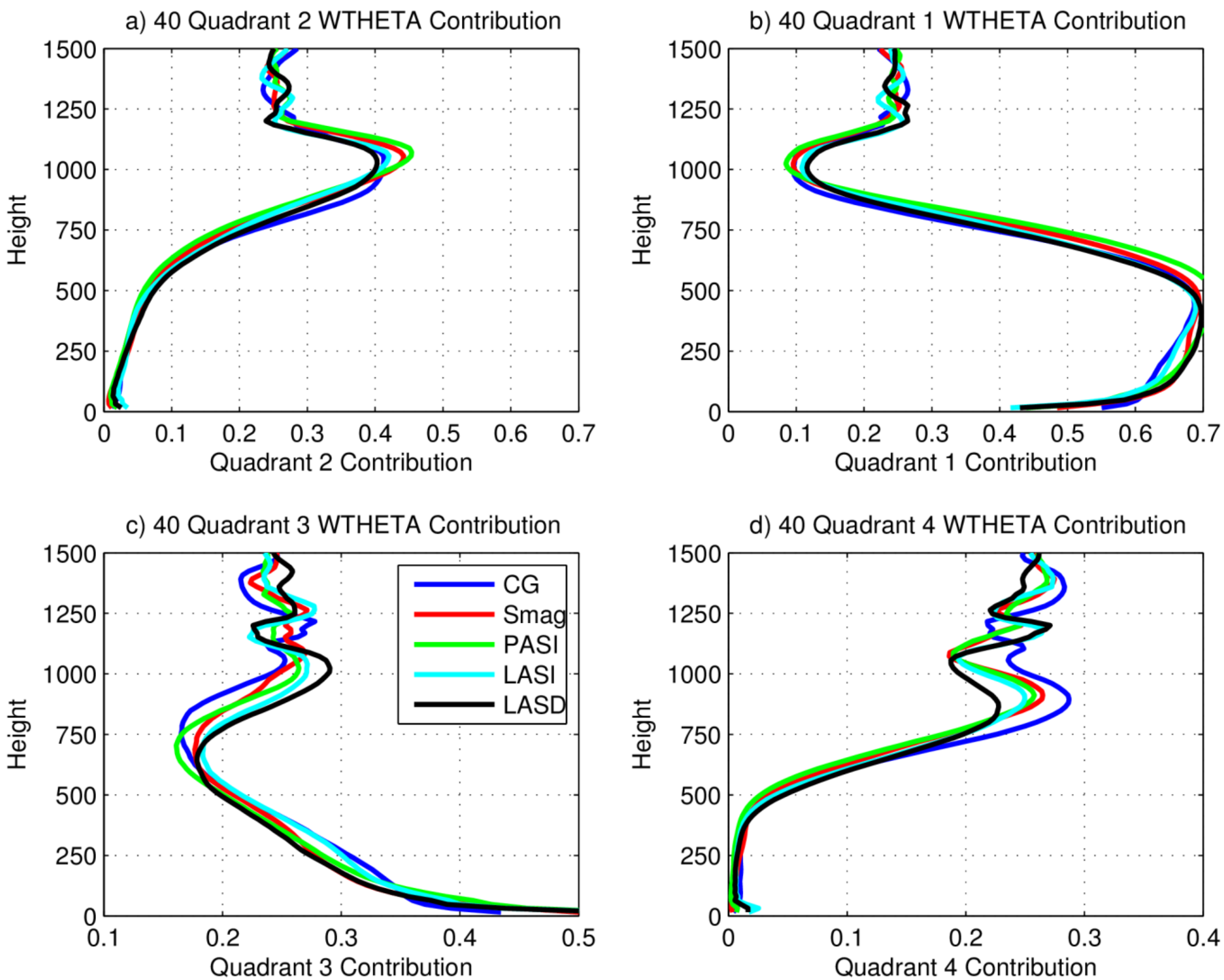
Resolution-dependence : strong flux, Smag



Qualitatively similar

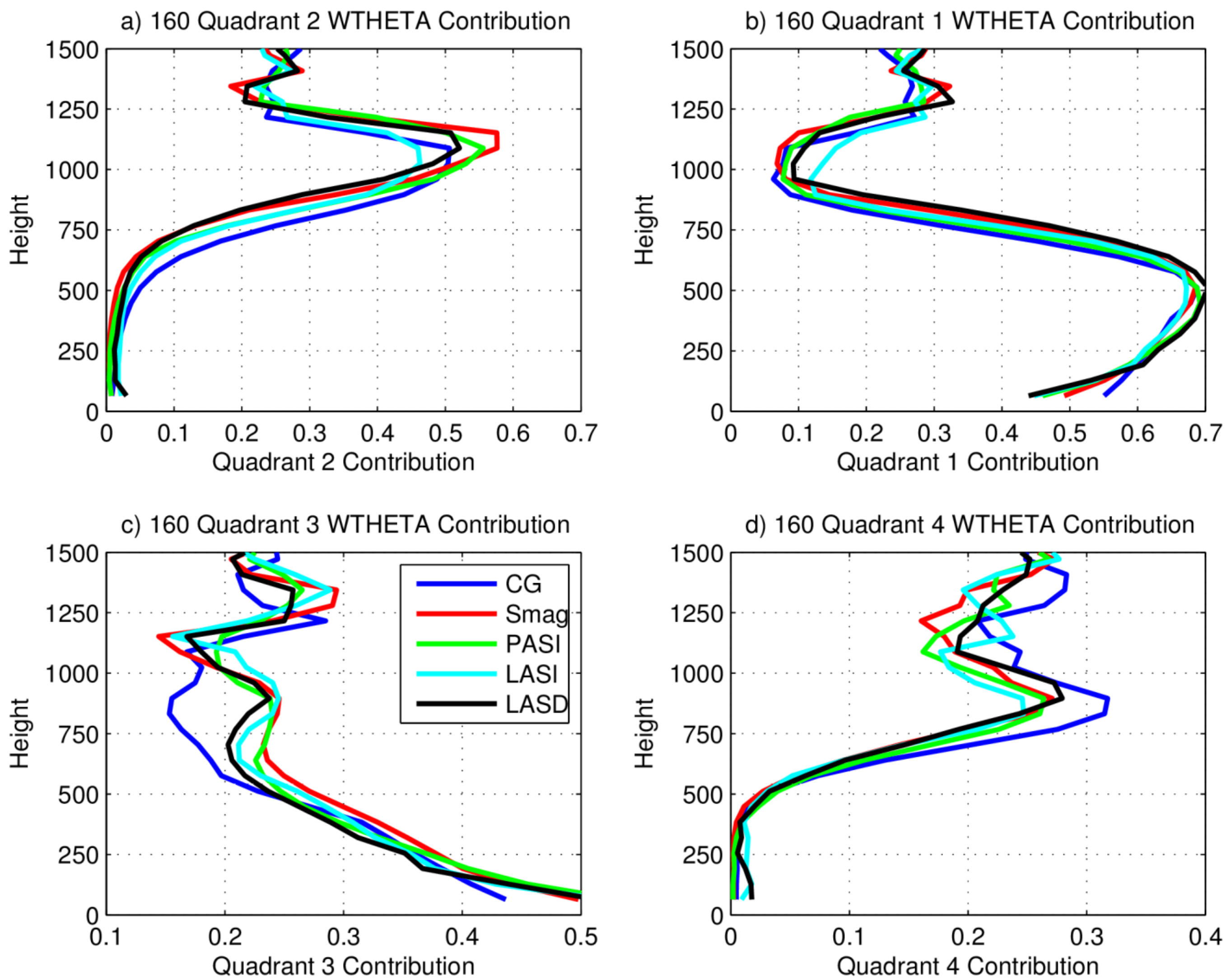
Larger differences from 200 m onwards

Model-dependence : weak flux, dx = 40 m



At higher resolutions all models roughly agree – as they should!

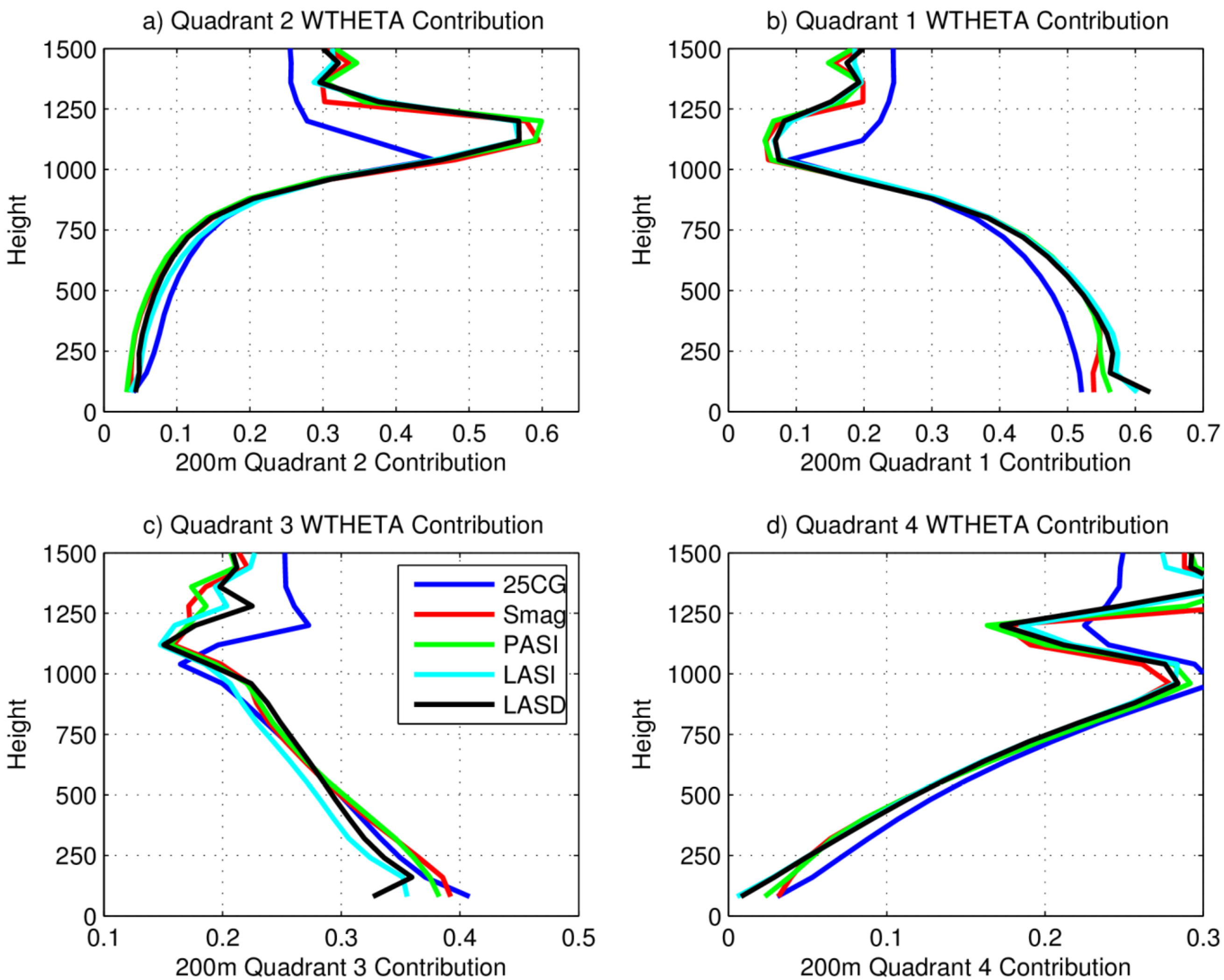
Model-dependence : weak flux, dx = 160 m



Larger differences than at higher resolutions

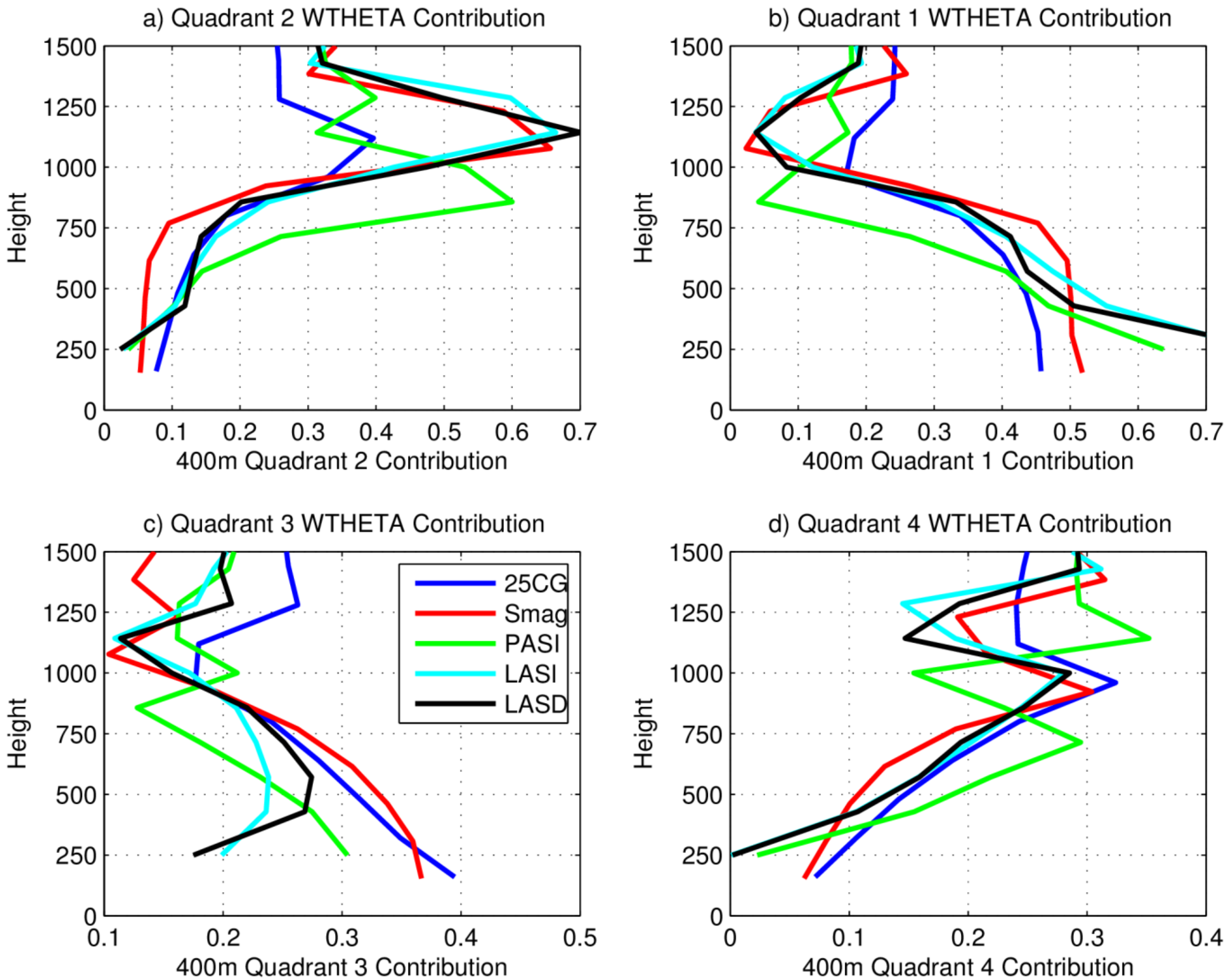
LASI slightly better

Model-comparison : strong flux, dx = 200 m



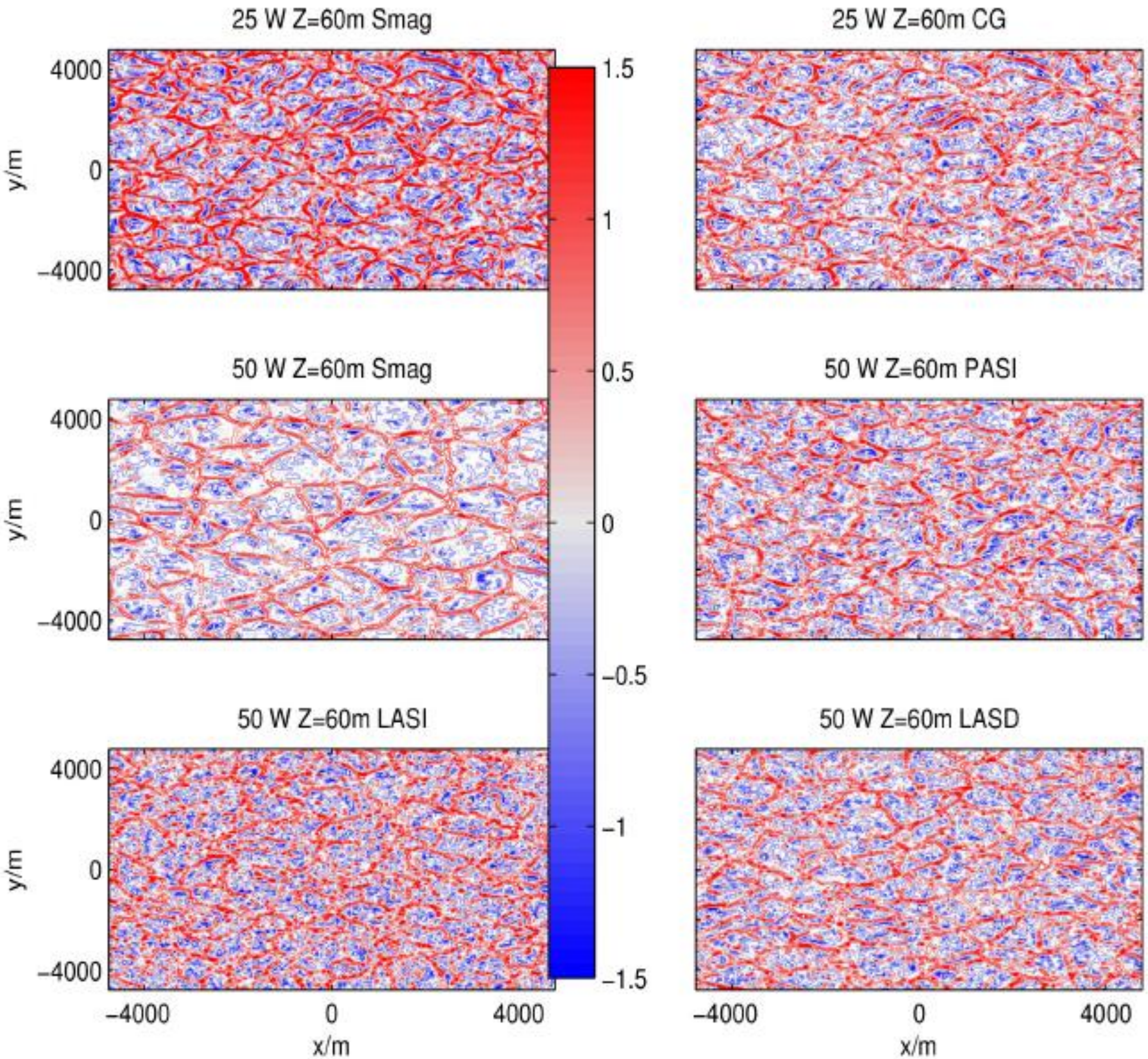
Difficult to distinguish between different models – all equally good

Model-comparison : strong flux, dx = 400 m



Difficult to distinguish between different models – all equally bad

Structures: strong flux, dx = 25 m – 50 m



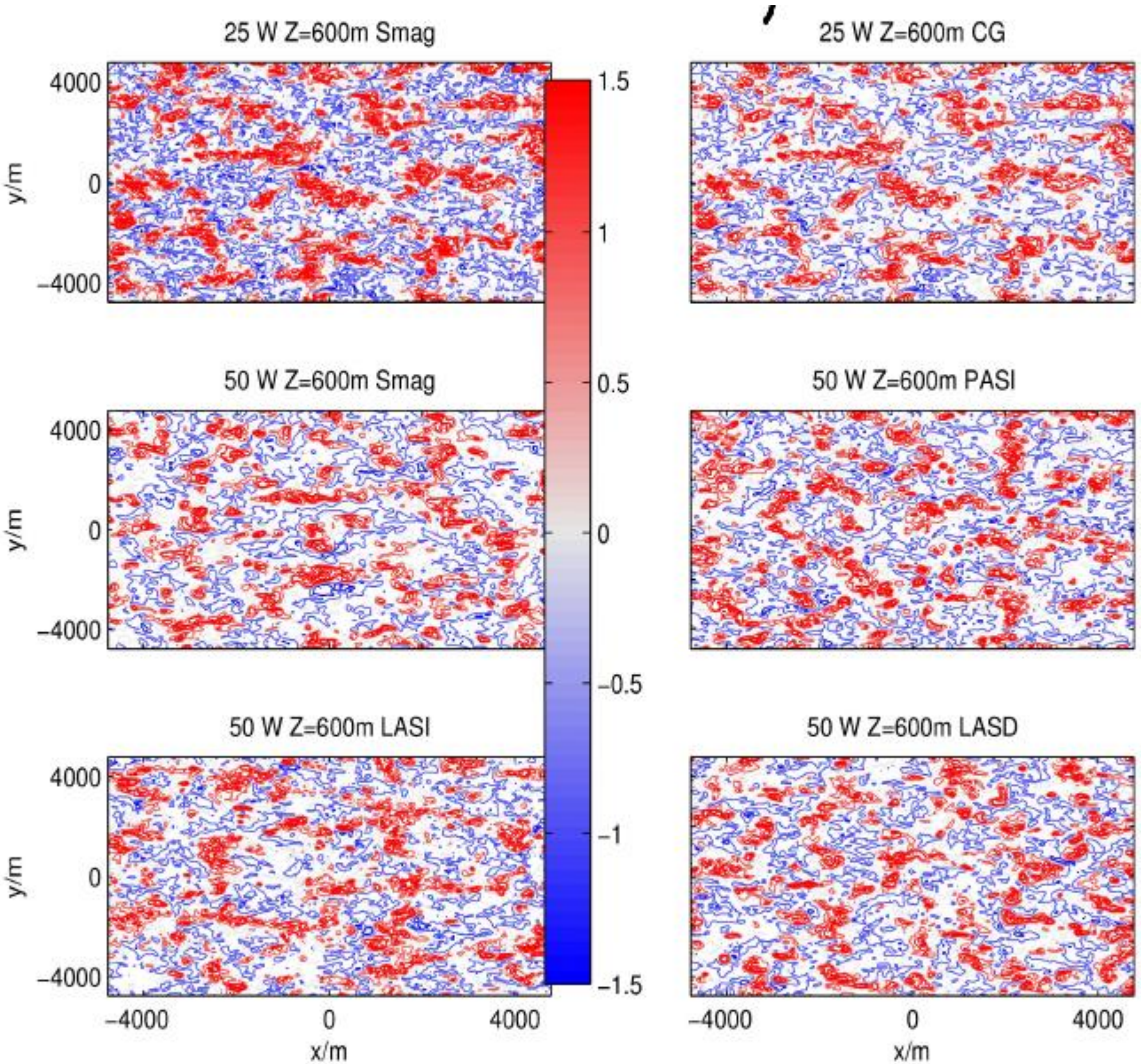
z = 60m

Mean variables almost the same

But structures look different

Smag is too smooth

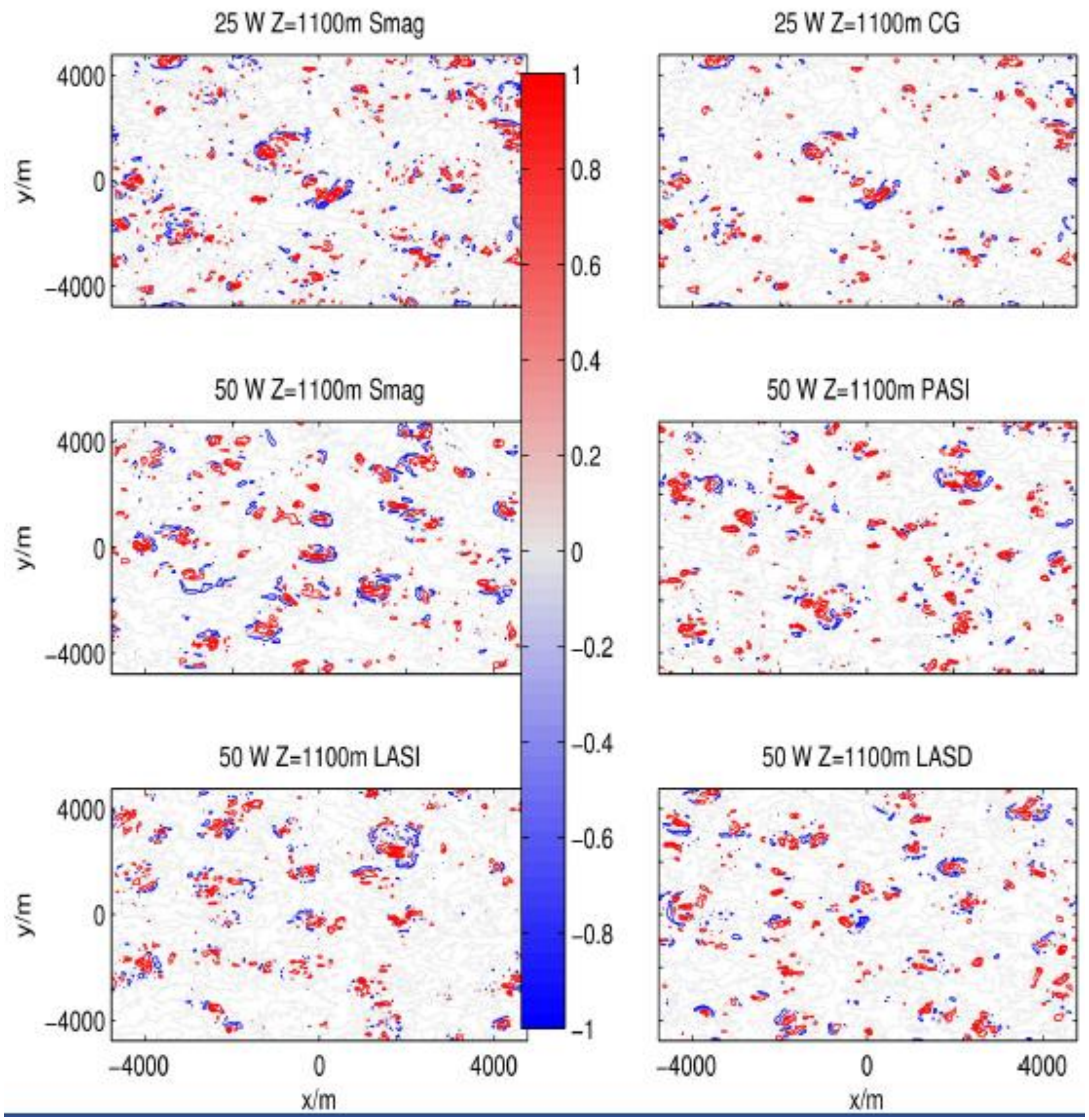
Structures: strong flux, dx = 25 m – 50 m



z = 600 m

All look roughly similar at this height

Structures: strong flux, dx = 25 m – 50 m

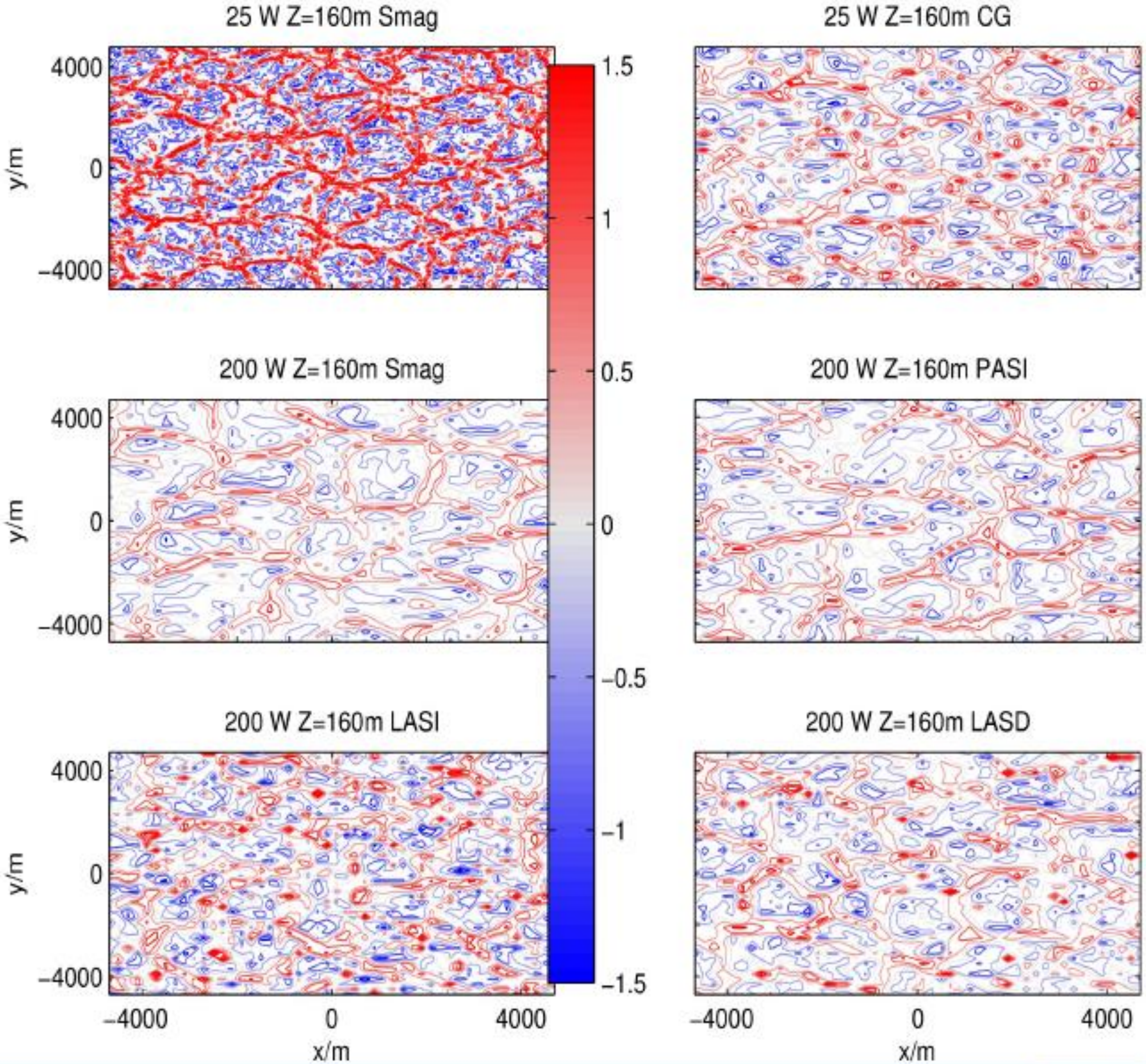


z = 1100 m

Again all look similar

No obvious improvement using dynamic models

Structures: strong flux, dx = 25 m – 200 m

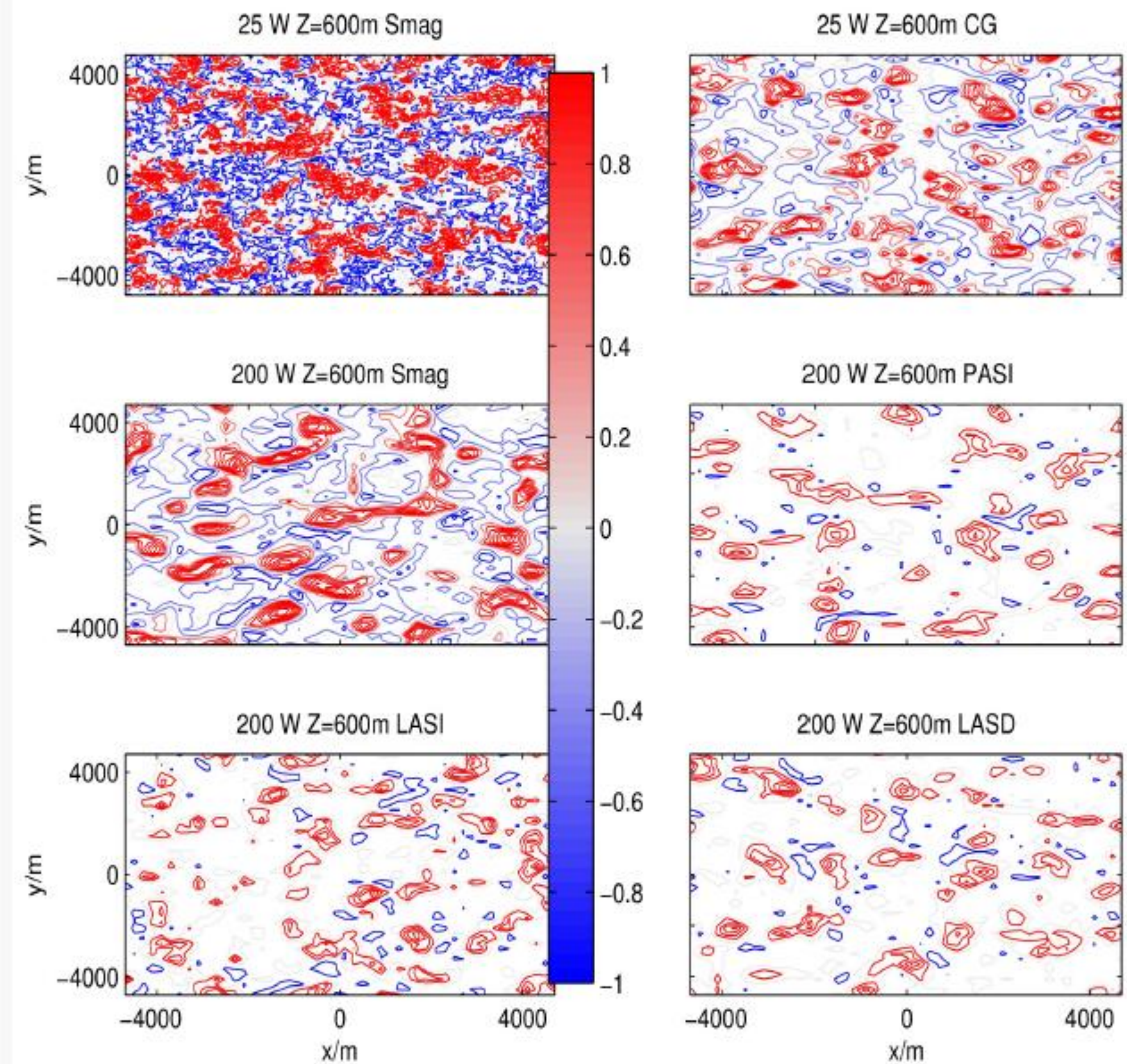


z = 160 m

Smag and PASI are too smooth

Lagrangian–averaged dynamic models seem to reproduce structures seen in higher-res runs slightly better

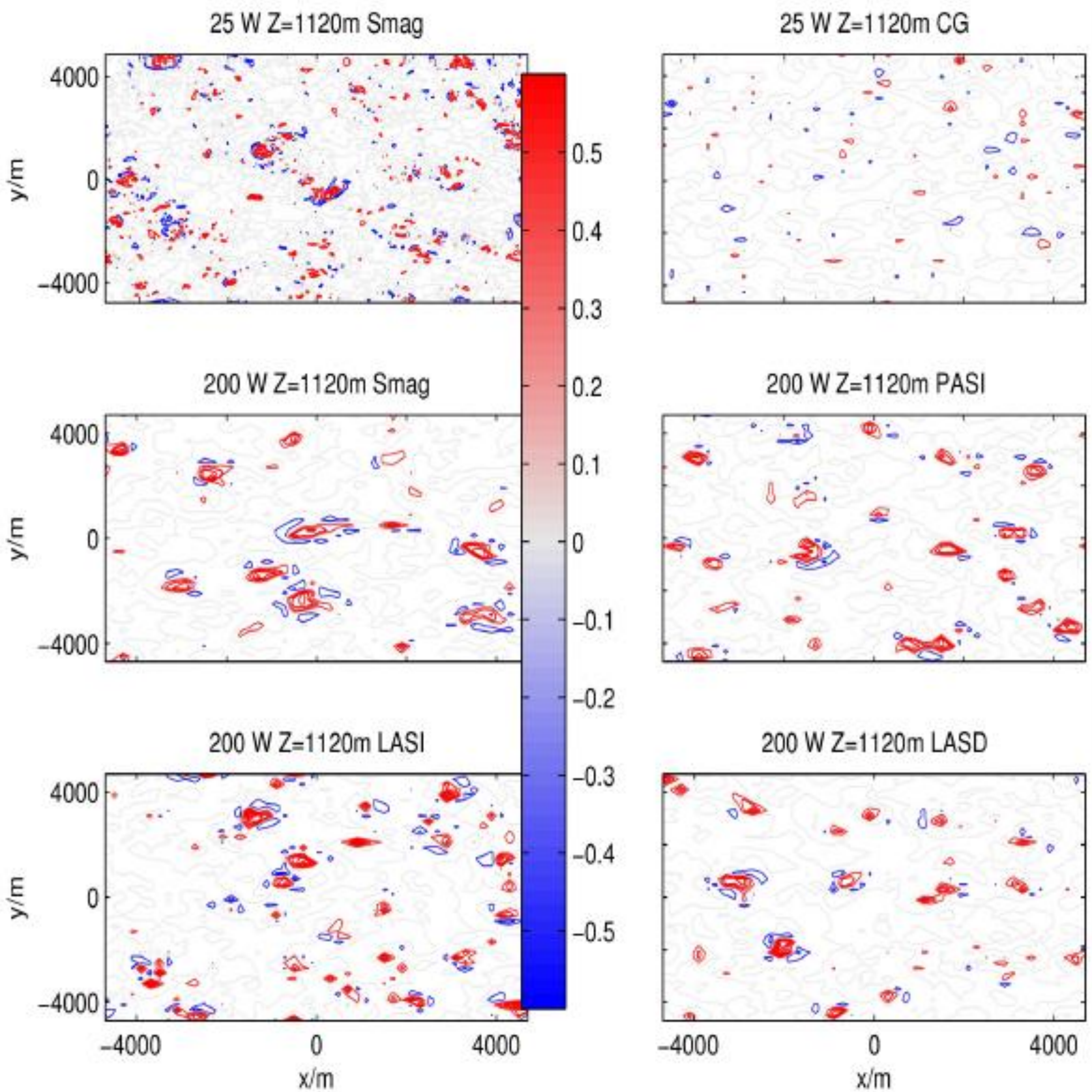
Structures: strong flux, dx = 25 m – 200 m



z = 600 m

Here Smag looks slightly better

Structures: strong flux, dx = 25 m – 200 m



z = 1120 m

Strong w' for all models

Lagrangian models make no improvement here

Conclusions

- Variants of dynamic model compared with Smagorinsky for convective boundary layer simulations

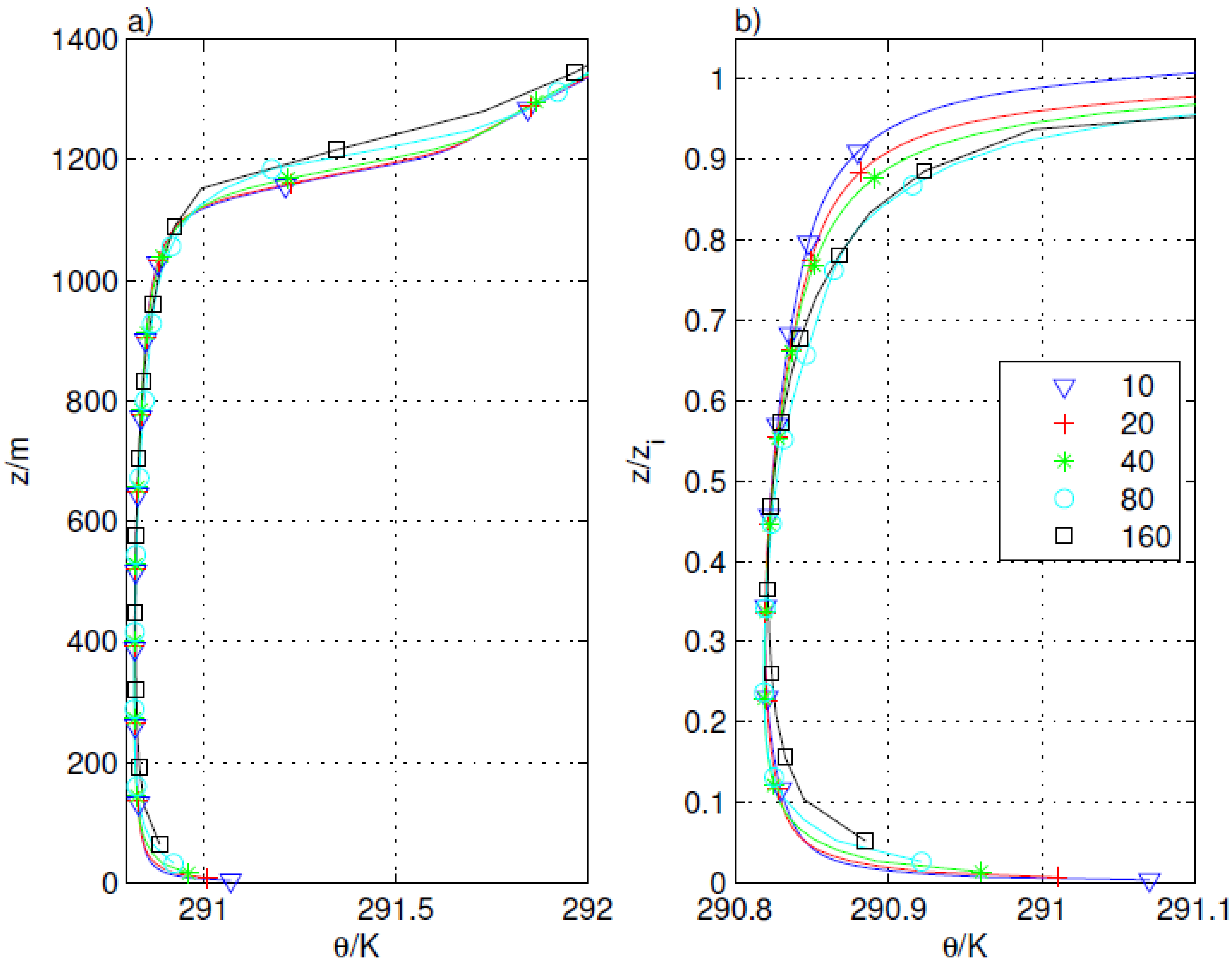
- Sub-grid model choice makes a difference for grid size of 200 m or larger

- Dynamic models in general neither better nor worse than Smagorinsky for the convective cases considered

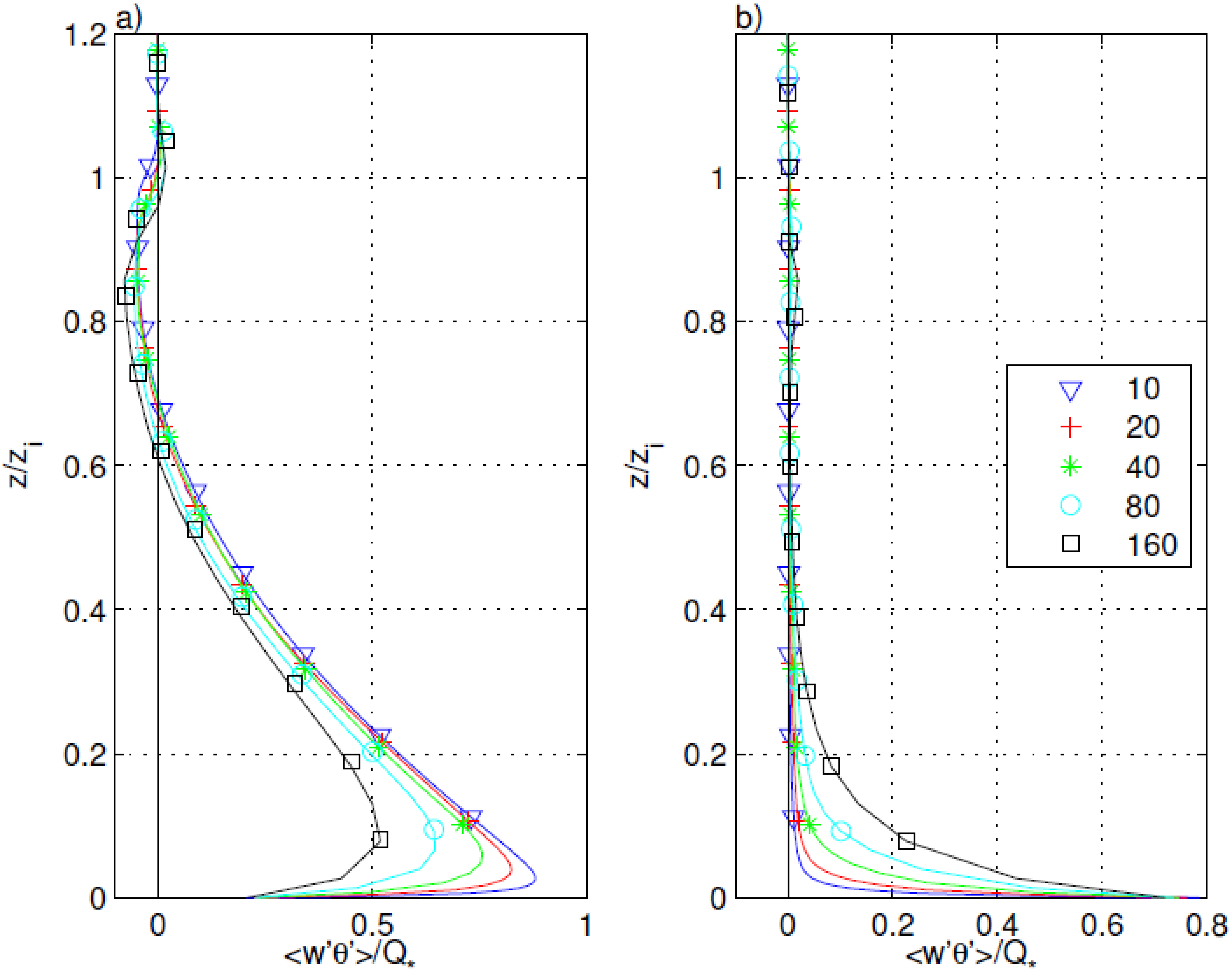
- Improvements found using the dynamic model for morning transition (work in progress)

Extra plots

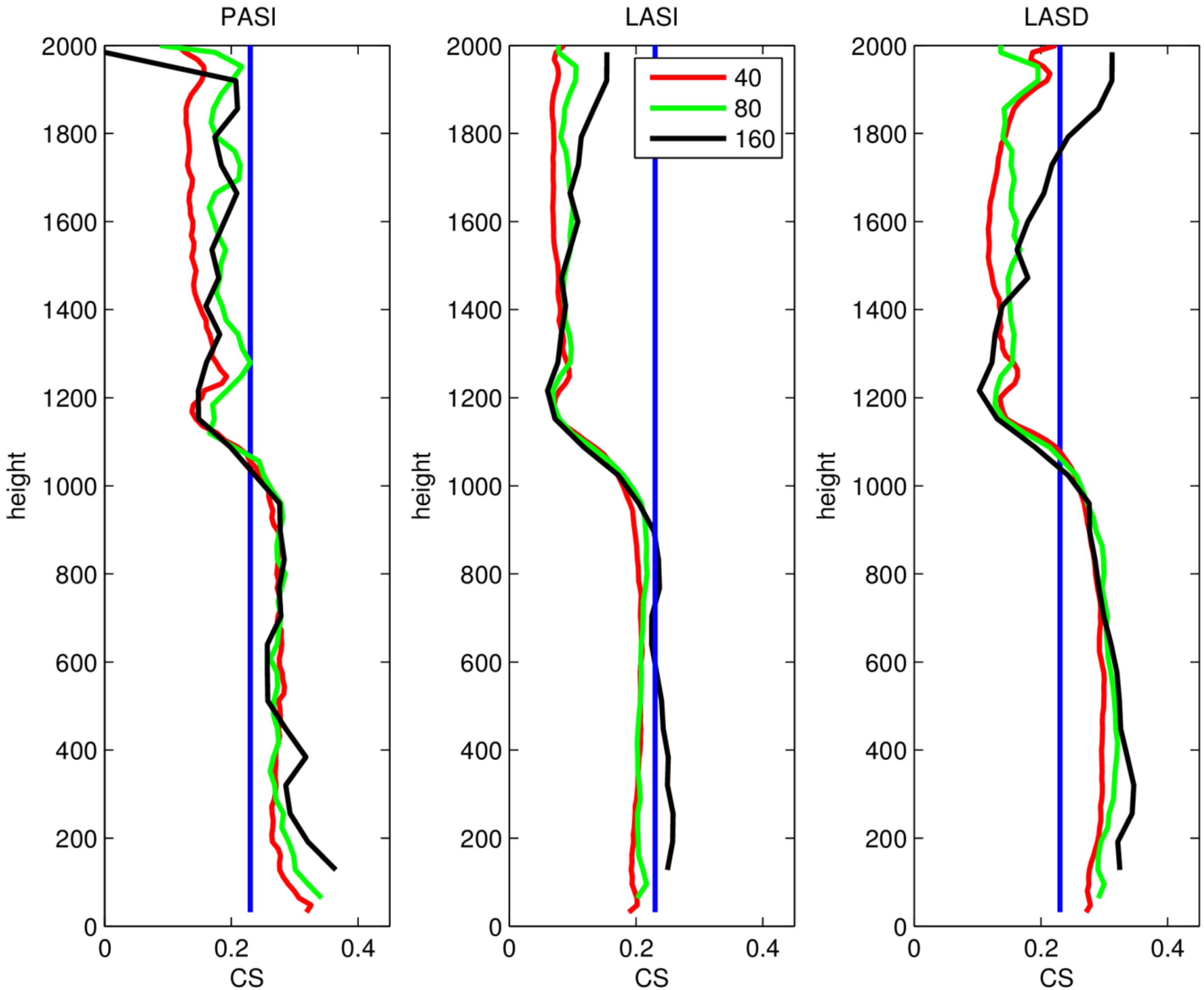
Potential temperature profile – weak flux



Heat flux profile – weak flux



Cs from dynamic models: weak flux



Cs from dynamic models: strong flux