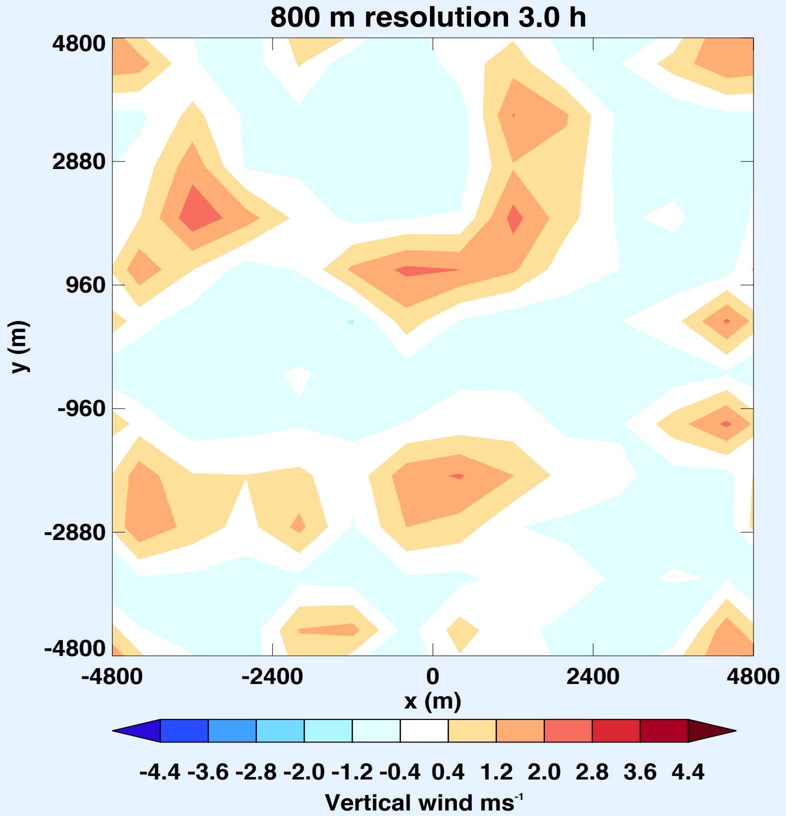
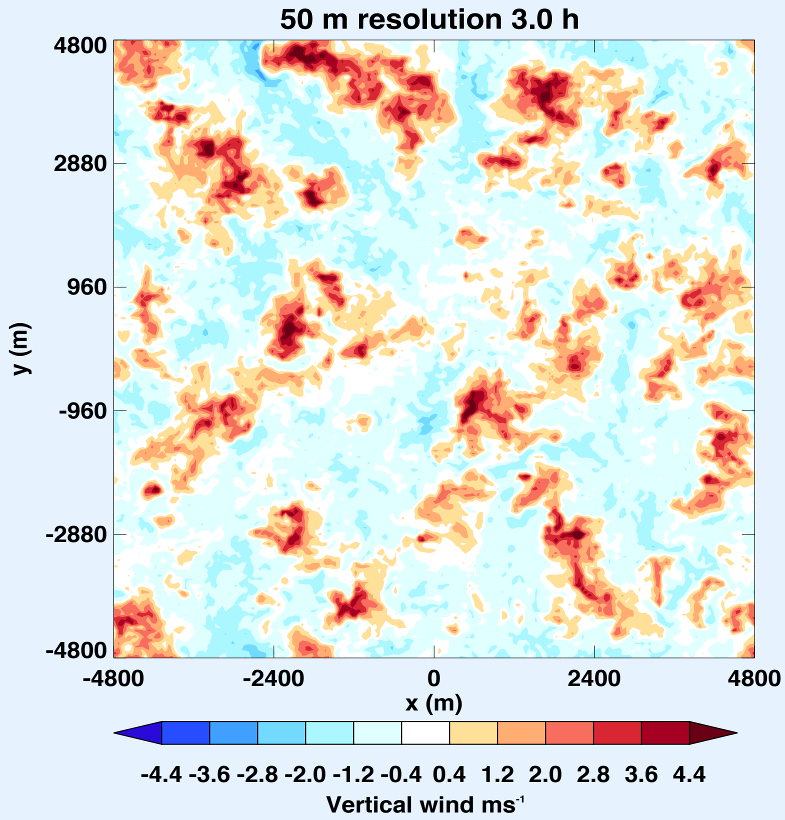
Modelling convective boundary layers in the terra-incognita





Bob Beare

University of Exeter

Thanks to Adrian Lock, John Thuburn and Bob Plant

Boundary layers in high resolution NWP

- MetUM forecasts at 1 km horizontal resolution but runs also at 100 m resolution.
- Convective boundary layer is **partially resolved**.
- “Terra-incognita”, Wyngaard 2004.
- **How do we represent the boundary layer at these scales?**

The boundary layer in the terra-incognita

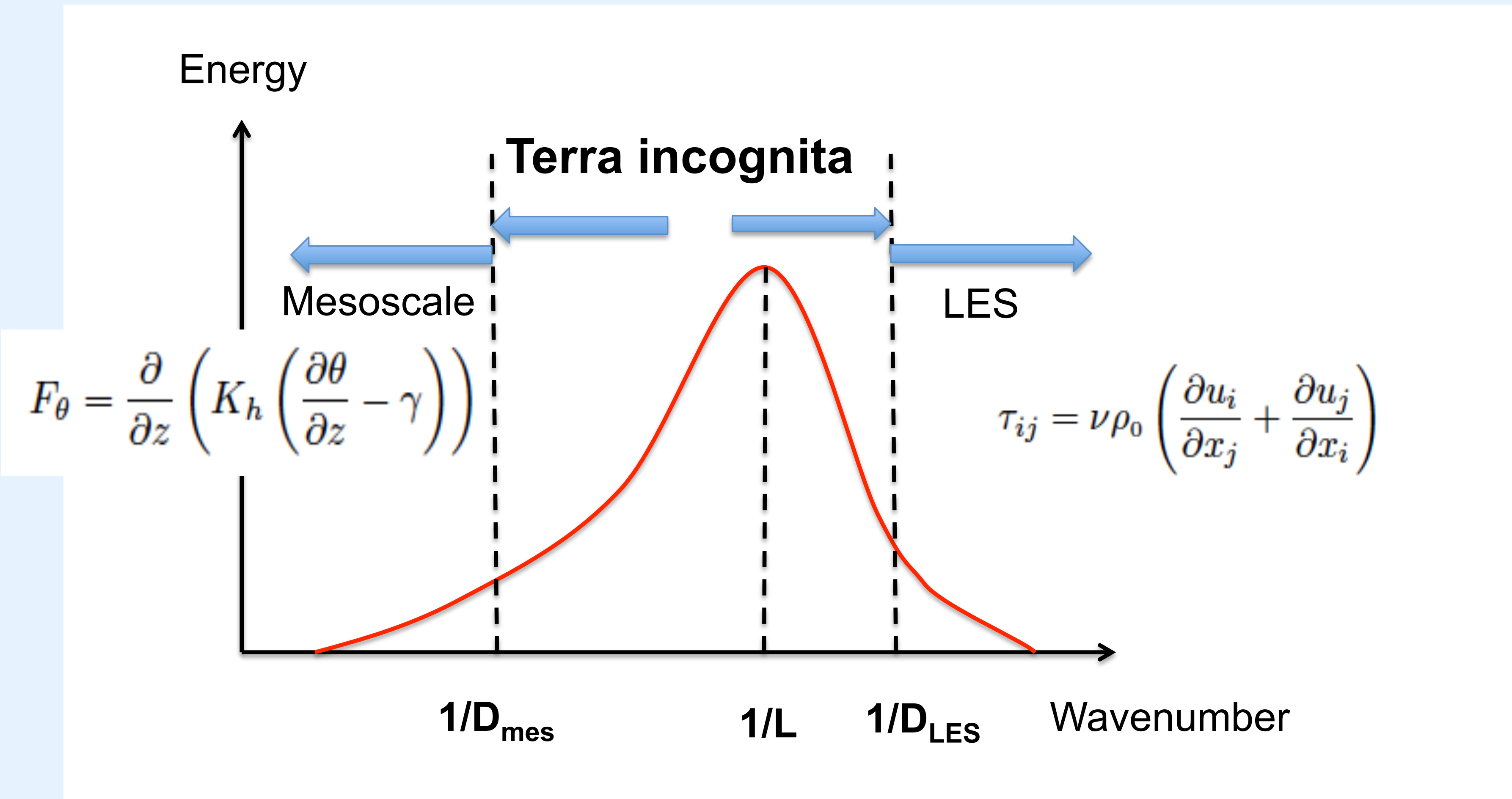


Figure based on Wyngaard 2004

Background

- Analysis of arrays of surface layer data (HATS) to derive closures (e.g. Wyngaard 04, Hatlee and Wyngaard 07)
- Using LES models to derive similarity functions for sub-grid/total ratio of fluxes (Honnert et al 2011)
- My approach: role of both the advection and sub-grid scheme; behaviour of boundary layer top entrainment flux.

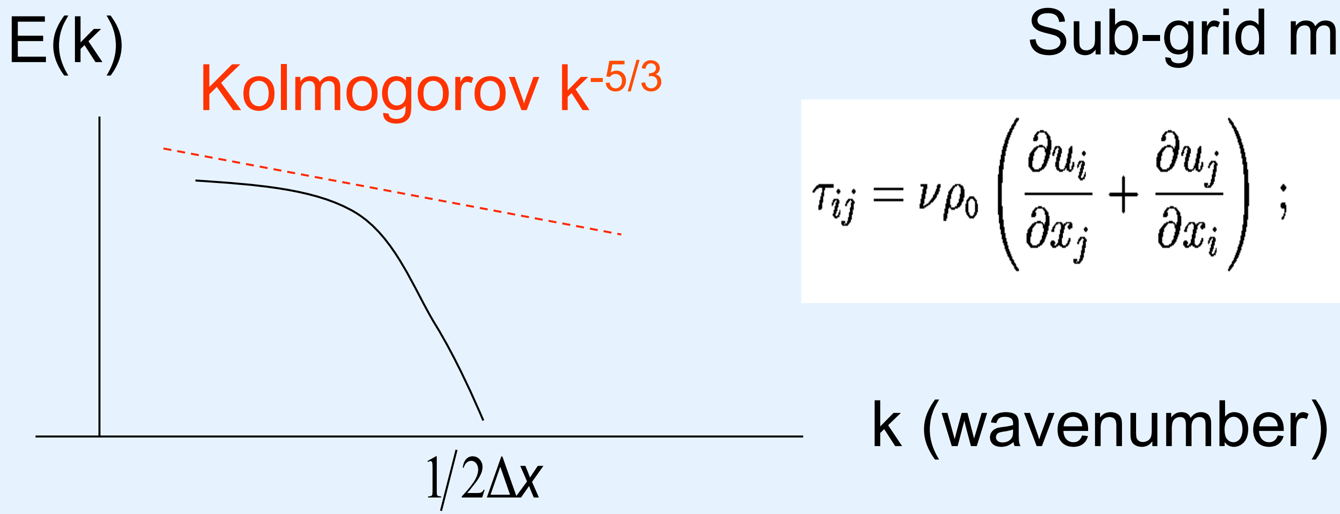
Large-eddy simulation

Navier-Stokes decomposed into resolved and sub-grid components

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_0\, \epsilon_{ij3}\, u_j - \frac{1}{\rho_0}\frac{\partial p}{\partial x_i} + \frac{g\theta}{\theta_0}\,\delta_{i3} + \frac{1}{\rho_0}\frac{\partial \tau_{ij}}{\partial x_j} + \mathcal{B}_{u_i}$$

$$\frac{\partial u_j}{\partial x_j} = 0$$

$$\frac{\partial \Theta}{\partial t} + u_j \frac{\partial \Theta}{\partial x_j} = \frac{1}{\rho_0}\frac{\partial \mathcal{H}_j}{\partial x_j} + \mathcal{B}_\theta$$



Sub-grid model:

$$\tau_{ij} = \nu\rho_0\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad ; \quad \nu = \lambda_l^2 S f(Ri_p)$$

Sources of diffusion in LES

Explicit sub-grid model

$$\tau_{ij} = \nu \rho_0 \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \; ; \quad \nu = \lambda_l^2 S f(Ri_p)$$

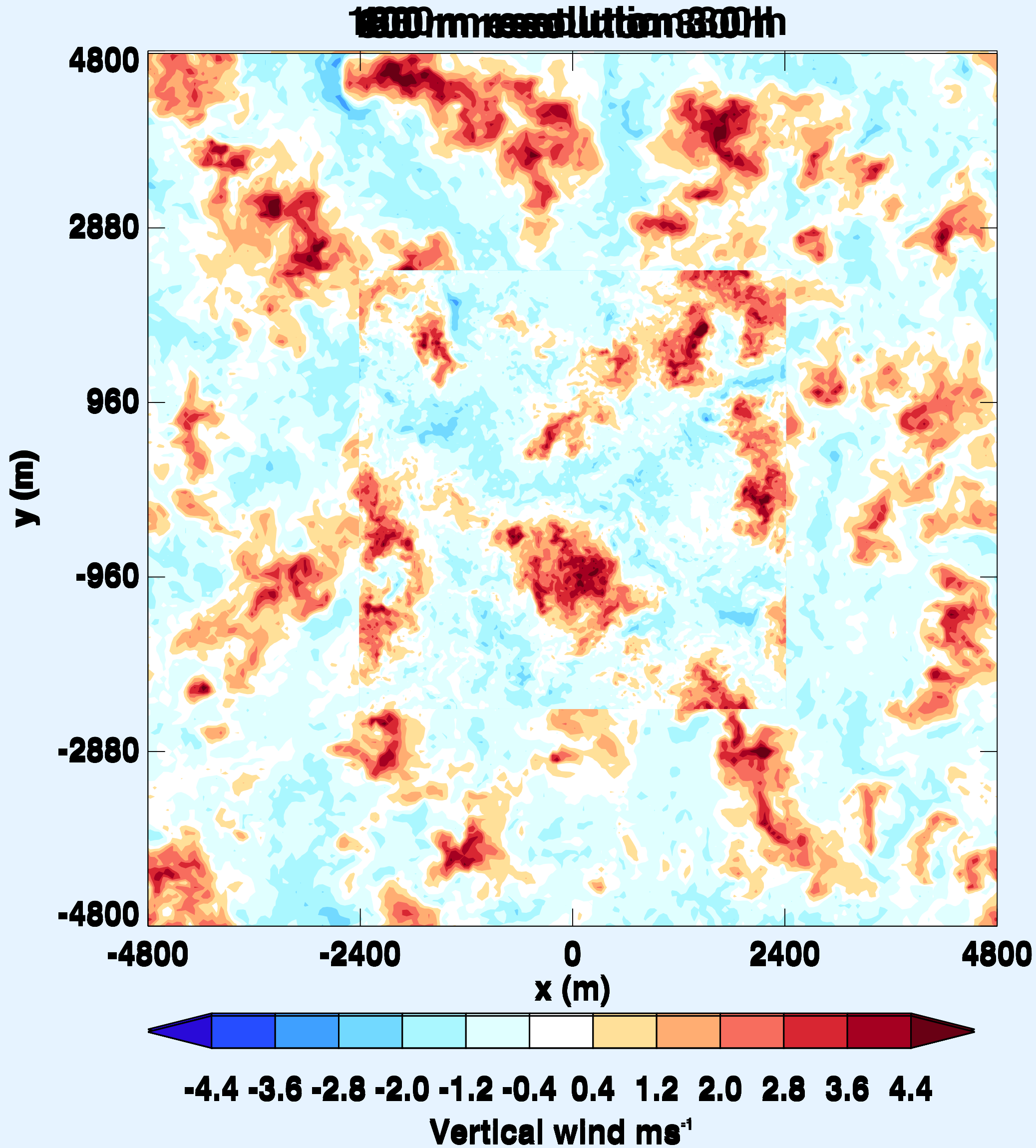
Implicit diffusion from advection scheme, e.g. 1D upstream advection

$$\frac{\partial f}{\partial t} + U \frac{\partial f}{\partial x} = -\frac{\Delta t}{2} f_{tt} + \frac{Uh}{2} f_{xx} - \frac{\Delta t^2}{6} f_{ttt} - \frac{Uh^2}{6} f_{xxx} + \cdots$$

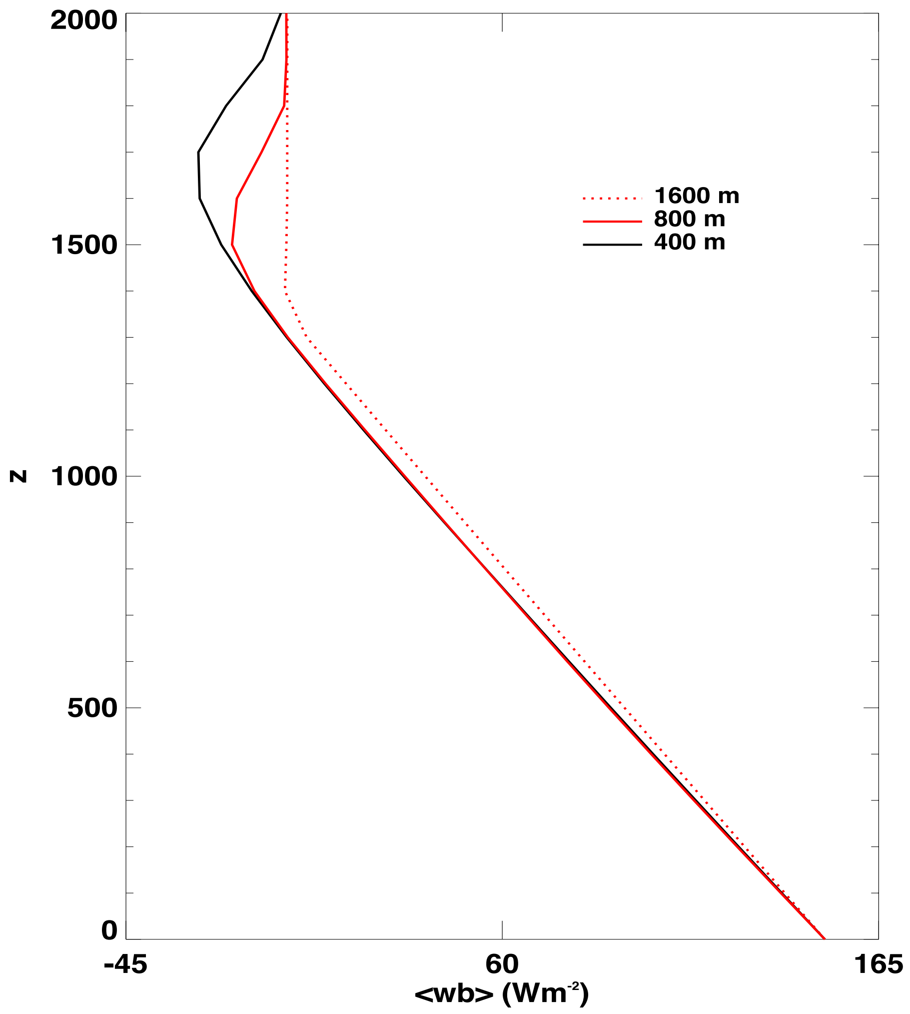
Experimental set up

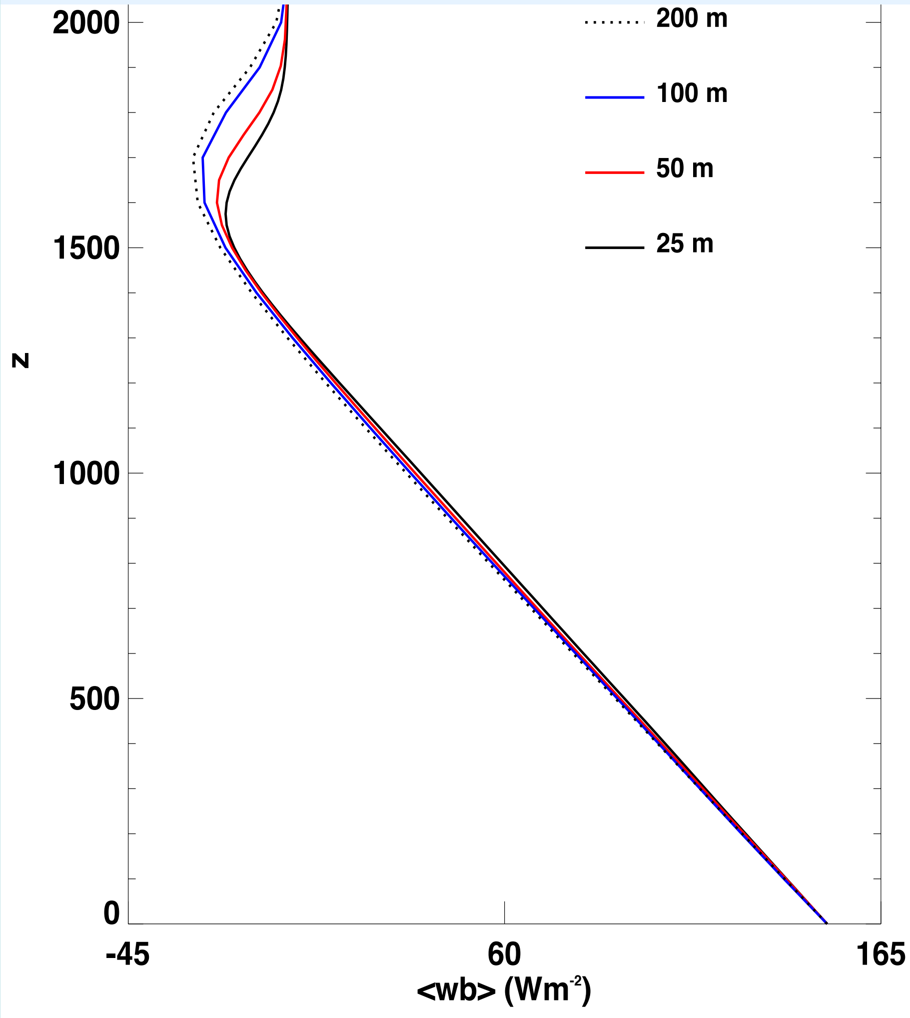
- Initial mixed layer of depth 1 km
- Domain 10 km x 10 km x 5 km
- Surface sensible heat 150 Wm^{-2}
  Geostrophic wind 2 ms^{-1}
- Run at horizontal resolutions of 1600, 800, 400, 200, 100, 50, 25 m

Horizontal w cross-sections at 1km

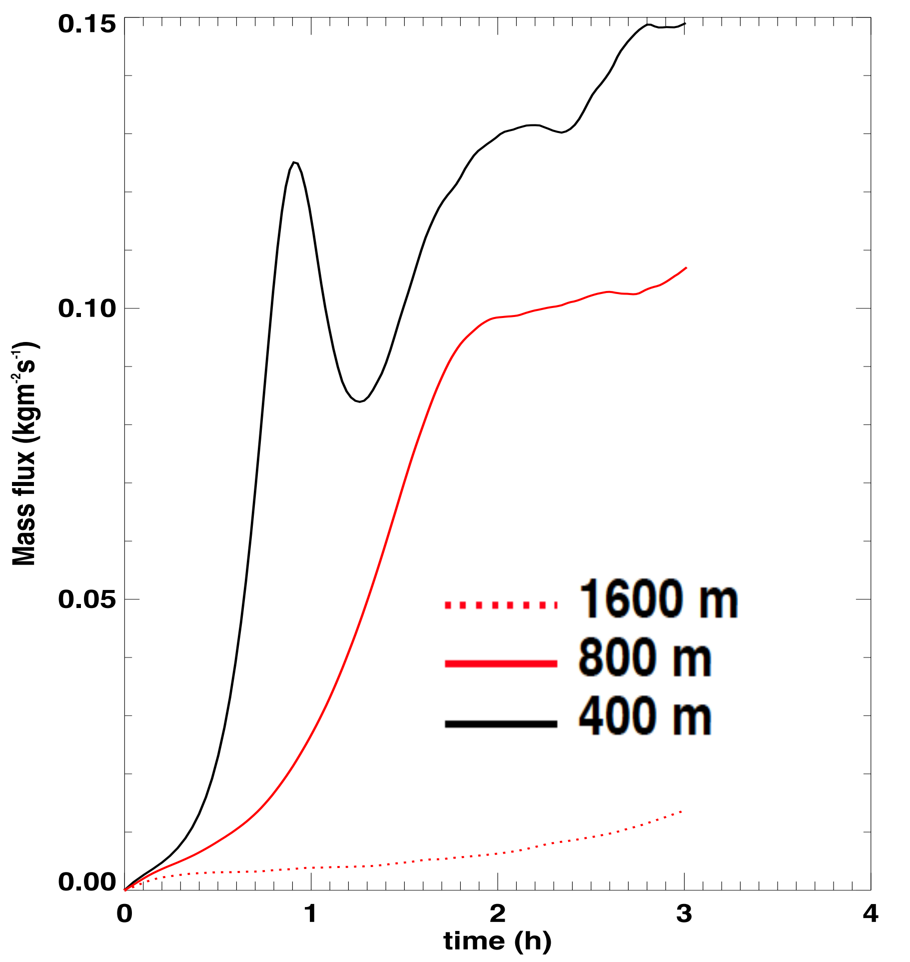


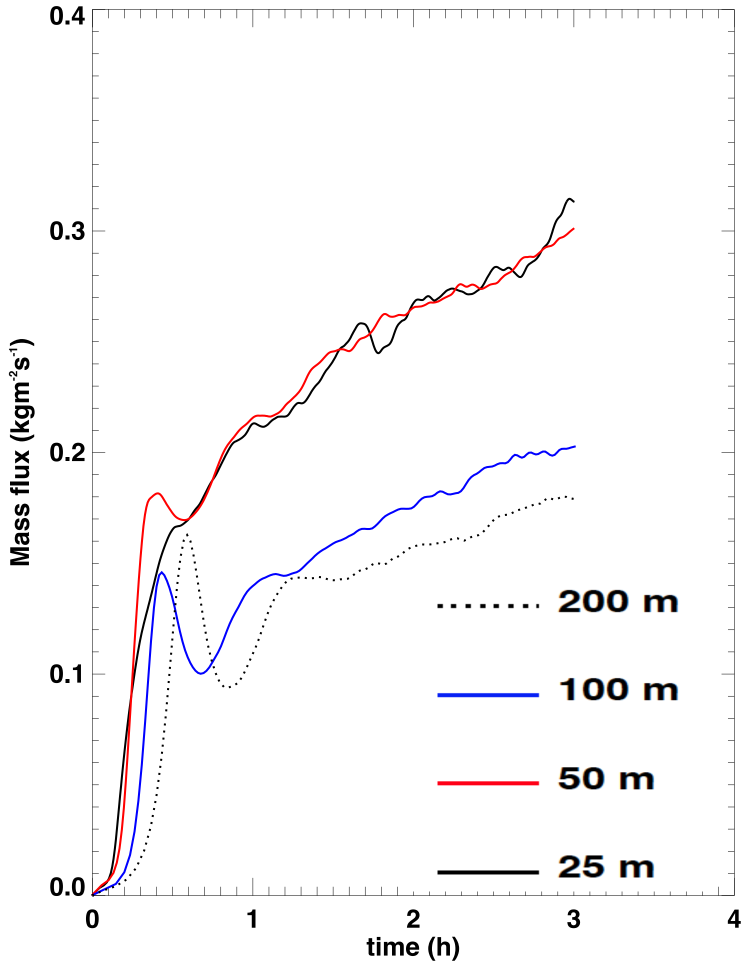
Entrainment in Terra-incognita





Spin up in the terra-incognita

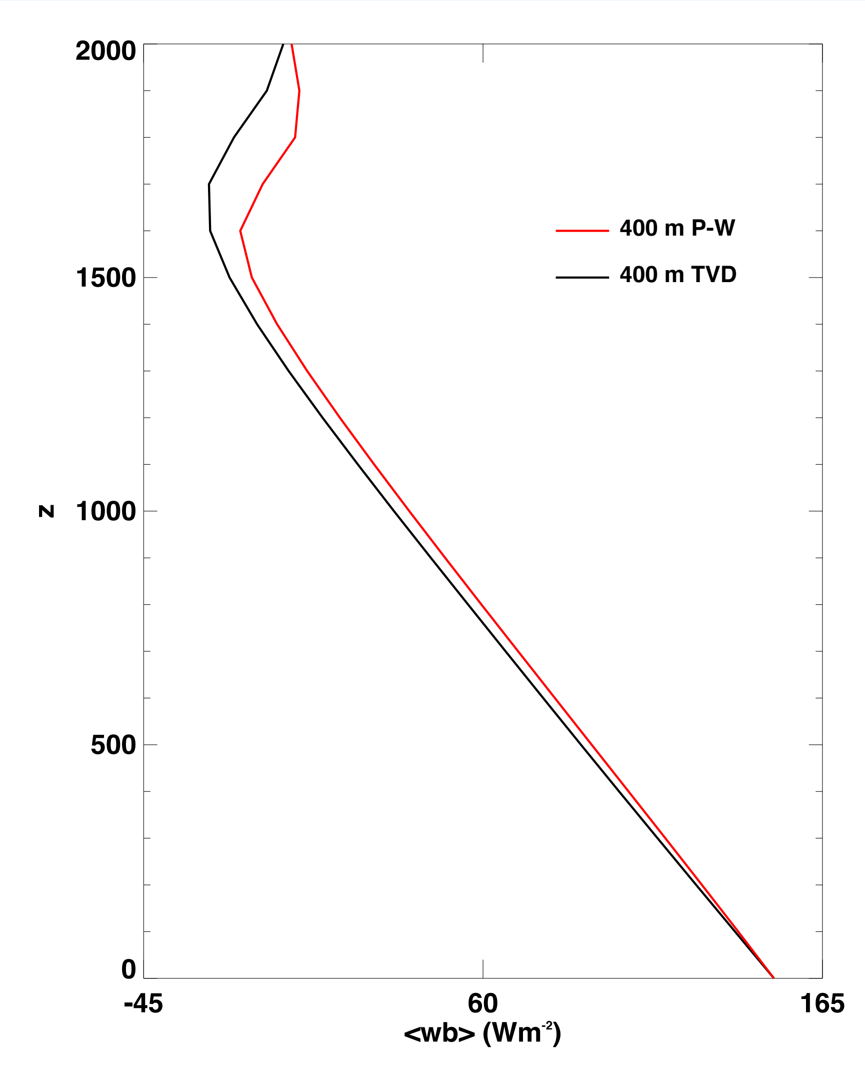


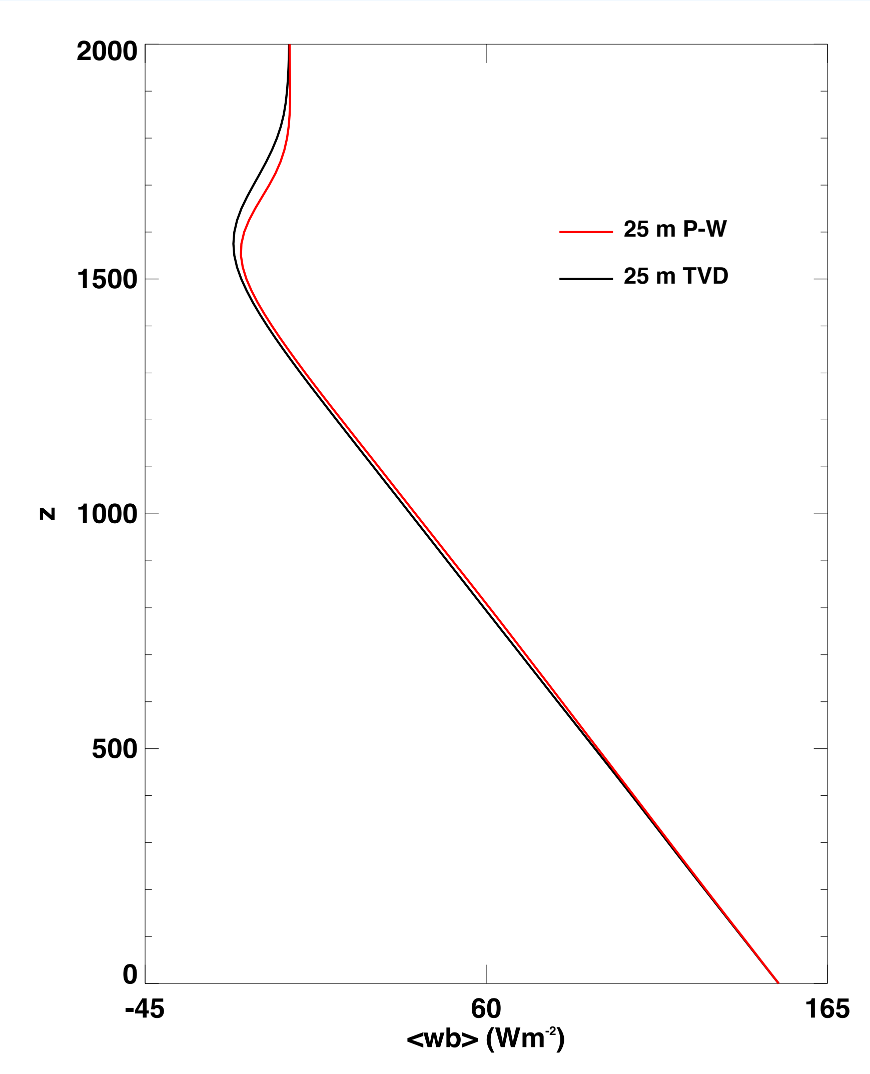


Experiments

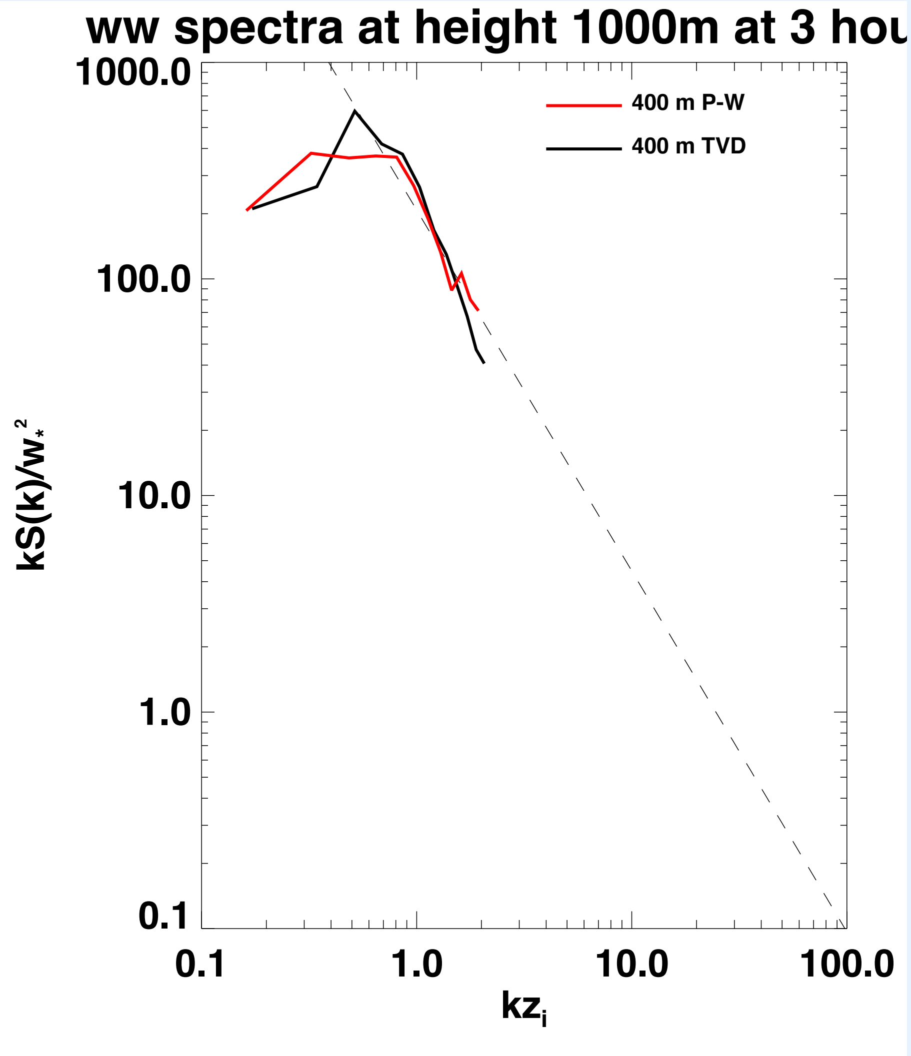
- 2 types of experiment:
  - Advection scheme fixed. Sub-grid model varied (e.g. backscatter on and off)
  - **Sub-grid model fixed. Advection scheme on potential temp. changed between:**
    - **Centred-difference scheme (PW)**
    - **Monotone, finite volume method (TVD)**
  - **TVD more dissipative than PW.**

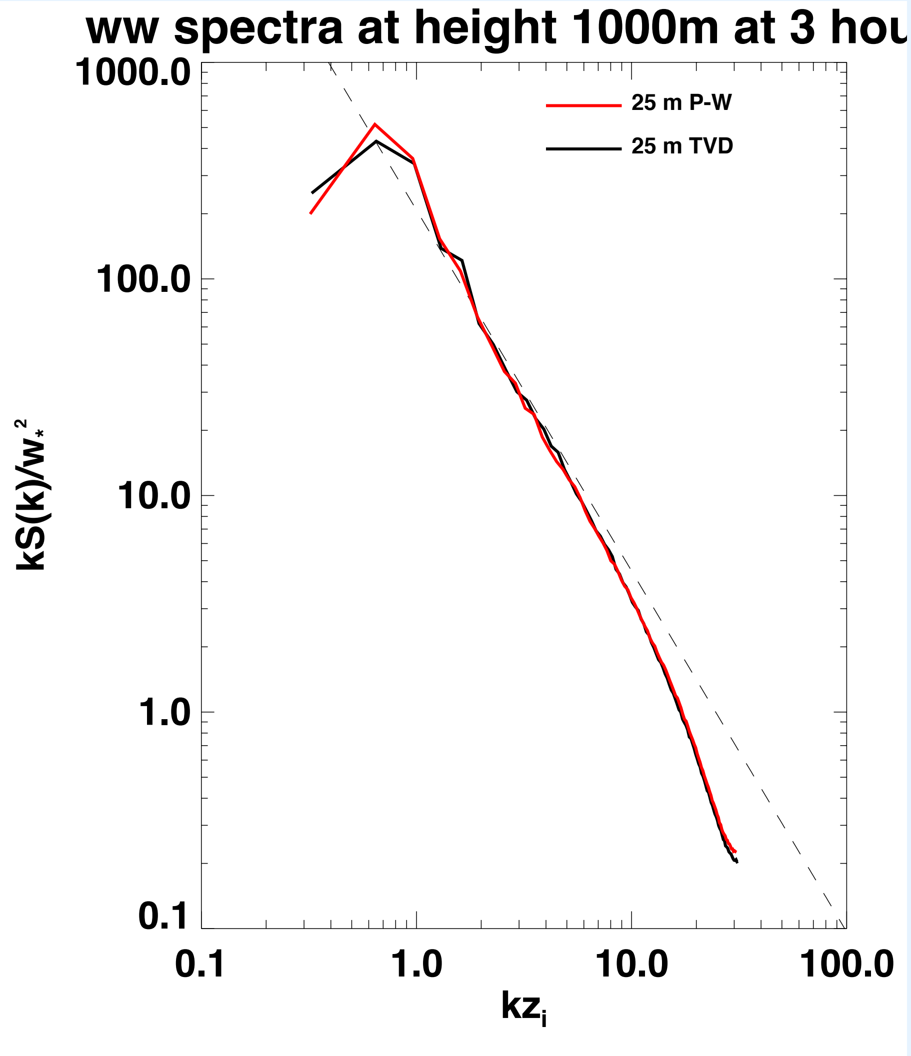
Entrainment and advection scheme



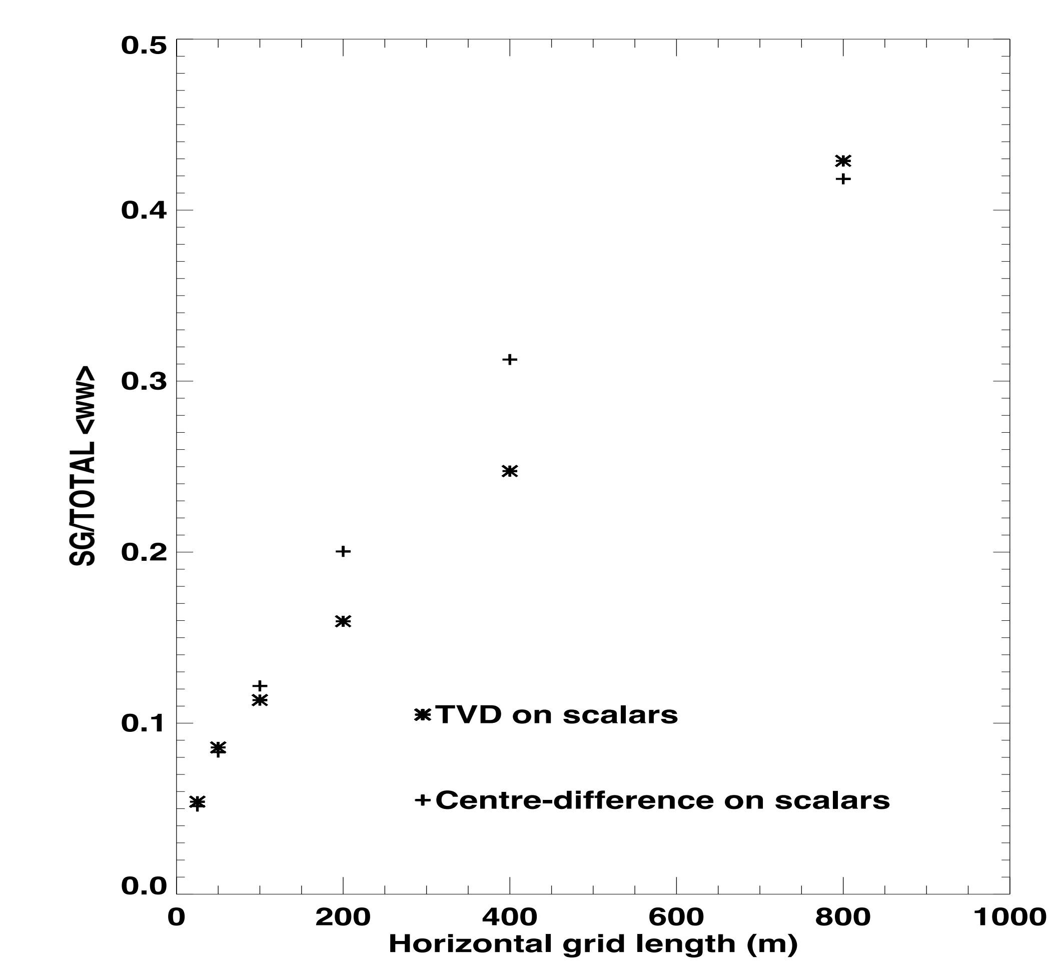


Vertical velocity spectra at 1 km

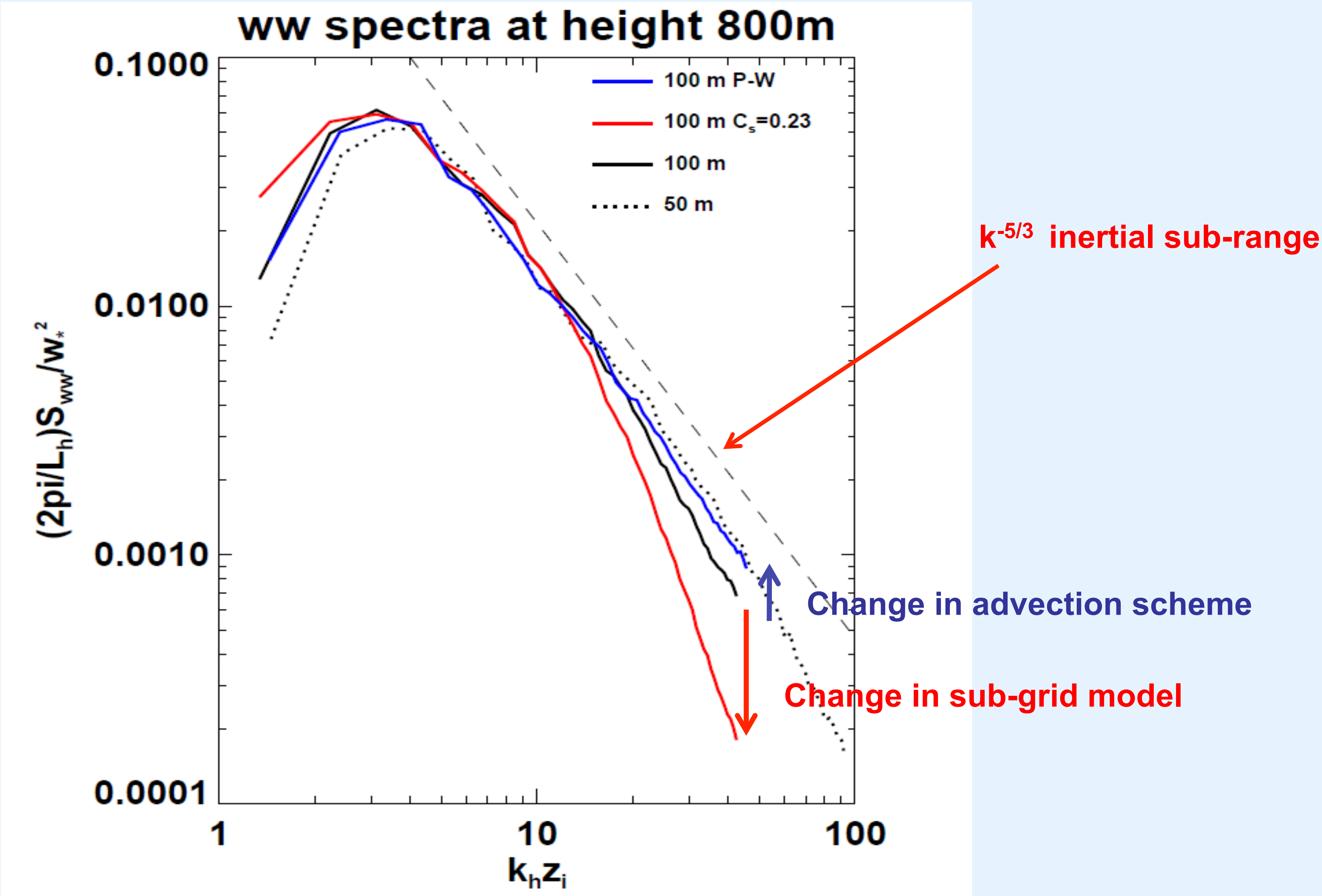




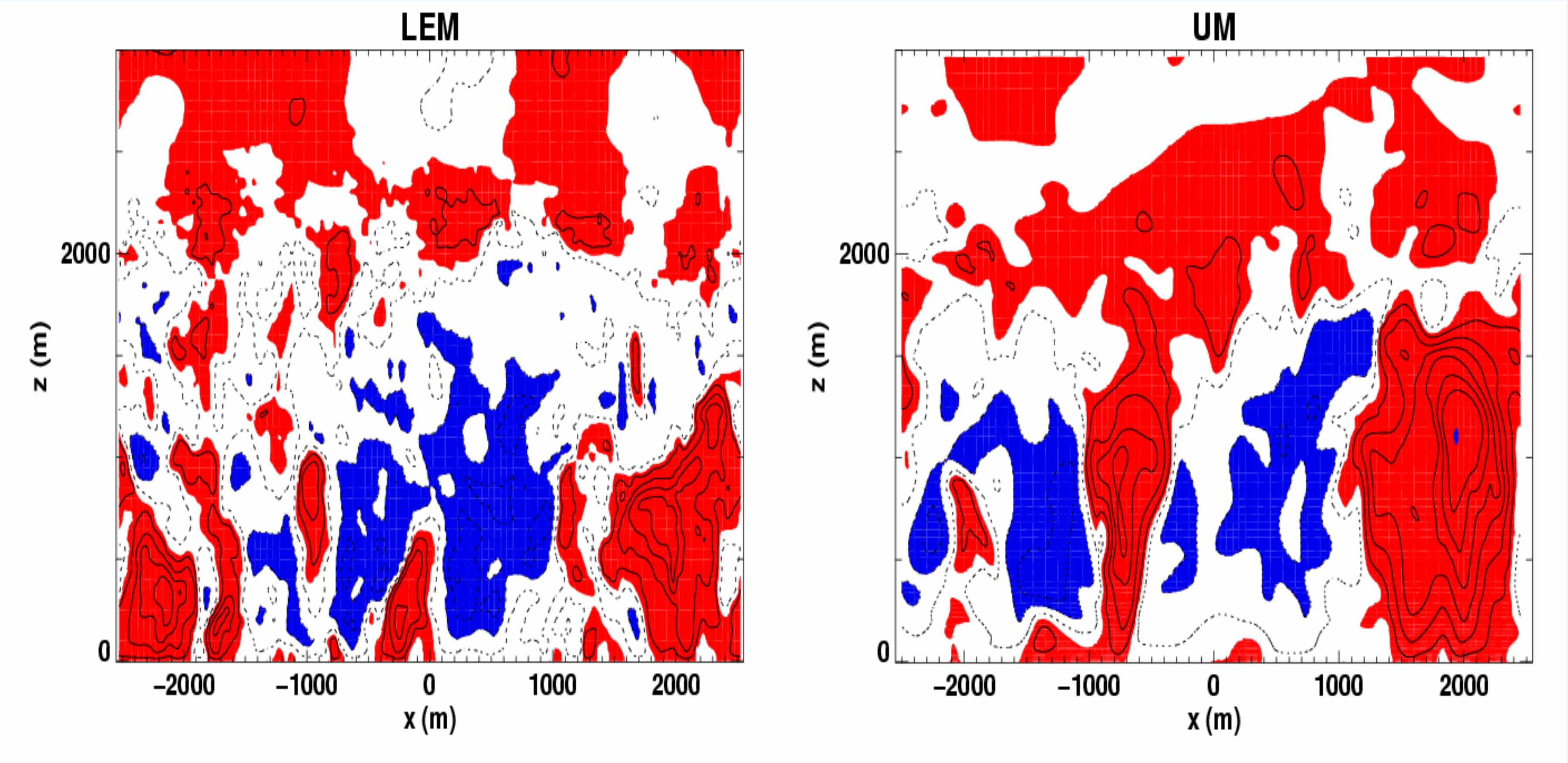
Interaction of sub-grid and advection scheme



Sub-grid model vs advection scheme



Met Office advection scheme implicit diffusion



Vertical velocity at 50 m resolution >1.5 m/s red; <1.5 m/s blue

Identical sub-grid models , different advection schemes

Beare et al 2007, Met Office report

Morning transition boundary layer

Lapworth 2006

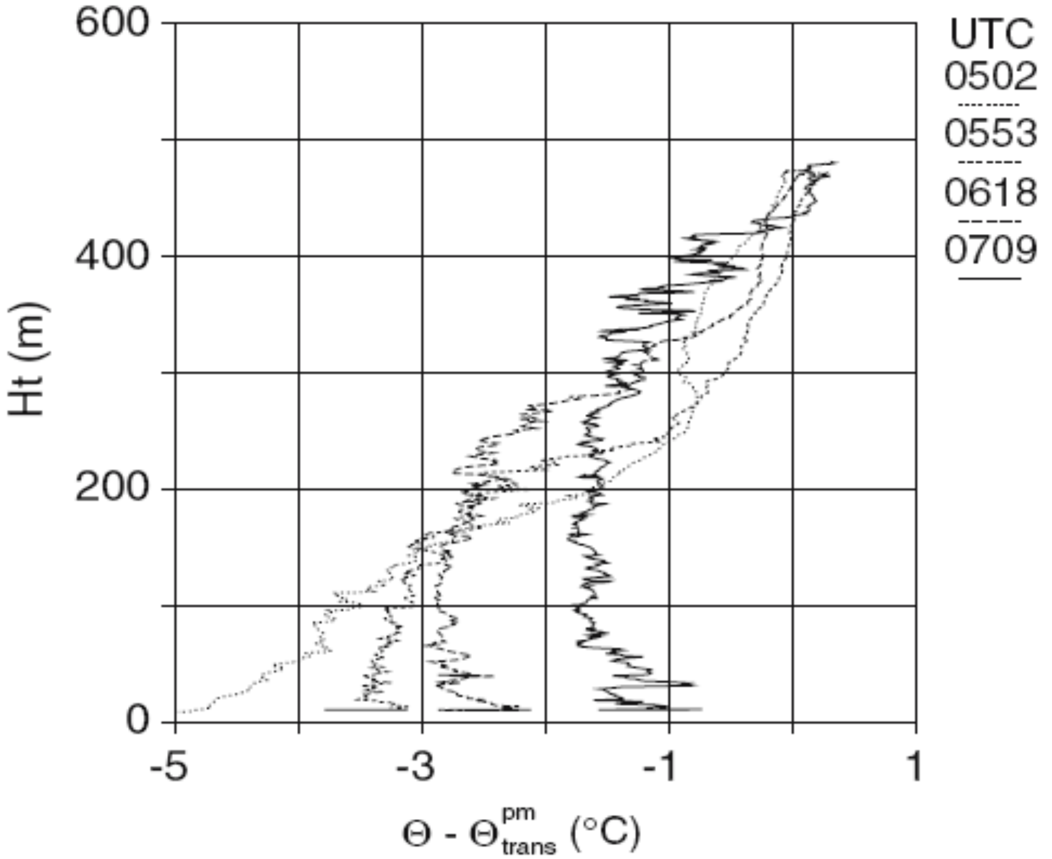
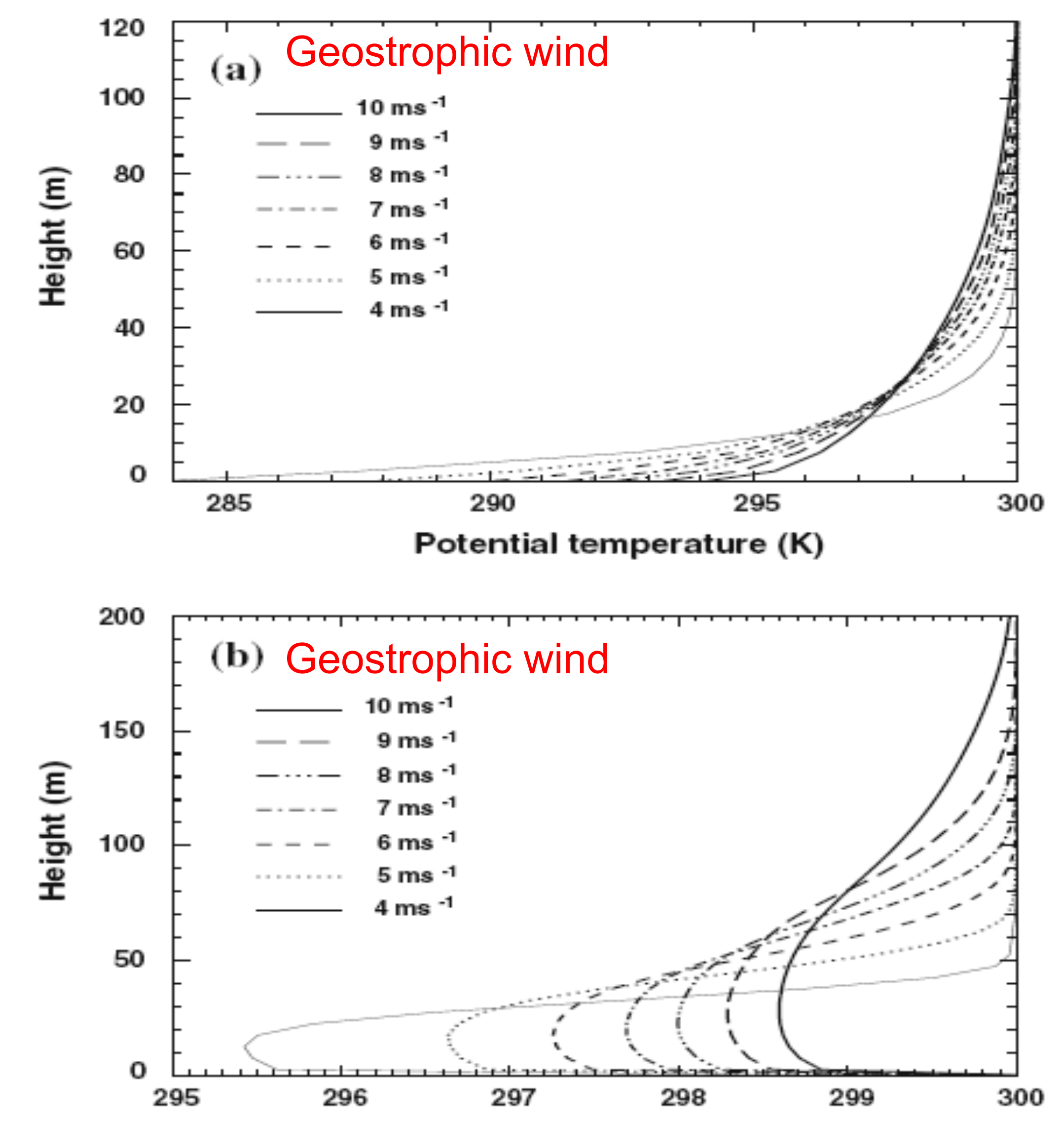
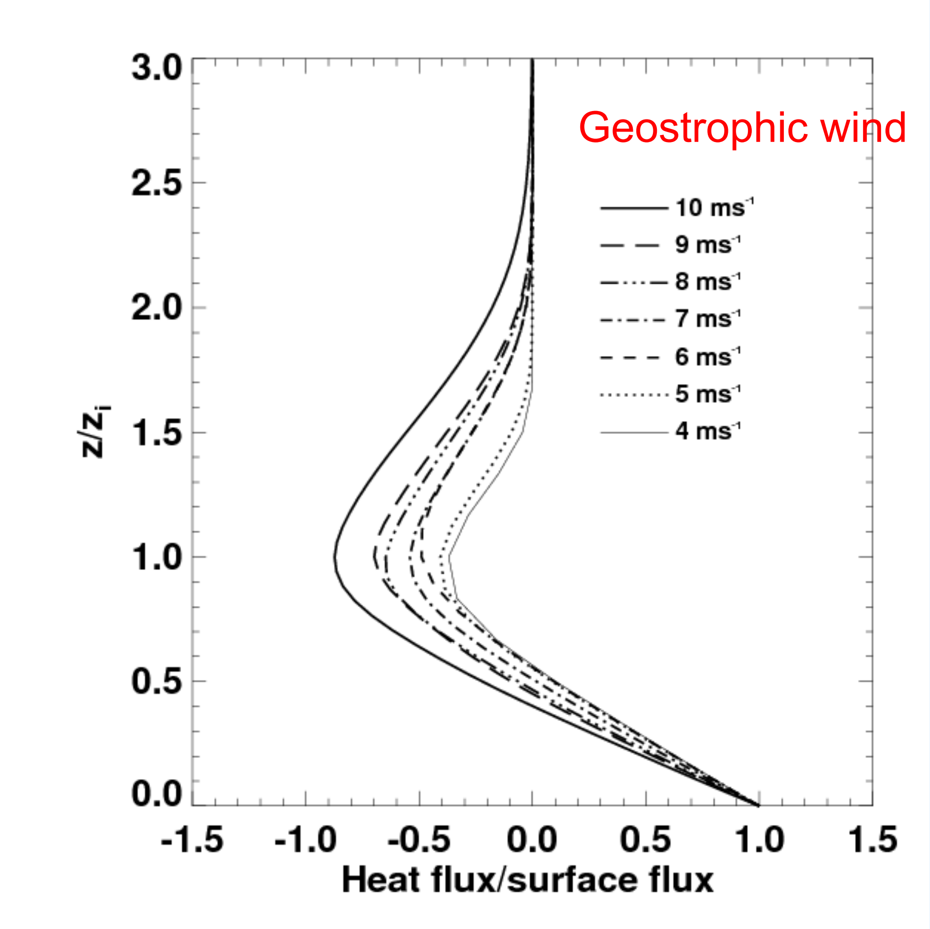


Figure 10. Observed profiles of potential temperature at Cardington during the morning of 10 July 2003, showing the increase in inversion height with surface heating. Gradient wind $U_g \approx 9\,\mathrm{m\,s^{-1}}$, cooling rate $r_c \approx 0.8\,°\mathrm{C\,h^{-1}}$, heating rate $r_h \approx 1.7\,°\mathrm{C\,h^{-1}}$, minimum overnight temperature $\Delta T_{min} \approx -6\,°\mathrm{C}$. For other definitions, see the legend to Figure 7.

Relation of stable boundary layer depth to geostrophic wind



Entrainment in the early morning mixed layer



Framework for boundary-layer parametrization in terra-incognita

1. Scaling for turning off column scheme

$$F_\theta = \frac{\partial}{\partial z}\left(K_h\left(\frac{\partial \theta}{\partial z} - \gamma\right)\right)$$

$$\beta = -\frac{\overline{w\theta_h}}{\overline{w\theta_0}} = \frac{C_f + A\left(u_*/w_*\right)^3}{1 + c_t/Ri_t}$$

$$\tau_{ij} = \nu\rho_0\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Scaling includes:

- Diffusion from sub-grid model,
- Diffusion from advection scheme
- Relevant integral scale

2. Modification for poor scale separation, e.g.: tensorial diffusion, stochastic backscatter or dynamic modelling?

Summary

- Terra-incognita for boundary layer modelling.
- Entrainment sensitive and non-linear function of grid length.
- Implicit diffusion from advection as important as sub-grid model diffusion.
- Implications for morning transition.
- Framework for parametrization.