Wind-turbine wakes in stable atmospheric boundary layers

Philip Hancock

and

Paul Hayden

EnFlo Laboratory, University of Surrey

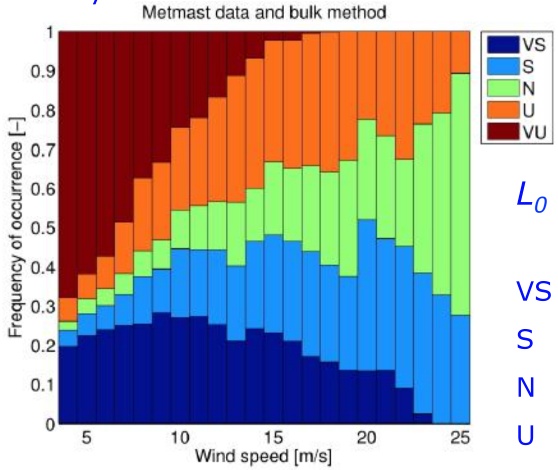
Offshore Wind 2018, Bremerhaven, Germany, 14-15th November.

Outline of presentation

- Some points about stability in the Atmospheric Boundary Layer (ABL)
- The EnFlo wind tunnel
- The model wind turbine (and instrumentation)
- Stable ABLs – no imposed inversion; with imposed inversion
- Wake measurements in stable ABLs
- Concluding comments

Example levels of stability - as inferred near the surface (in the surface layer)

North Hoyle[1]



L_0 = Obukhov length

VS $L_0 < 200$ m

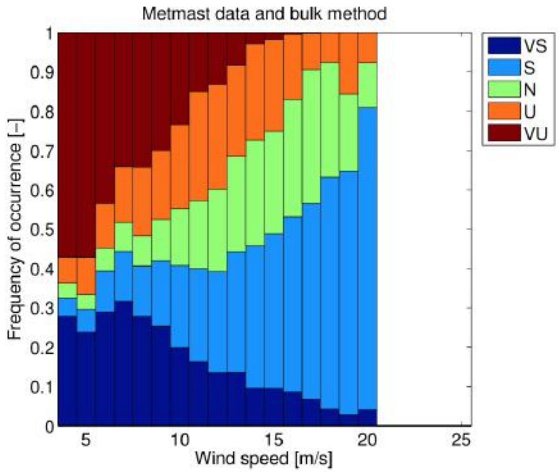
S $L_0 < 1000$ m

N $|L_0| > 1000$ m

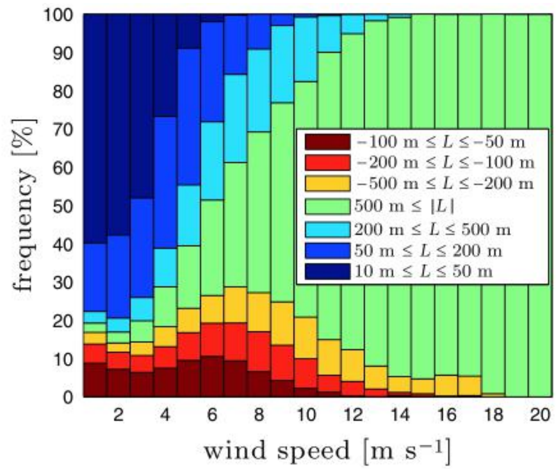
U $-1000 \text{ m} < L_0$

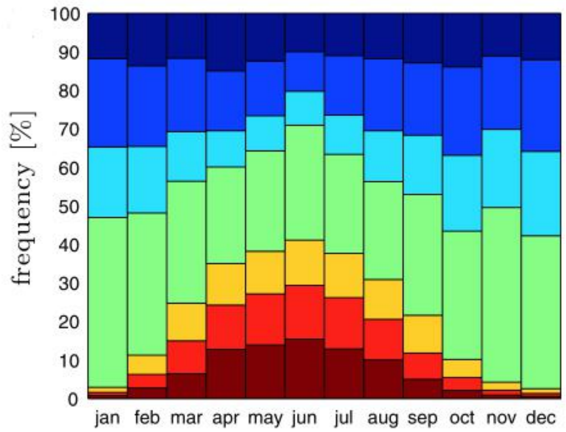
VU $-200 \text{ m} < L_0$

Egmond aan Zee[1]



Høvsøre[2]

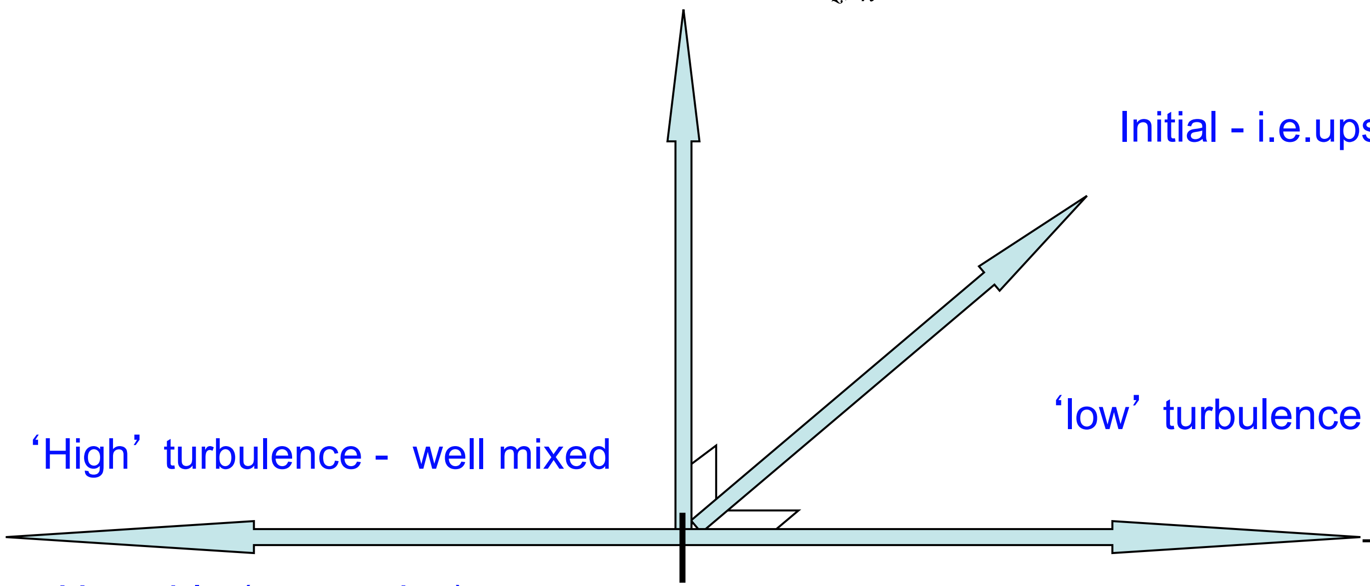




(1) Alblas, L, et al. (2014) J of Physics, Conf Series 555.

(2) Peña, A., et al. (2015) Boundary-Layer Meteorol.

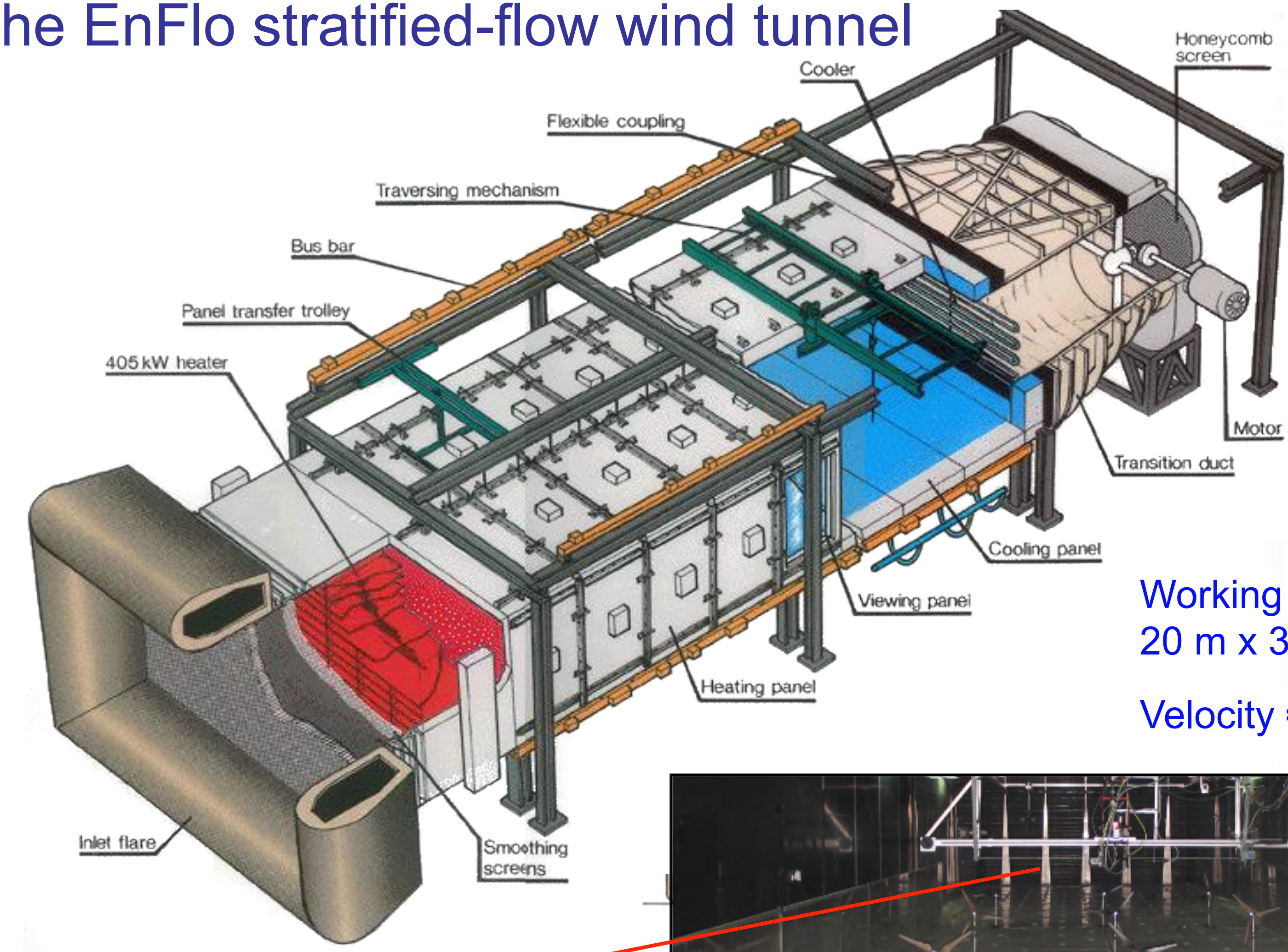
Independent parameters



ABL = Atmospheric Boundary Layer

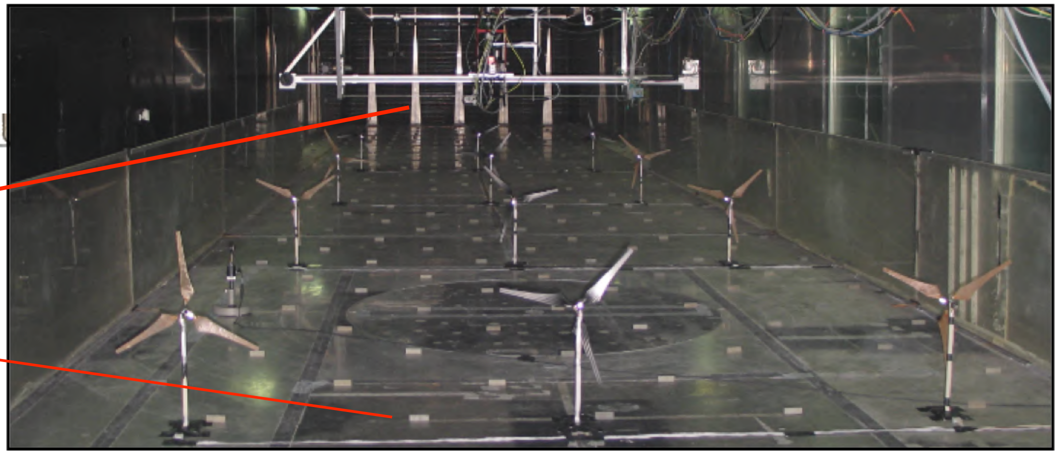
h = ABL height

The EnFlo stratified-flow wind tunnel



Working section size:
20 m x 3.5 m x 1.5 m

Velocity ≈ 1.5 m/s



Generators (spires)

Roughness elements

(for offshore)

The model turbine

1:300 scale "5MW turbine".

Model scale:

diameter = 416 mm.

design TSR = 6.

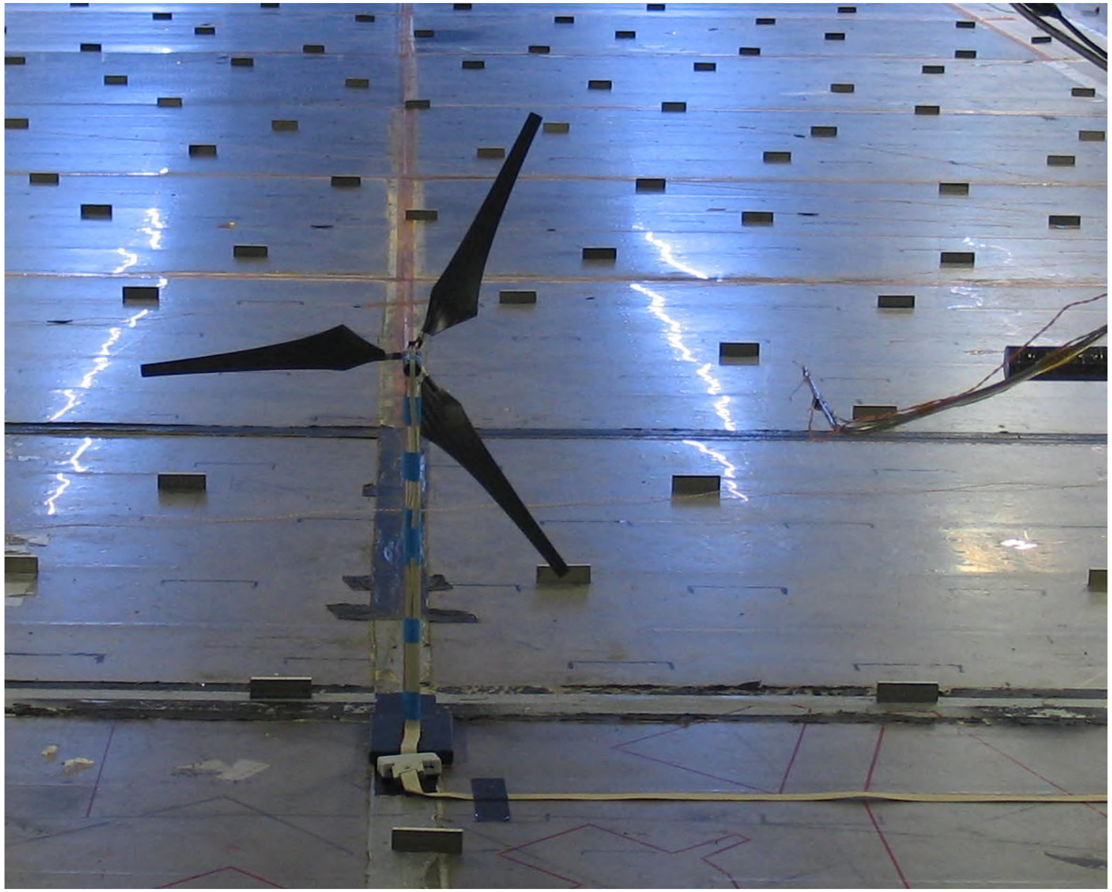
'flat-plate, large-chord' blades for low Reynolds number; twisted.

hub height = 300 mm.

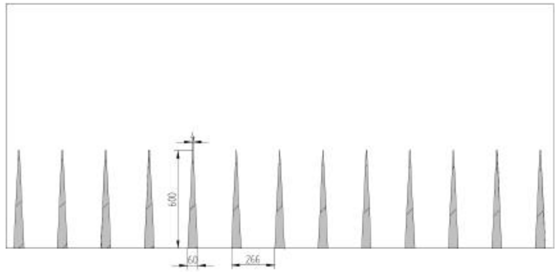
4-quadrant generator control.

Laser-Doppler two-component anemometry;

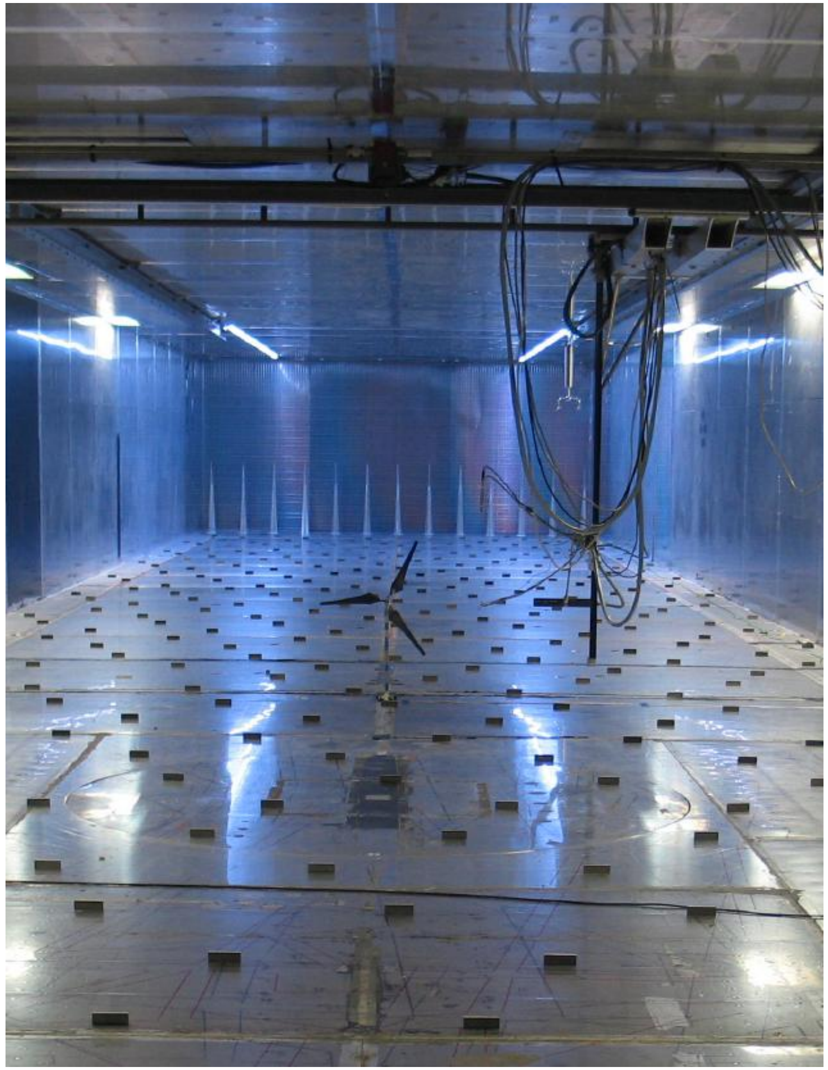
+ fast temperature probe to give turbulent heat flux.



Stable ABL setup



Small spires to represent smaller height of a stable boundary layer.



Inflow and initial surface conditions:

1 Uniform inlet temperature $\Theta(z)$

- simple, but does <u>not</u> work[1].

2 Non-uniform inlet profile,

- i.e. initial stratification

essential, but easy to get 'wrong'.

3 First part of floor must be uncooled.

[1] Hancock P E and Hayden P (2018) Boundary-Layer Meteorol.

Imposing an inversion

Inversion strength
$$\left.\frac{d\Theta}{dz}\right|_{z>h} = O\left(\frac{\Theta(h)-\Theta_0}{h}\right)$$

h = ABL height

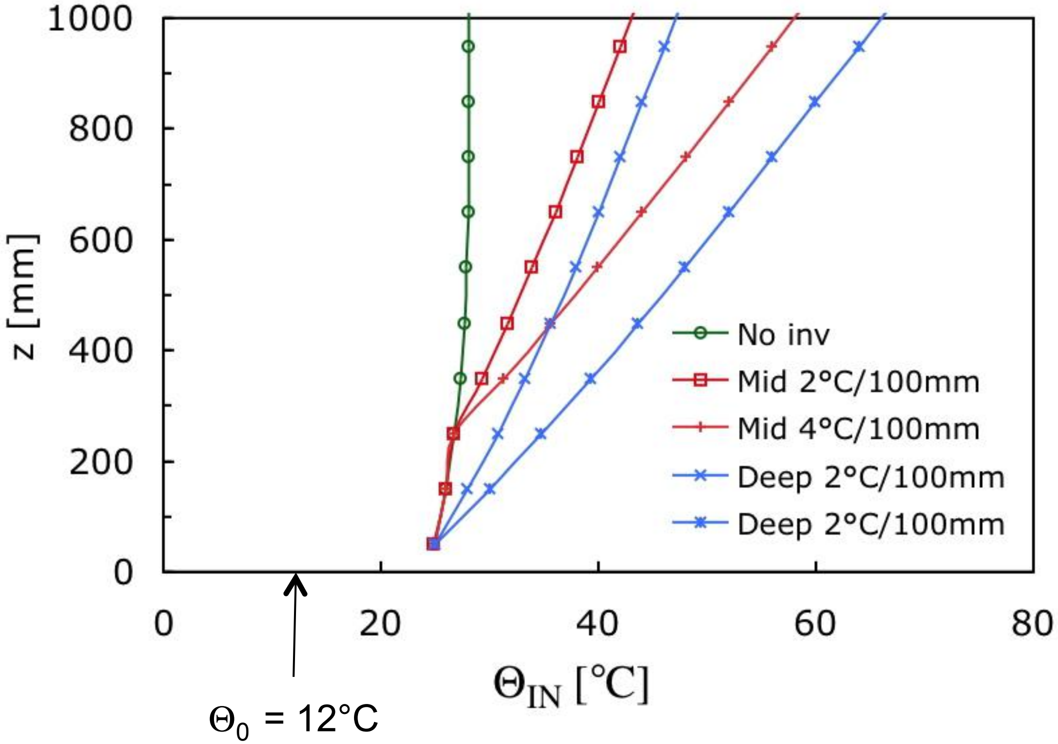
Θ_0 = surface temp

z > h - overlying inversion

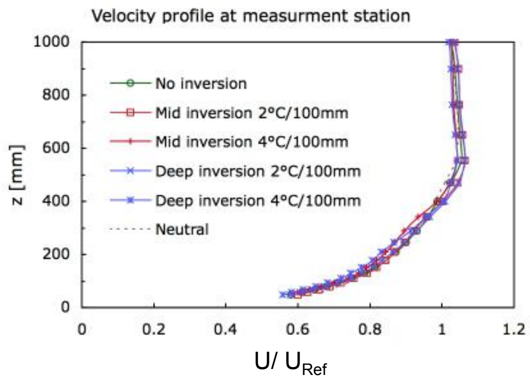
Depth of 'imposition':

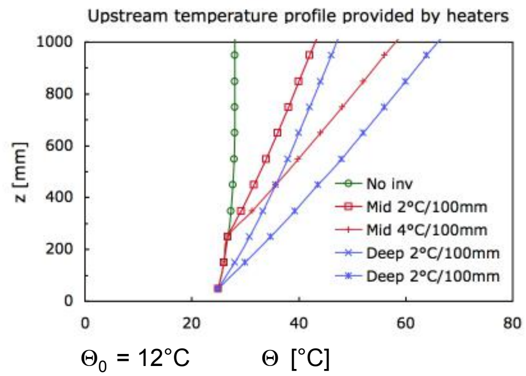
- Mid height of ABL
- Deep into ABL
  - into surface layer.

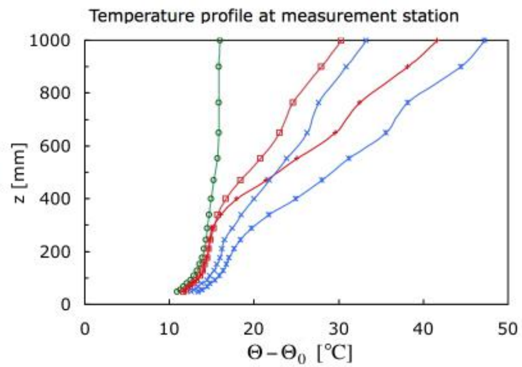
Imposed by inlet heaters.



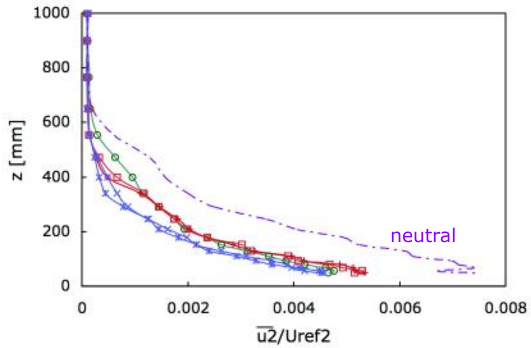
Stable ABLs - with imposed inversion: four cases + no inversion case

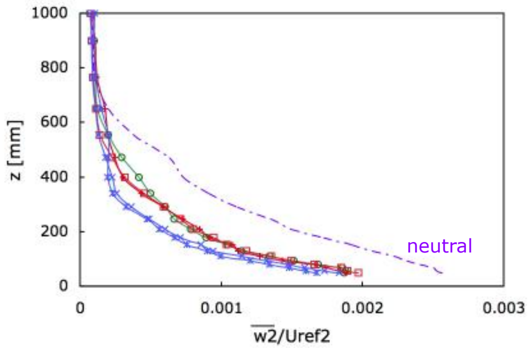


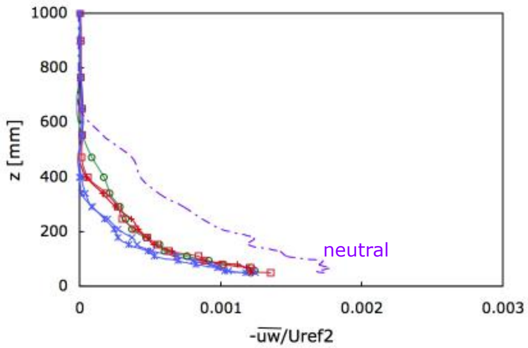


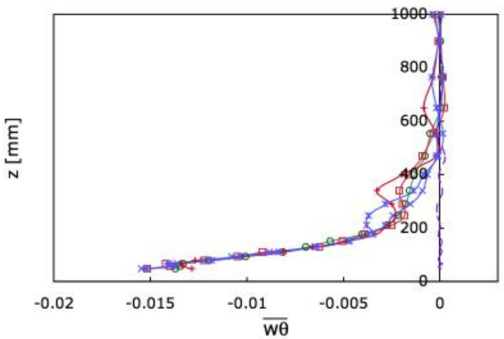


Reynolds stresses:









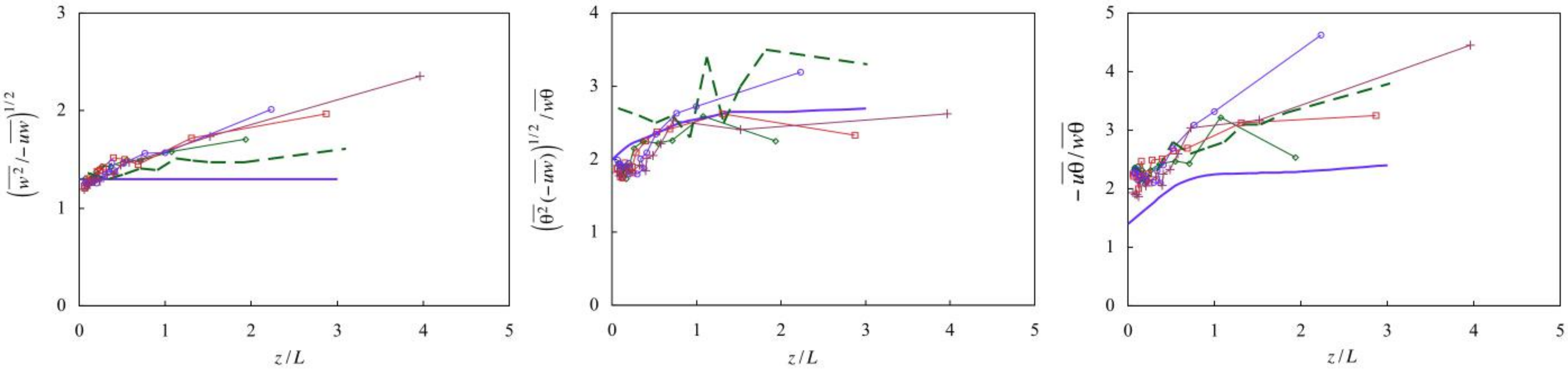
Nieuwstadt's local similarity scaling

Structural parameters as functions of *local* Obukhov length, *L*.

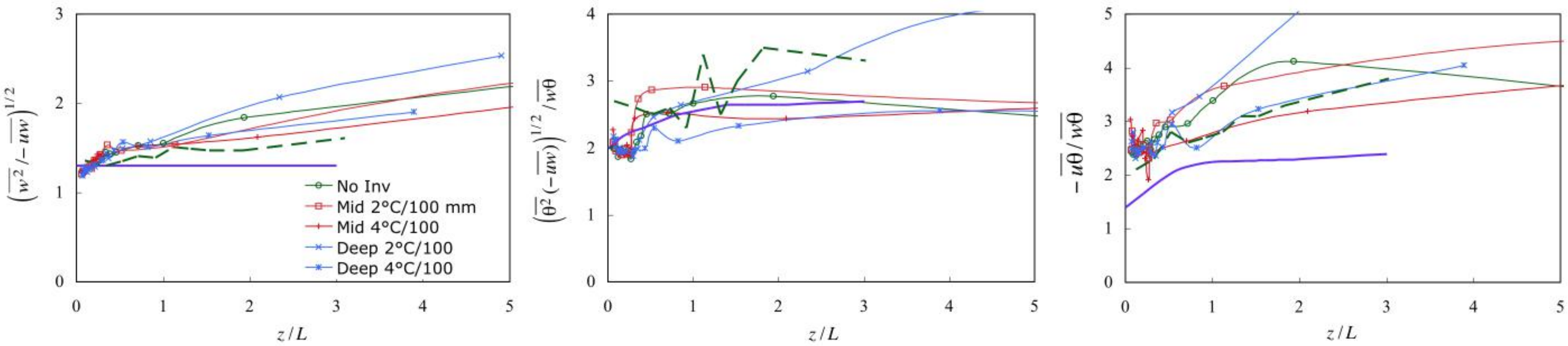
$$L \equiv -\frac{1}{\kappa}\frac{\Theta}{g}\frac{(-\overline{uw})^{3/2}}{\overline{w\theta}}$$

$$\left(\overline{w^2}/-\overline{uw}\right)^{1/2}, \quad \left(\overline{\theta^2}(-\overline{uw})\right)^{1/2}/\overline{w\theta}, \quad -\overline{u\theta}/\overline{w\theta}, \quad = F(z/L).$$

No inversion (at 4 streamwise stations) Full line: Nieuwstadt (1984); Broken line: Cabauw field data

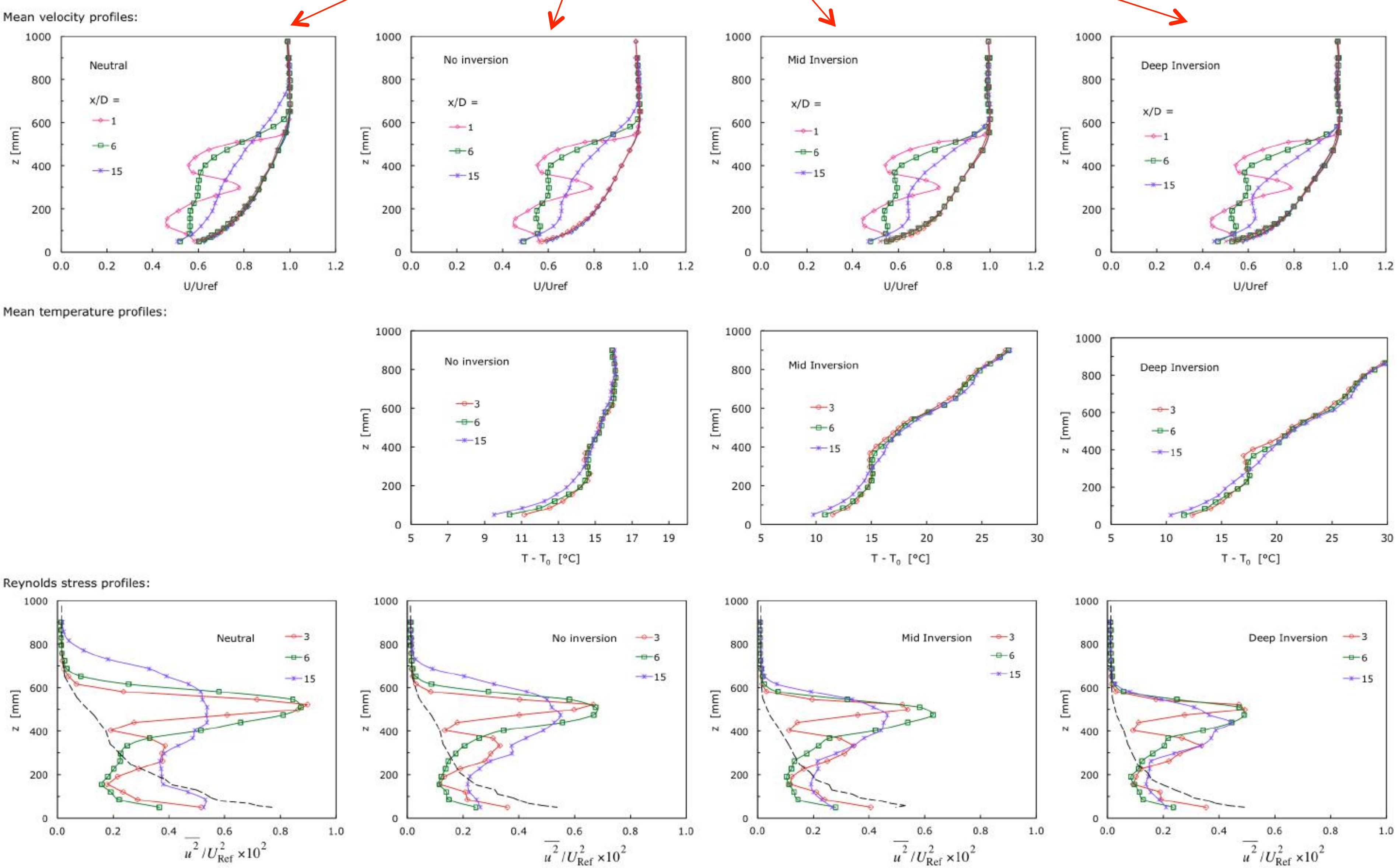


Four inversion cases (and no-inversion case)



Nieuwstadt FTM (1984) The turbulent structure of the stable, nocturnal boundary layer. J Atmos Sci 41, 2202-2216.
Hancock P E and Hayden P (2018) Boundary-Layer Meteorol.

Wake cases: neutral; no inversion; mid inversion; deep inversion



Concluding points - the ABL

Good progress in ABL simulation:

- of moderately-stable layer with imposed inversions of various strengths and penetrations
- good agreement with Nieuwstadt's local scaling, and with Cabauw field data.
- also good agreement with Sorbjan's scaling[1] (not shown)

The ABL:

Effects of the inversion are localized – and only small effect on near-surface heat fluxes.

Surface-layer scaling still applies.

Flow in top 2/3 depends in a complex way on the inversion.

Surface and imposed conditions are *in*dependent of each other.

[1]Sorbjan Z (2010) Q J R Meteorol Soc.

Concluding points - the wake

The Wake:

Wake develops progressively more slowly when an inversion is imposed.

Vertical growth almost ceases for the deep-inversion case.

Turbulence levels progressively reduced.

Separate from scale effects – deeper Neutral ABL

Further work:

Wake data as test-case data.

Infer physics of turbulence structure

- expect a) 'near wake' controlled by ABL turbulence,

b) 'far wake' to be *directly* affected by stable stratification