The collapse
of atmospheric turbulence…

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The Turbulent Structure of the Stable, Nocturnal Boundary Layer

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1. Introduction

Much progress has recently been made in the study of the daytime, convective boundary layer. Its turbulent structure has been described very satisfactorily in terms of so-called mixed-layer scaling (Kaimal *et al.*, 1976). In contrast, the study of the nocturnal, stable boundary layer is considerably less advanced and no scaling rules for it are as yet firmly established. In this investigation we will consider turbulence in stable circumstances. Our goal is twofold: first we formulate a scaling hypothesis for stable turbulence and then we apply it to explore the vertical turbulent structure of the nocturnal boundary layer.

The stable boundary layer is a notoriously difficult subject, not least because it occurs in various manifestations, each dominated by different physical processes. A few examples of such processes are topographical slope effects (Brost and Wyngaard, 1978), intermittent turbulence (Kondo *et al.*, 1978), and internal gravity waves (Finnigan and Einaudi, 1981). Each of these cases may require a different approach.

Another factor complicating a study of the nocturnal boundary layer is the lack of observations, especially above the surface layer. For this reason we conducted a number of experiments at the meteorological mast at Cabauw, The Netherlands. In these experiments, the measurement of vertical profiles of turbulence is emphasized. We select cases which are characterized by continuous turbulence and which do not show the presence of significant gravity-wave activity. Furthermore, the terrain rules out slope effects. This type of boundary layer develops frequently at Cabauw as a consequence of forcing by a sufficiently strong geostrophic wind (no less than ~5 m s^{-1}). It is considered to be representative of a stable boundary layer over flat terrain and we adopt it as the subject of this study.

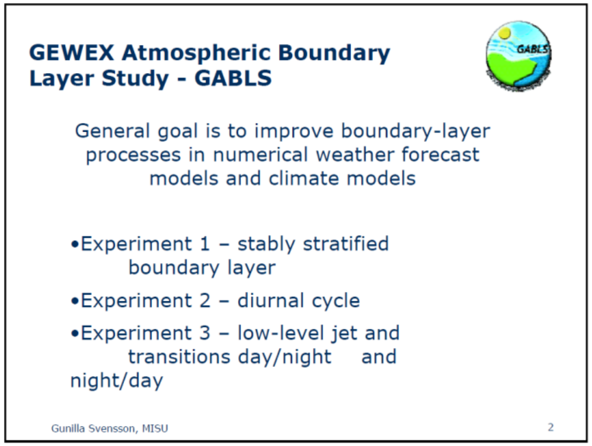
Previous studies of the turbulent, stable boundary layer (Caughey *et al.*, 1979; Mahrt *et al.*, 1979; Yamada, 1979) have presented turbulence variables, scaled in terms of the surface-layer fluxes u_*^2 and $\overline{w\theta}_0$, as a function of z/h, where h is the boundary-layer height. For instance, $\tau/u_*^2 = f(z/h)$ or $\overline{w\theta}/\overline{w\theta}_0 = f(z/h)$, where $\tau(z)$ and $\overline{w\theta}(z)$ are the kinematic momentum and heat fluxes, respectively. The adoption of such a procedure as a scaling hypothesis is justified only if the boundary-layer height can be taken as the representative length scale of turbulence. However, in stable conditions vertical motion is restricted. Consequently, turbulent eddies cannot extend across the whole boundary layer, so that the use of h as a characteristic scale is not necessarily appropriate. Therefore we adopt another approach here. The point of departure will be the existing theory of turbulence in stable conditions (Wyngaard, 1975; Brost and Wyngaard, 1978; Fitzjarrald, 1979). We show that this theory can be restated

Terre Incognita ?

GABLS I: Ugeo = 8 m/s

GABLS II: Ugeo = 9.5 m/s

GABLS III: Ugeo = 6.7-7.9 m/s



GEWEX Atmospheric Boundary Layer Study - GABLS

General goal is to improve boundary-layer processes in numerical weather forecast models and climate models

- Experiment 1 – stably stratified boundary layer
- Experiment 2 – diurnal cycle
- Experiment 3 – low-level jet and transitions day/night and night/day

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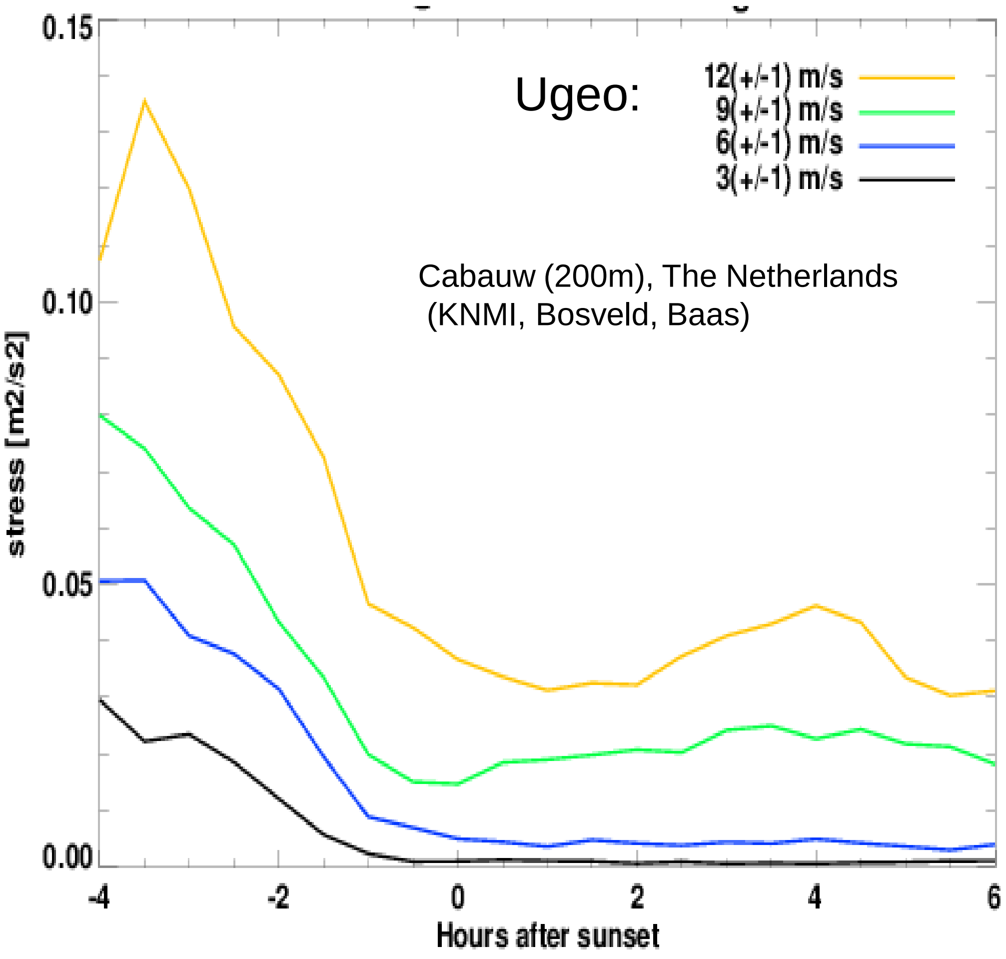
(Source: Svensson & Holtslag)

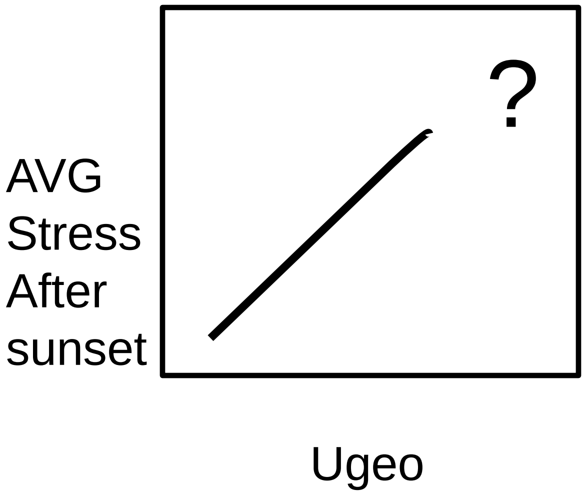
But what when 0< Geo < 6 m/s……?

- Cessation of evening turbulence & temperature extremes



Ugeo:

Cabauw (200m), The Netherlands
(KNMI, Bosveld, Baas)



AVG
Stress
After
sunset

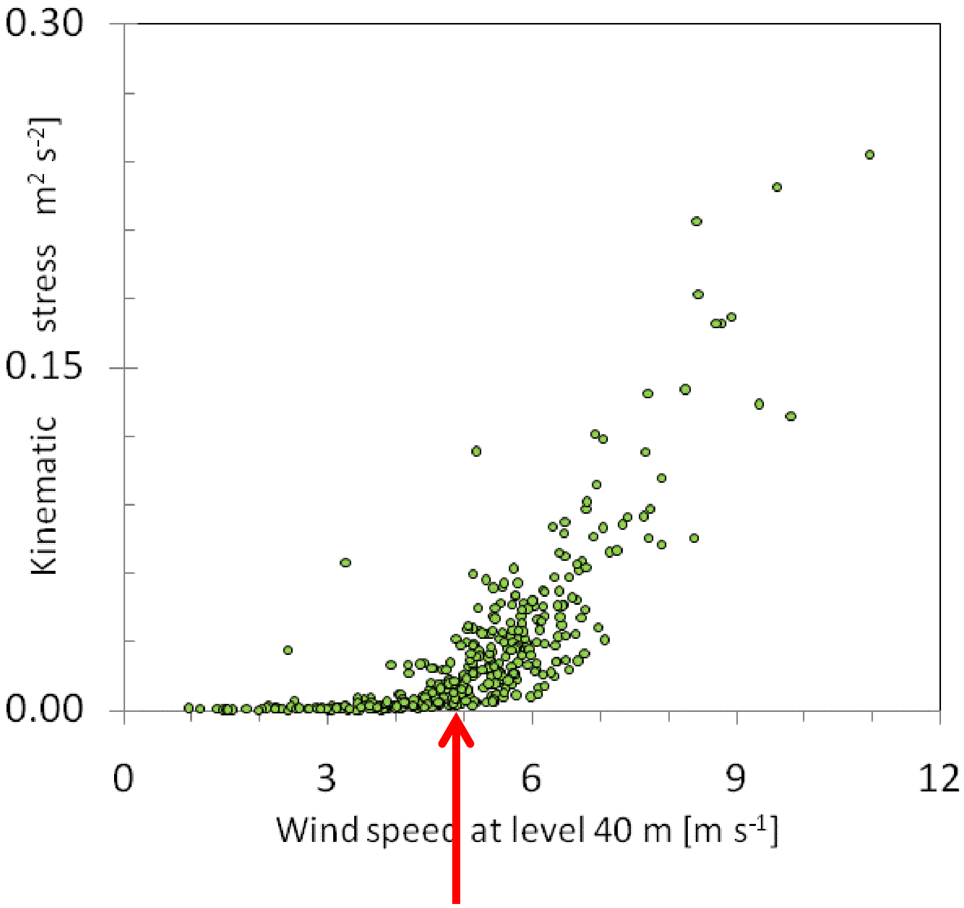
Ugeo

Cabauw

- 397 clear nights
- 4-hour evening averages stress and wind speed

Cabauw (200m), The Netherlands
(KNMI, Bosveld, Baas)

Hockey-stick



Goal: find mechanism & predict threshold

..a minimum wind speed needed for sustaining turbulence

Today

1: ‘naïve’ model based on MO under assumption fixed bulk shear

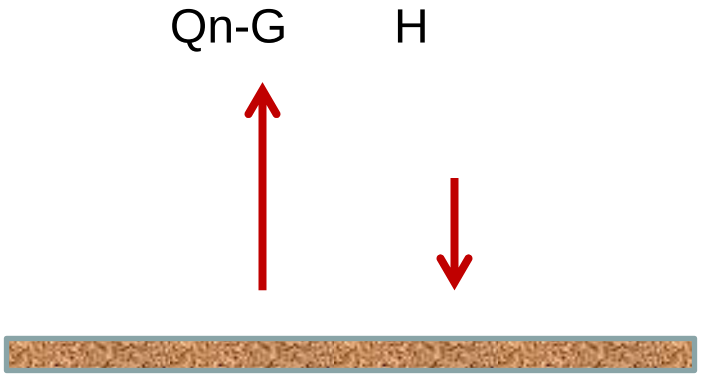
2: fixed shear assumption must be wrong **on long term!**

3: ….but **on short-term** it appears to be realistic!

4: application model formerly known as ‘naïve’

(1) MO-answer

Simplified surface energy balance:



Collapse possible when:

|Qn-G| > |H|

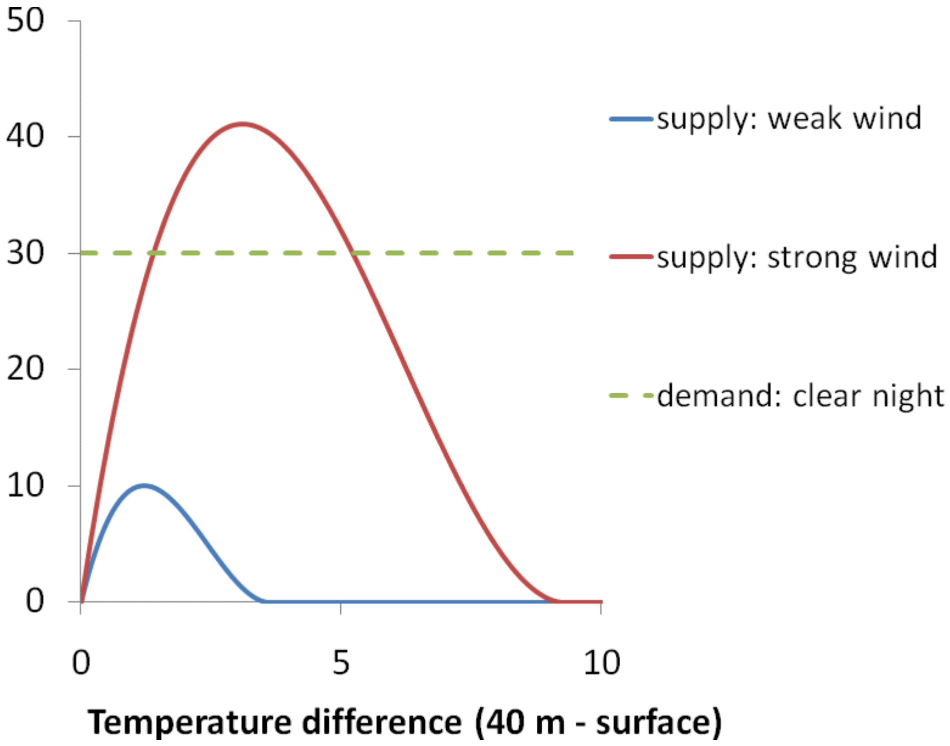
….. surface inversion intensifies, H to decreases further ! (pos. feedback)

Mechanism likely during clear skies, weak winds

(1) MO-answer

e.g. from Businger-dyer:

$$H = \rho c_p c_D U \Delta T \cdot (1 - \alpha R_b)^2$$



‘parabolic’ graph known since Taylor (1971),

Later e.g. : Malhi, Mahrt, Delage, Derbyshire, Van de Wiel, Basu,

Here: **consequences** explicitly interpreted in term of surface energy balance:

The maximum sustainable heat flux

Our ‘naïve’ model

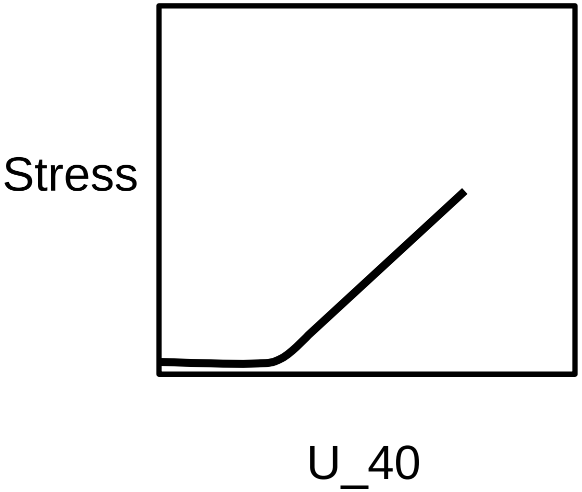
For each fixed value of U_40 , diagnose if solution is possible in:

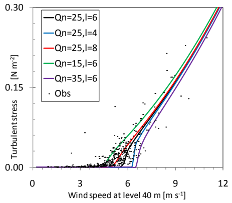
$$|Q_n| - |\lambda \Delta T| - |\rho c_p c_D U \Delta T \cdot f(R_b)| = 0$$

ΔT Is found, and stress diagnosed via:

$$\tau = \rho c_D U^2 \cdot f(R_b)$$

Finally:





..is it that simple?

(2) Unfortunately,…

Atmospheric bulk shear (or wind) is not fixed!

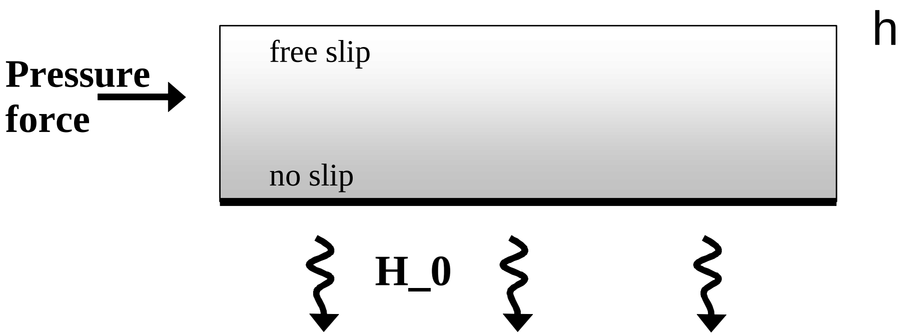
Pressure driven flows **recover** after collapse: shear increases….

… ‘naïve’ MO-approach appears good for wrong reason….

Step 3: deeper analysis needed on shear evolution:

theoretical channel flow

Stratified channel flow



h

Pressure force

free slip

no slip

H_0

No heat flux at z=h

Extraction heat
normalized as:

$$h/L_{EXT} = \frac{\kappa g h}{T_{ref}\,\rho\, c_p}\cdot\frac{H_0}{u_{*EXT}^3}$$

$$u_{*EXT} \equiv \sqrt{-(1/\rho)(\partial P/\partial x)h}$$

Multilayer model

$$\frac{\partial U}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}\frac{\partial \tau}{\partial z}$$

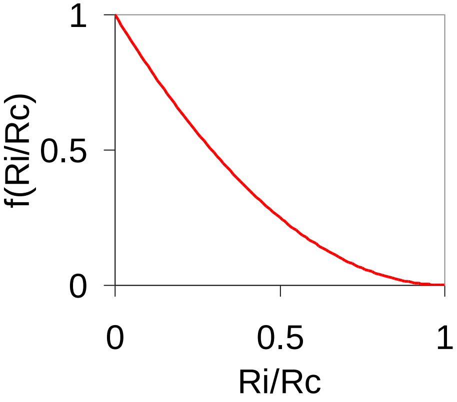
$$\frac{\partial T}{\partial t} = -\frac{1}{\rho c_p}\frac{\partial H}{\partial z}$$

local scaling (N84)
(log-linear similarity functions)

$$\boxed{\frac{\tau}{\rho} = K_m \frac{\partial U}{\partial z}}$$

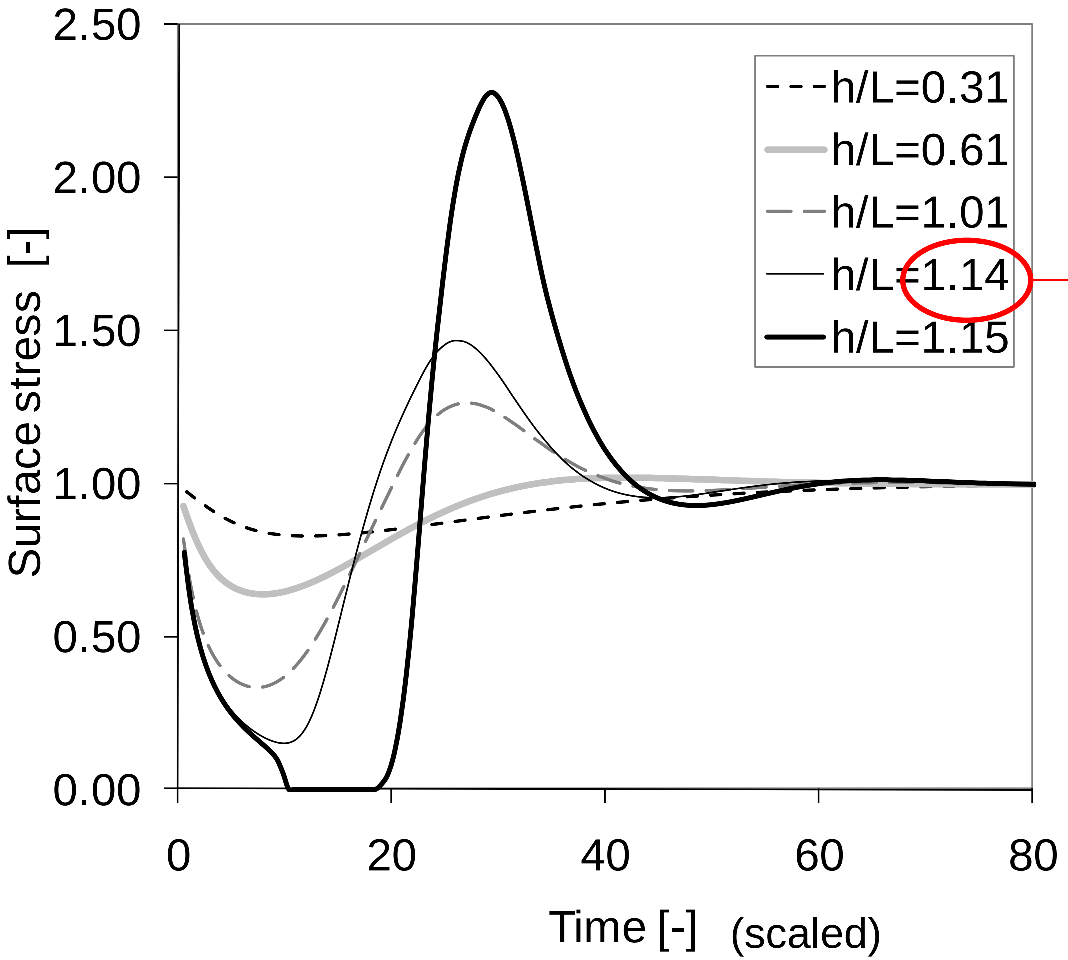
$$\boxed{\frac{H}{\rho c_p} = -K_H \frac{\partial T}{\partial z}}$$

$$K_{H,m} = l_n^2 \, (\partial U / \partial z) \, f\left(Ri\right)$$



100 vertical levels

Collapse of turbulence



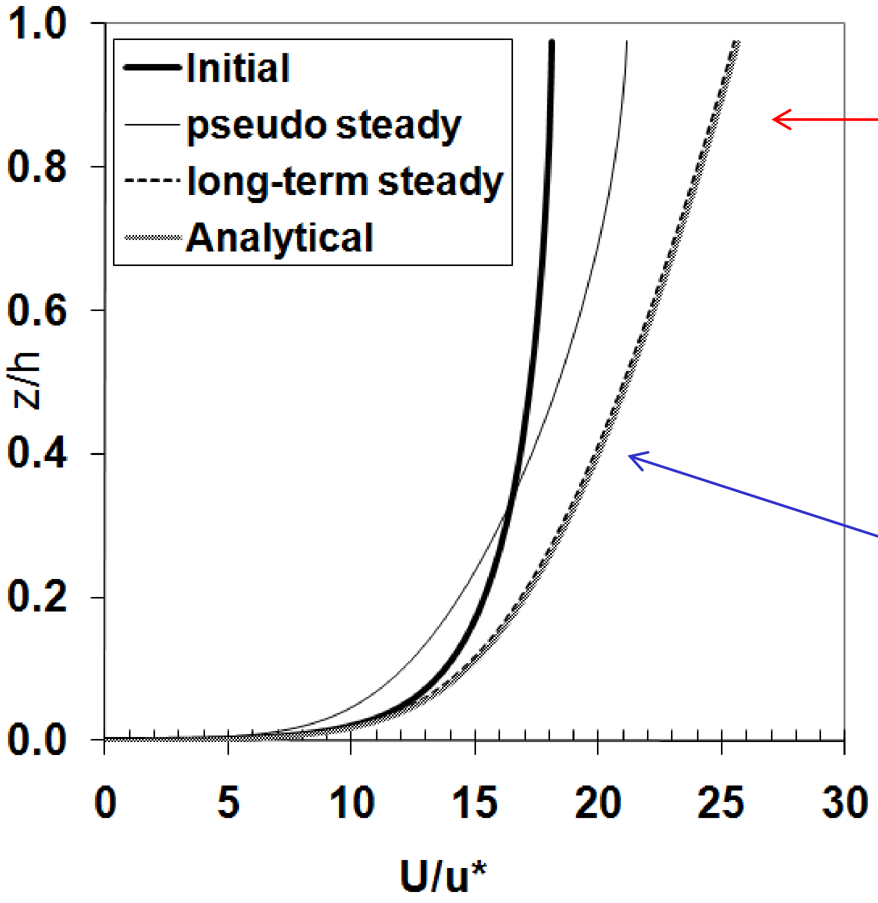
h/L =surface heat extraction

Maximum sustainable flux

← Inevitable recovery!

Our challenge
in transient part!

Wind profile development



More shear than in neutral conditions

Solution, next slide:

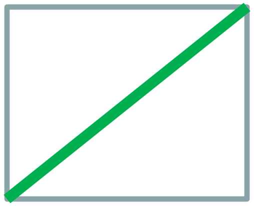
Long-term analytical solution

$$\frac{\partial U}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}\frac{\partial \tau}{\partial z} \qquad \frac{\partial T}{\partial t} = -\frac{1}{\rho c_p}\frac{\partial H}{\partial z}$$

$$z = z_0 \quad \begin{cases} U = 0 \\ H = H_0 \end{cases}$$

In steady-state :

$$0 = \frac{\partial(\partial U/\partial z)}{\partial t} = \frac{1}{\rho}\frac{\partial^2 \tau}{\partial z^2} \qquad 0 = \frac{\partial(\partial T/\partial z)}{\partial t} = \frac{1}{\rho}\frac{\partial^2 H}{\partial z^2}$$



$$z = h \quad \begin{cases} \tau = 0 \\ H = 0 \end{cases}$$

$$\tau, H = f(\partial U/\partial z, \partial T/\partial z,)$$

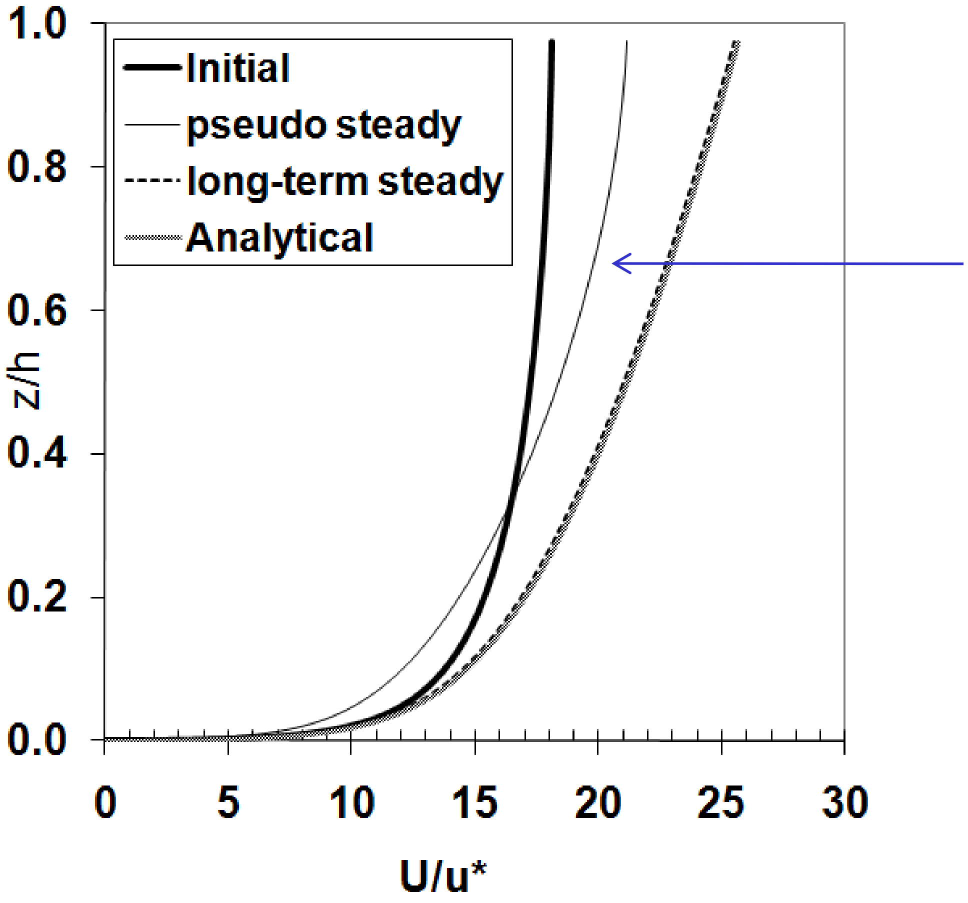
Solution:

…with q=z/h

$$\boxed{\kappa \frac{U(q)}{u_{*EXT}} = \left[2\sqrt{1-q} - 2\,\mathrm{atanh}\sqrt{1-q} + \alpha q \frac{h}{L}\right] - \left[2\sqrt{1-q_0} - 2\,\mathrm{atanh}\sqrt{1-q_0} + \alpha q_0 \frac{h}{L}\right]}$$

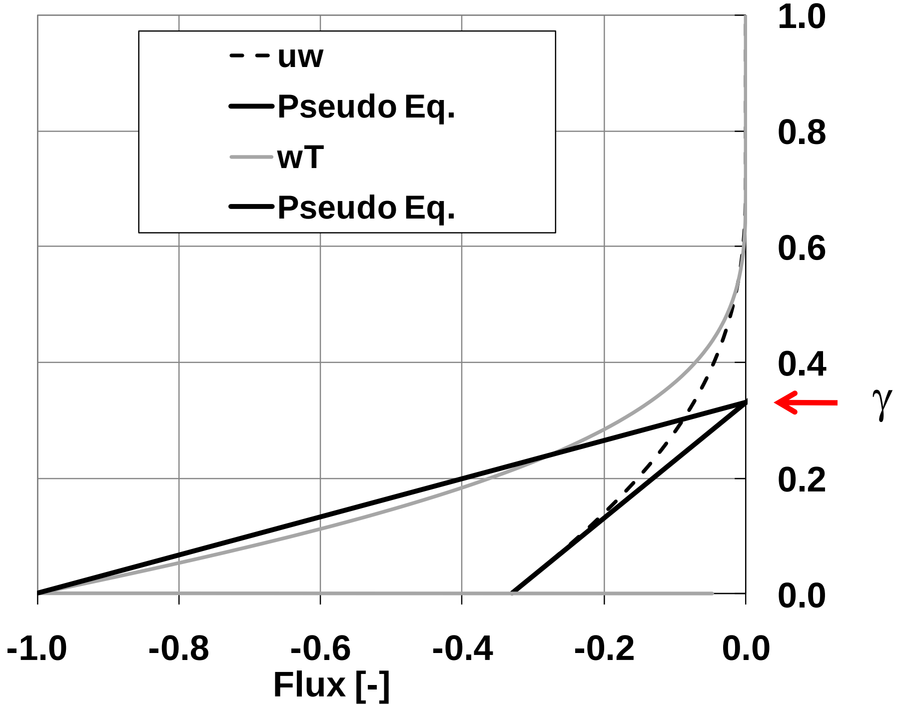
Assymptotically converges to MO close to surface

Wind profile development



Can we make quantitative prediction on transient shape?

Pseudo-steady state concept



..resembling long-term steady state

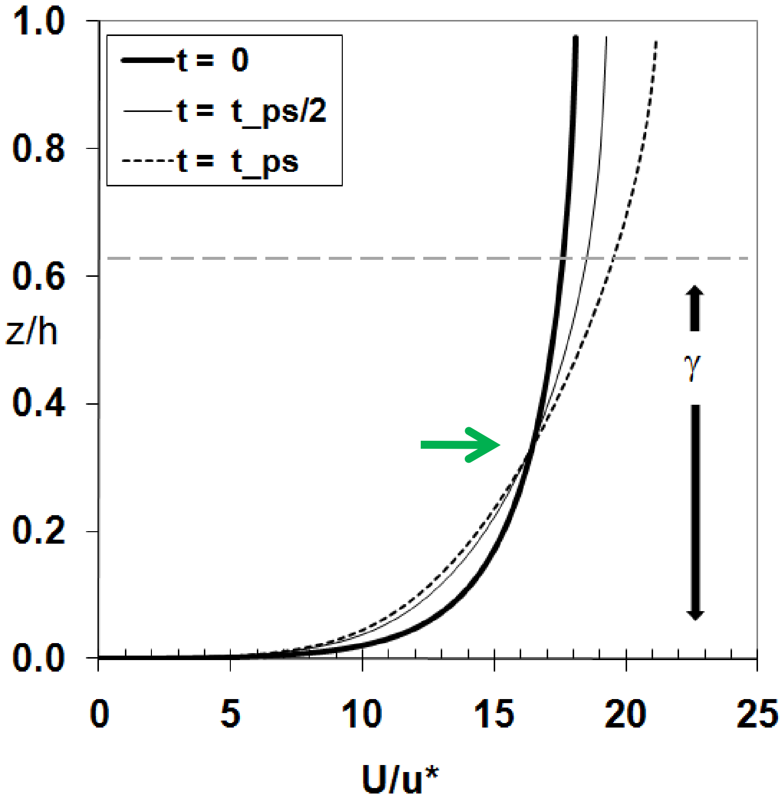
gamma instead of h!

Long-term steady state: surface stress/h = pressure gradient

Here: surface stress (and **hence** gamma) is unknown!

Alternative momentum constraint needed →

Profile development



1) Momentum tends to be conserved over depth gamma:

$$\int_{q0}^{\gamma}\left(\hat{U}(\hat{t}_{PS})-\hat{U}(0)\right)dq \approx 0$$

2) A velocity crossing point appears

…Due to rapid redistribution of momentum in lower domain

Hint

One conclusion can already be made:

Existence point of fixed velocity suggest
Rehabilitation naïve collapse mechanism!

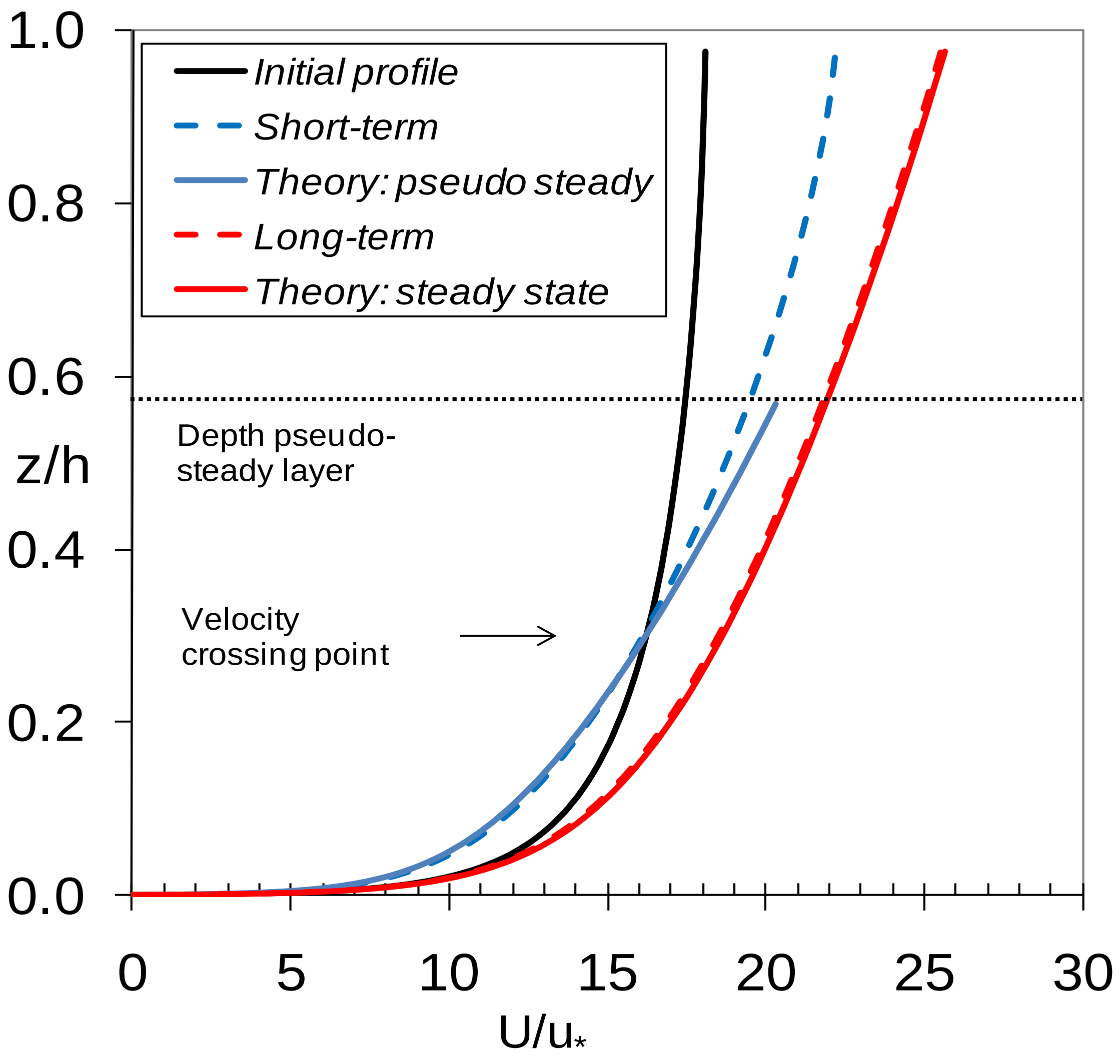
Next, assume explicitly:

$$\int_{q0}^{\gamma} \left(\hat{U}(\hat{t}_{PS}) - \hat{U}(0) \right) dq \approx 0$$

Now **Initial momentum & surface cooling**

determine the pseudo-steady solution →

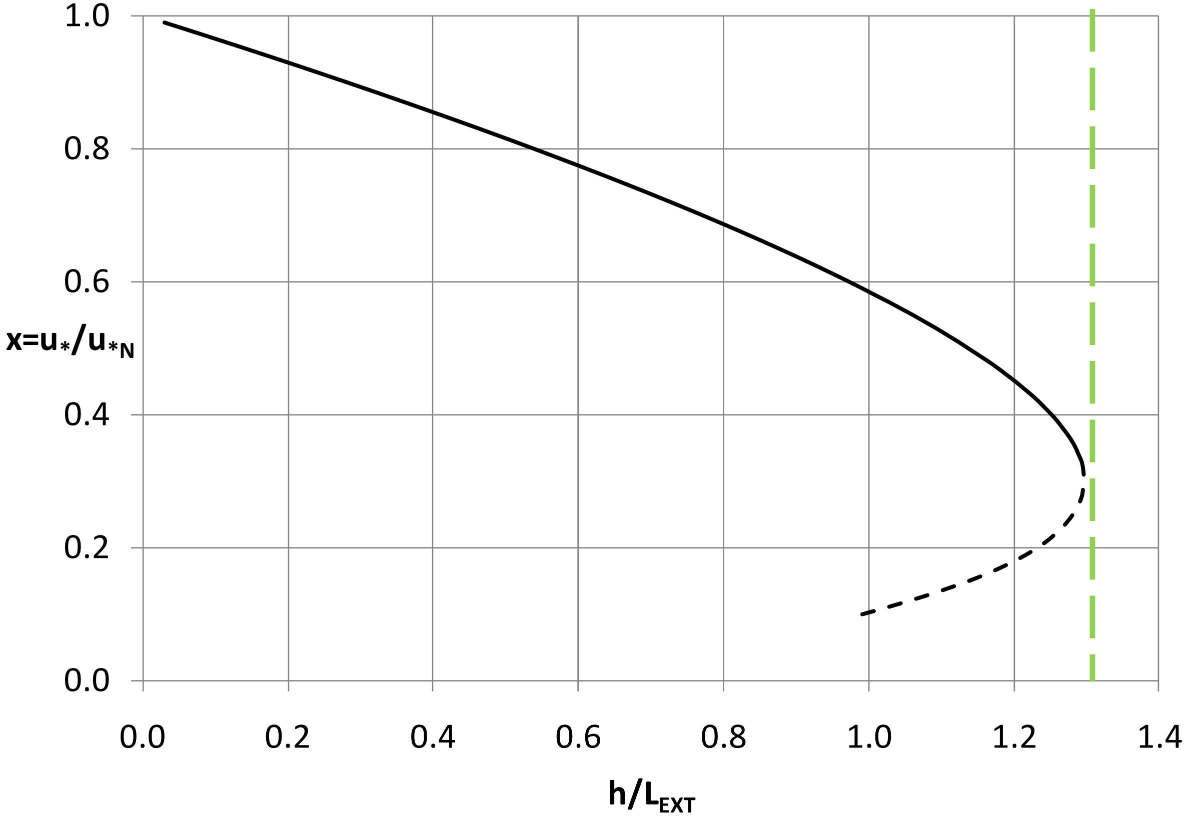
Validation (I)



model predicts level crossing point, all cases!

Validation (II)

Solution curve for given initial momentum and surface heat extraction



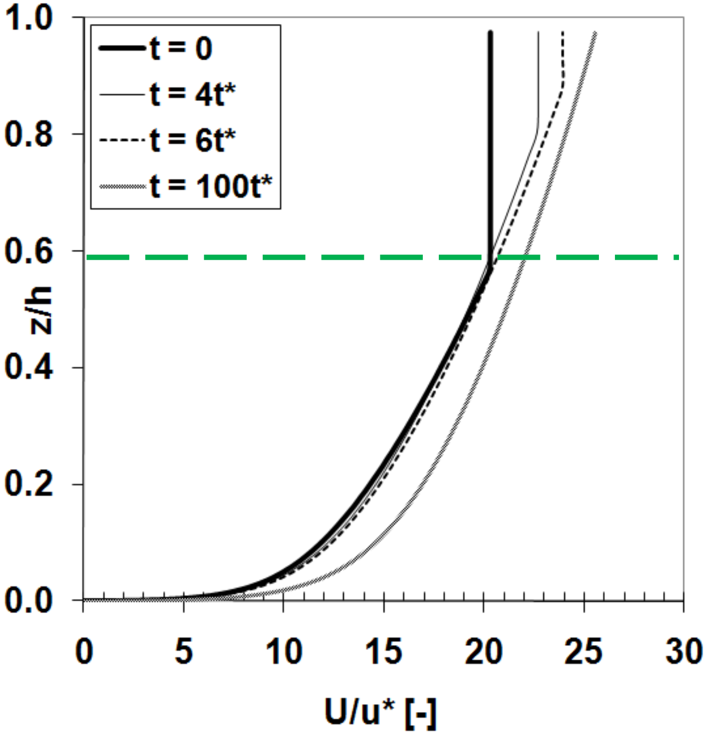
Theoretical maximum sustainable heat flux: h/L_max=1.29

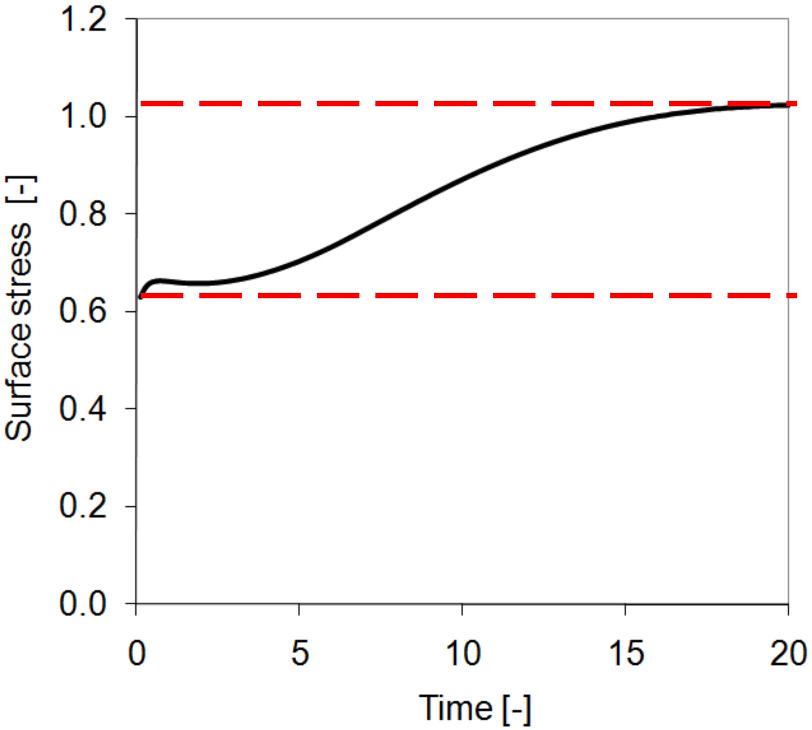
Numerical simulations indicate: h/L_max=1.14

pseudo-steady state real thing ?

With **pseudo-steady initial condition**

system should be ‘happy’ for a while:

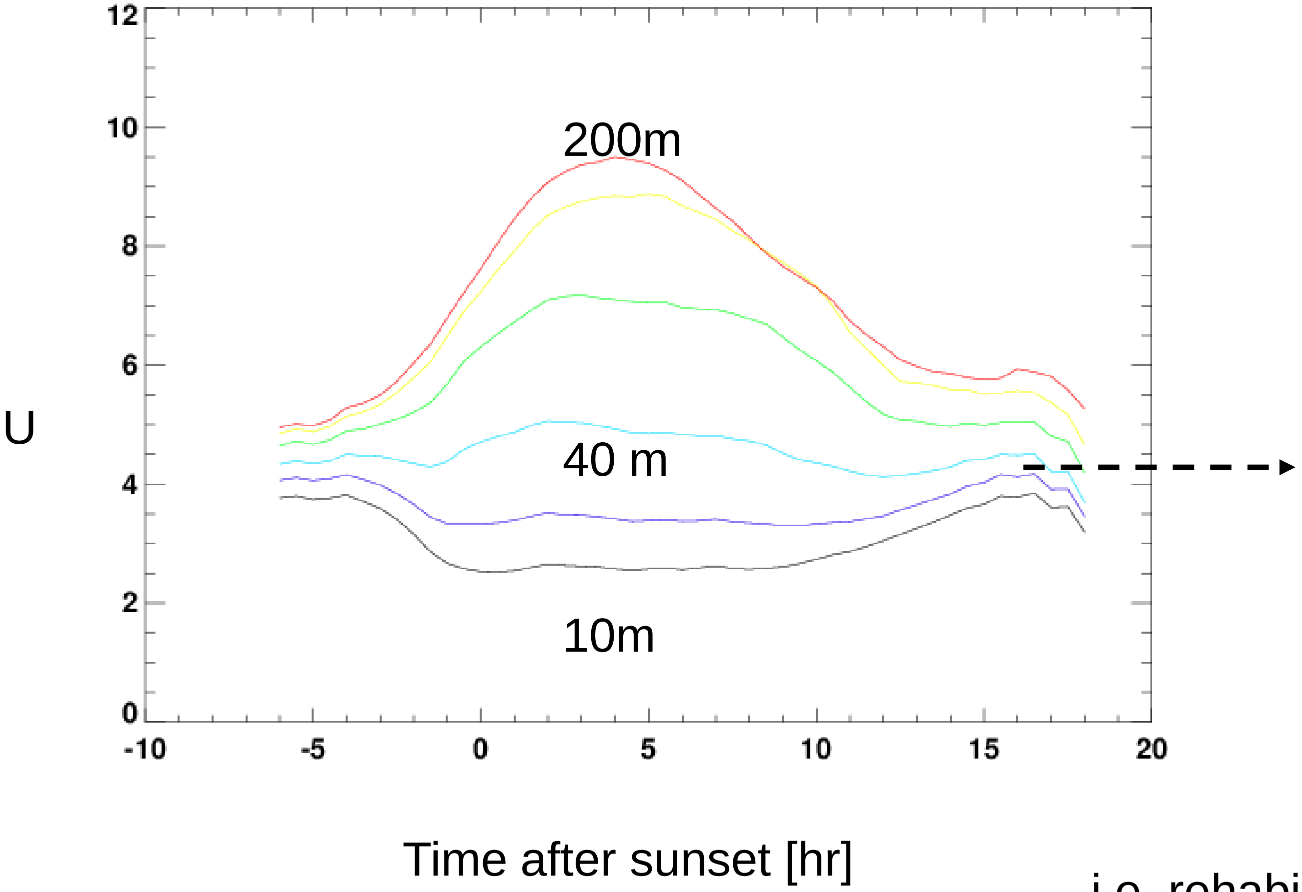




system indeed ‘locked’
in this initial condition

Back to Atmosperic BL

Wind speed composite from cases with 5<Ugeo<10



Appears constant around 40m

i.e. rehabilitation fixed wind assumption!

The ‘naïve’ model valid again:

For each fixed value of U_40 one can diagnose if a solution is possible in:

$$|Q_n| - |\lambda \Delta T| - |\rho c_p c_D U \Delta T \cdot f(R_b)| = 0$$

ΔT Is found, and stress diagnosed via:

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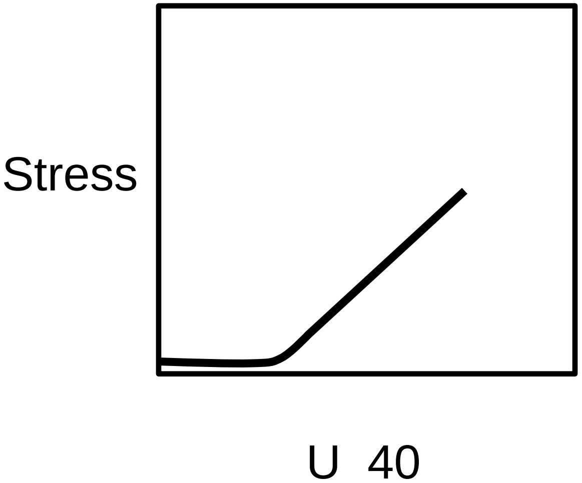
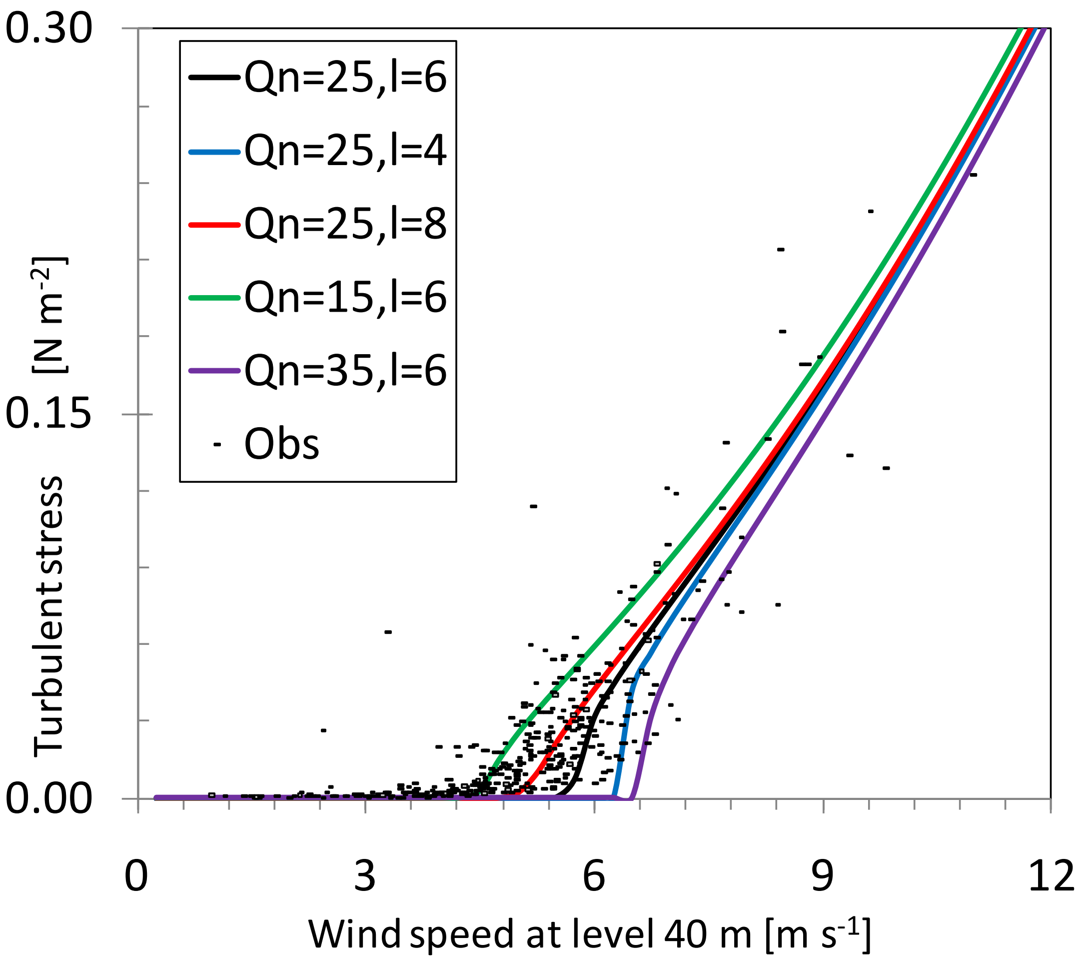


Prediction critical speed



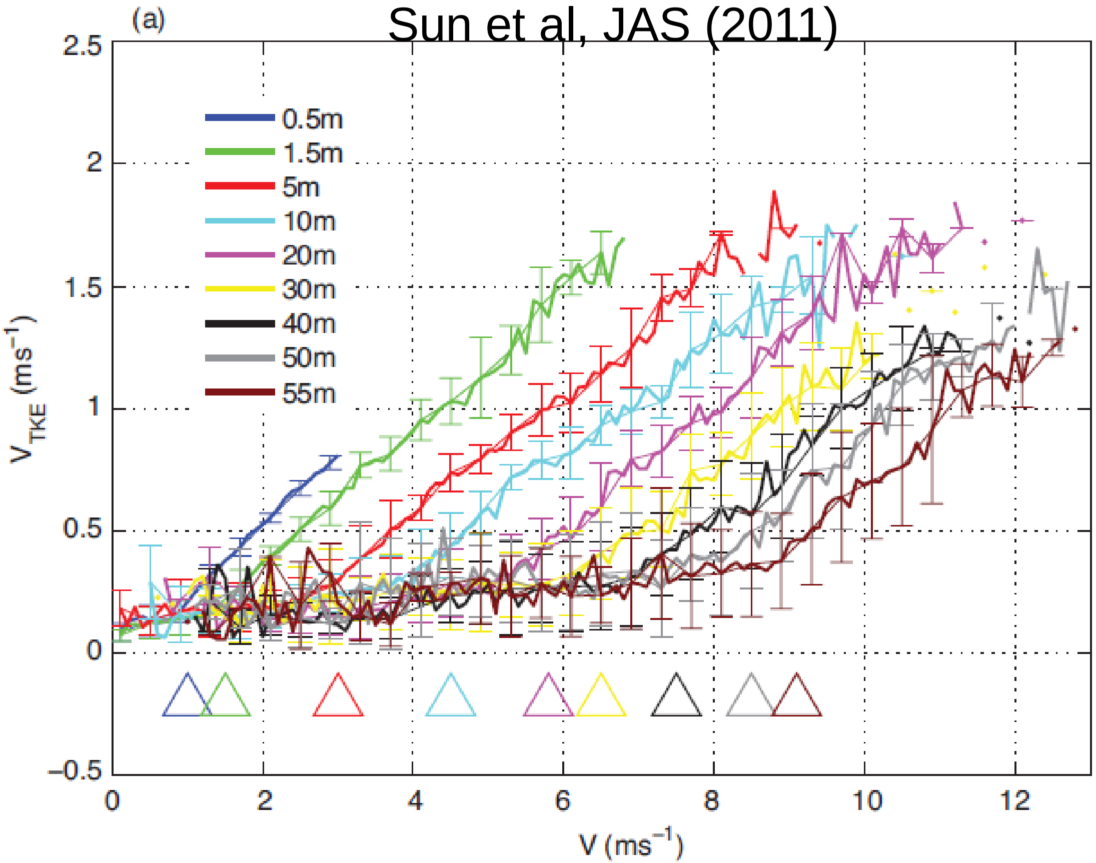
Hockey-stick robust feature

Level of fixed speed: z_ref

Why 40m?
What if fixed wind occurs at other level?

Theory predicts:

$$U_{\min} \propto \left(z_{ref}\,(\ln(z_{ref}/z_0))^2\right)^{1/3}$$


Sun et al, JAS (2011)

i.e. approximately logarithmic increase of Umin with z_ref

Conclusion

- Collapse understood from **maximum sustainable heat flux** mechanism

- Fixed shear approach useful
(~few hours after sunset)

(to be submitted *Quarterly J. Roy. Met. Soc.*

Poster Judith Donda

.....

……

Back to…‘classical’ continuous turbulent SBL (Ugeo > 5m/s),…

…exciting scaling with external forcings……

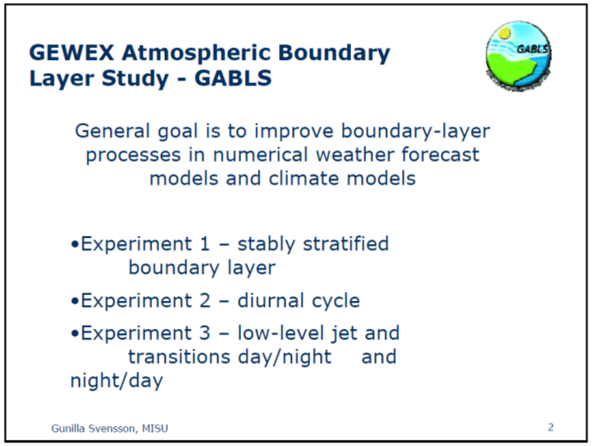
GABLS IV

Technische Universiteit **Eindhoven** University of Technology

GABLS I: Ugeo = 8 m/s

GABLS II: Ugeo = 9.5 m/s

GABLS III: Ugeo = 6.7-7.9 m/s



GEWEX Atmospheric Boundary Layer Study - GABLS

General goal is to improve boundary-layer processes in numerical weather forecast models and climate models

- Experiment 1 – stably stratified boundary layer
- Experiment 2 – diurnal cycle
- Experiment 3 – low-level jet and transitions day/night and night/day

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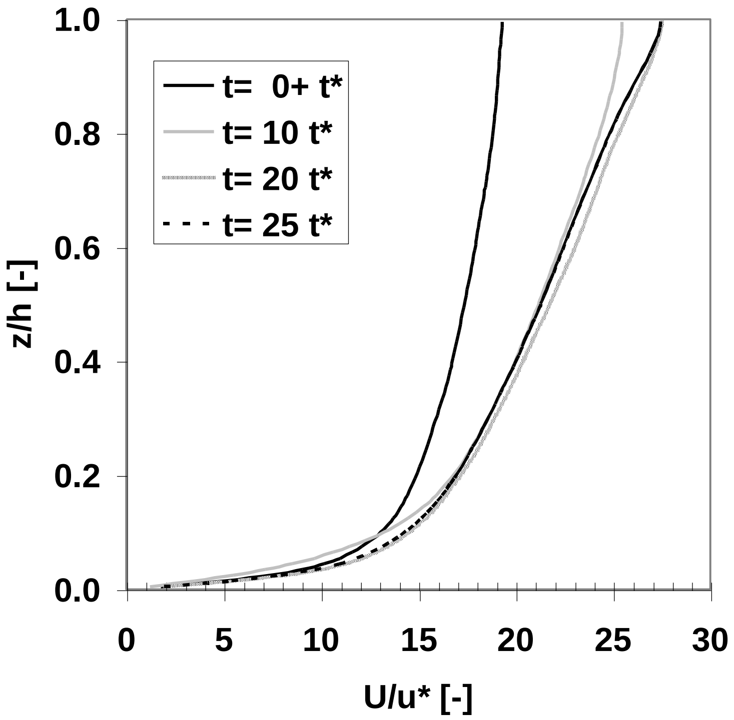
GABLS IV: low forcing: 0< Geo < 6 m/s……?

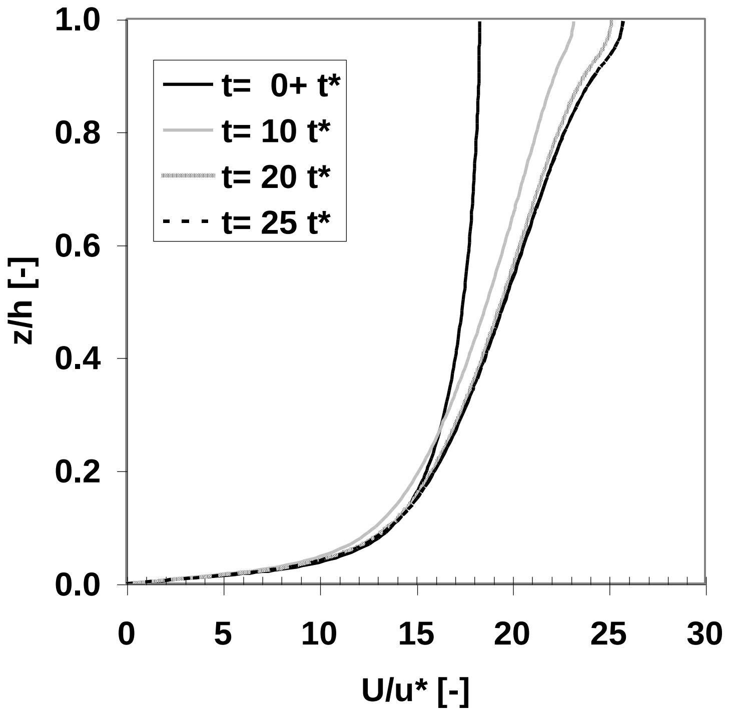
Thank you for your attention

Extra

Normalized cooling h/L_ext = 0.4

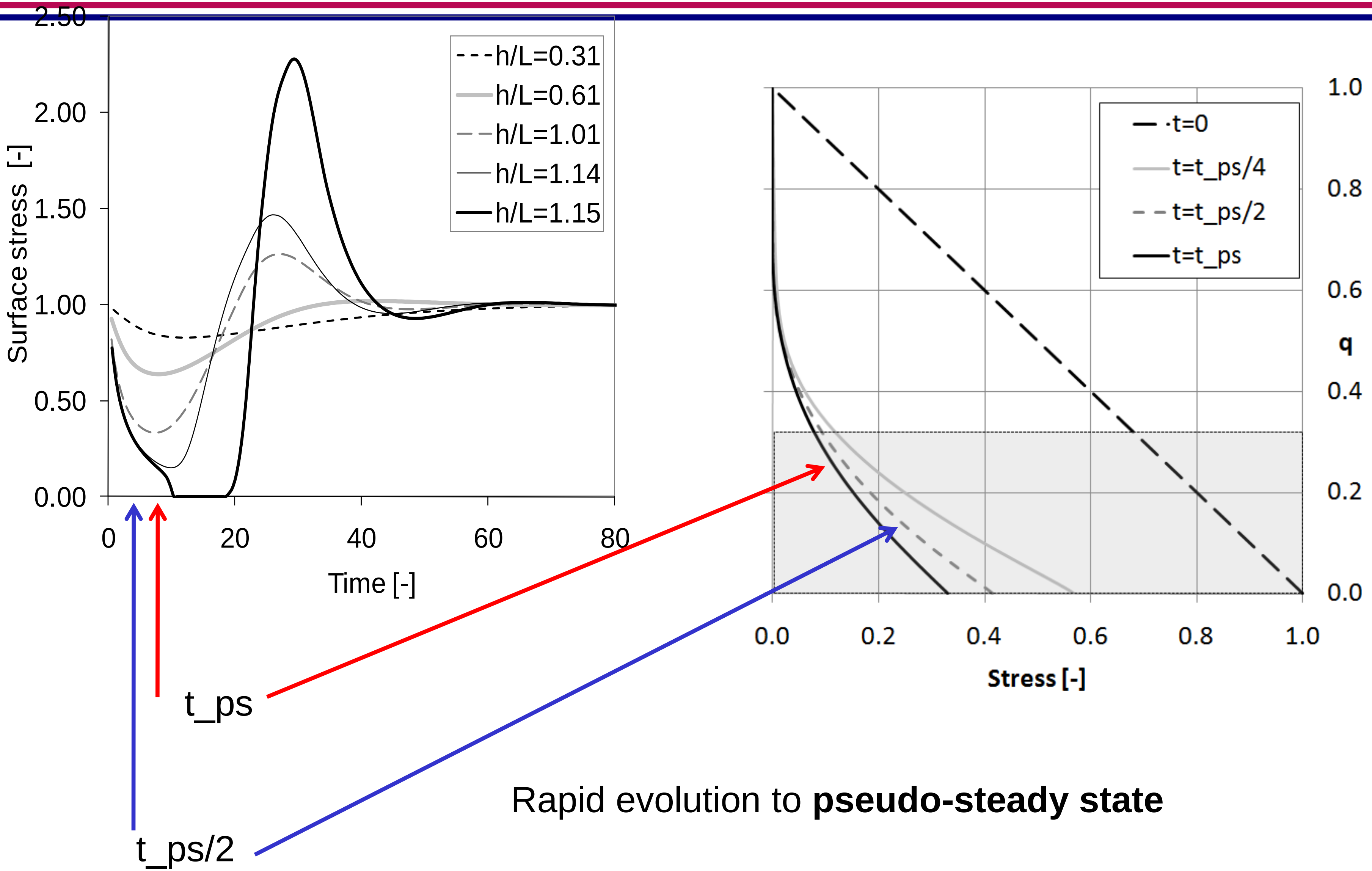


DNS



1-D Eddy diffusivity Model

EXTRA

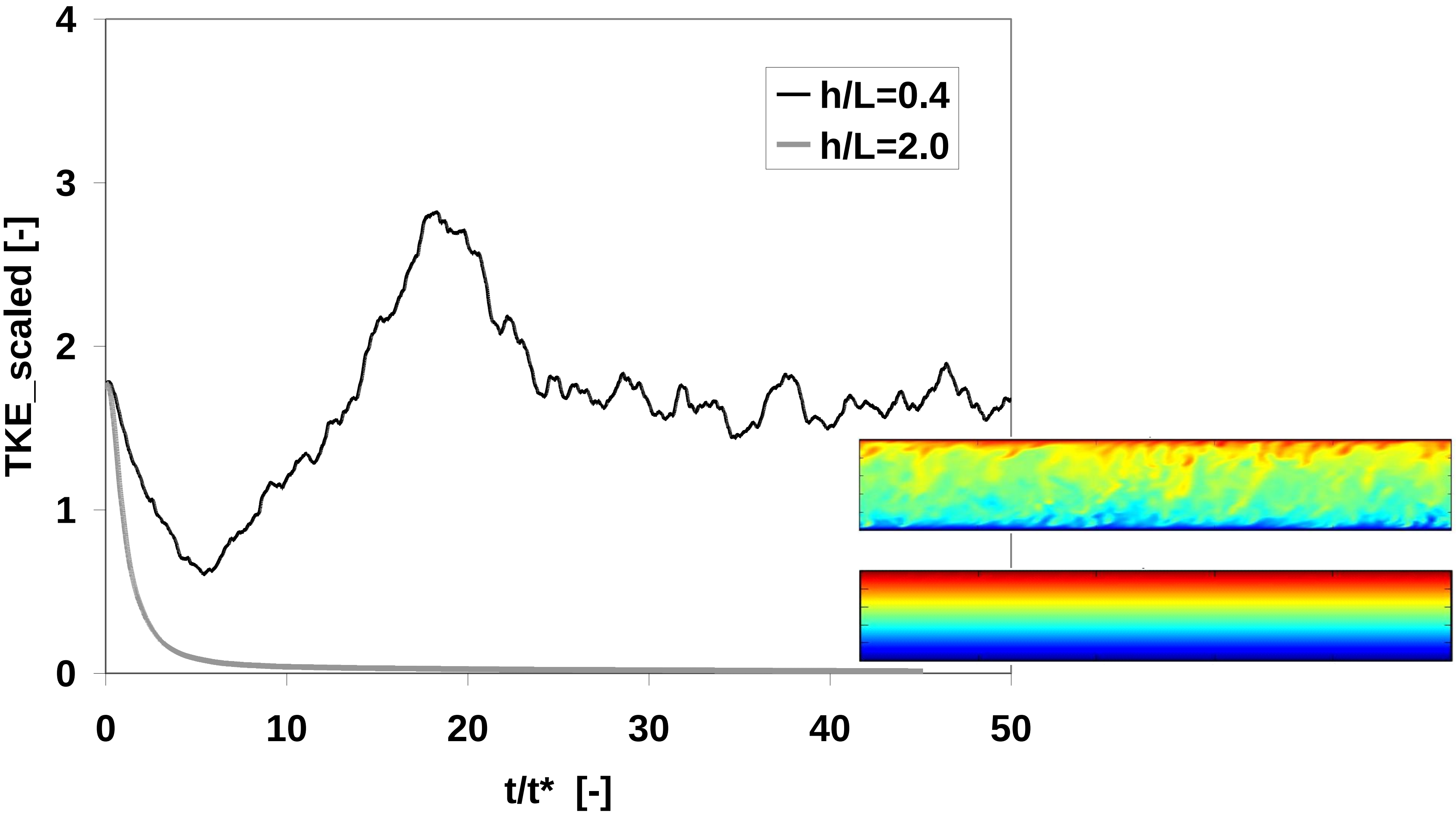


t_ps

t_ps/2

Rapid evolution to **pseudo-steady state**

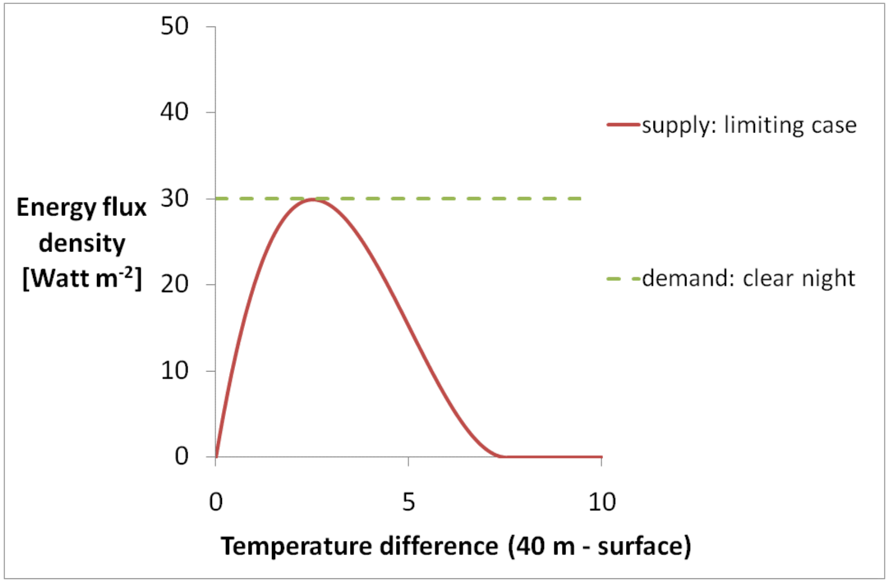
EXTRA

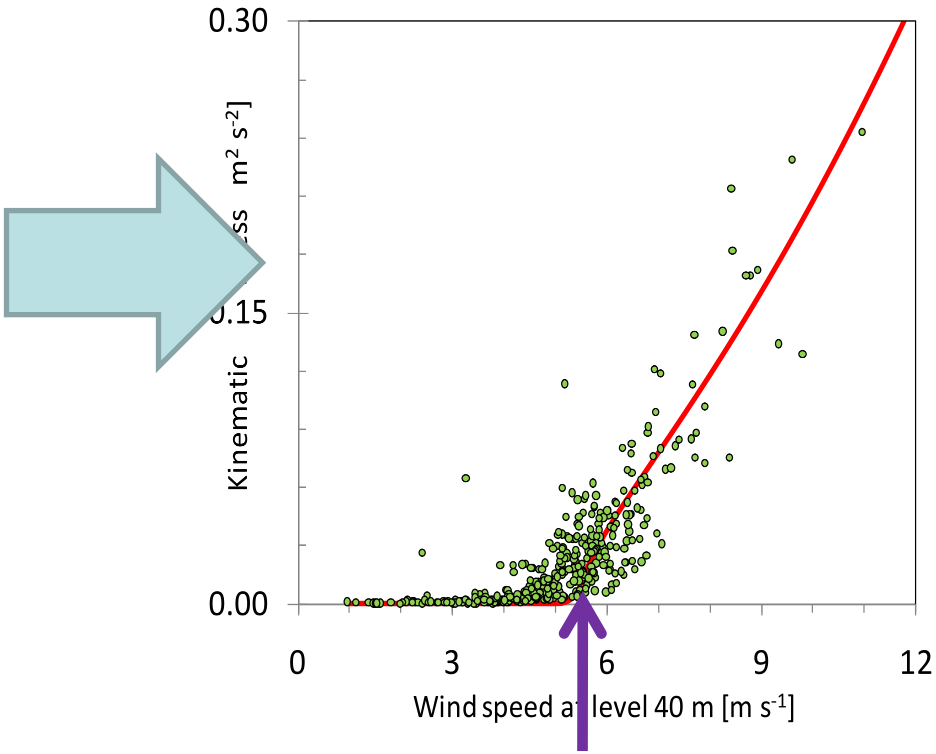


Application to atmosphere

Atmospheric velocity crossing point typically at 30-60m. Here say ~ 40m.

limiting case



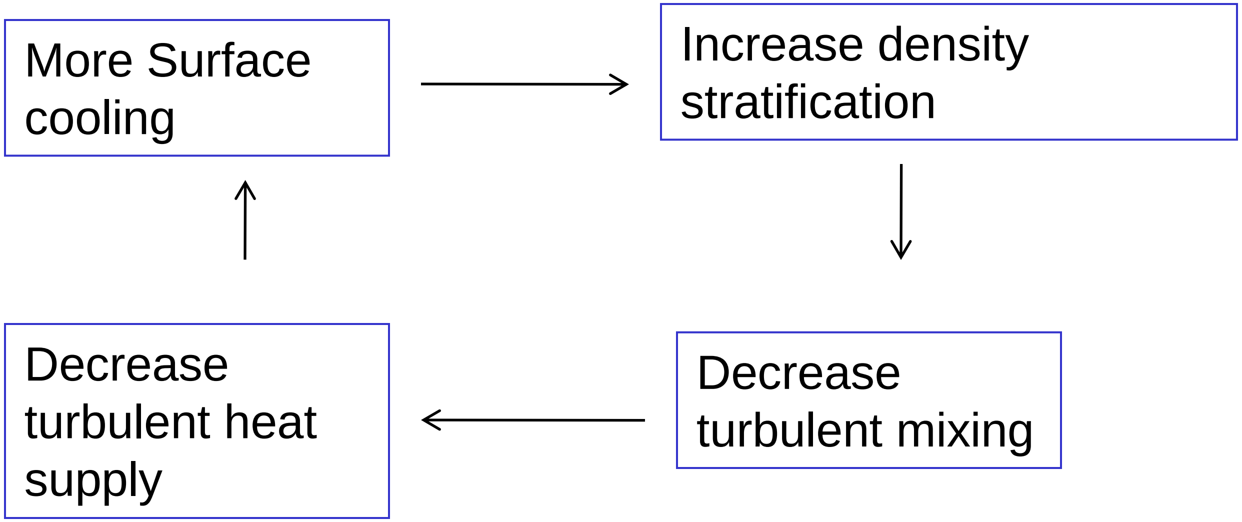


minimum velocity for surviving turbulence ~5 m/s

Positive feedback

Radiative cooling (demand) > turbulent heat flux (supply):

Demand ~fixed



More Surface cooling

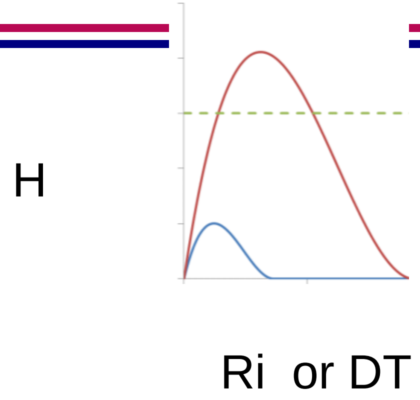
Increase density stratification

Decrease turbulent mixing

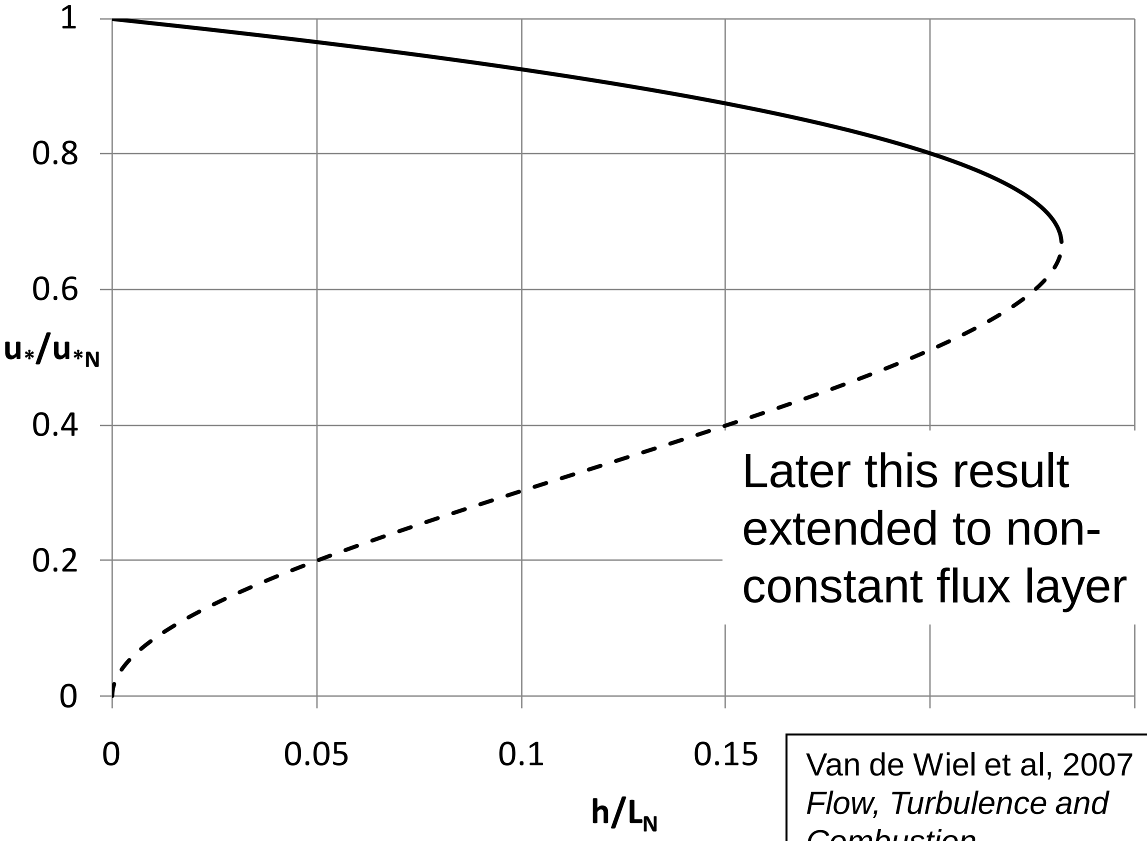
Decrease turbulent heat supply

…until all turbulent activity ceases...

Transformation



$$(1-\alpha R_b) = \frac{u_*}{(\Delta U)} \frac{\left[\ln\left(\frac{h}{z_0}\right)\right]}{\kappa}$$



$$u_{*N} = \Delta U \frac{\kappa}{\ln\left(\frac{h}{z_0}\right)}$$

Later this result extended to non-constant flux layer

Van de Wiel et al, 2007
Flow, Turbulence and Combustion

picture explains hockey-stick……..unfortunately…..