Stable Boundary Layer Parameterization

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Seminar: New developments in Modelling ABLs for NWP
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Key references

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State of the art

Surface fluxes

Surface layer concept: τ , F_θ , F_q = constant

Local M-O (1954) scaling: $L = -u_*^3 / F_{bs}$

Roughness length $z_{0u} \sim h_0$: no stability effect

SBL height

Local (RM,1935)⇔Z(1974): $N|_{\text{free-flow}}$ neglected

Closure

Down-gradient, Kolmogorov (1941): $K_M, K_H, K_D \sim E_K^{1/2} l_T$

TKE and ,e.g., ε -budgets: TPE disregarded

Improvements: to avoid Ri_{cr} and correct Pr_{turb}

Capping inversions low interest / no parameterization

Data Mid latitudes → residual layers (N=0) → SBL = nocturnal BL

Basic types of the stable and neutral ABLs

- Until recently ABLs were distinguished accounting only for $F_{bs}=F_*$:

  neutral at $F_*=0$

  stable at $F_*<0$

- Now more detailed classification:

  truly neutral (TN) ABL: $F_*=0$, $N=0$

  conventionally neutral (CN) ABL: $F_*=0$, $N>0$

  nocturnal stable (NS) ABL: $F_*<0$, $N=0$

  long-lived stable (LS) ABL: $F_*<0$, $N>0$

- Realistic surface flux calculation scheme should be based on a model applicable to all these types of the ABL

Content

- Revision of the similarity theory for stable and neutral ABLs
- Analytical approximation of mean profiles across the ABL
- Validation against LES and observational data (to be proceeded)
- Diagnostic & prognostic ABL height equations (to be included in operational routines)
- Surface-flux & ABL-height schemes for use in operational models

Classical similarity theory
and
current surface-flux schemes
(based on the SL-concept)

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Neutral stratification (no problem)

From logarithmic wall law:

$$\frac{dU}{dz} = \frac{\tau^{1/2}}{kz}, \quad \frac{d\Theta}{dz} = \frac{-F_\theta}{k_T \tau^{1/2} z}, \quad U = \frac{\tau^{1/2}}{k} \ln \frac{z}{z_{0u}}, \quad \Theta - \Theta_0 = \frac{-F_\theta}{k_T \tau^{1/2}} \ln \frac{z}{z_{0u}}$$

k, k_T von Karman constants; z_{0u} aerodynamic roughness length for momentum;
Θ_0 aerodynamic surface potential temperature (at z_{0u}) [Θ_0-Θ_s through z_{0T}]

It follows: $\tau_1^{1/2} = kU_1 (\ln z / z_{0u})^{-1}$, $F_{\theta 1} = -kk_T U_1 (\Theta_1 - \Theta_0)(\ln z / z_{0u})^{-2}$

$\tau_1 = \tau_*$, $F_{\theta 1} = F_*$ when $z_1 \approx 30$ m << *h* → OK in neutral stratification

Stable stratification: current theory

(i) local scaling, (ii) log-linear Θ-profile → both questionable

- When z_1 is much above the surface layer → $\tau_1 \neq \tau_*$, $F_{\theta 1} \neq F_*$
- Monin-Obukhov (MO) theory → $L = \dfrac{\tau^{3/2}}{-\beta F_\theta}$ (neglects other scales)→

$$\frac{kz}{\tau^{1/2}}\frac{dU}{dz} = \Phi_M(\xi), \quad \frac{k_T \tau^{1/2} z}{F_\theta}\frac{d\Theta}{dz} = \Phi_H(\xi), \quad \text{where} \quad \xi = \frac{z}{L}$$

- $\Phi_M = 1 + C_{U1}\xi$, $\Phi_H = 1 + C_{\Theta 1}\xi$ from z-less stratification concept

$$U = \frac{u_*}{k}\left(\ln\frac{z}{z_{u0}} + C_{U1}\frac{z}{L_s}\right), \quad \Theta - \Theta_0 = \frac{-F_*}{k_T u_*}\left(\ln\frac{z}{z_{u0}} + C_{\Theta 1}\frac{z}{L_s}\right)$$

- Ri$\equiv \beta(d\Theta/dz)(dU/dz)^{-2}$ → Ri$_c$ $= k^2 C_{\Theta 1} k_T^{-1} C_{U1}^{-2}$ (unacceptable)
- C_{U1} ~2, $C_{\Theta 1}$ also ~ 2 (factually increases with $z \backslash L$)

Stable stratification: current parameterization

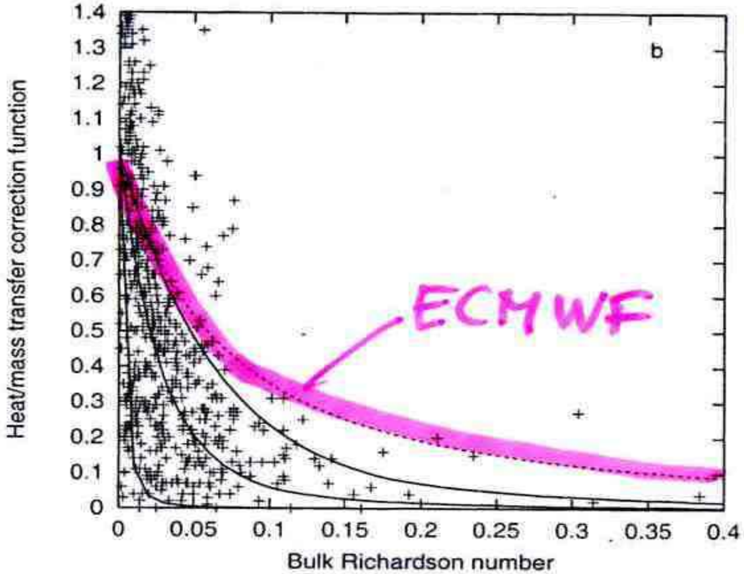
To avoid critical Ri modellers use empirical, heuristic correction functions to the neutral drag and heat/mass transfer coefficients

- Drag and heat transfer coefficients: $C_D = \tau /(U_1)^2$, $C_H = -F_{\theta s}/(U_1 \Delta\Theta)$
- Neutral: C_{Dn}, C_{Hn} – from the logarithmic wall law
- To account for stratification, correction functions (dependent only of Ri):

$$f_D(\mathrm{Ri}_1) = C_D / C_{Dn} \quad \text{and} \quad f_H(\mathrm{Ri}_1) = C_H / C_{Hn}$$

$\mathrm{Ri}_1 = \beta(\Delta\Theta)z_1/(U_1)^2$ (surface-layer "Richardson number") - given parameter

SS Zilitinkevich et al., 2002: Near-surface turbulent fluxes in stable stratification: Calculation techniques for use in general-circulation models. *Boundary-layer Meteorol.* **128**, 1571-1587



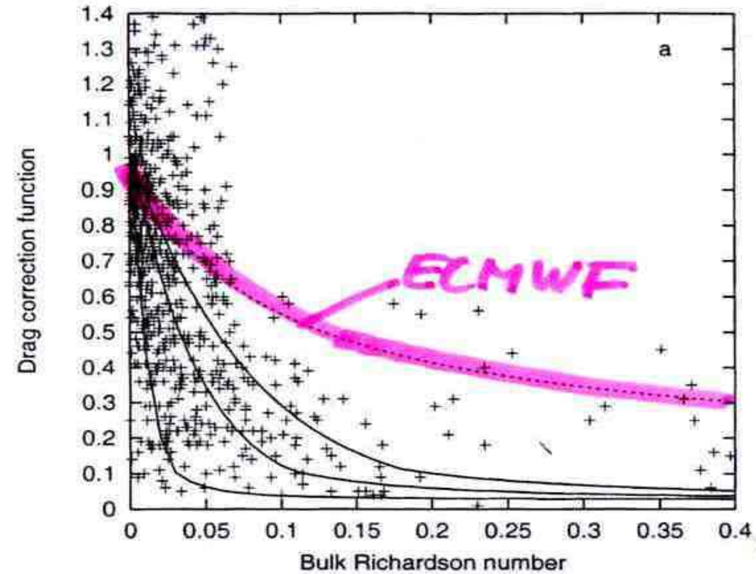


Figure 1. The correction functions (a) to the drag coefficient, f_D, and (b) to the heat and mass-transfer coefficients, $f_H = f_M$, versus the surface-layer bulk Richardson number Ri, see Eq. (7). Crosses are data from measurements at Halley, Antarctica. The correction functions from Louis *et al.* (1982) are shown by dashed lines.

$$C_D \equiv \frac{\tau_s}{u^2}, \quad C_H \equiv -\frac{F_{\theta s}}{u\Delta\theta}, \quad C_M \equiv -\frac{F_{qs}}{u\Delta q}. \qquad Ri \equiv \frac{(\beta\Delta\theta + 0.61 g\Delta q)z_1}{u^2} \qquad f_D = C_D/C_{Dn}, \quad f_H = C_H/C_{Hn}, \quad f_M = C_M/C_{Mn}$$

SS Zilitinkevich et al., 2002: Near-surface turbulent fluxes in stable stratification: Calculation techniques for use in general-circulation models. *Boundary-layer Meteorol.* **128**, 1571-1587

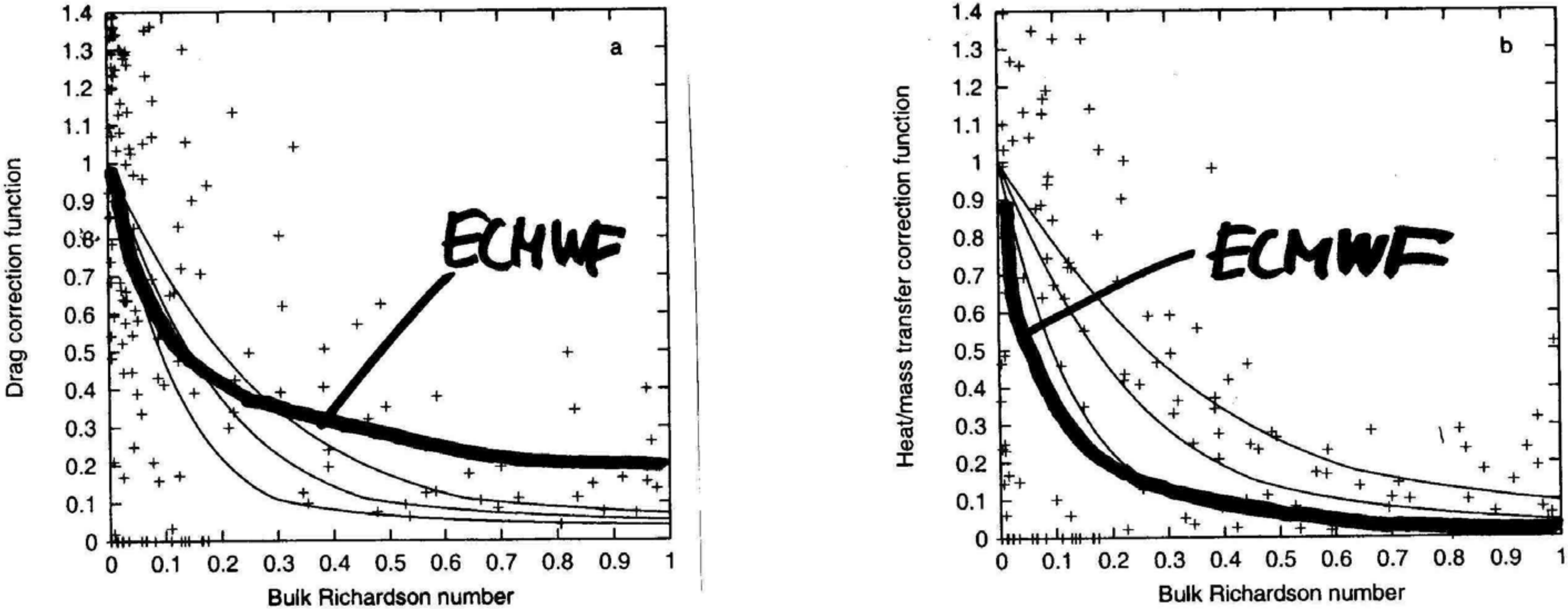


Figure 2. The same as in Fig. 1, but for Sodankyla, Arctic Finland: (a) f_D and (b) $f_H = f_M$. Crosses are measurements at this site.

Revised similarity theory
and
ABL flux-profile relationships

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Revised similarity theory

Zilitinkevich, Esau (2005) → besides Obukhov's $L = -\tau^{3/2}(\beta F_\theta)^{-1}$
two additional length scales:

$L_N = \dfrac{\tau^{1/2}}{N}$ non-local effect of the free flow static stability

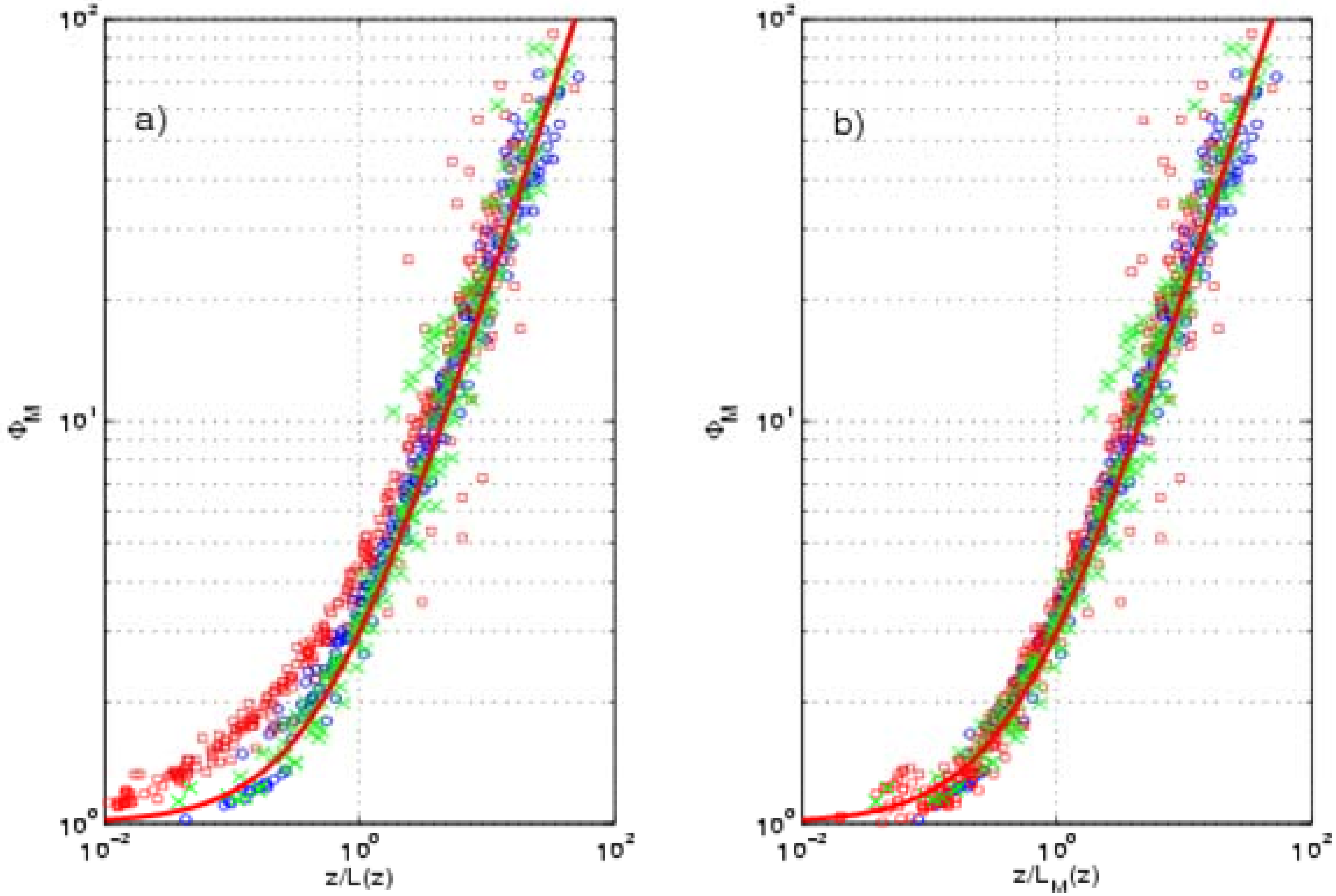
$L_f = \dfrac{\tau^{1/2}}{|f|}$ the effect of the Earth's rotation

$N \sim 10^{-2}\,\mathrm{s}^{-1}$ – Brunt-Väisälä frequency at $z>h$, f – Coriolis parameter $\tau = \tau(z)$

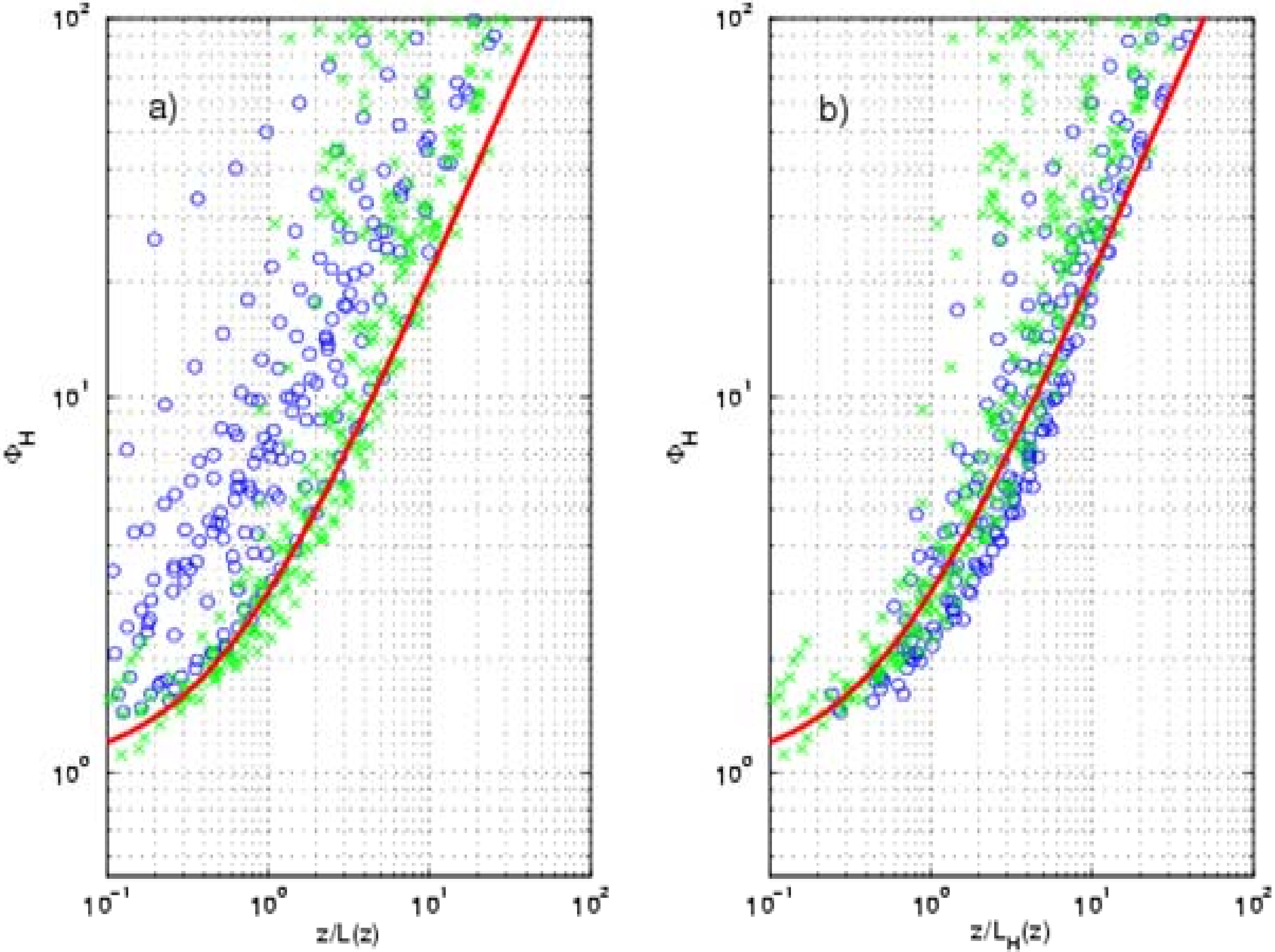
Interpolation: $\dfrac{1}{L_*} = \left[\left(\dfrac{1}{L}\right)^2 + \left(\dfrac{C_N}{L_N}\right)^2 + \left(\dfrac{C_f}{L_f}\right)^2\right]^{1/2}$ where C_N= 0.1 and C_f=1

Velocity gradient (conventionally neutral ABLs!)

$\Phi_M = kz\tau^{-1/2} dU/dz$ vs. z/L (a), z/L_* (b) x *nocturnal*; o *long-lived*; □ *conv. neutral*

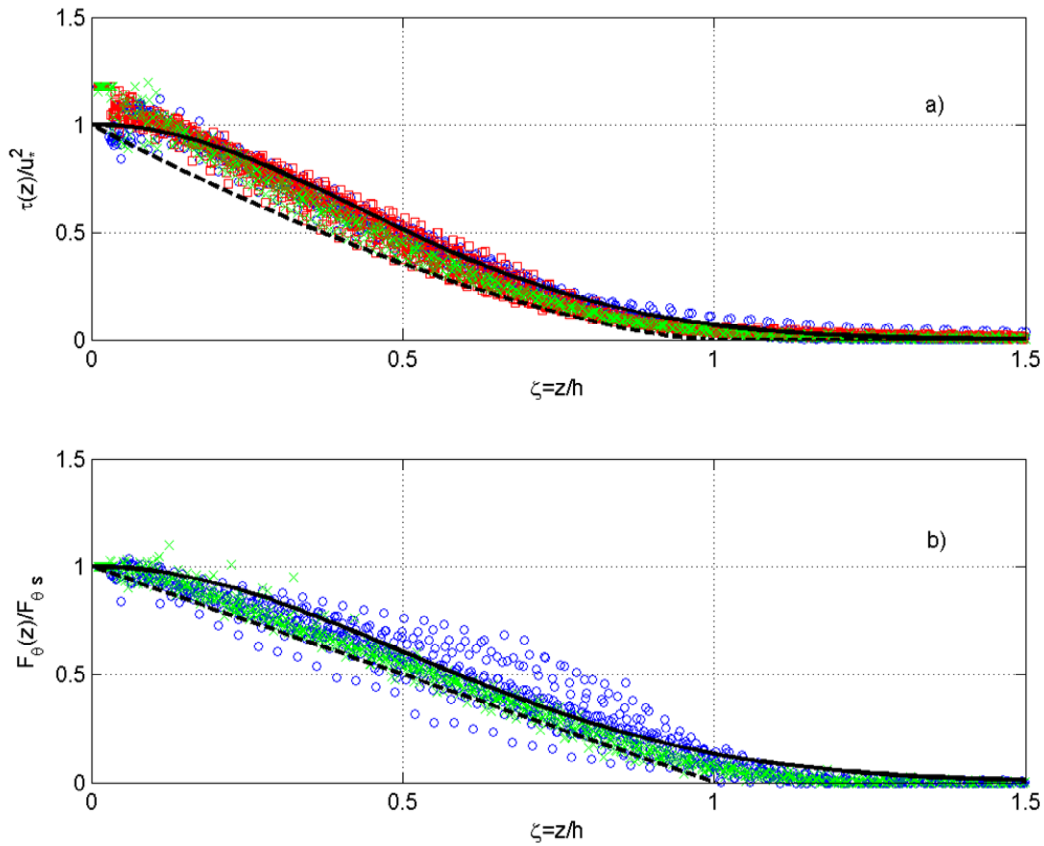


$\Phi_H = (k_T \tau^{1/2} z/F_\theta) d\Theta/dz$ vs. z/L (a), z/L_* (b)   x *nocturnal*; o *long-lived*



Vertical profiles of turbulent fluxes

Turbulent fluxes: data points – LES; dashed lines – atmospheric data, Lenshow, 1988); solid lines $\tau / u_*^2 = \exp(-\tfrac{8}{3}\varsigma^2)$, $F_\theta / F_{\theta s} = \exp(-2\varsigma^2)$; $\zeta = z/h$. ABL height $h = ?$



New mean-gradient formulation (no critical Ri)

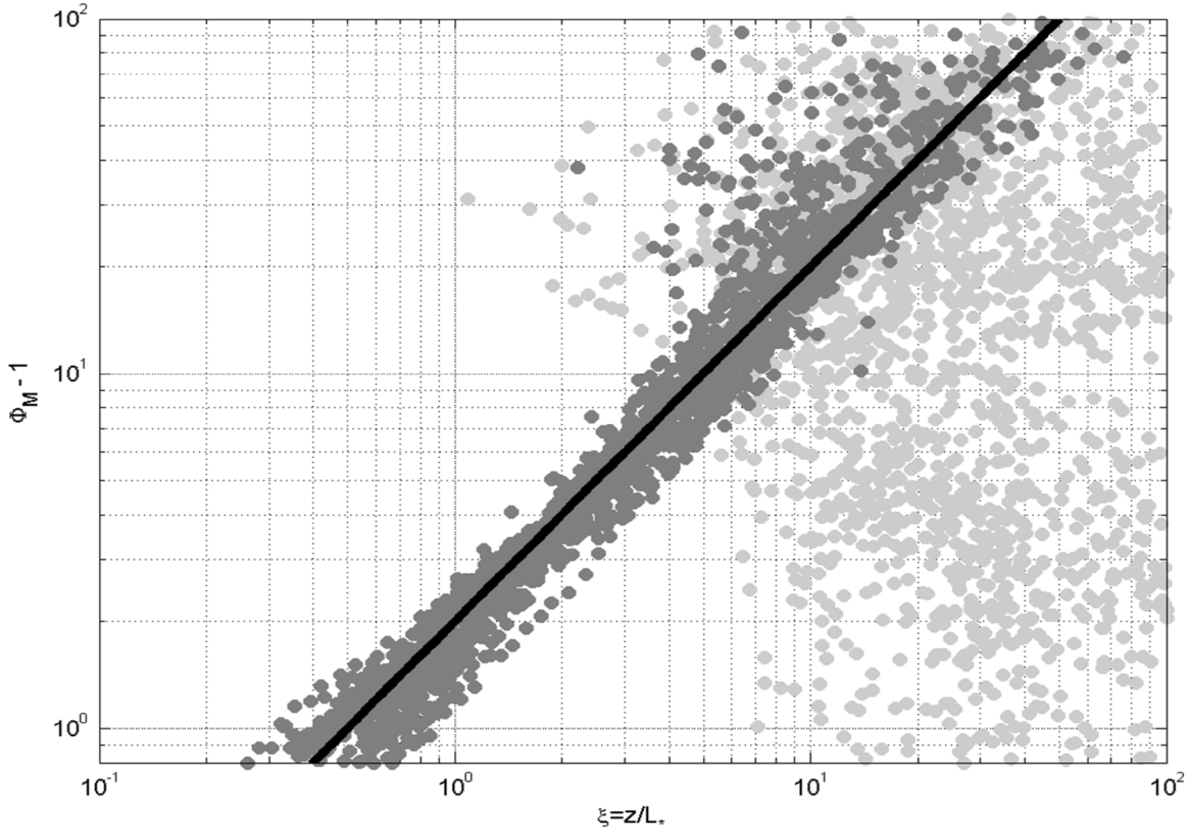
Flux Richardson number is limited: $$\mathrm{Ri}_f = \frac{-\beta F_\theta}{\tau dU/dz} > \mathrm{Ri}_f^\infty \approx 0.2$$

Hence asymptotically $\dfrac{dU}{dz} \to \dfrac{\tau^{1/2}}{\mathrm{Ri}_f^\infty L}$, and interpolating $\Phi_M = 1 + C_{U1}\xi$

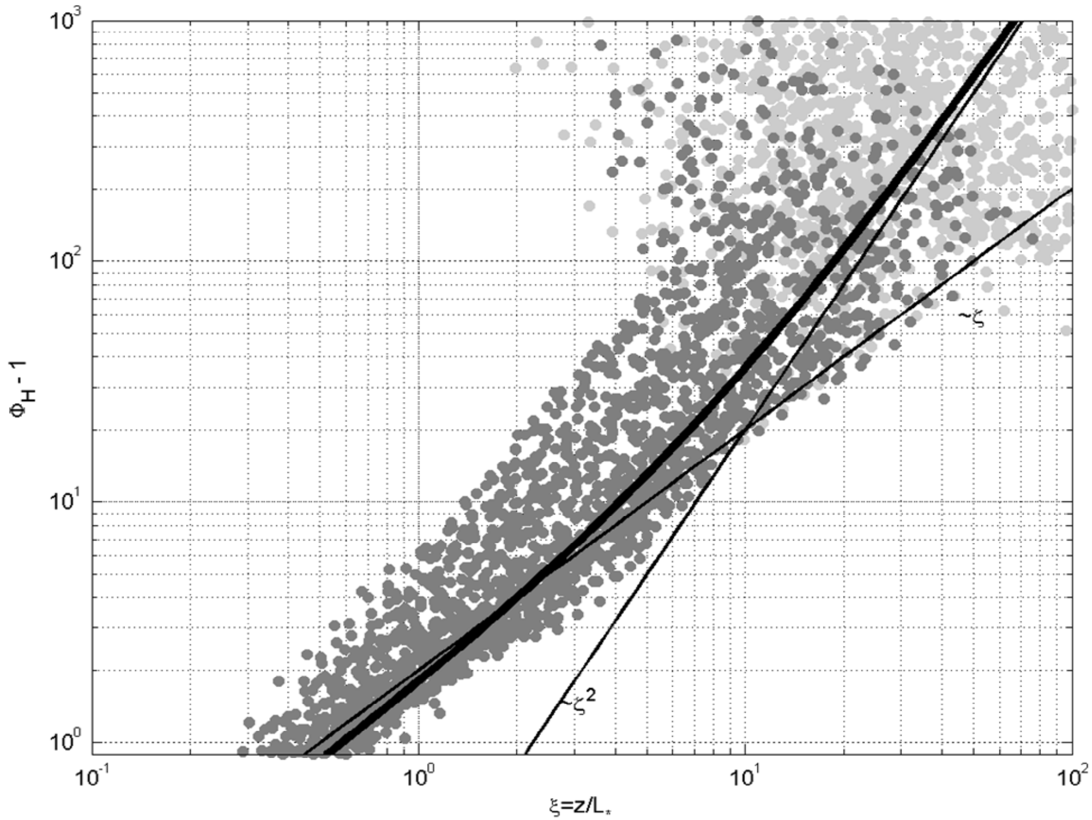
Gradient Richardson number becomes $$\mathrm{Ri} \equiv \frac{\beta d\Theta/dz}{(dU/dz)^2} = \frac{k^2}{k_T}\frac{\xi\Phi_H(\xi)}{(1+C_{U1}\xi)^2}$$

To assure no Ri-critical, ξ-dependence of Φ_H should be stronger then linear.

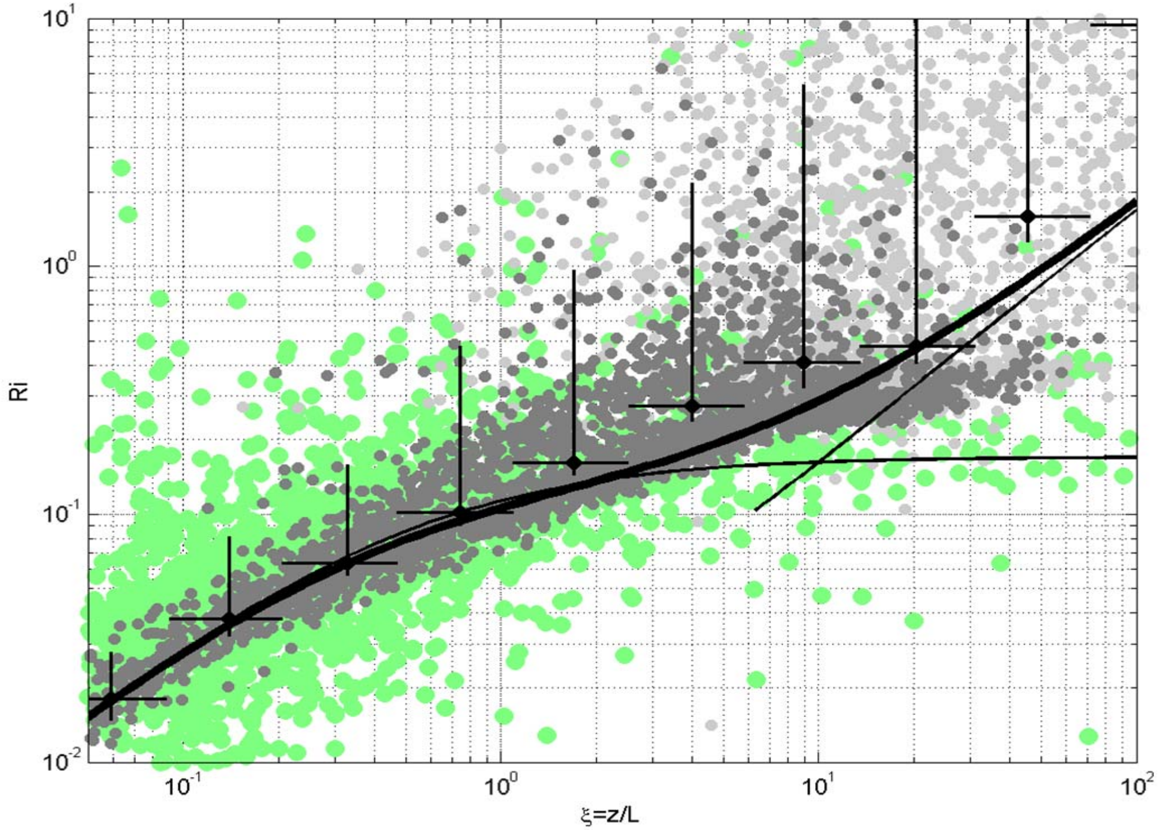
Including CN and LS ABLs: $\boxed{\Phi_M = 1 + C_{U1}\dfrac{z}{L_*}}$, $\boxed{\Phi_H = 1 + C_{\Theta 1}\dfrac{z}{L_*} + C_{\Theta 2}\left(\dfrac{z}{L_*}\right)^2}$



Φ_M vs. $\xi = z / L_*$, after LES DATABASE64 (all types of SBL). Dark grey points for *z*<*h*; light grey points for *z*>*h*; the line corresponds to $C_{U1} = 2$.



Φ_H vs. $\xi = z / L_*$ (all SBLs). Bold curve is our approximation: $C_{\Theta 1} = 1.8$, $C_{\Theta 2} = 0.2$; thin lines are $\Phi_H = 0.2\xi^2$ and traditional $\Phi_H = 1+2\xi$.



Ri vs. $\xi = z/L$, after LES and field data (SHEBA - green points). Bold curve is our model with C_{U1}=2, $C_{\Theta 1}$=1.6, $C_{\Theta 2}$=0.2. Thin curve is Φ_H=1+2ξ.

Mean profiles and flux-profile relationships

We consider wind/velocity and potential/temperature functions

$$\Psi_U = \frac{kU(z)}{\tau^{1/2}} - \ln\frac{z}{z_{0u}} \quad \text{and} \quad \Psi_\Theta = \frac{k_T \tau^{1/2}[\Theta(z) - \Theta_0]}{-F_\theta} - \ln\frac{z}{z_{0u}}$$

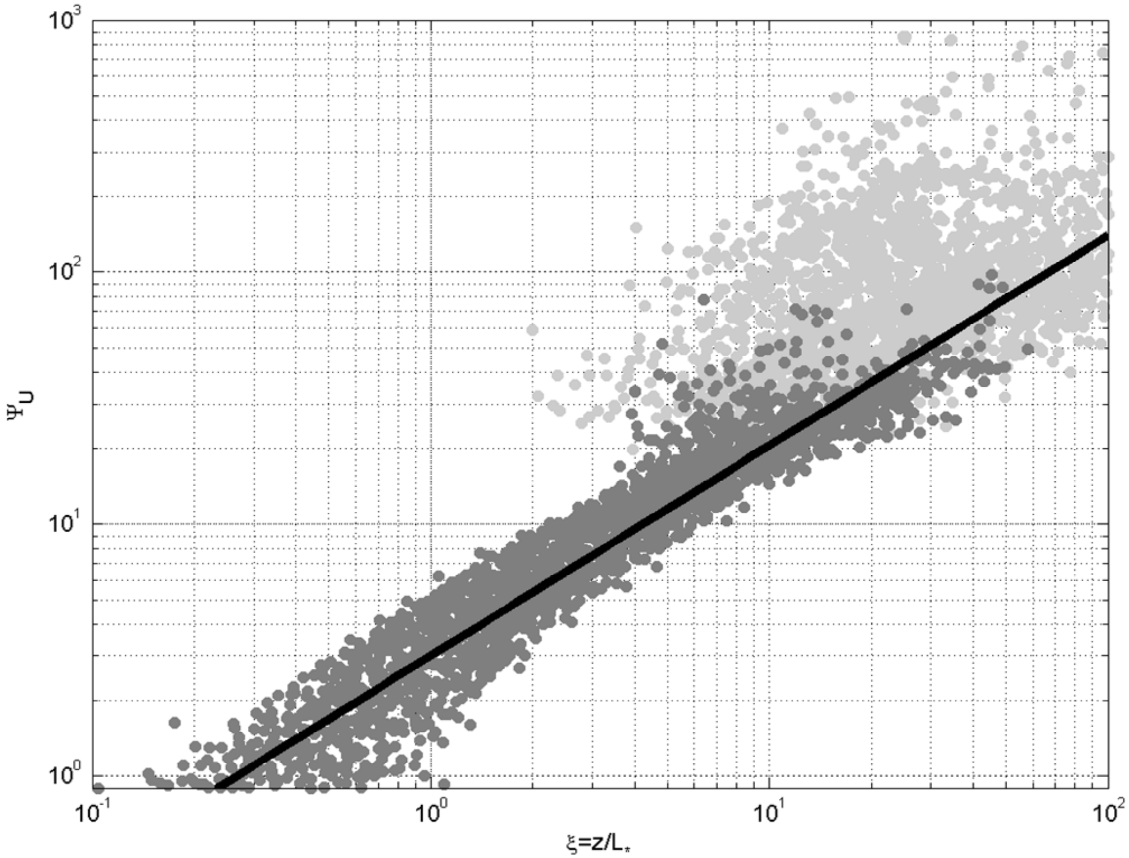
Our analyses show that Ψ_U and Ψ_Θ are universal functions of $\xi = z / L_*$

$$\Psi_U = C_U \xi^{5/6}, \quad \Psi_\Theta = C_\Theta \xi^{4/5}, \text{ with } C_U = 3.0 \text{ and } C_\Theta = 2.5$$

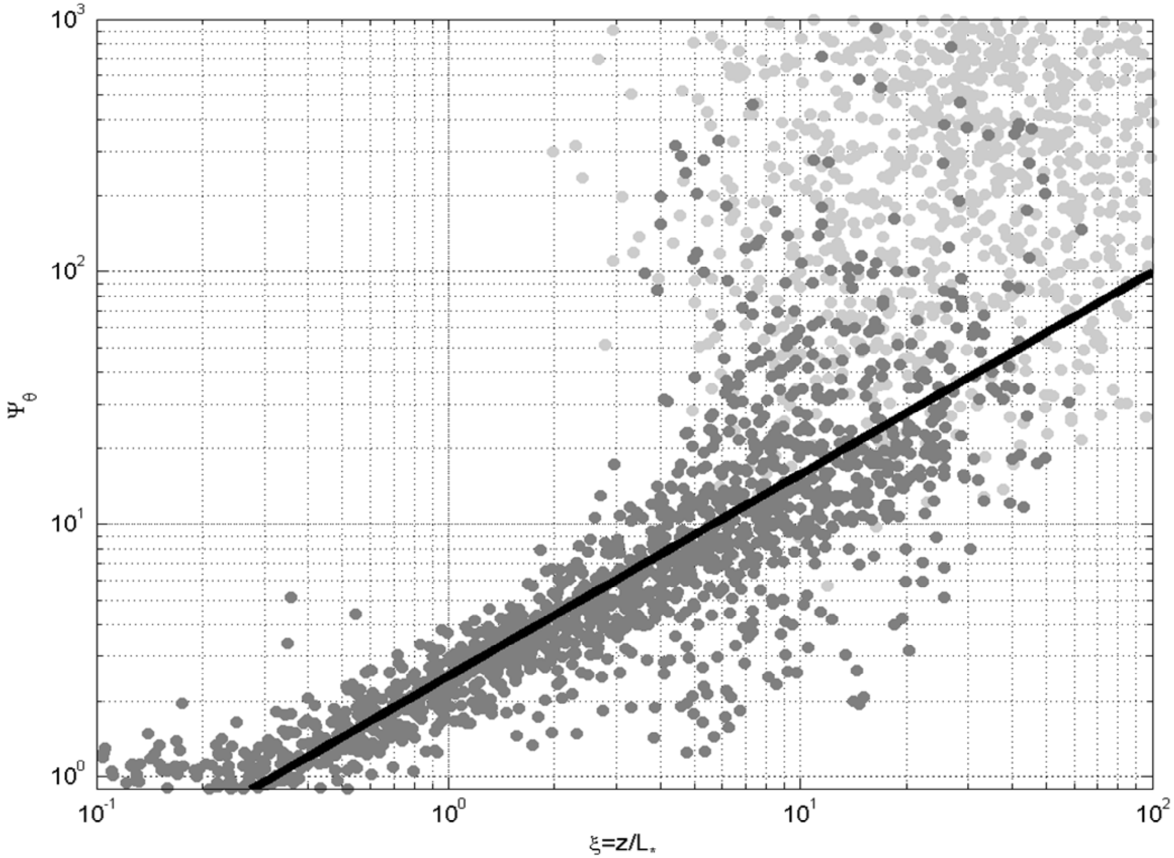
The problem is solved given

(i) z_{0u} and

(ii) τ and L as functions of z/h



Wind-velocity function $\Psi_U = k\tau^{-1/2}U - \ln(z/z_{0u})$ vs. $\xi = z/L_*$, after LES DATABASE64 (all types of SBL). The line: $\Psi_U = C_U \xi^{5/6}$, C_U=3.0.



Pot.-temperature function $\Psi_\Theta = k\tau^{-1/2}(\Theta - \Theta_0)(-F_\theta)^{-1} - \ln(z/z_{0u})$

(all types of SBL). The line: $\Psi_\Theta = C_\Theta \xi^{4/5}$ with C_U=3.0 and C_Θ=2.5.

Analytical wind and temperature profiles (SBL)

$$\frac{kU}{\tau^{1/2}} = \ln\frac{z}{z_{0u}} + C_U\left(\frac{z}{L}\right)^{5/6}\left[1+\frac{(C_N N)^2+(C_f f)^2}{\tau}L^2\right]^{5/12}$$

$$\frac{k_T\tau^{1/2}(\Theta-\Theta_0)}{-F_\theta} = \ln\frac{z}{z_{0u}} + C_\Theta\left(\frac{z}{L}\right)^{4/5}\left[1+\frac{(C_N N)^2+(C_f f)^2}{\tau}L^2\right]^{2/5}$$

where C_N=0.1 and C_f=1. Given $U(z)$, $\Theta(z)$ and N, these equations allow determining τ, F_θ, and $L=\tau^{3/2}(-\beta F_\theta)^{-1}$, at the computational level *z*.

Remain to be determined:

- ABL height and
- Roughmess length

ABL height

References

Zilitinkevich, S., Baklanov, A., Rost, J., Smedman, A.-S., Lykosov, V., and Calanca, P., 2002: Diagnostic and prognostic equations for the depth of the stably stratified Ekman boundary layer. *Quart, J. Roy. Met. Soc*., 128, 25-46.

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Factors controlling ABL height

Basic factors:

- Deepening due shear-generated turbulence
- Swallowing by earth's rotation and negative buoyancy forces:
  (i) flow-surface interaction, (ii) free-flow stability atmosphere

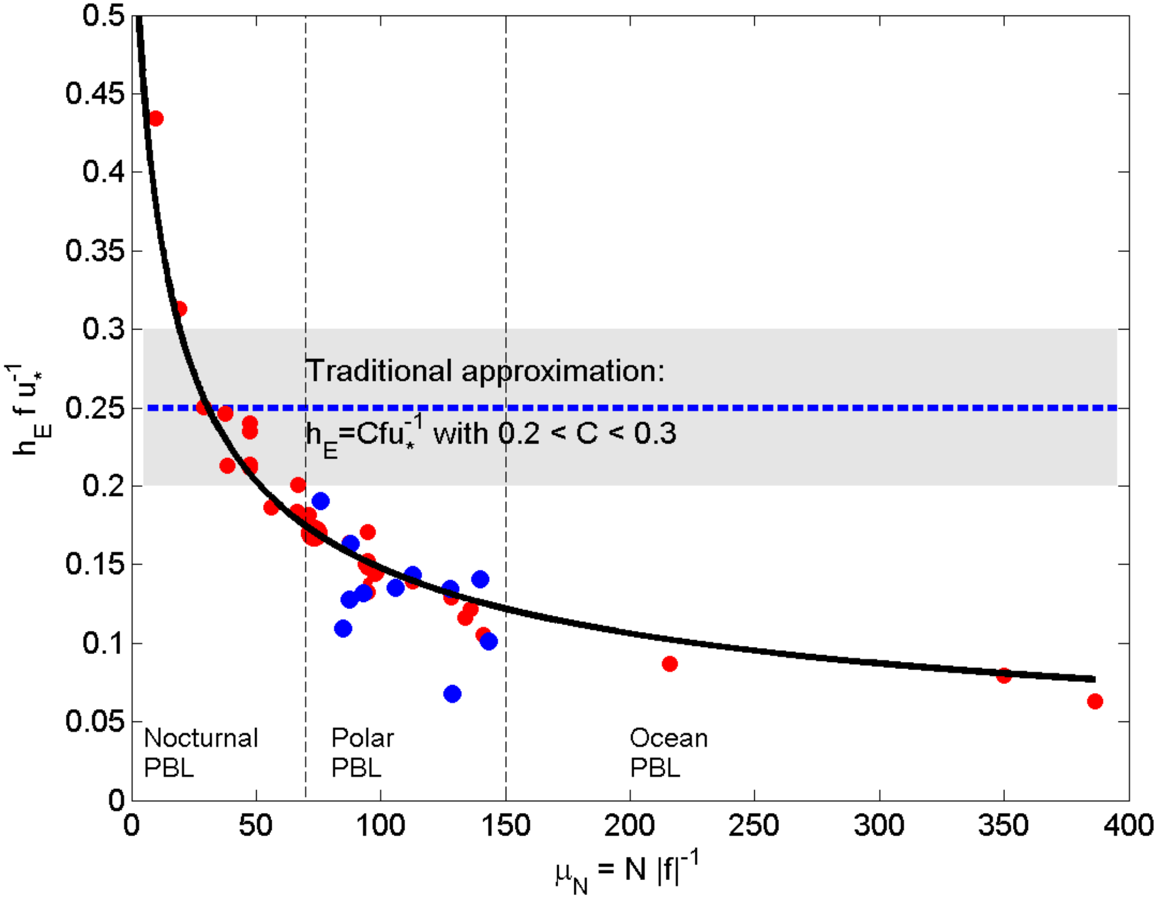
Additional factors:

- baroclinic shears (enhances deepening)
- large-scale vertical motions (both ways))
- temporal and horizontal variability

Strategy:

Basic regimes → theoretical models → general formulation

Neutral and stable ABL height



The dependence of the equilibrium conventionally neutral PPL height, h_E, on the free-flow Brunt-Väisälä frequency N after new theory (Z et al., 2007a, shown by the curve), LES (red) and field data (blue). Until recently the effect of N on h_E was disregarded

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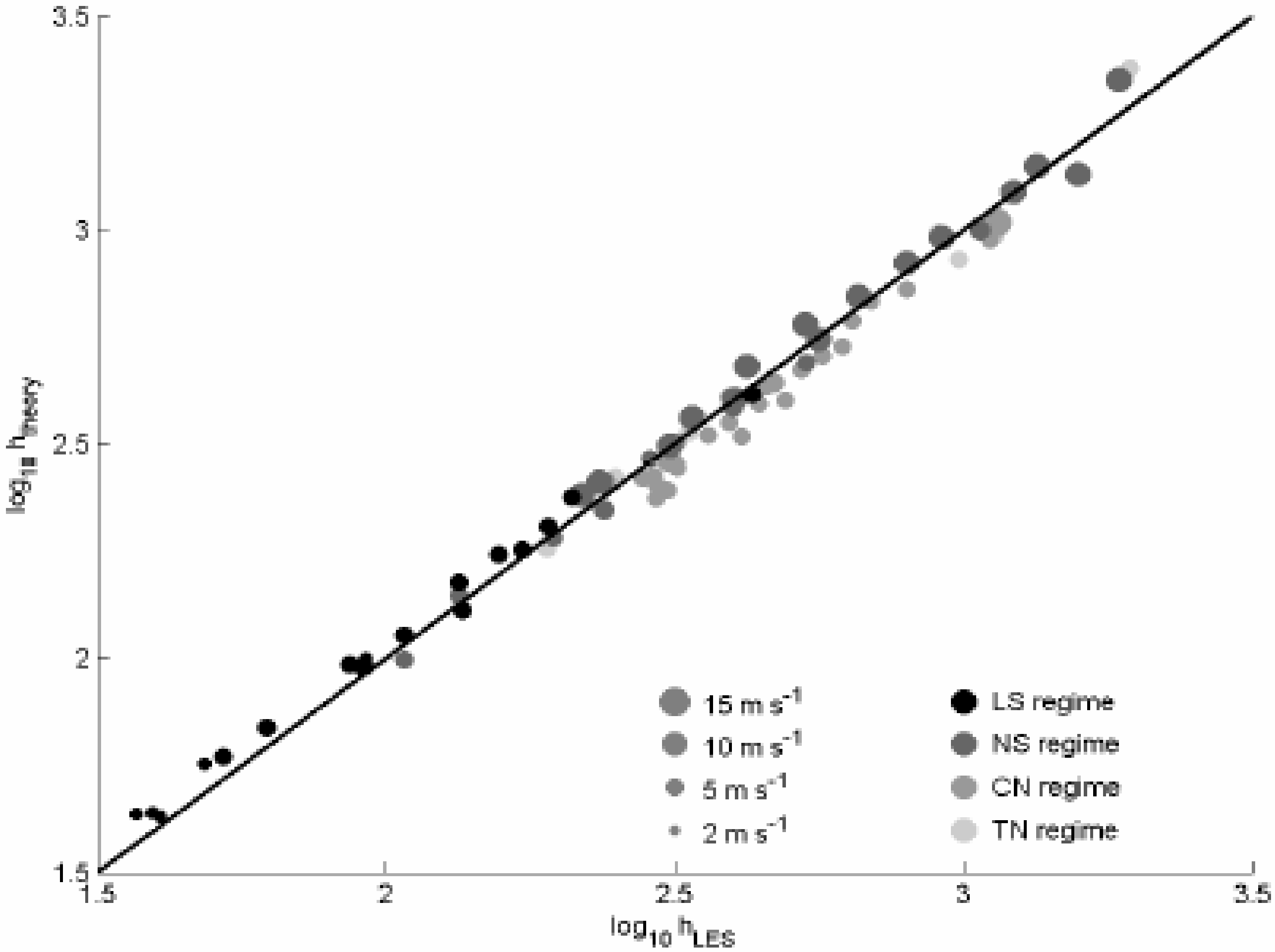
General case



Stage II: Correlation: h_{theory} vs. h_{LES} after all available LES data

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Modelling the stable ABL height

- Equilibrium

$$\frac{1}{h_E^2} = \frac{f^2}{C_R^2 \tau_*} + \frac{N|f|}{C_{CN}^2 \tau_*} + \frac{|f\beta F_*|}{C_{NS}^2 \tau_*^2} \qquad (C_R=0.6,\ C_{CN}=1.36,\ C_{NS}=0.51)$$

- Baroclinic: substitute $u_T = u_*(1+C_0\Gamma/N)^{1/2}$ for u_* in the 2nd term on the r.h.s.

- Vertical motions: $h_{E-\mathrm{corr}} = h_E + w_h t_T$, where $t_T = C_t h_E / u_*$

- Generally prognostic equation (Z. and Baklanov, 2002):

$$\frac{\partial h}{\partial t} + \vec{U}\cdot\nabla h - w_h = K_h \nabla^2 h - C_t \frac{u_*}{h_E}(h - h_E) \qquad (C_t = 1)$$

Given *h*, the free-flow Brunt-Väisälä frequency is $N^4 = \frac{1}{h}\int_h^{2h}\left(\beta \frac{\partial \Theta}{\partial z}\right)^2 dz$

Conclusions (surface fluxes and ABL height)

Background: Generalised scaling accounting for the free-flow stability,
No critical Ri (Φ_H consistent with TTE closure)
Stable ABL height model

Verified against
LES DATABASE64 (4 ABL types: TN, CN, NS and LS)
Data from the field campaign SHEBA
More detailed validation needed

Deliverable 1: analytical wind & temperature profiles in SBLs

Deliverable 2: surface flux and ABL height schemes
for use in operational models

Roughmess length

Stability dependences of the roughness length and displacement height

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Reference

S. S. Zilitinkevich, I. Mammarella, A. A. Baklanov, and S. M. Joffre, 2007: The roughness length in environmental fluid mechanics: the classical concept and the effect of stratification. *Boundary-Layer Meteorology.* In press.

Content

- Roughness length and displacement height:

$$u(z) = \frac{u_*}{k}\left[\ln\frac{z - d_{0u}}{z_{0u}} + \Psi_u\left(\frac{z}{L}\right)\right]$$

- No stability dependence of z_{0u} (and d_{0u}) in engineering fluid mechanics: neutral-stability z_0 = level, at which $u(z)$ plotted vs. $\ln z$ approaches zero; $z_0 \sim {}^1\!/_{25}$ of typical height of roughness elements, h_0

- Meteorology / oceanography: h_0 comparable with MO length $L = \dfrac{u_*^3}{-\beta F_{\theta s}}$

- Stability dependence of the actual roughness length, z_{0u}:

  $z_{0u} < z_0$ in stable stratification; $z_{0u} > z_0$ in unstable stratification

Surface layer and roughness length

Self similarity in the surface layer (SL) $1.6 h_0 < z < 10^{-1} h$

Height-constant fluxes: $\tau \approx \tau \,|_{z=5h_0} \equiv u_*^2$

u_* and z serve as turbulent scales: $u_T \sim u_*,\ l_T \sim z$

Eddy viscosity $(k \approx 0.4)$ $K_M\ (\sim u_T l_T) = k u_* z$

Velocity gradient $\partial U / \partial z = \tau / K_M = u_* / kz$

Integration constant: $U = k^{-1} u_* \ln z + \text{constant} = k^{-1} u_* \ln(z / z_{0u})$

z_{0u} (redefined constant of integration) is "roughness length"

"Displacement height" d_{0u} $U = k^{-1} u_* \ln\left[(z - d_{u0}) / z_{u0}\right]$

Not applied to the roughness layer (RL) $0 < z < 5h_0$

Parameters controlling z_{0u}

<u>Smooth surfaces:</u> viscous layer → $z_{0u} \sim \nu / u_*$

<u>Very rough surfaces:</u> pressure forces depend on:

obstacle height h_0

velocity in the roughness layer $U_R \sim u_*$

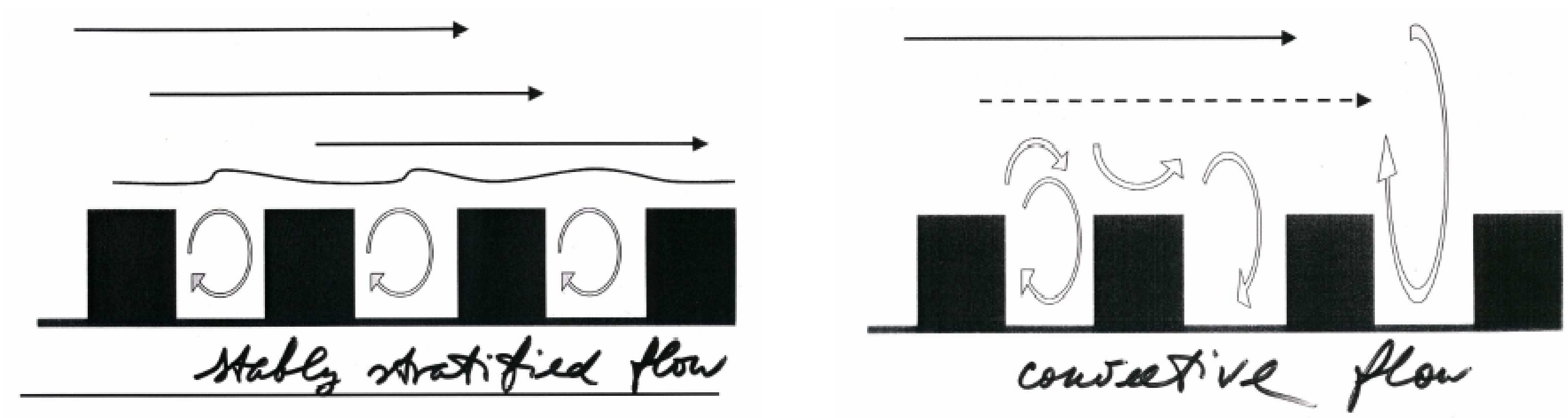
$z_{0u} = z_{0u}(h_0, u_*) \sim h_0$ (in sand roughness experiments $z_{0u} \approx \frac{1}{30} h_0$)

No dependence on u_*; surfaces characterised by $z_{0u} =$ constant

<u>Generally</u> $z_{0u} = h_0 f_0(\mathrm{Re}_0)$ where $\mathrm{Re}_0 = u_* h_0 / \nu$

Stratification at M-O length $L = -u_*^3 F_b^{-1}$ comparable with h_0

Stability Dependence of Roughness Length



For urban and vegetation canopies with roughness-element heights (20-50 m) comparable with the Obukhov turbulent length scale, L, the surface resistance and roughness length depend on stratification

Background physics and effect of stratification

Physically z_{0u} = depth of a sub-layer within RL $(0 < z < 1.6h_0)$ with 90% of the velocity drop from $U_R \sim u_*$ (approached at $z \sim h_0$)

From $\tau = K_{M(RL)} \partial U / \partial z$, $\tau \sim u_*^2$ and $\partial U / \partial z \sim U_R / z_{0u} \sim u_* / z_{0u}$

$$z_{0u} \sim K_{M(RL)} / u_*$$

$K_M(\mathrm{RL}) = K_M(h_0 + 0)$ from matching the RL and the surface-layer

Neutral: $K_M \sim u_* h_0 \Rightarrow$ classical formula $z_{0u} \sim h_0$

Stable: $K_M = k u_* z (1 + C_u z / L)^{-1} \sim u_* L \Rightarrow z_{0u} \sim L$

Unstable: $K_M = k u_* z + C_U^{-1} F_b^{1/3} z^{4/3} \sim F_b^{1/3} z^{4/3} \Rightarrow z_{0u} \sim h_0 (-h_0 / L)^{1/3}$

Recommended formulation

Neutral $\Leftrightarrow$ stable

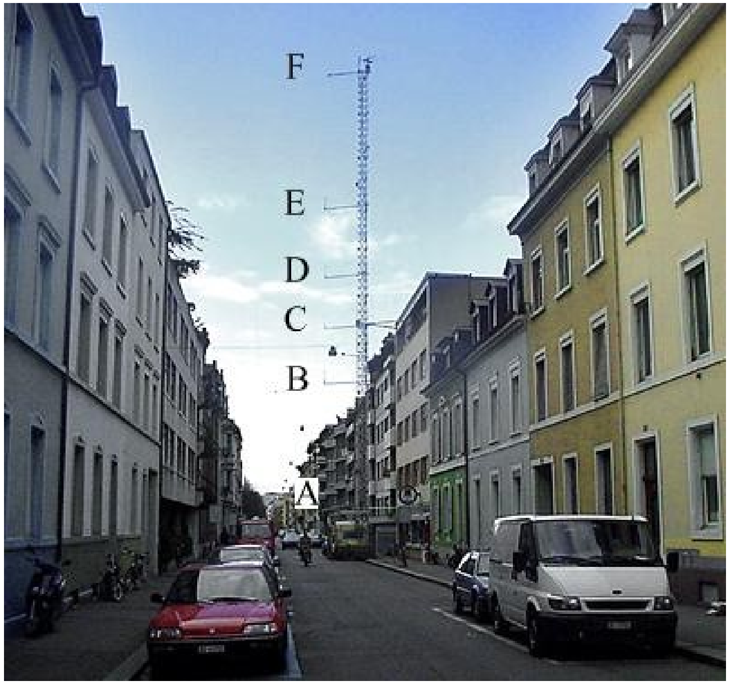
$$\frac{z_{0u}}{z_0} = \frac{1}{1 + C_{SS} h_0 / L}$$

Neutral $\Leftrightarrow$ unstable

$$\frac{z_{0u}}{z_0} = 1 + C_{US} \left(\frac{h_0}{-L} \right)^{1/3}$$

Constants: $C_{SS} = 8.13 \pm 0.21$, $C_{US} = 1.24 \pm 0.05$

Experimental datasets



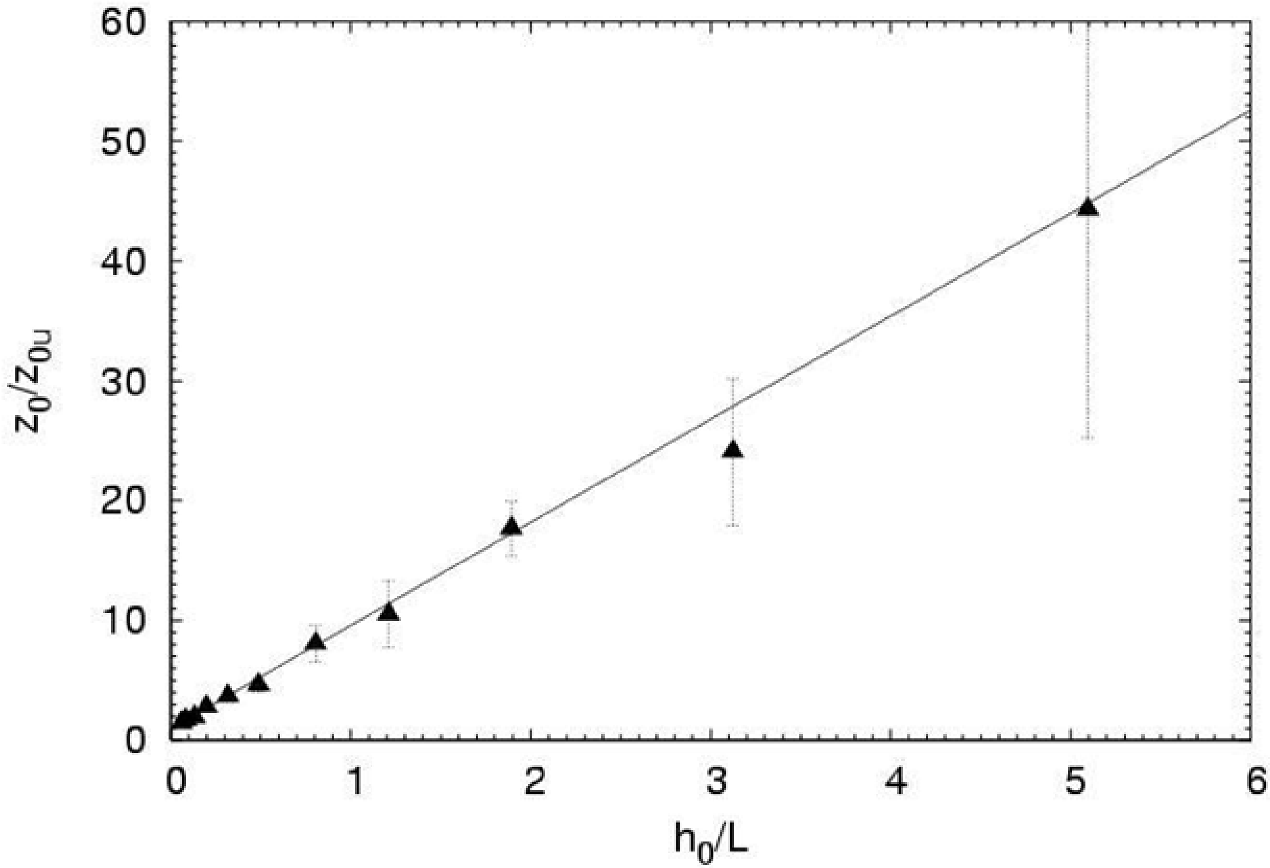
Sodankyla Meteorological Observatory, Boreal forest (FMI)

h ≈ 13 m, measurement levels 23, 25, 47 m

BUBBLE urban BL experiment, Basel, Sperrstrasse (Rotach et al., 2004)

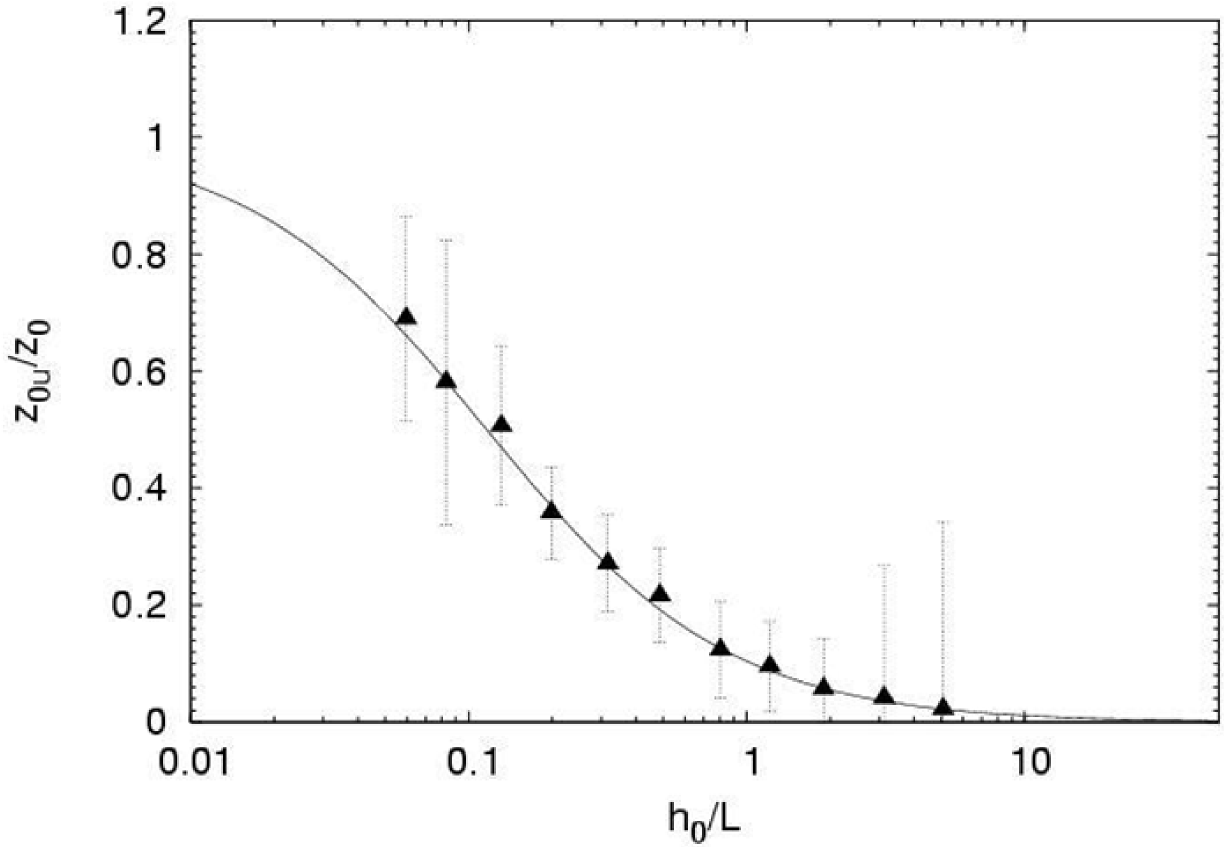
h ≈ 14.6 m, measurement levels 3.6, 11.3, 14.7, 17.9, 22.4, 31.7 m

Stable stratification



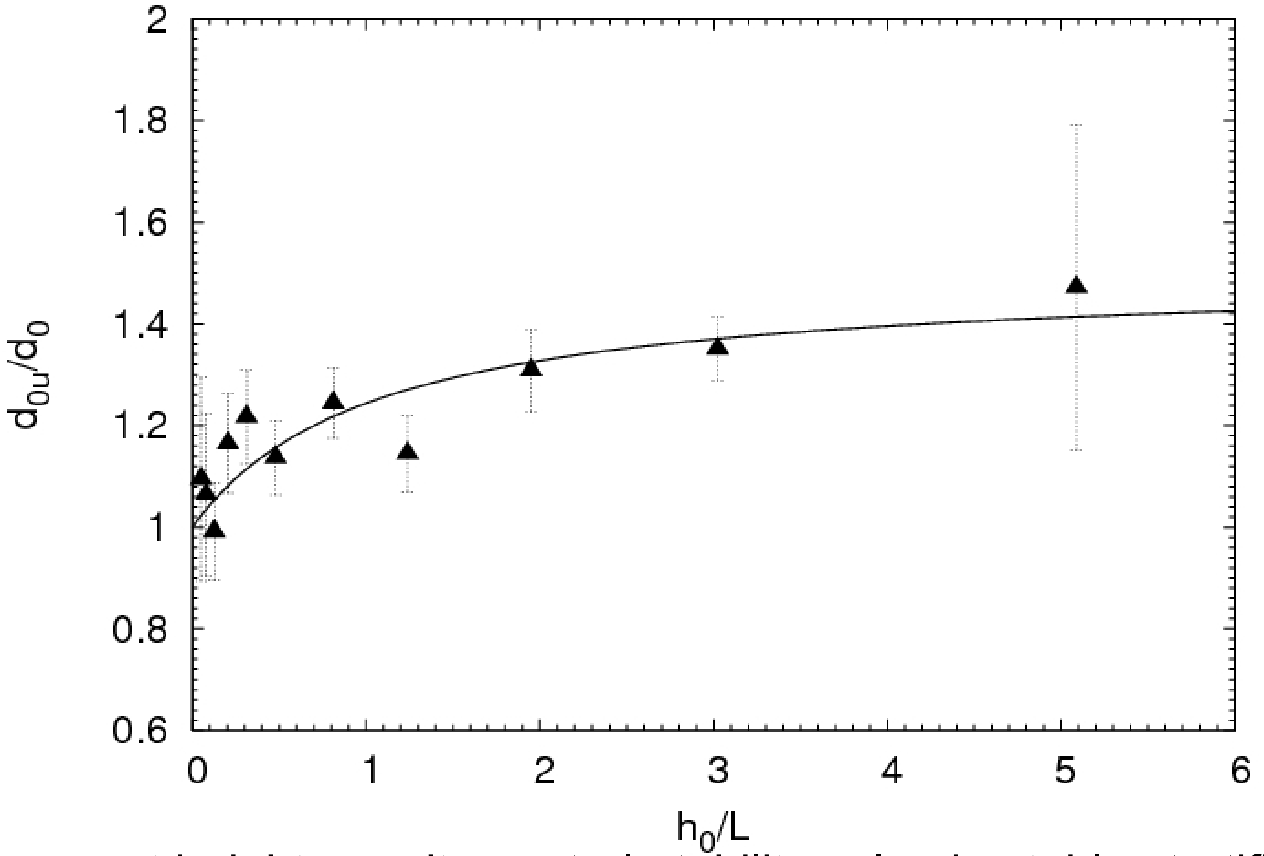
Bin-average values of z_0 / z_{0u} (neutral- over actual-roughness lengths) versus h_0/L in stable stratification for Boreal forest (h_0=13.5 m; z_0 =1.1±0.3 m). Bars are standard errors; the curve is $z_0 / z_{0u} = 1 + 8.13 h_0 / L$.

Stable stratification



Bin-average values of z_{0u}/z_0 (actual- over neutral-roughness lengths) versus h_0/L in stable stratification for boreal forest (h_0=13.5 m; z_0=1.1±0.3 m). Bars are standard errors; the curve is $z_{0u}/z_0 = (1+8.13h_0/L)^{-1}$.

Stable stratification



Displacement height over its neutral-stability value in stable stratification. Boreal forest (h_0 = 15 m, d_0= 9.8 m).

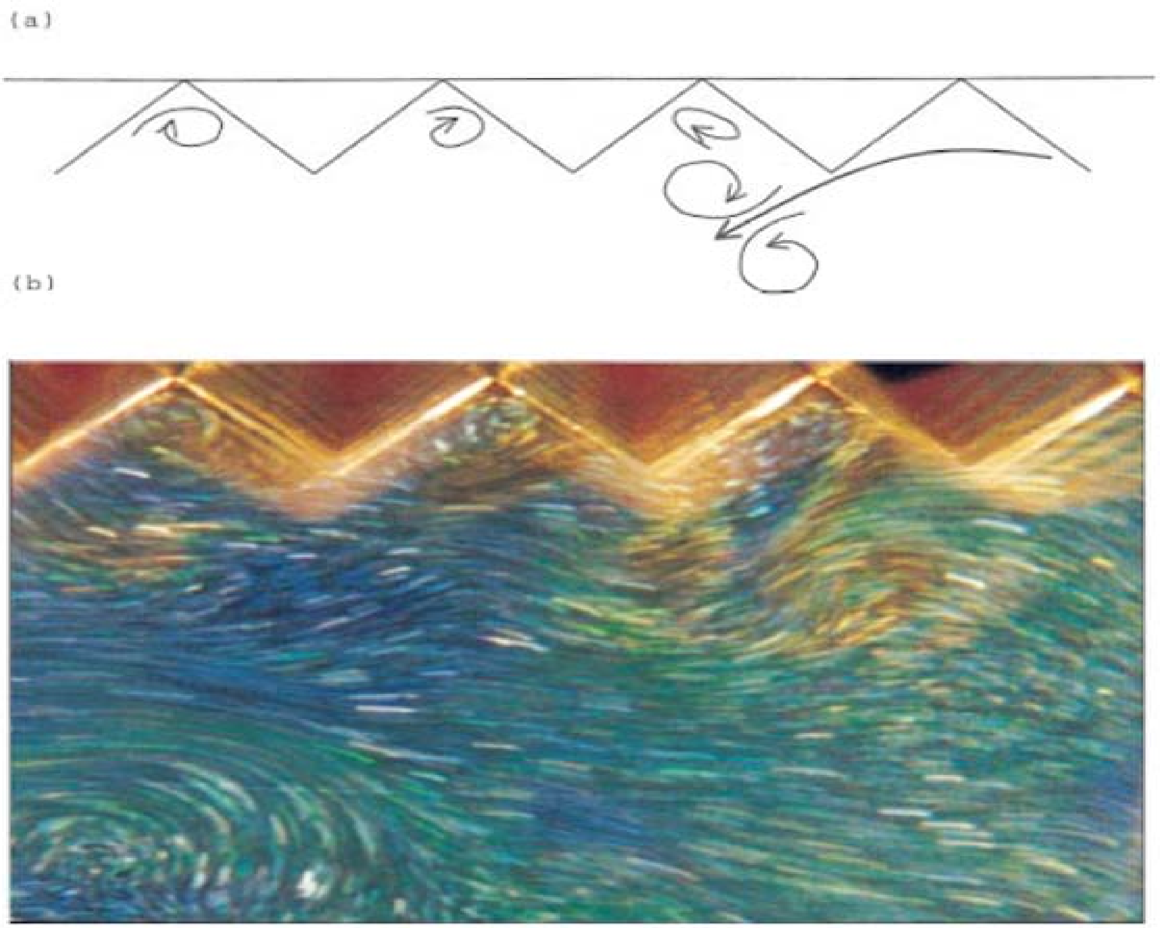
The curve is $$d_{0u}/d_0 = 1 + 0.5(h_0/L)(1.05 + h_0/L)^{-1}$$

Unstable stratification

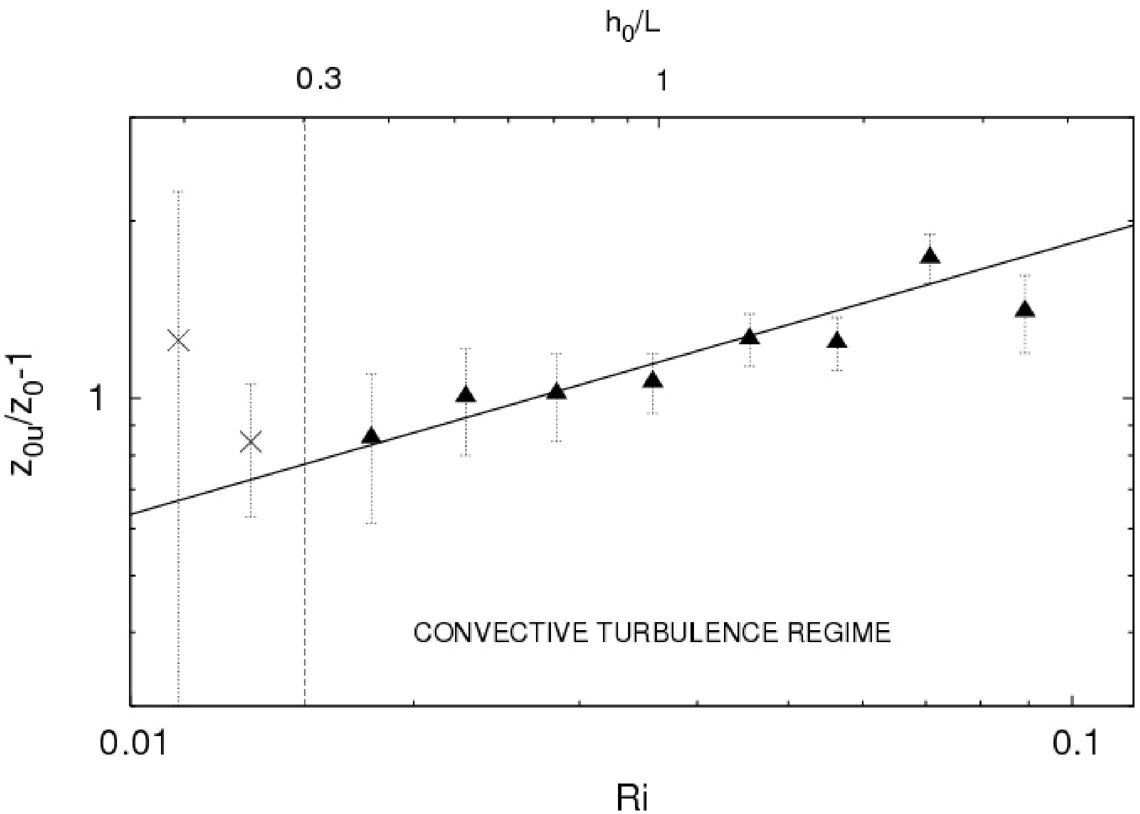
Convective eddies extend in the vertical causing $z_0 > z_{0u}$

VOLUME 81, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1998

Y.-B. Du and P. Tong, Enhanced Heat Transport in Turbulent Convection over a Rough Surface

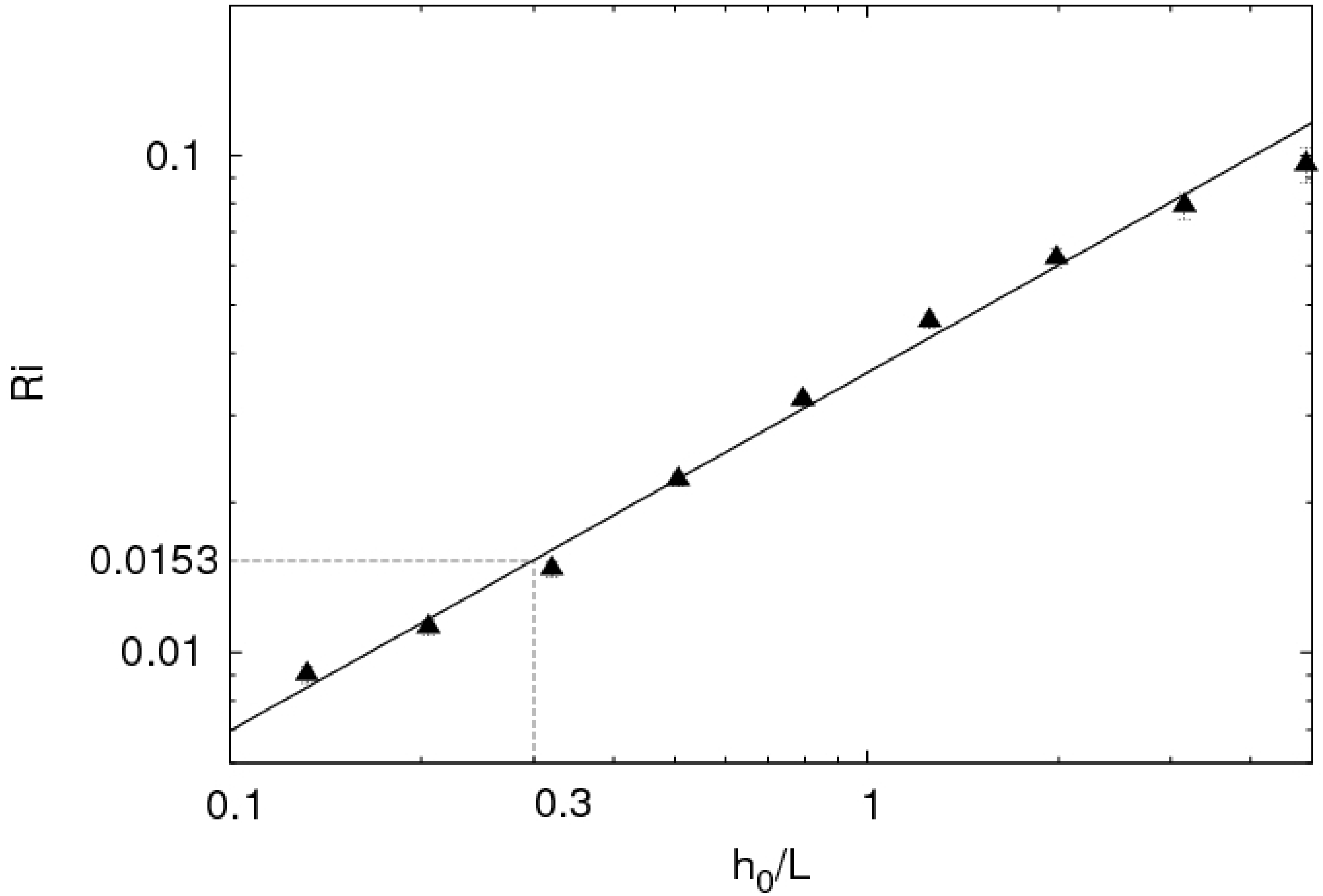


Unstable stratification



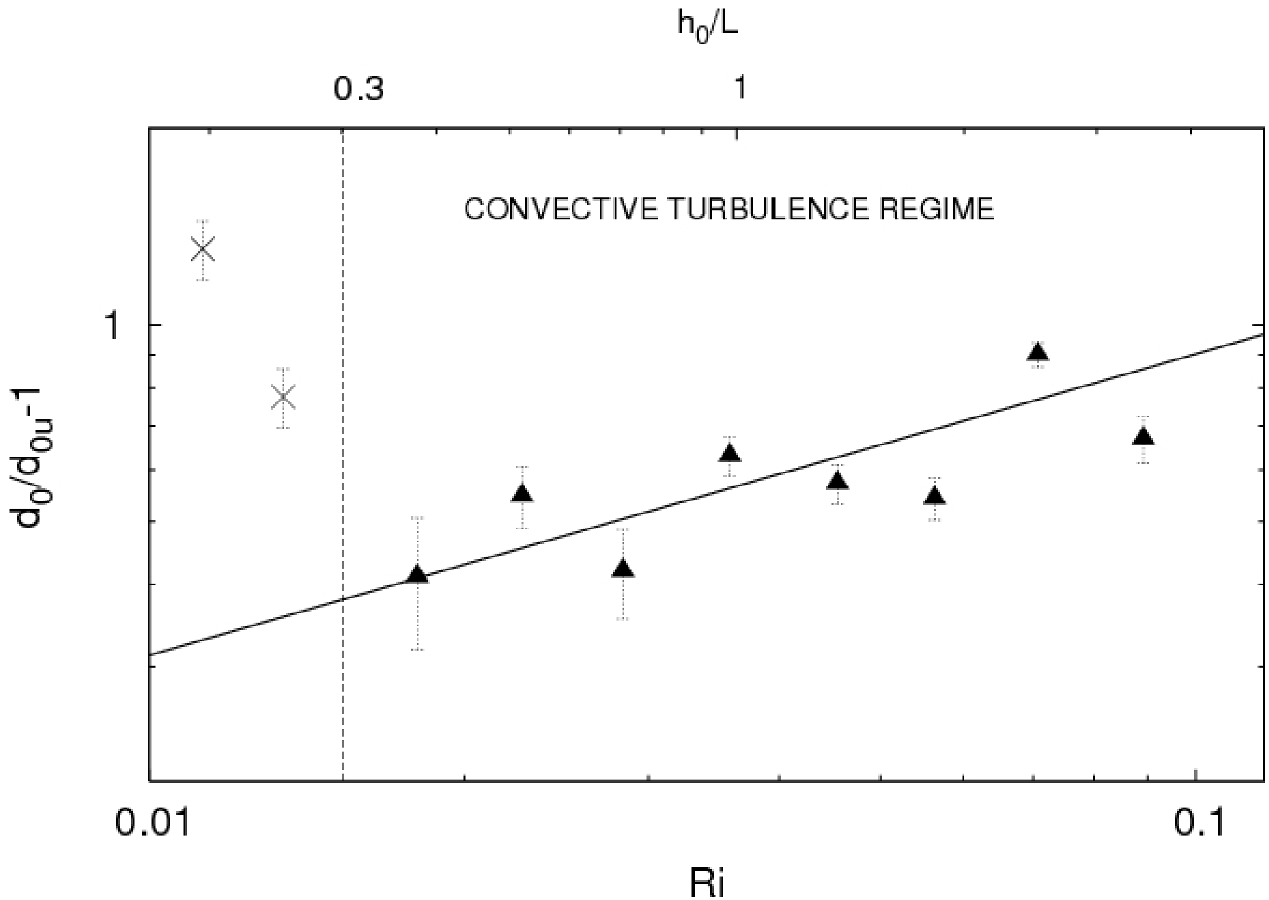
Unstable stratification, Basel, z_0/z_{0u} vs. Ri = $(gh_0/\Theta_{32})(\Theta_{18}-\Theta_{32})/(U_{32})^2$
Building height =14.6 m, neutral roughness z_0 =1.2 m; BUBBLE, Rotach et al., 2005).
h_0/L through empirical dependence on Ri on (next figure)
The curve ($z_0/z_{0u} = 1+5.31\mathrm{Ri}^{6/13}$) confirms theoretical $z_{0u}/z_0 = 1 + 1.15(h_0/{-L})^{1/3}$

Unstable stratification



Empirical Ri = 0.0365 $(h_0/-L)^{13/18}$

Unstable stratification



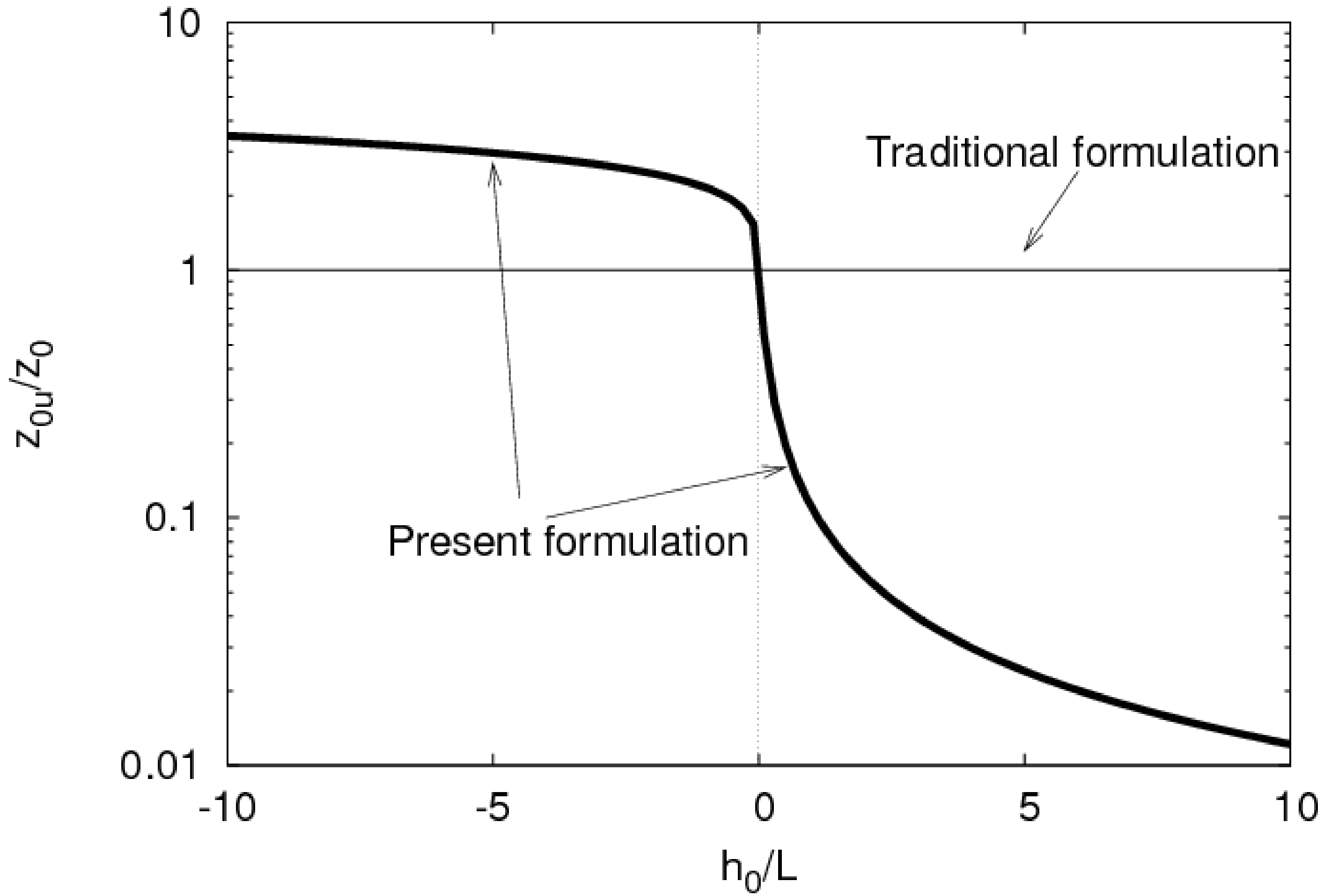
Displacement height in unstable stratification (Basel): $d_0 / d_{ou} - 1$ versus Ri

The line confirms theoretical dependence: $d_{0u} = \dfrac{d_0}{1 + C_{DC}(h_0 / -L)^{1/3}}$

STABILITY DEPENDENCE OF THE ROUGHNESS LENGTH

in the "meteorological interval" -10 $< h_0/L <$10 after new theory and experimental data

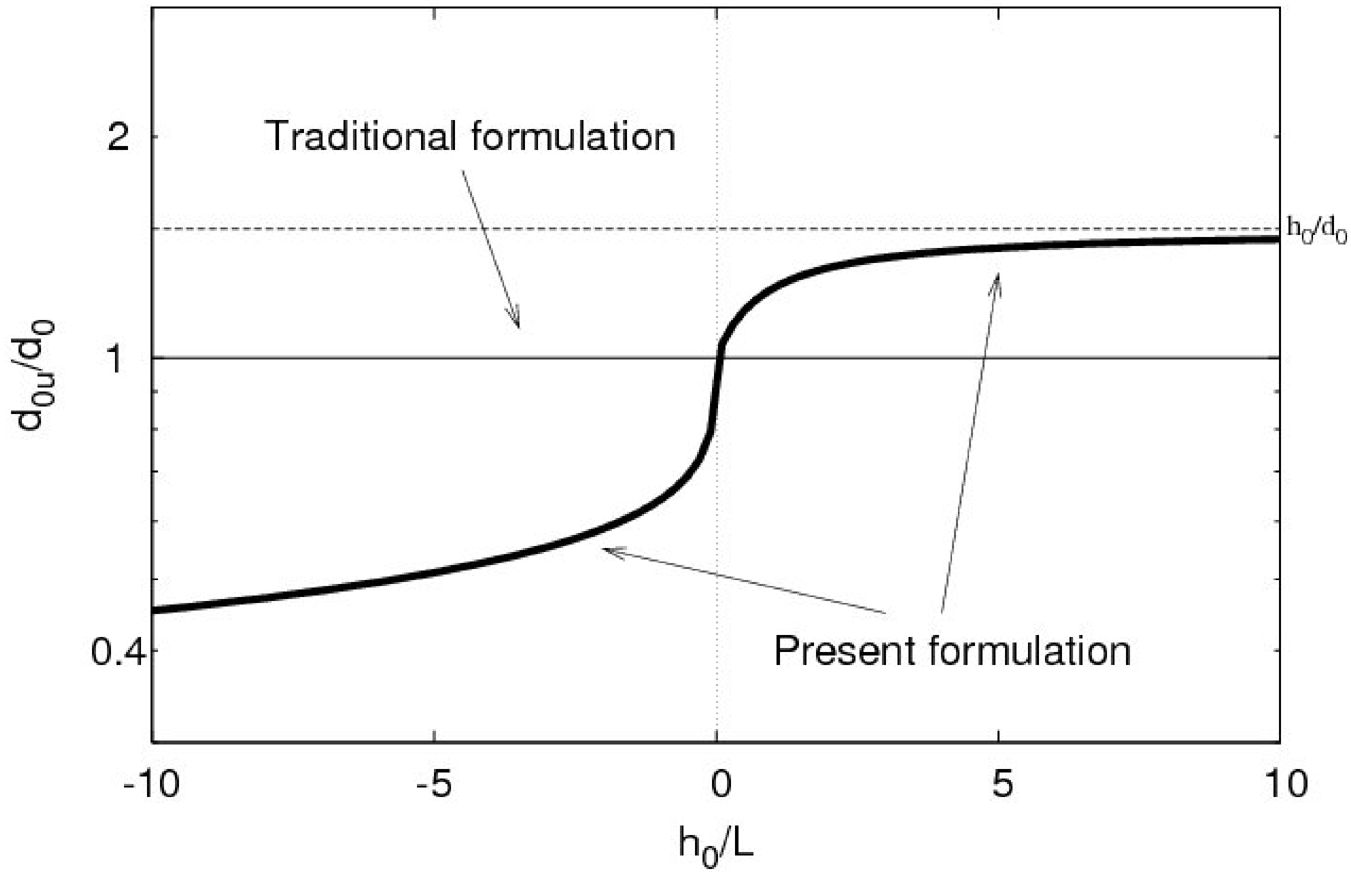
Solid line: z_{0u}/z_0 versus h_0/L Thin line: traditional formulation $z_{0u} = z_0$



STABILITY DEPENDENCE OF THE DISPLACEMENT HEIGHT

in the "meteorological interval" $-10 < h_0/L < 10$ after new theory and experimental data

Solid line: d_{0u}/d_0 versus h_0/L **Dashed line:** the upper limit: $d_0 = h_0$



Conclusions (roughness & displacement)

- Traditional: roughness length and displacement height fully characterised by geometric features of the surface
- New: essential dependence on hydrostatic stability especially in stable stratification
- Logarithmic intervals in the velocity profiles diminish over very rough surfaces in both very stable and very unstable stratification
- Applications: to urban and terrestrial-ecosystem meteorology
- Especially: urban air pollution episodes in very stable stratification

Thank you

University of Helsinki

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