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1) Workshop on Design and Use of Regional Weather
Prediction Models, *April 11 - 19*

2) Conference on Current Efforts Toward Advancing the Skill of Regional Weather
Prediction. Challenges and Outlook, *April 20 - 22*

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Physical grounds for improved parameterization of stable boundary layers in atmospheric models

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Abstract
In operational numerical weather prediction (NWP) models the surface layer (that is the lower 1/10 of the PBL) is always parameterized in the spirit of the Monin-Obukhov similarity theory, whereas the upper part of the PBLs is resolved (in fact only assumed to be resolved). This approach could cause considerable errors when applied to the long-loved stable PBLs (in particular those typical of Arctic Regions), whose heights are of the same order as the height of the lower computational level (~30 m). In such cases the very concept of the "constant-flux surface layer" becomes inapplicable. Instead, a new approach is proposed based on advanced PBL bulk resistance and heat/mass transfer laws and PBL depth formulations, accounting for non-local effects of the static stability and baroclinic shears in the free atmosphere (above the PBL). At the present stage, the theoretical background for this approach is developed, and the major theoretical results are verified through LES. Further efforts are needed to comprehensively validate the new theory against observational data, to develop on this basis a user-friendly PBL algorithm, to implement it in operational NWP model(s), and to perform case studies and statistical analyses of the r.m.s. error and bias of the weather forecasts using the "standard" and the "equipped" versions of the NWP model.

Basic idea

Standard approach in NWP models (e.g. HIRLAM):

- The upper part of the PBLs resolved (in fact only assumed to be resolved)
- The "constant-flux" surface layer (SL = 10% of PBL) parameterised (M-O similarity theory)

It fails in Arctic stable PBLs with heights *h* of the same order as the height of the lower computational level z_1~30m (the concept of SL inapplicable)

An alternative (based on advanced PBL theory) is to parameterise the entire PBL + capping inversion:

- Prediction equation for PBL depth *h* accounting for the free-flow stability and baroclinicity
- Analytical capping-inversion model (for $\Delta\theta_{CI}$)
- PBL bulk resistance and heat/mass transfer law for the turbulent fluxes at the surface $\vec{\tau}$, F_θ, F_q
- Multi-limit scaling & analytical mean profiles to determine turbulent fluxes throughout the PBL

Key Points

- **Principally different types of stable PBLs: nocturnal (N) and long-lived (LL)**

- **LL PBL height could be of order 30 m or less – no use of the "constant-flux" surface layer (MO similarity theory inapplicable)**

- **Capping inversions above LL PBL (*T*-jump up to 20 K) – overlooked of all NWP models**

- **Resistance laws presented in textbooks on BLM but not practically used: poor accuracy**

- **Why so poor?**

- **Overlooked mechanisms**

- **Advanced theory and its validation through LES and field data**

Stable and neutral planetary boundary layers (PBLs)

Traditional local theory

Neutral PBLs	$F_{\theta s} = 0$
Nocturnal Stable	$F_{\theta s} < 0$

Neither N nor Γ are taken into account

Non-local theory

Truly Neutral	$F_{\theta s} = 0$, N=0, Γ=0
Conventionally Neutral	$F_{\theta s} = 0$, N>0, $\Gamma \neq 0$
Nocturnal Stable	$F_{\theta s} < 0$, N=0, Γ=0
Long-lived Stable	$F_{\theta s} < 0$, N>0, $\Gamma \neq 0$

Traditional background

The MO-theory suggests log-linear profiles of the mean wind, u, potential temperature, θ, and specific humidity, q:

$$u(z) = \frac{u_*}{k}\left(\ln\frac{z}{z_{0u}} + C_u\frac{z}{L}\right)$$

$$\theta(z) = \theta_s + \frac{\theta_*}{k_T}\left(\ln\frac{z}{z_{0T}} + C_\theta\frac{z}{L}\right)$$

$$q(z) = q_s + \frac{q_*}{k_q}\left(\ln\frac{z}{z_{0q}} + C_q\frac{z}{L}\right)$$

$u_* \equiv \sqrt{\tau_s}$ **friction velocity**

$\theta_* \equiv -F_{\theta s}/u_*,\ q_* \equiv -F_{qs}/u_*$ **θ and q scales**

z_{0u}, z_{0T}, z_{0q} **roughness lengths**

$k \approx 0.4, k_T \approx k_q \approx 0.42$ **von Karman constants**

$C_u \approx$ **2.1 and** $C_\theta \approx C_q \approx$ **3.2** **other constants**

$$L = -\frac{u_*^3}{\beta F_{\theta s} + 0.61 g F_{qs}} = \frac{u_*^2}{\beta\theta_* + 0.61 g q_*}$$

Monin-Obukhov length

Surface fluxes in current GCMs

Let z_1 is the lower calculation level. A GCM predicts

$$u = u(z_1),\ \Delta\theta = \theta(z_1) - \theta_s,\ \Delta q = q(z_1) - q_s$$

Given z_{0u}, z_{0T}, z_{0q}, the MO theory equations can be solved for u_*, θ_*, q_* and *L*, and for the fluxes

$$\tau_s = u_*^2,\quad F_{\theta s} = -u_*\theta_*,\quad F_{qs} = -u_* q_*.$$

Inconveniences:

(i) transcendental system of equations

(ii) non-zero turbulent fluxes only when $\mathrm{Ri} < \mathrm{Ri}_c$, decoupling at $\mathrm{Ri} > \mathrm{Ri}_c$

Here, Ri is surface-layer bulk Richardson number

$$\mathrm{Ri} \equiv \frac{(\beta\Delta\theta + 0.61g\Delta q)z_1}{u^2}$$

and Ri_c is its critical value (supposed to be ~0.3).

In GCMs decoupling at $\mathrm{Ri} > \mathrm{Ri}_c$ is unacceptable:

(i) technically: numerical instability

(ii) physically: principal drawbacks of the local theory
contribution from sub-grid scales

Drag & heat/mass transfer

$$C_D \equiv \frac{\tau_s}{u^2}, \quad C_H \equiv -\frac{F_{\theta s}}{u\Delta\theta}, \quad C_M \equiv -\frac{F_{qs}}{u\Delta q}$$

In neutral stratification

$$C_{Dn} = \frac{k^2}{[\ln(z_1 / z_{0u})]^2},$$

$$C_{Hn} = \frac{kk_T}{\ln(z_1 / z_{0u})\ln(z / z_{0T})},$$

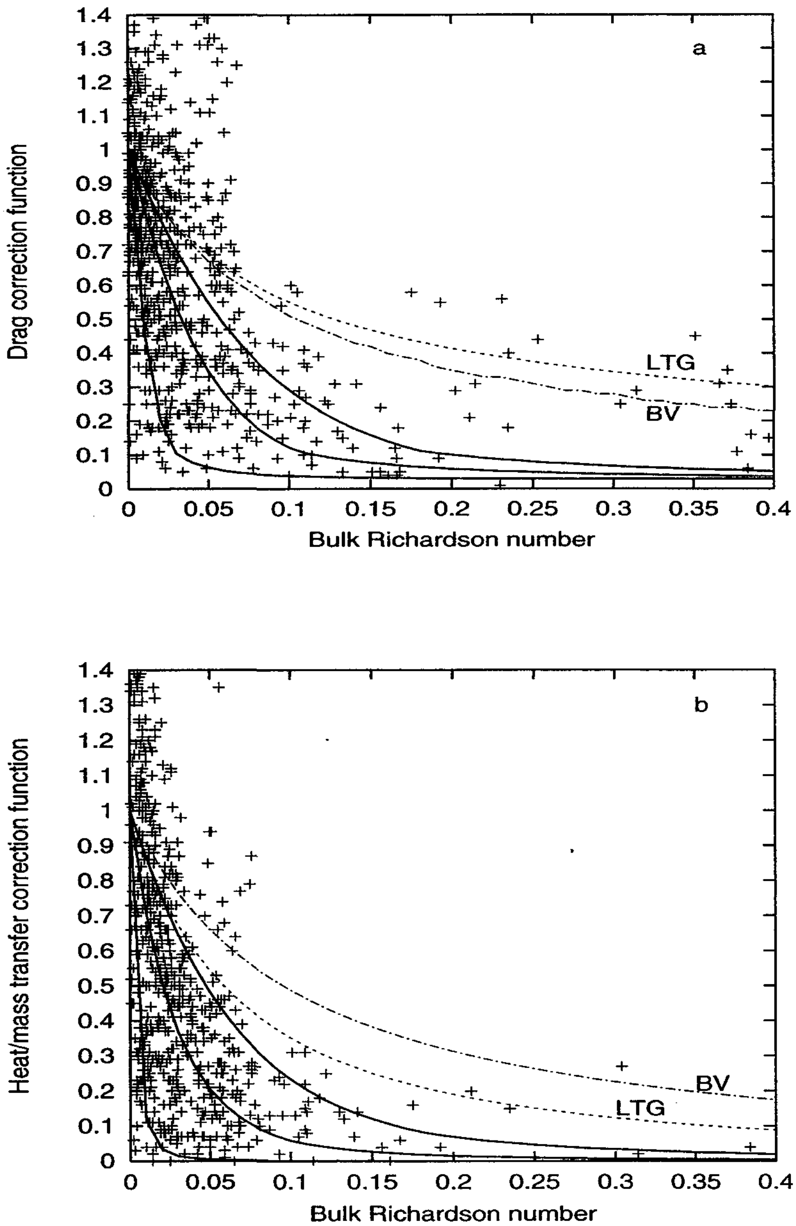
$$C_{Mn} = \frac{kk_q}{\ln(z_1 / z_{0u})\ln(z / z_{0q})}$$

The effect of stratification is taken into account through correction functions <u>dependent on only Ri</u>

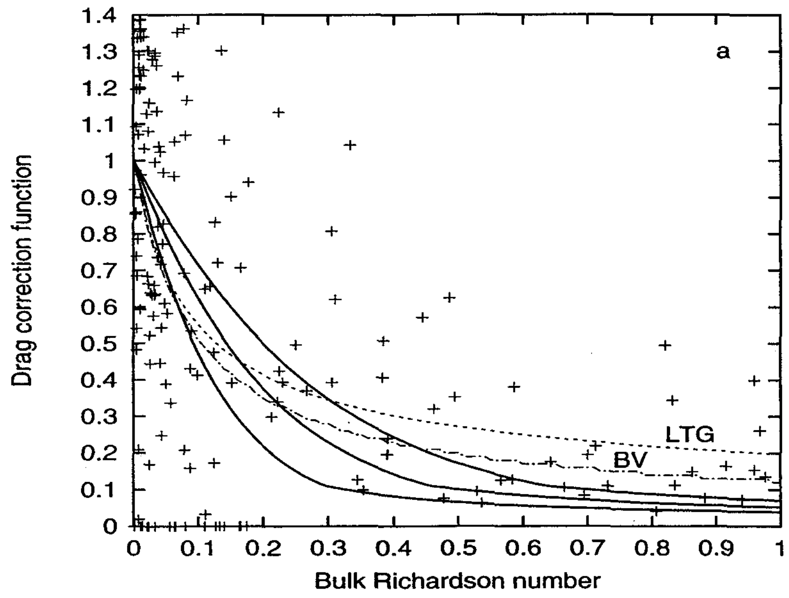
$$f_D = \frac{C_D}{C_{Dn}}, \quad f_H = \frac{C_H}{C_{Hn}}, \quad f_M = \frac{C_M}{C_{Mn}}$$

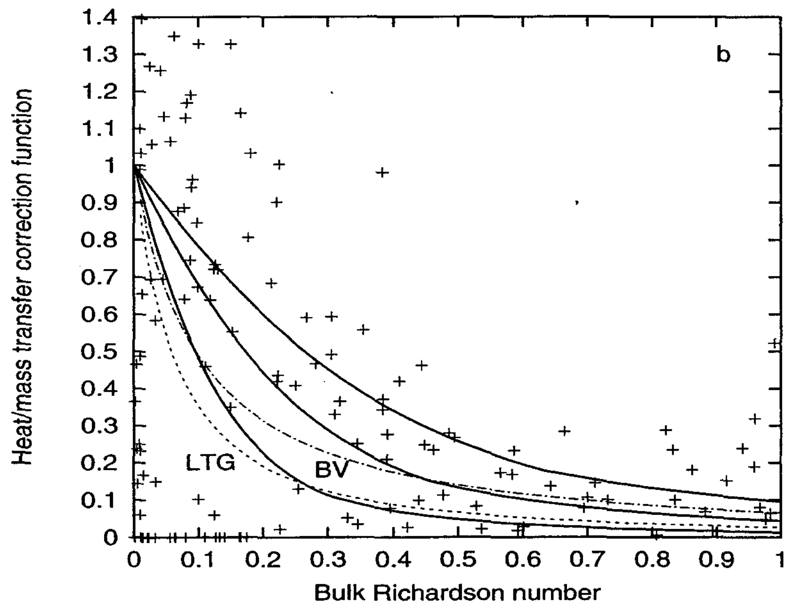
(Louis, 1979; Källen, 1996; Beljaars and Viterbo, 1998). Generally, f_D, f_H and f_M depend on z_{0u}, z_{0T}, z_{0q} and some other parameters (Z, Perov and King, 2002).

BUT ANY FLUX-CALCULATION SCHEME BASED ON THE CONCEPT OF THE CONSTANT-FLUX SURFACE LAYER IS INAPPLICABLE TO SHALLOW PBLs



The correction functions (a) to the drag coefficient, f_D, (b) to the heat and mass transfer coefficients, $f_H = f_M$, versus bulk Richardson number Ri, after measurements at Halley, Antarctica (Zilitinkevich, Perov & King, 2002). Solid lines, after op cit; dashed lines (LTG), after Louis et al. (1982); dash-and-dot lines (BV), after Beljaars and Viterbo (1998).





The correction functions (a) to the drag coefficient, f_D, and (b) to the heat and mass transfer coefficients, $f_H = f_M$, vs. bulk Richardson number, Ri, after measurements at Sodankyla, Arctic Finland (Zilitinkevich, Perov & King, 2002). Solid lines, after *op cit*; dashed lines (LTG) after Louis et al., 1982); dash-and-dot lines (BV) after Beljaars & Viterbo, 1998).

PBL Depth

2002

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.

Zilitinkevich, S.S., and Baklanov, A., 2002: Calculation of the height of stable boundary layers in practical applications. *Boundary-Layer Meteorol.* **105**, 389-409.

Zilitinkevich S. S., and Esau, I. N., 2002: On integral measures of the neutral, barotropic planetary boundary layers. *Boundary-Layer Meteorol.* **104**, 371-379.

2003

Zilitinkevich S. S., and Esau, I. N., 2003: The effect of baroclinicity on the depth of neutral and stable planetary boundary layers. *Quart, J. Roy. Met. Soc.* **129**, 3339-3356.

Motivation

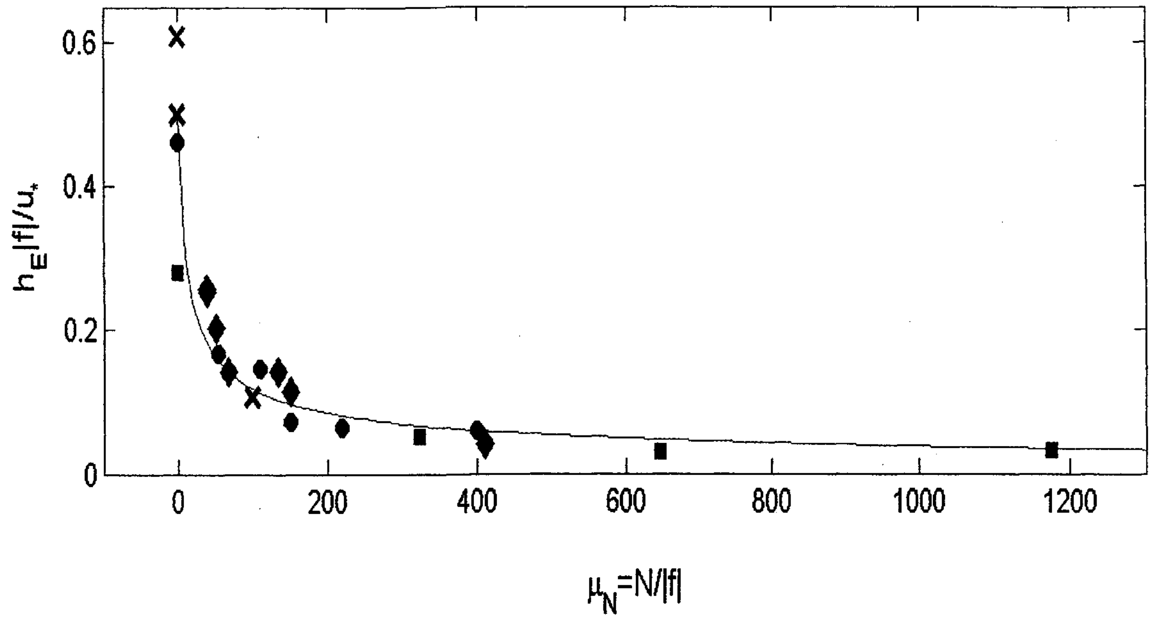
- **Contradicting PBL depth formulations: diagnostic, prognostic, bulk *Ri* concept… no consensus**

- **Multiple mechanisms and scales:**

<u>Universally accepted:</u>
- **Earth's rotation**
- **negative buoyancy flux at the surface**

<u>Overlooked:</u>
- **free-flow stability**
- **baroclinic shear**
- **large-scale vertical velocity**
- **non-steady developments**

CNPBL depth ($N > 0$)



Dimensionless CNPBL depth $|f|h_{LES}/u_*$ **vsersus imposed-stability parameter,** μ_N

after new LES (Esau, 2003), earlier LES (Mason & Thomson, 1987; Lin et al., 1997) and DNS (Coleman, 1999). The theoretical line is

$$h_E = 0.7\frac{u_*}{|f|(1+0.28N/|f|)^{1/2}}$$

Over decades, the neutral PBL depth was calculated as $h_E = C_R u_* / |f|$, which resulted in wide spread of empirical estimates of the empirical coefficient: $0.1 < C_R < 0.7$.

Baroclinic fluid

Free-atmosphere parameters

Shear $$\Gamma = \left|\frac{d\mathbf{u}_g}{dz}\right| = \frac{g}{|f|T}\left[\left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial x}\right)^2\right]^{1/2}$$

Brunt-Väisälä frequency $$N \equiv \left(\frac{g}{T}\frac{\partial \theta_v}{\partial z}\right)^{1/2}$$

Parameter of baroclinicity $$\mu_\Gamma = \frac{\Gamma}{N} = \mathrm{Ri}^{-1/2}$$

Richardson number $$1 < \mathrm{Ri} = \left(\frac{N}{\Gamma}\right)^2 < 10$$

Critical $\mathrm{Ri}_c = 0.25$ $\Rightarrow$ **When** N **diminishes, wind shear generates turbulence throughout**

Baroclinic turbulent velocity scale

$$u_T^2 = u_*^2(1 + C_0\mu_\Gamma), \qquad C_0 = \text{constant}$$

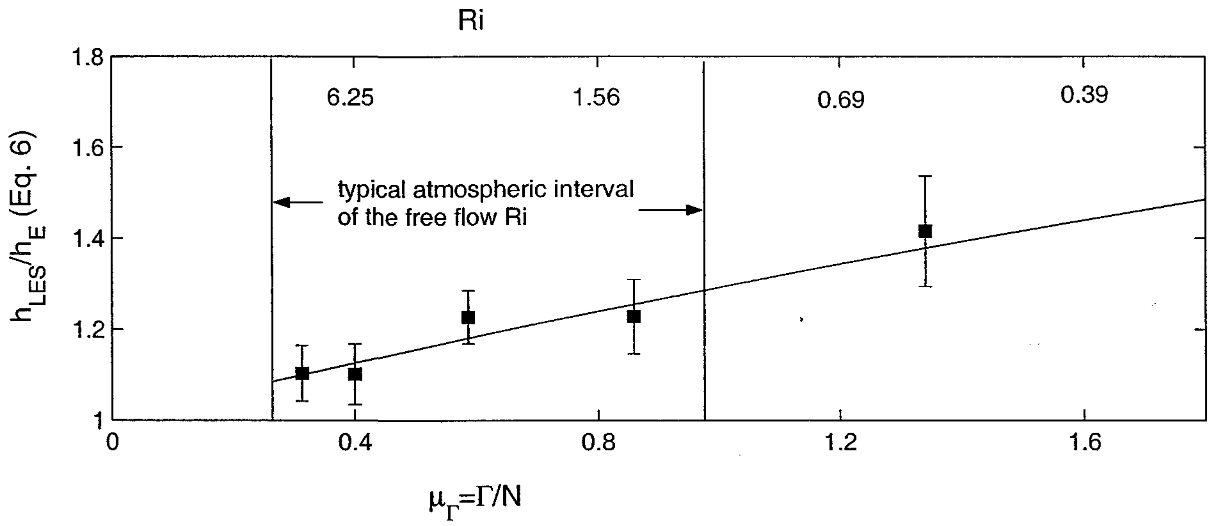
Derived from

$$u_T^2 = u_*^2 + C' K_M^* \Gamma, \qquad l_T \sim u_T / N, \qquad K_M^* = u_T l_T$$

Baroclinic, conventionally neutral

$$h_E = C_R \frac{u_*}{|f|} (1+C_0\mu_\Gamma)^{1/2} \left(1+\frac{C_R^2 C_{uN}}{C_S^2}\mu_N\right)^{-1/2}$$

$$\equiv [h_E(\text{barotropic Eq.6})](1+C_0\mu_\Gamma)^{1/2}$$



The ratio of the baroclinic to barotropic PBL depth $R = h_{LES} / [h_E(\text{Eq.6})]$ versus $\mu_\Gamma = \Gamma / N$

The upper scale shows Richardson numbers, Ri. Theoretical curve, $R = (1+C_0\mu_\Gamma)^{1/2}$ with $C_0 = 0.7$, closely matches data from new LES (squares) over the whole range of Ri or μ_Γ.

Conclusions (PBL depth)

- **Equilibrium barotropic PBL: h_E depends on**
  - earth's rotation **(Coriolis parameter f)**
  - surface-layer stability **(buoyancy flux F_{bs}; internal-stability parameter $\mu = u_* / |f| L$)**
  - **free-flow stability (Brunt-Väisälä frequency N; imposed stability parameter $\mu_N = N / |f|$)**

- **Baroclinicity increases PBL depth**
  - h_E depends on geostrophic shear Γ, which involves the free-flow Ri = $(N/\Gamma)^2$, or $\mu_\Gamma = \Gamma / N$

- **Widely used critical-Ri approach is poorly grounded (overlooks the roles of N, Γ, z_0, f)**

- **Recommended prognostic h-equation:**

$$\frac{\partial h}{\partial t} + \mathbf{u} \cdot \nabla h - w_h = -\frac{h - h_E}{t_E} + K_h \nabla^2 h$$

Needed:
t_E, K_h, empirical / LES validation, testing in GCMs

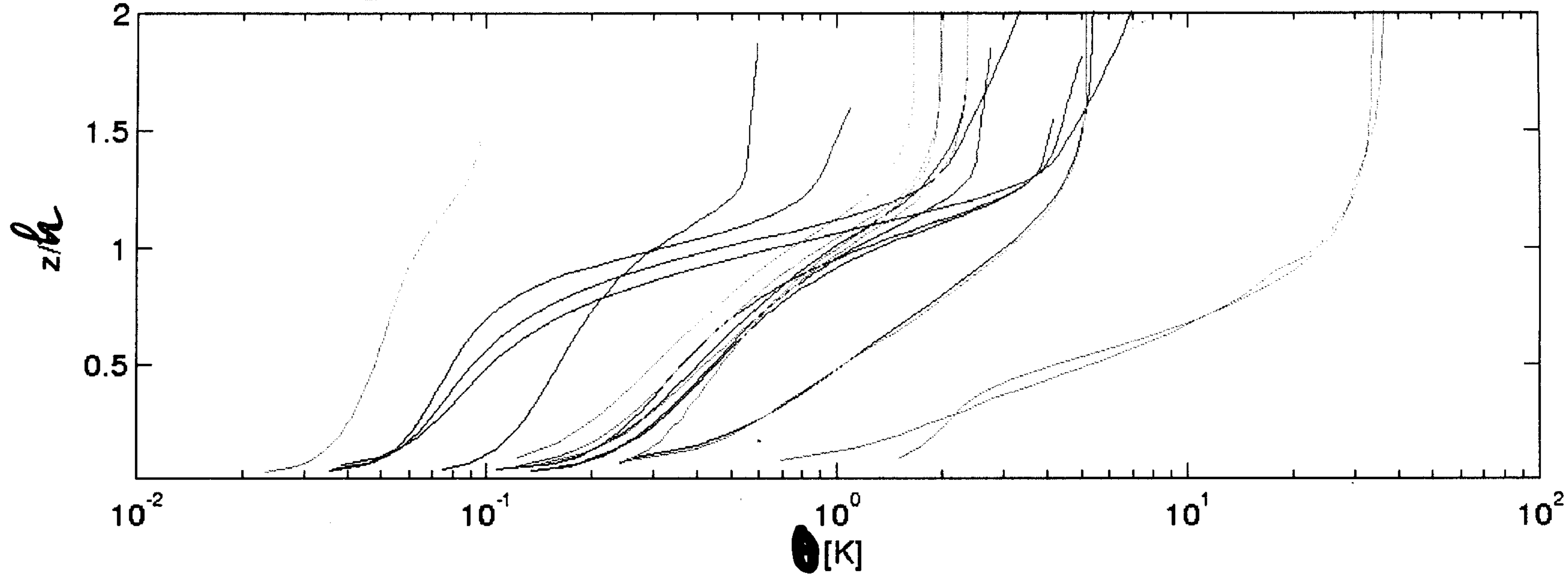
Capping inversion

2004

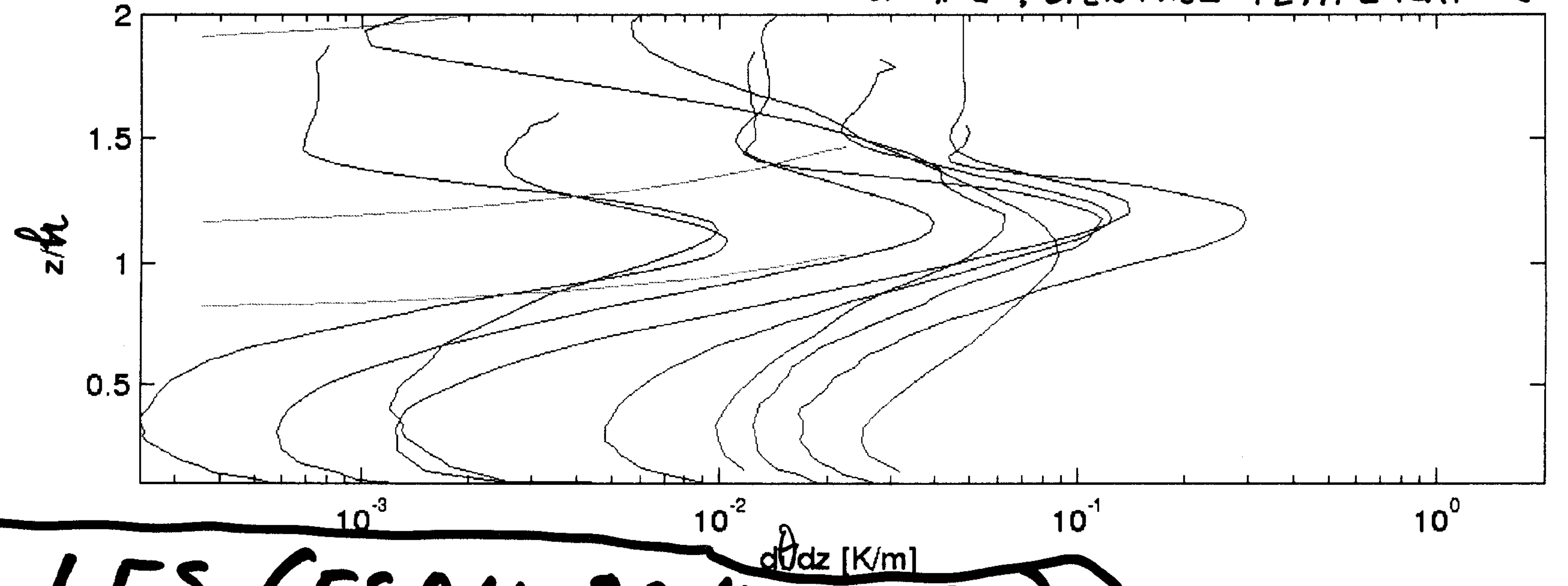
Zilitinkevich S. S., and Esau, I. N., 2004: Resistance and heat transfer laws for stable and neutral boundary layers: old theory advanced and re-eveuated. *Quart. J. Roy. Met. Soc.* In press.

CAPPING INVERSIONS

VERTICAL PROFILES OF POTENTIAL TEMPERATURE $\theta(z)$



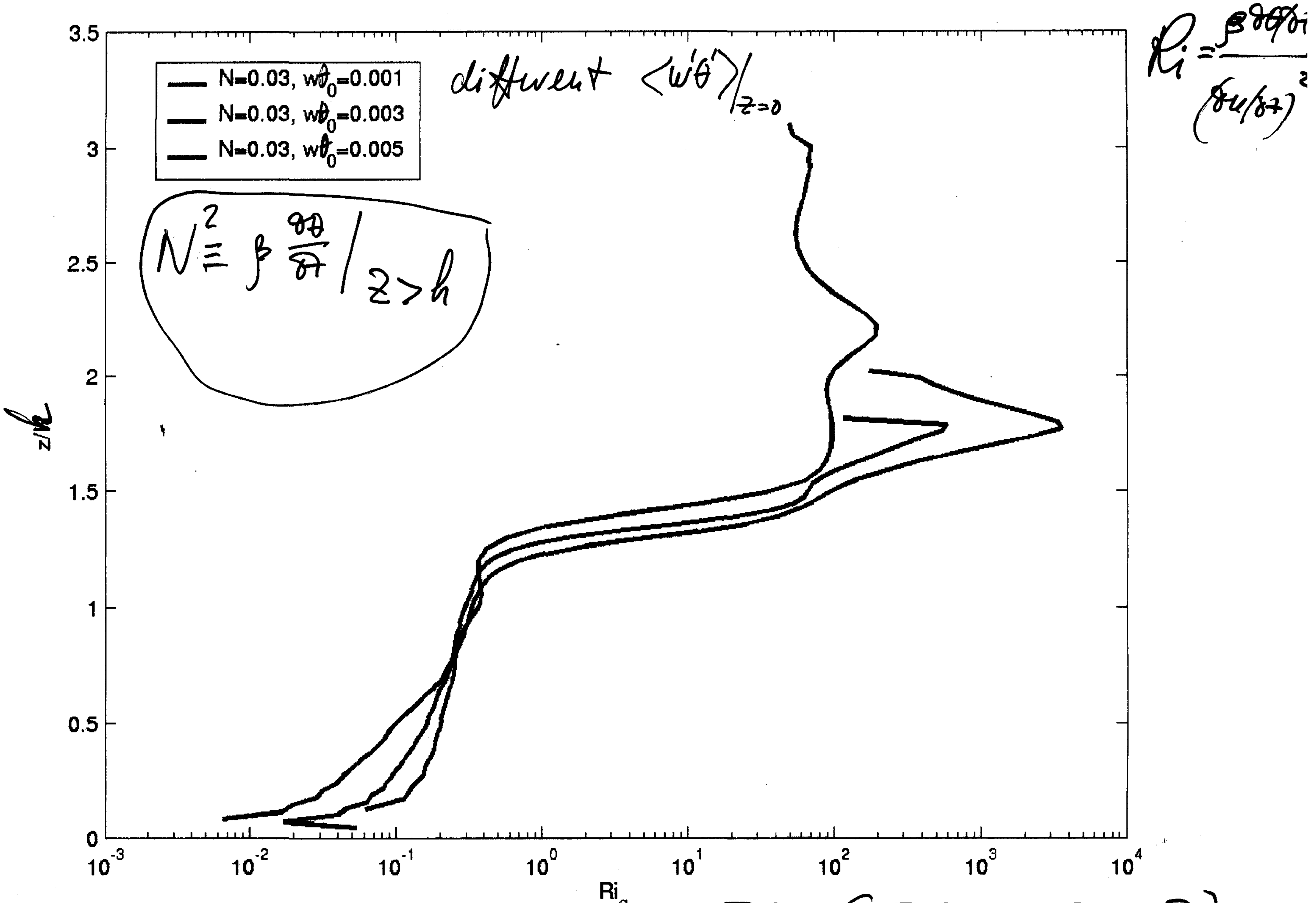
VERTICAL PROFILES OF THE POTENTIAL TEMPERATURE GRADIENT $\frac{\partial \theta}{\partial z}$



h is the PBL depth

in LES (ESAU, 2004-2005)

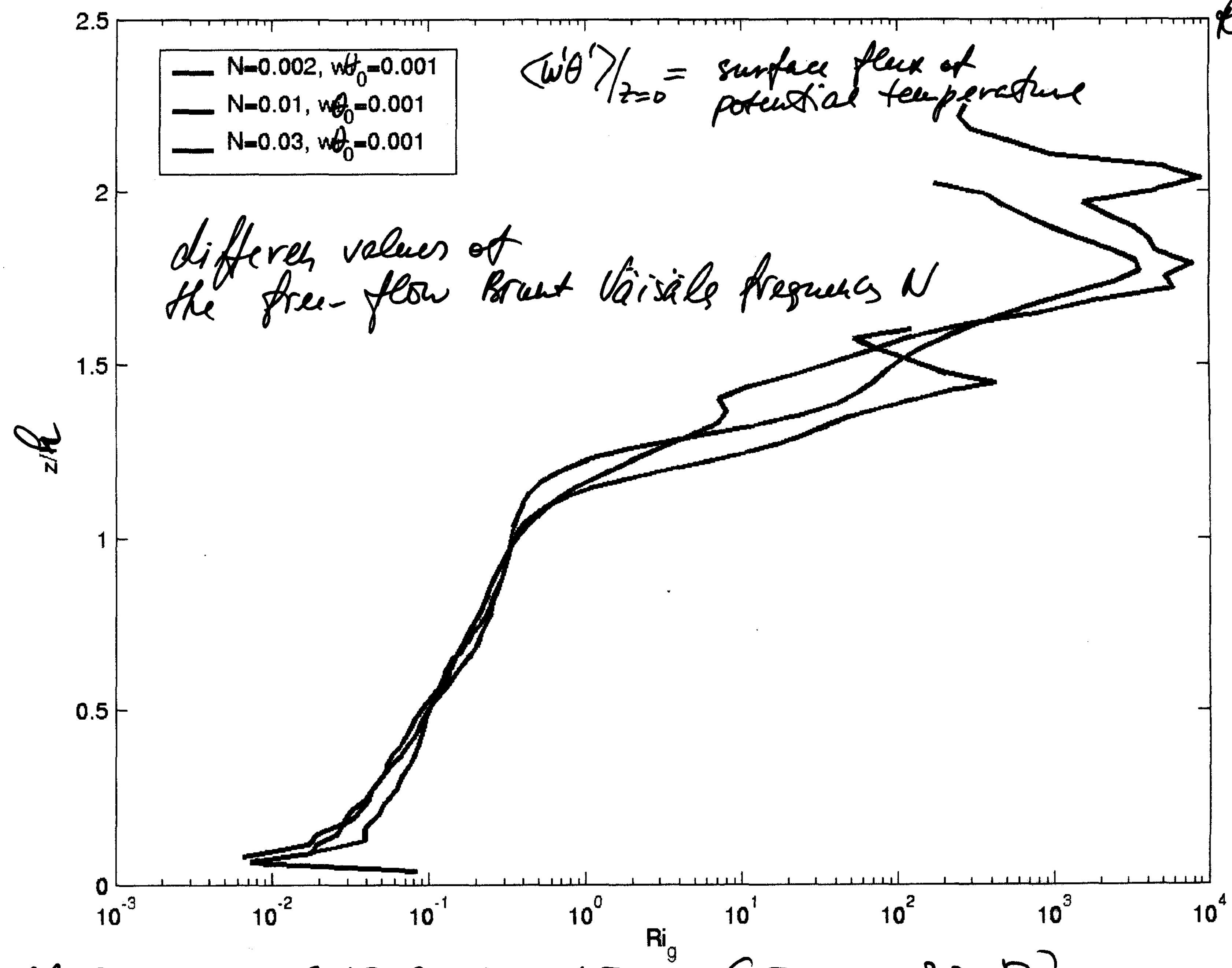
VERTICAL PROFILES OF THE GRADIENT RICHARDSON NUMBER



CAPPING INVERSION IN LES (ESAU, 2005)

VERTICAL PROFILES OF THE GRADIENT RICHARDSON NUMBER

$$Ri = \frac{\beta \frac{\partial \theta}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2}$$



CAPPING INVERSIONS IN LES (ESAU, 2005)

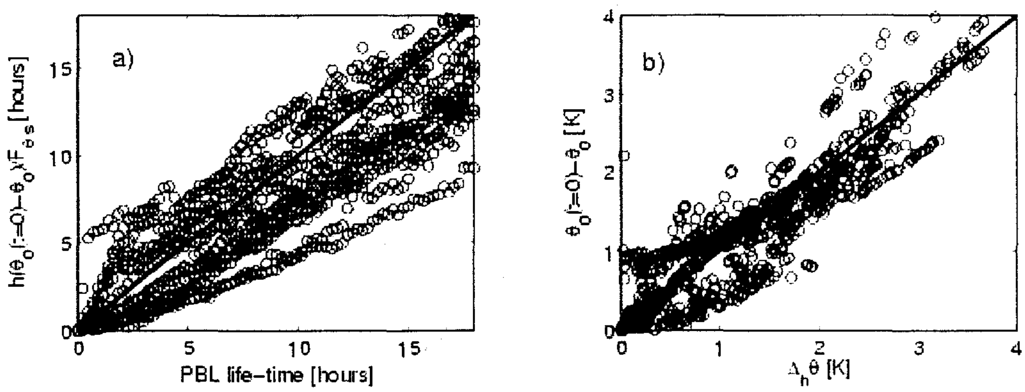
SIMPLE MODEL OF CAPPING INVERSION

LES data on temporal changes in the aerodynamic surface potential temperature θ_0 and the increment $\Delta\theta_{CI}=\theta(h+\frac{1}{2}\delta)-\theta(h-\frac{1}{2}\delta)$ across the capping inversion of depth $\delta=0.5h$

(a) Temporal changes of the normalised surface temperature drop $(\theta_0|_{t=0}-\theta_0)h/F_{\theta s}$

(b) The increment $\Delta\theta_{CI}$ versus the drop $(\theta_0|_{t=0}-\theta_0)$

The lines are $(\theta_0|_{t=0}-\theta_0)=-F_{\theta s}h^{-1}t$ and $\Delta\theta_{CI}=(\theta_0|_{t=0}-\theta_0)$



CONCLUSION: FURTHE WORK NEEDED

Resistance and heat/mass transfer

PBL mean profiles *u*(*z*), *T*(*z*), *q*(*z*)

1967

Zilitinkevich, S.S., Laikhtman, D.L., Monin, A.S., 1967: Dynamics of the atmospheric boundary layer. *Izv., AN SSSR, FAO*, **3**, No. 3, 297-333.

1968

Zilitinkevich, S.S., Chalikov, D.V., 1968: On the resistance and heat /mass transfer laws in the interaction between the atmosphere and the underlying surface. *Izv. AN SSSR, FAO*, **4**, No. 7, 765-772.

1989

Zilitinkevich, S.S., 1989: Velocity profiles, resistance laws and dissipation rate of mean flow kinetic energy in a neutrally and stably stratified planetary boundary layer. *Boundary-Layer Meteorol.*, **46**, 367-387.

Zilitinkevich, S.S., 1989: The temperature profile and heat transfer law in a neutrally and stably stratified planetary boundary layer. *Boundary-Layer Meteorol.*, **49**, 1-5.

1998

Zilitinkevich, S., Johansson, P.-E., Mironov, D.V., and Baklanov, A., 1998: A similarity-theory model for wind profile and resistance law in stably stratified planetary boundary layers. *Journal of Wind Engineering and Industrial Aerodynamics* **74-76**, 209-218.

2002

Zilitinkevich S. S., and Esau, I. N., 2002: On integral measures of the neutral, barotropic planetary boundary layers. *Boundary-Layer Meteorol.* **104**, 371-379.

2004

Zilitinkevich S. S., and Esau, I. N., 2004: Resistance and heat transfer laws for stable and neutral boundary layers: old theory advanced and re-eveuated. *Quart. J. Roy. Met. Soc.* In press.

History (local models)

Rossby-Montgomery (1935) ***neutral*** resistance law for $C_g = u_*/G$ and cross-isobaric angle α:

$$\tilde{A} = \ln(C_g \mathrm{Ro}) - \frac{k}{C_g}\cos\alpha \quad \tilde{B} = \mp\frac{k}{C_g}\sin\alpha$$

$\tilde{A}, \tilde{B}$ dimensionless coefficients

$\mathrm{Ro} \equiv G/|f|z_0$ surface Rossby number

Z (1967); Z & Chalikov (1968) ***nocturnal*** $\tilde{A}$, $\tilde{B}$ depend on the internal stability parameter

$$\mu = \frac{u_*}{|f|L} \quad \left(L = \frac{u_*^3}{-\beta F_{\theta s}}\right) \qquad (-10^3 < \mu < 10^3)$$

Heat transfer: $\frac{k_T}{C_{Td}} = \ln(C_g \mathrm{Ro}) - \tilde{C}$, $C_{Td} = \frac{\theta_*}{\Delta\theta_0}$

PBL is considered as neutral when $\mu = 0$

Z & Deardorff (1974) ***non-steady nocturnal***

$$\frac{k}{C_{gd}}\cos\alpha = \ln\frac{h}{z_{0u}} - A \qquad \frac{k}{C_{gd}}\sin\alpha = -\frac{fh}{u_*}B$$

$$\frac{k_T}{C_{Td}} = \ln\frac{h}{z_{0u}} - C$$

A and B depend on $\frac{h}{L}$

Advanced PBL scaling

Local M-O ***nocturnal*** PBL $L = -\tau^{3/2}(\beta F_\theta)^{-1}$

Non-local ***long-lived*** PBL $L_N = u_* / N$

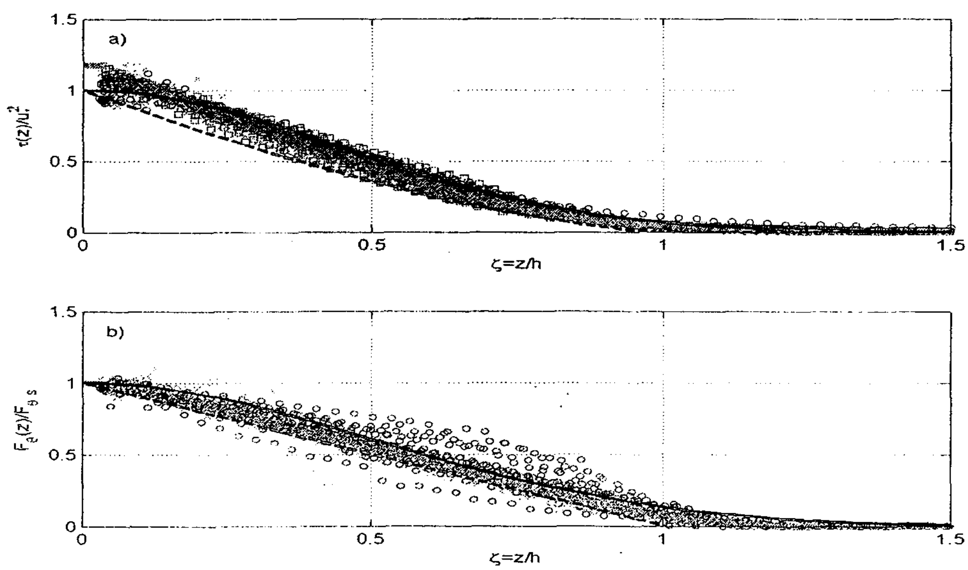
Rotational ***truly neutral*** PBL $L_f = u_* / |f|$

General

$$\frac{1}{L_{\{M,H\}}} = \left[\left(\frac{1}{L}\right)^2 + \left(\frac{C_{\{NM,NH\}}}{L_N}\right)^2 + \left(\frac{C_{\{fM,fH\}}}{L_f}\right)^2 \right]^{1/2}$$

Flux profiles $\frac{\tau}{u_*^2} = f_\tau\left(\frac{z}{h}\right), \quad \frac{F_\theta}{F_{\theta s}} = f_{F\theta}\left(\frac{z}{h}\right)$

LES x *nocturnal*; o *long-lived*; □ *convent.neutral*



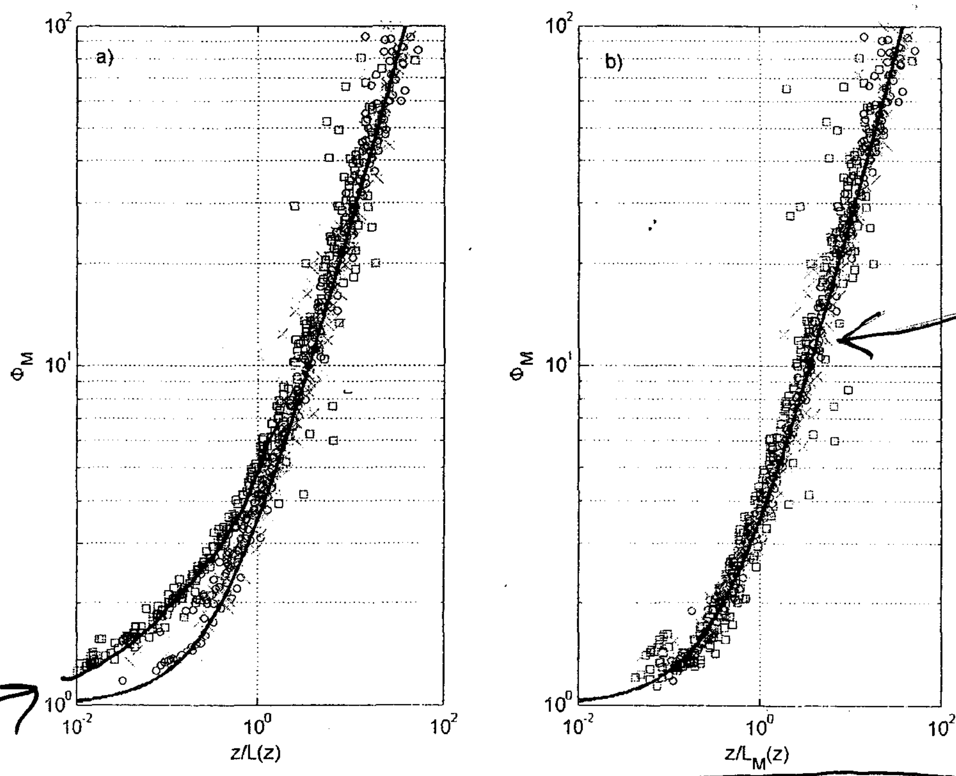
L/L_N decreases with increasing height $\varsigma = z/h$

Velocity shear (L_M instead of L)

Scaling

Log & z − less $\qquad \dfrac{\partial u}{\partial z} = \dfrac{\tau^{1/2}}{kz}\left[1+\left(\dfrac{C_u z}{L_M}\right)\right] \approx \dfrac{C_u \tau^{1/2}}{k L_M}$

LES $\Phi_M = \dfrac{kz}{\tau^{1/2}} \dfrac{\partial u}{dz}$ versus z/L (a) and z/L_M (b)



good collapse throughout the PBL

⇓

ANALYTYC APPROXIMATION OF THE MEAN WIND PROFILE

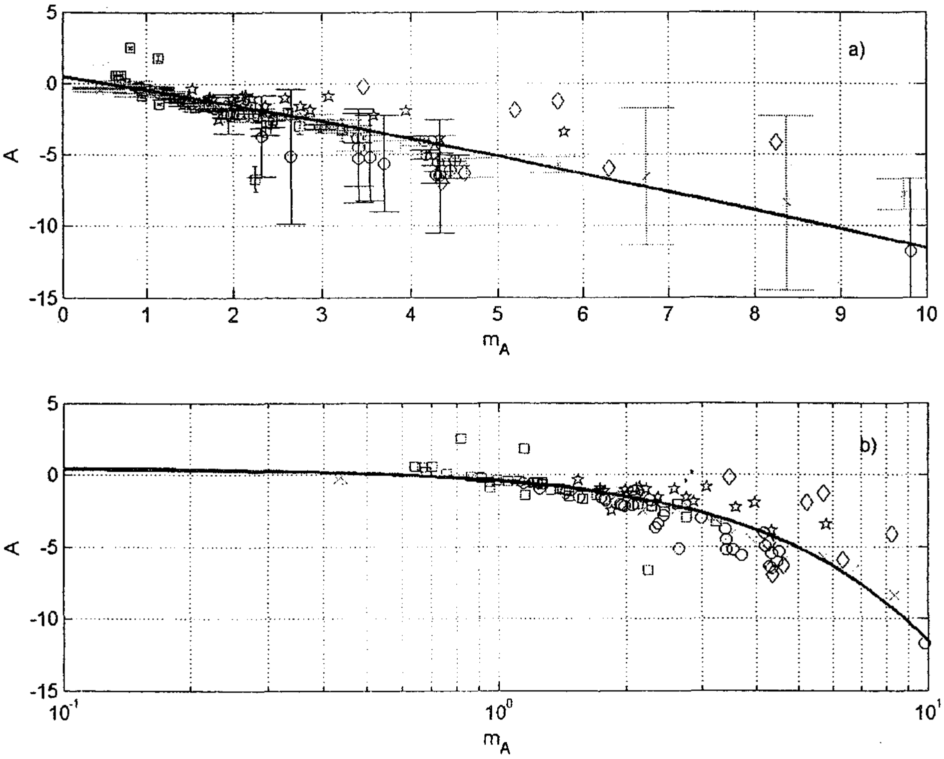
$\Phi_M = 1 + 2.5 z/L \qquad \Phi_M = 1 + 2.5 z/L_M$

$C_{NM} = 0.1$, $C_{fM} = 1$

x *nocturnal*; o *long-lived*; □ *conventionally neutral*

Geostrophic-drag function

$$A = \ln\frac{h}{z_{0u}} - k\frac{u_g}{u_*} \text{ vs. } m_A = \left[\left(\frac{h}{L_s}\right)^2 + \left(\frac{C_{NA}h}{L_N}\right)^2\right]^{1/2}$$



x <u>*nocturnal*</u>; o <u>*long-lived*</u>; □ <u>*conventionally neutral*</u>

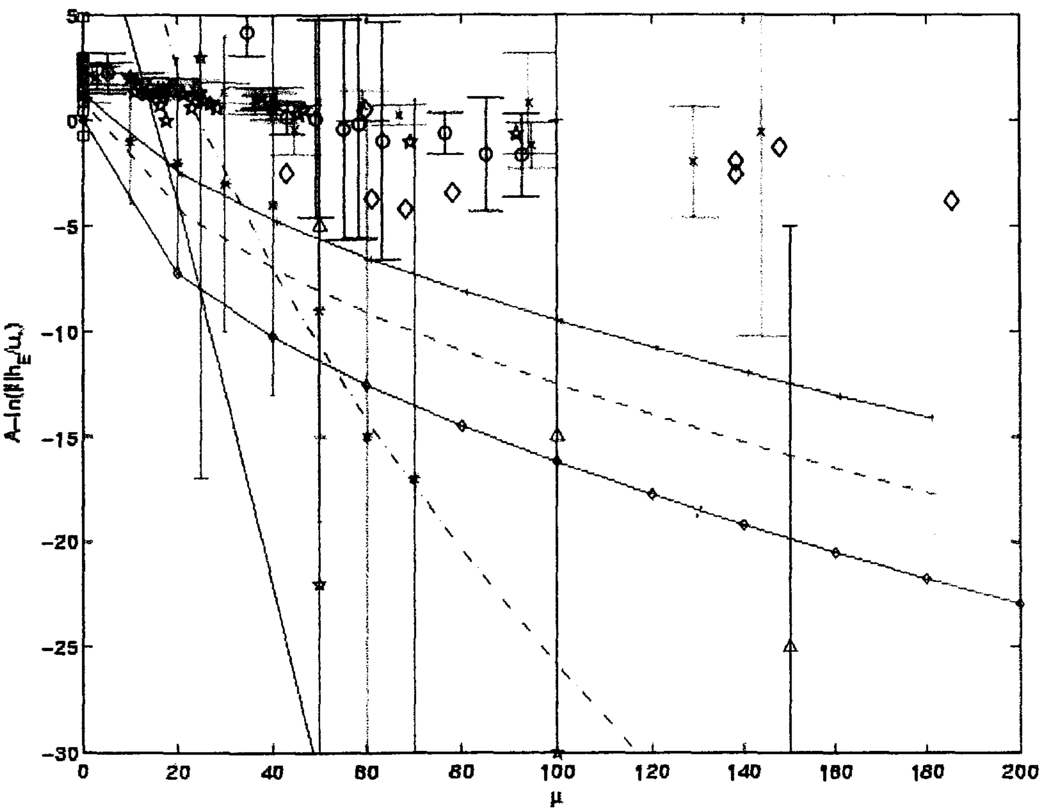
Theory $A = -1.4m_A + \ln(e^{0.5} + m_A)$, C_{NA}=0.09

New LES: x, o and □ for nocturnal, long-lived and conventionally neutral PBLs. Earlier LES: ◊ (Brown *et al.*, 1994) and ☆ (Kosovic and Curry, 2000). Error bars show ±3 standard deviation intervals for each LES run (*i.e.* 96% statistical confidence). Semi-log coordinates demonstrates how the theory performs in near-neutral and moderate-stability regimes.

⇒ ALGORITHM : u_* through PBL external parameters

Traditional presentation of geostrophic-drag function

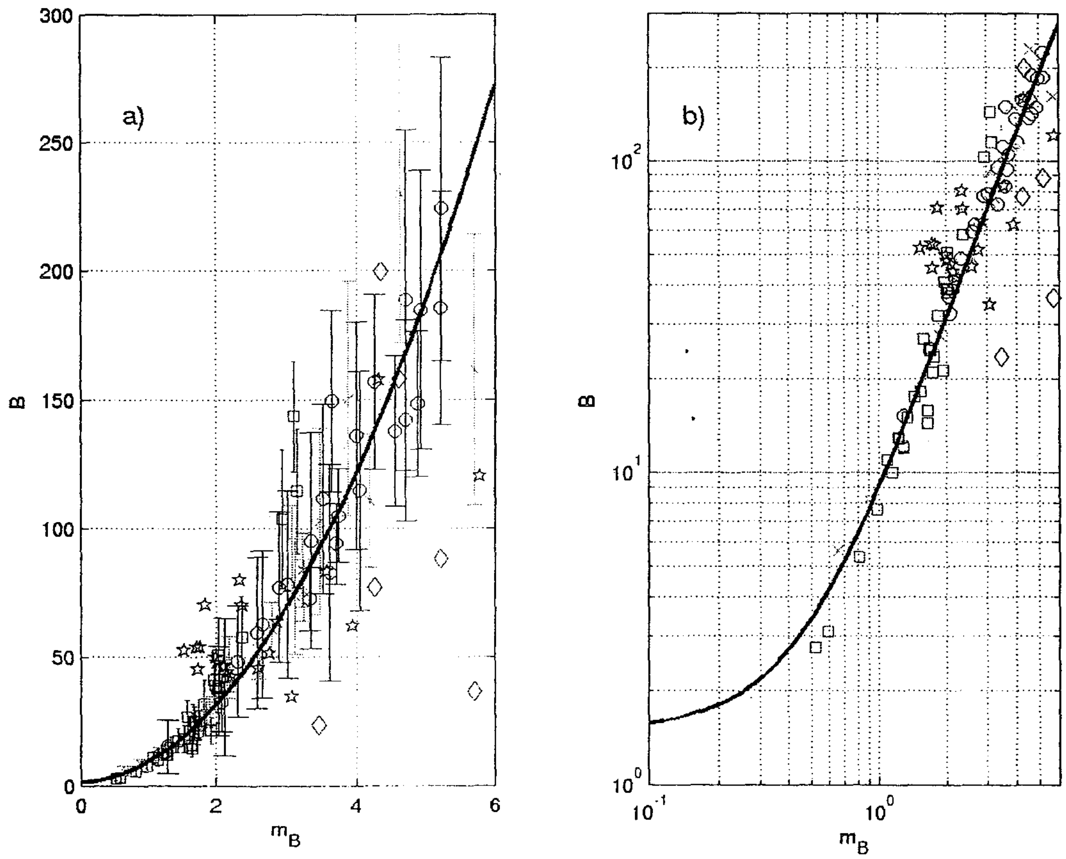
$\tilde{A} \equiv A - \ln(|f|h_E / u_*)$ versus $\mu = u_* / |f|L$.



New LES: □, x, o for conventionally neutral, nocturnal, and long-lived PBLs; earlier LES: ◊ Brown *et al.* (1994), ☆ Kosovic & Curry (2000); field data: * Cabauw (Nieuwstadt, 1981), Δ Wangara (Yamada, 1976), + Russian sites (Zilitinkevich & Chalikov, 1968). Curves: earlier models summarised by Byun, 1991): —— Vachat and Musson-Genon, — — Arya, —•— Long and Guffey, —+— Brost and Wyngaard, —◊— Derbyshire. Error bars show the ±3 standard deviation intervals.

Cross-isobaric angle function

$$B = k\frac{v_g}{fh} \text{ vs. } m_{\{A,B\}} = \left[\left(\frac{h}{L_s} \right)^2 + \left(\frac{C_{\{NA,NB\}} h}{L_N} \right)^2 \right]^{1/2}$$



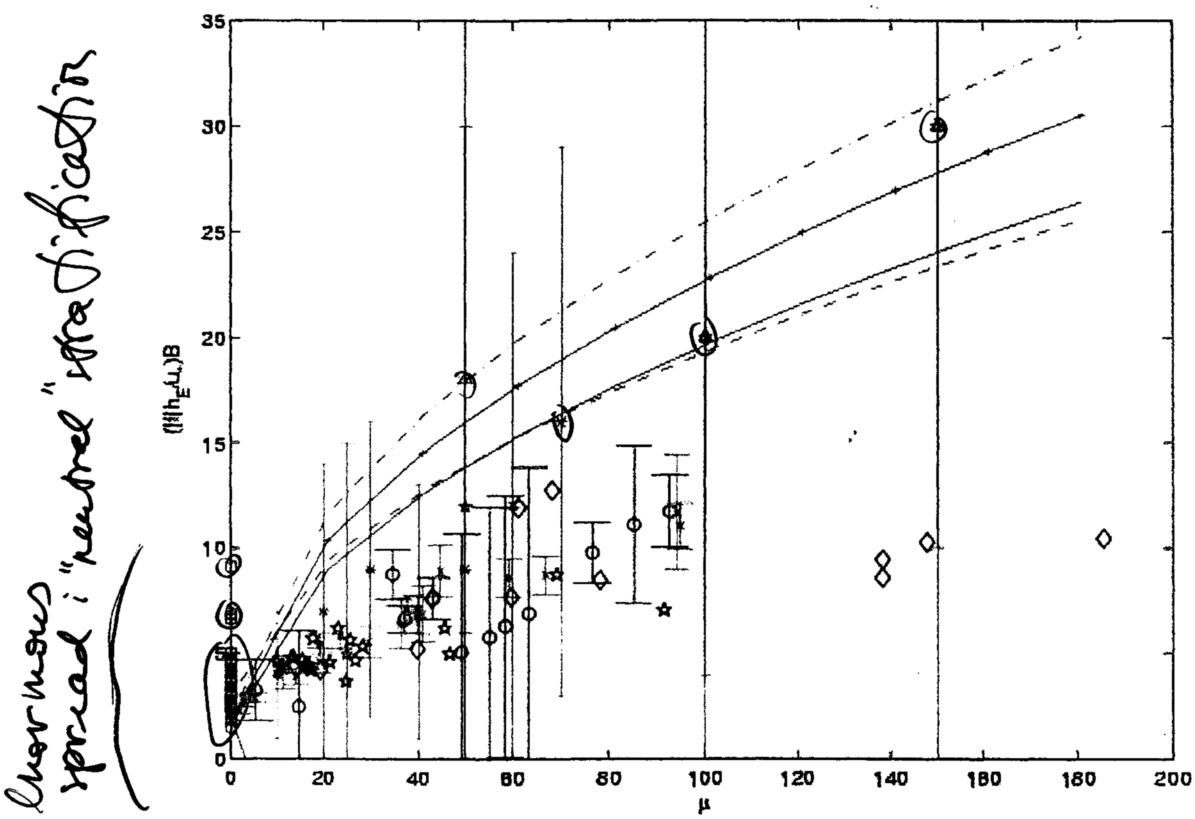
x *nocturnal*; o *long-lived*; □ *conventionally neutral*

Theory $B = 1.5 + 7.5m_{NB}^2$, with C_{NB}=0.13

$tg(\alpha) = \frac{v_g}{u_g} \Rightarrow$ ALGORITHM: (α) trough PBL external parameters

Traditional presentation of cross-sobaric angle function

$$\widetilde{B}(\mu) \equiv (|f| h_E / u_*) B \quad \text{versus} \quad \mu = u_* / |f| L$$



Potential temperature (L_H or L)

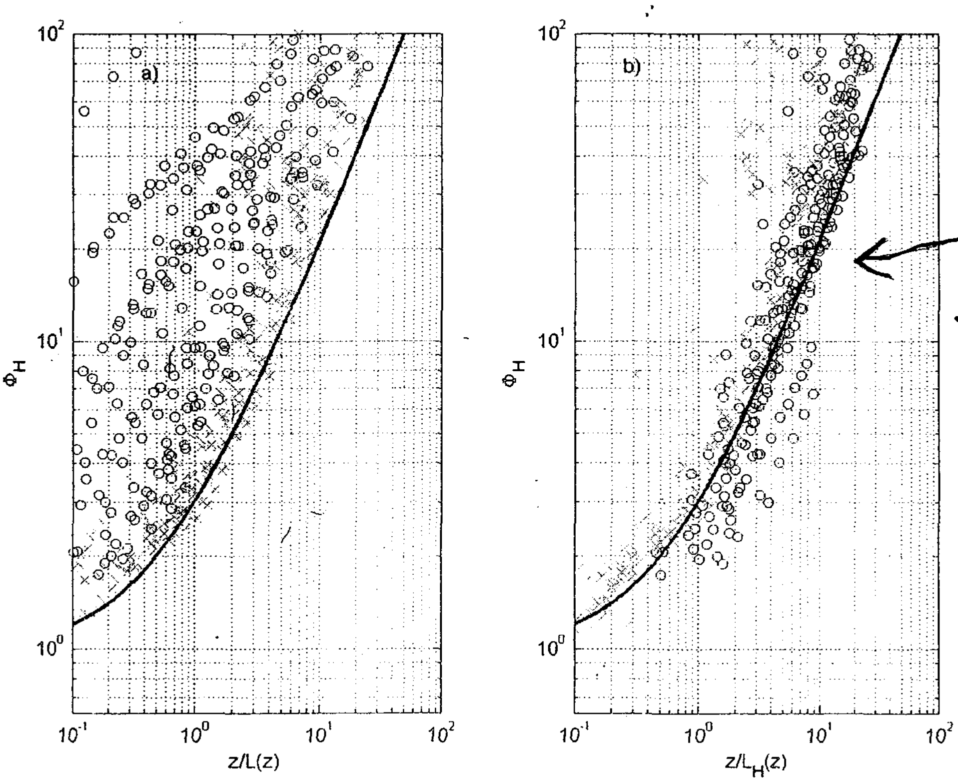
Inflation point on top of PPBL $z = h - \frac{1}{2}\delta_{CI}$: $\partial\theta / \partial z$ approaches minimum and starts growing

Scaling Log & z − less

$$\frac{\partial\theta}{\partial z} = \frac{\tau^{1/2}}{k_T z}\left[1 + \left(\frac{C_\theta z}{L_H}\right)\right] \approx \frac{C_\theta \tau^{1/2}}{k_T L_H}$$

LES $\Phi_M = \frac{k_T z}{\theta_*}\frac{\partial\theta}{dz}$ versus

(a) z/L (b) z/L_H with $C_{NH} = 0.6$



reasonable collapse ⇓ ANALYTICAL APPROXIMATION throughout the PBL

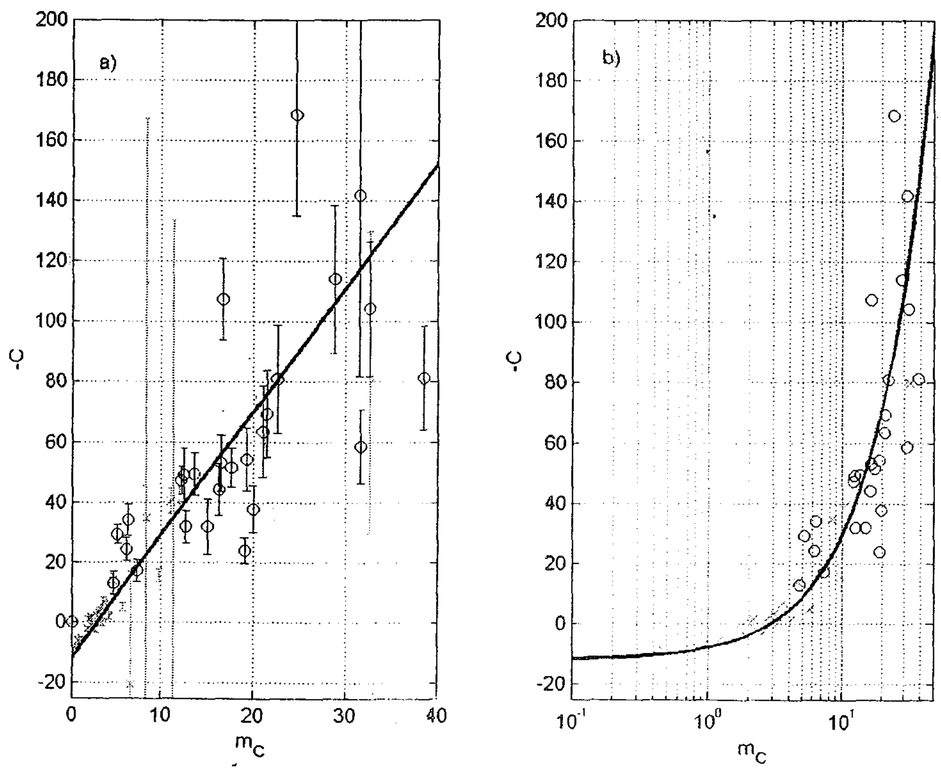
$\Phi_H = 1 + 2z/L$ $\Phi_H = 1 + 2z/L_H$

x ***nocturnal*** o ***long-lived***

Resistance law for potential temperature

$$C = \ln\frac{h}{z_{0u}} - k_T \frac{\Delta\theta_{PBL}}{\theta_{*s}}$$

versus $m_C = \left[\left(\frac{h}{L_s}\right)^2 + \left(\frac{C_{NC}h}{L_N}\right)^2\right]^{1/2}$ $(C_{NC}=1.2)$



$$C = -4.1m_C + \ln(e^{12} + m_C)$$

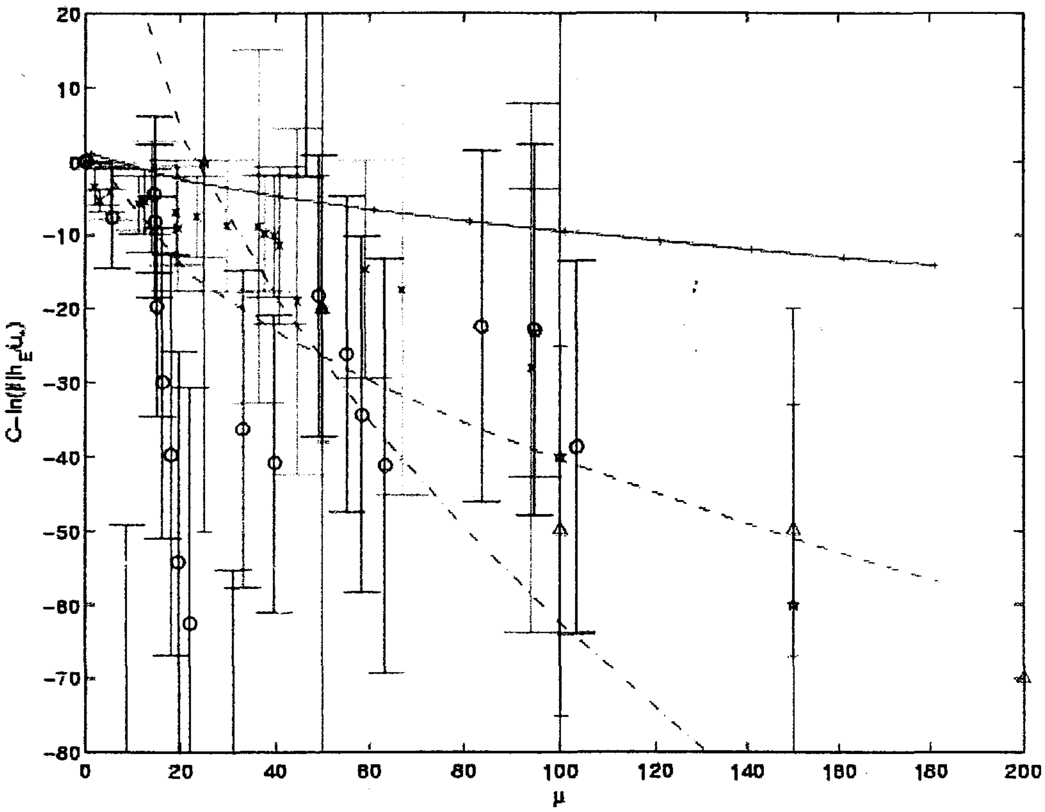
x – ***nocturnal*** PBLs; **o** – ***long-lived*** PBLs

ALGORITHM: $\theta_* \equiv \frac{-F_{\theta s}}{u_*}$ through PBL external parameters

$F_{\theta s} \longrightarrow$ heat flux

Traditional presentation of the potential temperature resistance function

$$\tilde{C}(\mu) \equiv C - \ln(|f| h_E / u_*) \text{ versus } \mu = u_* / |f| L$$



Conclusions (Resistance Laws)

- Account for free-flow stability, baroclinicity and non-steady evolution
- Revised surface-layer scaling $L \Rightarrow L_{\{M,H\}}$
- Limited applicability of earlier models: *A*, *B*, *C* as functions of $\mu = \frac{u_*}{|f| L_s}$ or $\frac{h}{L_s}$
- Advanced formulation for cross-isobaric angle: role of the Coriolis parameter
- Physical basis for new surface-flux scheme applicable to shallow PBLs (for use in NWP)
- Application to oceanic PBLs: dominant role of external stability parameter $\mu_N = N / |f|$
- Analytical model (theory + LES) for wind, temperature, eddy viscosity / conductivity, applicable to different types of stable PBLs

GENERAL CONCLUSIONS

- Advanced scaling for wind, temperature and eddy viscosity/conductivity applicable to stable PBLs of different nature

- Comprehensive revision of earlier PBL depth equations: account for free-flow stability, baroclinicity and non-steady evolution

- Advanced resistance and heat-transfer laws, limited applicability of earlier models considered *A*,*B*,*C* as functions of $\mu = u_* / fL$

- Physical background for improved surface-flux scheme applicable to shallow PBLs (demand from operational models)

- Applications to oceanic PBLs: dominant role of external stability parameter $\mu_N = N / |f|$