NEW DEVELOPMENTS IN MODELLING AND PARAMETERIZATION OF STABLE PBLs

Sergej Zilitinkevich

Meteorological Research, Finnish Meteorological Institute, Helsinki, FI
Atmospheric Sciences, Dept. of Physics, University of Helsinki, Finland
Nansen Environmental & Remote Sensing Centre NERSC, Bergen, NO

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Workshop on ***PARAMETERIZATION OF STABLE BOUNDARY LAYER IN NUMERICAL WEATHER PREDICTION MODELS***
Finnish Meteorological Institute, Helsinki, 3-5 December 2012

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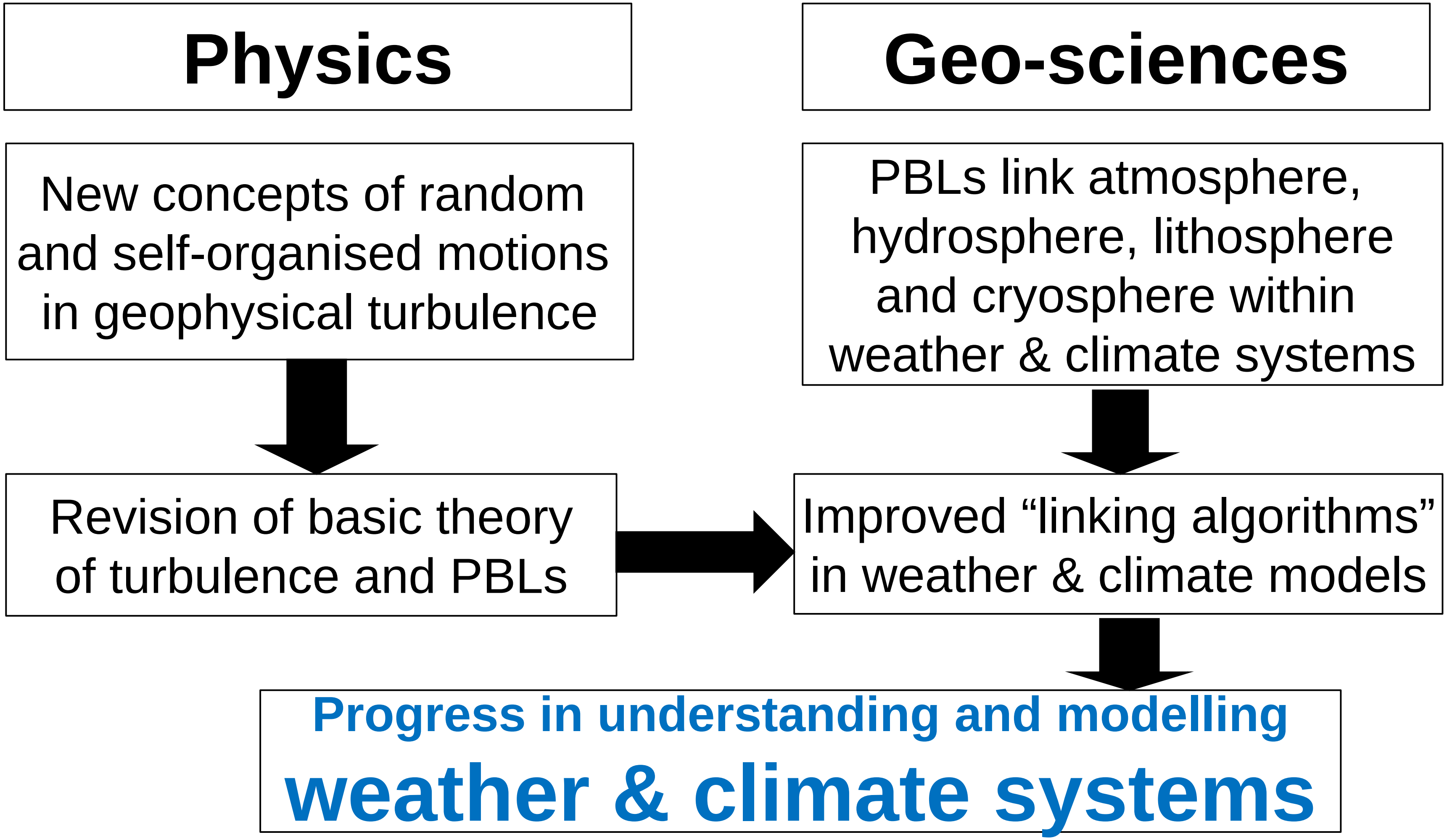
Geophysical turbulence and planetary boundary layers (PBLs)



Physics

Geo-sciences

New concepts of random and self-organised motions in geophysical turbulence

PBLs link atmosphere, hydrosphere, lithosphere and cryosphere within weather & climate systems

Revision of basic theory of turbulence and PBLs

Improved “linking algorithms” in weather & climate models

Progress in understanding and modelling

weather & climate systems

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Role of planetary boundary layers (PBLs): TRADITIONAL VIEW

“**Surface fluxes**” through the
AIR
and
WATER (**LAND**) interface
fully characterise interaction between
ATMOSPHERE and OCEAN/LAND

Monin-Obukhov similarity theory (1954) (conventional framework for determining surface fluxes in operational models) disregards non-local features of both convective and long-lived stable PBLs

Role of PBLs: MODERN VIEW

Because of very stable stratification to the atmosphere and ocean beyond the PBLs and convective zones, strong density increments inherent in the PBL outer boundaries prevent entities delivered by surface fluxes or anthropogenic emissions to efficiently penetrate from the PBL into the free atmosphere or deep ocean.

Hence the PBL heights and the fluxes due to entrainment at the PBL outer boundaries essentially control extreme weather events (e.g., heat waves associated with convection; or strongly stable stratification events triggering air pollution).

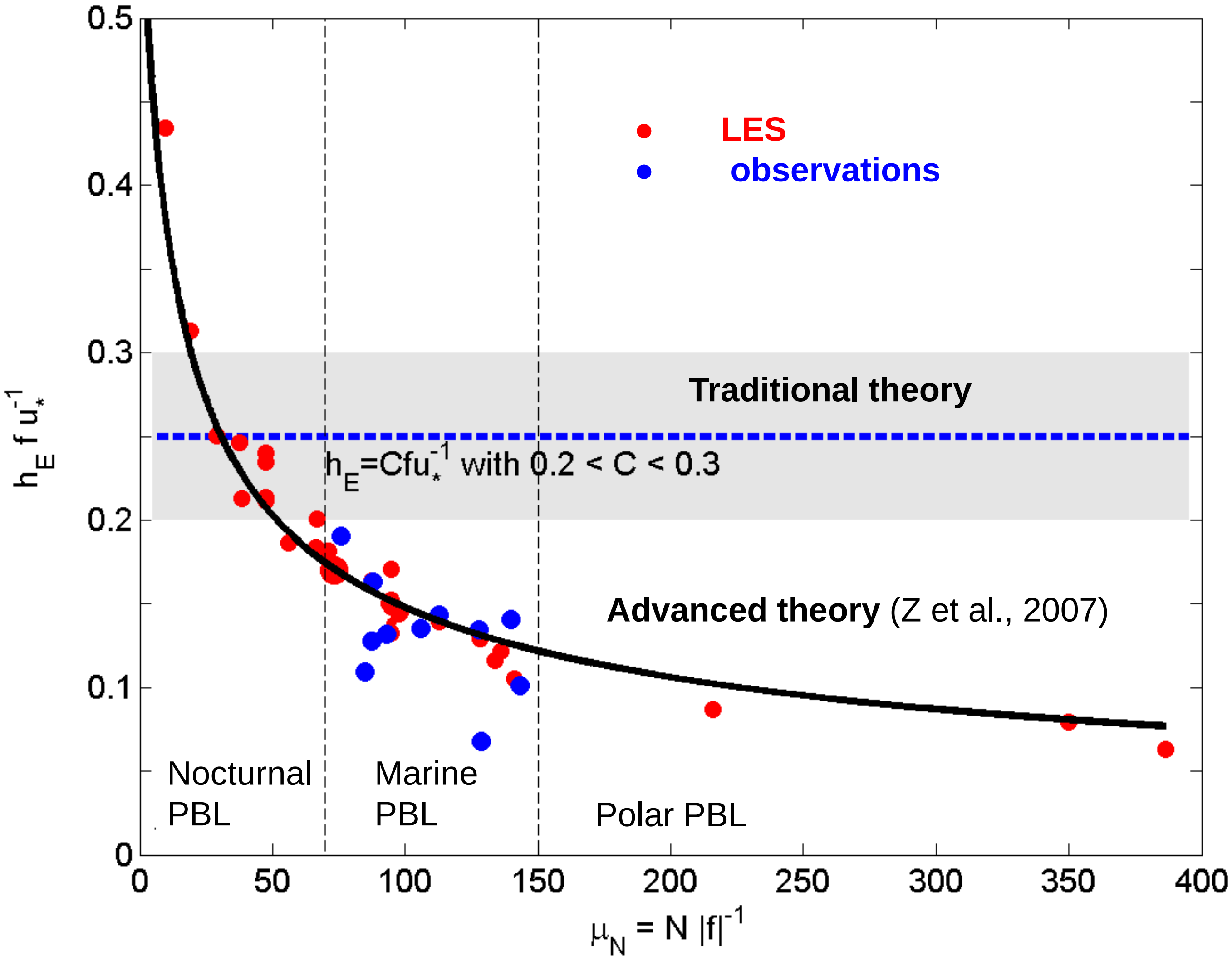
This concept (equally relevant to the hydrosphere) brings forth the problem of <u>determining the PBL depth and the turbulent entrainment</u> in numerical weather prediction, air/water quality and climate modelling.

Very shallow boundary layer separated form the free atmosphere by capping inversion

PBL height visualised by smoke blanket (Johan The Ghost, Wikipedia)

Capping inversion prevents PBL – free flow exchange

PBL shallowing due to free-flow stability



Dashed line – traditional TN PBL model

Heavy curve – CN PBL model

Red points – LES

Blue points – atmospheric data

The effect of free-flow Brunt-Väisälä frequency N on the equilibrium CN PBL height h_E

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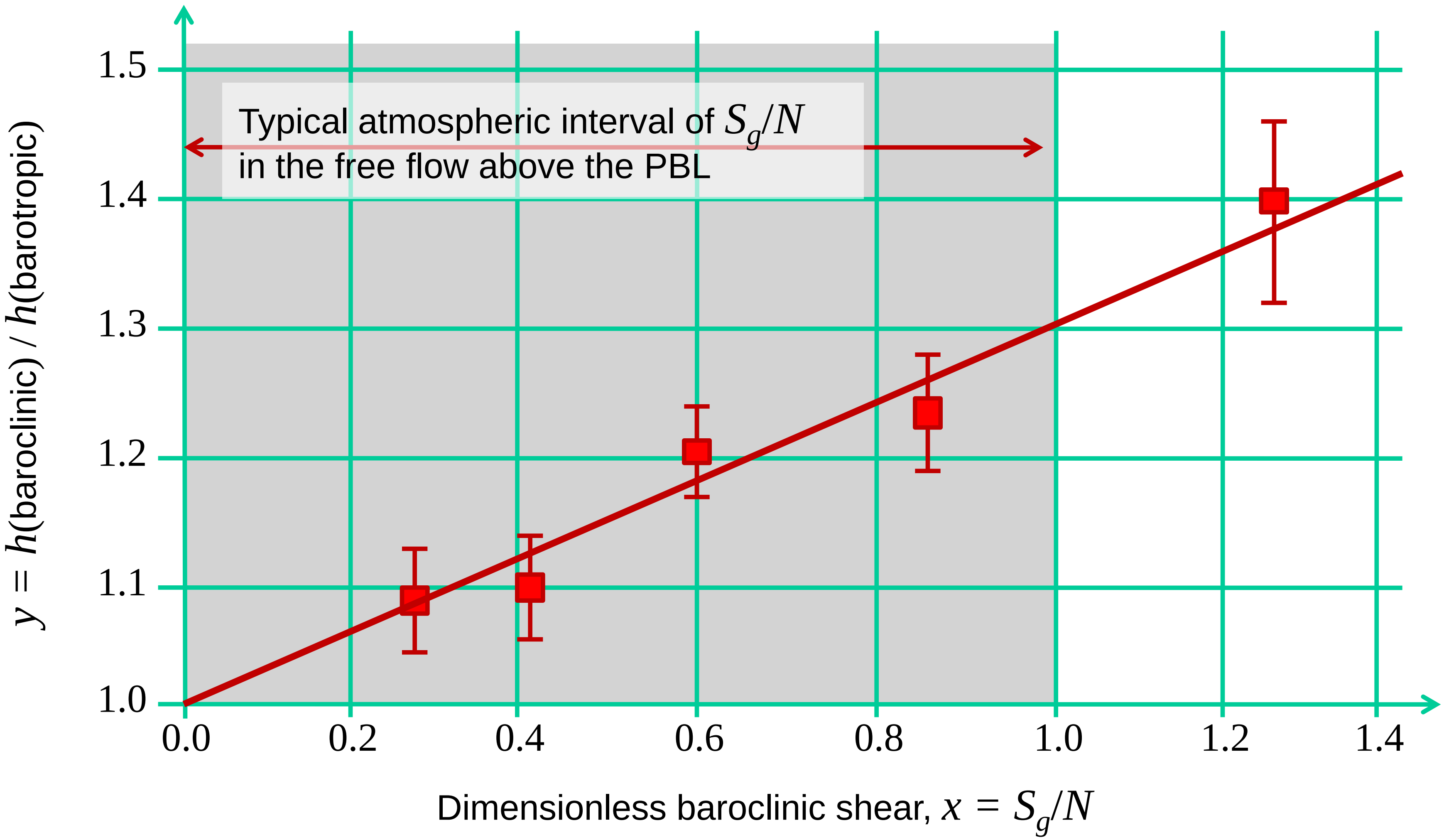
PBL deepening due to baroclinic shear

Theoretical model $y = (1 + 0.67x)^{1/2}$ against LES (LESDATABASE64, NERSC)



Turbulence cut-off problem

Buoyancy $b = (g/\rho_0)\rho$ (g – acceleration due to gravity, ρ –density)

Velocity shear $S = dU/dz$ (U – velocity, z – height)

$$\boxed{Ri = \frac{db/dz}{(dU/dz)^2}}$$

Richardson number characterises static stability:

the higher Ri (or z/L), the stronger suppression of turbulence

Key question **What happens with turbulence at large Ri?**

Traditional answer **Turbulence degenerates, and at Ri exceeding a critical value ($Ri_{\text{critical}} < 1$) the flow inevitably becomes laminar (Richardson, 1920; Taylor, 1931; Prandtl, 1930,1942; Chandrasekhar, 1961;…)**

In fact **field, laboratory and numerical (LES, DNS) experiments show that GEOPHYSICAL (very high Re) turbulence is maintained up to $Ri \sim 10^2$**

Modellers were forced to VIOLENTLY preclude the turbulence cut-off

Milestones

Prandtl-1930's followed Boussinesq's idea of the down-gradient transfer (K-theory), determined $K \sim l u_T$, and expressed u_T heuristically through the mixing length l

Kolmogorov-1942 (**for neutrall stratication**) followed Prandtl's concept of eddy viscosity $K_M \sim l u_T$; determined $u_T = (\mathrm{TKE})^{1/2}$ through TKE budget equation with dissipation $\varepsilon \sim (\mathrm{TKE})/t_T \sim (\mathrm{TKE})^{3/2}/l_\varepsilon$; and assumed $l_\varepsilon \sim l$ (grounded **in neutral stratification**)

Obukhov-1946 and then the entire turbulence community extended Kolmogorov's closure to **stratified flows** **keeping it untouched**, except for inclusion of the buoyancy term in the TKE equation. **Its sole use has caused cutting off TKE in supercritical stable stratification**

This approach, **missed** **turbulent potential energy** (TPE) and its interaction with TKE); **overlooked** inapplicability **of Prandtl's relation** $K \sim l u_T$ to the eddy conductivity K_H; and **disregarded** **principal deference between** l_ε and l

For practical applications Mellor and Yamada (1974) developed **corrections preventing unacceptable turbulence cut-off** in "supercritical" static stability

Energy- & flux-budget (EFB) closure (2007-12)

Budget equations for major statistical moments

Turbulent kinetic energy (TKE) E_K

Turbulent potential energy (TPE) E_P

Vertical flux of temperature $F_z = <\theta w>$ [or buoyancy $(g/T)F_z$]

Vertical flux of momentum $\tau_{iz} = <u_i w>$ $(i = 1,2)$

Relaxation equation for the dissipation time scale $t_T = E_K/\varepsilon_K = l(E_K)^{-1/2}$

Accounting for TPE → vertical heat flux (that “killed” TKE in Kolmogorov type closures) **drops out from the equation for total turbulent energy (TTE = TKE + TPE)**

Heat-flux budget equation → imposes a limit on the vertical heat flux and assures **self-preservation of turbulence** → **no** Ri-**critical in the energetic sense**

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Disclosed two principally different regimes of stably stratified turbulence

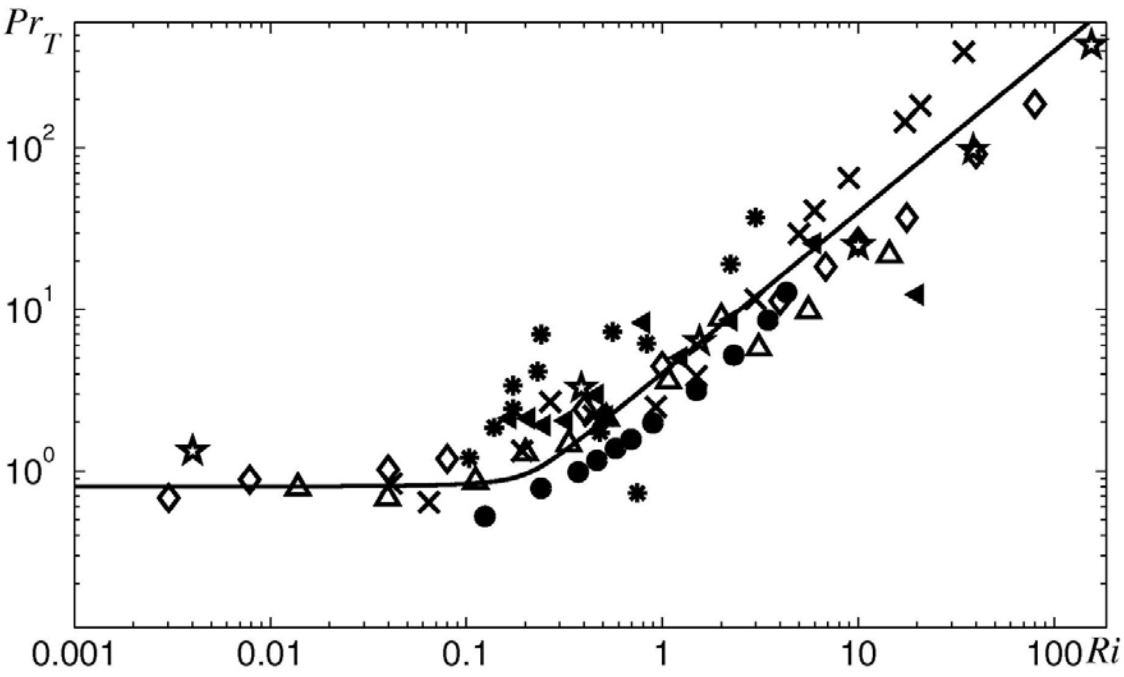
”Strong turbulence” in boundary layer flows with $K_M \sim K_H$ at $Ri < Ri_c$

”Weak turbulence” in the free atmosphere with $Pr_T = K_M / K_H \sim 4\ Ri$ at $Ri >> Ri_c$

MOS theory disregards weak turbulence at $z/L >> 1$ and yields artefact Ri_c

PBL height = the boundary between *strong*- and *weak-turbulence* regimes

Turbulent Prandtl number $Pr_T = K_M/K_H$ versus Ri

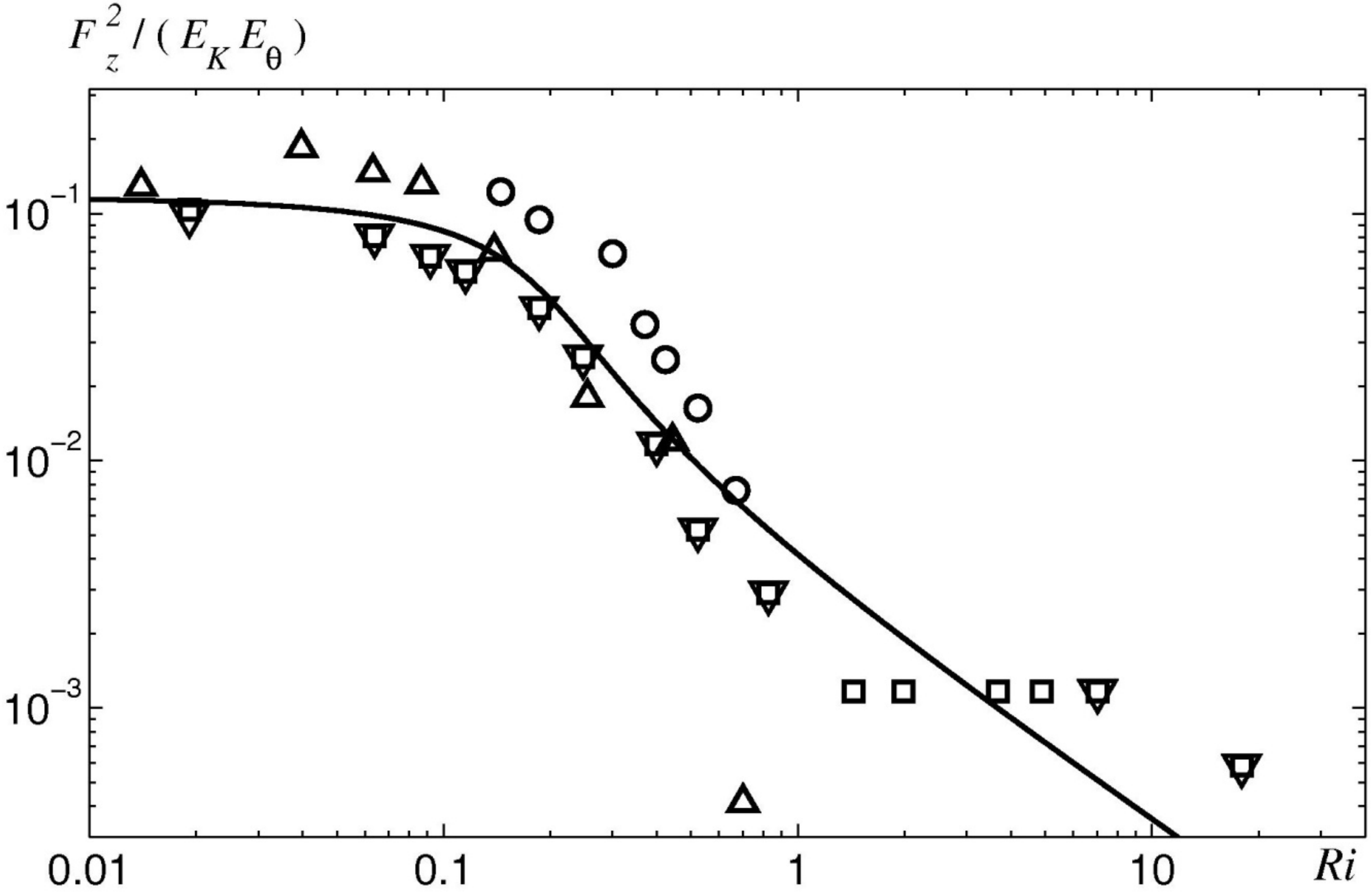


Atmospheric data: ◀ (Kondo et al., 1978), ✱ (Bertin et al., 1997); laboratory experiments: ×(Rehmann & Koseff, 2004), ◇(Ohya, 2001), ●(Strang & Fernando, 2001); DNS: ☆(Stretch et al., 2001); and LES: △(Esau, 2009). The curve sows our EFB theory. The “strong” turbulence ($Pr_T \approx 0.8$) and the “weak” turbulence ($Pr_T \sim 4\ Ri$) match at $Ri \sim 0.25$.

MOS assumes $Pr_T = constant$

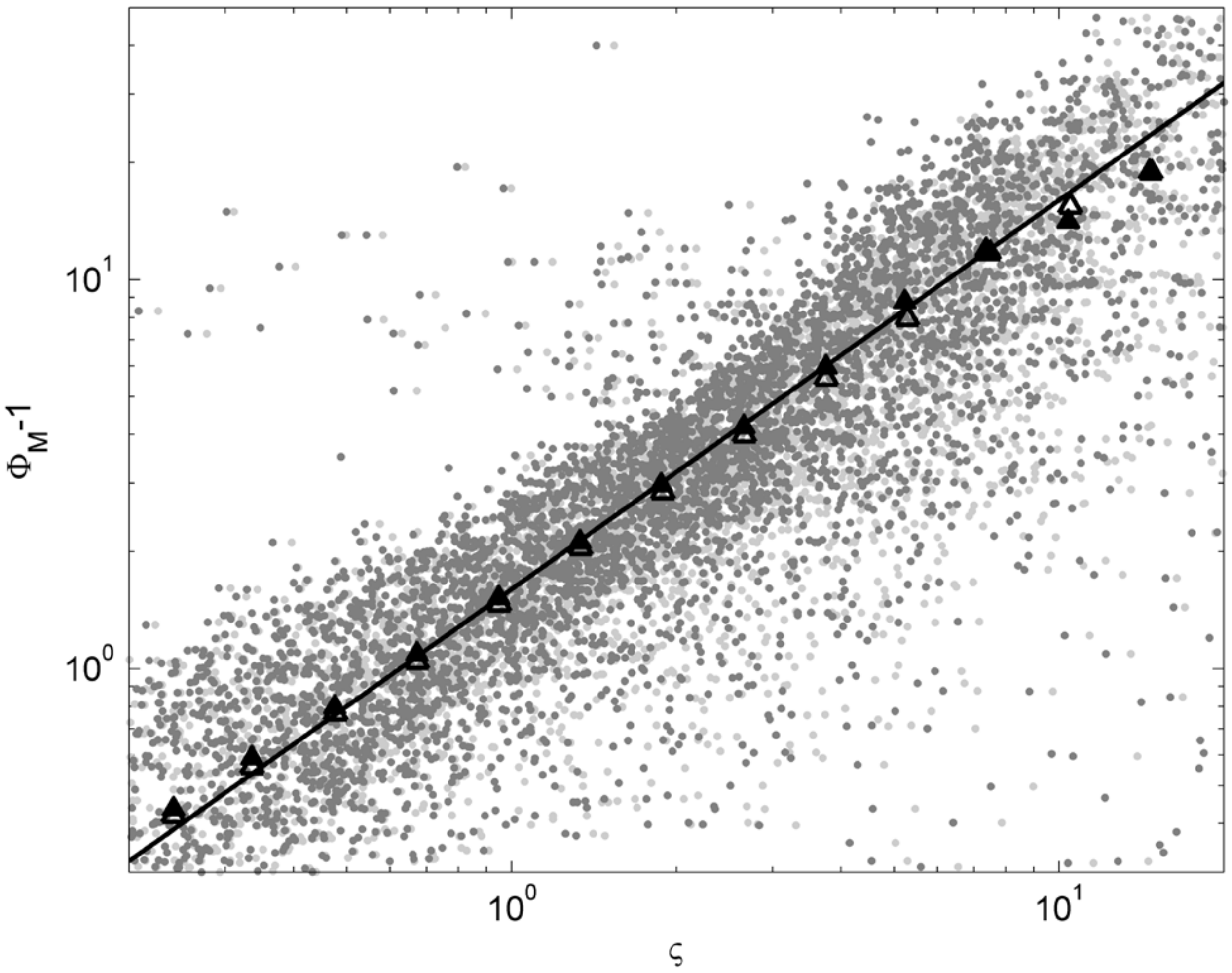
Dimensionless heat flux: practically constant in *strong* turbulence and sharply decreases in *weak* turbulence

MOS assumes $F_z/(E_K E_\theta)^{1/2} = constant$



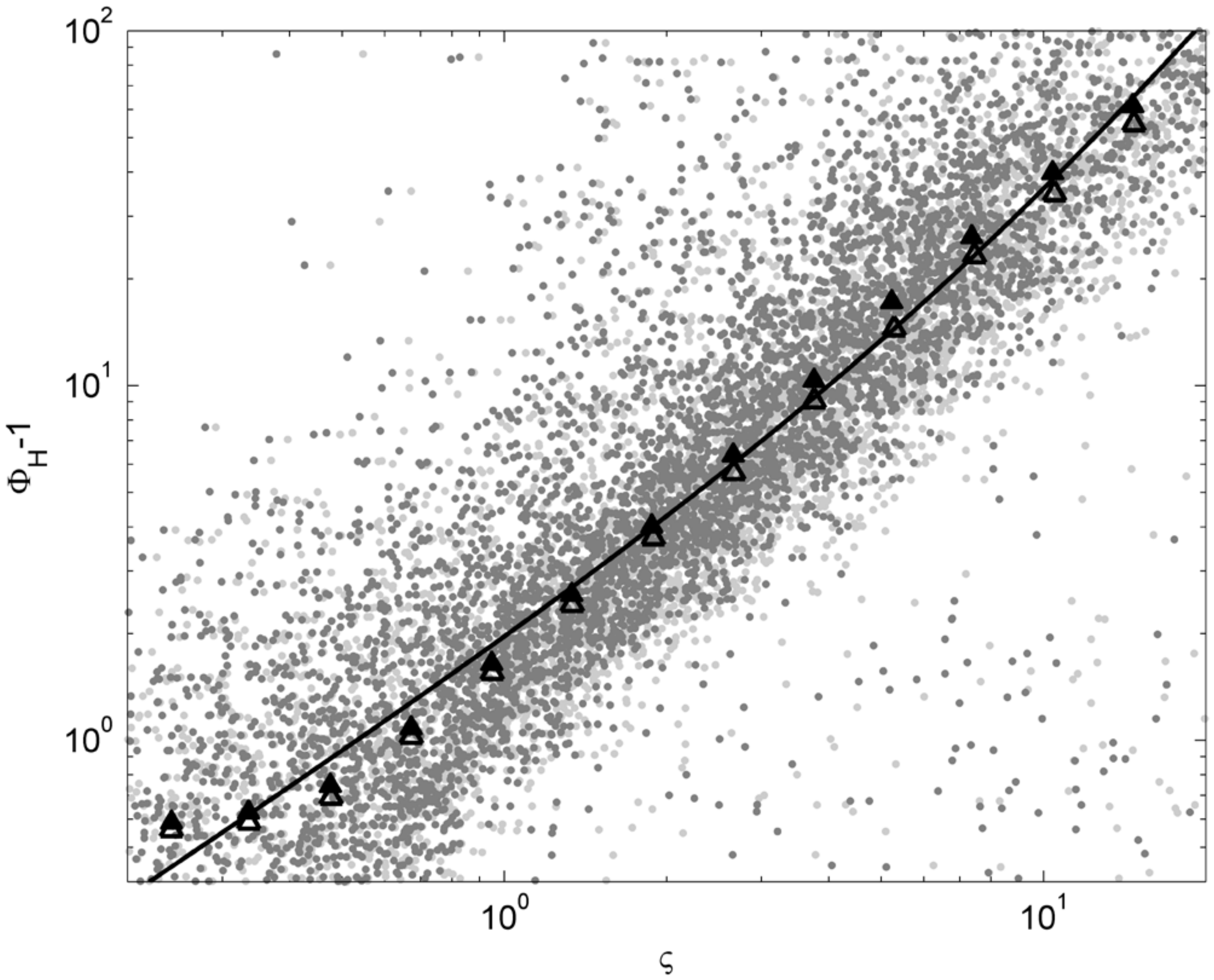
Dimensionless velocity gradient $\Phi_M = (kz/u_*)/(\partial U/\partial z)$ versus $\zeta = z/L$ after LES (dots) and the EFB model (curve)

MOS OK



Dimensionless temperature gradient $\Phi_H = (-k_T z \tau^{1/2} / F_z)(\partial\Theta / \partial z)$ versus $\zeta = z/L$ after LES (dots) and the EFB model (curve)

MOS fails



Conclusions

- **EFB turbulence closure → wider vision of geophysical stably stratified turbulence**

- **No Ri_c in the energetic sense: experimental data confirm this conclusion up to $Ri \sim 10^3$**

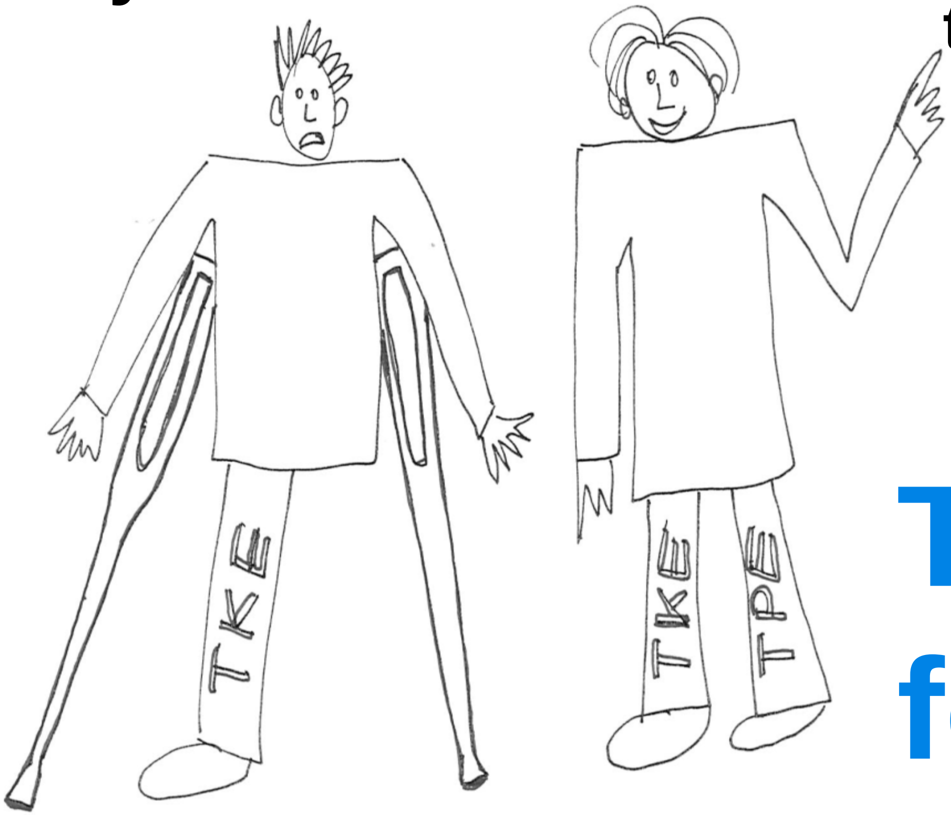
- **Instead: THRESHOLD $Ri \sim 0.2\text{-}0.3$ (cf. hydrodynamic instability limit) separating regimes of “strong” and “weak“ turbulence → just the boundary between PBL and free atmsophere → another view at the PBL height**

- **MOS is applicable to the “strong” turbulence regime typical of boundary layer flows but inapplicable to the “weak turbulence regime” typical of the free atmosphere and capping inversions**

Turbulence does not degenerate up to very strong stratification

From «only TKE»

to«TKE + TPE»



Thank you for your attention

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