Surface-layer turbulence and Monin-Obukhov similarity theory revisited

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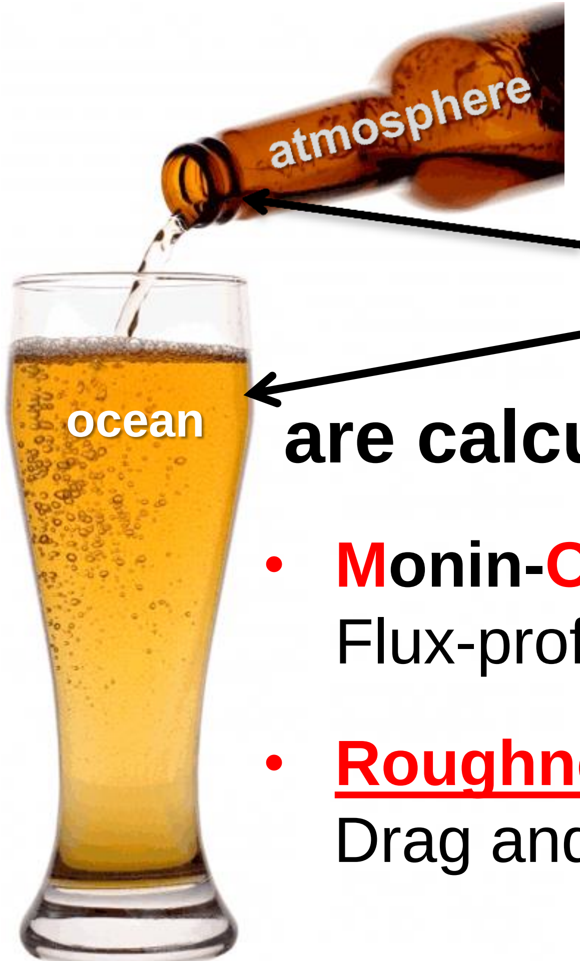
Air-land/water interaction



<u>Vertical turbulent fluxes</u> linking

the atmosphere
with land/water surface

are calculated on the basis of

- **Monin-Obukhov Similarity Theory <u>MOST</u> (1954)**
  Flux-profile relationships in the surface layer

- **<u>Roughness lengths</u> for momentum and scalars**
  Drag and heat/mass transfer at the very surface

However, MOST fails in both very stable and unstable stratification

Virtual parameters and hypothetical concepts

Flux-profile relations expressing turbulent fluxes of momentum $\tau = u_*^2 = -K_M \partial U / \partial z$, temperature $F_\theta = -K_H \partial \Theta / \partial z$, etc. through wind-speed U, potential temperature Θ, etc. at a given height z are based on **turbulent viscosity** K_M, **conductivity** K_H, **diffusivity** K_D

$$K_{M,H,D} = (u_* z) f_{M,H,D}(z/L)$$

where $L = u_*^3 / (-g/T_0) F_\theta$ is Obukhov length-scale, and $f_{M,H,D}$ are universal functions whose shapes are **prescribed by MOST**

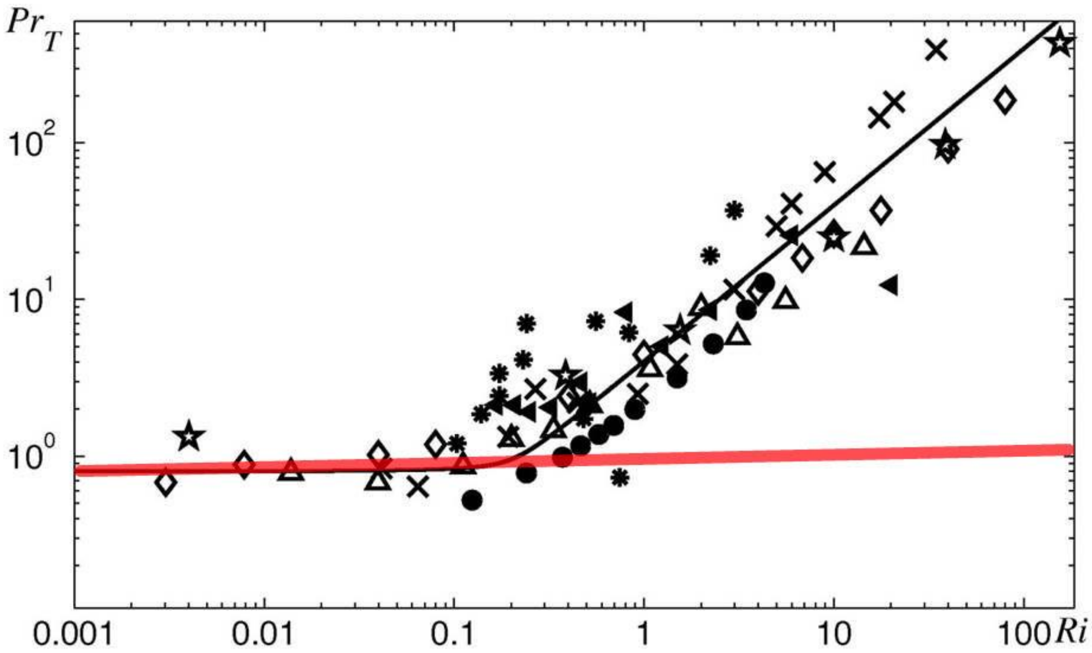
E.g. MOST-based flux-profile relation: $U(z) = \frac{\tau^{1/2}}{k} \left(\ln \frac{z}{z_0} + C_u \frac{z}{L} \right)$

allows determining τ, from measured U; known roughness length for momentum z_0; and F_θ determined from its own relation.

Historically, much efforts focused on MOST, while roughness lengths of natural surfaces remained poorly understood

MOST in stable stratification

Ignores self-control of temperature flux, F_θ, and prescribes similar turbulent viscosity and conductivity: $Pr_T = K_M / K_H = constant$, which entails erroneous turbulence cut off at $Ri > Ri_c = 0.25$



Turbulent Prandtl number vs. Richardson number **black line shows modern theory (EDB, Z et al., 2007-2017)** **MOST shown by red line prescribes collapse of turbulence at $Ri > 0.25$**

Data **Atmospheric:** Kondo et al., 1978, Bertin et al., 1997; **Laboratory:** Rehmann, Koseff, 2004, Ohya, 2001, Strang, Fernando, 2001; **DNS:** Stretch et al., 2001; **LES:** Esau, 2009

Self-control of turbulence

via counter-gradient heat flux **missed in MOST**

F_θ-budget yields both downgradient and countergradient contributions (EFB-closure Z et al., 2007, 2013)

$$F_\theta = C_1 t_T \beta \langle \theta^2 \rangle - C_2 t_T E_z \frac{\partial \Theta}{\partial z}$$

The key feedback:

→ Larger temperature gradient $\partial \Theta / \partial z$ causes

→ **larger negative heat flux** F_θ

→ hence larger turbul. potential energy $E_P = \dfrac{g \langle \theta^2 \rangle}{2T_0 \left(\partial \Theta / \partial z \right)} = -C_3 t_T \dfrac{g}{T_0} F_\theta$

→ hence, stronger potential temperature fluctuations $\langle \theta^2 \rangle$ and

→ stronger counter-gradient (positive) heat flux $C_\theta \beta \langle \theta^2 \rangle$

→ which **compensates for firming up the negative heat flux** F_z **and prevents collapse of turbulence in super-critical startification**

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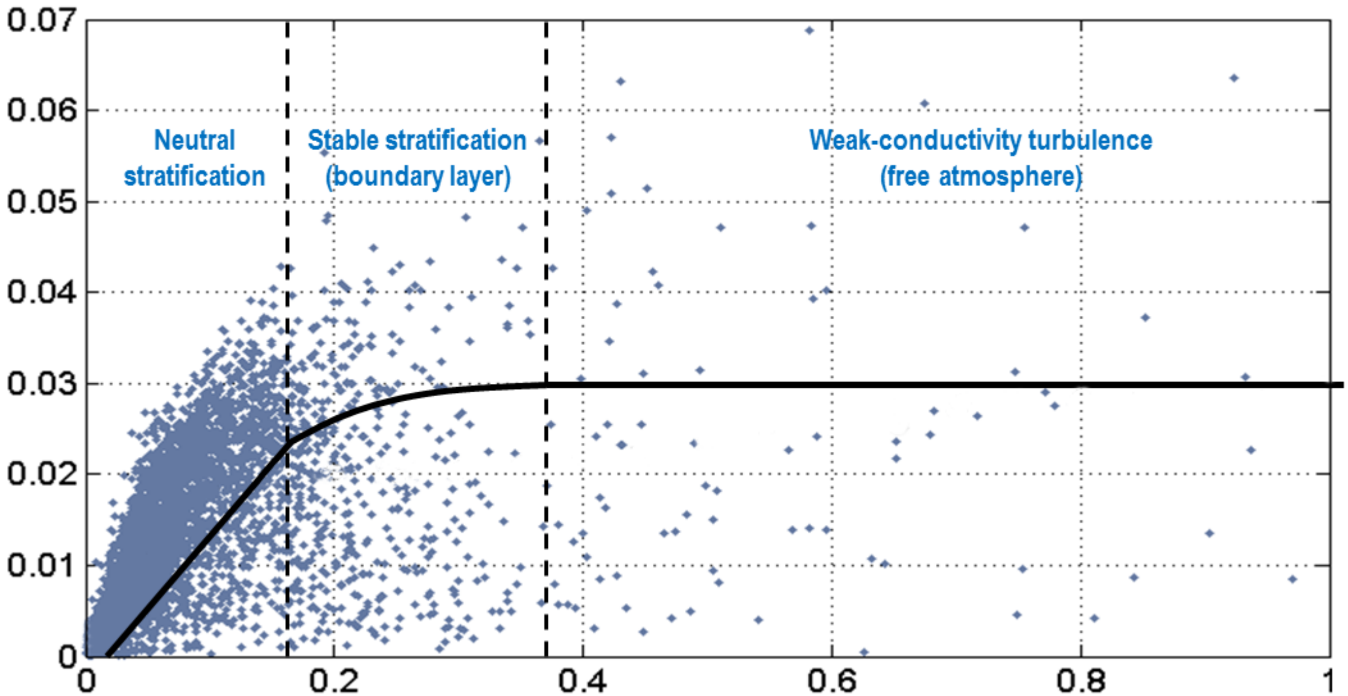
The temperature flux vs. temperature gradient

$$\frac{gF_\theta}{T_0 E_K S}$$



wind shear

$$S = \partial U / \partial z$$

B/V frequency

$$N = \left(\frac{g}{T_0} \frac{\partial \Theta}{\partial z} \right)^{1/2}$$

Ri number

$$Ri = \left(N/S \right)^2$$

Data and theory show non-gradient heat transfer at $Ri > 0.25$

Almost neutral ($0<z/L<0.5$) **MOST OK** $F_\theta \sim N^2, \quad K_H \sim E_K^{1/2} z$

Moderate ($0.5<z/L<<10$) **MOST acceptable** $F_\theta \sim N, \quad K_H \sim E_K / N$

Very stable ($z/L>>10$) **MOS fails** F_θ ndependent of $N, \quad K_H \sim E_K S / N^2$

Stable stratification imposed form above

“Long-lived” stably-stratified planetary boundary layer (**LL PBL**) in Bergen visualized by water haze (winter 2012, courtesy T. Wolf). Strong static stability above LL PBLs make them very shallow and affects the surface layer via additional length-scale, $L_N = \tau^{1/2}/N$, where N is the buoyancy-frequency in the free atmosphere. **MOST is inapplicable.**

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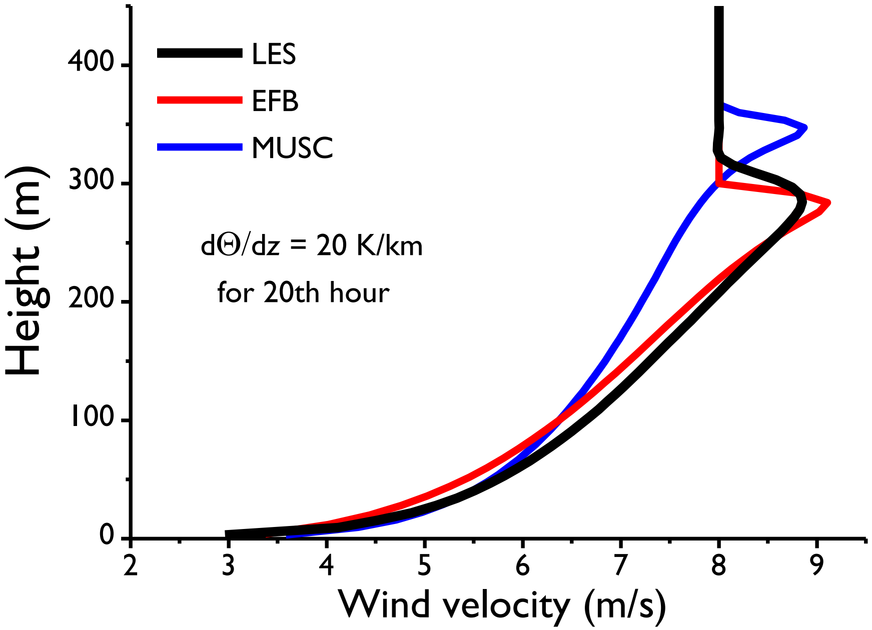
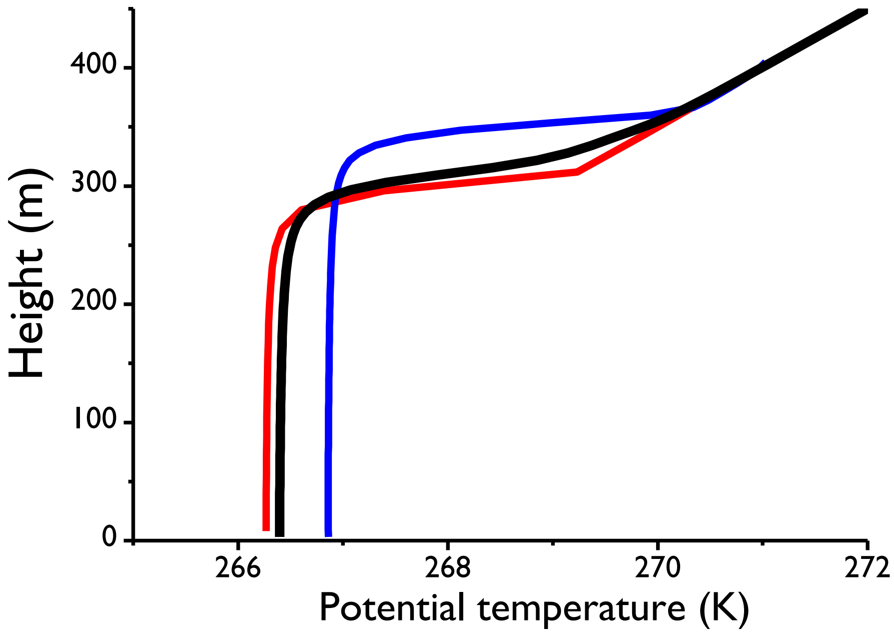
Conventionally Neutral (CN) PBL

= PBL with zero heat flux at the surface, affected by stable stratification in the free atmosphere. Figures show CN PBL evolving against stable stratification, which causes the downward heat flux at the upper boundary, **affecting the entire PBL**

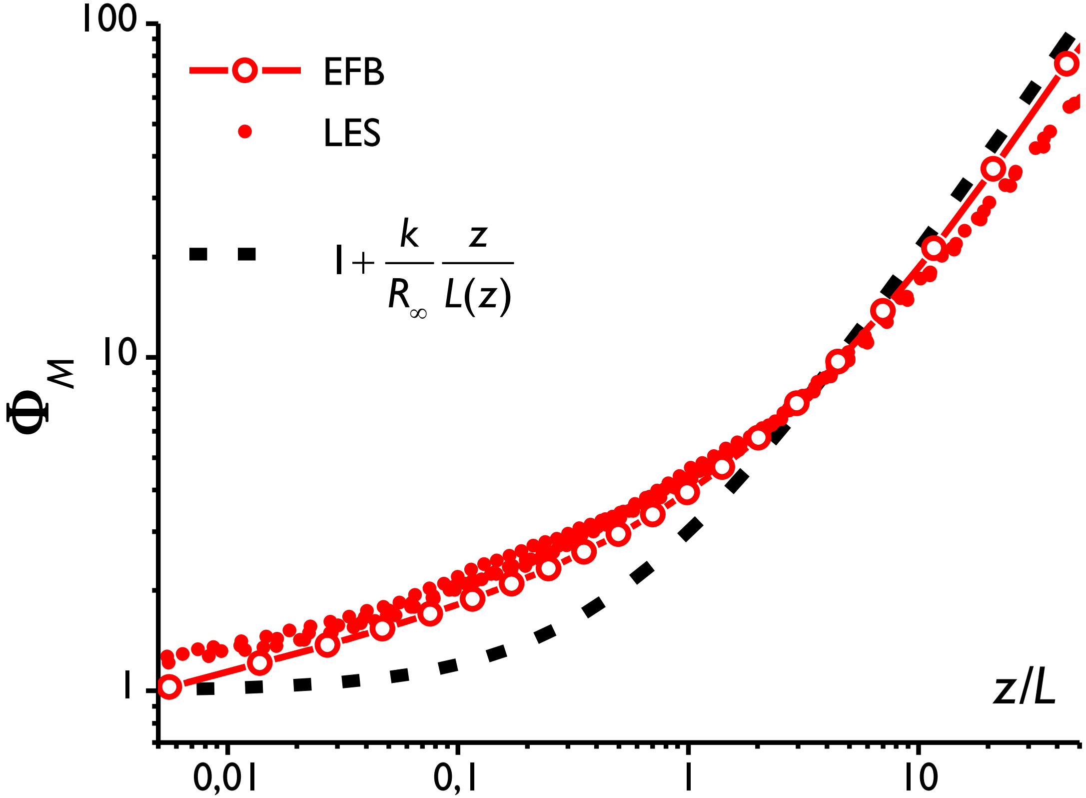




Traditional theories/models <u>overwarm PBL</u> and <u>overestimate its height</u>; <u>MOST yields wrong mean profiles in surface layer</u>

Conventionally neutral PBL: velocity gradient

Initially homogeneous PBL evolves against stable stratification in the free atmosphere causing negative (downward) heat flux at the upper boundary. The surface heat flux is kept equal to zero.



MOST: wrong mean profiles, overestimated friction velocity…

MOST in unstable stratification

- Neglects principal difference between the shear-generated ***mechanical*** turbulence and buoyancy-generated ***anarchy*** turbulence characterised by **inverse energy transfer from smaller to larger plumes towards self-organised structures**
- Wrongly formulates **horizontal velocity fluctuations, strongly overestimates horizontal fluxes and diffusion**
- Consideres large-scale self-organised convective structures as large turbulent eddies, which causes **underestimation of the surface fluxes**, especially strong in calm-weather convection

Now these failures are improved but eclectically: keeping MOST untouched and without understanding of real physical processes

Self-organisation in turbulent convection

Cells in **viscous convection** (Benard 1900, Rayleigh 1916)

Cells / **rolls** in **turbulent convection** atmosphere/LES/DNS/lab

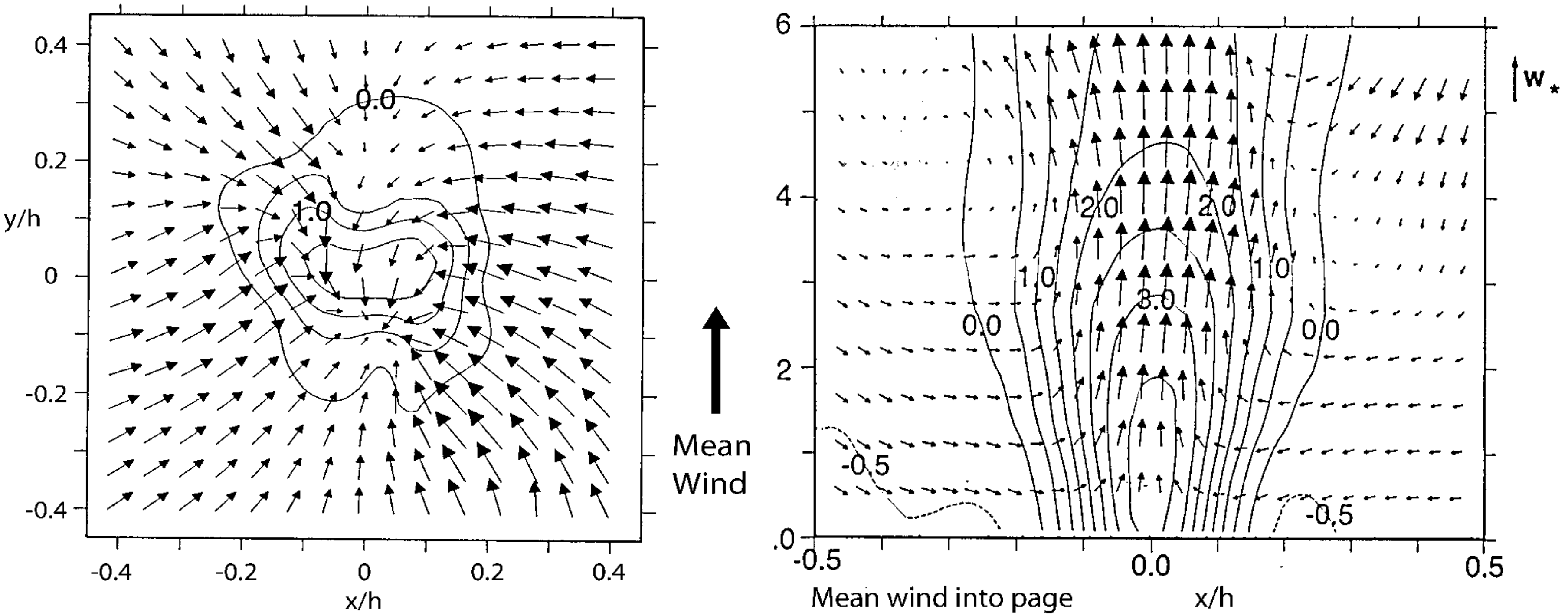
No analogy to rolls in viscous convection

Rolls are excited by turbulent large-scale instability triggered by non-gradient horizontal heart flux (Elperin et al, 2002, 2005)

Self-organisation is missed in the conventional turbulence paradigm and in old theories such as

- Convective heat/mass transfer law
- MOST

Self-organised structures in the atmosphere



Williams & Hacker (1992) airborne measurements: Arrows show self-organised velocity field; solid lines, deviations of potential temperature θ from its averaged value $<\theta>$. Lines $\theta - <\theta> = 0$ mark the updraught.

The near-surface convective winds (up to a few m/s) generate mechanical turbulence, strongly enhancing the heat transfer. <u>MOST overlooks this mechanism</u>.

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Strengthening heat/mass transfer in free convection: non-classical mechanism

Large-scale self-organised structures

↓

Convective winds towards the plume base

↓

Near-surface wind shears generate mechanical turbulence (**overlooked in traditional theories**)

↓

Strongly enhanced heat/mass transfers

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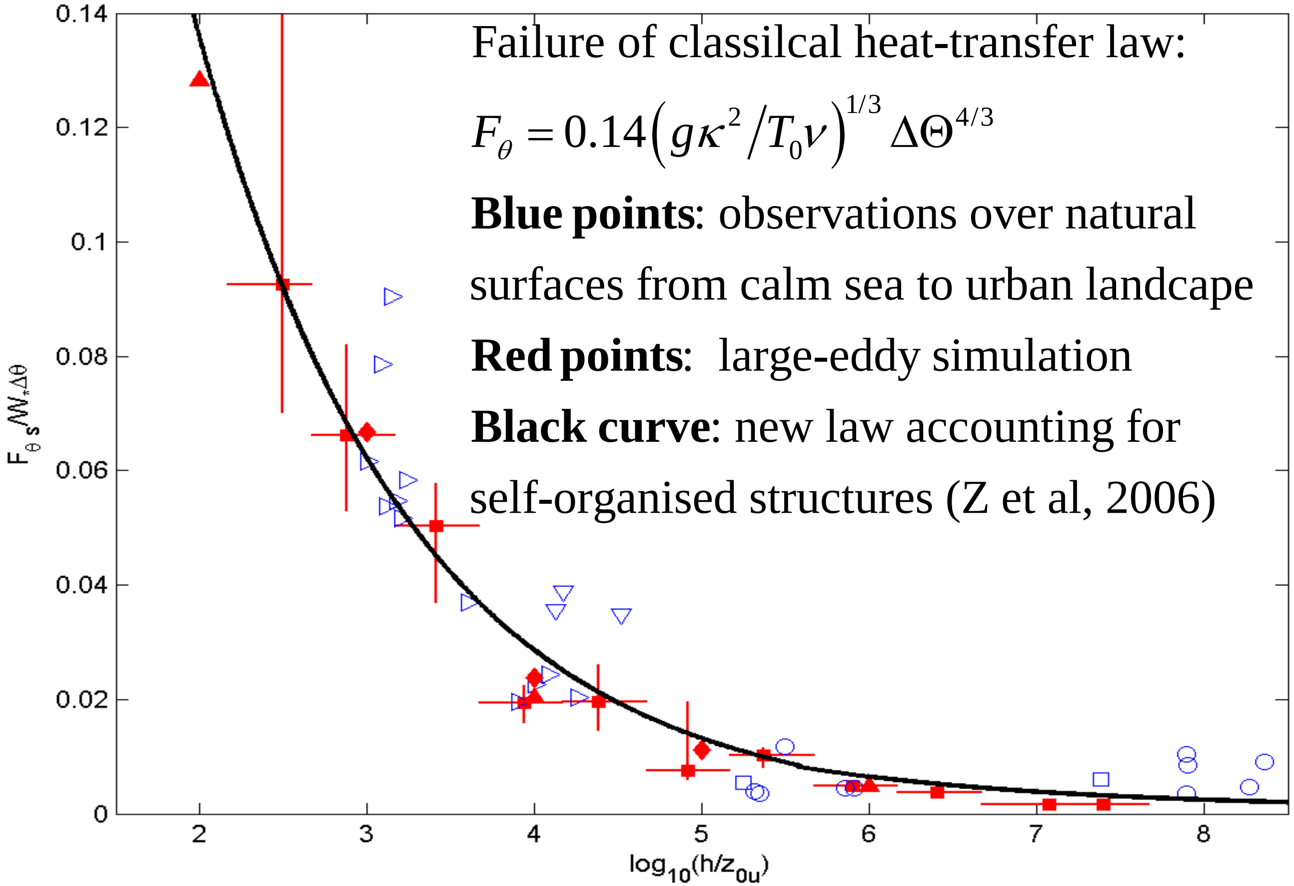
Heat-transfer in calm-weather convection



is much stronger than in classical theories and <u>depends on CBL height</u>, *h*, <u>and wind-roughness length</u>, z_{0u}

New law, $F_\theta = f(h/z_{0u})\left(gh/T_0\right)^{1/2}\Delta\Theta_s^{3/2}$ involves factor $h^{1/2}$ and function $f(h/z_{0u})$ shown in the Figure but **missed in the classical heat-transfer law**,

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What is wrong in MOST?

MOST is based on <u>TURBULENCE PARADIGM</u> rooted in Kolmogorov (1941, 1942), who considered only the shear-generated <u>*mechanical*</u> turbulence <u>in neutrally stratified</u> flows. His followers <u>plainly extended</u> his vision to <u>stratified flows</u>:

Turbulent flow = superposition of organised mean flow and chaotic turbulence → NOT TRUE in unstable stratification, which causes additional type of motion: <u>self-organised convective structures</u>

Turbulence = multi-scale chaos with the <u>forward cascade</u> of kinetic energy towards smaller scales – aiming at viscous dissipation → NOT TRUE in unstable stratification, which causes the buoyancy-generated <u>*anarchy*</u> turbulence with inverse energy transfer towards self-organised structures, co-existing with <u>*mechanical*</u> turbulence

Turbulent fluxes = mean gradients multiplied by turbulent viscosity, conductivity or diffusivity (<u>analogy with molecular-diffusion</u>) → good approximation only for neural and weakly stratified flows; NOT TRUE for horizontal fluxes and also for vertical fluxes in strong convection and strongly stable stratification

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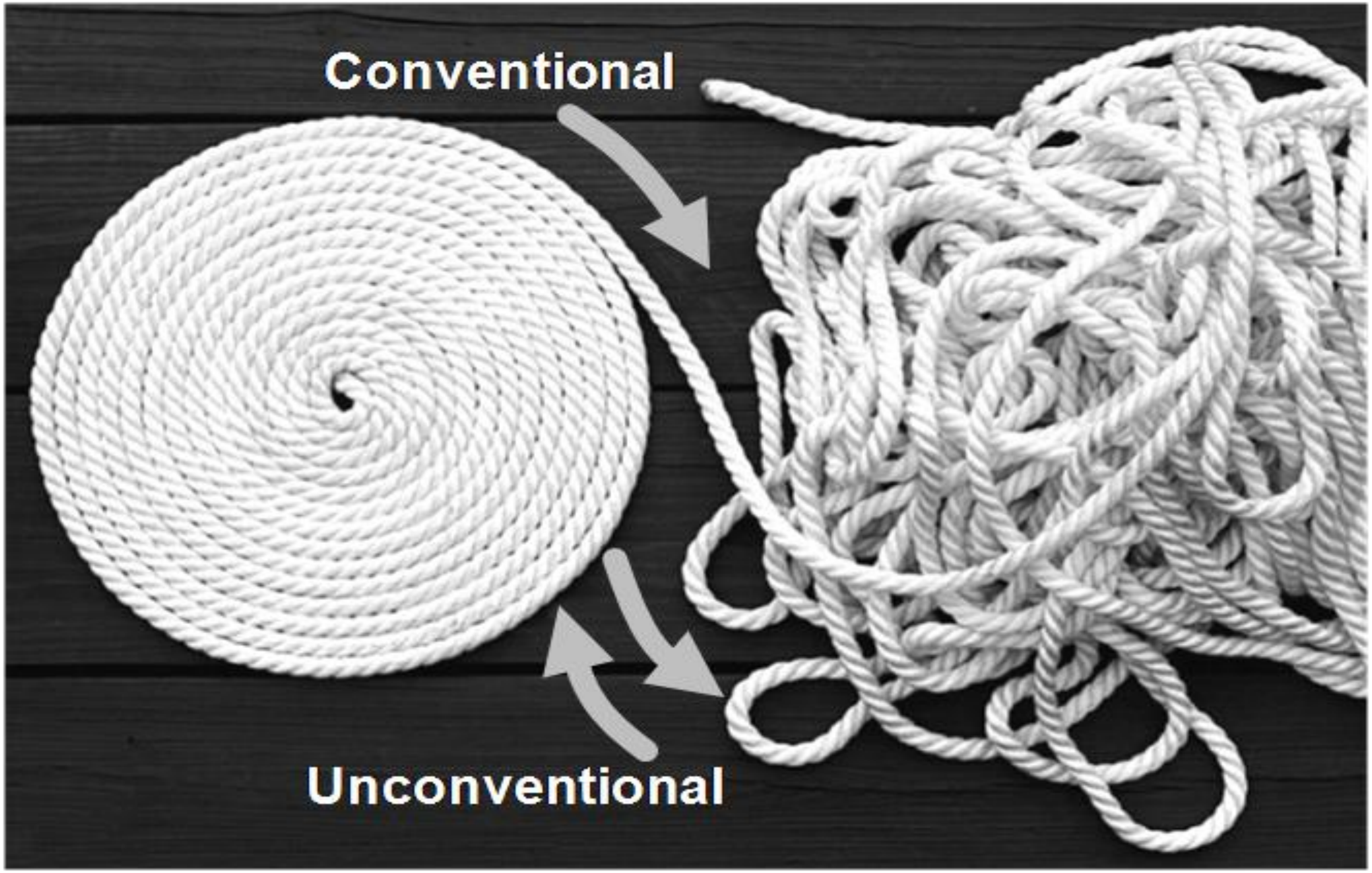
Revised paradigm of stratified turbulence:



chaos out of order (Kolmogorov)

co-exists with order out of chaos (Prigogine)