Towards revision of conventional theory of turbulence in stratified flows

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Frontiers in Oceanic, Atmospheric and Cryospheric Boundary Layers

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CONTENT

Current paradigm of the theory of turbulence basically follows Kolmogorov (K-1941). However, Kolmogorov focused on the shear-generated turbulence in neutrally stratified flows

Extension of his paradigm to stably-stratified and boyancy-generated turbulence was done by his followers without proof

New vision / paradigm of turbulence accounts for its SELF-CONTROL IN STABLE STRATIFICATION AND SELF-ORGANISATION IN UNSTABLE STRATIFICATION

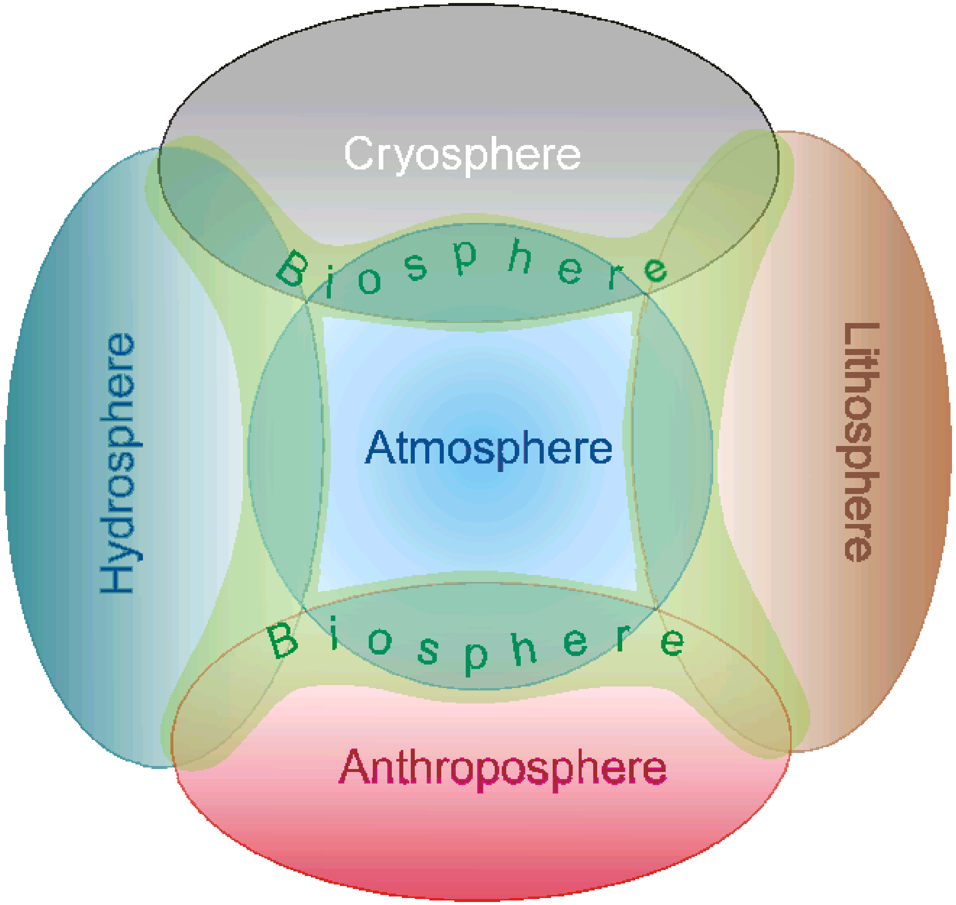
Turbulence and planetary boundary layers (PBLs)

Turbulence is strong in **PBLs** and **weak** beyond (in the free atmosphere and ocean thermocline), coexists with mean flow, and makes our planet **comfortable for life**

PBLs (green lenses)

couple geospheres into Earth system

host 99% of biosphere and the anthroposphere



Turbulence in climate-bio/technosphere system

Vitally important:

- **Performs vertical transports** across the atmosphere, and hydrosphere
- **Couples geospheres into climate-biosphere-technosphere system**

Ever present in harmony with mean flow:

- Doesn't degenerate due to self-control **even in super-critical stability**
- Doesn't dominate due to it self-organization **even in calm-weather turbulent convection**

TURBULENCE

Leonardo da Vinci: **Mult-scale** chaotic eddies

Richardson (1920): Direct **energy cascade**

Kolmogorov (1941): **Quantified the cascade**

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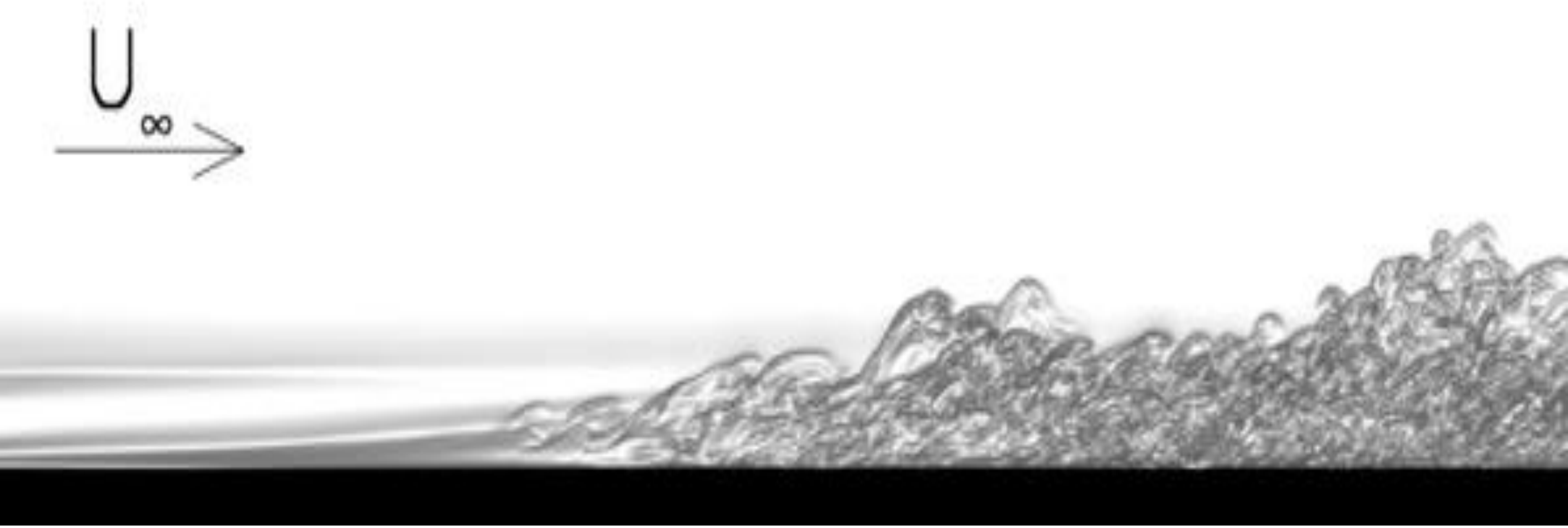
"Engineering" TURBULENCE in neutral boundary-layer flow over flat plate



Common vision (**paradigm**): dynamic instability causes energy cascade from large to small eddies towards dissipation: **chaos our of order (Kolmogorov, 1941)**

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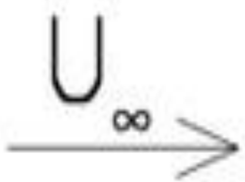
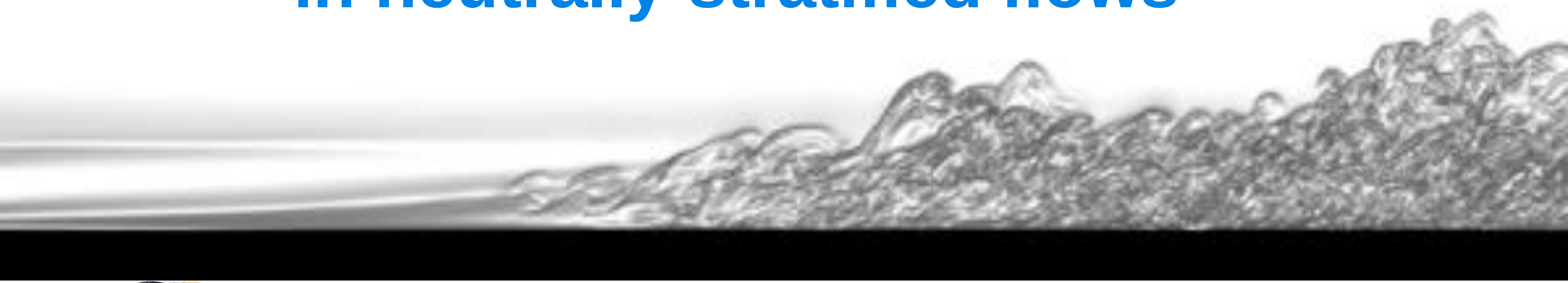
Conventional vision: Kolmogorov-1941

- **Two types of moton: regular mean flow + chaotic turbulence**
- **Instability of sheared flow → large eddies break down to produce smaller 3-D eddies → direct (forward) cascade of Turbulent Kinetic Energy (TKE) → towards viscous dissipation at smallest scales → the dissipation rate defined as** $\mathrm{TKE} / t_T \sim (\mathrm{TKE})^{3/2}/z$
- **Turbulence energetics fully defined by the TKE budget Equation**
- **Turbulent fluxes = gradients multiplied by exchange coefficients**



Shear-generated turbulence in neutrally-stratified flows



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Followers of Kolmogorov adopted his paradigm to stratified flows word for word (missing Turbulent Potential Energy and many other principal features)

Thanks to realistic results **for weakly / moderately stratified flows** the paradigm still underlies calculation of turbulence in geophysical, astrophysical and engineering applications, e.g., in atmospheric surface layer (since Monin & Obukhov, 1954)

Modern experiments and DNS reveal

- **non-gradient fluxes in strongly stable and unstable lows**
- **inverse energy cascade (anarchy) in convective turbulence**

The time is ripe to revise old paradigm, and to develop new theory of stratified turbulence

Breakdown of laminar flow
Very narrow spectrum: Pre-TURBULENCE?

Convective turbulence in the atmosphere

Buoyant plumes do not break down in contrast to shear-generated eddies!

Turbulence in economy, policy, life … and art

Vincent van Gogh *The Starry Night*, June 1889, The Museum of Modern Art, New York

The word **TURBULENCE** is used in very wide sense

with no exact definition even in physics!

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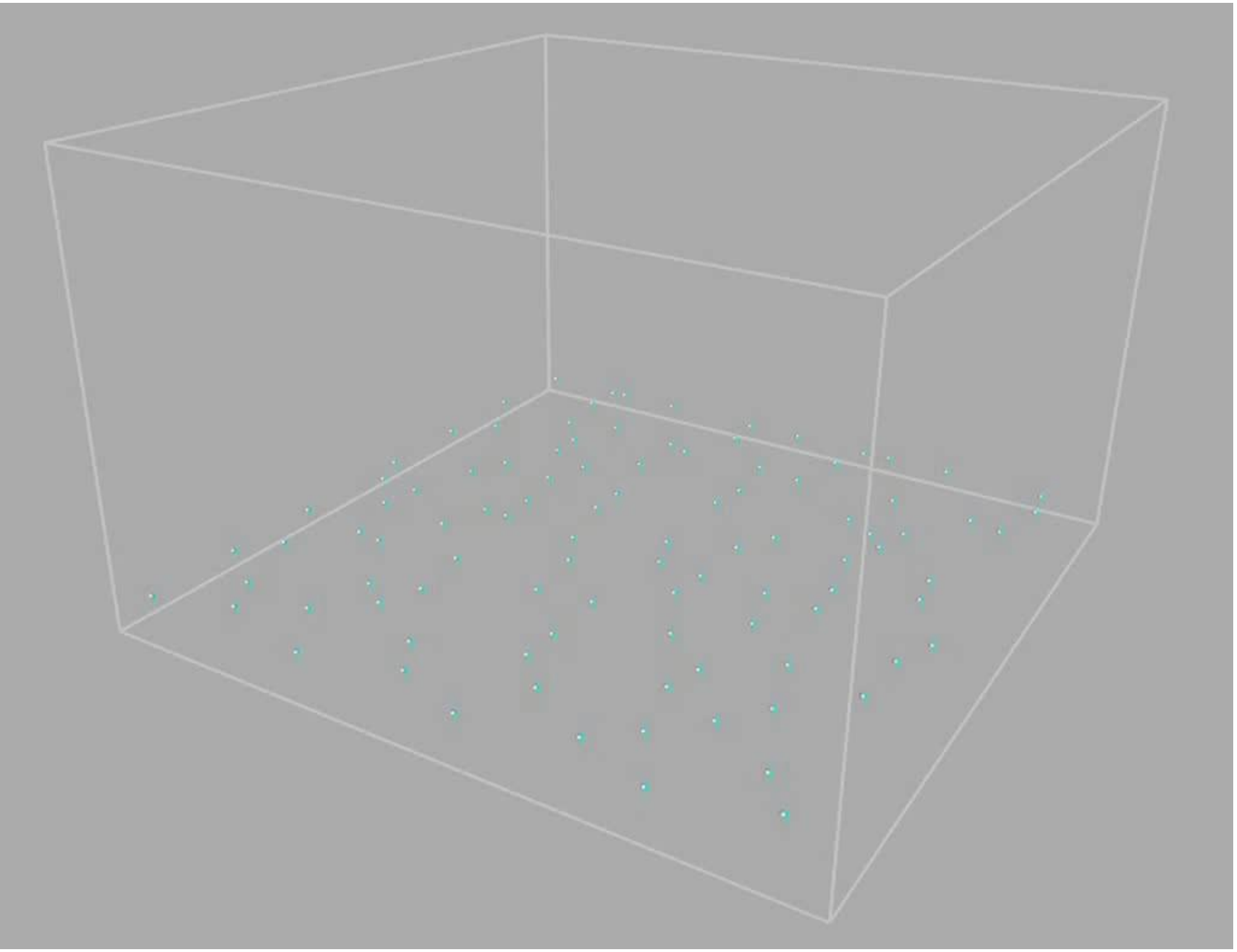
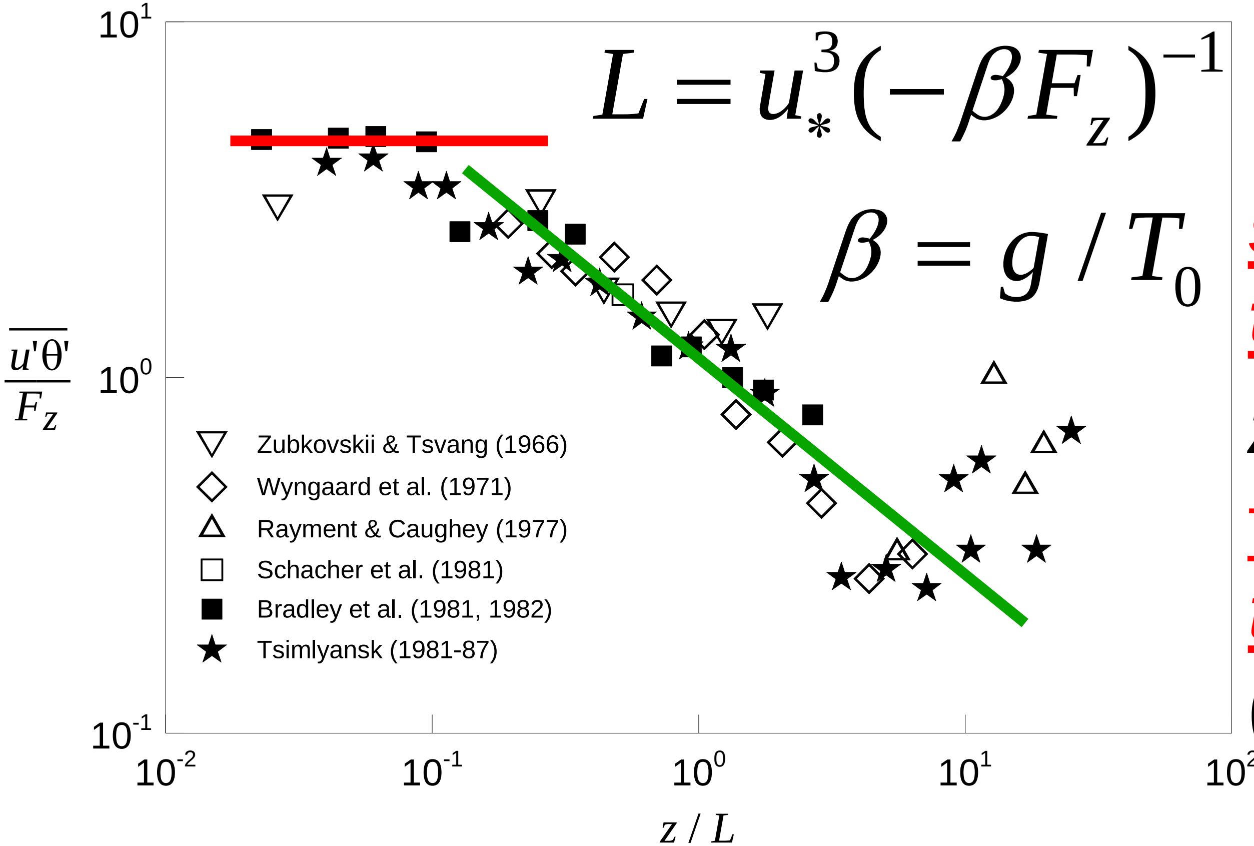
CONVECTIVE TURBULENCE
in Procrustean bad of conventional theory



Buoyant plumes do not break down but merge to built larger plumes → inverse energy cascade to self-organised cells or rolls → order out of chaos = **ANARCHY TURBULENCE**

Ratio horizontal/vertical heat flux F_x/F_z vs z/L



MO-1954 based on K-1941, is valid in ***shear-generated turbulence*** layer $z_0 < z < 0.1L$ but fails in the ***anarchy turbulence*** layer $0.1L > z > 10L$

MO = direct cascade = generation of horizontal TKE by **breaking** plumes: $u' \sim w' \sim (\beta F_z z)^{-1/3}$ → F_x/F_z = constant

Anarchy (Z, 2013): $u' \sim \tau/(\beta F_z z)^{-1/3}$ → $F_x/F_z \sim (z/L)^{-2/3}$

Data: Kader & Yaglom (1990)

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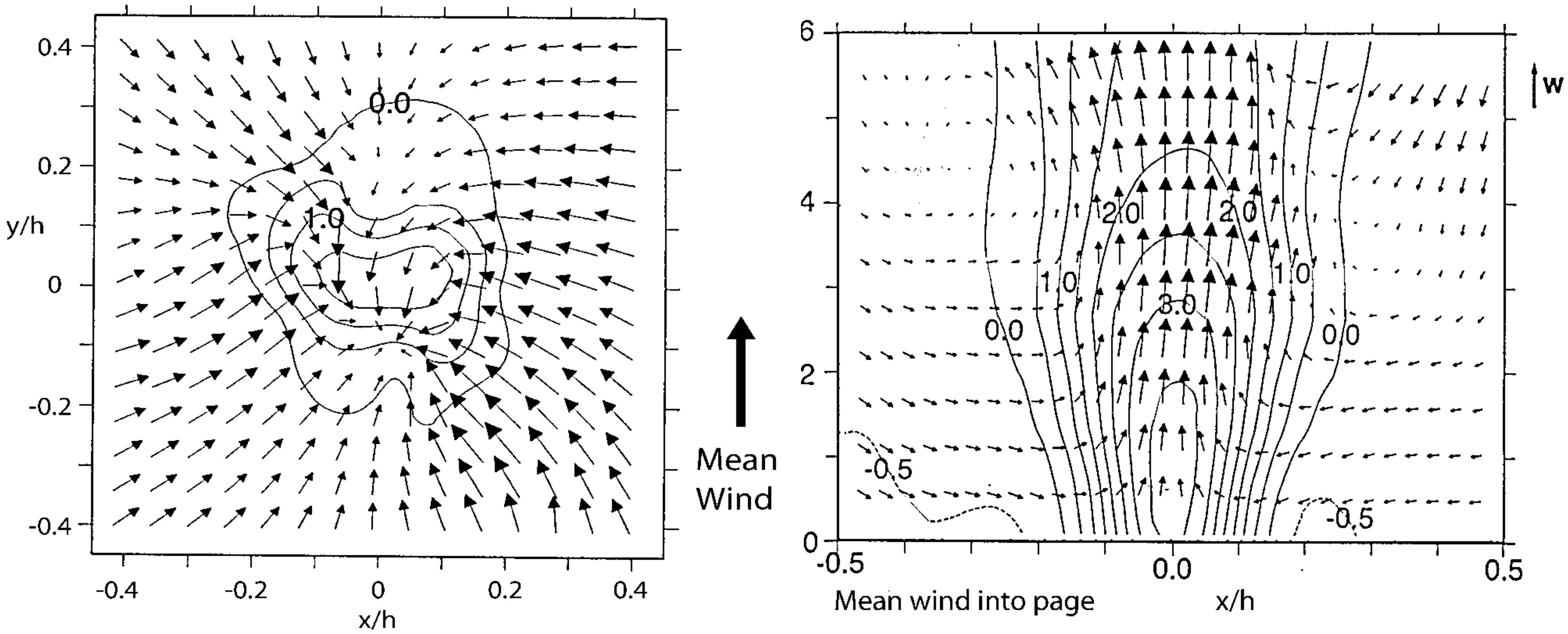
Self organization of convective TURBULENCE



Airborne measurements in **atmosphere** (Williams, Hacker, 1992). Arrows show **self-organised wind pattern**. Solid lines show deviations of potential temperature θ from its mean value $<\theta>$; the lines $\theta - <\theta> = 0$ mark side walls of large buoyant plume.

Enhanced heat/mass transfer in free convection

Large-scale self-organised structures

↓

Convective winds towards the plume base

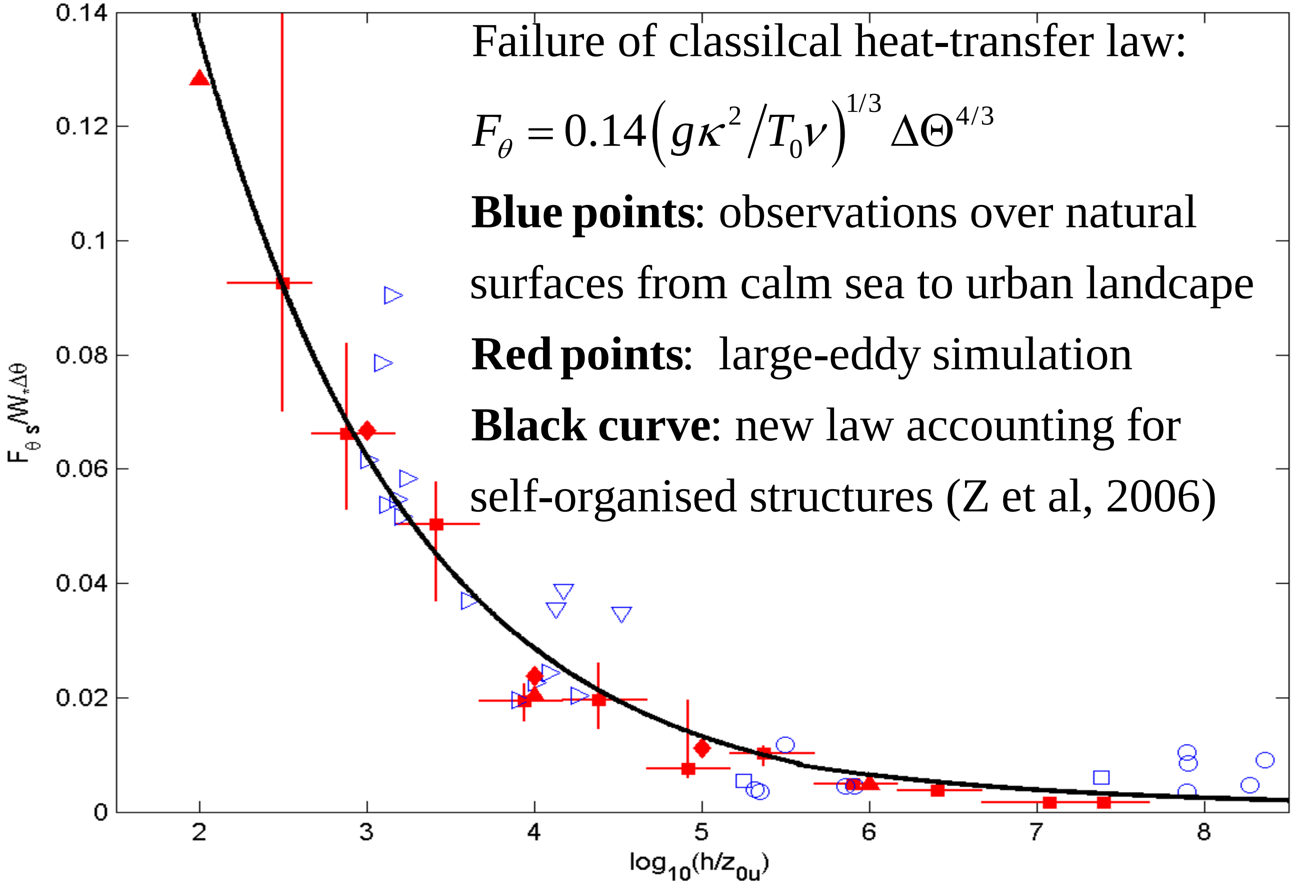
↓

Internal boundary layer → mechanical turbulence
(**overlooked in conventional theories**)

↓

Strongly enhanced heat/mass transfer

Heat-transfer in calm-weather convection



Heat transfer is much stronger than traditional theory predicts.

It <u>depends on PBL height</u> (*h*) and <u>roughness length</u> (z_{0u}), both mossed in traditional theory

New law $F_\theta = f\left(h/z_{0u}\right)\left(gh/T_0\right)^{1/2}\Delta\Theta^{3/2}$ properly calculates the heat flux over rough surfaces **whereas traditional theory underestimates this flux to an order of magnitude and more**

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Remarks on turbulence in unstable stratification

Traditional theory:

does not distinguish shear-generated ***mechanical*** turbulence *and* buoyancy-generated ***anarchy*** turbulence characterised by **inverse energy cascade from smaller to larger plumes towards self-organised structures → order out of chaos (Prigogine-1982)**

is erroneous as applied to horizontal mixing, fluxes and diffusion

overlooks large-scale self-organised motions, and strongly **underestimates surface fluxes**, especially in calm weather

In modelling practice, these failures are corrected but only empirically, without physical explanation

TURBULENCE IN STABLE STRATIFICATION

Sub-critically stable **well-mixed** PBL differs from **super-critically** stable **but yet turbulent** free flow aloft (Altay, Russ ia, 28.08.2010, photo SZ)

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Stably stratified turbulence: *strong-mixing* in PBL and *weak-conductivity* aloft ($Ri > Ri_c$)

Shallow PBL is seen due to water haze (Bergen). Old theory did not distinguish turbulence in stable PBL and **supercritically** stable free flow. The problem is solved by the EFB closure theory (Z et al., 2007-2013).

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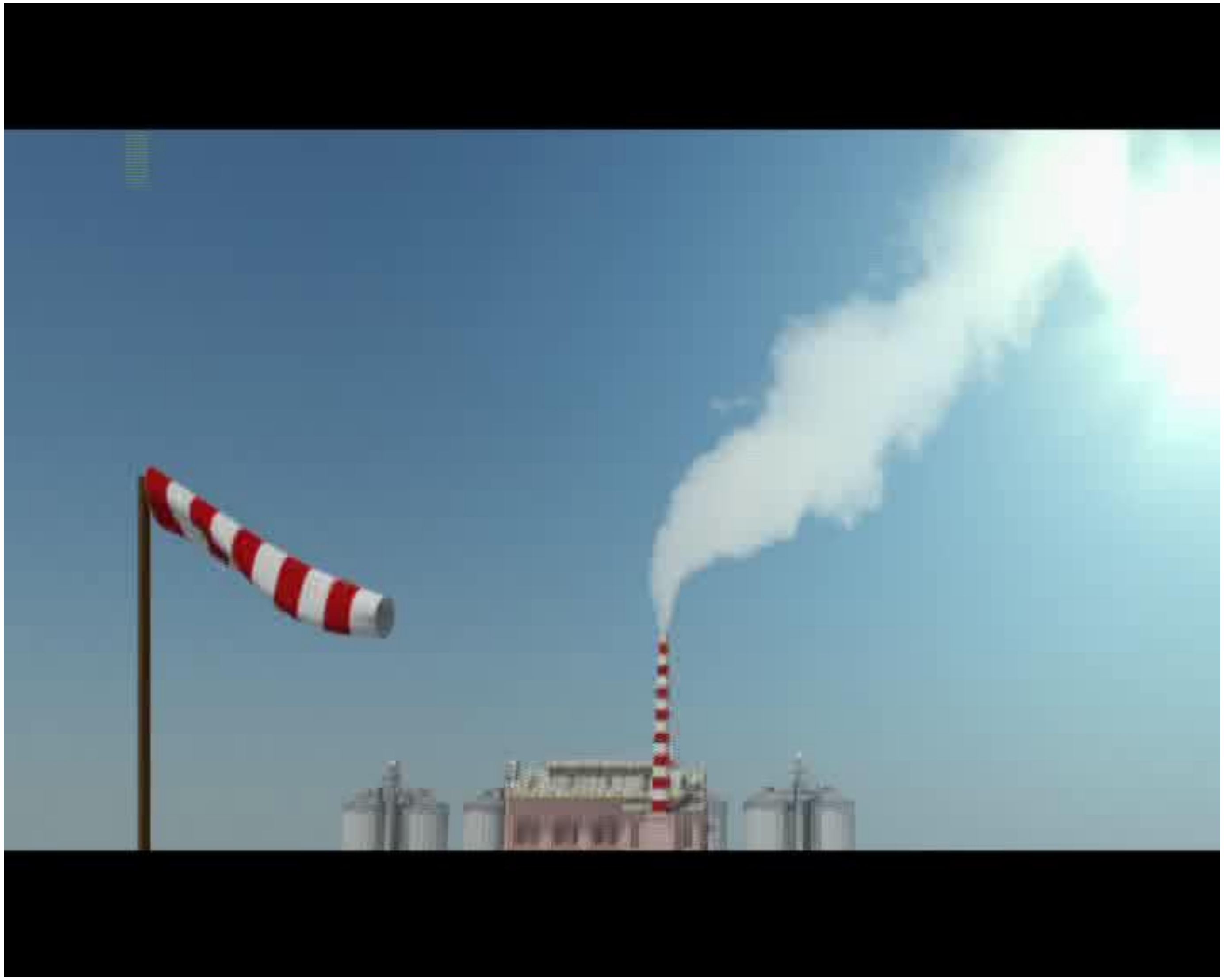
PBL height and air pollution



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Self-control of turbulence in stable stratification

via counter-gradient heat flux missed in K-1941, MO-1954

F_θ -budget reveals downgradient and countergradient terms comprising the **factual** heat flux

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

Key feedback assuring self-control (Z et al., 2007, 2013)**:**

Increasing temperature gradient $\partial \Theta / \partial z$ immediately **enhances**

(1) Total (**negative**) fluxes of heat F_θ and buoyancy $F_b = \beta F_\theta$

(2) Hence mean squared temperature $\left\langle \theta^2 \right\rangle = -C_3 t_T F_\theta \, \partial \Theta / \partial z$

(3) And thus the counter-gradient **positive** share of heat flux $C_1 t_T \left\langle \theta^2 \right\rangle$

This compensates for enhancing total (negative) heat flux and prevents collapse of turbulence in super-critical stratification

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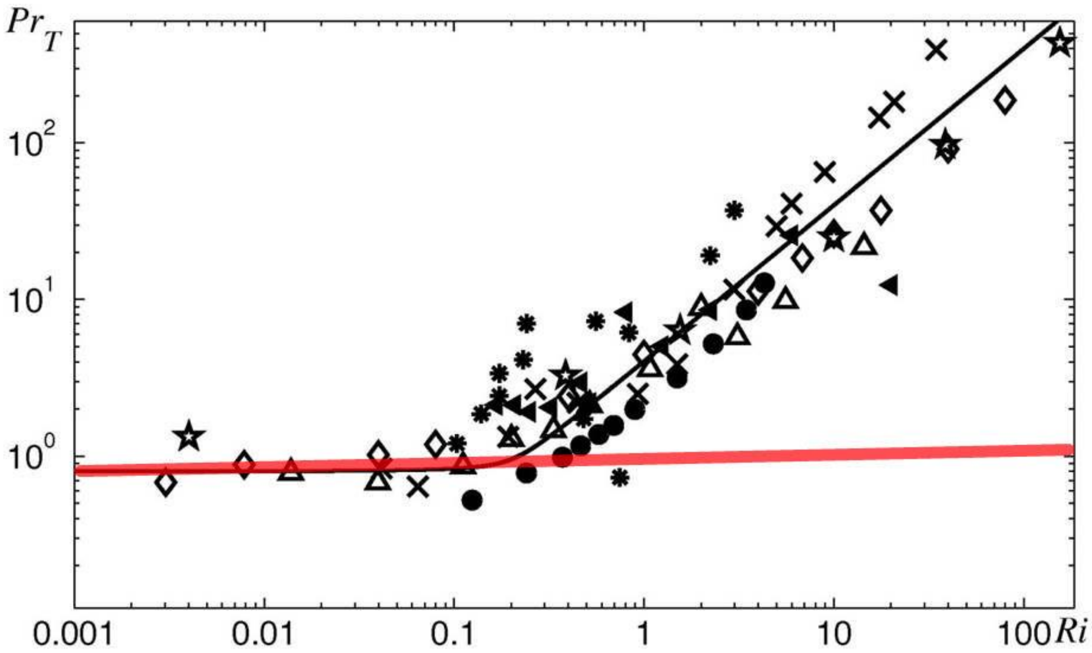
Prandtl no. Pr_T vs. Richardson no. Ri

K-1941, MO-1954 ignore self-control of heat flux, F_θ, and suggest similarity of viscosity and conductivity: $Pr_T = K_M/K_H = constant$

This entails erroneous turbulence cut off at $Ri > Ri_c = 0.25$



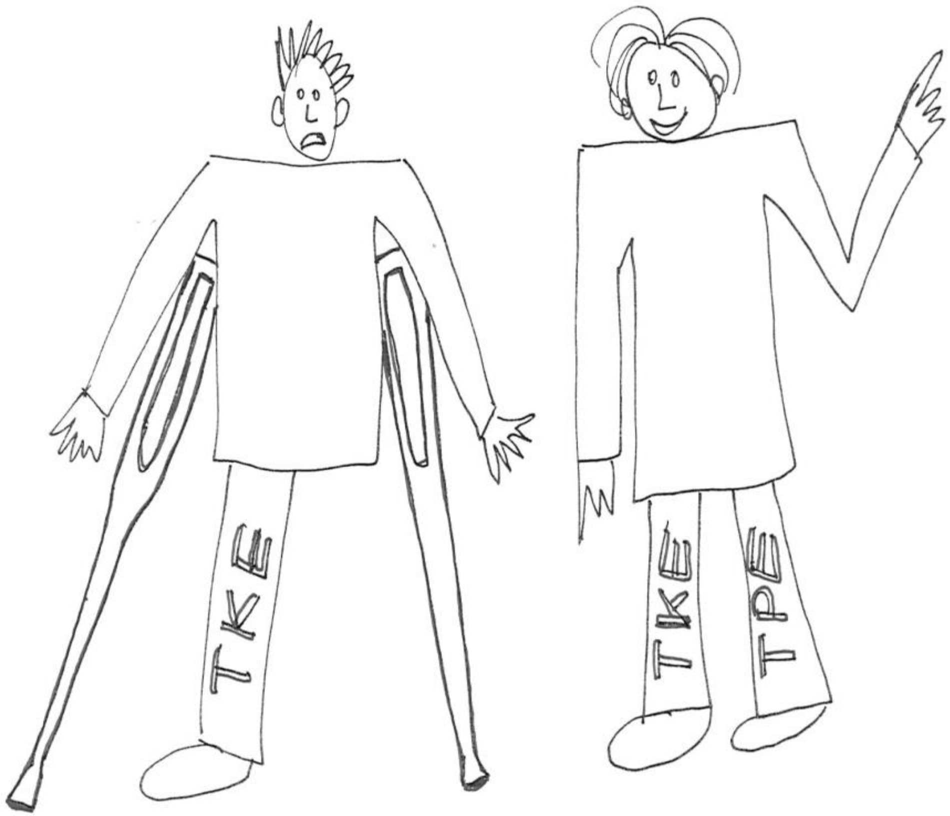
Black line: Pr_T after the EFB turbulence closure (Z et al., 2007-2017)

Red line: Pr_T predicted by conventional theory (e.g. MO-1954)

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

Remarks on turbulence in stable stratification

From hypothetical turbulent exchange coefficients and energetics limited to TKE



to flux-budget equations yielding down-gradient and non-gradient transports,

TKE + TPE energy budget,

self-control of heat flux,

surviving of turbulence in supercritical stratification,

and many other "heretical" features of turbulence …

We have finally got rid of misleading analogy with molecular transports

Prior paradigms originated from doubtful analogy with chaotic molecular motions

1. Boussinesq (1877)

The concept of **turbulent exchange coefficients**: viscosity, K_M, heat-conductivity, K_H, and diffusivity, K_D, analogous to molecular coefficients but much larger and to be determined empirically

2. Prandtl (1930)

$K_{M,H,D} = l dU/dz$ are products of **mixing length** l and **turbulent velocity** u_T analogous to molecular **pathway** and **velocity**. In boundary layers: $l \sim z$.

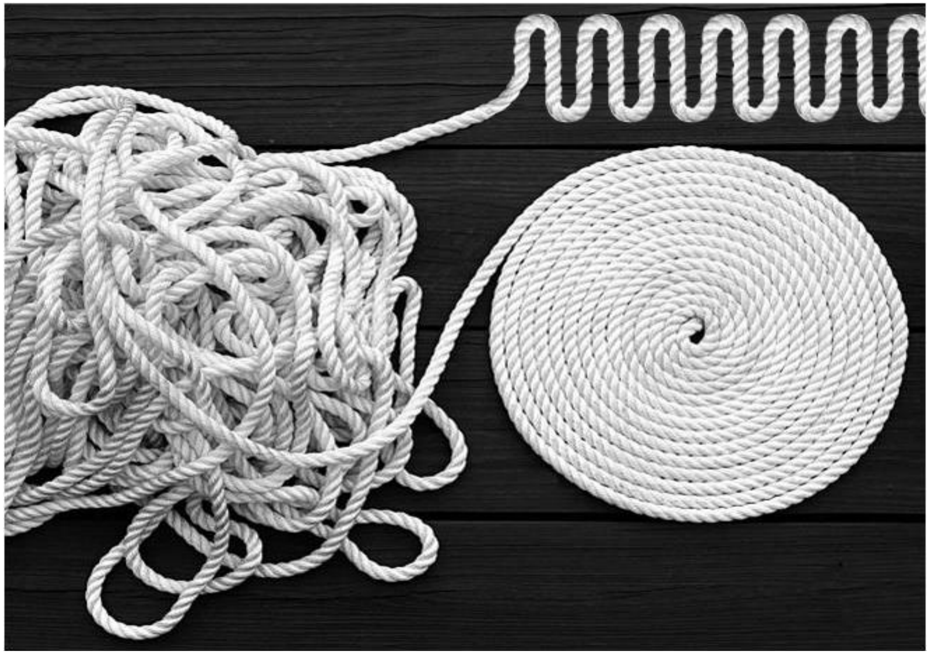
3. Kolmogorov (1941-1942)

TKE cascade towards dissipation = $(\text{TKE})^{3/2}/l$

TKE budget equation to determine $u_T = (\text{TKE})^{1/2}$,

but yet downgradient fluxes ($K_{M,H,D}$ defined after Prandtl)

Conclusion: revised vision of turbulence



Conventional PARADIGM:
K-1941 *NEUTRAL* stratification
(1) regular **mean flow**
(2) chaotic **turbulence** → only the **forward energy cascade** from larger to smaller eddies towards **viscous dissipation**
(3) **down-gradient** transport

Revised PARADIGM: *ANY* stratification
(1) **mean flow**
(2) **usual turbulence** with **forward cascade** towards dissipation
(3) both **down-gradient** and **non-gradient** turbulent transports
(4) **anarchy turbulence** with **inverse energy cascade** towards
(5) **large-scale organised structures** (secondary circulations)

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ALEXANDER OBUKHOV,

physicist, mathematician, key founder of theory of stratified turbulence

was born 100 year ago: in May 1918

The Obukhov length

$$L = u_*^3 (-\beta F_z)^{-1}$$

is forever inherent part of the theory of turbulence