Cognitive chaos: Why turbulence sustains in supercritically stratified free atmosphere?

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It is widely recognised that in very stable stratifications, at Richardson numbers (*Ri*) exceeding the critical value $Ri_c \sim 0.25$, turbulence ultimately decays and the flow becomes laminar. This is so, indeed, at low Reynolds numbers (*Re*), in particular, in laboratory experiments; but this is not necessarily the case in the very-high-*Re* geophysical flows. The free atmosphere and deep ocean are almost always turbulent in spite of the strongly supercritical stratifications: $1 << Ri < 10^3$. Until recently, this phenomenon remained unsolved.

The Energy- and Flux-Budget (EFB) turbulence-closure theory (Zilitinkevich et al., 2007, 2008, 2009, 2013) has disclosed the following “turbulence self-control” mechanisms explaining paradoxical persistence of the very stably stratified geophysical turbulence:

- Historically, the role of the negative heat (buoyancy) flux, $F_b > 0$, in the budget equation for turbulent kinetic energy (TKE) was identified as merely consumption of TKE by the buoyancy forces. This led to the seemingly logical conclusion that the sufficiently strong static stability causes the buoyancy flux sufficiently strong to exceed the rate of the TKE generation by the velocity shear and thus to kill turbulence.
- However, considering the TKE equation together with the budget equation for turbulent potential energy [TPE proportional to the squared buoyancy (potential temperature) fluctuations] immediately shows that the role of F_b in the turbulence energetics is nothing but conversion of TKE into TPE (F_b is precisely equal to the rate of this conversion), so that F_b does not affect at all the total turbulent energy (TTE = TKE + TPE).
- Moreover, as follows from the buoyancy-flux budget equation, TPE generates positive (directed upward) buoyancy flux irrespective of the sign of the buoyancy gradient. This is only natural: the more buoyant (warmer) fluid particles rise up, the less buoyant (cooler) particles sink down, so that both contribute to the positive buoyancy (heat) flux counteracting to the usual, negative flux generated by the mean buoyancy (temperature) gradient.
- In this context, strengthening the negative buoyancy flux leads to decreasing TKE and increasing TPE. The latter enhances the counter-gradient share of the total flux, thus reducing $\left|F_b\right|$ and, by this means, increasing TKE.

This negative feedback (disregarded in the conventional concept of down-gradient turbulent transport) imposes a limit on the maximal possible value of F_b (independent of the vertical gradient of buoyancy) and prevents degeneration of turbulence.

The EFB theory has predicted that the familiar critical Richardson number, $Ri_c \sim 0.25$, characterising the hydrodynamic instability limit and the turbulent-laminar flow transition at low Reynolds numbers, remains a principal threshold in the very-high-*Re* turbulence; but here it separates the two turbulent regimes of dramatically different nature:

- $Ri < Ri_c$: the familiar “strong-mixing turbulence” typical of boundary-layer flows, wherein turbulent Prandtl number is practically constant: $Pr_T \sim 1$ (the so-called “Reynolds analogy”);
- $Ri > Ri_c$: the newly revealed “wave-like turbulence” typical of the free atmosphere and deep ocean, wherein Pr_T sharply increases with increasing *Ri* (asymptotically as $Pr_T \approx 5Ri$).

This theoretical finding fits well with experimental evidence. Modellers have long been aware that the turbulent heat transfer in the free atmosphere is much weaker than the momentum transfer. The EFB theory gives authentic formulation for this heuristic rule and provides a physically grounded method for modelling geophysical turbulence up to very stable startifications.

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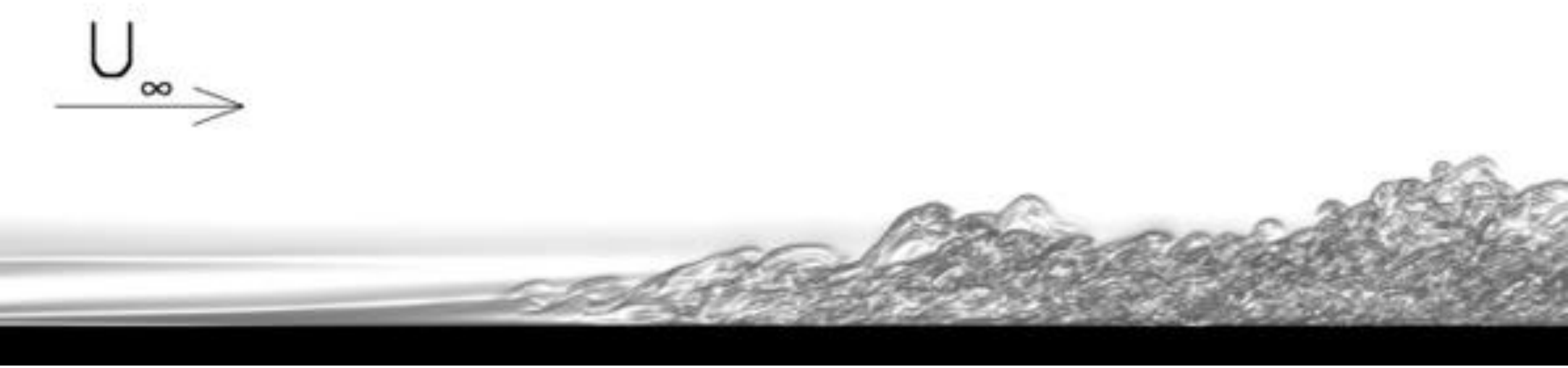
TURBULENCE in a flow over flat plate



Laminar to turbulent flow transition
is controlled by the Reynolds number
Re = (velocity x depth of the layer)/viscosity.

Laminar to turbulent flow transition

Turbulent convection in atmosphere

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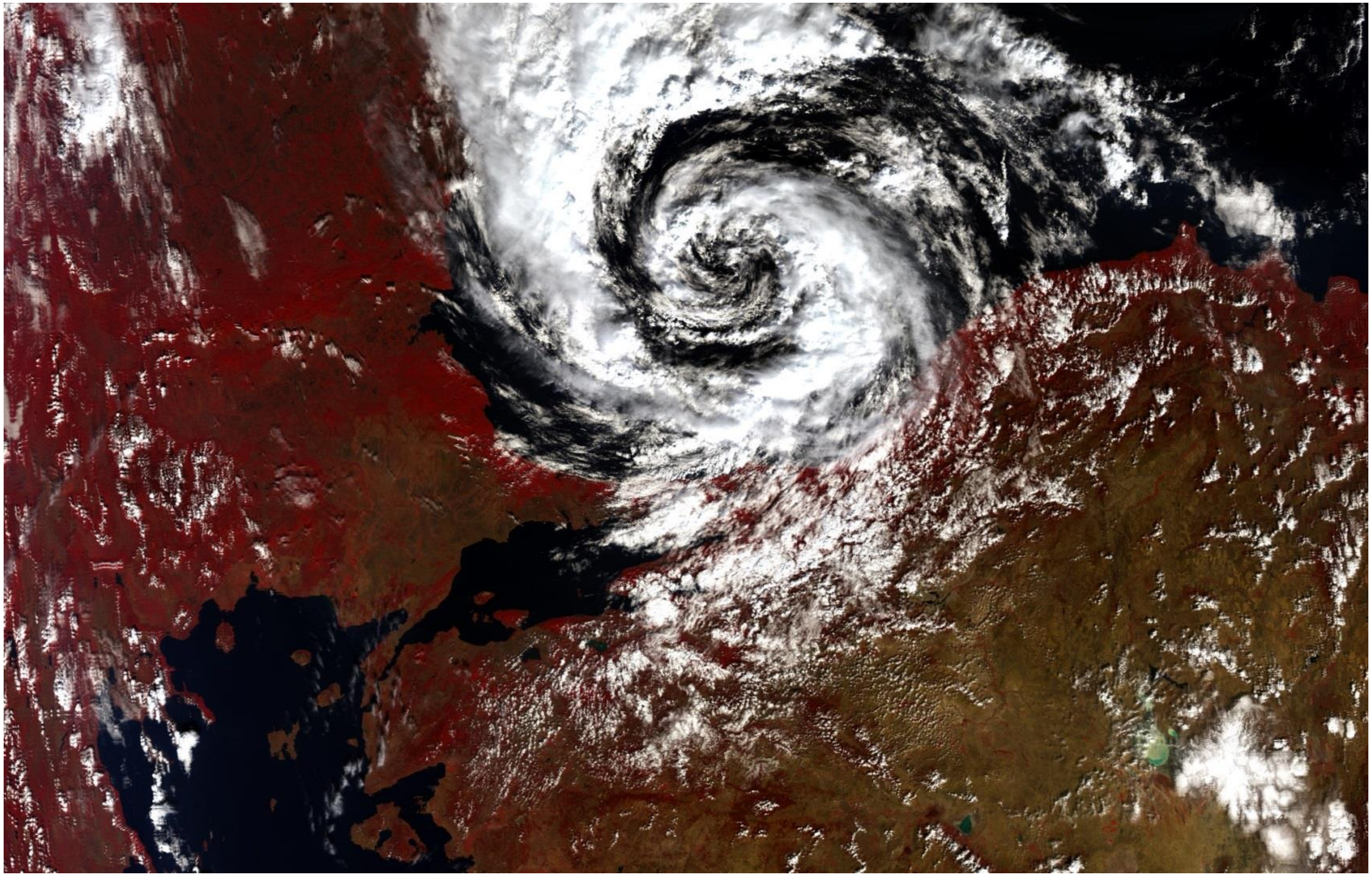
Convective plumes are seen due to condensation of water vapor in updraughts

Topical-like cyclone over Black Sea 27.9.2005



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Down wash in wake flow

“Turbulence” in art

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

The word *turbulence* is applied to phenomena of different nature: lack of certain definition

TURBULENCE IN CLIMATE SYSTEM

Turbulence performs vitally important “**SERVICES**”:
- vertical transport and
- air-sea/land/biosphere interaction

Turbulence is ever present in the balk atmosphere and ocean, **in spite of the extreme static stability**
The Richardson-number criterion:
Ri = “static stability” / “dynamic instability” > 100
In laboratory the static stability kills turbulence
already at Ri > Ric = 0.25!

Until recently <u>domination of supercritically stably stratified turbulence remained unexplained</u>

Convection and convective turbulence

Convection is driven by the potential energy of unstable stratification, for example, over warm Earth surface heated by solar radiation or in clouds cooled from above due to the long-wave radiation

Convective PBL performs very efficient transfer of energy (heat), mass and momentum from the surface upward → very important “**SERVICE**” against extremes

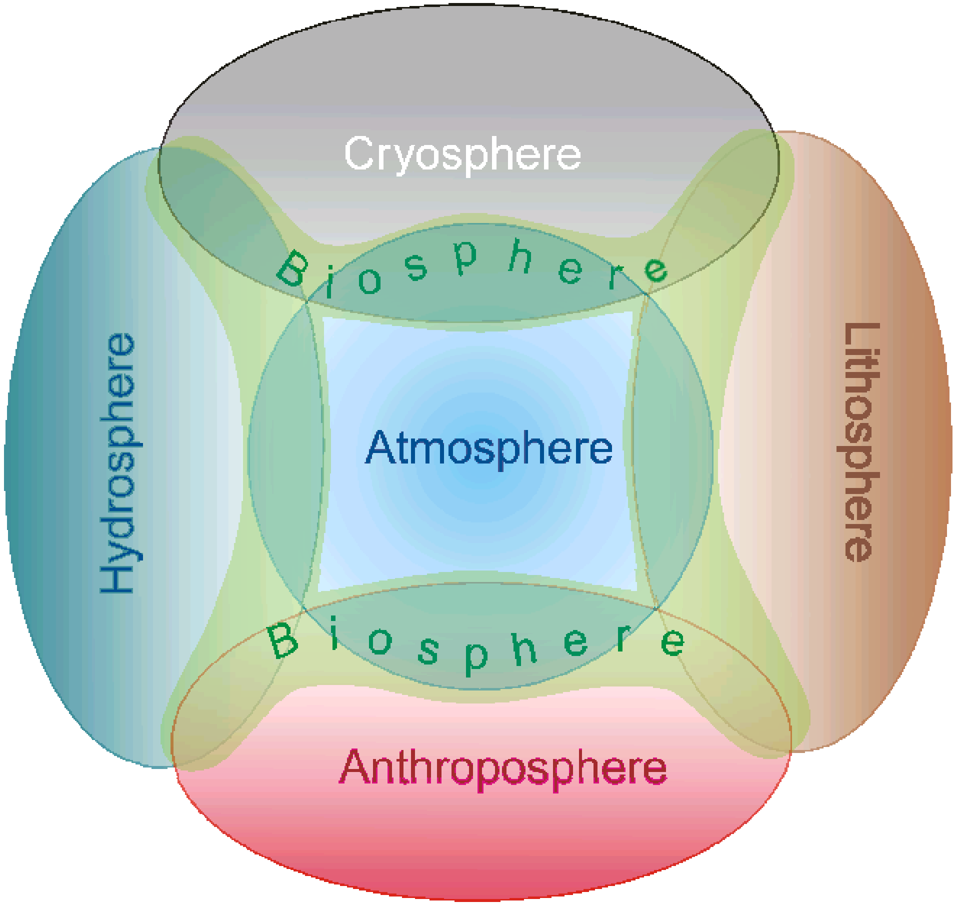
Conventional theory disregarded self-organization of convective turbulence, and treated it as principally the same type of fully chaotic motions as mechanical turbulence → **contradicts to experimental evidence**

Turbulence and planetary boundary layers (PBLs)

Turbulence – STRONG in PBLs and WEAK in the free atmosphere/ocean – is kept in "COGNITIVE" shares with the mean flow all over the fluid geospheres

PBLs (dark green lenses) couple the atmosphere, hydrosphere, lithosphere, biosphere and cryosphere into interconnected Earth systems

PBLs host 90% of biosphere and the entire anthroposphere



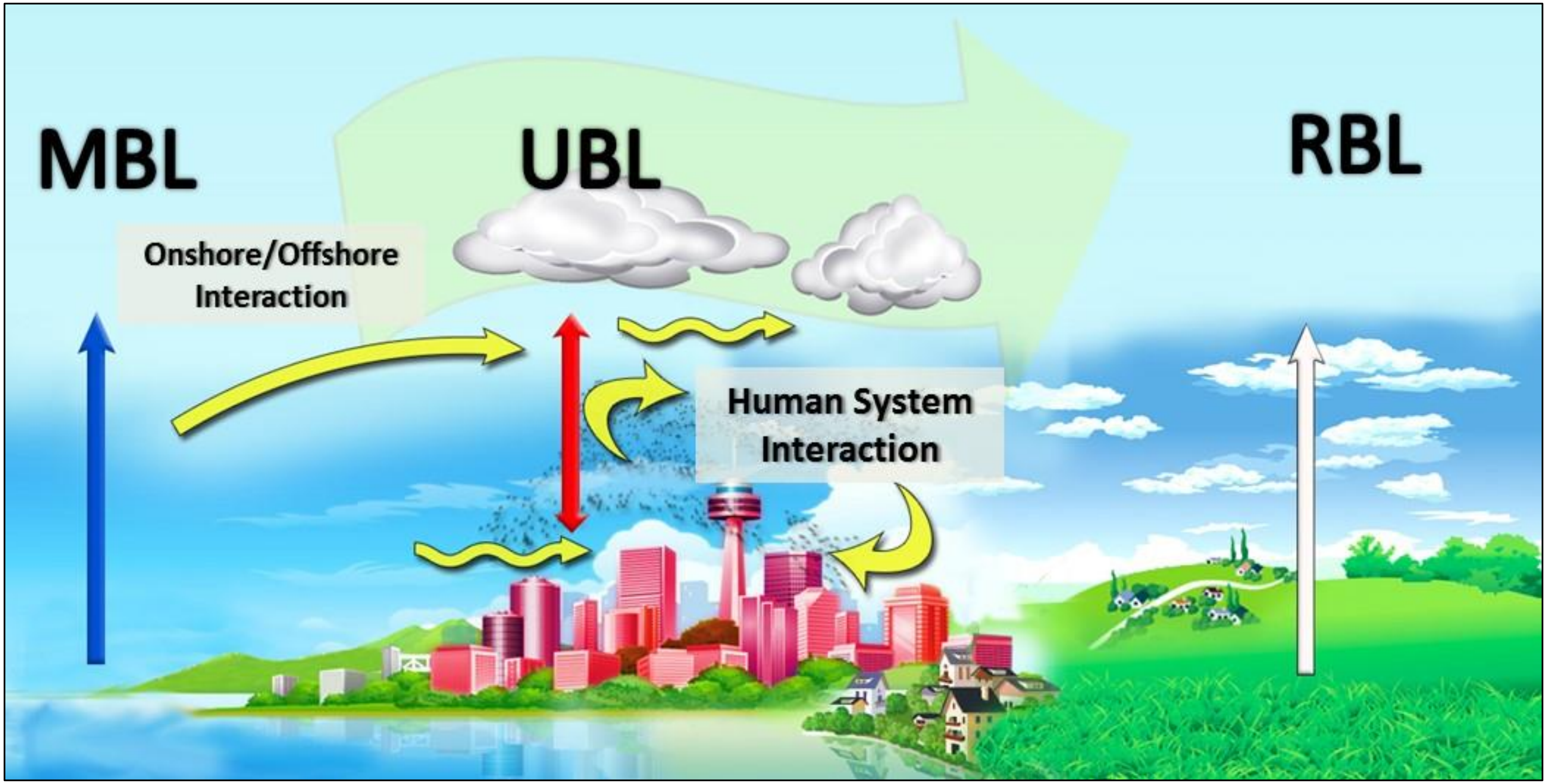
Stable PBL

Shallow, stably-stratified planetary boundary layer (PBL) in Bergen visualized by water haze (winter 2012, courtesy T. Wolf)

Conventional theory fails to explain the difference between turbulence in the PBL and free atmosphere

Deep, well mixed, cloudy convective layer

PBLs control fine features of local weather, air pollution and microclimate: <u>PBL-climates</u>



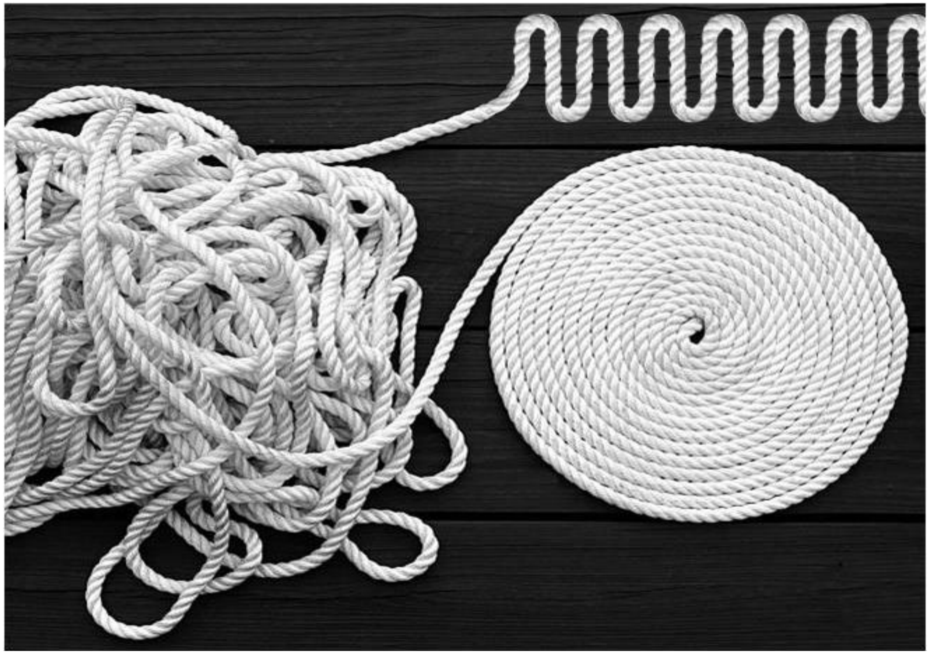
REVISION OF THE CONVENTIONAL CONCEPT

TRADITIONAL PARADIGM

K-1941 *NEUTRAL* stratification

(1) regular **mean flow**

(2) chaotic **turbulence** → only
forward energy cascade
from larger to smaller eddies
towards **viscous dissipation**



REVISED PARADIGM up in the air *ANY* stratification

(1) **mean flow**

(2) **usual turbulence** with **forward cascade** towards dissipation

(3) **anarchy turbulence** with **inverse energy transfer**
from smaller to larger eddies (in turbulent convection) towards

(4) **large-scale organised structures** (secondary circulations)

TURBULENT CONVECTION

Conventional theory

- treats convective mixing as usual turbulence according to classical paradigm
- gets in conflict with experimental evidence
- subject to principle revision

Self-organisation in turbulent convection

Cells in **viscous convection** (Benard 1900, Rayleigh 1916)
Cells or **rolls** in **turbulent convection** clearly seen in LES
after filtering small-scale fluctuations

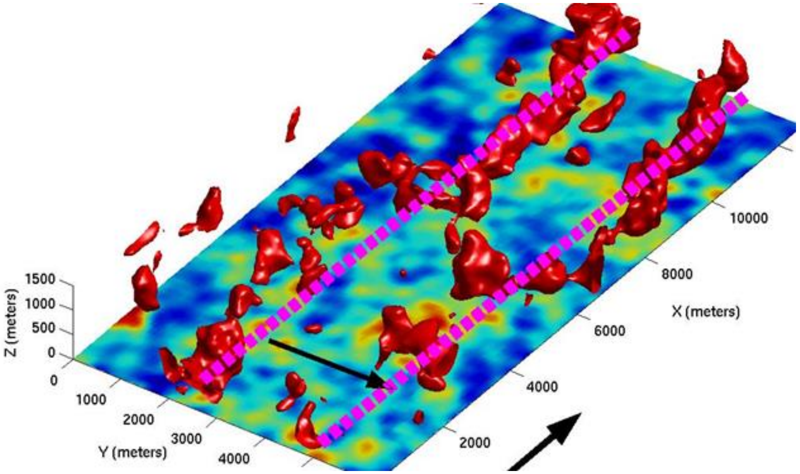
There is no analogy to rolls in viscous convection:

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

Self-organisation missed in universally recognised theories

- Heat/mass transfer law
- Prandtl theory of free convection
- Monin-Obukhov similarity theory
- etc., etc.

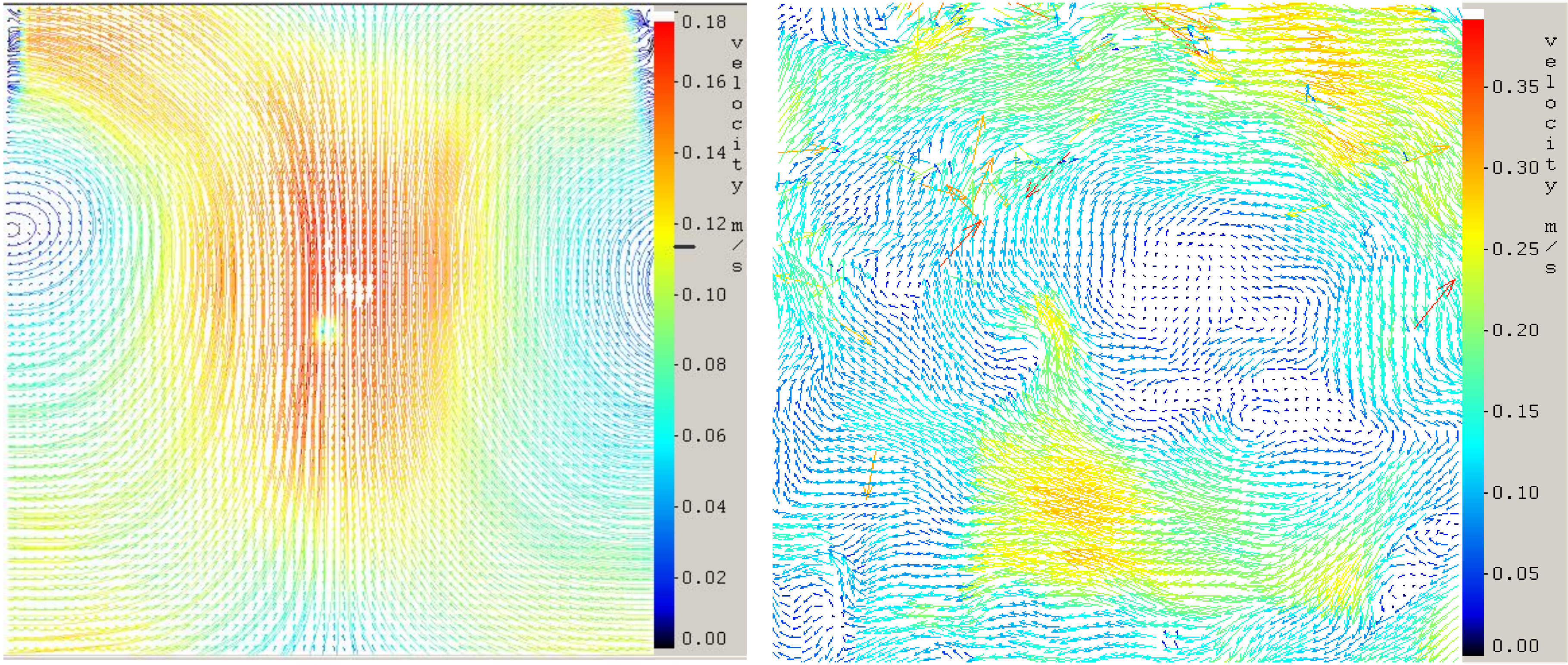
Self-organisation in Convective PBL



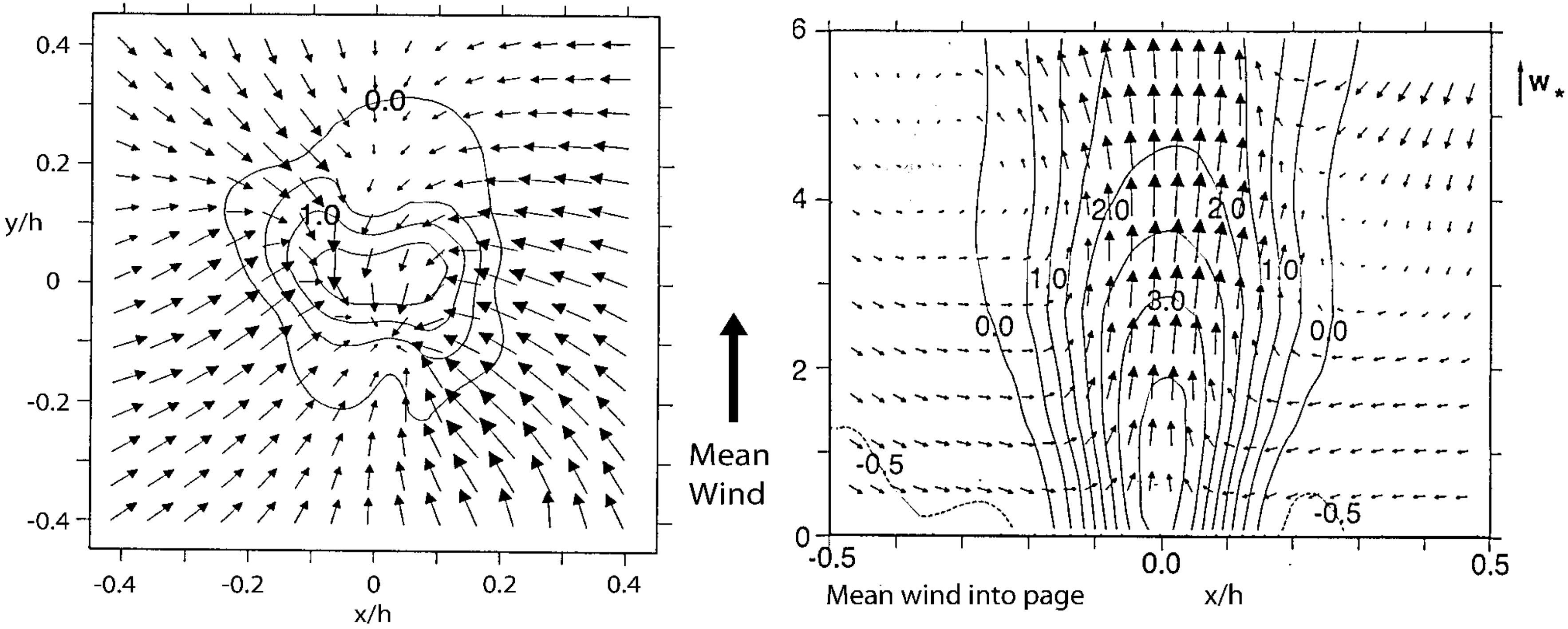
Self-organization of turbulence into large-scale structures: **rolls** (upper left aerial photo by J. Gratz, USA); **cells** (upper right, ENVISAT image A2002050, Florida, NASA visualized by clouds); and **rolls in LES** (left figure – by I. Esau)

Self-organisation in laboratory

Shear-free turbulent connection in tank heated from below: vertical (left) and horizontal (right) cross-sections (Mech. Engng. Ben-Gurion University, Israel)

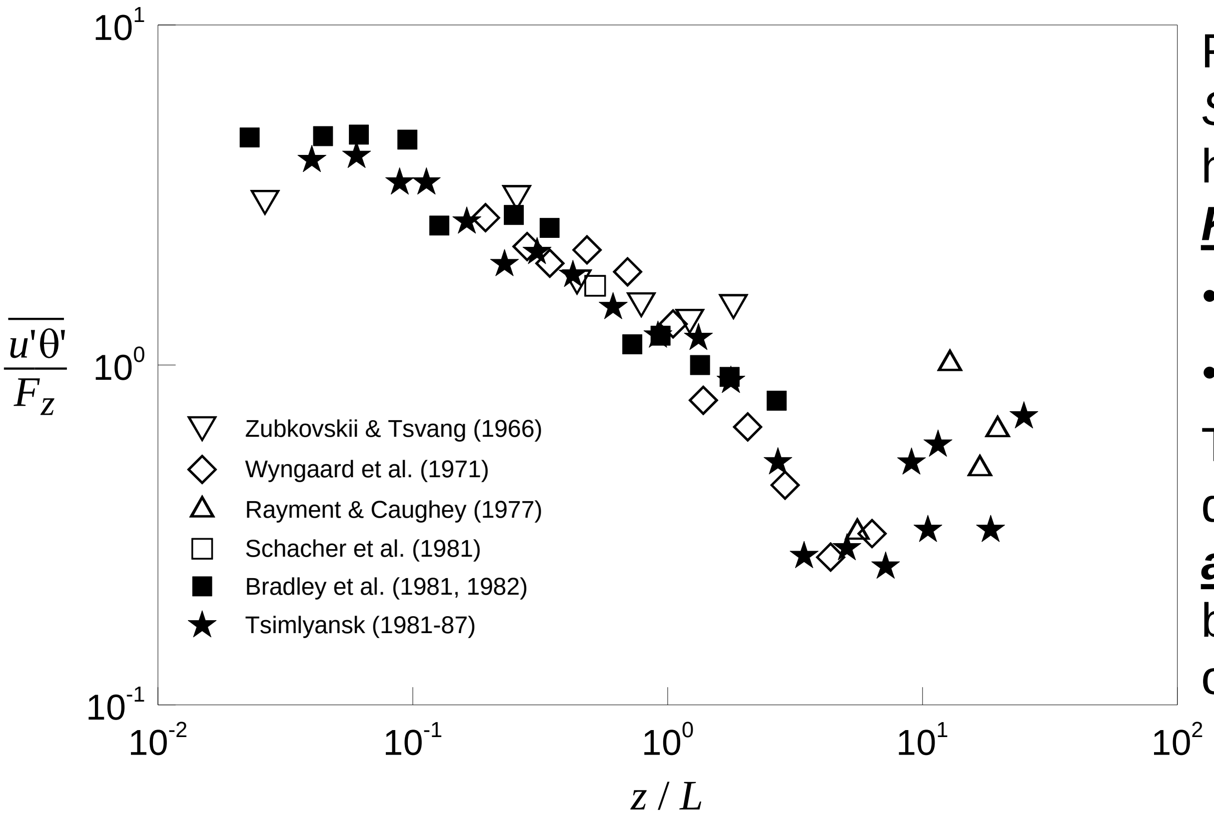


Self organisation in atmospheric convection



Williams and Hacker (1992) airborne measurements: Arrows show the self-organised velocity field. Solid lines show deviations of potential temperature θ from its averaged value $<\theta>$. The iso-surface $\theta - <\theta> = 0$ marks the side walls of the updraught.

Horizontal / vertical heat flux ratio F_x/F_z vs. z/L



Failure of the *Monin-Obukhov Similarity Theory* (MOST) in the height-interval between the two ***Kolmogorov-turbulence*** layers

- log layer: $z < 0.1L$
- and CBL core $z > 10L$

The layer $0.1L < z < 10L$ is dominated by the unusual ***anarchy turbulence*** fed by the buoyancy forces (and feeing the organised structures)

Kolmogorov turbulence: $F_x/F_z =$ const. in log-layer $(0 < z < 0.1L)$, and again constant in CBL core $(z < 10L)$, where turbulent part of kinetic energy is small

Anarchy turbulence: $F_x/F_z \sim (z/L)^{-2/3}$ **(MOST fails)** at $0.1L < z < 10L$

Data from Kader & Yaglom (1990), consistent with DNS by O. Druzunin (2015)

Heat/mass transfer in free convection: non-classical mechanism

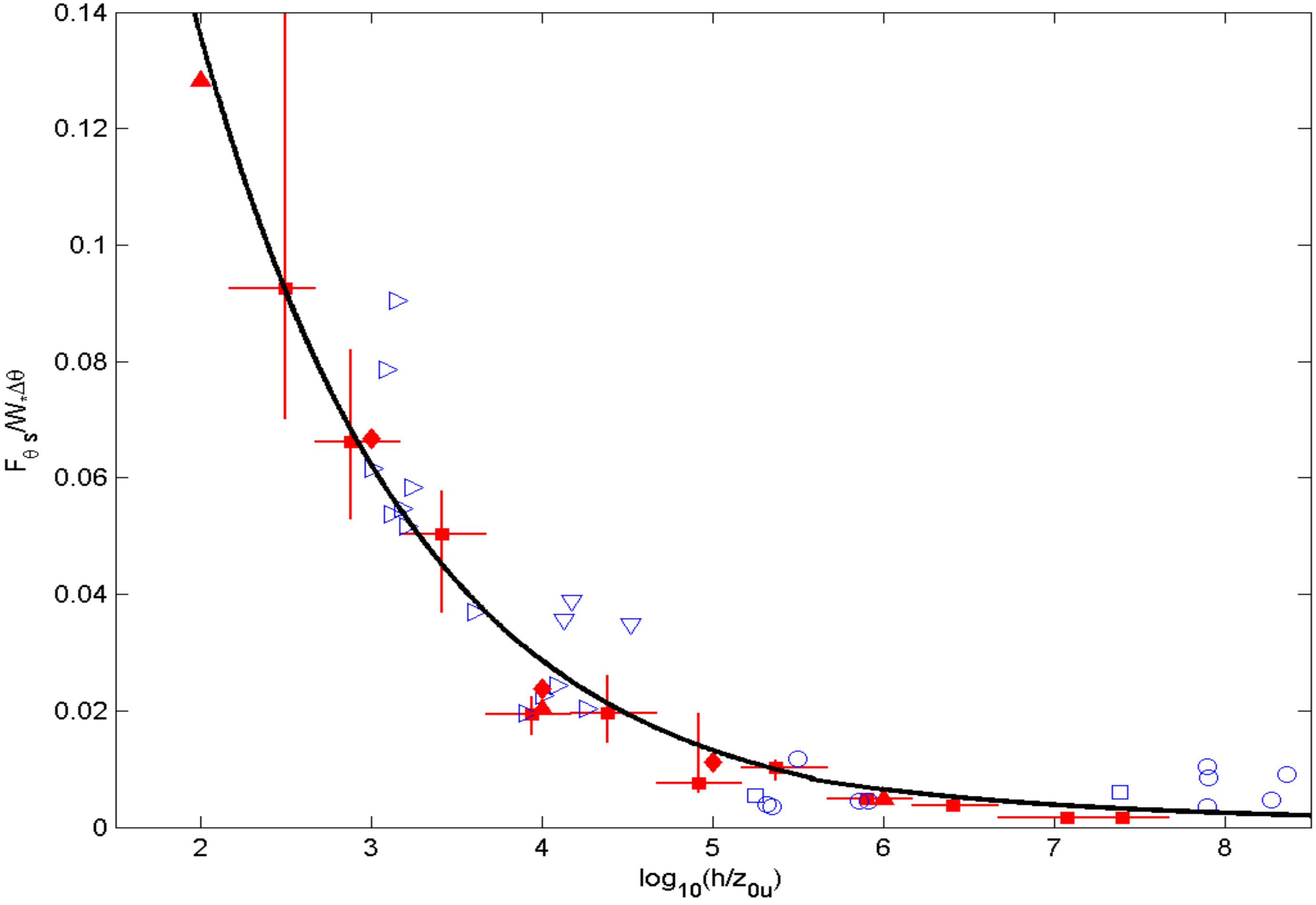
Large-scale self-organised structures

Convective winds towards the plume base

Internal boundary layer → surface shear → mechanical turbulence (**historically overlooked**)

Strongly enhanced heat/mass transfers

Heat-transfer is much stronger than in classical theory and depends on other parameters: h/z_{0u}



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TWO TYPES of stably stratified turbulence

Shallow sub-critically stable, mixed PBL separates from super-critically stable but yet turbulent free atmosphere (Altay, Russia, 28.08.2010, photo SZ)

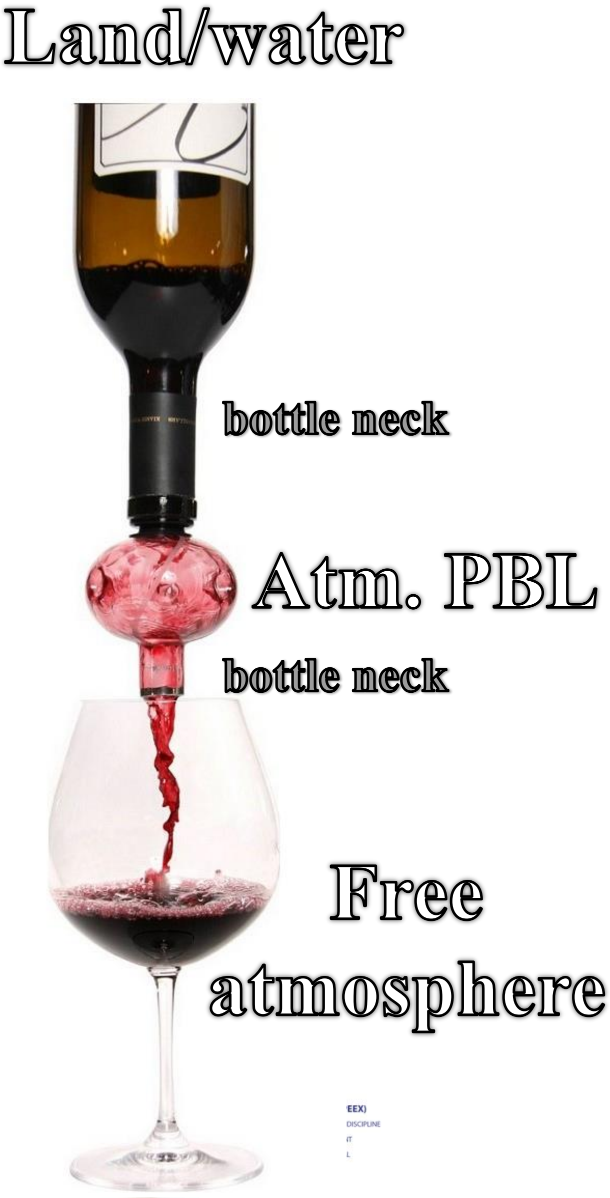
Practical aspect: polluted urban PBLs

Shallow polluted PBL over Moscow 19.03.2015, 10:00 a.m. – view from 18th floor of main building of Moscow University (courtesy S. Dobrolyubov)

Role of planetary boundary layers (PBLs)
TRADITIONAL VIEW

Surface fluxes between
AIR
and
WATER (or **LAND**)
fully characterise interaction between
ATMOSPHERE and OCEAN/LAND

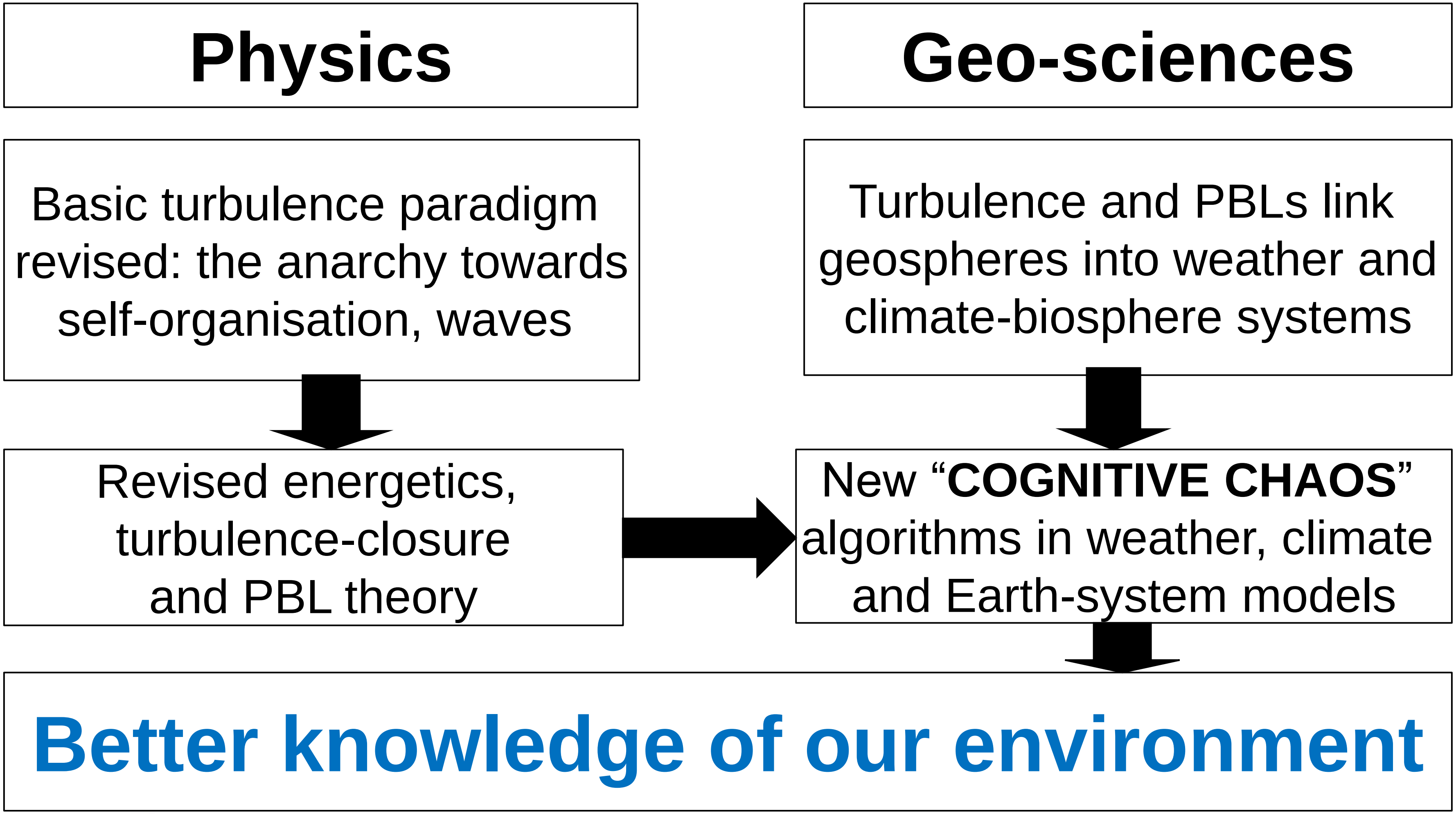
Role of PBLs: MODERN VIEW



Atmospheric PBLs acts similarly to the wine aerator:

Very stable stratification at the PBL outer boundary prevents entities delivered by surface fluxes or by emissions to immediately penetrate from PBL into the free atmosphere or vice versa

Geophysical turbulence and planetary boundary layers (PBLs)



Physics

Basic turbulence paradigm revised: the anarchy towards self-organisation, waves

Revised energetics, turbulence-closure and PBL theory

Geo-sciences

Turbulence and PBLs link geospheres into weather and climate-biosphere systems

New “**COGNITIVE CHAOS**” algorithms in weather, climate and Earth-system models

Better knowledge of our environment

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