Large organized structures in stably stratified turbulent shear flows

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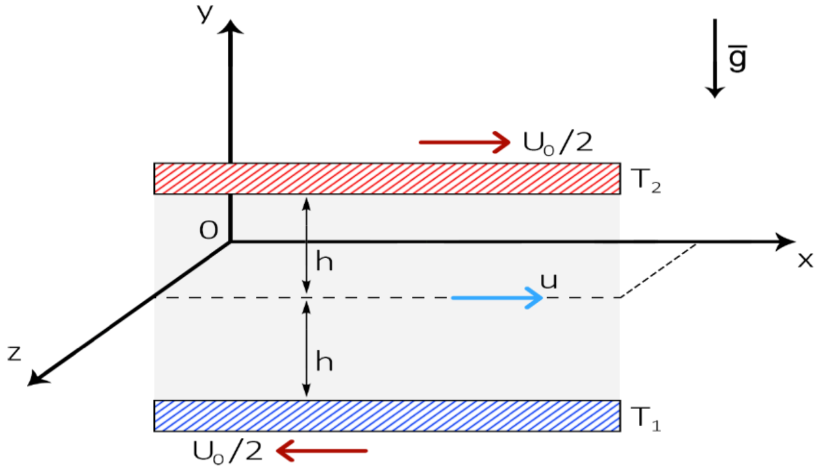
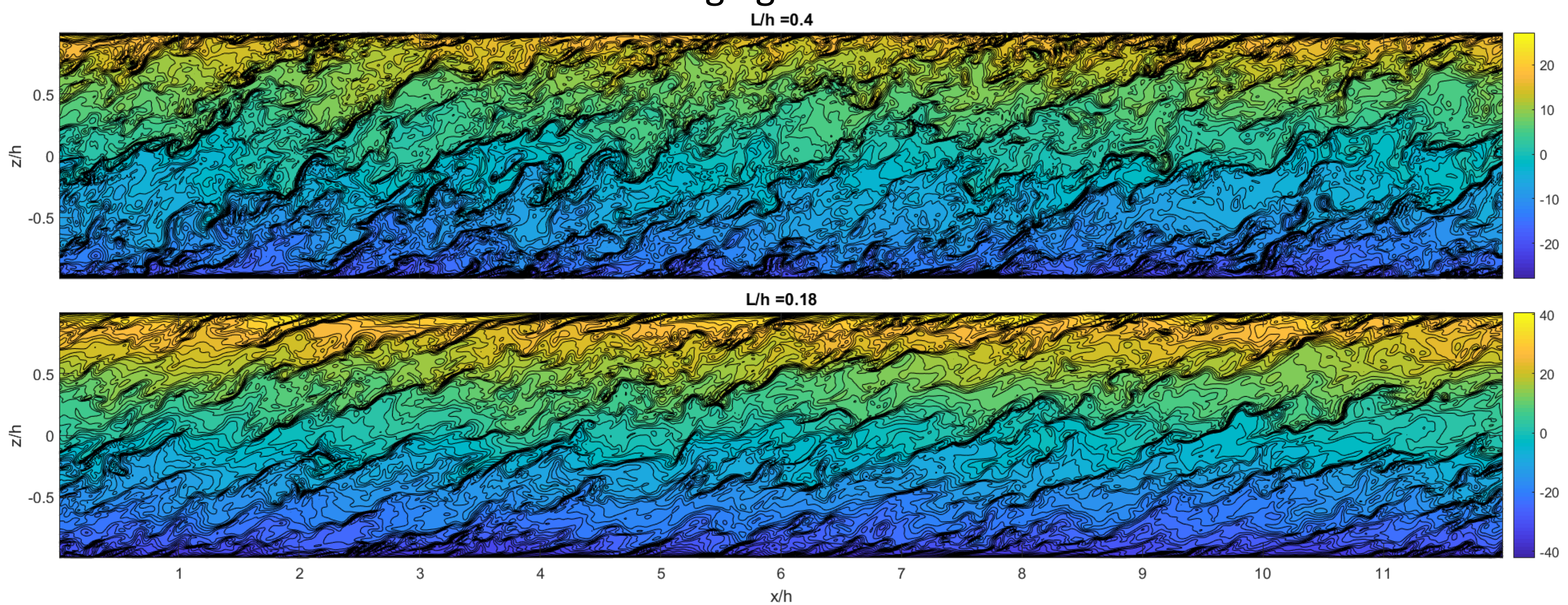
DNS and LES of a stably stratified turbulent Couette flow



Glazunov A. V., Mortikov E. V. , Barskov K. V., Kadantsev E.V., Zilitinkevich S.S., Layered structure of stably stratified turbulent shear flows // Izvestiya - Atmospheric and Oceanic Physics. — 2019. — Vol. 55, no. 4. — P. 312–323.

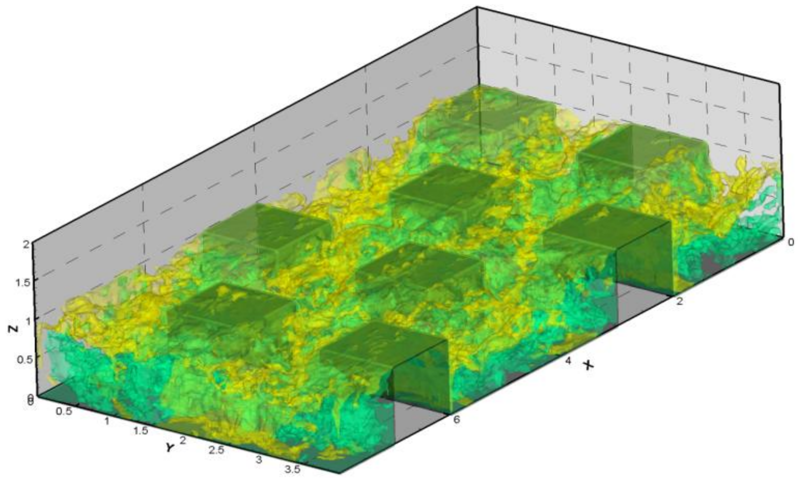
Vertical cross-section. Temperature isolines.

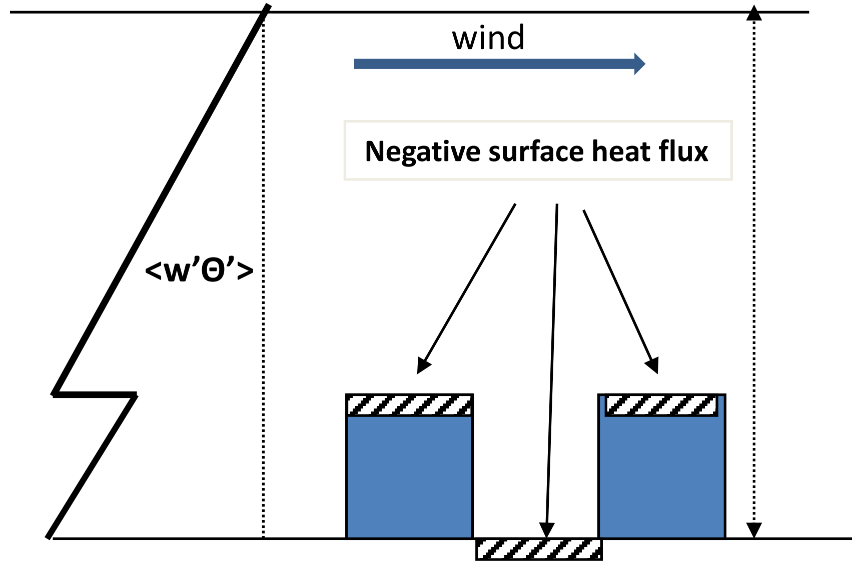
Large scale irregular inclined layers with weak stratification, separated by very thin layers with large gradients



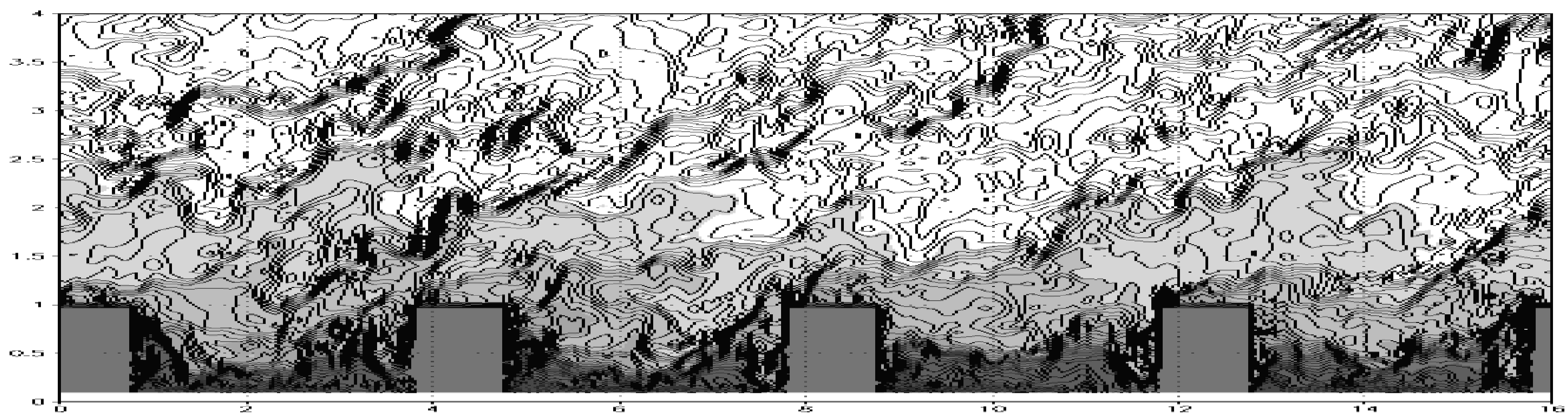
Large eddy simulation

Stably stratified turbulent flow above urban-like canopy (*GlazunovA.V. , Izv., Atmos. Ocean. Phys., 2014, V. 50, № 3, P. 236-245)*





Vertical cross-section. Temperature isolines.

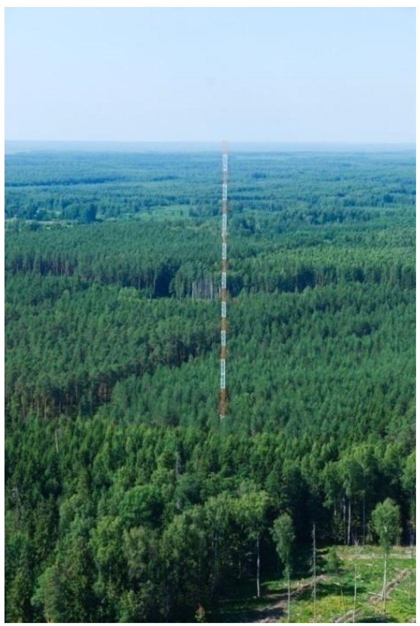


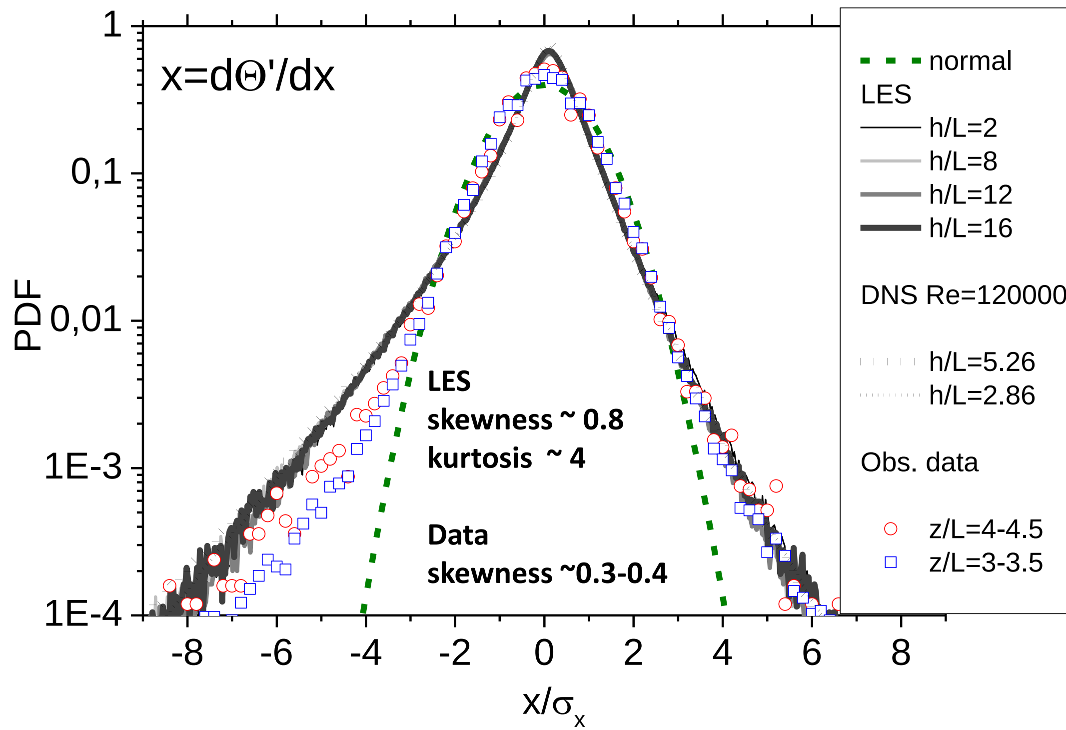
The existence of such layered structures in nature ?

The specific shape of PDFs of temperature gradients is indicative of its jumplike changes along the wind direction. This agrees with a representation of the temperature field as inclined layers with weak stratification, separated by thin sublayers with strong stratification.

SMEAR II (Station for Measuring Ecosystem-Atmosphere Relations), Finland

Measurements T′(t)
Height of sensor – 67 m
Frequency - 10 Hz





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Other confirmations of the existence of layered structures

Sullivan, P.P., Weil, J.C., Patton, E.G., Jonker, H.J. and Mironov, D.V., 2016. Turbulent winds and temperature fronts in large-eddy simulations of the stable atmospheric boundary layer. Journal of the Atmospheric Sciences, 73(4), pp.1815-1840.

Stably stratified Ekman layer (LES, ~10^9 grid points)

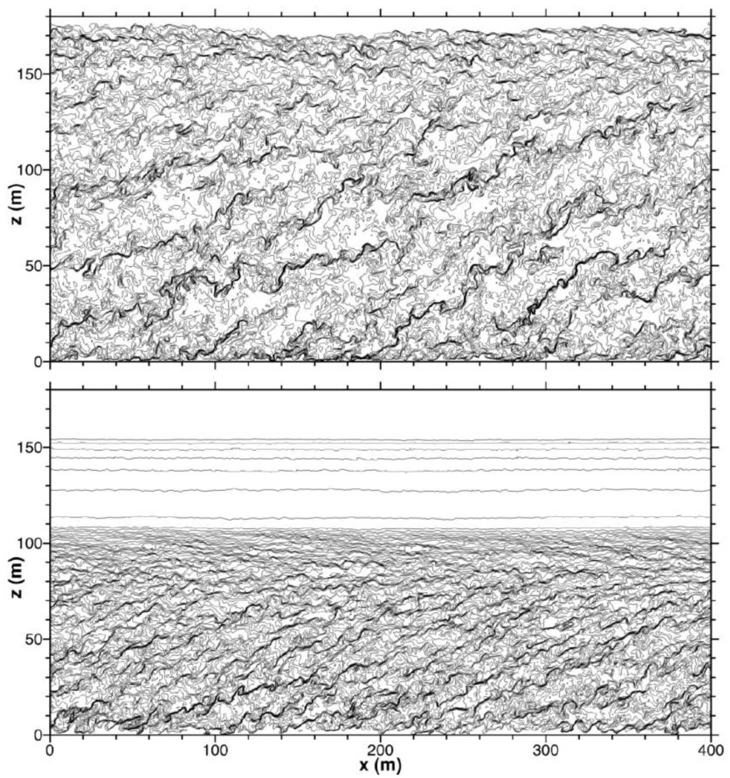
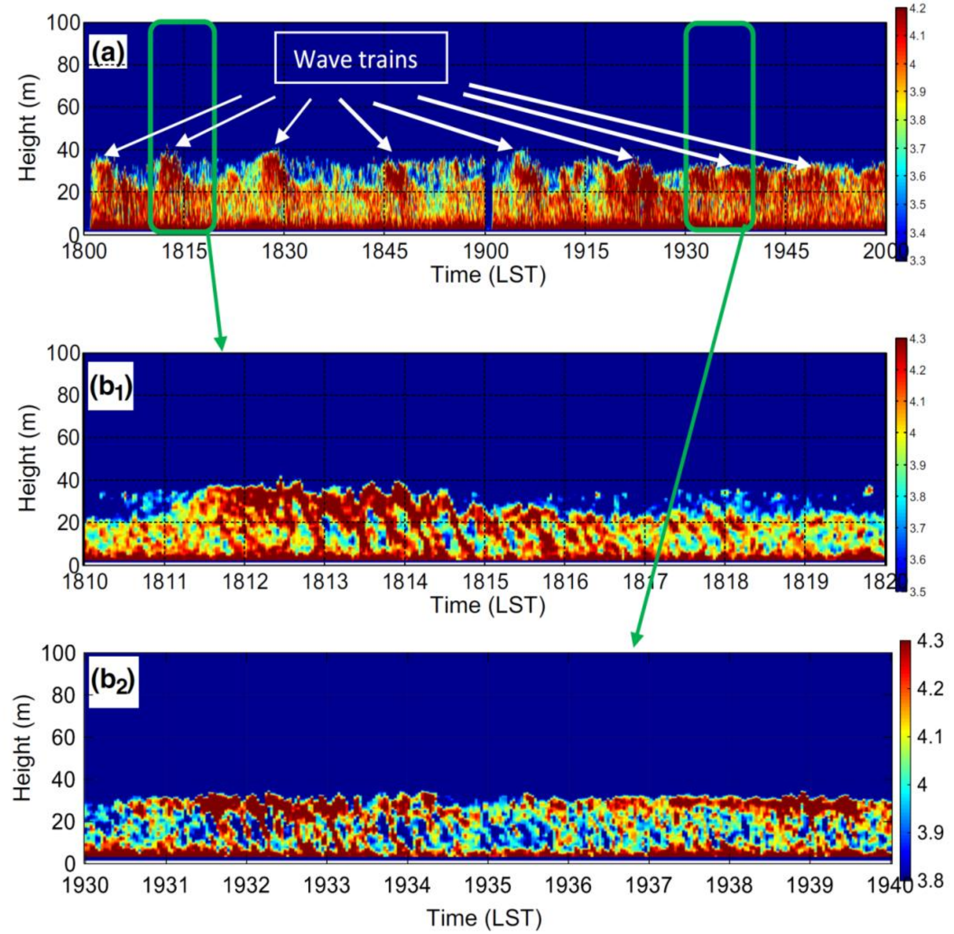


Figure 10: Contours of the temperature difference $\theta - \theta_o$ in an x-z plane at $y = 200$ m at $t \sim 9$ hrs. Upper panel stratification $z_i/L = 1.7$ (the same slice as in the upper panel of Fig. 9) with 71 equally spaced contour levels spanning the range $[-2, 0]$ K. Lower panel $z_i/L = 6.0$ with 101 contour levels spanning the range $[-8.0, 0.5]$ K. Notice how the tilt angle of the fronts is reduced with stronger stratification.

Petenko I., Argentini S., Casasanta G., Genthon C., Kallistratova M. Stable Surface-Based Turbulent Layer During the Polar Winter at Dome C, Antarctica: **Sodar and In Situ Observations** //Boundary-Layer Meteorology. – 2018. – C. 1-28.



Conclusion:

Large-scale layered structures are a common feature of stably stratified turbulent flows

Subjects for further investigations :

Mechanisms of structures arising

Spatial and temporal scales associated with structures

Influence of the large layered structures on the turbulence and on the heat and momentum transport

Turbulence at the large gradient Richardson number ?

$$Ri < 0{,}25$$

$$Ri = \frac{g/\Theta_0 (d\langle\Theta\rangle/dz)}{|d\langle\mathbf{u}\rangle/dz|^2}$$

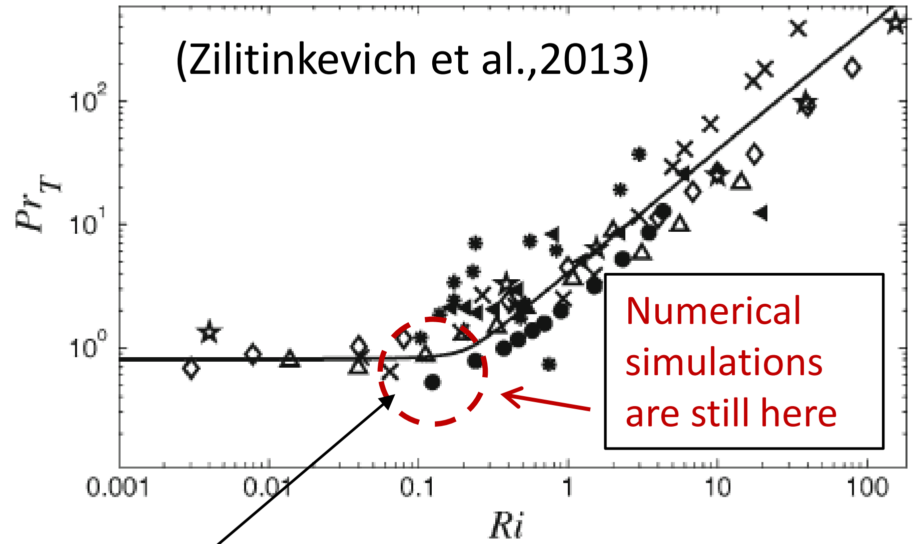
Miles–Howard criterion
(may be nonstrict due to nonlinear effects…)

$$Rf = \frac{gQ}{\Theta_0(\mathbf{S}\cdot\tau)}$$

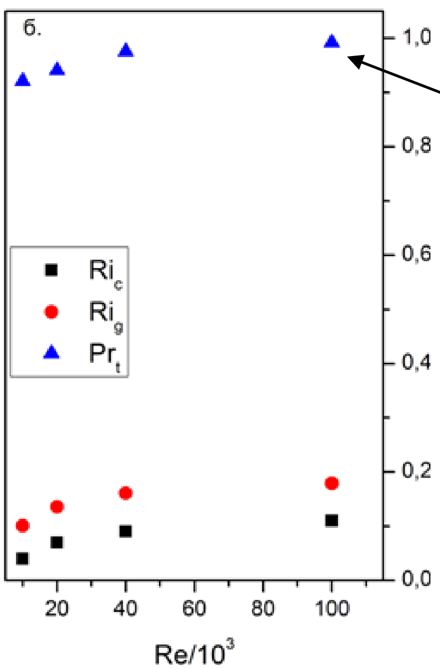
$$Rf < 1$$

TKE budget
(strict criterion)

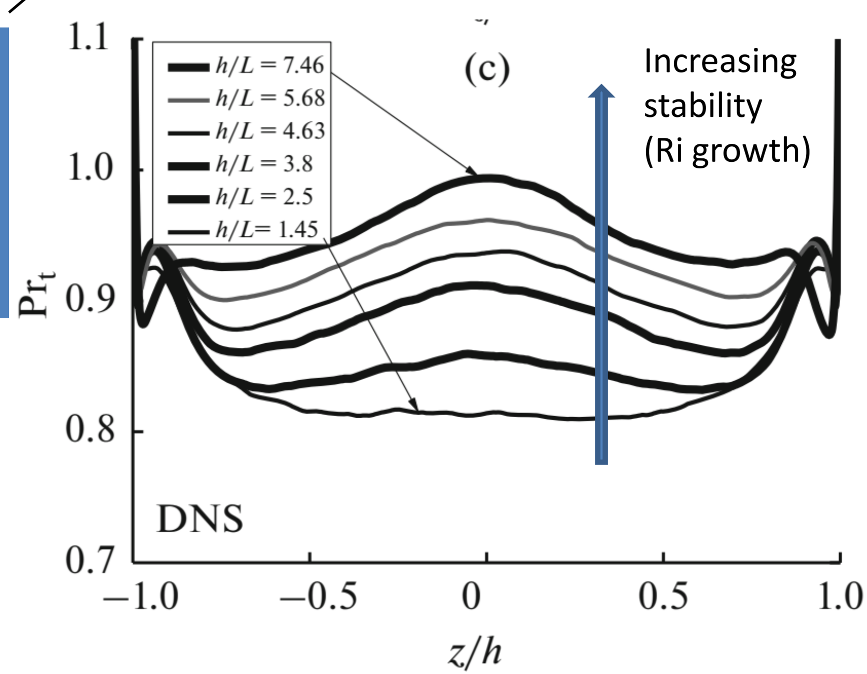
$$Pr = \frac{K_m}{K_h} = \frac{\phi_h}{\phi_m} = \frac{Ri}{Rf}$$



Increasing of *Pr* with *Ri* growth should be an indicator of maintaining turbulence



~10^8 grid nodes
Supercomputer
«Lomonosov 1»
MSU
~ 10^2 hours
~ 1000 cores



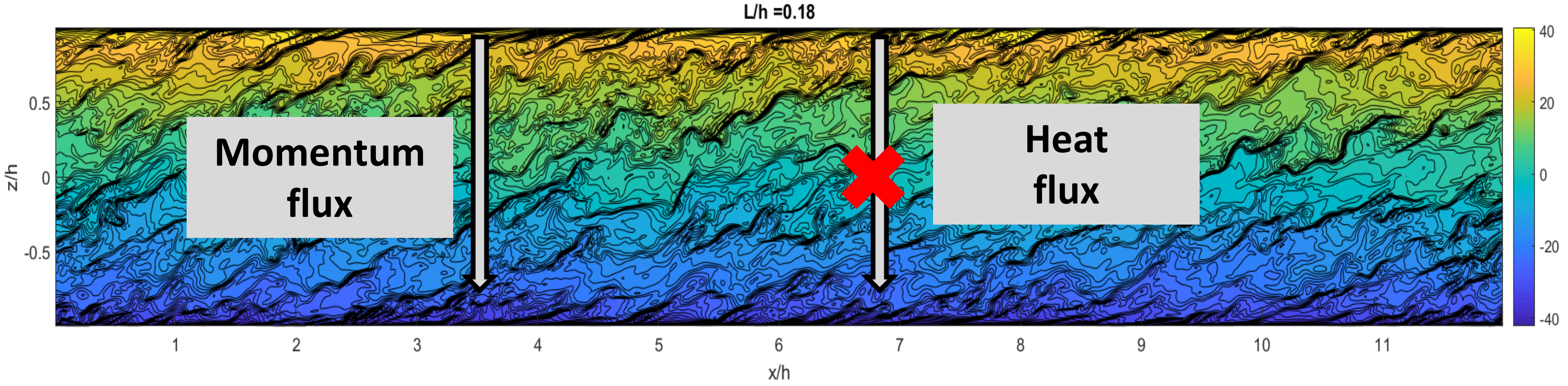
The DNS and LES results demonstrate an increase in the turbulent Prandtl number with increasing Ri.

It can be hypothesized that turbulence is self-organized and produces multilayered stratified fluid, so that:

the exchange of momentum between layers occurs mainly through its redistribution by pressure fluctuations,

while

the turbulent heat exchange, which requires air-mass mixing, is largely blocked.



Simplified linearised model of large scale disturbances in Couette flow:

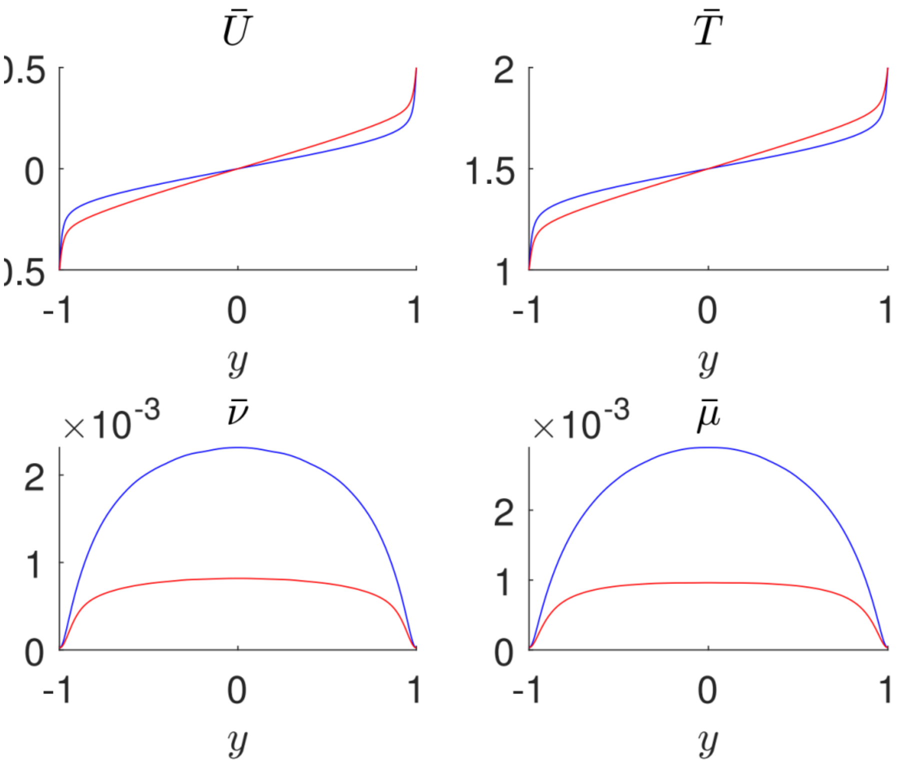
$$\frac{\partial u'}{\partial t} + \bar{U}\frac{\partial u'}{\partial x} + \frac{d\bar{U}}{dy}v' + \frac{\partial p'}{\partial x} - \Delta_\nu u' = 0$$

$$\frac{\partial v'}{\partial t} + \bar{U}\frac{\partial v'}{\partial x} + \frac{\partial p'}{\partial y} - \Delta_\nu v' - \mathrm{Ri}T' = 0$$

$$\frac{\partial w'}{\partial t} + \bar{U}\frac{\partial w'}{\partial x} + \frac{\partial p'}{\partial z} - \Delta_\nu w' = 0$$

$$\frac{\partial T'}{\partial t} + \bar{U}\frac{\partial T'}{\partial x} + \frac{d\bar{T}}{dy}v' - \Delta_\mu T' = 0$$

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} + \frac{\partial w'}{\partial z} = 0$$



Turbulent viscosity and diffusivity coefficients
(obtained from DNS data):

$$\bar{\nu}(y) = -\tau \Big/ \left(\frac{d\bar{U}}{dy}\right), \quad \bar{\mu}(y) = -F_T \Big/ \left(\frac{d\bar{T}}{dy}\right)$$

$$\tau = \overline{U'V'} - \frac{1}{\mathrm{Re}}\frac{d\bar{U}}{dy} \qquad F_T = \overline{T'V'} - \frac{1}{\mathrm{PrRe}}\frac{d\bar{T}}{dy}$$

disturbances:

$$u' = e^{\mathrm{i}\alpha x+\mathrm{i}\gamma z}u_{\alpha\gamma},\quad v' = e^{\mathrm{i}\alpha x+\mathrm{i}\gamma z}v_{\alpha\gamma},\quad w' = e^{\mathrm{i}\alpha x+\mathrm{i}\gamma z}w_{\alpha\gamma}$$

$$p' = e^{\mathrm{i}\alpha x+\mathrm{i}\gamma z}p_{\alpha\gamma},\quad T' = e^{\mathrm{i}\alpha x+\mathrm{i}\gamma z}T_{\alpha\gamma}$$

Energy norm:

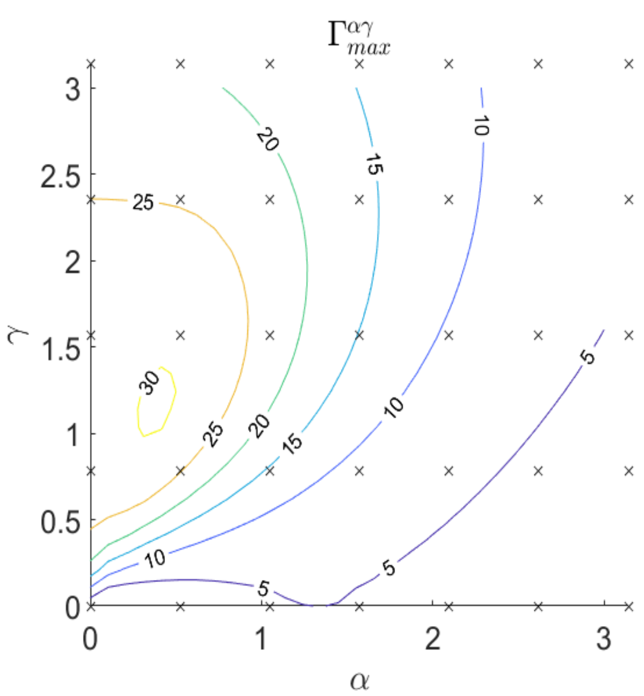
(kinetic + potential energy)

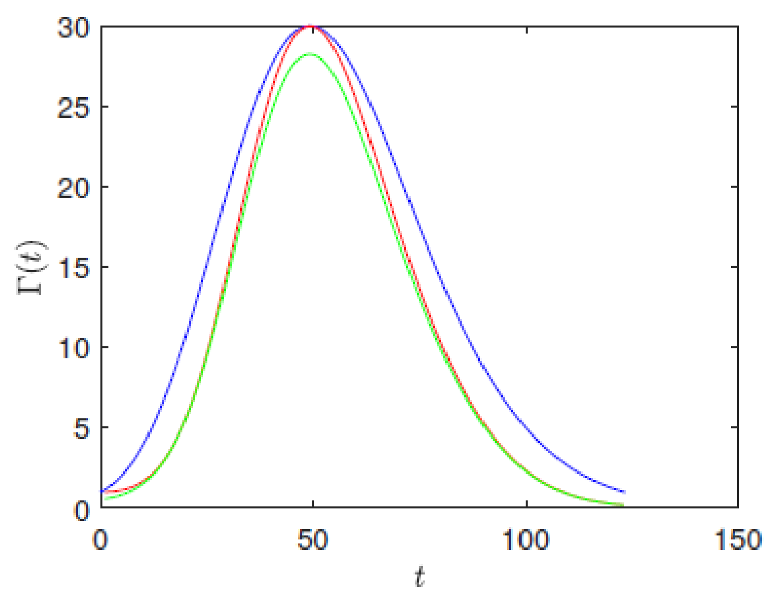
$$\mathcal{E}_t = \frac{1}{2}\int_{-1}^{1}\left(|u_{\alpha\gamma}|^2 + |v_{\alpha\gamma}|^2 + |w_{\alpha\gamma}|^2 + \frac{\mathrm{Ri}}{d\bar{T}/dy}|T_{\alpha\gamma}|^2\right)\,dy$$

The maximal possible growth:

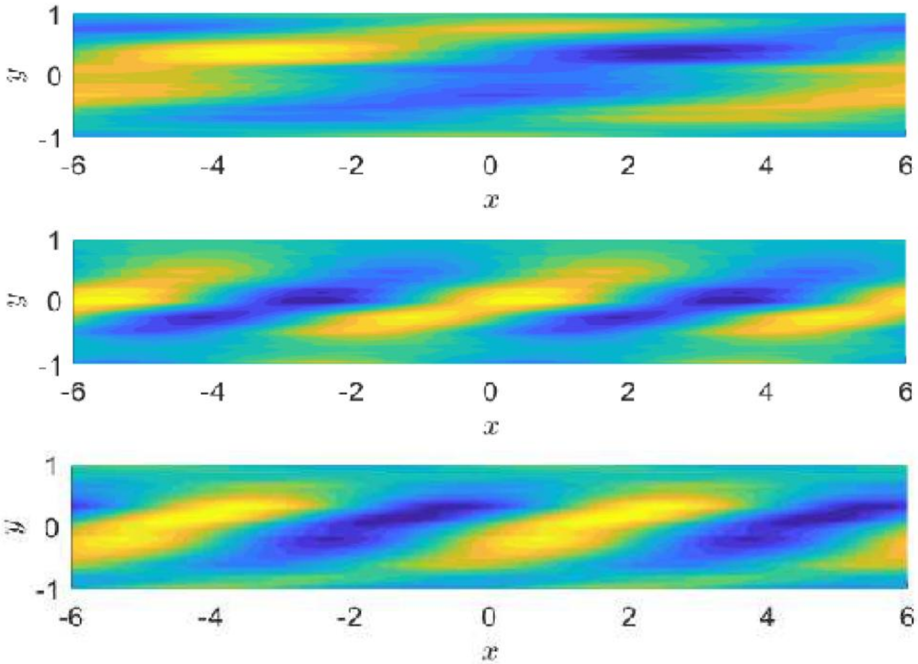
$$\Gamma^{\alpha\gamma}_{\max} = \max_{t\geq 0}\max\frac{\mathcal{E}_t}{\mathcal{E}_0}$$

The disturbances for which $\Gamma^{\alpha\gamma}_{\max}$ are attained - **the optimal disturbances**

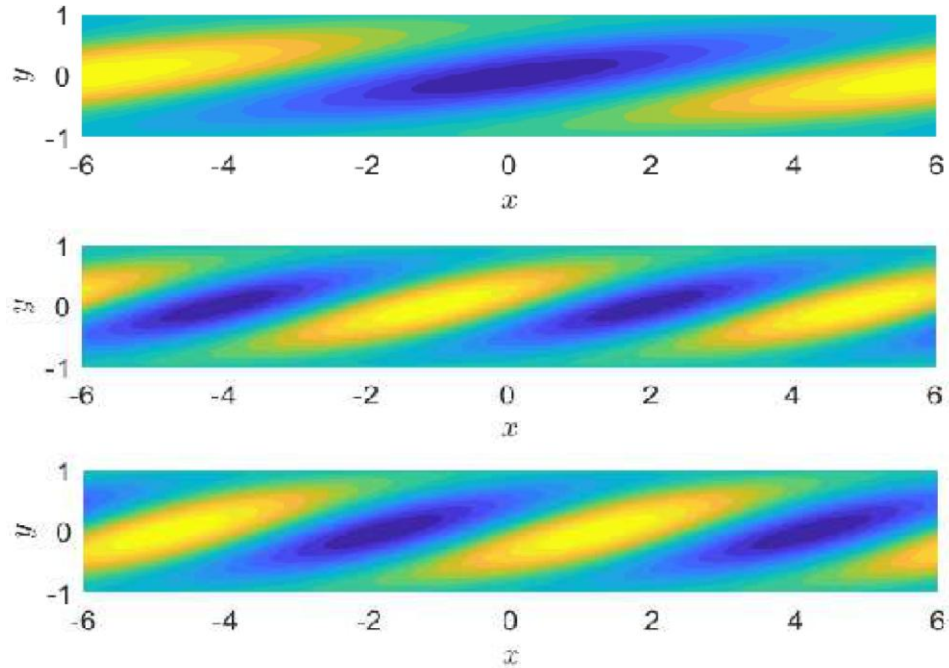




Large-scale harmonics obtained from DNS temperature field:



Correspondent optimal disturbances at the moment of maximal growth:



Glazunov A.V., Zasko G.V., Mortikov E.V., Nechepurenko Yu.M., Optimal disturbances of stably stratified turbulent Couette flow // Doklady Physics, 2019, V. 487, N. 3, P. 308-312.

Zasko G.V., Glazunov A.V., Mortikov E.V., Nechepurenko Yu.M., Large-scale structures in stratified turbulent Couette flow and optimal disturbances // Russ. J. Numer. Anal. Math. Modelling, 2020, V. 35, N. 1, P. 37-53.

Conclusion:

Layered structures observed in the stably stratified turbulent flow have spatial scales and configurations coinciding with the scales and configurations of optimal disturbances of the linear model.

Subjects for further investigations :

Mechanisms of arising of thin layers with large temperature gradients. Nonlinearity?

Temporal statistic of large-scale optimal disturbances generation in multiscale turbulent flow. (additional specialized hi-Re DNS runs are needed)