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Why turbulence sustains in the 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: $1 \ll Ri < 10^3$. 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 function 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 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 stratification.