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Why turbulence sustains in supercritically stratified free atmosphere?

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It is widely believed that in very stable stratifications, at Richardson numbers (*Ri*) exceeding critical value $Ri_c \sim 0.25$ turbulence decays and flow becomes laminar. This is so at low Reynolds numbers (*Re*), e.g., in lab experiments; but this is not true in very-high-*Re* geophysical flows. Free atmosphere and deep ocean are turbulent in spite of strongly supercritical stratifications: $1 << Ri < 10^3$. Until recently, this paradox remained unexplained.

The Energy- and Flux-Budget (EFB) turbulence-closure (Zilitinkevich et al., 2013) has disclosed the following turbulence self-control mechanisms. Until recently, the role of negative buoyancy flux, $F_b > 0$, in turbulence energetics was treated in terms of the turbulent kinetic energy (TKE) budget equation and understood as just consumption of TKE by the buoyancy forces. This has led to the conclusion that sufficiently strong static stability causes the negative buoyancy flux sufficiently strong to exceed the TKE generation rate and thus to kill turbulence. However, considering TKE equation together with budget equation for turbulent potential energy (TPE proportional to the squared buoyancy fluctuations) shows that the role of F_b in turbulence energetics is nothing but conversion of TKE into TPE (F_b just quantifies the rate of this conversion); so that F_b does not affect 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. Indeed, the warmer fluid particles (with positive buoyancy fluctuation) rise up, whereas the cooler particles sink down, so that both contribute to the positive buoyancy flux opposing to the usual, negative flux generated by mean buoyancy 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 reduces $|F_b|$ and, eventually, increases TKE.

The above negative feedback was disregarded in the conventional concept of down-gradient turbulent transport. This mechanism imposes a limit on the maximal (independent of the buoyancy gradient) value of $|F_b|$ and thus prevents degeneration of turbulence.

The EFB theory has predicted that the critical Richardson number, $Ri_c \sim 0.25$, characterising the hydrodynamic instability limit and the turbulent-laminar flow threshold at low Reynolds numbers, remains a principal threshold also 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 remaines 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 sharply increases with increasing *Ri* (asymptotically as $Pr_T \approx 5\ Ri$).

This theoretical finding fits well with experimental evidence. Modellers long ago knew that turbulent heat transfer in the free atmosphere should be taken much weaker than the momentum transfer. The EFB theory gives authentic formulation for this rule and provides physically grounded method for modelling turbulence up to very stable startifications.