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Physics and energetics of turbulent mixing in stratified fluids

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Turbulent mixing is a key process in stratified fluids, which in the ocean is responsible for the downward transfer of heat that is necessary to counteract the cooling of the deep ocean by high-latitude deep water formation. It is also the main mechanism responsible for the vertical dispersion of tracers in a stable stratification. In the context of climate modelling, its importance stems from key aspects of the ocean circulation such as the poleward heat transport and meridional overturning circulation being very sensitive to its representation. Because the intensity of mixing depends on the energy sources responsible for the stirring, which may be affected by climate change, there has been much interest lately in developing energetically consistent mixing parameterisations. This is complicated, however, because the energetics of turbulent stratified mixing remain poorly understood and controversial. For instance, it is often said and assumed that turbulent mixing raises the centre of the gravity of the fluid. Physically, it is widely accepted that such an increase of the centre of gravity occurs at the expenses of the available potential energy (APE) dissipated by turbulent molecular diffusion. That such an explanation is valid is unclear, however, because it is easy to construct counter-examples of stratification for which the centre of gravity of the fluid decreases at a rate that is negatively correlated to the rate at which APE is dissipated. Moreover, how the dissipated APE is supposed to increase the centre of gravity is unclear, because it is in general a much smaller source of diabatic heating than the viscously dissipated kinetic energy. Physically, viscous dissipation increases the centre of gravity via the expansion resulting from the resulting Joule heating, but the effect is generally accepted to be negligibly small, so logically, the expansion resulting from the dissipated APE should be even smaller. The main aim of this work is to argue that changes in background gravitational potential energy primarily results from the competition between the expansion/contraction of the lower/upper part of the fluid resulting from the warming/cooling associated with the relaxation towards homogeneous potential or in-situ temperature. In the Boussinesq limit, the volume contracts less than it expands with the total volume remaining approximately constant, which is why the centre of gravity is observed to increase. For a strongly nonlinear equation of state for which the thermal expansion increases with temperature, however, contraction can dominate over the expansion, making it possible for the centre of gravity to decrease. It follows that the physics of the changes in gravitational potential energy is dominated by compressibility effects and conversions with internal energy, in contrast to what has been usually assumed so far, with profound implications for the development of energetically-consistent mixing parameterisations.