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Nonlinear Multiscale Modelling of Layering in Turbulent Stratified Fluids

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One of the most fascinating, and surprising, aspects of stratified turbulence is the spontaneous formation of density staircases, consisting of layers with nearly constant density, separated by interfaces with large density gradients. Within a staircase, there are two key lengthscales: the layer depth, and the interface thickness. Density staircases appear in regions of the ocean where the overall stratification is stable, and can be induced experimentally by stirring a fluid with a stable salt gradient. Staircases also appear as a result of double diffusive convection, in both oceanic and astrophysical contexts. Turbulent transport through staircases is enhanced compared to non-layered regions, so understanding their dynamics is crucial for modelling salt and heat transport.

Progress has been made numerically and experimentally, but the fundamental aspects of the problem are not yet fully understood. One leading theory is the Phillips Effect: layering occurs due to the dependence of the turbulent density flux on the density gradient. If the flux is a decreasing function of the gradient for a finite range of gradients, then negative diffusion causes perturbations to grow into systems of layers and interfaces.

An important extension of the Phillips theory is by Balmforth, Llewellyn-Smith and Young [J. Fluid Mech., 335:329-358, 1998], who developed a k-ε style model of stirred stratified flow in terms of horizontally averaged energy and buoyancy fields. These fields obey turbulent diffusion equations, with fluxes depending on a mixing length. The parameterisation of this lengthscale is key to the model, as it must pick out both layer and interface scales. This phenomonological model parameterises terms based on dimensional arguments, and neglects diffusion for simplicity. This model produces clear density staircases, which undergo mergers where two interfaces combine to form one. Layers take up the interior of the domain, while edge regions on either side expand inwards at a rate of $t^{1/2}$, removing layers from the outside in. Eventually the edge regions fill the entire domain, so the long time behaviour of the layers cannot be seen.

We present a similar model for stirred stratified layering derived directly from the Boussinesq equations, including molecular and viscous diffusion, so the model can be tailored to specific conditions to make realistic predictions. We show that the layered region can evolve indefinitely through mergers, by taking fixed-buoyancy boundary conditions to prevent the expansion of the edge regions. We investigate the effects of diffusion on layer formation and evolution, finding that it acts to stabilise the system, both by decreasing the range of buoyancy gradients that are

susceptible to the layering instability, and by decreasing the growth rates of perturbations. The lengthscale of the instability also increases, with larger viscosities and diffusivities producing deeper layers with less sharp interfaces.

This model can be used as a more general framework for layering phenomena. Extending to equations for energy, temperature and salinity can model double diffusive layering. More general parameterisations for the fluxes allow it to be adapted to other settings, including potential vorticity staircases in atmospheres and **E**×**B** staircases in plasmas.