We study the restratification of the oceanic surface mixed layer that results from lateral inhomogeneities in the surface density field. Mixed layer models are quite successful at reproducing the deepening of the mixed layer, but the restratification phase is not well understood and model bias is especially large when there are horizontal variations in the density field. These lateral inhomogeneities give way to ageostrophic baroclinic instabilities which dump the horizontal density gradients under the effect of rotation. These mixed-layer instabilities (MLI) differ from ocean interior instabilities because of the weak surface stratification, and the fact that their lower ‘boundary’ is a density jump in the transition layer between the mixed layer and the ocean interior. Spatial scales are O(1-10 km) and growth rates are faster than a day. We use both linear stability analysis and fully nonlinear simulations to study the impact of MLI on mixed layer restratification. Finally we discuss the issue of parameterization of MLI-driven restratification in mixed layer models.

The ocean mixed layer (ML) is a layer of weak stratification in the upper 100 m overlying the more stratified thermocline. The ML is not horizontally homogeneous: there are numerous lateral density gradients that are in geostrophic balance with a sheared velocity \( U = f \cdot \nabla z \). This is sketched out in Figure I.4, where we show the ocean interior (top panel) and its mixed layer (bottom panel). In the ML, the density surfaces suffer a gravitational settling, driven by the surface wind stress (solid = quasi-geostrophic, dashed = Stone (1971) ageostrophic estimate).

Initially, the density surfaces drop gravitationally into an inertial oscillation about the state where the density anomaly \( \rho \) is zero. This stage of the adjustment is detailed by Tandon and Garrett (1994) and Ou (1984). The first two snapshots show the range of this oscillation in our simulation. However, this oscillating state is not stable to MLI. Initially they grow as Eady (1949)-like waves much as predicted by the preceding analysis and with the ageostrophic growth rates due to Stone (1971). Day 8.5 above shows these waves nicely. The waves extract available potential energy from the mean stratification and drive a straining/restratification of the initial front.

The restratification is enhanced as the waves reach finite amplitude and begin to nonlinearly interact strongly. The fully nonlinear waves are shown at day 25 above. Note that their length-scale has increased dramatically, as expected from an inverse energy cascade.

The following figure shows the restratification process for a weak front (0.1K/10km) and a strong front (0.5K/10km). Note the initial inertial oscillations and the significantly stronger restratification that occurs as the MLI develop. The effect of restratification by MLI may be parameterized by a Gent and McWilliams (1990) parameterization. However unlike in the ocean interior where a diffusivity of \( O(1000 \text{ m}^2/\text{s}) \) is appropriate, we see that for MLI, \( O(10-100 \text{ m}^2/\text{s}) \) is better. Previous attempts to use Gent and McWilliams (1999) too rapidly restratified the ML, but they used interior values of Gent-McWilliams diffusivity rather than MLI diffusivity values. Still, the implied magnitude of MLI’s vertical eddy heat flux is significant compared to other mixed layer processes (e.g., diurnal-average surface fluxes and entrainment \( O(100 \text{ W/m}^2) \)).

Eddy statistics from two nonlinear calculations with different initial front strengths.