

Imbalance and energy cascades.

The kinetic energy in the general circulation of the ocean is forced mainly at large space and long time scales, yet it must be viscously dissipated at very small scales in equilibrium. Large- and mesoscale circulations typically satisfy a momentum-balanced dynamics (e.g., geostrophy and its generalizations). Yet balanced turbulent cascades are very inefficient in energy dissipation. This leads to the fundamental question of how the necessary dissipation is accomplished for the general circulation in equilibrium.

We are investigating a possible local route to dissipation through interior, turbulent cascade dynamics of the circulation. In Oceanic General Circulation Models, the local route to dissipation is implied by the use of *ad hoc* horizontal and vertical eddy viscosities to parameterize this cascade, and the associated interior dissipation rate is a substantial fraction of the volume integrated total.

There are explicitly specifiable limits to the regime of validity for balanced dynamics. Violation of these limits leads to energy transfer at intermediate spatial scales from balanced to unbalanced motions, including inertia-gravity waves.

Unbalanced turbulent cascades are much more efficient in their energy dissipation and spatial radiation causing energy redistribution. Thus, the important bottleneck in the local route for general-circulation dissipation is loss of balance and its evolutionary consequences. This bottleneck is the focus of our research.

We have demonstrated the occurrence of several unbalanced, linear instabilities near the limits of balanced validity. As a next step we determined their finite-amplitude evolutionary behavior, including the cascade to dissipation. We use computational models based on different dynamical approximations, in order to help distinguish among different mechanisms of forward energy cascades. In this talk we will discuss the nonlinear equilibration of a forced, unstable homogeneous vertical shear flow that is in thermal wind balance. We will compare the very different dynamics of a model based on the QG equations and a Boussinesq model. The Boussinesq model exhibits constant rates of mixing and dissipation when, with increasing resolution, the eddy viscosities and diffusivities are reduced to smaller and smaller values. This is being accomplished by means of unbalanced motions and a forward energy cascade. This remains true even when the overall Rossby number of the basic state is small. In that case, dissipation and mixing events are concentrated in intermittent, localized areas of the flow

where the Rossby number reaches $\mathcal{O}(1)$ values. In contrast, the QG model becomes less and less efficient in mixing and dissipation of energy. Unlike the Boussinesq model, the QG dissipation efficiency becomes negligible in the limit of large resolution and small eddy viscosities.