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Breaking the Balance: Mechanisms of Oceanic Kinetic Energy Transfers from Geostrophic to Ageostrophic Motions

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Abstract

Oceanic kinetic energy (KE) cascades critically depend on the mechanisms by which oceanic mesoscale eddies forfeit balance and channel energy into submesoscale turbulence and the internal wave (IW) continuum. Yet the sequence of processes that dismantles this balance and mediates the ensuing downscale flux is still not well understood. This dissertation places loss of balance (LOB) at centre stage, interrogating three dynamical gateways — (i) front–IW energy exchanges, (ii) mixed-layer (ML) frontal instability, and (iii) the radiative instability of mesoscale vortices — to quantify their efficiency in exporting mesoscale KE to smaller, dynamically active scales.

First, we diagnose KE pathways using an idealised configuration that couples a 2D front undergoing strain-induced semigeostrophic frontogenesis and IW vertical modes. Near-inertial waves (NIWs) trapped inside the sharpening frontal zone siphon mesoscale kinetic energy through divergent-shear production; that energy is subsequently routed into the unbalanced ageostrophic secondary circulation via ageostrophic-shear production. As the front sharpens and horizontal convergence of the ASC intensifies, the newly identified convergent-production (CP) term emerges as the dominant energy exchange term, allowing NIWs to extract frontal KE directly and thereby accelerating LOB. The prominence of CP explains the enhanced transfer of KE from balanced motions to IWs observed in surface-intensified frontal zones of realistic ocean simulations.

Second, a linear stability analysis of geostrophically adjusted, zero-potential vorticity (PV) fronts maps how finite Rossby number effects reshape ML instability. Classical baroclinic modes prevail when $Ro \ll 1$, but a resonance between a Rossby wave and an inertia-gravity wave (IGW) gives rise to an inertia critical layer (ICL) instability mode of comparable growth rate. Because the ICL taps IGW, it provides a direct conduit through which balanced KE is converted into unbalanced KE, thereby motivating and quantifying the onset of LOB. At this stage, shear production rivals buoyancy flux in the

perturbation energy budget, signalling that shear-driven pathways must be represented in ML parameterizations.

Finally, high-resolution, wind-forced channel simulations reveal the spontaneous emission of spiral-shaped IWs from an O(1) Rossby number anticyclonic mesoscale eddy. A 2D linear stability analysis demonstrates that this emission is driven by a radiative instability involving a vortex-Rossby mode that resonates with an outward-propagating IW. This hybrid Rossby–IW mode renders the balanced vortex energetically leaky, channelling mesoscale KE into the high-frequency IW continuum and thereby leading to LOB. Together, these pathways divert the mesoscale KE into submesoscale motions and the IW continuum, and therefore offer a compact, process-based recipe for representing LOB fluxes in large-scale ocean and climate models.