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Internal wave turning depths in the oceans (Lewis Fry Richardson Medal Lecture)

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Tidal flow over the continental shelf break and ocean bottom topography generates internal gravity waves ("internal tides") that account for a significant part of the energy budget of the oceans and hence play a role in determining climate. Internal tides propagate at an angle θ with respect to the horizontal, where (neglecting Coriolis effects) sinθ = ω/N (where ω = tidal frequency and N = Brunt-Väisälä buoyancy frequency). Our group's laboratory experiments reveal that intense resonant boundary currents occur when the angle θ matches the local topographic slope angle. This resonant condition is approximated well along the continental slopes of the oceans, which may explain why the continental slope angles are typically only a few degrees, much less than the angle of repose. To determine how the local buoyancy frequency N(z) varies with depth z, we have examined data from the World Ocean Circulation Experiment (WOCE). An analysis of the more than 18000 WOCE data sets for temperature(z) and salinity(z) reveals the existence at many locations of "turning depths": depths below which the M2 semi-diurnal internal tides cannot propagate. Below a turning depth (typically 4-5 km), an internal tide becomes exponentially damped and hence does not reflect and scatter from the ocean floor as is often assumed. We will also present results from numerical simulations of the Navier-Stokes equations and laboratory experiments on internal wave reflection, propagation, and tunneling for tidal flow over topography that lies below a turning depth. While experiments and models yield insights into internal wave dynamics, many important phenomena such as wave breaking and mixing remain poorly understood, thus providing challenges for future research.