Multi-scale research on 3D dynamics of nonlinear internal wave and topography interaction

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Introduction

Nonlinear internal waves (NLIWs) are multi-scale phenomenon generated from basin-scale tidal and seiche motions acting over 10s to 100s of km (e.g., Jackson 2007; Boegman et al 2003). They steepen and propagate with 0.1 to 1 km wavelengths (e.g., Horn et al 1999; Boegman et al 2003; Klymak and Moum 2003) and degenerate in 0.1 to 100 cm turbulent eddies (Boegman and Ivey 2009; Barad and Fringer 2010). Numerical modeling of NLIWs across these scales and in three-dimensions (3D) remains a challenge (Horn et al 1999; Hodges et al 2000; Boegman and Dorostkar 2011; Dorostkar 2012), causing many lab and numerical studies to be limited to two dimensions (2D). In the present research, we investigate the 3D generation and propagation of NLIWs, at multiple scales, using massively parallel high-resolution numerical simulations and idealized laboratory experiments.

Numerical Simulations

We apply hydrostatic and nonhydrostatic versions of the MITgcm to Cayuga Lake for an 11-day wind forced simulation with mixing with coefficients as given in Dorostkar (2012) and Boegman and Dorostkar (2011). Simulations are done with 22 m, 40 m, 113 m and 454 m horizontal grid spacing and 98 non-uniformly spaced z-levels ranging from 0.5 m to 2.95 m using an unprecedented 226 million computational cells.

The model accurately reproduced the basin-scale seiche motions (Dorostkar et al 2010). As the grid was refined, the nonhydrostatic model converged with the evolving solitary waves having almost unchanged wavelengths. Conversely, the hydrostatic simulations produced a packet of spurious high-frequency solitary-type waves with grid dependent wavelengths; representing a balance between nonlinear steepening and numerical, as opposed to physical dispersion. Computation of grid leptic ratio (λ, Vitousek and Fringer 2011) and ratio of real-time to run-time for the various grids shows the 40 m grid (λ=2) to provide a reasonable balance between the need to minimize nonhydrostatic computational overhead as well as capture physical dispersion (Dorostkar 2012; Dorostkar et al 2013). Simulations on the 113 m grid were dominated by numerical dispersion (λ=6), while those on the 22 m grid had unreasonable runtimes (nonhydrostatic runtime = 13 × hydrostatic runtime). Despite the quasi-2D domain, the NLIW dynamics were found to be fundamentally 3D, refracting and reflecting of headlands and variations in the lake cross-section (Boegman and Dorostkar 2011).

Laboratory Experiments

Experiments were conducted in the 6m×0.75m×0.65m glass-walled flume, filled with a two-layer fresh and saline water stratification (Aghsaee 2011), with waves being generated via lock release. The tank was equipped with a Nortek Vectrino II profiling acoustic Doppler velocimeter and a LaVision stereo Particle Image Velocimetry system.

The NLIWs were found to degenerate through global instability, where the induced eddies are 3D in nature. Transverse velocity fluctuations are observed at the onset of global instability, but are up to 6 times smaller than vertical velocity fluctuations (w'). In comparison to 2D numerical simulations (Aghsaee et al 2012), both w' and the height to which eddies propagate (h) are smaller in the 3D lab flow ($w'/c_0 \sim 0.7$ and h/H=0.35 in 2D vs. $w'/c_0 \sim 0.1$ and h/H=0.2 in 3D, where H is the water depth and c_0 the linear phase speed) confirming momentum transfer and enhanced dissipation along the transverse dimension (e.g., Fringer and Street 2003). The global instability process was observed to trigger sediment resuspension. Bed stress was elevated beneath the wave trough and through the turbulent wake; however, sediment resuspension was only observed within the wake, where vertical turbulent velocities were able to lift particles into the water column. Similar results have been observed where NLIWs break on sloping topography (Boegman and Ivey 2009; Aghsaee et al 2010). Our results suggest that this NLIW resuspension process may be parameterized with the Shileds parameter.

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