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Modeling basin-scale internal waves in a stratified lake

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Abstract

Basin-scale internal waves provide the driving forces for vertical and horizontal fluxes in a stratified lake below the wind-mixed layer. Thus, correct modeling of lake mixing and transport requires accurate modeling of basin-scale internal waves: examining this capability with a hydrostatic, *z*-coordinate three-dimensional (3D) numerical model at coarse grid resolutions is the focus of this paper. It is demonstrated that capturing the correct thermocline forcing with a 3D mixed-layer model for surface dynamics results in a good representation of low-frequency internal wave dynamics. The 3D estuary and lake computer model ELCOM is applied to modeling Lake Kinneret, Israel, and is compared with field data under summer stratification conditions to identify and illustrate the spatial structure of the lowest-mode basin-scale Kelvin and Poincaré waves that provide the largest two peaks in the internal wave energy spectra. The model solves the unsteady Reynolds-averaged Navier–Stokes equations using a semi-implicit method similar to the momentum solution in the TRIM code with the addition of quadratic Euler–Lagrange discretization, scalar (e.g., temperature) transport using a conservative flux-limited approach, and elimination of vertical diffusion terms in the governing equations. A detailed description is provided of turbulence closure for the vertical Reynolds stress terms and vertical turbulent transport using a 3D mixed-layer model parameterized on wind and shear energy fluxes instead of the convential eddy viscosity/diffusivity assumption. This approach gives a good representation of the depth of the mixed-layer at coarse vertical grid resolutions that allows the internal waves to be energized correctly at the basin scale.

Wind stresses, surface heating, and density currents form the driving energy fluxes of a stratified lake. The basin-scale energy flux from the wind is of particular interest because of its dominant role in setting the thermocline in motion, which, in the absence of inflows and outflows, is the primary energy store for transport and mixing below the wind-mixed layer. Thus, modeling the basin-scale internal wave behavior is an a priori requirement to modeling and quantifying the flux paths of nutrients in a stratified lake (Imberger 1994). This paper takes a first step in this direction by analyzing our ability to model basin-scale internal waves that are seen in Lake Kinneret, Israel.

Energy flux path in a stratified lake—Energy flux through a stratified lake has a fundamental dependence on forced and free baroclinic motions. The wind imparts both momentum and turbulent kinetic energy (TKE) to the water in the surface layer. The TKE distributes momentum vertically in the water column, initiating downwind transport in the surface layer, which results in metalimnion depression at the downwind end and upwelling at the upwind end (for general discussion, *see* Mortimer 1974; Imberger and Patterson 1990). When the wind duration exceeds one quarter of the basin-scale internal wave period, the forced metalimnion tilt overshoots the equilibrium position (i.e., the balance between barotropic and baroclinic tilts), resulting in a long internal wave response (Heaps and Ramsbottom 1966). If the horizontal length scales are larger than the internal Rossby radius of deformation, the response will be rotational Kelvin and Poincaré waves (Csanady 1967) whose evolution is modified by nonlinear wave steepening (Bennett 1973; Farmer 1978), topography (Romea and Allen 1984; Thorpe 1998), wave–wave interaction (Phillips 1977 §5.4), and dissipation (Hopfinger 1987; Imberger and Ivey 1991; Ivey and Imberger 1991). The episodic nature of wind events allows internal waves to develop into a symphony of free and forced internal waves at a variety of scales that may be affected by resonance between periodicity of wind forcing and the waves' natural frequencies. Finally, there is a feedback loop between the internal wave field and stratification: vertical mixing, energized by internal waves, changes the stratification, which, in turn, changes the dynamics of the internal waves (Imberger 1994).

Boundary layers and mixing by internal waves—Recent evidence shows that seiching by long-period, basin-scale waves in a stratified lake generates a turbulent benthic boundary layer that can be many meters thick in the hypolimnion (Lemckert and Imberger 1998). At the other end of the spectrum, it has been demonstrated in laboratory settings that higher-frequency waves with short horizontal wavelengths break on sloping boundaries and lose most of their energy (Ivey and Nokes 1989; DeSilva et al. 1997; Michallet and Ivey 1999). The resulting boundary layer turbulence en-

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