Limnol. Oceanogr., 48(3), 2003, 983–994
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Modeling circulation in lakes: Spatial and temporal variations

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Abstract

The influence of spatial and temporal variations in wind forcing on the circulation in lakes is investigated using field data and the three-dimensional Estuary and Lake Computer Model (ELCOM) applied to Lake Kinneret. Lake Kinneret field data from six thermistor chains and eight wind anemometers deployed during July 2001 are presented. Internal wave motions are well reproduced by the numerical model when forced with a spatially uniform wind taken from a station near the lake center; however, simulated seiche amplitudes are too large (especially vertical mode 2) and lead observations by 3–10 h (for a 24-h period wave) at different locations around the lake. Consideration of the spatial variation of the wind field improves simulated wave amplitude, and phase error at all stations is reduced to less than 1.5 h. This improvement is attributable to a better representation of the horizontally averaged wind stress and can be reproduced with a spatially uniform wind that has the same horizontally averaged wind stress as the spatially varying wind field. However, a spatially varying wind field is essential for simulating mean surface circulation, which is shown to be predominantly directly forced by the surface-layer–averaged wind stress moment.

Wind blowing over a lake surface forms a highly turbulent surface mixing layer. Turbulence rapidly distributes momentum, transferred from wind to water, over the depth of this layer such that (initially) the surface water moves downwind as a slab (Spigel and Imberger 1980). Basin-scale, wind-induced motions depend on interactions of spatially and temporally varying wind forcing with bathymetry, density distribution, and the earth's rotation. These motions include basin-scale internal waves driven by temporal variations in wind stress and basin-scale mean circulation driven by spatial variations in wind stress (direct circulation) or by rectification of internal wave motions (residual circulation) (Strub and Powell 1986). Energy from basin-scale motions is dissipated via turbulent mixing at the lake boundary or by shear in the lake interior when there is density stratification (see Imberger [1998] for a review).

During summer months, Lake Kinneret in Israel is highly temperature stratified and strongly forced by a daily sea breeze. The resulting basin-scale internal seiches are dominated by a vertical mode 1, 24-h–period Kelvin wave, accompanied by 12- and 20-h Poincaré waves in both vertical modes 1 and 2 (Antenucci et al. 2000). Using analytic and numerical methods, Ou and Bennett (1979) showed that the mean cyclonic surface-layer circulation could be explained using a spatially uniform wind and, hence, could be classified as residual circulation. More recently, Pan et al. (2002) used the surface wind field predicted by a three-dimensional (3D) atmospheric model to force a 3D hydrodynamic model of Lake Kinneret. They showed that the curl of the wind stress could account for the simulated depth-averaged vorticity and, hence, that the mean circulation in Lake Kinneret is direct. Numerical model results presented in this article confirm the interpretation of Pan et al. (2002).

This work considers the effects of spatial and temporal variability in the wind field on basin-scale motions in lakes. We begin with a description of the numerical methods used to reproduce the internal wave field in Lake Kinneret. We then show that the next model skill level for representing evolution of the dynamic density field in a lake requires both

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Acknowledgments

The first author was the recipient of an international postgraduate research scholarship and a University of Western Australia postgraduate award. The field experiments were funded by the Israeli Water Commission, via the Kinneret modeling project, conducted jointly by the Kinneret Limnological Laboratory and the Centre for Water Research. The support of the Kinneret Limnological Laboratory and Centre for Water Research field staff is gratefully acknowledged. The authors thank Jason Antenucci and Robert Spigel for comment on an earlier version of this manuscript. Ben R. Hodges was partially supported by an Office of Naval Research Young Investigator Program Award, grant N00014-01-1-0574, Program Officer Manuel Fiadeiro. Roman Stocker was the recipient of G. Marin and A. Gini scholarships. This article represents Centre for Water Research reference ED 1693-BL.