Environmental Modelling & Software 24 (2009) 473–488

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

A hydrostatic/non-hydrostatic grid-switching strategy for computing high-frequency, high wave number motions embedded in geophysical flows

Daniel Botelho [a,*], Jorg Imberger [a], Chris Dallimore [a], Ben R. Hodges [b]

[a] Centre for Water Research, The University of Western Australia, Crawley, WA, Australia
[b] Civil, Architectural and Environmental Engineering Department, The University of Texas at Austin, Austin, TX, USA

A R T I C L E I N F O

Article history:
Received 28 November 2007
Received in revised form
15 September 2008
Accepted 16 September 2008
Available online 14 November 2008

Keywords:
Non-hydrostatic model
ELCOM
Grid-switching
Internal waves
Wave modelling

A B S T R A C T

Hydrostatic and non-hydrostatic models were used to simulate the generation of internal surges and associated soliton-like trailing waves from the non-linear steepening of low-frequency basin-scale waves. Results confirmed that the process cannot be modelled using the hydrostatic approximation. A grid-switching strategy was developed to reduce the simulation run-time of the non-hydrostatic model; a low-resolution grid using a hydrostatic computation of the flow field is dynamically switched to a high-resolution grid in the region of propagation of the leading internal surge, using a non-hydrostatic computation of the flow field. The strategy takes advantage of the small time scale required for non-hydrostatic effects to become important such that a high-resolution grid is invoked only when and where these effects become large. Run-time reduction, conservation of the interpolation scheme involved in the grid switching and strategies for field scale studies were addressed. In relation to the laboratory experiments, the grid-switching strategy predicted the phase speed and the amplitude of the leading internal surge similarly to the uniform-grid models, however, the trailing soliton-like waves lost some of their signature. All non-hydrostatic models predicted the features of the energy flux path between low- and high-frequency waves.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Due to their importance in the fluxes of momentum and energy in an enclosed basin, internal waves have been studied since the end of the 19th century (Mortimer, 1974). Internal waves are ubiquitous in stratified lakes, varying widely in origin, depth, and length/time scales, depending on the stratification and forcing of the system on which they propagate. Herein we confine our focus to the free internal wave response of a continuously stratified system with two constant-density layers separated by a smoothly varying pycnocline. As is consistent for lakes of small to medium size, the effects of the Earth's rotation are neglected. At the lower end of the frequency spectrum, basin-scale waves (often-called seiches) form after the thermocline is tilted in response to the application of a surface wind stress. Inertia leads to a free wave response of the thermocline and the resulting basin-scale internal waves redistribute the wind's energy below the surface-mixed layer. Additionally, higher frequency internal waves are observed to form and propagate freely within the metalimnetic wave guide. These waves, either dissipate within the interior of the lake, or shoal and break on the perimeter of the basin (Thorpe et al., 1972; Farmer, 1978; Wiegand and Carmack, 1986; Saggio and Imberger, 1998; Boegman et al., 2003; Horn et al., 2001; Boegman et al., 2005a). In a time scale analysis supported by laboratory studies for a two-layer system, Horn et al. (2001) identified five different regimes characterizing the energy transfer from basin-scale waves to higher frequency waves in terms of the slope of the initial pycnocline tilt and the relative depths of the pycnocline to the total basin depth. Their study was limited to the energy transfer originating from non-linear steepening of basin-scale waves degenerating into an internal surge (also called rarefaction and hereafter also referred to as a leading soliton) that evolves into a packet of soliton-like waves (hereafter also referred to as solitons or solitary waves).

Over the past decade, significant attention has been directed towards simulation of free-surface gravity waves (Casulli and Stelling, 1995, 1998; Casulli, 1999; Koçyigit et al., 2002; Stelling and Zijlema, 2003; Yuan and Wu, 2004; Chen, 2003, 2005; Zijlema and Stelling, 2005). More recently numerical solutions of non-hydrostatic internal wave motions have been a focus of several researchers (Wadzuk and Hodges, 2004; Daily and Imberger, 2003; Fringer and Street, 2003; Shen and Evans, 2004; Venayagomoorthy and Fringer, 2005, 2006, 2007a,b; Fringer et al., 2006). As yet, practical computational non-hydrostatic methods that are readily transferable between research groups and models have not been

* Corresponding author. Present address: Coastal, Ocean and Simulations Group, Infrastructure and Environment, Worley Parsons Sevices Pty Ltd, Level 7, QV1 Building, 250 St Georges Terrace, Perth, WA 6000, Australia. Tel.: +61 08 64881684; Fax: +61 892788110.
E-mail address: daniel.botelho@worleyparsons.com (D. Botelho).

1364-8152/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsoft.2008.09.008

developed. A key difficulty for non-hydrostatic models is computing the generation and propagation of small length-scale high-frequency waves evolving from a basin-scale seiche. The transfer of energy from basin-scale internal waves to high-frequency waves is controlled by the interaction between non-linear steepening and non-hydrostatic dispersion, which is readily modelled by the weakly non-linear Korteweg de Vries equation (Benney, 1966; Bogucki et al., 1997; Horn et al., 2002). Therefore, to correctly simulate this degeneration process with the Navier–Stokes equations, a model must reproduce both non-linearities and non-hydrostatic pressure (Wadzuk and Hodges, 2004). However, the small length-scale of high-frequency waves requires a much smaller grid than required for resolving the basin-scale seiche. Uniformly applying a high-resolution grid across all possible internal wave propagation regions requires massive computation power (Fringer et al., 2006) an effort presently beyond the fastest single-processor workstations.

In the evolution from a basin-scale seiche to a solitary wave train, there is a disparity between the longer time scale for non-linear steepening and the shorter equilibrium time scale for the non-hydrostatic dispersive effects leading to solitary wave formation (Horn et al., 2002). Herein, this time scale disparity is used in developing a grid-switching technique for efficient simulation of internal wave evolution. We demonstrate that refining the model grid size and applying a non-hydrostatic solution only when a necessary degree of wave steepness is achieved in the basin-scale wave field can significantly reduce the computational requirements. Prior to wave steepening, a hydrostatic solution on a coarser grid is sufficient for practical modelling. This paper provides (1) details of the grid-switching model and the grid refinement algorithm, (2) results of model tests and comparisons of the models with the laboratory experiments of Horn et al. (2001) and the spectral analysis in Boegman et al. (2005b), and (3) discussion of the model results and how this methodology can be applied to flows in lakes.

2. Numerical model description

2.1. Overview

The model CWR-ELCOM (Centre for Water Research – Estuary and Lake Computer Model) was the basis for the numerical codes used in this paper. ELCOM solves the three-dimensional (3D) incompressible Boussinesq RANS equations (Reynolds Averaged Navier Stokes) using an approach similar to the TRIM model of Casulli and Cheng (1992). ELCOM applies finite-difference discretizations of momentum for computational efficiency with finite-volume discretizations of continuity and scalar transport to ensure local and global conservation. Time-marching is semi-implicit, wherein the free surface is advanced implicitly (removing severe time step limitation associated with barotropic modes) while the momentum and baroclinic terms are explicitly discretized with semi-Lagrangian and forward-Euler schemes, respectively. Thus, ELCOM has CFL time step limitations for both baroclinic modes and advection. Spatial difference stencils are second-order central differences, except for scalar transport (third-order ULTIMATE QUICKEST, Leonard, 1991) and momentum advection (3rd order upwind, Hodges, 2000). For vertical mixing in stratified flows, ELCOM uses a mixed-layer scheme based on turbulent kinetic energy budgets, which does not require a vertical eddy viscosity (Hodges et al., 2000; Laval et al., 2003a). While horizontal eddy viscosity and eddy diffusivity can be modelled with ELCOM, they are herein neglected and molecular viscosity ($10^{-6}\ \mathrm{m^2\,s^{-1}}$) and salinity diffusion ($1.4\times10^{-9}\ \mathrm{m^2\,s^{-1}}$) coefficients are used.

In the present work, both the original hydrostatic ELCOM model and a new hybrid hydrostatic/non-hydrostatic grid-switching adaptation of the model were compared. The governing equations and numerical schemes of hydrostatic ELCOM and antecedent were adequately addressed elsewhere (Casulli and Cheng, 1992; Hodges, 2000; Hodges et al., 2000; Laval et al., 2003a). This new hybrid model contains both hydrostatic solutions (following the original ELCOM) and non-hydrostatic solutions using the governing equations and fractional-step method proposed in Casulli (1999) for TRIM and originally adapted to ELCOM in Wadzuk and Hodges (2004). The non-hydrostatic method of Casulli (1999) uses the hydrostatic solution as a predictor step, followed by a Poisson solution of the non-hydrostatic pressure and velocity/free surface correction steps. As the basic methods were detailed in the above references, herein we focus on the new hybrid method and grid-switching strategy.

To allow variable horizontal grid resolution as a function of pycnocline steepness, we applied the non-uniform-grid method of Laval et al. (2003a) and adapted the non-hydrostatic Poisson solution of Casulli (1999) to allow non-uniform horizontal grids. Using a fully implicit stencil the Poisson Eqs. (27) and (28) in Casulli (1999) are replaced with

$$
\begin{aligned}
&\Delta t\left[\frac{\left(q^{n+1}_{i+1,j,k}-q^{n+1}_{i,j,k}\right)\Delta z_{i+1/2,j,k}-\left(q^{n+1}_{i,j,k}-q^{n+1}_{i-1,j,k}\right)\Delta z_{i-1/2,j,k}}{\Delta x_{i,j,k}\Delta x_{i+1/2,j,k}}\right.\\
&\quad+\frac{\left(q^{n+1}_{i,j+1,k}-q^{n+1}_{i,j,k}\right)\Delta z_{i,j+1/2,k}-\left(q^{n+1}_{i,j,k}-q^{n+1}_{1,j-1,k}\right)\Delta z_{i,j-1/2,k}}{\Delta y_{i,j,k}\Delta y_{i,j+1/2,k}}\\
&\quad\left.+\frac{\left(q^{n+1}_{i,j,k+1}-q^{n+1}_{i,j,k}\right)}{\Delta z_{i,j,k+1/2}}-\frac{\left(q^{n+1}_{i,j,k}-q^{n+1}_{i,j,k-1}\right)}{\Delta z_{i,j,k+1/2}}\right]\\
&\quad=\frac{\tilde{u}^{n+1}_{i+1/2,j,k}\Delta z_{i+1/2,j,k}-\tilde{u}^{n+1}_{i-1/2,j,k}\Delta z_{i-1/2,j,k}}{\Delta x_{i,j,k}}\\
&\qquad+\frac{\tilde{v}^{n+1}_{i,j+1/2,k}\Delta z_{i,j+1/2,k}-\tilde{v}^{n+1}_{i,j-1/2,k}\Delta z_{i,j-1/2,k}}{\Delta y_{i,j,k}}+\tilde{w}^{n+1}_{i,j,k+1/2}\\
&\qquad-\tilde{w}^{n+1}_{i,j,k-1/2}\\
&\quad=0,\ k=m,m+1,\ldots,M-1
\end{aligned}
\tag{1a}
$$

$$
\begin{aligned}
&\Delta t\left[\frac{\left(q^{n+1}_{i+1,j,M}-q^{n+1}_{i,j,M}\right)\Delta z_{i+1/2,j,M}-\left(q^{n+1}_{i,j,M}-q^{n+1}_{i-1,j,M}\right)\Delta z_{i-1/2,j,M}}{\Delta x_{i,j,k}\Delta x_{i+1/2,j,k}}\right.\\
&\quad+\frac{\left(q^{n+1}_{i,j+1,M}-q^{n+1}_{i,j,M}\right)\Delta z_{i,j+1/2,M}-\left(q^{n+1}_{i,j,M}-q^{n+1}_{1,j-1,M}\right)\Delta z_{i,j-1/2,M}}{\Delta y_{i,j,k}\Delta y_{i,j+1/2,k}}\\
&\quad\left.-\frac{\left(q^{n+1}_{i,j,M}-q^{n+1}_{i,j,M-1}\right)}{\Delta z_{i,j,M-1/2}}\right]-\frac{q^{n+1}_{i,j,M}}{g\Delta t}\\
&\quad=\frac{\tilde{\eta}^{n+1}_{i,j,M}-\eta^{n}_{i,j,M}}{g\Delta t}+\frac{\tilde{u}^{n+1}_{i+1/2,j,M}\Delta z_{i+1/2,j,M}-\tilde{u}^{n+1}_{i-1/2,j,M}\Delta z_{i-1/2,j,M}}{\Delta x_{i,j,M}}\\
&\quad+\frac{\tilde{v}^{n+1}_{i,j+1/2,M}\Delta z_{i,j,M}-\tilde{v}^{n+1}_{i,j-1/2,M}\Delta z_{i,j,M}}{\Delta y_{i,j,M}}-\tilde{w}^{n+1}_{i,j,M-1/2}
\end{aligned}
\tag{1b}
$$

where Δt is the model time step, Δx and Δy are the horizontal grid sizes and z is the vertical grid size. n is the time level, and i, j, and k are the Cartesian coordinates of the centre of the grid cells in the x, y, and z directions, respectively. q is the hydrodynamic (non-hydrostatic) pressure divided by a reference density. $\tilde{\eta}$ is the free-surface elevation computed at the “hydrostatic” predictor step, $\tilde{u}$, $\tilde{v}$, and $\tilde{w}$, are the velocities computed at the “hydrostatic” predictor step in the x, y, and z directions, respectively (Casulli, 1999). g is the

Download English Version:

https://daneshyari.com/en/article/570038

Download Persian Version:

https://daneshyari.com/article/570038

Daneshyari.com