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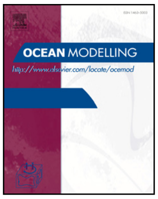

Incorporating floating surface objects into a fully dispersive surface wave model

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ABSTRACT

The shock-capturing, non-hydrostatic, three-dimensional (3D) finite-volume model NHWAVE was originally developed to simulate wave propagation and landslide-generated tsunamis in finite water depth (Ma, G., Shi, F., Kirby, J. T., 2012. Ocean Model. 43-44, 22-35). The model is based on the incompressible Navier-Stokes equations, in which the z-axis is transformed to a σ-coordinate that tracks the bed and surface. As part of an ongoing effort to simulate waves in polar marginal ice zones (MIZs), the model has now been adapted to allow objects of arbitrary shape and roughness to float on or near its water surface. The shape of the underside of each floating object is mapped onto an upper σ-level slightly below the surface. In areas without floating objects, this σ-level continues to track the surface and bed as before. Along the sides of each floating object, an immersed boundary method is used to interpolate the effects of the object onto the neighboring fluid volume. Provided with the object's shape, location, and velocity over time, NHWAVE determines the fluid fluxes and pressure variations from the corresponding accelerations at neighboring cell boundaries. The system was validated by comparison with analytical solutions and a VOF model for a 2D floating box and with laboratory measurements of wave generation by a vertically oscillating sphere. A steep wave simulation illustrated the high efficiency of NHWAVE relative to a VOF model. In a more realistic MIZ simulation, the adapted model produced qualitatively reasonable results for wave attenuation, diffraction, and scattering.

1. Introduction

With the growing focus on global warming and its effects in the polar regions, increasing attention has been paid to modeling the interaction of waves with ice floes in marginal ice zones (MIZs) along the edges of Arctic and Antarctic pack ice. As areas of open water continue to grow in the Arctic during spring and summer months, more powerful waves are playing an increasingly important role in the breakup and recession of the sea ice (Thomson and Rogers, 2014). However, at present their representation in operational models such as WAVEWATCH III (Tolman, 2009) and Arctic Cap (Posey et al., 2010) is either crudely parameterized or completely neglected (Zhao et al., 2015). Development and validation of more accurate, physically based representations of wave-ice interaction is urgently needed.

Although mathematical representations of wave-ice interaction were first developed in the mid-20th century (Keller and Weitz, 1953; Evans and Davies, 1968; Wadhams, 1973; Squire et al., 1995), the sophistication and variety of theoretical and numerical wave-ice models accelerated considerably as polar research became a priority and more sophisticated semi-analytical models were developed (Meylan and Squire, 1994; Shen et al., 1998; Peter and Meylan, 2004; Bennetts et al., 2007; Kohout and Meylan, 2007). While some modelers have focused on representing the MIZ as a continuous material with varying viscoelastic properties (Zhao and Shen, 2013; Rogers and Orzech, 2013; Zhao and Shen, 2015), other investigators, beginning with Wadhams (Wadhams, 1986) and Meylan (Meylan, 1993; Meylan and Squire, 1996) have instead modeled individual floes as flexible thin elastic plates (Hermans, 2013a; Andrianov et al., 2004; Gayen et al., 2005). A common

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approach has been to use linear potential flow theory (as described in Squire, 2007) in combination with a thin-plate ice model to simulate wave-floe interaction (Kohout and Meylan, 2008; Williams et al., 2013; Meylan et al., 1997; Bennetts et al., 2010). While this method is very useful for estimating attenuation of smaller amplitude waves by floes, it neglects floe collisions and rafting, as well as the overwash of floes by steeper waves (Yiew et al., 2016). Results from several recent lab experiments (Toffoli et al., 2015; Bennetts et al., 2015; Bennetts and Williams, 2015) suggest that floe overwash plays a role in producing increased attenuation rates measured for steeper waves. Field measurements from Kohout et al. (2014) and Meylan et al. (2014) also indicate a possible amplitude dependence in wave transmission rates, which is not captured by linear potential theory or represented in larger scale ocean models. Bennetts and Williams (2015) note that floe collisions may reduce wave-energy transmission in more densely packed marginal ice fields. To address some of the issues associated with ice floe properties and behavior, other modelers have used the discrete element method (DEM) to directly represent single or multiple ice floes, simulating their evolution and tracking their motion in response to currents and/or waves (Hopkins and Thorndike, 2006; Hopkins and Shen, 2001; Hermans, 2013b; Polojärvi and Tuhkuri, 2013; Xu et al., 2012; Song et al., 2014).

The wave model adaptations to be described herein are part of a larger effort to investigate and address the above issues by implementing a realistic 3D representation of the interactions between waves and Arctic ice floes in small domains of O(1-10 km^2). In this coupled system, waves are to be represented using the phase-resolving, fully dispersive surface wave model NHWAVE (Ma et al., 2012). Ice floes are represented using the open-source DEM package LIGGGHTS (Kloss et al., 2012), in a manner similar to the latter category of modelers described above (Orzech et al., 2016; Bateman et al., 2014; Orzech et al., 2014). The system is limited to first-year ice, for which vertical thickness (O(m)) is small relative to horizontal dimensions (O(100 m)). This property makes it convenient to represent ice floe effects on waves as surface boundary conditions in the wave model.

The present article focuses on the wave component of this system, describing the development of numerical methods for the NHWAVE model to correctly represent the fluid response to rigid objects at its surface. Unlike most of the wave-ice models cited above, in which the motion of the freely floating floes is coupled to the waves, objects considered here are either fixed or moving with a prescribed oscillatory motion. As such, they are generally uncoupled from surrounding fluid oscillations and thus act to alter and/or generate surface waves in their vicinity. Vertically oriented surface object effects are incorporated into the model by directly mapping a near-surface σ-level onto the underside (and, if necessary, the top) of each floating object. Horizontally oriented effects are interpolated to fluid cell walls using extensions of the immersed boundary approach. The model is compared to potential-flow models for linear waves and 2D geometries, and to a lab experiment for a 3D geometry. Additional qualitative evaluations are performed for steep waves and a larger scale field-based case.

The following sections detail the specific changes made to NHWAVE, then describe and provide results from convergence tests, comparative analytical simulations, an experimental validation, and the qualitative steep-wave and large-scale cases. Section 2 presents a comparative overview of the wave model in a historical context, followed by a brief review of the governing equations and numerical methods of NHWAVE. A more detailed description of the theory and methods for incorporating floating objects and mapping σ-levels is provided in Section 3. Validation test parameters and all test results are summarized in Section 4, and discussion and conclusions are presented in Section 5.

2. Wave model

2.1. Background

The behavior of floating objects and their interaction with water waves and currents have been studied from the earliest days of sailing and shipping. Theoretical and modeling efforts have primarily focused on how waves affect ships or structures, as in studies of nonlinear ship dynamics (Spyrou and Thompson, 2000), conditions leading to capsize (Soliman and Thompson, 1991; McCue and Troesch, 2005), and wave-object or wave-platform interactions (Wall et al., 2007; Clauss, 2002; Isaacson and Nwogu, 1987). Wave-structure interaction is usually modeled by the boundary integral method (BIM; e.g., Skourup et al., 1992; Grilli et al., 1994) or a computational fluid dynamics model (CFD; e.g., Hieu and Tanimoto, 2001; Shen and Chan, 2008). BIM is based on potential flow theory and does not allow for calculation of energy dissipation due to wave breaking and friction between flows and structures. Traditional CFD models use either the Volume-of-Fluid (VOF) method or the Marker-and-Cell (MAC) method to treat the free surface or the wave-structure interface and are thus computationally expensive. The smoothed particle hydrodynamics (SPH) method (Gingold and Monaghan, 1977), which treats the fluid as a collection of discrete elements, has also been used to model wave-object interaction (e.g. Rogers et al., 2010), but it is even more computationally demanding.

Models based on the multi-layer Boussinesq equations have been shown to be robust and efficient at simulation of non-linear wave propagation (Nwogu, 1993; Wei et al., 1995) and extended to represent turbulence in the water column (Kim and Lynett, 2011). However, assumptions inherent to these models (i.e., $kh < 3$) limit them to predicting only weakly dispersive shallow water waves in intermediate water depth. In addition, floating objects and the free surface itself can cut through their computational cells in an arbitrary way, significantly affecting the accuracy of their boundary conditions and ultimately degrading their velocity estimates.

The recently developed model NHWAVE (Ma et al., 2012) uses a different approach, solving the Navier-Stokes equations in a transformed domain with a surface/bed-following σ-coordinate instead of a Cartesian z-coordinate. The free surface is treated as a single-valued function of horizontal location, which resolves the issues with arbitrary intersection of cells discussed above. The model defines dynamic pressure at vertically-facing cell sides (i.e., along the σ-levels), which allows for accurate application of the pressure boundary condition at the free surface. With this model configuration, a very small number (i.e., fewer than 10) of vertical levels is required to accurately describe wave dispersion. The Harten Lax and van Leer (HLL) Riemann approximation (Harten et al., 1983) is used to determine fluxes at cell faces. A shock-capturing Godunov-type approach is employed, allowing the model to deal with discontinuous flow conditions resulting from breaking waves or sudden surface impacts. These simplifications also considerably reduce the computational requirements of the model.

The Pressure Decimation and Interpolation (PDI) Method was added to NHWAVE by Shi et al. (2015), who confirmed that the dynamic pressure can be modeled accurately with only a small number of vertical layers. This significantly increased model efficiency for simulating non-hydrostatic, baroclinic processes. Most recently, Derakhti et al. (2015) carried out extensive model validations of NHWAVE against laboratory data. The focus of their study was to examine the model's capability of predicting breaking waves in both the surf zone and deep water. Results showed that NHWAVE accurately predicted depth-limited breaking waves using only 4 σ-layers and steepness-limited breaking waves using as few as 8 σ-layers.