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Numerical Simulation of Solitary-Wave Scattering and Damping in Fragmented Sea Ice

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ABSTRACT

A numerical model for direct phase-resolved simulation of nonlinear ocean waves propagating through fragmented sea ice is proposed. In view are applications to wave propagation and attenuation across the marginal ice zone. This model solves the full equations for nonlinear potential flow coupled with a nonlinear thin-plate formulation for the ice cover. Distributions of ice floes can be directly specified in the physical domain by allowing the coefficient of flexural rigidity to be spatially variable. Dissipation due to ice viscosity is also taken into account by including diffusive terms in the governing equations. Two-dimensional simulations are performed to examine the attenuation of solitary waves by scattering and damping through an irregular array of ice floes. Wave attenuation over time is quantified for various floe configurations.

KEY WORDS: flexural-gravity waves; ice floes; scattering; solitary waves; spectral method; viscosity; wave attenuation.

INTRODUCTION

The rapid decline of summer ice extent that has occurred in the Arctic Ocean over recent years has prompted a surge of research activity and, in particular, the role of ocean waves in controlling sea-ice morphology has been increasingly recognized. This is especially relevant in the context of climate change as the resulting ice melting and proliferation of open water promote further wave growth over increasing fetches, thus allowing long waves to propagate larger distances into the ice field. Of particular interest is the marginal ice zone (MIZ) which is the fragmented part of the ice cover closest to the open ocean and, as such, it is a very dynamic region strongly affected by incoming ocean waves. By breaking up the sea ice, waves cause it to become more fragmented, which in turn increases their capacity to further penetrate and damage the ice cover. Unfortunately, such information has not been factored into previous climate predictions and this is now becoming a pressing issue. State-of-the-art forecasting models of wind-driven gravity waves are only beginning to be tested with crude parameterizations for wave-ice interactions (Doble and Bidlot, 2013).

While the problem of ocean waves interacting with sea ice has drawn attention for some time now, the vast majority of theoretical studies have used linear approximations of the governing equations. In view is the description of wave attenuation through ice-covered seas. This direction of inquiry has produced an abundant literature and has reached a high degree of sophistication spanning a variety of situations. For the MIZ, two different approaches have commonly been adopted: (i) continuum models for waves propagating through an inhomogeneous ice cover described as a uniform material with effective properties including viscosity or viscoelasticity (Wang and Shen, 2010; Zhao et al, 2015), and (ii) separate-floe models where the ice cover is composed of individual floes with possibly different characteristics (Kohout and Meylan, 2008; Bennetts and Squire, 2009). Unlike case (i) that includes dissipative processes, case (ii) focuses on wave attenuation by scattering (i.e. directional spreading) through the heterogeneous ice field. Indeed, measurements from Wadhams et al (1988) provided evidence that wave scattering by ice floes is the dominant mechanism for energy attenuation in the MIZ. In case (i), an explicit formula for the linear dispersion relation can be derived and can provide a theoretical basis for subgrid parameterizations in wave forecasting models. Case (ii) leads to solving a mixed boundary value problem where quantities measuring the degree of wave reflection and transmission can be determined. Theoretical predictions based on scattering theory typically give an exponential decay of linear waves with distance traveled through sea ice (Bennetts and Squire, 2012).

Despite some progress in recent years, the nonlinear theory is still in its infancy. A body of work has focused on the analysis and simulation of flexural-gravity waves in continuous uniform sea ice, and has employed thin-plate theory (Euler–Bernoulli theory when strains are finite and/or infinitesimal) for the ice combined with nonlinear potential-flow theory for the fluid. Results include weakly nonlinear modeling in various asymptotic regimes as well as direct numerical simulation (Părău and Dias, 2002; Milewski et al, 2011; Guyenne and Părău, 2015). Numerical and theoretical results on nonlinear waves propagating in fragmented sea ice are even more scarce, and this largely remains an open problem. An attempt has been made by e.g. Hegarty and Squire (2008) who devised a boundary integral method to compute the perturbative second-order solution for the problem of large-amplitude ocean waves interacting with a compliant floating raft such as an ice floe.

In the present paper, we describe a numerical model recently proposed by Guyenne and Părău (2017), which allows for phase-resolved simulation of nonlinear ocean waves propagating through fragmented sea ice. This approach is based on the full time-dependent equations for nonlinear potential flow and can directly incorporate spatial distributions of ice floes. The ice cover is viewed as an elastic material according to the special Cosserat theory of hyperelastic shells (Plotnikov and Toland, 2011), with an ad-hoc modification to define its spatial dependence. This