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An elastic–viscous–plastic sea ice model formulated on Arakawa B and C grids

Sylvain Bouillon [a,c,*], Miguel Ángel Morales Maqueda [b], Vincent Legat [c], Thierry Fichefet [a]

[a] G. Lemaître Institute of Astronomy and Geophysics (ASTR), Université catholique de Louvain, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium
[b] Proudman Oceanographic Laboratory (POL), 6 Brownlow Street, Liverpool L3 5DA, United Kingdom
[c] Center for Systems Engineering and Applied Mechanics (CESAME), Université catholique de Louvain, 4 Avenue G. Lemaître, B-1348 Louvain-la-Neuve, Belgium

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ABSTRACT

The elastic–viscous–plastic (EVP) sea ice rheology has been introduced in the large-scale Louvain-la-Neuve sea-Ice Model, version 2 (LIM2), and its performance has been evaluated. Centred difference versions of the rheology have been implemented on both an Arakawa B grid and a C grid, and their performance have been intercompared in coupled simulations with the Nucleus for European Modelling of the Ocean (NEMO) model. Integrations with both implementations lead to fairly similar results which compare well with observations and with previous LIM simulations. The C grid version, however, offers a number of advantages: (a) easier ice coupling with NEMO, which is itself defined on a C grid; (b) possibility of representing ice transport across one-cell-wide straits and passages; (c) better representation of inertial-plastic compressive waves. For these reasons, we recommend the use of the C grid EVP formulation of the ice dynamics in future LIM applications.

1. Introduction

The dynamic component of most sea ice models designed for climate studies is based on the ice momentum balance formulation of Hibler (1979). In this model, sea ice is assumed to be a non-linear viscous–plastic (VP) material whose resistance to deformation depends on its instantaneous state of motion and several large-scale scalar properties, such as ice thickness and lead fractional area. The VP formulation of Hibler (1979) has known many successes, but it is computationally expensive and not well suited for efficient parallel integrations. The numerical method first used to solve the VP dynamics was a relatively slow implicit point relaxation method (Hibler, 1979). More efficient implicit methods have been proposed subsequently, namely, the line relaxation method (Zhang et al., 1997) and the alternating direction implicit method (Zhang and Rothrock, 2000). However, the most popular alternative for the calculation of the VP dynamics is the elastic–viscous–plastic (EVP) formulation of Hunke and Dukowicz (1997). Distinctive advantages of the EVP dynamics over the VP dynamics is that it is much simpler to program and can be solved explicitly in time, thus easing parallelization.

Because of the appealing numerical properties of the EVP dynamics, a growing number of large-scale, coupled ocean-sea ice and atmosphere-ocean-sea ice models have adopted this formulation (e.g., Randall et al., 2007). Prompted by this trend, we have incorporated the EVP rheology in the Louvain-la-Neuve sea-Ice Model, LIM (Fichefet and Morales Maqueda, 1997; Fichefet and Morales Maqueda, 1999). LIM is the default sea ice module of the Nucleus for European Modelling of the Ocean (NEMO, http://www.locean-ipsl.upmc.fr/NEMO/). LIM is also widely used outside the NEMO project. It is the sea ice component of the global coupled sea ice-ocean model CLIO (Goosse and Fichefet, 1999), and has been coupled to the ocean general circulation models OPA (Océan PArallélisé), which is the precursor of NEMO (Madec et al., 1999), and MOM3 (Modular Ocean Model, version 3, Hofmann and Morales Maqueda (2006)), as well as to Earth system models of intermediate complexity CLIMBER3α (Montoya et al., 2005) and LOVECLIM (Driesschaert et al., 2007), and to the climate general circulation model IPSL-CM4 (Marti et al., submitted for publication). Simulations with the coupled OPA-LIM model have been analyzed by Timmermann et al. (2005), and a new version of the model including an arbitrary number of ice thickness categories and a multi-layer halo-thermodynamic module has been recently completed by Vancoppenolle et al. (2009).

Official releases of LIM have, until now, employed the VP dynamics formulation, although a cavitating fluid approach was also briefly tested by Fichefet and Morales Maqueda (1997), and the versions of LIM coupled to MOM3 and CLIMBER3α do incorporate already implementations of the EVP dynamics. However, this work is the first attempt to evaluate the impact of the EVP parameterization on LIM.

* Corresponding author. Address: G. Lemaître Institute of Astronomy and Geophysics (ASTR), Université catholique de Louvain, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium. Tel.: +32 10 47 30 67; fax: +32 10 47 47 22.
E-mail address: sylvain.bouillon@uclouvain.be (S. Bouillon).

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We have tested three versions of the EVP dynamics in LIM, namely, the most recent bilinear discretization of Hunke and Dukowicz (2002) on an Arakawa B grid, and two simpler discretizations that we will describe here in full, the first of which is also formulated on a B grid, while the second is for a C grid. We present results of simulations with the coupled OPA-LIM model, each employing one of the three EVP formulations that we have just referred to. For comparison, a fourth integration was also carried out with the original VP parameterization. Reassuringly, all three EVP discretizations produce very similar results. However, the C grid version is the one that has been chosen for use within the NEMO project, as it is faster than any of the other two and affords a more direct coupling with the ocean component of NEMO, which is an updated version of OPA and is also discretized on a C grid.

The article is organized as follows. Section 2 succinctly describes LIM. Section 3 discusses issues pertaining to the new discretization of the model dynamics, specially as regards the new implementation on a C grid. Section 4 presents an intercomparison of key results from the numerical simulations. Conclusions are presented in Section 5.

2. Model description

The version of LIM used in this study (LIM2) is described in full detail in Timmermann et al. (2005) and references therein. Therefore, only a brief summary of the model, with emphasis on its dynamics, is given here.

The thermodynamic part of LIM (Fichefet and Morales Maqueda, 1997; Fichefet and Morales Maqueda, 1999) uses a three-layer model for the vertical heat conduction within snow and ice. The storage of latent heat in brine pockets is taken into account, and sea ice growth and decay rates are obtained from the ice energy budget. Air-ice and air-ocean heat fluxes are computed using empirical parameterizations described by Goosse, 231, and the ice-ocean heat flux is computed as in McPhee (1992).

The model dynamics are based on the two-category (consolidated ice plus leads) approach of Hibler (1979). This two-category ice cover is treated as a two-dimensional compressible fluid driven by winds and oceanic currents. Sea ice resist deformation with a strength which increases monotonically with ice thickness and concentration.

The conservation of linear momentum for sea ice is expressed as in Leppäranta (2005) by

$$m\boldsymbol{u}_t = \nabla\cdot\boldsymbol{\sigma} + A(\tau_a+\tau_w) - mf\boldsymbol{k}\times\boldsymbol{u} - mg\nabla\eta, \tag{1}$$

where m is the ice mass per unit area, $\boldsymbol{u}$ is the ice velocity, $\boldsymbol{\sigma}$ is the internal stress tensor, A is the ice area fraction, or concentration, τ_a is the wind stress, τ_w is the ocean stress (typically quadratic), f is the Coriolis parameter, $\boldsymbol{k}$ is an upward pointing unit vector, g is the gravity acceleration and η is the ocean surface elevation with respect to zero sea level. Note that the momentum advection is being ignored in (1) and that the wind and ocean stresses are multiplied by the ice concentration as suggested by Connolley et al. (2004).

Calculation of sea ice internal forces in LIM has customarily been done using the VP approach of Hibler (1979), which, in practice, is a particular case of the EVP formulation of Hunke and Dukowicz (1997). A description of the general framework for the VP and EVP formulations of the ice internal stresses is given in Hunke and Dukowicz (2002) and Hunke and Lipscomb (2006). For completion, we reproduce here the key elements of such a framework. Let us denote σ_{11}, σ_{22} and σ_{12} the components of the ice internal stress tensor, and let

$$\sigma_1 = \sigma_{11}+\sigma_{22}, \tag{2}$$

$$\sigma_2 = \sigma_{11}-\sigma_{22}, \tag{3}$$

$$D_D = \frac{1}{h_1h_2}\left(\frac{\partial}{\partial\xi_1}(h_2u)+\frac{\partial}{\partial\xi_2}(h_1v)\right), \tag{4}$$

$$D_T = \frac{1}{h_1h_2}\left(h_2^2\frac{\partial}{\partial\xi_1}(u/h_2)-h_1^2\frac{\partial}{\partial\xi_2}(v/h_1)\right), \tag{5}$$

$$D_S = \frac{1}{h_1h_2}\left(h_1^2\frac{\partial}{\partial\xi_2}(u/h_1)+h_2^2\frac{\partial}{\partial\xi_1}(v/h_2)\right), \tag{6}$$

where D_D, D_T and D_S are the divergence, horizontal tension and shearing strain rates, respectively, ξ_1 and ξ_2 are generalized orthogonal coordinates, and h_1 and h_2 are the associated scale factors. With these definitions, the stress tensor is given by

$$\sigma_1 = \left(\frac{D_D}{\Delta}-1\right)P, \tag{7}$$

$$\sigma_2 = \frac{D_T}{e^2\Delta}P, \tag{8}$$

$$\sigma_{12} = \frac{D_S}{2e^2\Delta}P, \tag{9}$$

where P is the ice compressive strength, e is the ratio of principal axes of the elliptical yield curve (see below) and Δ, a measure of the deformation rate, is given by

$$\Delta = \sqrt{D_D^2+\frac{1}{e^2}(D_T^2+D_S^2)}. \tag{10}$$

Note that the tensor given by (7)–(9) is entirely equivalent to the more classic Reiner–Rivlin formulation used by Hibler (1979).

This rheology links the compressive stress, σ_1, to the shearing stress, $\sigma_s = \sqrt{\sigma_2^2+4\sigma_{12}^2}$, by the following quadratic relation,

$$(\sigma_1/P+1)^2 + e^2(\sigma_s/P)^2 = 1 \tag{11}$$

which defines an elliptical yield curve. The ice compressive strength P is empirically related to the ice thickness per unit area, h, and ice concentration, A, by $P = P^*he^{-C(1-A)}$, where P^* and C are empirical constants.

In (7)–(9), a regularization is needed when Δ goes to zero. A simple regularization is to set a lower bound, Δ_{min}, for Δ. For values of Δ smaller than Δ_{min}, sea ice behaves like a linear viscous fluid undergoing very slow creep. As we shall see below, if the plastic behavior of sea ice is to be accurately represented, Δ_{min} must be sufficiently small (say $10^{-9}\ \mathrm{s}^{-1}$ or less). Note that Δ_{min} is directly related to the ζ_{max} parameter used in Hibler (1979) by $\zeta_{max} = P/(2\Delta_{min})$.

An alternative regularization was proposed by Hunke and Dukowicz (1997), and it consists in introducing time dependence and an artificial elastic term in (7)–(9), leading to the EVP formulation:

$$2T\sigma_{1,t}+\sigma_1 = \left(\frac{D_D}{\Delta}-1\right)P, \tag{12}$$

$$\frac{2T}{e^2}\sigma_{2,t}+\sigma_2 = \frac{D_T}{e^2\Delta}P, \tag{13}$$

$$\frac{2T}{e^2}\sigma_{12,t}+\sigma_{12} = \frac{D_S}{2e^2\Delta}P, \tag{14}$$

where T is a time scale that controls the rate of damping of elastic waves. Note that, while (12)–(14) become (7)–(9) in the steady state, static flow in the EVP rheology is represented by an elastic deformation, and so imposing a minimum value of Δ is no longer necessary. Hunke and Dukowicz (1997) showed that the numerical solution of (1) in combination with (12)–(14) does indeed converge to the VP stationary solution as long as the elastic time scale T is several times smaller than the time scale of variation of the external forcing.