Ocean Modelling 91 (2015) 23–37

Contents lists available at ScienceDirect

Ocean Modelling

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

Presentation of the dynamical core of neXtSIM, a new sea ice model

Sylvain Bouillon[a,b,*], Pierre Rampal[a,b]

[a] Nansen Environmental and Remote Sensing Center, Bergen, Norway
[b] Bjerknes Centre for Climate Research, Bergen, Norway

ARTICLE INFO

Article history:
Received 15 August 2014
Revised 20 April 2015
Accepted 21 April 2015
Available online 25 April 2015

Keywords:
Sea ice model
Lagrangian
Rheology
Multifractal scaling
Arctic

ABSTRACT

The dynamical core of a new sea ice model is presented. It is based on the Elasto–Brittle rheology, which is inspired by progressive damage models used for example in rock mechanics. The main idea is that each element can be damaged when the local internal stress exceeds a Mohr–Coulomb failure criterion. The model is implemented with a finite element method and a Lagrangian advection scheme. Simulations of 10 days are performed over the Arctic at a resolution of 7 km. The model, which has only a few parameters, generates discontinuous sea ice velocity fields and strongly localized deformation features that occupy a few percent of the total sea ice cover area but accommodate most of the deformation. For the first time, a sea ice model is shown to reproduce the multifractal scaling properties of sea ice deformation. The sensitivity to model parameters and initial conditions is presented, as well as the ability of the Lagrangian advection scheme at preserving discontinuous fields.

1. Introduction

Sea ice dynamics, and more specifically its brittle deformation, exhibit scale invariance properties in both the temporal and spatial domains (Marsan and Weiss, 2010; Weiss, 2013). Scale invariance is a frequent characteristic of dynamical systems where energy introduced at large scale is redistributed towards smaller scales, down to the dissipation scale (e.g., the development of turbulence down to the viscous dissipation scale). In the case of sea ice, the kinetic energy is mainly coming from the wind stress, which varies over typical time and length scales $T_{\mathrm{wind}} \approx 3$–6 days and $L_{\mathrm{wind}} \approx 100$–1000 km, respectively. A large part of this energy is transferred to the ocean but a non-negligible part is dissipated by friction during sea ice fracturing events. These events last a few minutes (Marsan et al., 2011) and occur along faults of tens of meters (Schulson, 2004). Above this dissipation scale, sea ice drift and deformation show scaling properties over several orders of magnitude, from a few hours to a few months, and from hundreds of meters to hundreds of kilometers (Marsan et al. (2004), Rampal et al. (2008)). These properties are in fact quite universal in complex dynamical systems and are likely to emerge from the interaction of a large number of components rather than from a specific process occurring at small scales. This explains for example why simplistic models such as random fuse or random spring models are capable of reproducing complex statistical properties observed for failure in disordered materials, e.g. damage localization and power law distribution of avalanche size (Nukala et al., 2005). The external forcing is one source of scaling in the sea ice dynamics, and should become predominant as the ice cover is more fractured. However, the statistical properties of sea ice dynamics differ from those of ocean and atmosphere dynamics (Rampal et al., 2009). An important characteristic of sea ice dynamics is the multifractality of the scale invariance of sea ice deformation (Weiss and Marsan, 2004), which seems to emanate from the intrinsic properties of solid materials characterized by brittle mechanical behavior (Weiss, 2013).

To correctly reproduce scale invariance properties of sea ice dynamics may be important to better understand the exchanges of energy between the ocean and the atmosphere, which are highly influenced by the opening and closing of leads in the ice cover. In winter, deformation contributes to about 25–40% of the ice production (Kwok, 2006) and the presence of leads, which cover only a few percent of the domain, may account for more than 70% of the upward heat fluxes (Marcq and Weiss, 2012) and for half the salt rejection (Morison and McPhee, 2001). To correctly forecast sea ice motion and deformation would also give crucial information (e.g., the presence of ridges) for ship operations in ice covered areas. Therefore, we think that sea ice models used for forecasting and climate studies should be also evaluated regarding their ability to reproduce the statistical properties of sea ice drift and deformation.

This paper presents the dynamical core of a new sea ice model called neXtSIM, which is based on an innovative mechanical modeling framework. Sea ice dynamics are simulated using an adapted and optimized version of the Elasto–Brittle rheology originally presented in Girard et al. (2011), which initially was inspired by a progressive damage model used to simulate rock mechanics (Amitrano et al.,

* Corresponding author. Tel.: +4740331699.
E-mail address: sylvain.bouillon@nersc.no (S. Bouillon).

http://dx.doi.org/10.1016/j.ocemod.2015.04.005
1463-5003/

1999). The main ingredients of this dynamical sea ice model are detailed, and the ability of the model to generate sea ice deformation fields having correct statistical and scaling properties is demonstrated. An extensive sensitivity study is performed to evaluate the pertinence of each key ingredient of the model. In Section 2 we present the main equations of the model. Section 3 describes how these equations are discretized in space and time and which advection scheme the model uses. Section 4 shows the results of a reference simulation of 10 days over the central Arctic, for which we also present a sensitivity analysis with respect to initial conditions and to some key sea ice mechanical parameters. Note that for short time scale simulations, we assume the impact of thermodynamical processes on the dynamics as being negligible. This study is the first step towards a more complete presentation of neXtSIM, in which e.g. sea ice thermodynamics should be implemented. We do not present a comparison of the simulated fields to observed fields in order to keep this paper focused on the description of the model and to make it accessible to a large scientific audience. The evaluation of the predictive skill of the model or its impact on other components of the climate system is therefore out of scope of this paper.

2. Model description

At the present stage, the dynamical component of neXtSIM is kept as simple as possible and has only five prognostic variables (See Tables 1 and 2 for the list of variables and parameters used in the model). h, hereafter called sea ice thickness, is the volume of ice per unit area and A, hereafter called sea ice concentration, is the surface of ice per unit area. $\boldsymbol{u}$ is defined as the horizontal sea ice velocity and $\boldsymbol{\sigma}$ is the internal stress tensor. The damage d is a non-dimensional scalar variable, which is equal to 0 for undamaged material and to 1 for completely damaged material.

One of the objectives for the model is to reproduce the failure zones that are observed from satellites at a resolution of 10 km. As in Hutchings et al. (2005), we assume that sea ice is heterogeneous at the scale of the model, which corresponds to its resolution Δx (here about 10 km). The sea ice thickness, concentration, damage, internal stress and deformation rate tensors are defined for each element and could strongly vary from one element to the next one. The velocities are defined at the corners of each element. Our model is continuous and uses a Lagrangian approach, i.e. while the nodes are moving accordingly to the ice motion the elements remain connected and always cover the same domain. Eulerian approaches might also be used but then one should use advection schemes that are able to transport highly heterogeneous fields while conserving the extreme gradients present at the scale of the elements.

Table 1
Variables used in the model.

Symbol	Meaning	Units
h	Sea ice thickness	m
A	Sea ice concentration	–
d	Sea ice damage	–
$\boldsymbol{u}$	Sea ice velocity	m s^{-1}
$\boldsymbol{\sigma}$	Sea ice internal stress	N m^{-2}

Table 2
Parameters used in the model with their values for the simulations presented in this study. Underlined values are for the reference simulation.

Symbol	Meaning	Values	Units
ρ_a	Air density	1.3	kg m^{-3}
c_a	Air drag coefficient	0.003	–
θ_a	Air turning angle	0	degree
ρ_w	Water density	1025	kg m^{-3}
c_w	Water drag coefficient	0.004	–
θ_w	Water turning angle	25	degrees
ρ_i	Ice density	917	kg m^{-3}
ν	Poisson coefficient	0.3	–
μ	Internal friction coefficient	0.7	–
Y	Elastic modulus	9	GPa
Δx	Mean resolution of the mesh	7	km
Δt	Time step	800	s
T_d	Damage relaxation time	10^{20}	s
c	Cohesion parameter	[8, <u>4</u>, 2, 1, 0.5]	kPa
α	Compactness parameter	−[40, <u>20</u>, 10, 0]	–

2.1. Evolution of sea ice thickness, concentration and velocity

The evolution equations for sea ice thickness, concentration and velocity are similar to those used in one-thickness category sea ice models. When the thermodynamics terms are neglected, the evolution of h and A are given by:

$$\frac{Dh}{Dt} = -h\nabla\cdot\boldsymbol{u}, \tag{1}$$

$$\frac{DA}{Dt} = -A\nabla\cdot\boldsymbol{u}, \tag{2}$$

where $\frac{D\phi}{Dt}$ is the material derivative of ϕ (being either a scalar or a vector). A is limited to a maximum value of 1.

The evolution of sea ice velocity comes from the vertically integrated sea ice momentum equation:

$$\rho_i h\frac{D\boldsymbol{u}}{Dt} = \nabla\cdot(\boldsymbol{\sigma}h) + A(\boldsymbol{\tau}_a + \boldsymbol{\tau}_w) - \rho_i hf\boldsymbol{k}\times\boldsymbol{u} - \rho_i hg\nabla\eta, \tag{3}$$

where ρ_i is the ice density, $\boldsymbol{\tau}_a$ and $\boldsymbol{\tau}_w$ are the surface wind (air) and ocean (water) stresses, respectively, f is the Coriolis parameter, $\boldsymbol{k}$ is the upward pointing unit vector, g is the gravity acceleration and η is the ocean surface elevation.

It should be noted that in the sea ice community the term internal stress often refers to the vertically integrated (or depth-integrated) internal stress, which has units of Nm^{-1}. Such a definition may lead to confusion as in Girard et al. (2011) where the integrated internal stress (in Nm^{-1}) was compared to cohesion and tensile strength defined in Nm^{-2} (Pa). To avoid confusion, we introduce the integration of the internal stress $\boldsymbol{\sigma}$ (in Nm^{-2}) in the momentum equation as in Sulsky et al. (2007). The internal stress is assumed to be homogeneously distributed in the ice volume and $\boldsymbol{\sigma}h$ corresponds to the integral of the internal stress within that volume.

The surface wind (air) and ocean (water) stresses, $\boldsymbol{\tau}_a$ and $\boldsymbol{\tau}_w$ respectively, are both multiplied by the sea ice concentration as in Connolley et al. (2004) and Hunke and Dukowicz (2003). The air stress $\boldsymbol{\tau}_a$ is computed following the quadratic expression:

$$\boldsymbol{\tau}_a = \rho_a c_a\,|\boldsymbol{u}_a|\left[\boldsymbol{u}_a\cos\theta_a + \boldsymbol{k}\times\boldsymbol{u}_a\sin\theta_a\right], \tag{4}$$

where $\boldsymbol{u}_a$ is the air velocity, ρ_a the air density, θ_a the air turning angle and c_a the air drag coefficient. The water stress $\boldsymbol{\tau}_w$ is computed following the quadratic expression:

$$\boldsymbol{\tau}_w = \rho_w c_w\,|\boldsymbol{u}_w - \boldsymbol{u}|\left[(\boldsymbol{u}_w - \boldsymbol{u})\cos\theta_w + \boldsymbol{k}\times(\boldsymbol{u}_w - \boldsymbol{u})\sin\theta_w\right], \tag{5}$$

where $\boldsymbol{u}_w$ is the ocean velocity, ρ_w the reference density of seawater, θ_w the water turning angle and c_w the water drag coefficient.

2.2. Evolution of sea ice internal stress and damage

The evolution of sea ice internal stress and damage is based on three main ingredients: the linear elasticity, the failure envelope and the link between local damage and internal stress.

2.2.1. Linear elasticity

Assuming planar stress and linear elasticity as in Girard et al. (2011), Hooke's law in matrix notation (see for example Bower (2011)