Combined rheology code

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1 Background

Sea ice dynamics are governed by the momentum equation, including a contribution of internal stress ($\boldsymbol{\sigma}$), which is calculated from the strain rates using sea ice rheology as follows (here $\mathbf{u}$ and m are the ice velocity and mass; $\boldsymbol{\tau}_a$ and $\boldsymbol{\tau}_o$ are the air-ice and ice-ocean stresses; f and $\mathbf{k}$ are the Coriolis parameter and the unity vector):

$$m\frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \boldsymbol{\sigma} + \boldsymbol{\tau}_a + \boldsymbol{\tau}_o - mg\nabla H - \mathbf{k} \times mfF\mathbf{u}. \tag{1}$$

Feltham (2005) combined Elastic-Viscous-Plastic (EVP) rheology and an extended collisional (COL) rheology, creating a unified sea ice rheology (Table 1) suitable for both the central pack ice and the MIZ [1]. The stress tensor is defined as follows (here ϵ is the strain rate tensor and δ the Kronecker delta):

$$\sigma_{ij} = 2\left(\eta^{EVP} + \eta^{COL}\right)\dot{\epsilon}_{ij} + \left(\left(\zeta^{EVP} + \zeta^{COL}\right) - \left(\eta^{EVP} + \eta^{COL}\right)\right)\dot{\epsilon}_{kk}\delta_{ij} - \frac{1}{2}\left(P^{EVP} + P^{COL}\right)\delta_{ij}, \tag{2}$$

with η the shear viscosity, ζ the bulk viscosity and P the replacement pressure. The turbulent kinetic energy of the ice floe motion (granular temperature) sets the contribution of collisional rheology. Evolution of the granular temperature (G_T) can be derived from different sources and sinks as:

$$\frac{DG_T}{Dt} = diffusion + wind\ and\ ocean\ stress\ fluctuations + internal\ stress \\ - floe\ rubbing - floe\ collisions + wave\ surge, \tag{3}$$

see also equation 2.7 in Feltham (2005).

2 Repository

This repository contains the supplementary data for the PhD thesis titled "Impact of surface waves on sea ice and ocean in the polar regions" by Stefanie Rynders (see table 2 for a list of files) [4]. The combined ice rheology is implemented in the Los Alamos CICE model (version

Table 1: Elastic-Viscous-Plastic (EVP) and Collisional rheologies formulation

	collisional	EVP
shear viscosity (η)	$\dfrac{\gamma(1+e')}{3\pi}\dfrac{\sqrt{2}G_T^{1/2}}{L_f}$	$P/2e^2\Delta$
bulk viscosity (ζ)	$\dfrac{\gamma(1+e')}{\pi}\dfrac{\sqrt{2}G_T^{1/2}}{L_f}$	$P/2\Delta$
replacement pressure (P)	$\gamma\dfrac{\sqrt{2}}{\pi^2}(1+e')\dfrac{2G_T}{L_f^2}$	$P^* he^{-c(1-A)}$

L_f floe size
e': restitution coefficient
P^*: sea ice strength
ρ_s: sea ice density
h: sea ice thickness
A: sea ice concentration
e: eccentricity of the yield curve
0 <g(a) >1

Table 2: List of files included in this repository

description	Readme.pdf
	internal stress equations.pdf
code	ice_gtemp.F90
	ice_gtemp_nosurge.F90
	ice_dyn_evcp.F90
	ice_dyn_evcp_nosurge.F90

5.1) and tested in the 1-degree resolution global NEMO (version 3.6) Ocean General Circulation model [2, 3]. The modules require floe size as a variable. If wave surge is used for the granular temperature calculation, wave information on amplitude, period and length are also required, as well as the water depth. There are different options regarding the parameterisations. One can choose whether to use a predefinied granular temperature or one that is calculated by solving the granular temperature equation (*gran_temp_const* true or false resp.). In case of a preset granular temperature there is a choice between a constant value, a profile that depends linearly on latitude or one that depends exponentially on latitude (*gran_temp_prof* 'const', 'lin' or 'exp' resp.).

2.1 Combined collisional and elastic-viscous-plastic rheology

The derivation of the equations, based on the EVP equations in the CICE manual, can be found in supplementary file 'internal stress equations.pdf' The code can be found in ice_dyn_evcp.F90 and ice_dyn_evcp_nosurge.F90, the latter corresponds to the granular temperature code without wave surge. This module is based on the ice_dyn_evp.F90 module.

2.2 Granular temperature calculation

The granular temperature is an added tracer in CICE. It will be advected alongside the existing tracers using the advection method chosen in the namelist. The module ice_gtemp.F90 contains the calculation of the source and sink terms, including wave surge. The module ice_gtemp_nosurge.F90 is the alternative without wave surge inclusion. They also contain the code for initialisation, and reading and writing of the restart files, similar to existing tracers.

References

[1] Feltham, D.L. Granular flow in the marginal ice zone. *Phil. Trans. R. Soc. A*, 363:1677–1700, July 2005. doi: 10.1098/rsta.2005.1601.

[2] Hunke, E.C.; Lipscomb, W.H.; Turner, A.K.; Jeffery, N., and Elliott, S. *CICE: the Los Alamos Sea Ice Model Documentation and Software User's Manual Version 5.0 LA-CC-06-012*. Los Alamos National Laboratory, Los Alamos NM 87545, December 2013.

[3] Madec, G. *NEMO ocean engine (Draft edition r5171)*. Note du Pole de modelisation, Institut Pierre-Simon Laplace (IPSL), France, no 27 issn no 1288-1619 edition, 2014.

[4] S., Rynders. *Impact of surface waves on sea ice and ocean in the polar regions*. PhD thesis, University of Southampton, Ocean and Earth Sciences, 2017.