Implementation of a Combined Elastic-Viscous-Plastic and Collisional Sea Ice Rheology

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1. Abstract

The changes in sea ice and growing economic activity in the Polar Oceans necessitate new climate and forecasting models that can simulate the MIZ (Marginal Ice Zone). Current ice models do not model the surface ocean waves, which determine the MIZ width, or the sea ice rheology that represents MIZ ice dynamics. This study presents an implementation of collisional ice rheology that takes into account jostling of ice floes and also includes the effects of the ice floe size distribution on internal ice stresses.

2. Background

The Marginal Ice Zone (MIZ) is a transitional area between the open ocean and pack ice measuring up to several hundred kilometers across. It is characterised by high surface ocean waves and consists of severely fragmented sea ice with ice floes less than 100m in diameter. With declining summer Arctic sea ice cover and increased wave heights in the Arctic Ocean, the Artic MIZ widened by about 40 percent during the last three decades.[1]

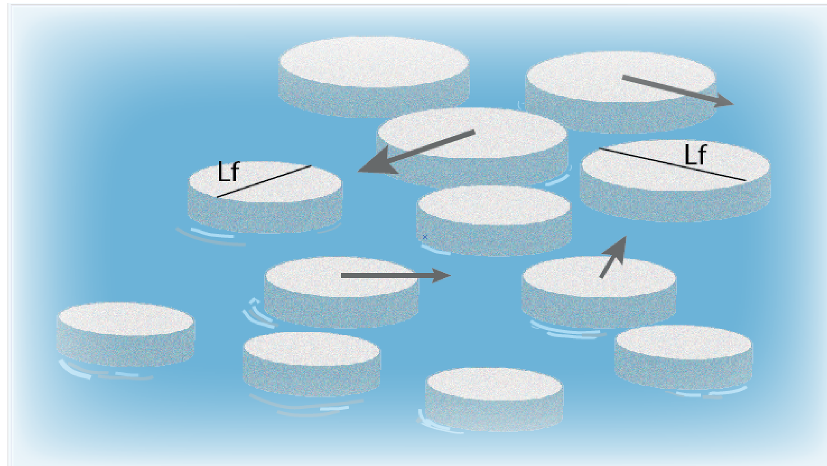

Fig. 1: Schematic representation of the Marginal Ice Zone indicating the newly introduced variables mean floe size L_f, and granular temperature (velocity fluctuations)

3. Methods

Sea ice dynamics are governed by the momentum equation, including a contribution of internal stress, which is calculated from the strain rates in rheology.

$$m\frac{Du}{Dt} = -mfk \times u + \tau_a + \tau_o + \nabla \cdot \sigma$$

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

Elastic-Viscous-Plastic rheology, suitable for central pack ice, is currently used in most sea ice models. Collisional rheology is derived by Shen et al. (1987) from energy conservation during the floe collisions and extended by Feltham et al.[2,3] It can be combined with the Elastic-Viscous-Plastic rheology, creating a unified sea ice rheology suitable for both the central pack ice and MIZ.[3]

	Collisional	EVP
Shear viscosity	$\eta = \frac{\gamma(1+e')}{3\pi}\frac{\sqrt{2}T^{1/2}}{L_f}$	$\eta = \frac{P}{2\Delta e^2}$
Bulk viscosity	$\zeta = \frac{\gamma(1+e')}{3\pi}\frac{\sqrt{2}T^{1/2}}{L_f}$	$\zeta = \frac{P}{2\Delta}$
Replacement pressure	$P = \gamma\frac{\sqrt{2}}{\pi^2}(1+e')\frac{2T}{L_f^2}$	$P = g(A)P^{*}h$

T: granular temperature
L_f: floe size
e': coefficient of restitution
P*: ice strength
ρ_s: ice density
h: ice thickness
A: ice concentration
e: eccentricity of yield curve
0< g(A) < 1

Two new variables are introduced: granular temperature, which is a measure of the velocity fluctuations, and mean floe size (Fig. 1). Granular temperature is parameterised based on ice concentration, an exponential decay is chosen with granular temperature equal to 0.01 m^2/s^2 at the ice edge, decaying to 0.001 m^2/s^2 at 0.4 ice concentration. Floe sizes are calculated using the Lupkes parametrisation for floe sizes or set to a constant 300 m.[4]

The Lupkes parameterisation is based on the ice concentration in an expression of the form $L \sim L_{min} f(A)^{\beta}$ with minumum floe size L_{min} 8 m and β = 0.75.
The combined ice rheology is implemented in the Los Alamos CICE model and tested in the 2-degree resolution global NEMO (Nucleus for European Modelling of the Ocean) Ocean General Circulation model.[5,6] The 10-year run is forced by CORE2 repeated normal year climatological forcing.

4. Results

Effect of rheology

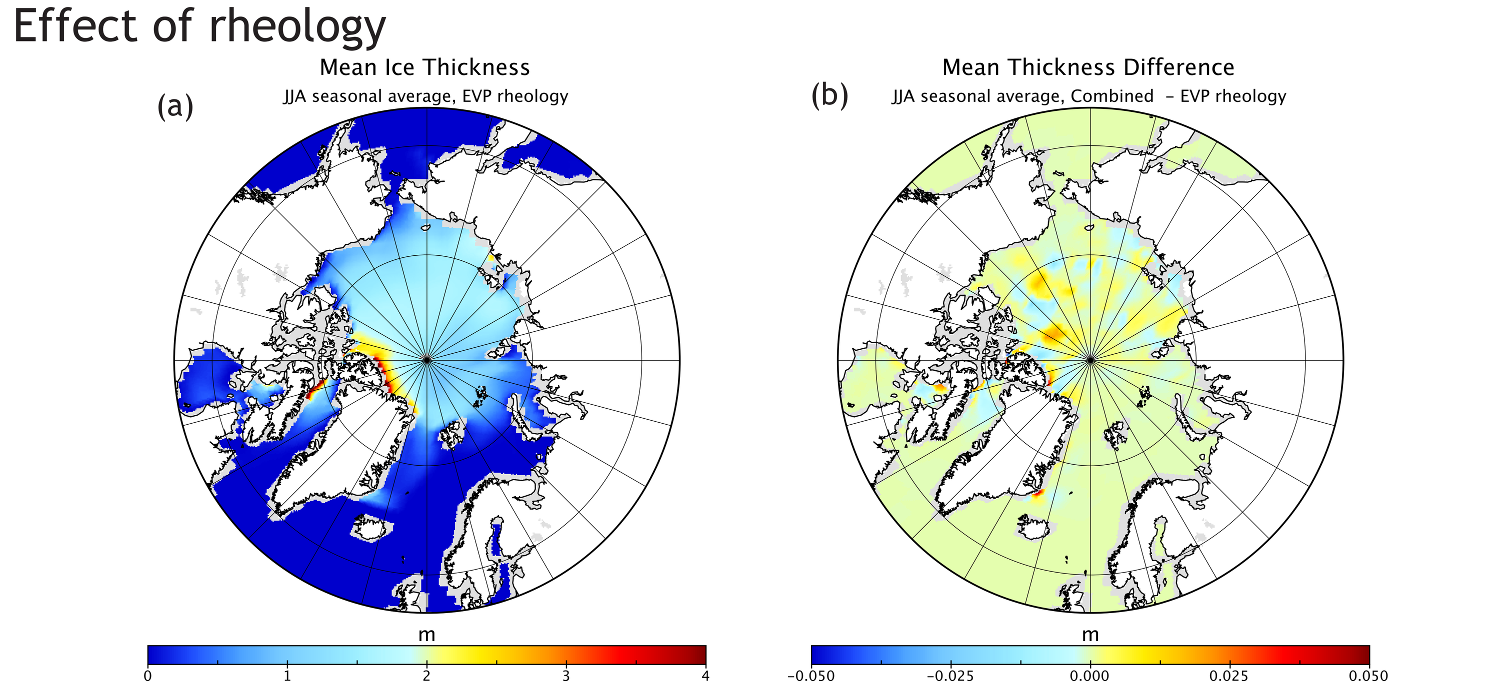

Fig.2: Arctic summer mean ice thickness from the EVP simulation (a) and difference with the Combined rheology simulation (b).

Effect of ice fragmentation

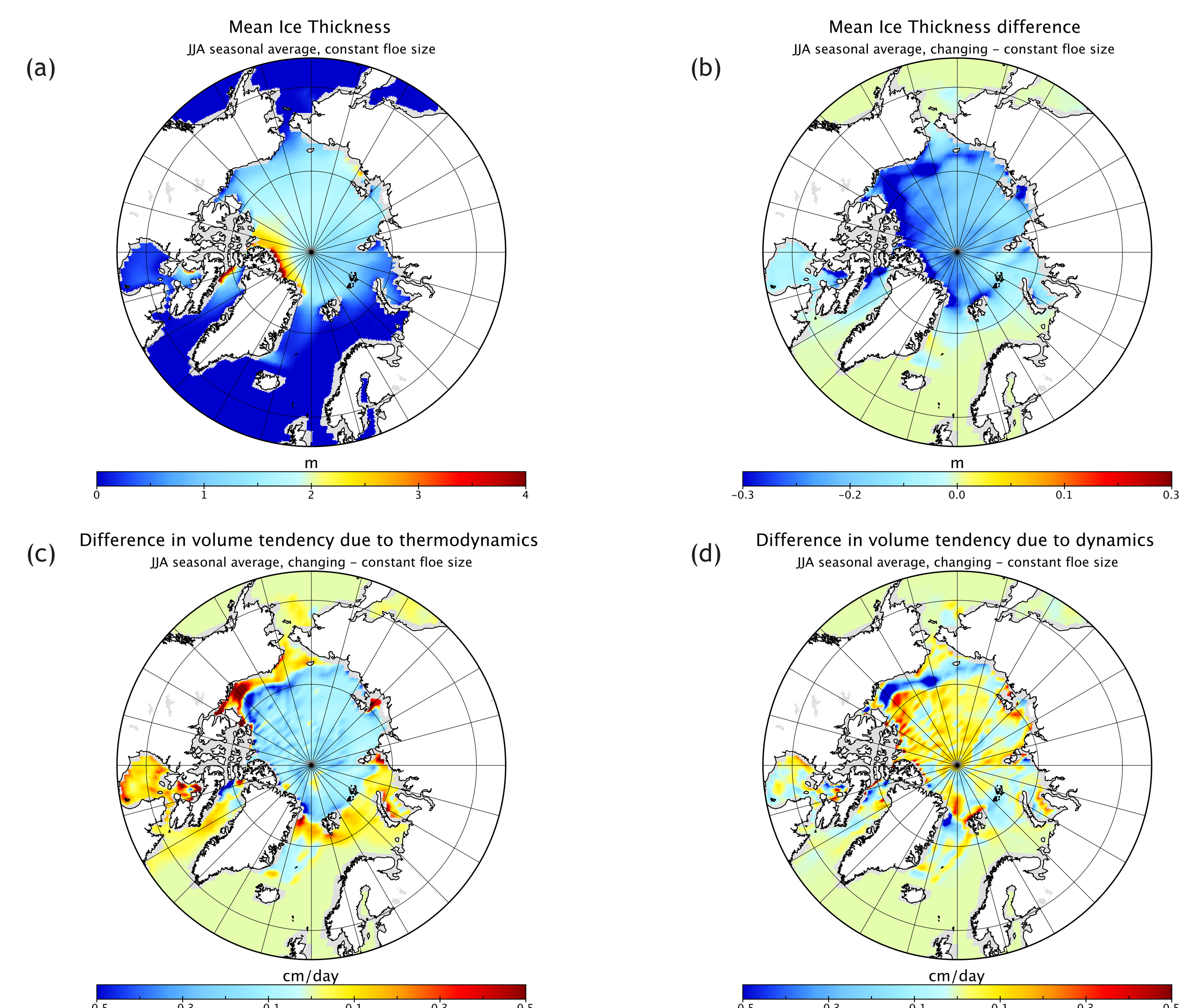

Fig. 3: Arctic summer mean ice thickness from the constant floe size (300 m) simulation (a) and difference with using the Lupkes parameterisation (b). Volume tendency can be split into a thermodynamical (c) and a dynamical contribution (d).

Overall, the change in Arctic ice thickness due to rheology is small (Fig. 2). This can be expected to be different in the higher resolution simulations, which would resolve the MIZ better. Effects of ice fragmentation through lateral melting are much larger (Fig. 3). The volume tendency shows the effect of changing floe sizes through thermodynamics, resulting in lower ice thickness in the central Arctic, with dynamics lowering ice volume in the Beaufort Sea (Fig. 3 c and d). There is an increase in both lateral and basal ice melting in the central Arctic, though basal melt decreases in the Marginal Ice Zone (Fig. 4 a). The effect of changing floe sizes on the Southern Ocean ice thickness is minimal (Fig. 5).

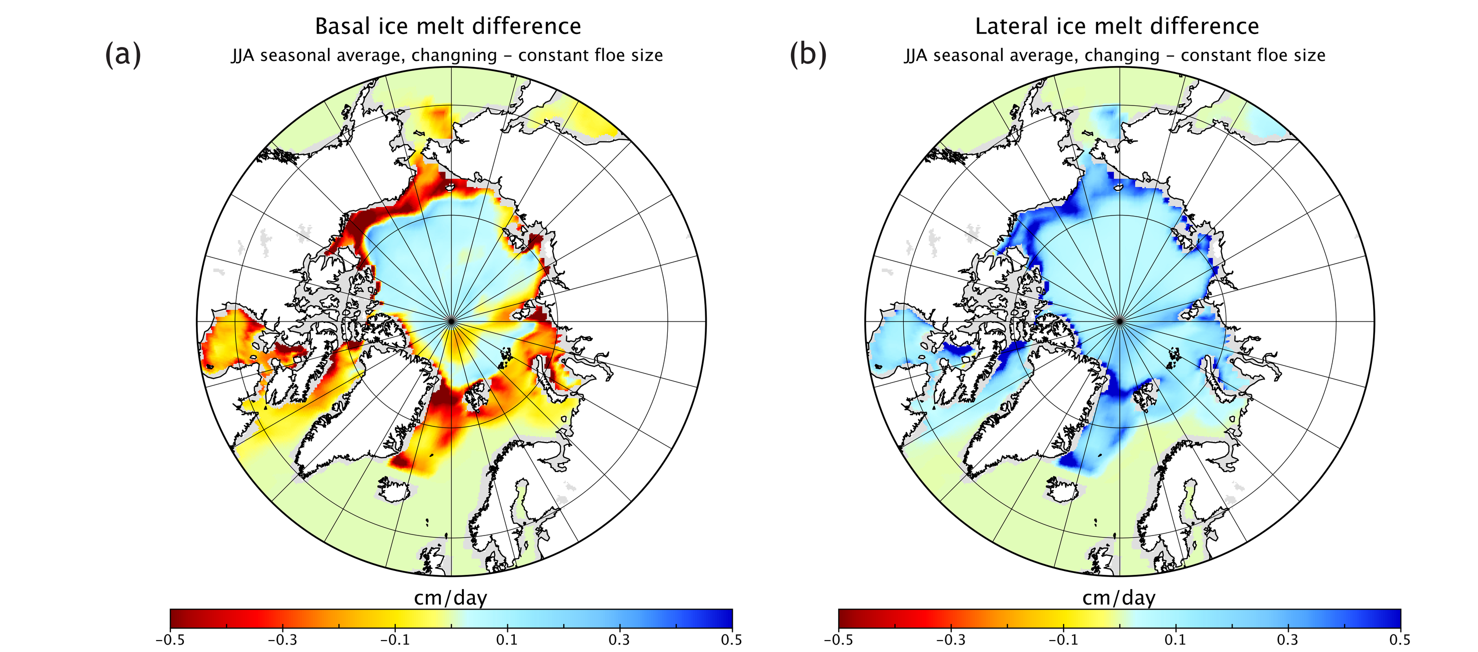

Fig. 4: Arctic summer difference between Lupkes parameterisation and constant floe size (300 m) simulations: (a) basal ice melt, (b) lateral ice melt.

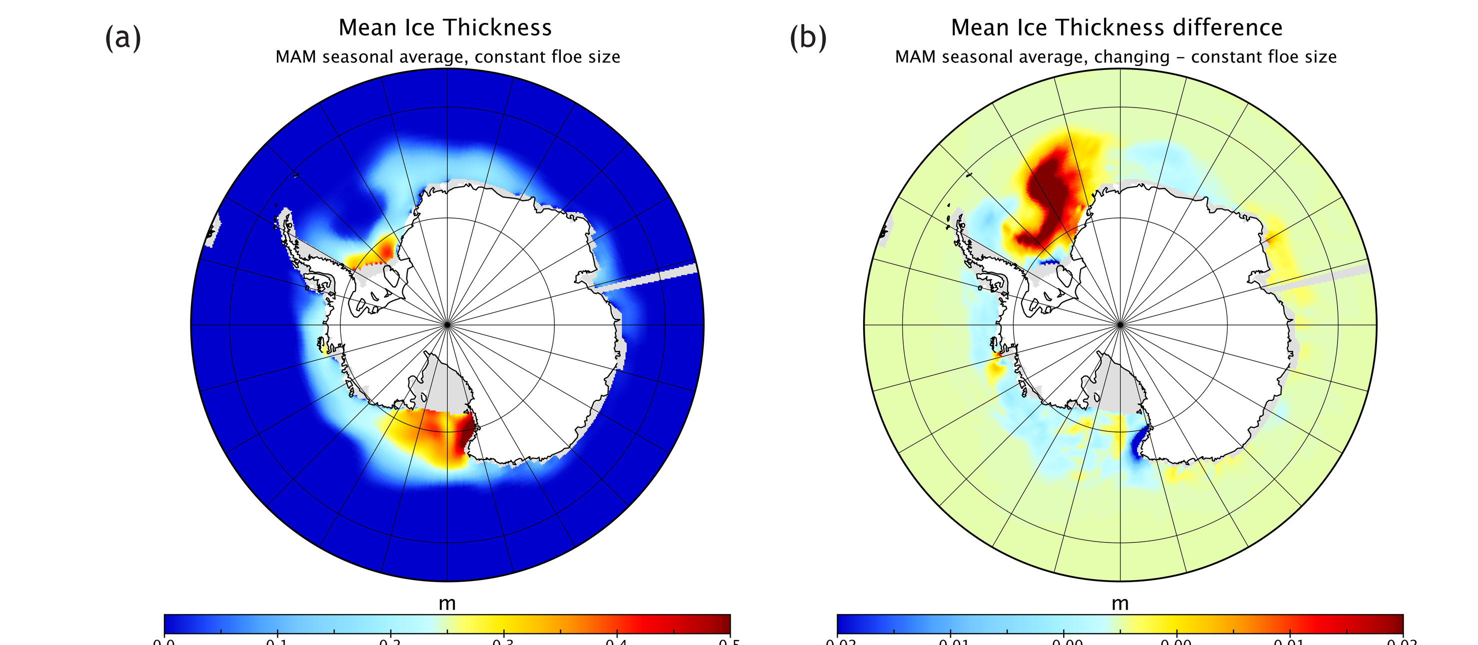

Fig. 5: Antarctic summer ice thickness from the constant floe size (300m) simulation (a) and difference between the constant floe size simulation and using the Lupkes parameterisation (b).

Conclusion + Outlook

In conclusion, the simulation with floe size depending on ice concentration, shows a bigger effect on the ice thickness than changing rheology. The next step will be to investigate the combined effect of rheology and floe fragmentation, taking into account thermodynamics in calculating floe sizes. Calculating the granular temperature from an evolution equation, instead of using a parameterisation, could change its magnitude and spatial pattern, possibly changing its influence on ice thickness.

References

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