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A new continuum rheological framework for sea ice modelling

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Sea ice is a highly heterogeneous material, which, unlike glacier ice, deforms rapidly under the action of the wind and ocean currents, hence in the brittle regime. Much larger deformations also occur once faults, or ice “leads”, are formed that divide the ice cover into ice plates called “floes”, as these plates move relative to each other with much reduced mechanical resistance, setting its overall drift and long-term motion. Making reliable predictions of the deformation and drift of this highly complex component of the polar oceans is becoming essential in the context of (1) forecasting the opening of shipping routes, (2) inferring the mechanical constraints on offshore structures and ships and (3) estimating the future evolution of both its summer and winter extent.

We developed a new rheological framework in the view of reproducing the relevant fracturing processes and post-fracturing deformation of the ice cover in continuum sea ice models at regional to global and weakly to seasonal scales. The approach taken draws from the similarity in mechanical behaviour between sea ice and rock-like materials such as the Earth crust. Brittle fracturing, Coulomb stress redistribution, extreme space/time localization and scaling properties have indeed been recognized in both materials. In both materials also, fracturing activates deformations that can be much larger than that associated with the fracturing itself and relax a significant amount of stress.

The model, named Maxwell-elasto-brittle (Maxwell-EB), combines the concepts of elastic memory, progressive damage mechanics and relaxation of stresses. A viscous-like relaxation term is added to a linear-elastic constitutive law together with an effective viscosity that evolves with the local level of damage of the material, like its elastic modulus. This framework allows for part of the internal stress to dissipate in large, permanent deformations along the faults/leads once the material is highly damaged while retaining the memory of small, elastic deformations over undamaged areas. A healing mechanism is also introduced, counterbalancing the effects of damaging over large time scales.

Simulations of the flow of sea ice at the scale of the Arctic ocean will be presented and compared to observations of sea ice deformation. We will show that the model successfully reproduces the main characteristics of sea ice mechanics: extreme strain localization, anisotropy, intermittency and the associated scaling laws. The importance of representing these characteristics in regional or global, coupled ice-ocean or atmosphere-ice-ocean models will be discussed in terms of the capability of these models to simulate accurately the ice/ocean/atmosphere heat exchanges that set the mid to long term state (thickness and extent) of the sea ice cover.