A fracture field for large-scale ice dynamics: Ice-shelf calving parameterized in PISM-PIK

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Abstract

Recent observations and investigations emphasize the crucial role of ice-shelf fracture mechanics in the discussion on the stability of the polar ice sheets and related uncertainties in the prediction of the rate of eustatic sea level rise. We account for fracture mechanics occurring in ice shelves and along its boundaries in the large-scale prognostic Potsdam Parallel Ice Sheet Model (PISM-PIK[1,2]) by introducing a two-dimensional field variable. Fractures can be created and healed with respect to the local strain rate pattern and existing fractures can be advected with the flow downstream. In addition to the localization of potential fracture zones also observed longitudinal surface structures can be explained. Crevasses and those band structures are observed to influence the material properties and hence the overall ice shelf dynamics. The memory of past deterioration links the dynamics at the front with those in the inner part of the ice shelf (even grounding line processes) in a more realistic way and gives rise to a fracture based calving parameterization at the ice shelf front.

First-order strain-rate based calving law

Ice shelves spread towards the ocean and experience compression across the main flow direction when confined in embayments (denoted by green and red arrows in Fig.1).

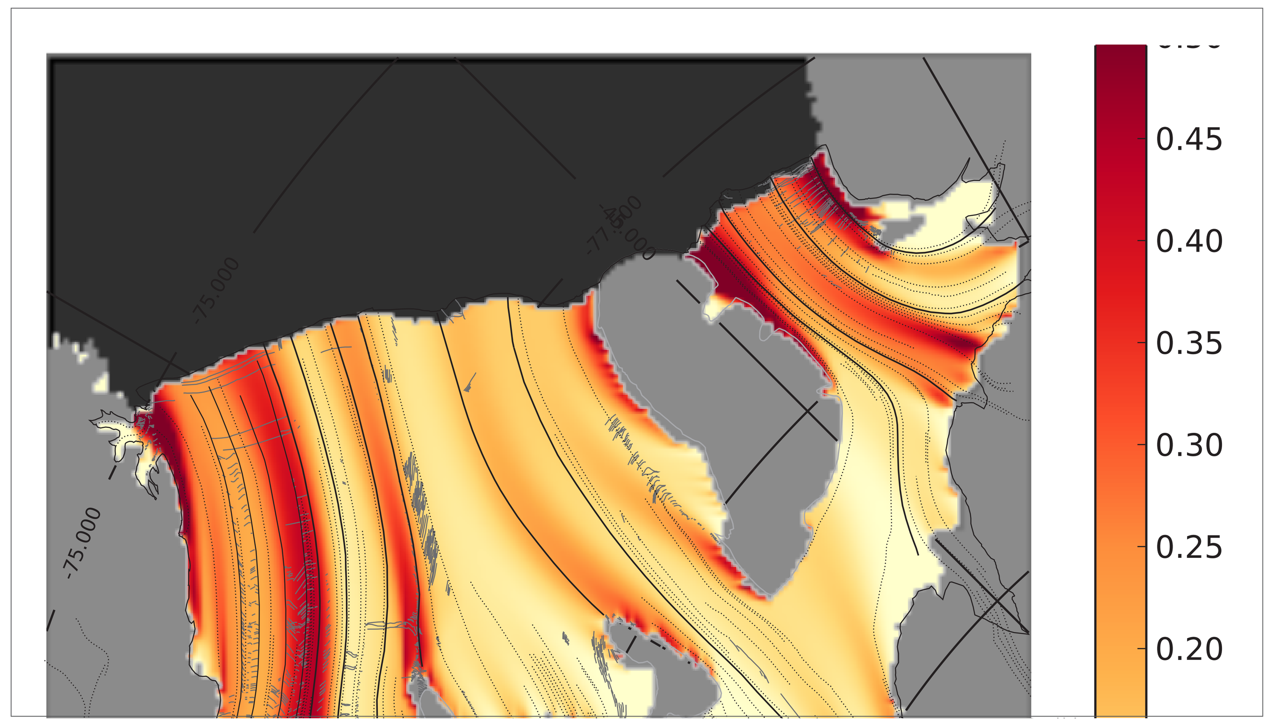

Fig.1: Schematic of confined ice shelf spreading towards ocean. Arrows denote expansion and compression along and across the main flow direction.

Beyond the confinement ice shelves can spread also sidewards and crevasse propagation and rift opening is observed to occur both parallel and perpendicular to the main flow direction. Tabular icebergs get detached from the ice shelf along intersecting rifts, which is called calving.

Spreading or compression is prescribed by strain rates defined as the symmetric part of the gradient of the vertically integrated velocities in the ice

$$\dot{\epsilon} = \dot{\epsilon}_{i,j} := \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$

A first-order kinematic relation between a temporally-averaged horizontal calving rate, C, and the rotationally invariant determinant of the strain rate or its eigenvalues, $\dot{\epsilon}_+$ and $\dot{\epsilon}_-$, at the terminus is given by

$$C_1 := K_1 \cdot \det(\dot{\epsilon}) = K_1 \cdot \dot{\epsilon}_+ \cdot \dot{\epsilon}_- \quad \text{if} \quad \dot{\epsilon}_\pm > 0$$

The proportionality constant, K, comprises all material properties of the ice at the calving front.[3]

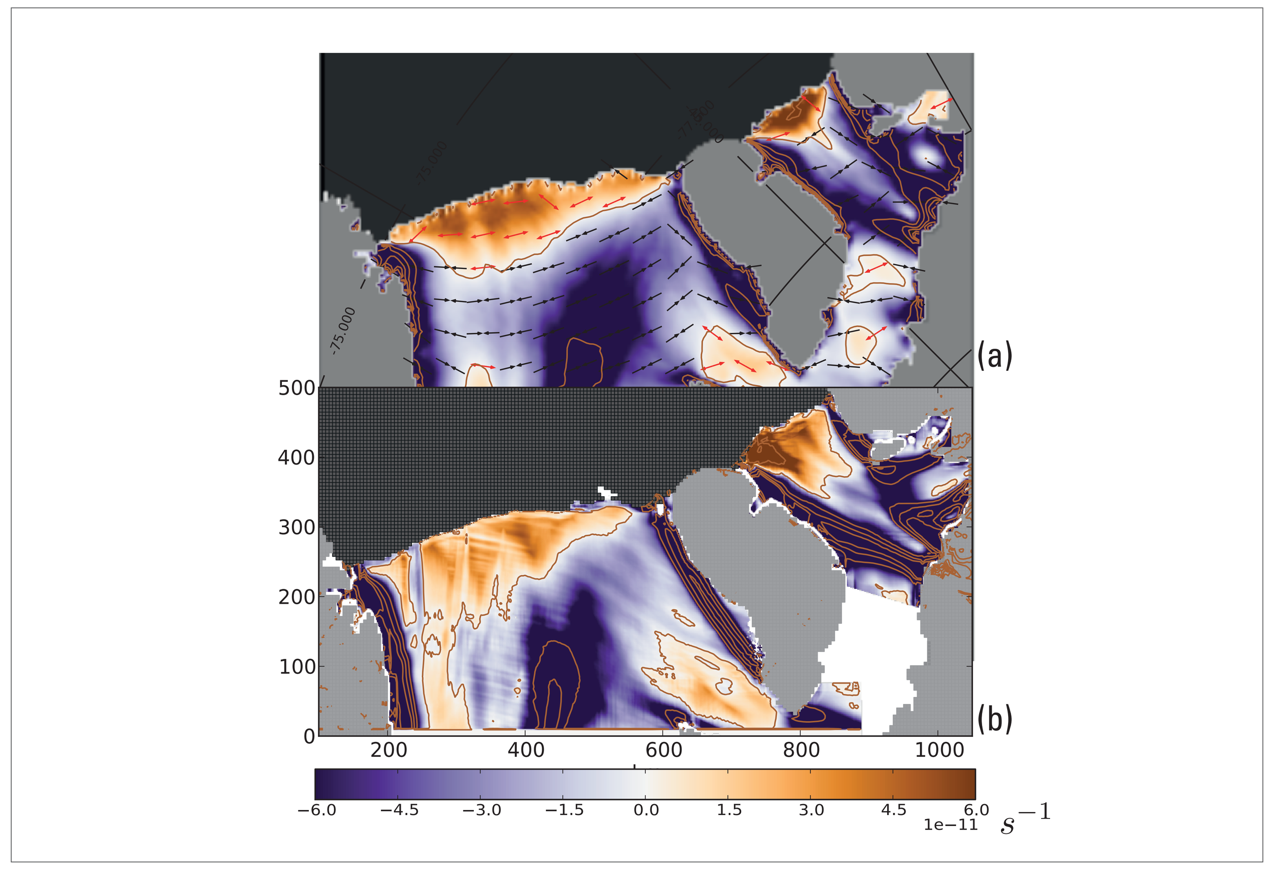

Fig.2: Minor strain rate eigenvalue, $\dot{\epsilon}_-$, derived from (a) a diagnostic model in Shallow Shelf Approximation (SSA) and from (b) observed surface velocities (I. Joughin) reveal a transition from compressive to extensive flow in the front region of Filchner-Rønne Ice Shelf, which can be associated with a stabilizing arch (Doake et al., 1996).

Fracture density field

Crevasses are mostly initiated in regions of strong side shear or close to the grounding line. The fractured ice is transported downstream through regions, where the strain rate regime may allow for propagation or closure of existing fractures. We define a measure for the density of abundant fractures as $\phi \in [0,1]$ and let it advect with the ice.[4] Contributions to the fracture density field when a certain critical value for the major principal strain rate component is exceeded, can be defined as (see Pralong & Funk 2005, with constant B)

$$f_s := B \cdot (1-\phi) \cdot (\dot{\epsilon}_+ - \dot{\epsilon}_{cr}) \quad \text{if} \quad \dot{\epsilon}_+ > \dot{\epsilon}_{cr}$$

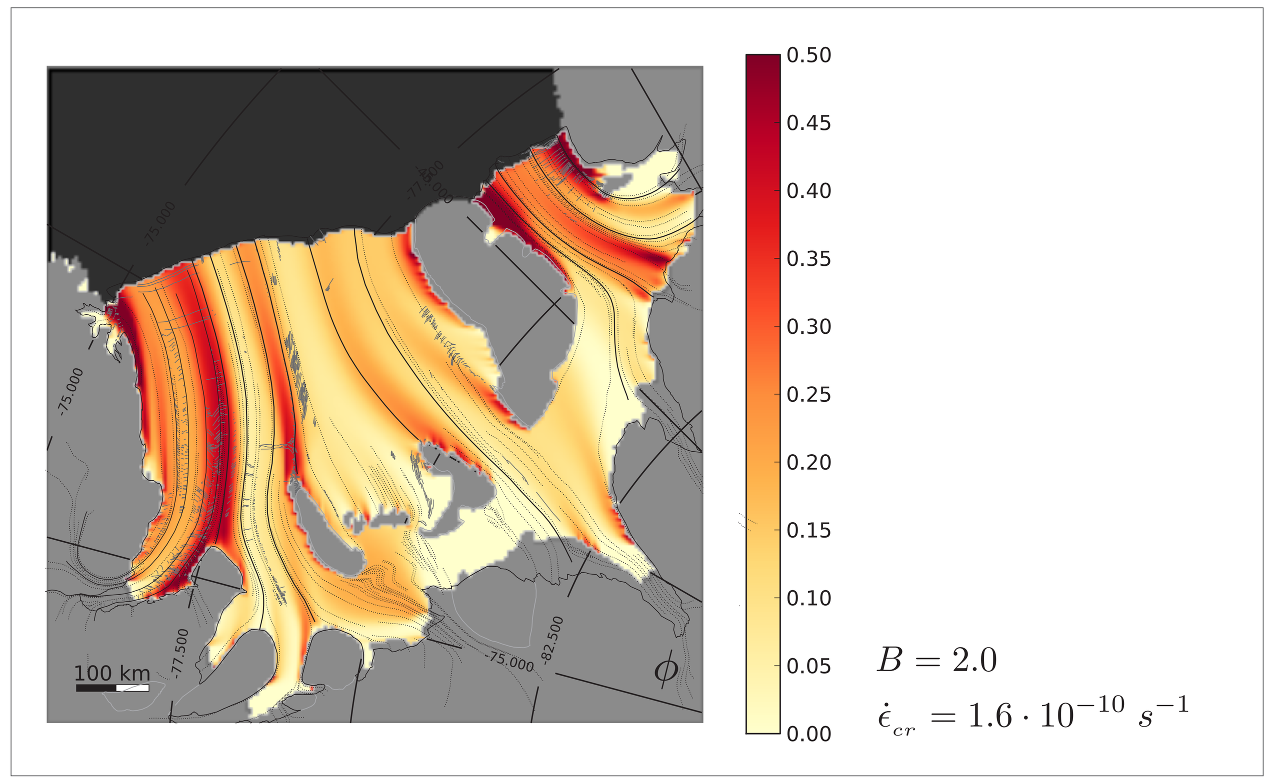

Fig.3: Steady state fracture density field for Filchner-Rønne with constant boundary condition. The location of redish areas agree well with overlaid observed bands of surface features (Hulbe et al., 2010).

Calving events are more likely to occur when the ice at the front is highly fractured. With the help of the fracture density field we find a calving relation at the front as delayed response to fracture processes occurring further upstream. Hence, we can define a fracture-enhanced calving rate as

$$C_2 := K_2(\phi) \cdot \det(\dot{\epsilon})$$

Observed fracture bands in ice shelves act as zones of weak ice rheology and partly detach adjacent ice shelf areas. The fracture density field can be used to account for these affects to simulate more realistic velocity distributions and gain possibly a better understanding of catastrophic calving events.

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