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A hybrid ice model - Including small scale icebergs into sea-ice models

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1 Introduction

2 Hyprid ice-mélange model

3 Numerical results

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Ice-mélange

- icebergs store a lot of freshwater
- Antarctic & Greenland Ice Sheet mass loss has increased (Kjeldsen, 2015 & Depoorter, 2013)
- climate models usually do not resolve nor parameterize ice mélange

Aim: efficiently model ice mélange in climate models

The Economic Times: *NASA scientists fly over Greenland to track melting ice*, **visited: 26.11.2020**

Ice-mélange model

Parameterization

- e.g buttressing effect (Schlemm and Levermann 2021)

Particle models

- sea-ice floes and icebergs are particles (Robel 2017)
- numerically to expensive for climate models

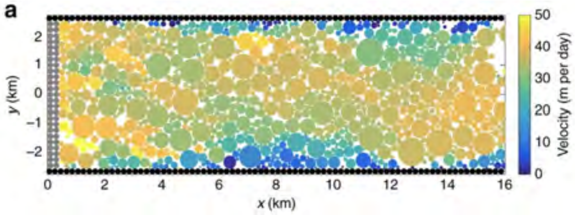

Figure source: Robel 2017

Ice-mélange model

Continuum models

- single continuum e.g. (Burton et. al 2018)
- joint continuum sea-ice and icebergs for cavitating fluid (Vankova and Holland 2017)

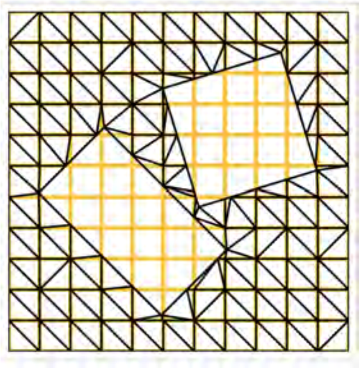

Figure source: Vankova and Holland 2017

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How to efficiently include icebergs?

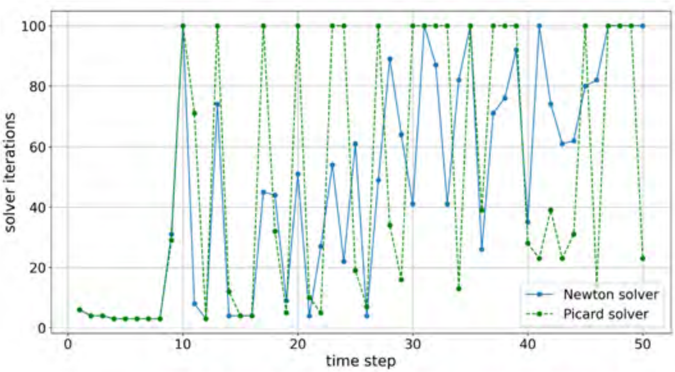

Figure: simple test case with a spatial resolution of 100m

Aim: represent icebergs as particles ($\sim 100s$ m) in large scale climate simulations ($\sim 10s$ km)

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How to efficiently include icebergs?

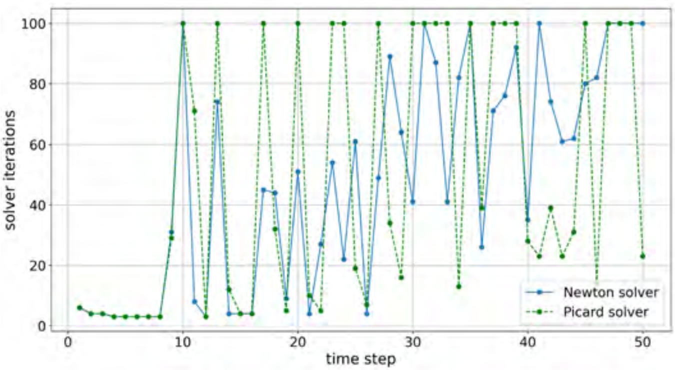

Figure: simple test case with a spatial resolution of 100m

Aim: represent icebergs as particles ($\sim$ 100*s* m)
in large scale climate simulations ($\sim$ 10*s* km)

Hybrid ice-mélange model

Idea: joint continuum: icebergs as thick compact pieces of sea ice

Goal:

- realization in the **viscous-plastic** sea-ice model
- represent icebergs by **particles** and couple them to the continuum

Figure: coupling sea-ice continuum and iceberg particles

Hyprid ice-mélange model

Variables:

- ice-mélange velocity $\mathbf{v} \in \mathbb{R}^2$
- icebergs are modeled by particles $\{p\}$ with radius r_p and height h_p
- ice-mélange thickness H and concentration A

$$H(x,y,t) = \begin{cases} H_{ice}(x,y,t) & \text{if} \quad p(x,y,t) \notin (x,y) \in \Omega, \\ h_p & \text{if} \quad p(x,y,t) \in (x,y) \in \Omega. \end{cases}$$

$$A(x,y,t) = \begin{cases} A_{ice}(x,y,t) & \text{if} \quad p(x,y,t) \notin (x,y) \in \Omega, \\ 1 & \text{if} \quad p(x,y,t) \in (x,y) \in \Omega. \end{cases}$$

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Momentum equation

$$\rho_{\text{ice}} H \partial_t \mathbf{v} = \underbrace{\text{div}(\boldsymbol{\sigma})}_{\text{rheology}} + \underbrace{F}_{\text{external forces}}$$

Modified rheology

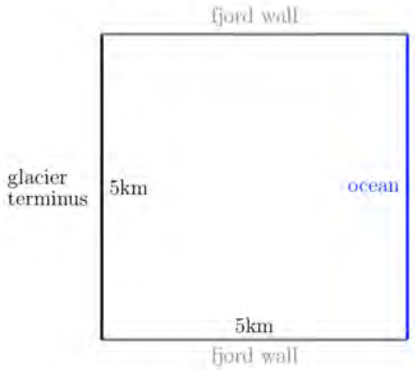
$$\boldsymbol{\sigma} = 2\eta\dot{\epsilon} + (\zeta - \eta)(\dot{\epsilon}_{11} + \dot{\epsilon}_{22}) I - \frac{P - T}{2}\delta_{ij}, \tag{1}$$

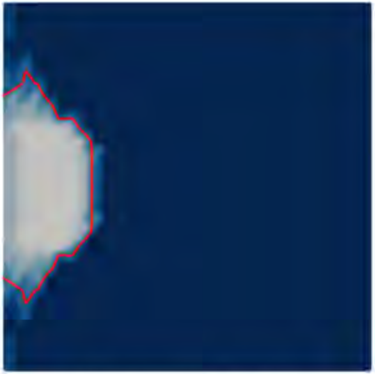
with the bulk and shear viscosities

$$\zeta = \frac{P + T}{2\Delta(\mathbf{v})}, \quad \eta = \frac{\zeta}{4} = \frac{P + T}{2\Delta(\mathbf{v})4}. \tag{2}$$

$$T = \begin{cases} 0 & \text{if } p(x, y, t) \notin (x, y), \\ P^{\star} H & \text{if } p(x, y, t) \in (x, y). \end{cases} \tag{3}$$

Iceberg pushed against a wall

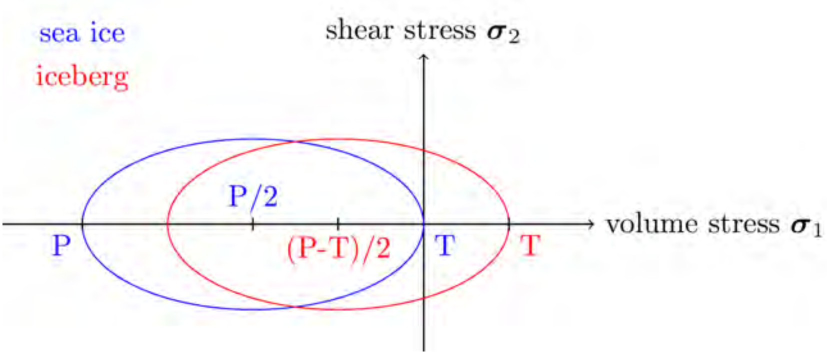




(a) standard VP rheology

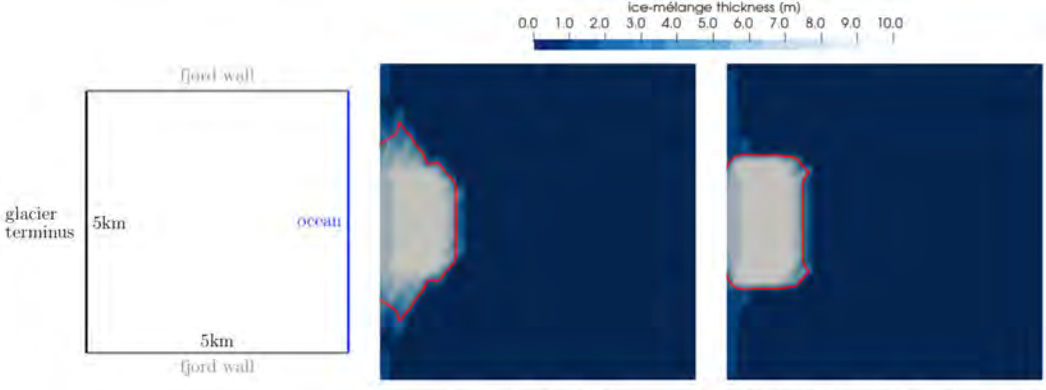
Idea: Include tensile strength for icebergs into the rheology

Viscous-plastic rheology



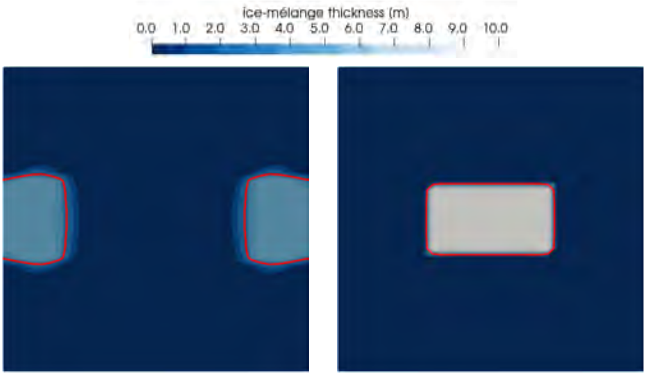
Note: Tensile strength has been introduce to the visous-plastic model
e.g. landfast ice: König and Holland (2010);
modification of the rheology Ringeisen et. al (2021)

Modified rheology for iceberg



(a) standard VP rheology (b) VP rheology with tensile strength

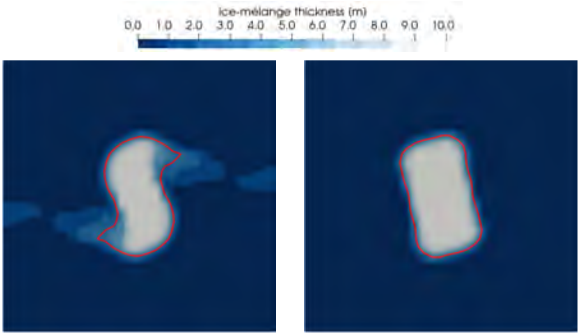
Modified rheology for iceberg - diverging wind field



(a) standard VP rheology

(b) VP rheology with tensile strength

Modified rheology for iceberg - shearing wind field



(a) standard VP rheology

(b) VP rheology with tensile strength

Coupling of particle and continuum methods

Let K be a grid cell:

- iceberg concentration and thickness

$$A_{\text{iceberg}}|_K = \sum_{p\in K} \frac{\pi r_p^2}{|K|}, \quad H_{\text{iceberg}}|_K = \sum_{p\in K} \frac{h_p \pi r_p^2}{|K|}, \tag{4}$$

- ice-mélange concentration and thickness

$$A|_K = \min(A_{\text{iceberg}}|_K + A_{\text{ice}}|_K, 1), \tag{5}$$

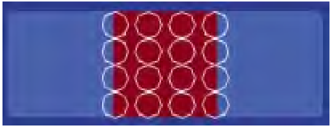
$$H|_K = H_{\text{iceberg}}|_K + H_{\text{ice}}|_K. \tag{6}$$

Coupling of particle and continuum methods

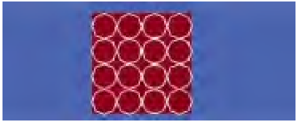
- **tensile strength**

$$T = \begin{cases} 0 & \text{if } A_{\text{iceberg}}|K < \frac{\pi(0.5\sqrt{|K|})^2}{|K|}, \\ cP^\star HA_{ice} & \text{else.} \end{cases} \qquad (7)$$

- **iceberg motion**: divergent wind field



without sea-ice



with sea-ice

Iceberg coupling

- The particles are advected based on the continuum ice-mélange velocity **v**.
- Inelastic collision model for overlapping particles

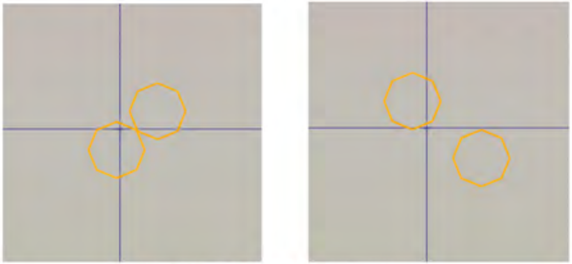


Figure: Closeup of ceberg-iceberg interaction.

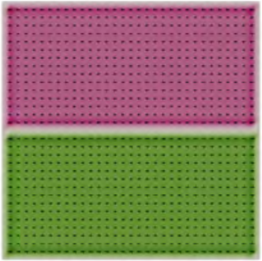


Figure: Velocity field.

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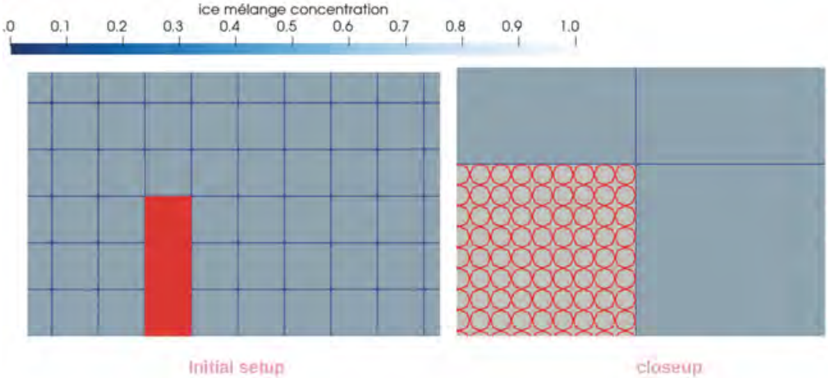
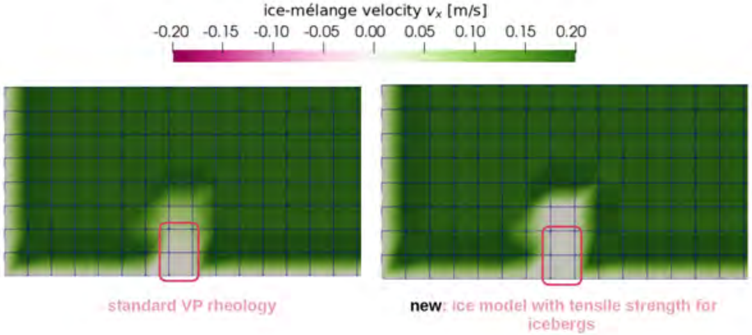
Subgrid scale grounding



- three grid cells filled with icebergs (4096 per cell)
- $r_p = 125$m
- 16 km grid cells
- ocean forcing from the left to the right
- lower two grid cells filled with grounded icebergs

Tensile strength for icebergs



- three grid cells filled with icebergs (4096 per cell)
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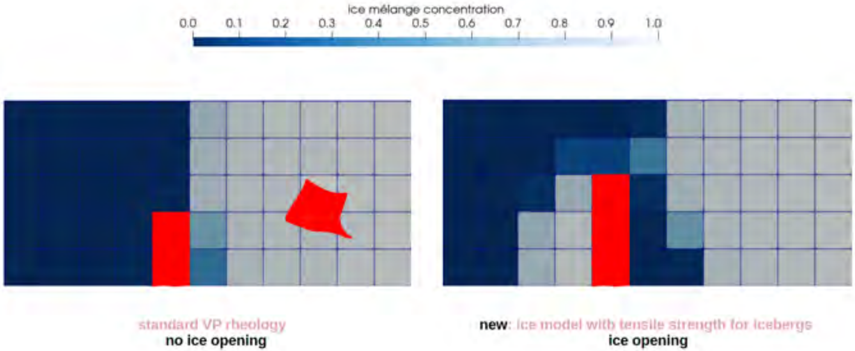
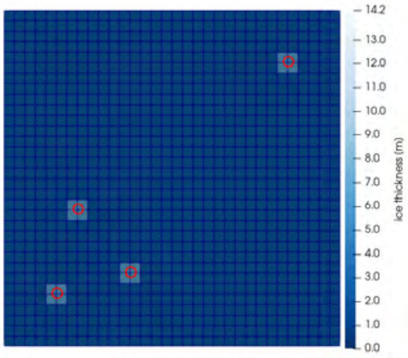
- lower two grid cells filled with **grounded icebergs**

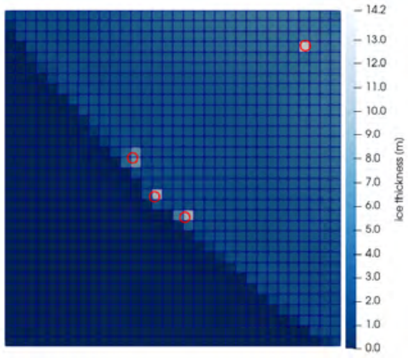
Tensile strength for icebergs



Advection test: Icebergs trapped in sea-ice



(a) initial setup



mélange transported with diagonal wind

Model limitations and perspectives

limitation

- iceberg size much smaller than horizontal grid cell
- icebergs are round disks
- threshold for the tensile strength

perspectives

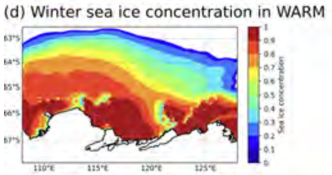
- coupling of continuum sea-ice models and particle iceberg models
- model landfast ice in the Southern Ocean poorly represented in climate models

Perspective: future land fast ice projections


Research article

15 Nov 2022

Influence of fast ice on future ice shelf melting in the Totten Glacier area, East Antarctica

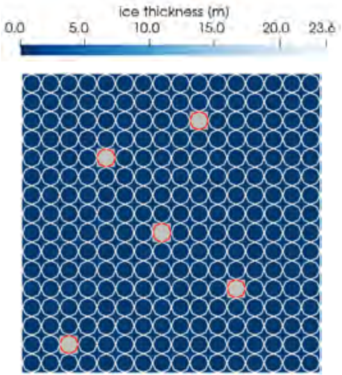


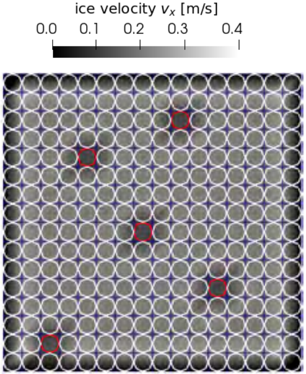
(Van Atcher et al 2022)

- need to include a realistic presentation of fast ice in climate models
- need to include moving icebergs

Alternative: Sea-ice floes and icebergs as particles

Set of particles $p = \{p_{\text{seaice}}, p_{\text{iceberg}}\}$,





circles: red=icebergs, white= sea-ice floes

Coupling to the continuum momentum equation

continuum mélange thickness

$$H|_K = \sum_{p \in K} \frac{h_p r_p^2}{|K|}, \quad (8)$$

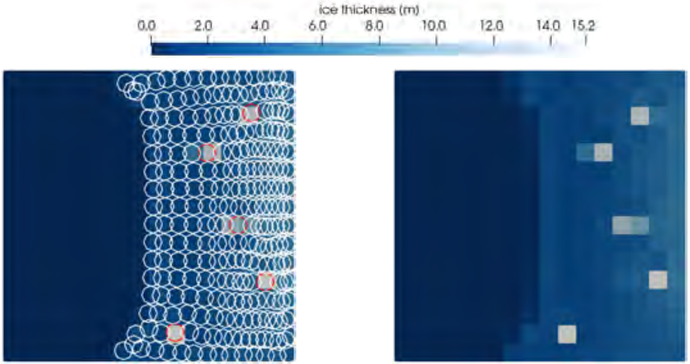
continuum mélange concentration

$$A|_K = \min(\sum_{p \in K} \frac{\pi r_p^2}{|K|}, 1) \quad (9)$$

To activate the tensile strength for the icebergs in the momentum equation :

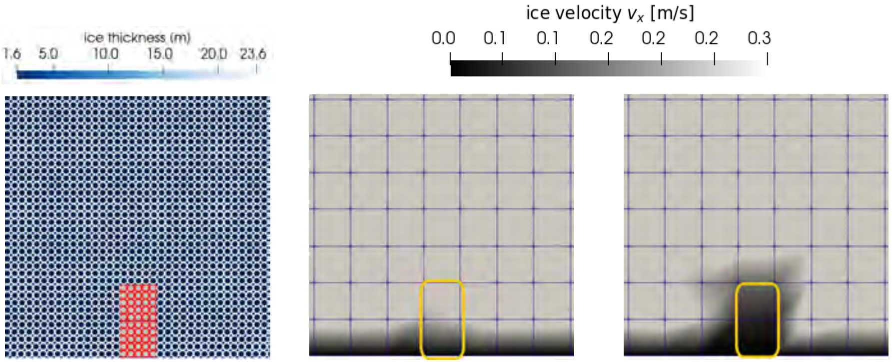
$$T = \begin{cases} 0 \text{ if } \sum_{p_{\text{iceberg}} \in K} \frac{\pi r_{p_{\text{iceberg}}}^2}{|K|} < \frac{\pi (0.5\sqrt{|K|})^2}{|K|}, \\ P^\star H^m \text{ else.} \end{cases} \quad (10)$$

Simple advection test: without particle collision



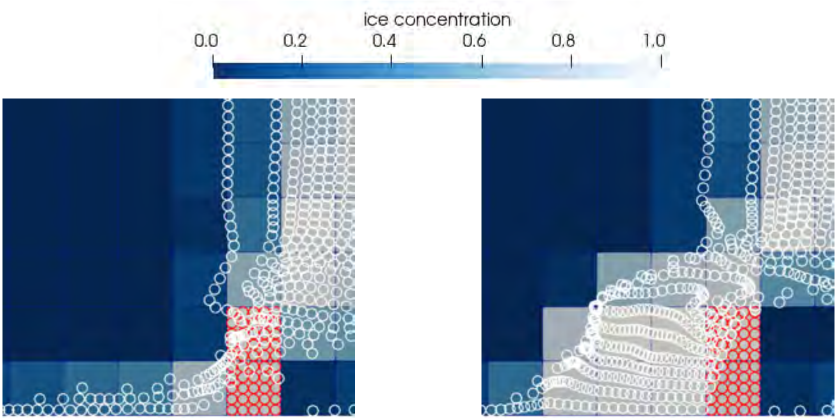
(a) particle representation (b) continuum mélange thickness

Subgrid iceberg grounding: sea-ice floes and icebergs as particles



(a) (b) no tensile strength (c) with tensile strength

Tensile strength for icebergs



(a) standard VP
sea-ice floes drift through icebergs

(b) new: with tensile strength for icebergs
sea-ice piles up in front of icebergs

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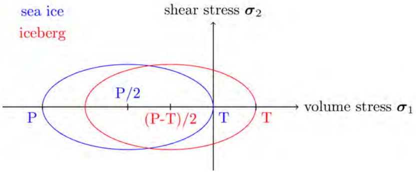
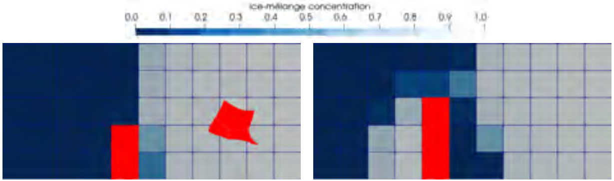
Summary-Development of a hybrid ice model

- joint continuum of sea-ice floes and icebergs
- modeling of icebergs via particles on a sub-grid scale
- coupling of continuum and particle method via a particle in cell scheme
- context of the viscous-plastic sea-ice model



Tensile strength for icebergs



(a) standard VP rheology
(b) VP rheology with tensile strength

Lead opening due to grounded icebergs

Kahl,Mehlmann, Notz: *A hybrid ice-mélange model based on particle and continuums methods*, **EGUsphere [preprint]**