On modelling a mechanically-challenging component of the climate system: sea ice

Véronique Dansereau

Aurélien Rigotti[1], Anne-Sarah Amblard[1], Nicolas Mokus[1], Jérôme Weiss[1]
Pierre Rampal[2], Laurent Brodeau[3], Aurélie Albert[2], Stéphanie Leroux[3],
Pierre Saramito[4], Einar Olason[5]
Thomas Richter[6]

1 ISTerre 2 IGE 3 datlas 4 Laboratoire Jean Kuntzmann 5 NERSC 6 Otto von Guericke Universität Magdeburg

Université Grenoble Alpes

Workshop "Interfaces dans le système climatique"
27-29 Mai 2024

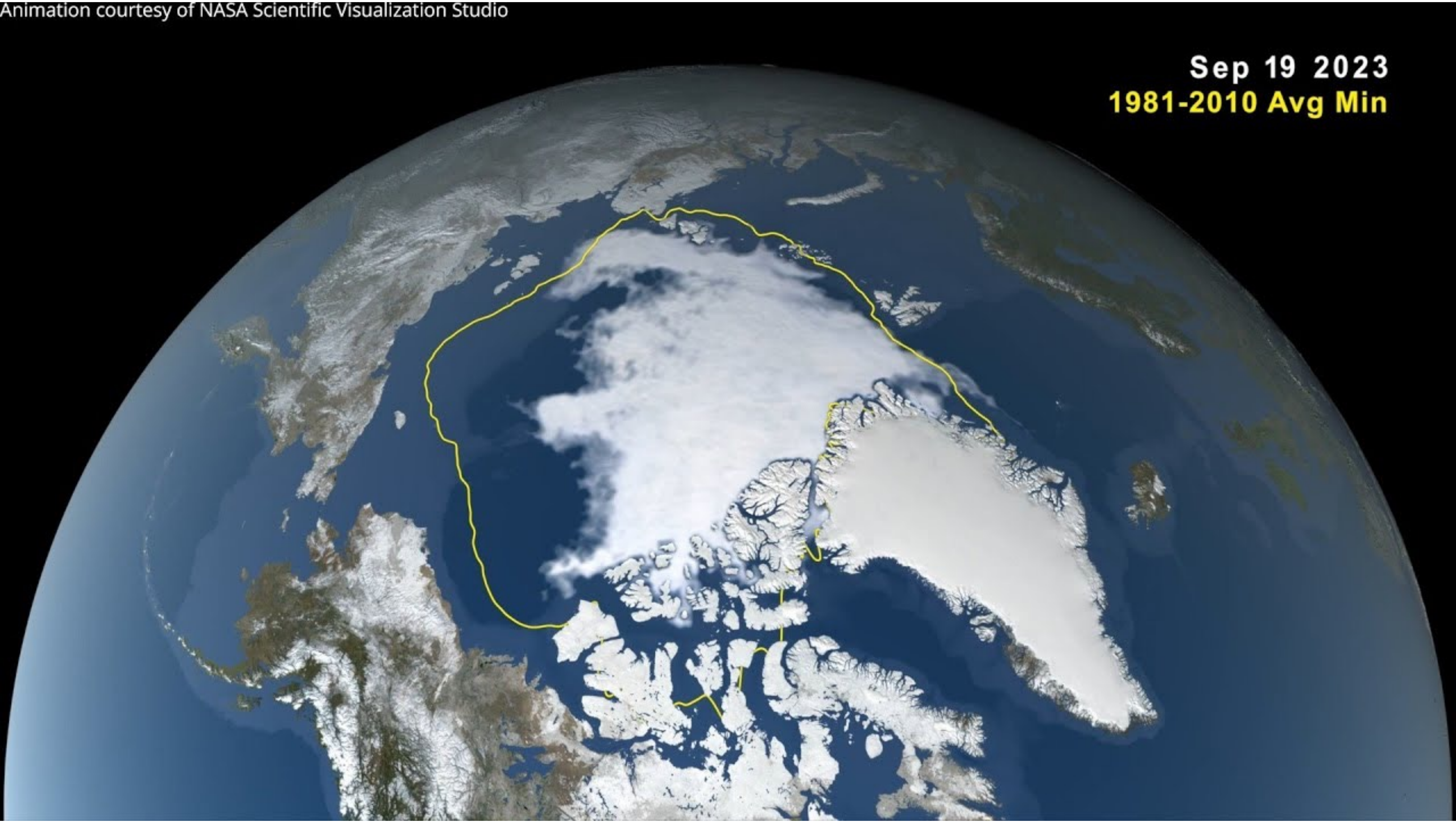
Schmidt Sciences

This research received support through Schmidt Sciences, LLC.

OUTLINE

- **What is sea ice?**
  - A mechanically-complex material
  - Why is this important?
- **How do we model it?**
  - Past approaches
  - Recent approach
  - Validations
- **What impact on the climatic system?**
  - (ongoing) coupling to the ocean
  - (ongoing) coupling to the atmosphere
- **Discussion?**

What is sea ice?



From: NASA Global Climate Change
https://www.youtube.com/watch?v=I0f9HjFqD6I

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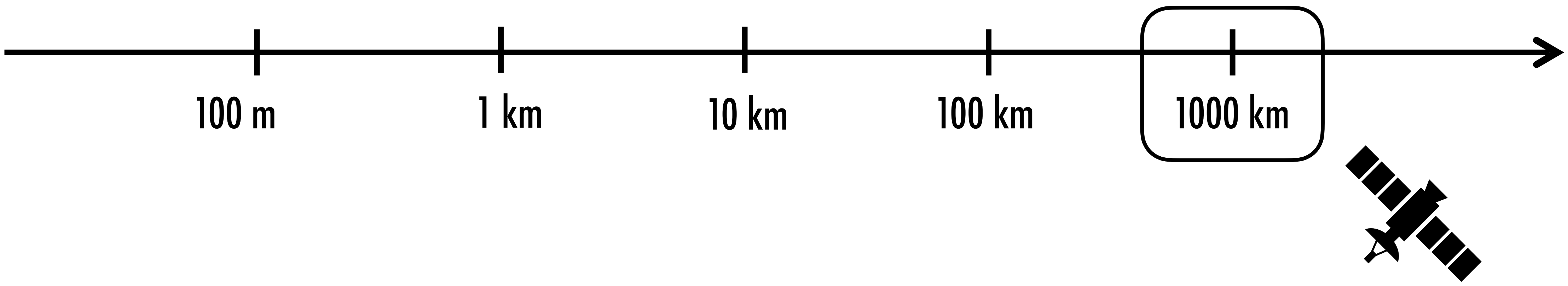

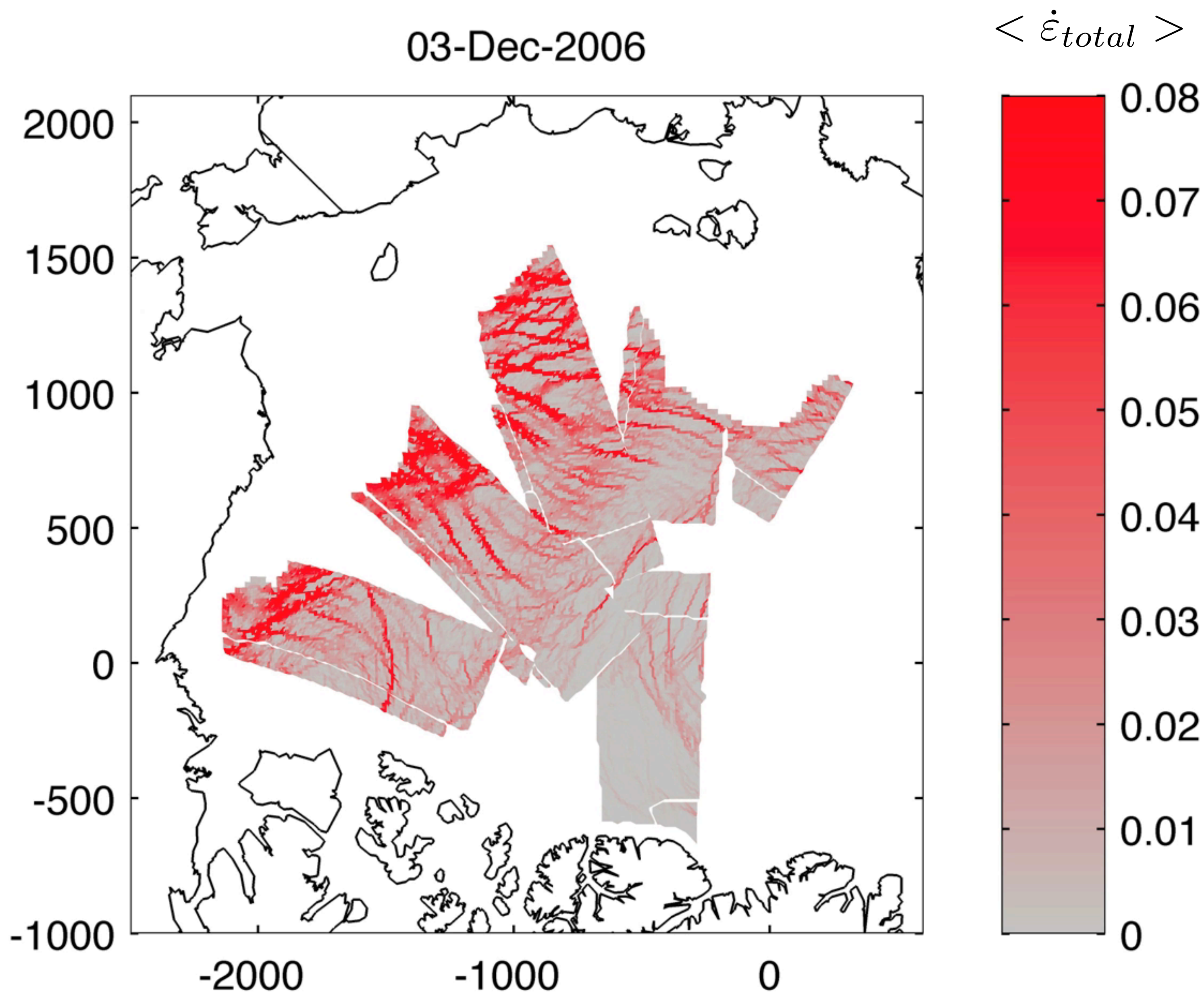

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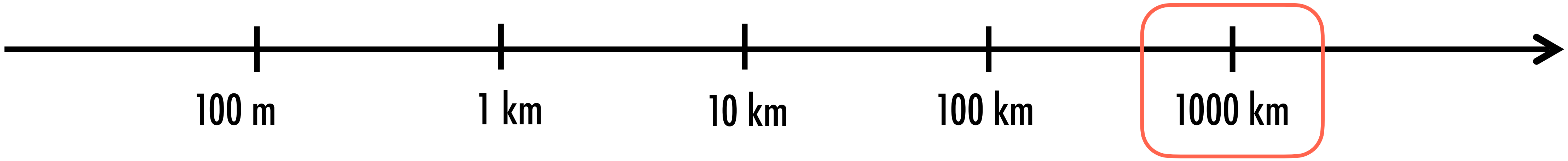

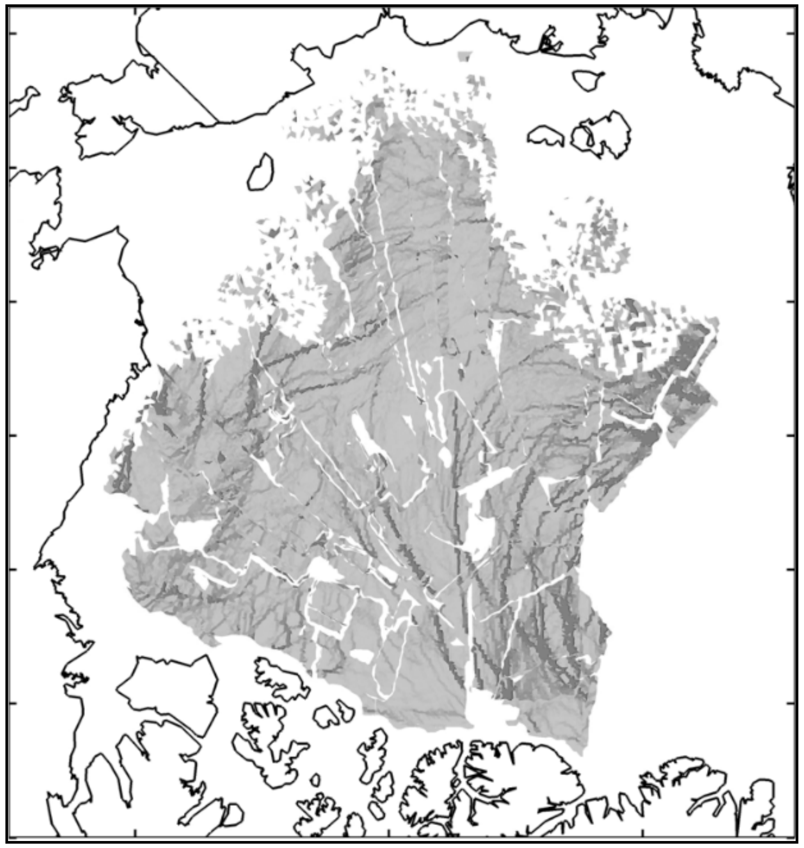

Deformation rate, from RGPS data (day^{-1})

Credit: S. Bouillon

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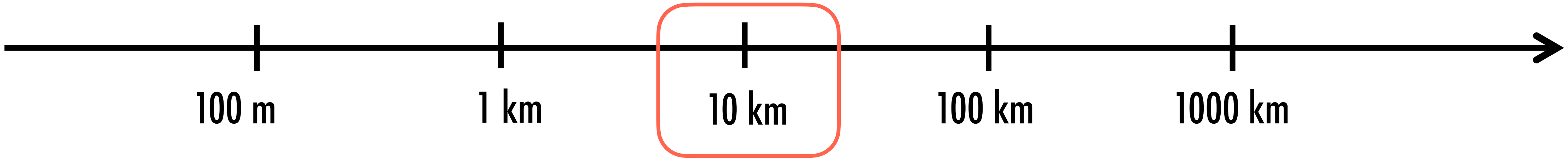
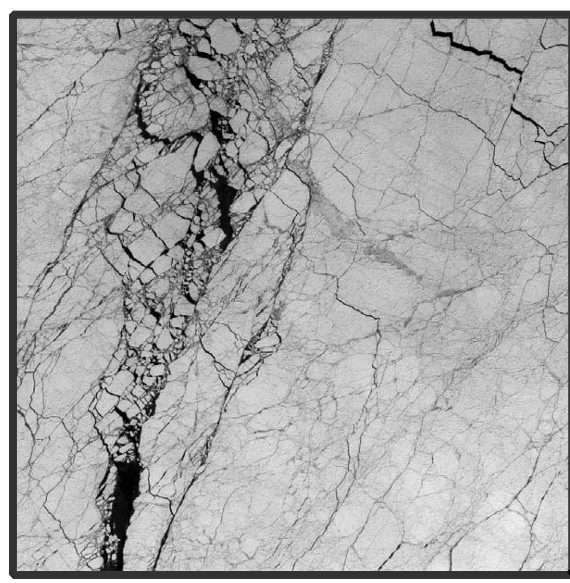
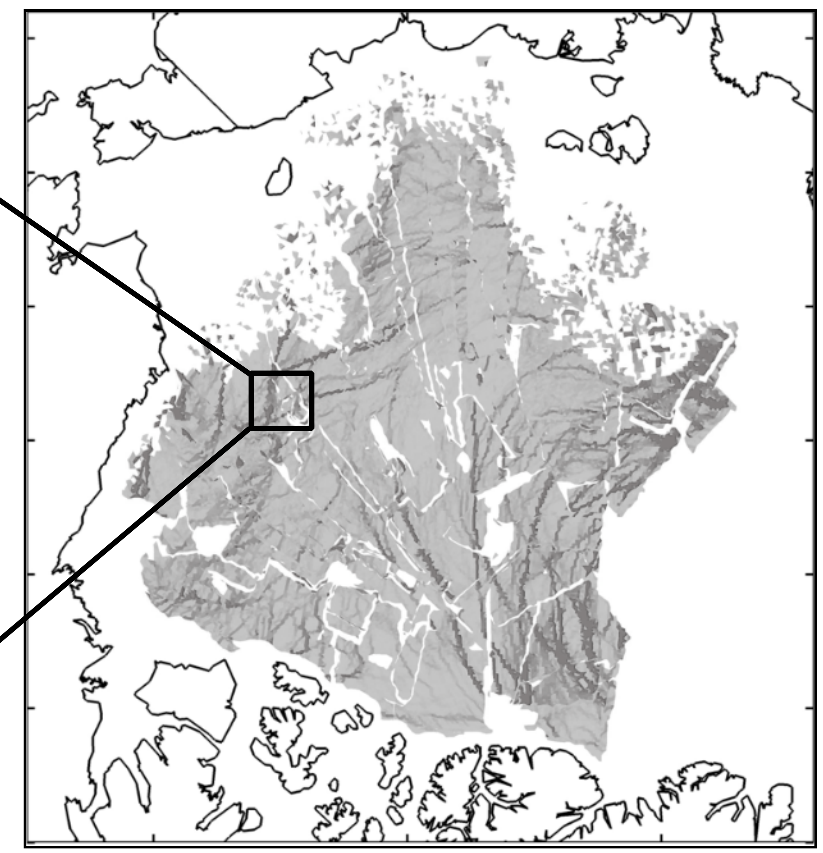




SPOT 50x50 km image



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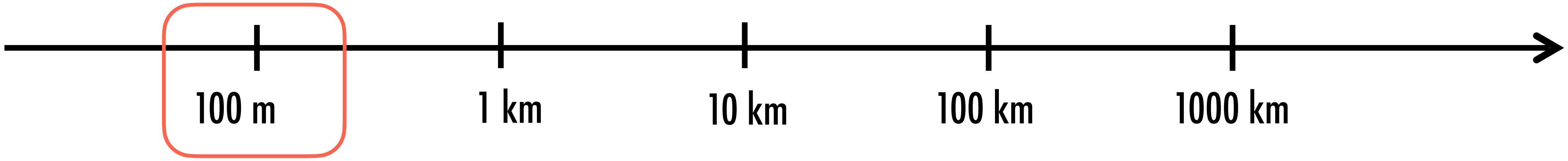
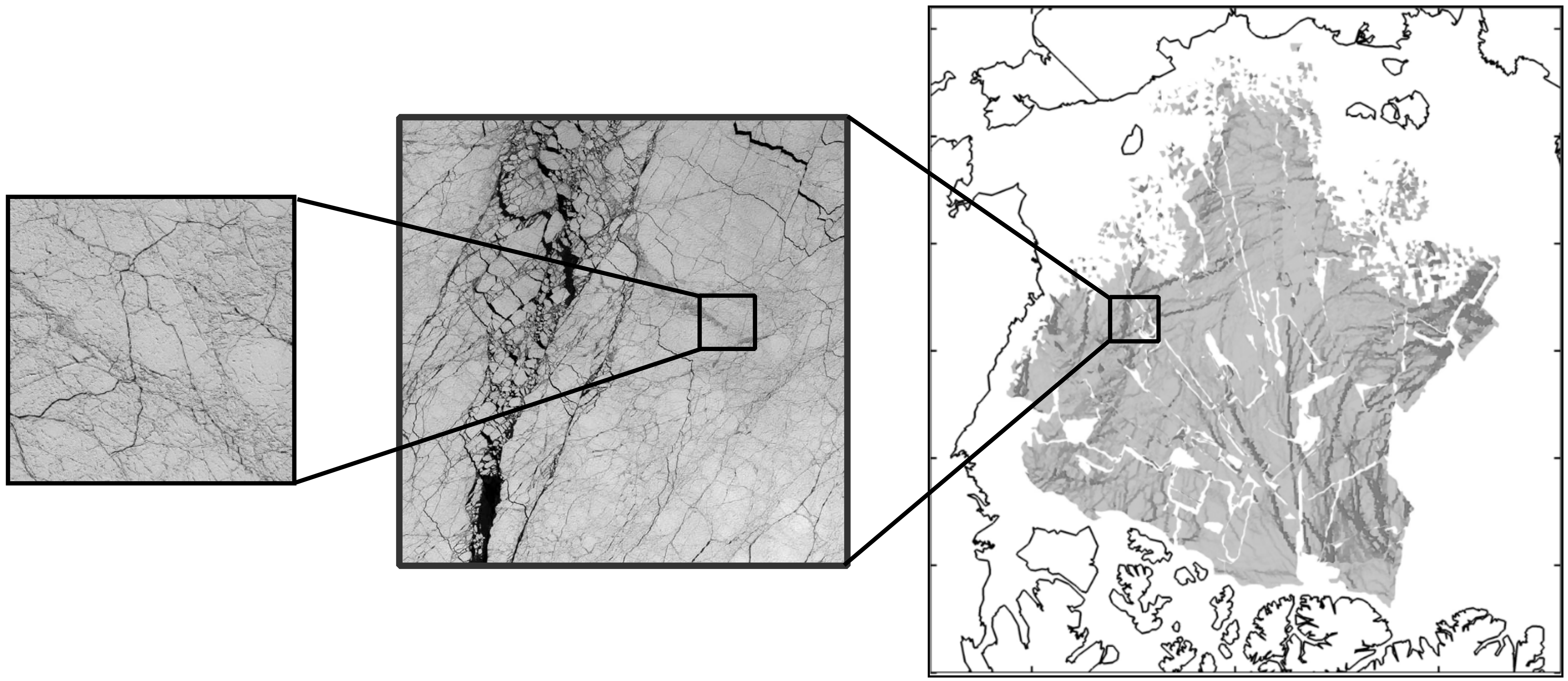
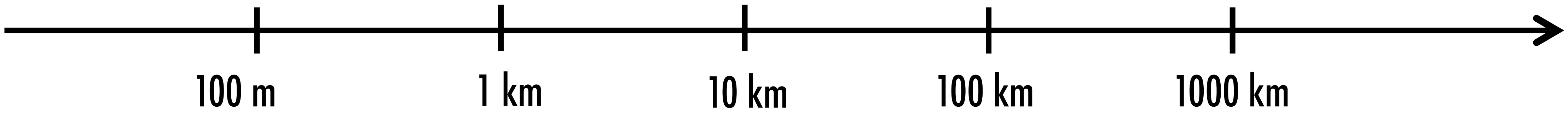


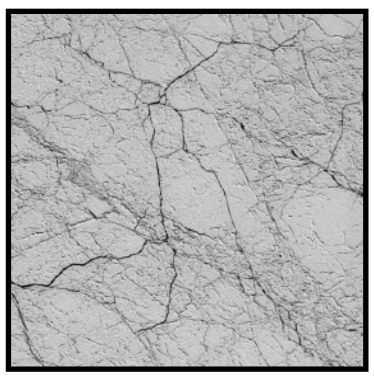


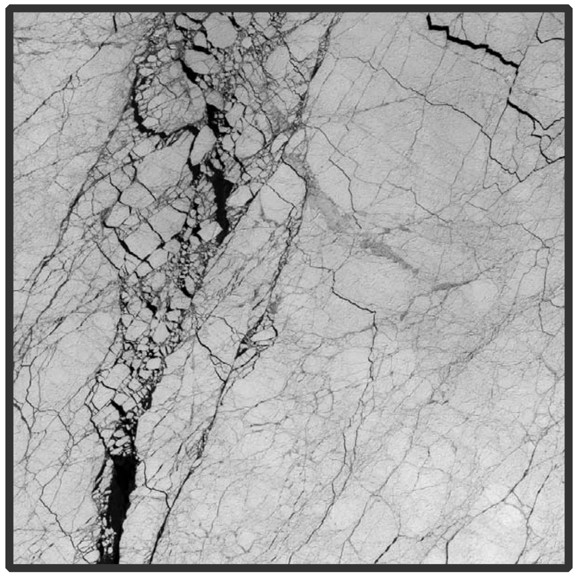
BRITTLE SOLID

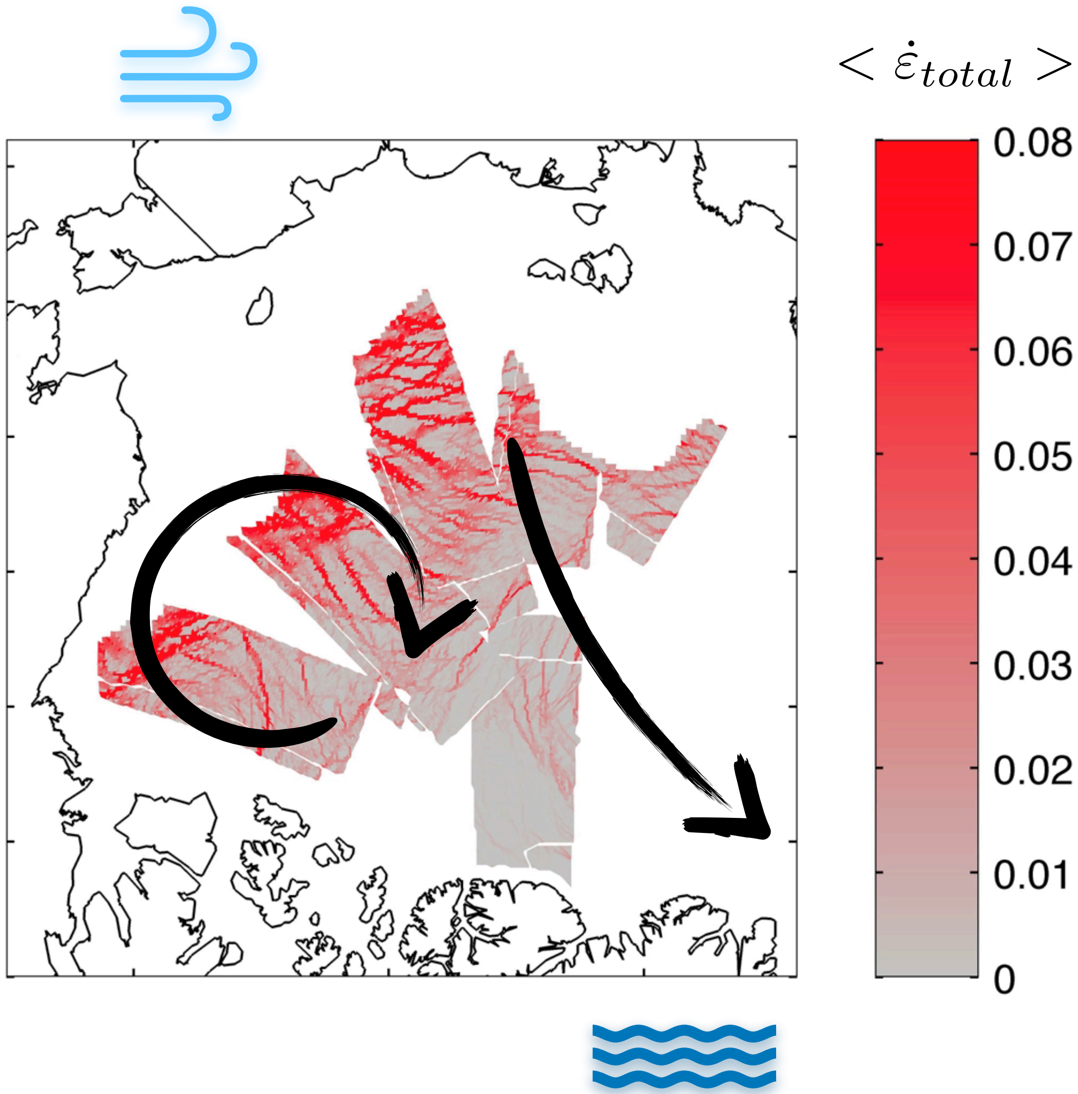
(fragile, ou cassant)

What is sea ice?









FLUID-*ish*

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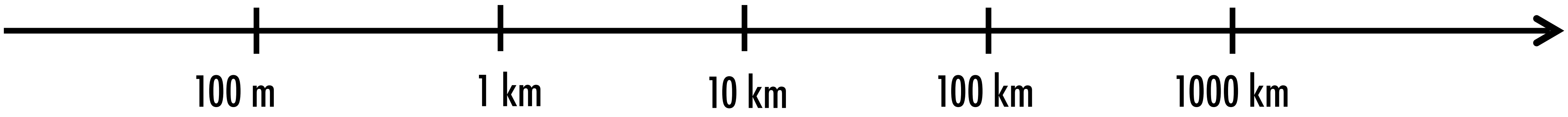

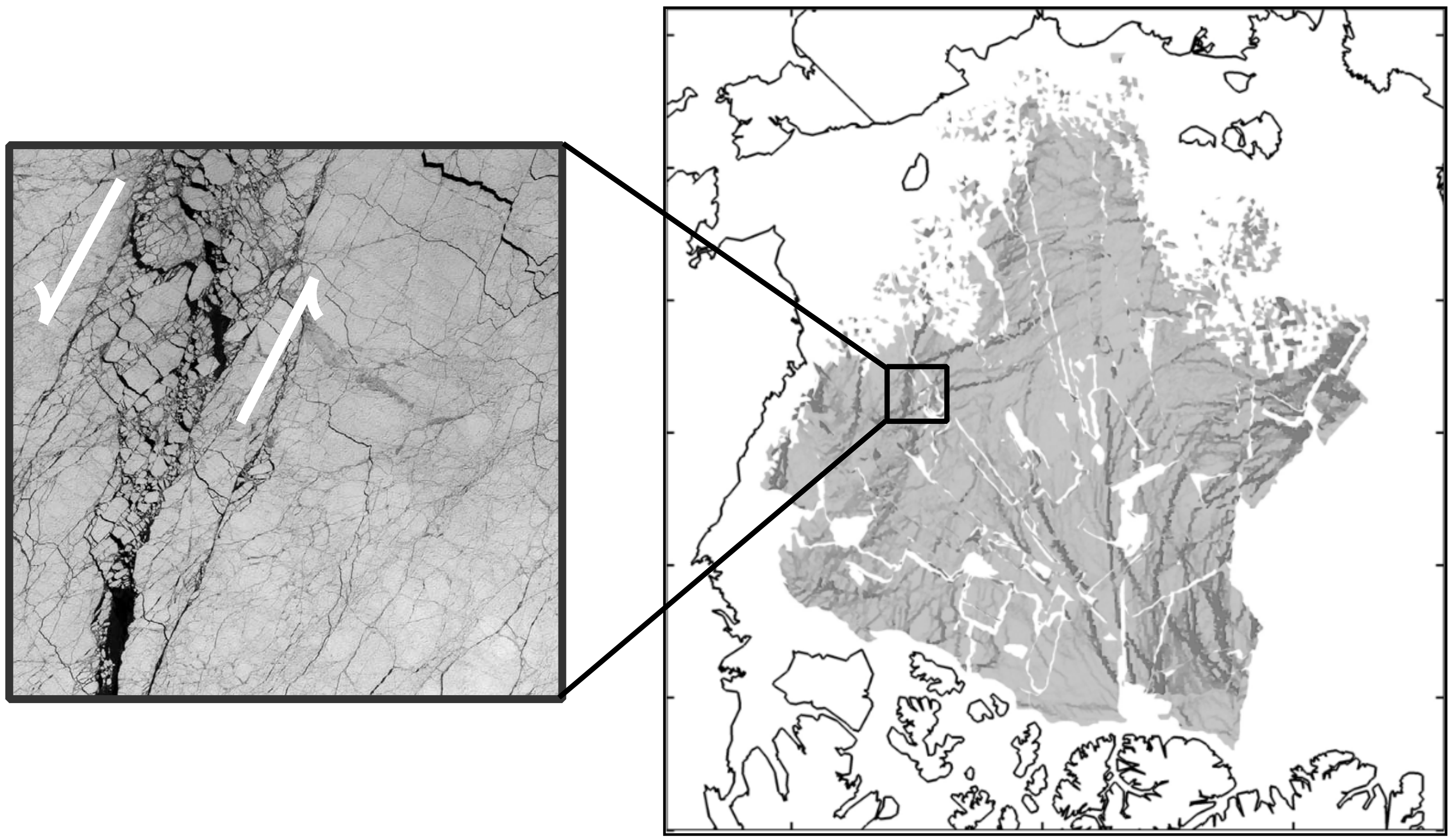

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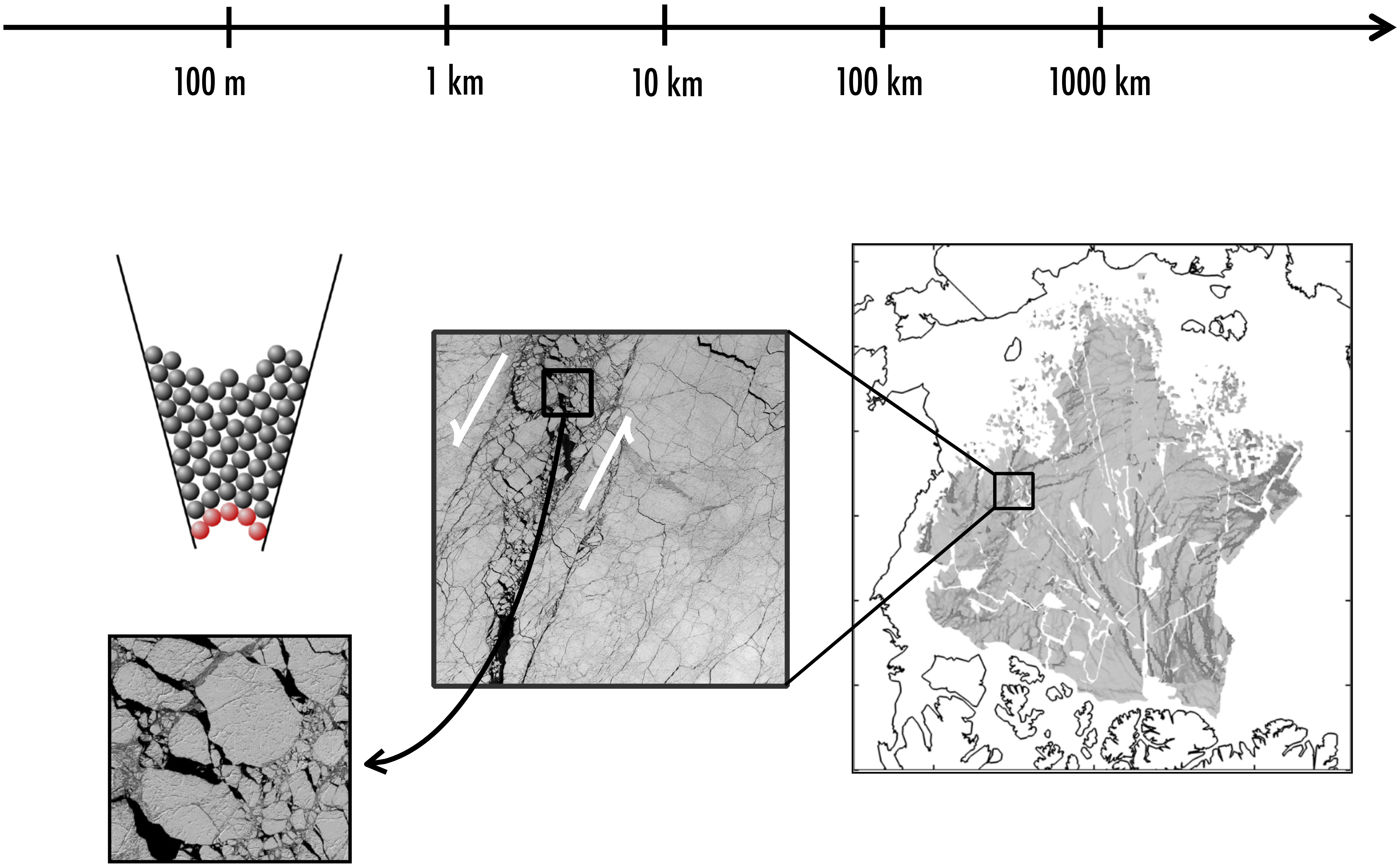
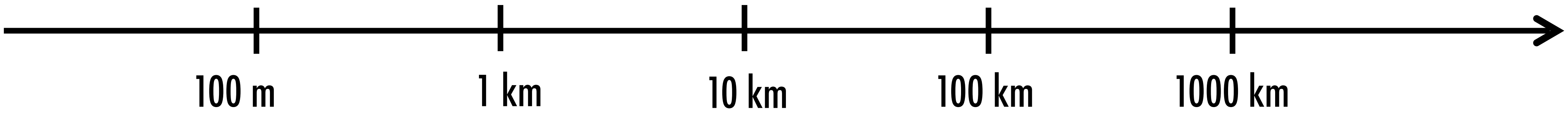
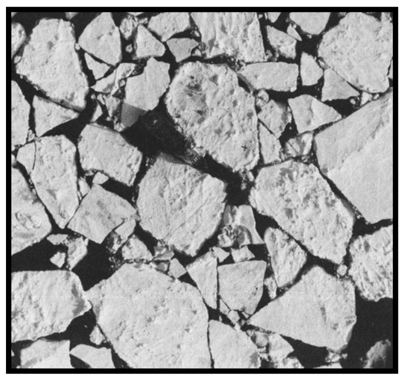


In shear bands
collision + friction
jamming

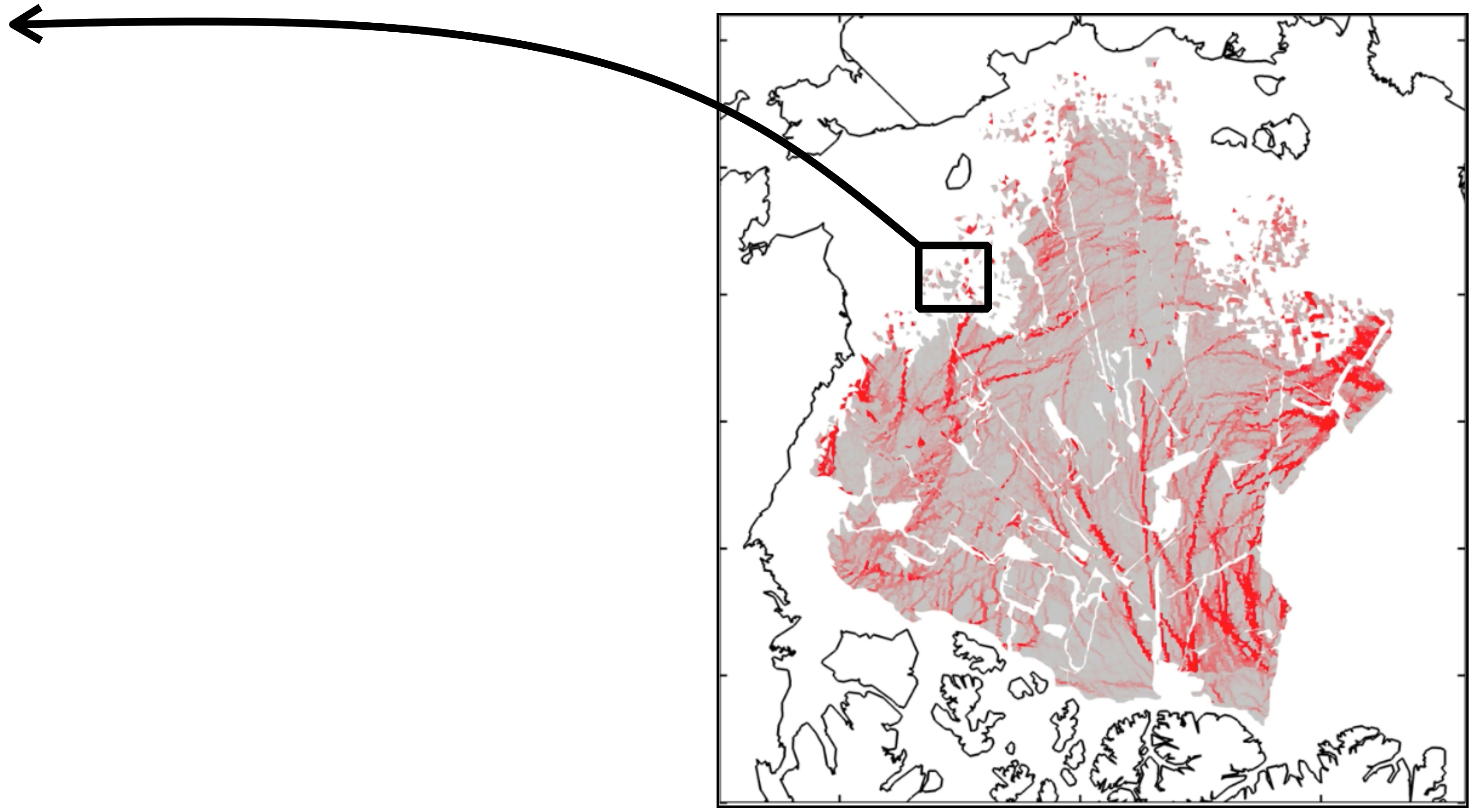
GRANULAR MEDIA

What is sea ice?





“Marginal Ice Zone”
wave breaking
collision+friction



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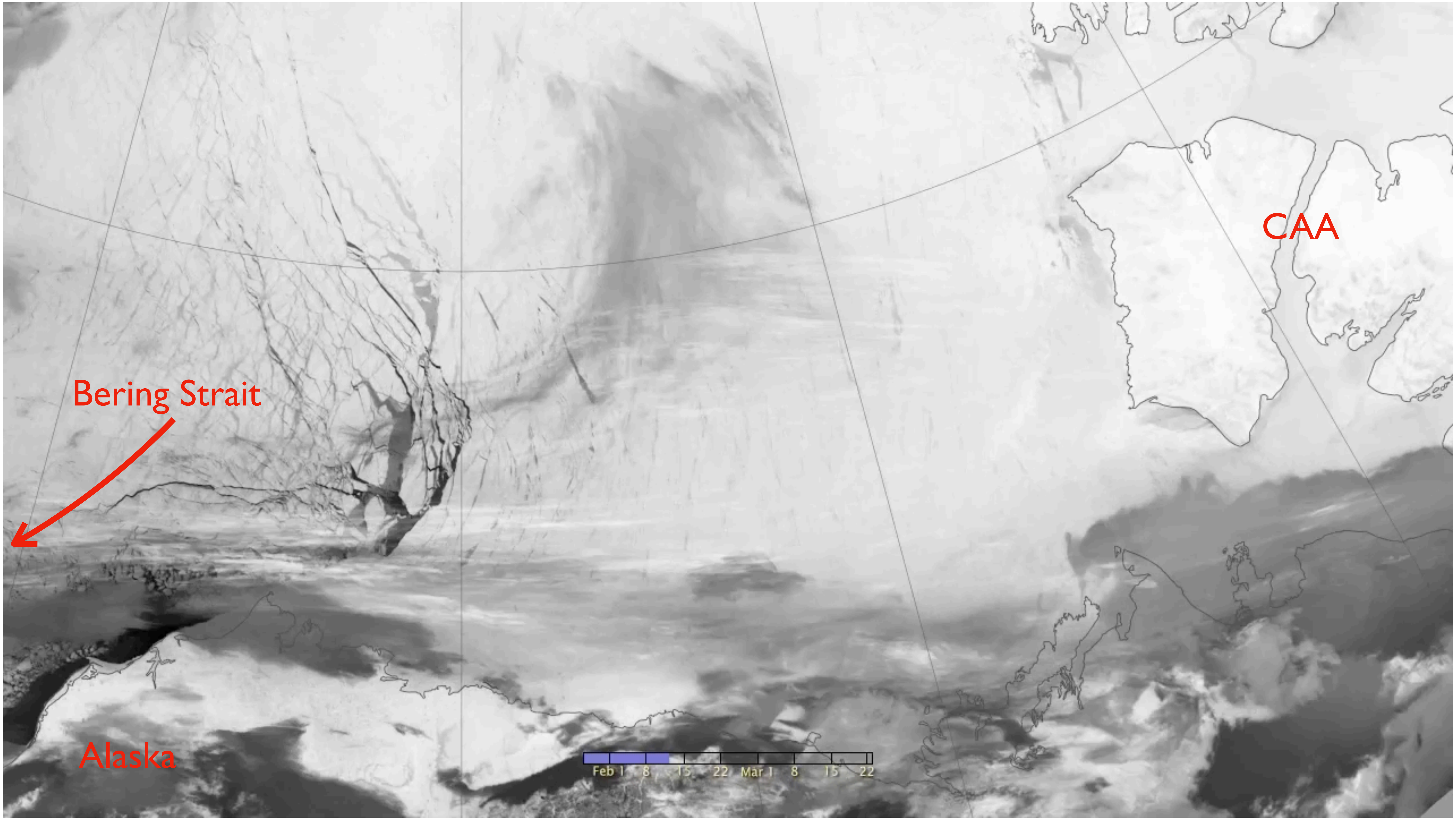
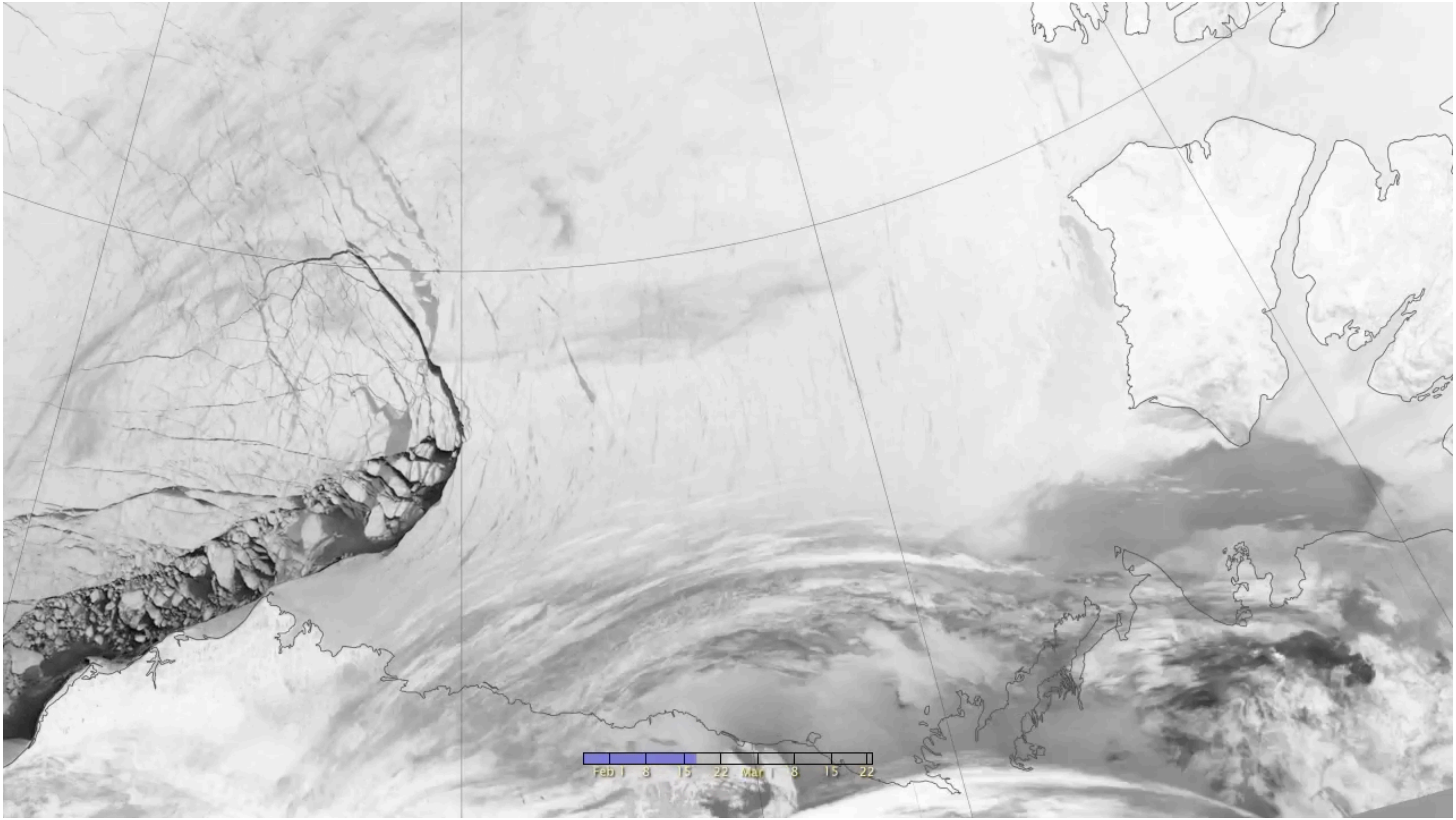


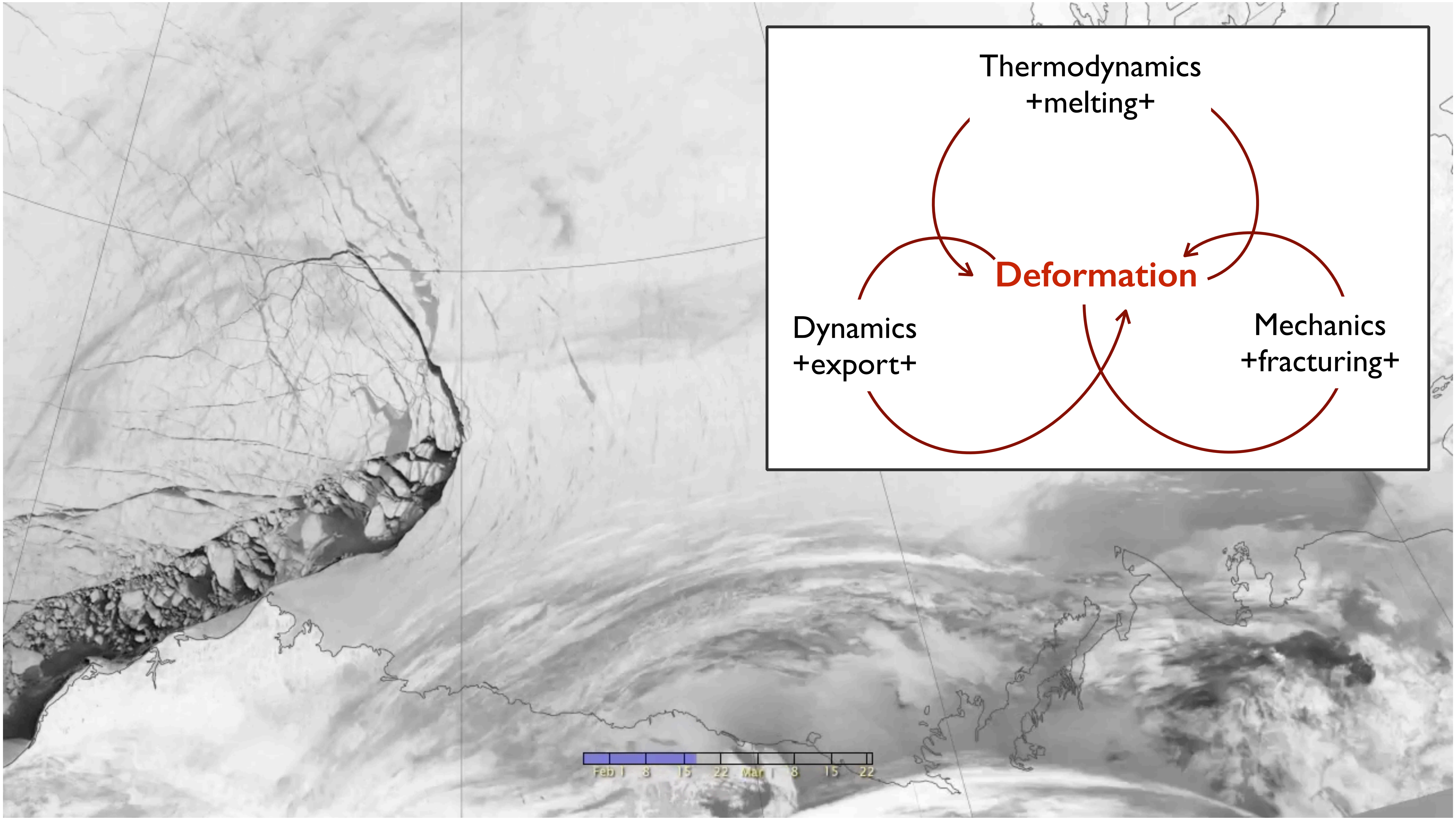
February 2013 : storm event in the Beaufort Sea
NASA/GSFC MODIS Rapid Response
https://earthobservatory.nasa.gov/

Why is this mechanical behavior ***important***?



BRITTLE SOLID → GRANULAR MEDIA → FLUID

Why is this mechanical behavior ***important***?



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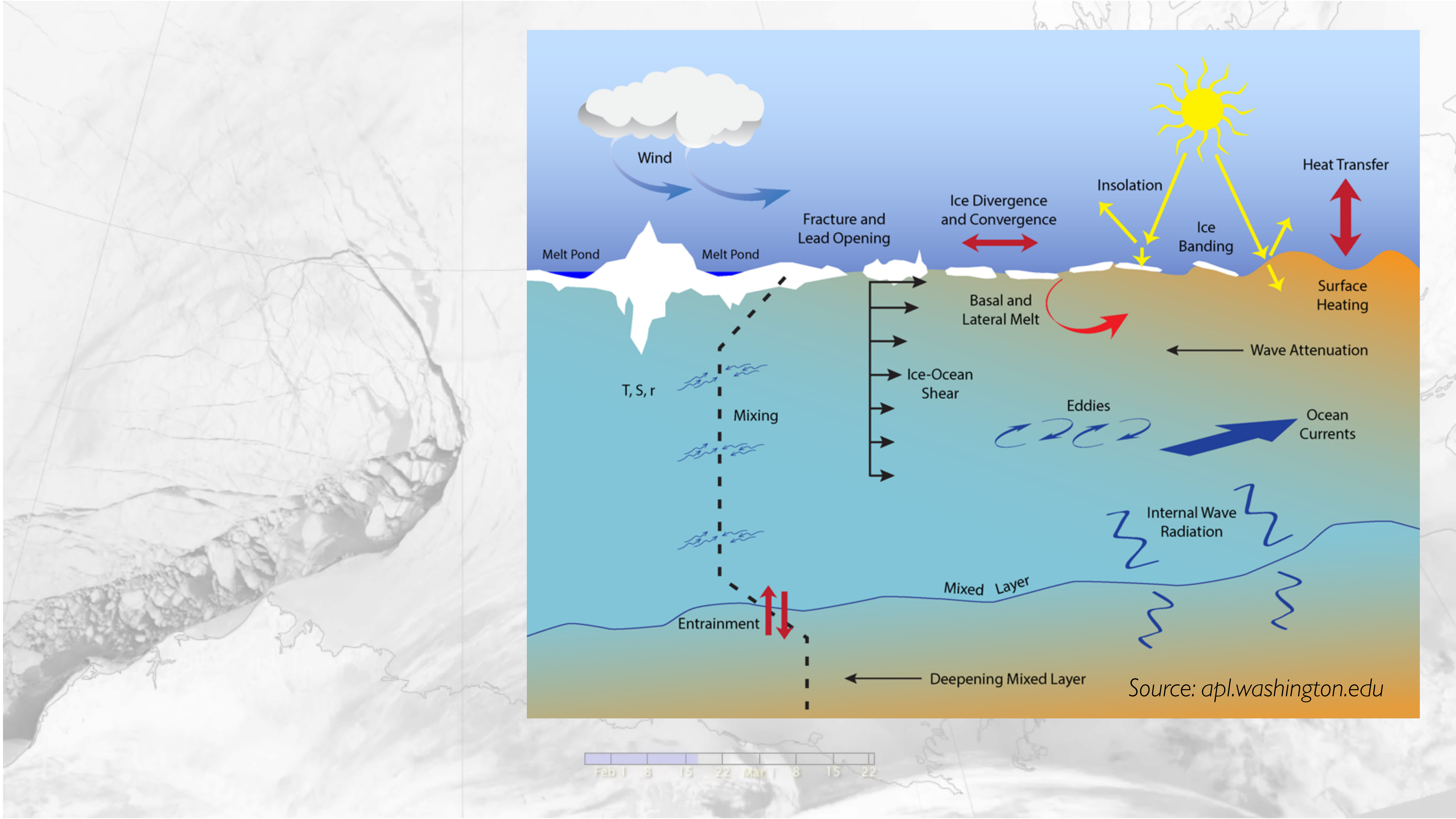

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How do we **model** sea ice deformation?

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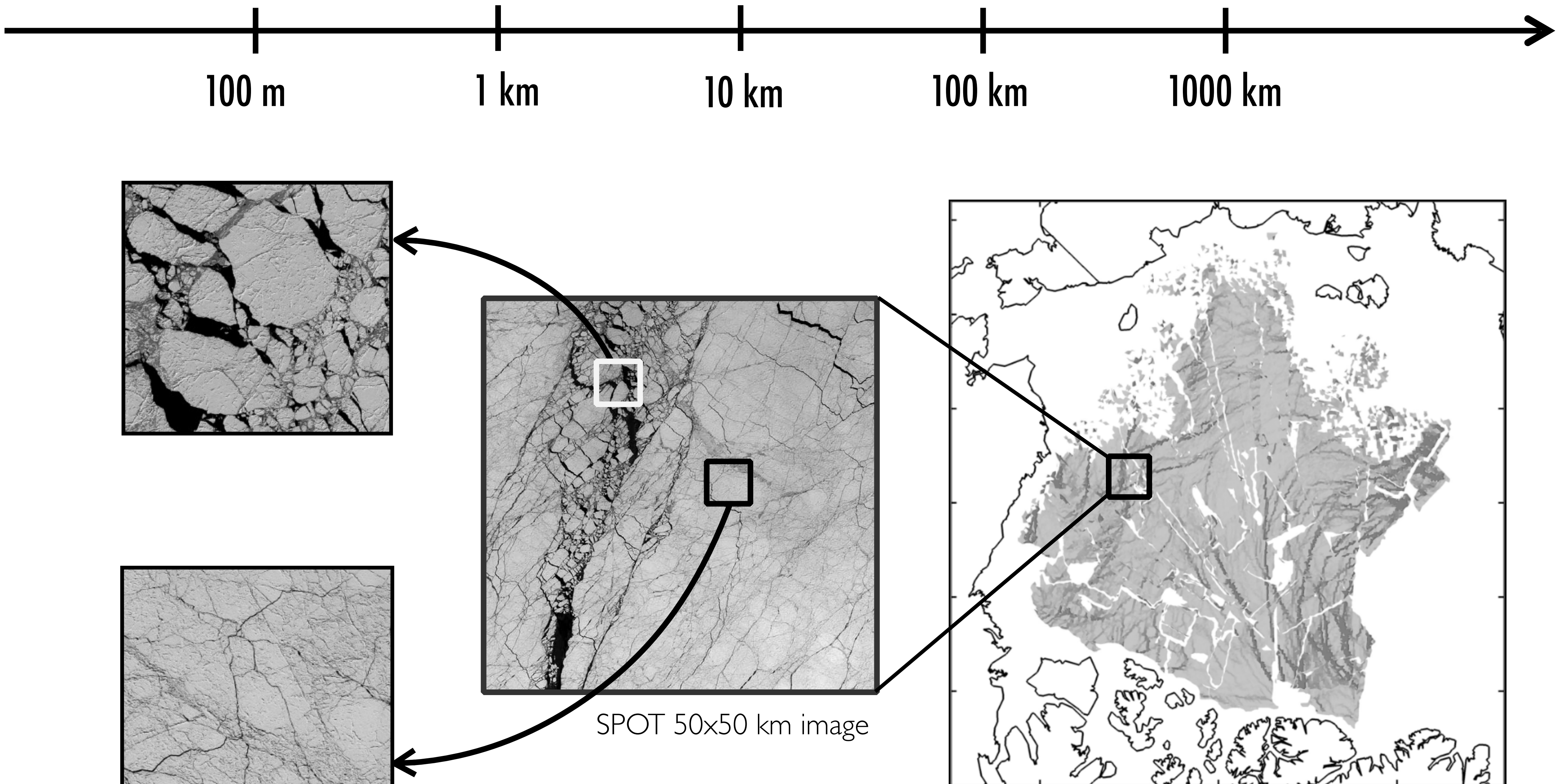
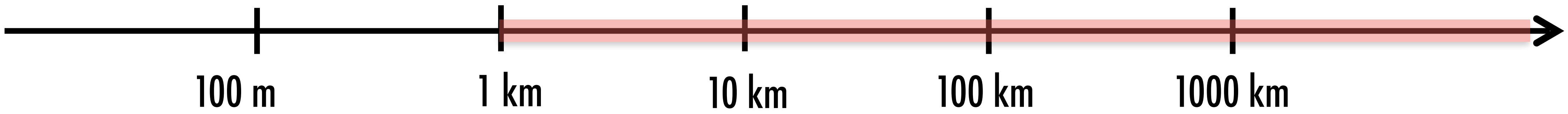
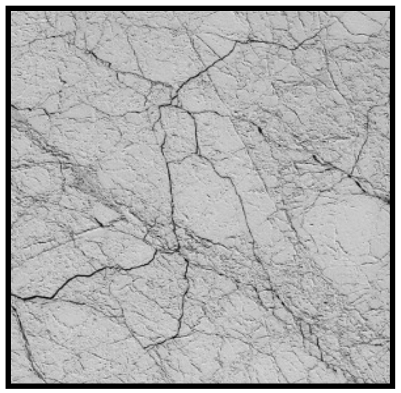


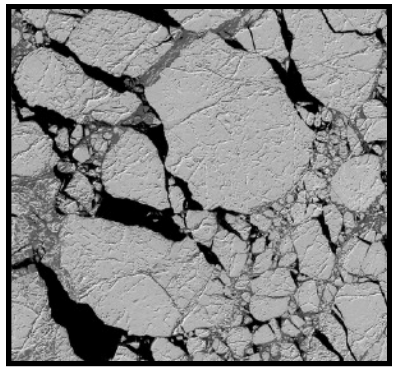
Deformation rate map, from RGPS data (day^{-1})

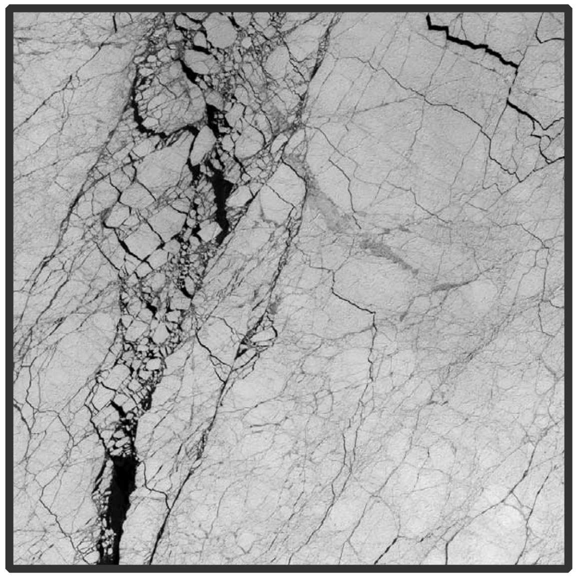
Credit: S. Bouillon

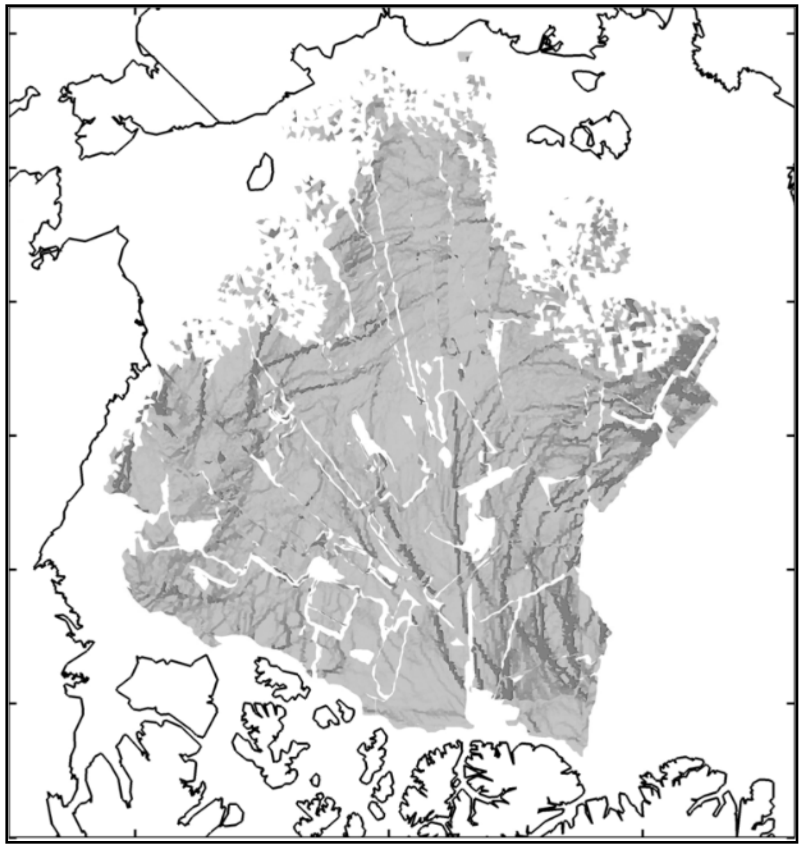
How do we **model** sea ice deformation?











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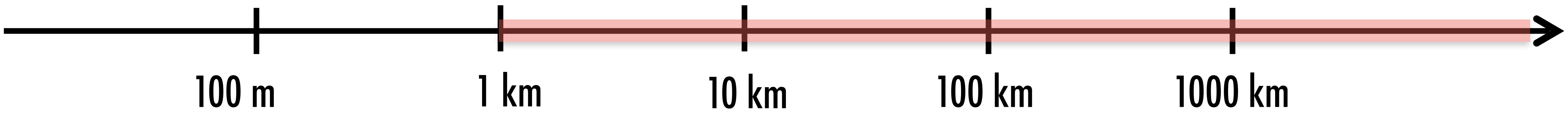

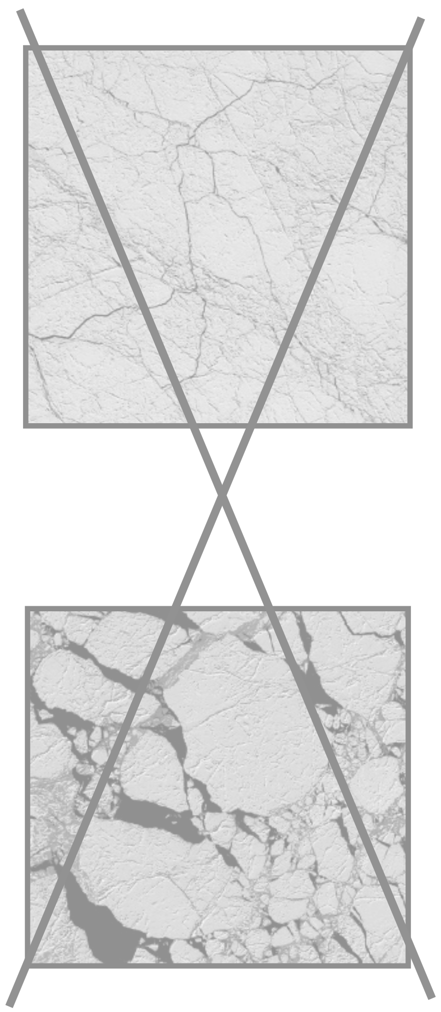

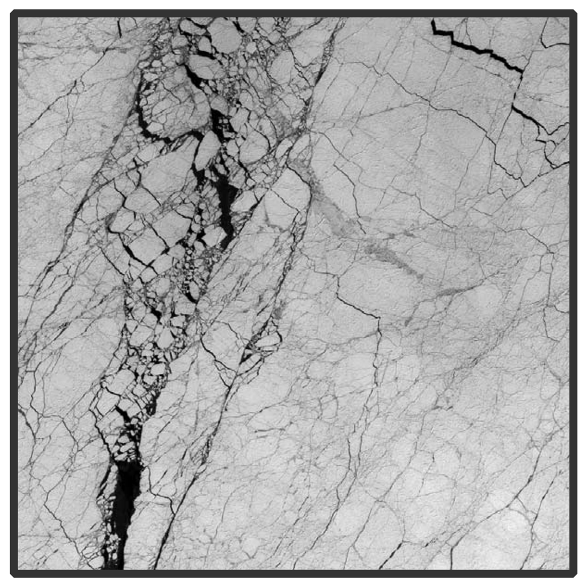

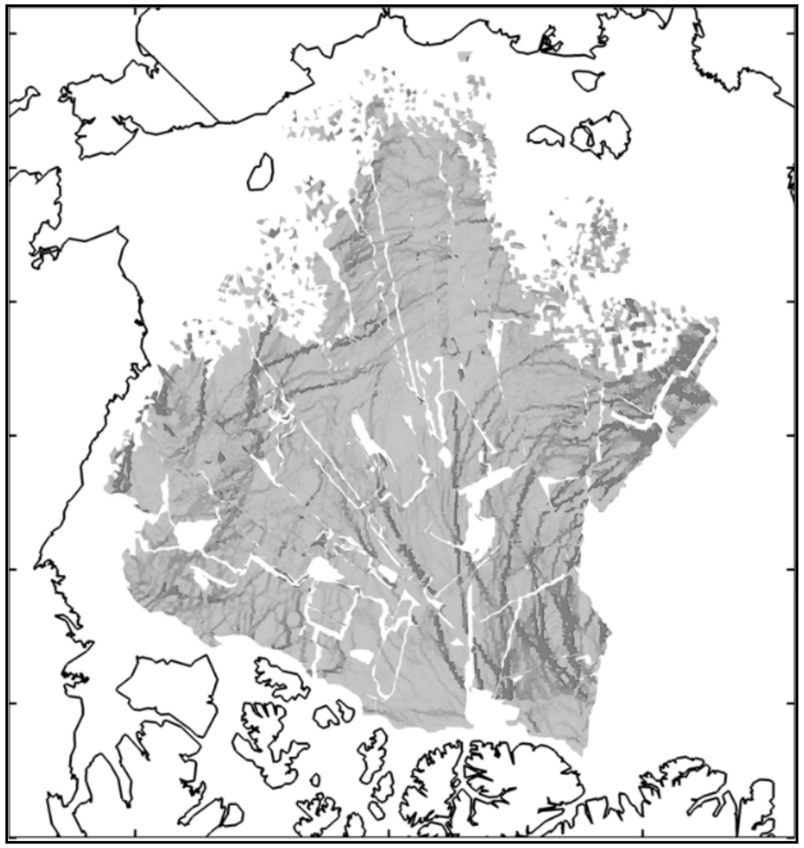

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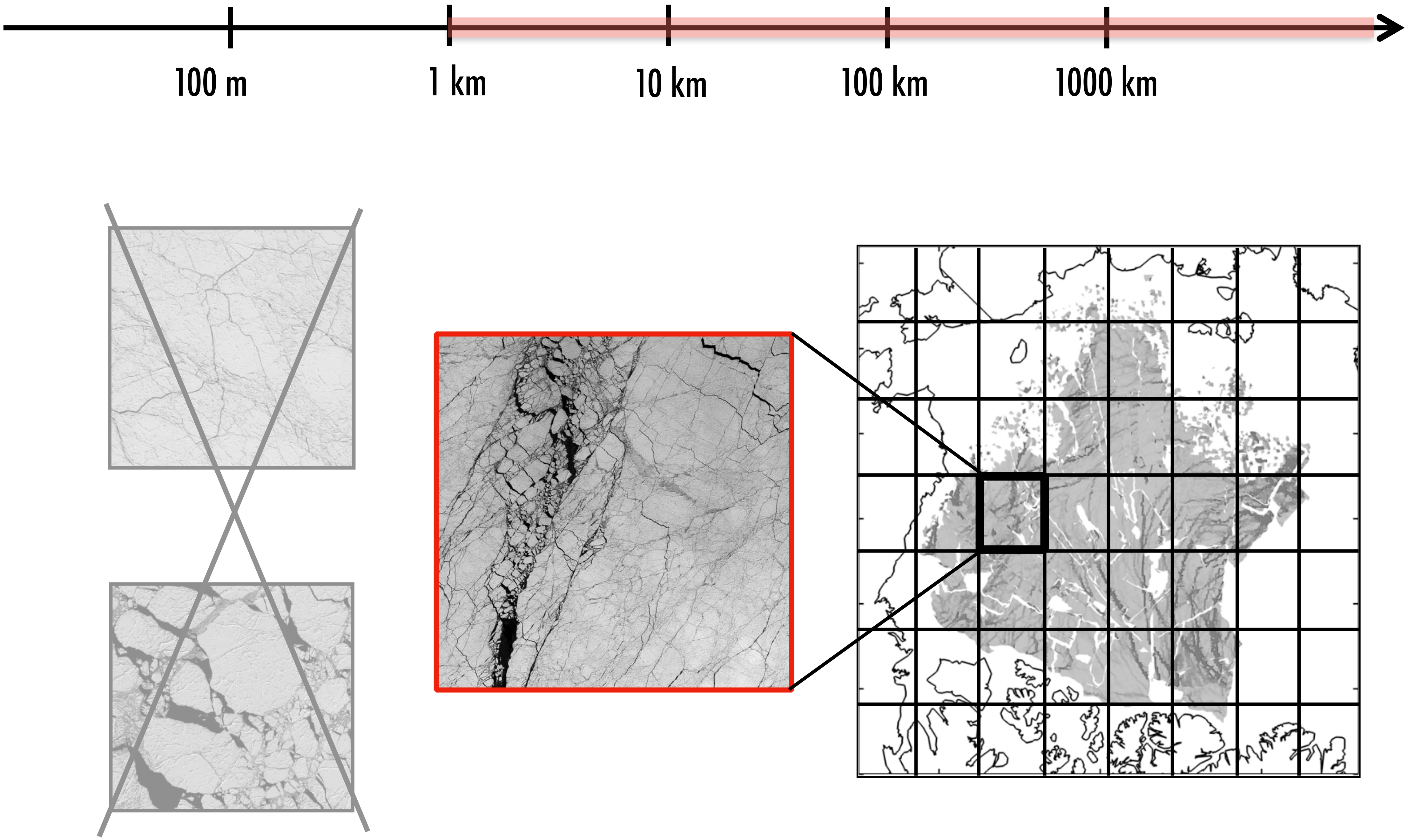

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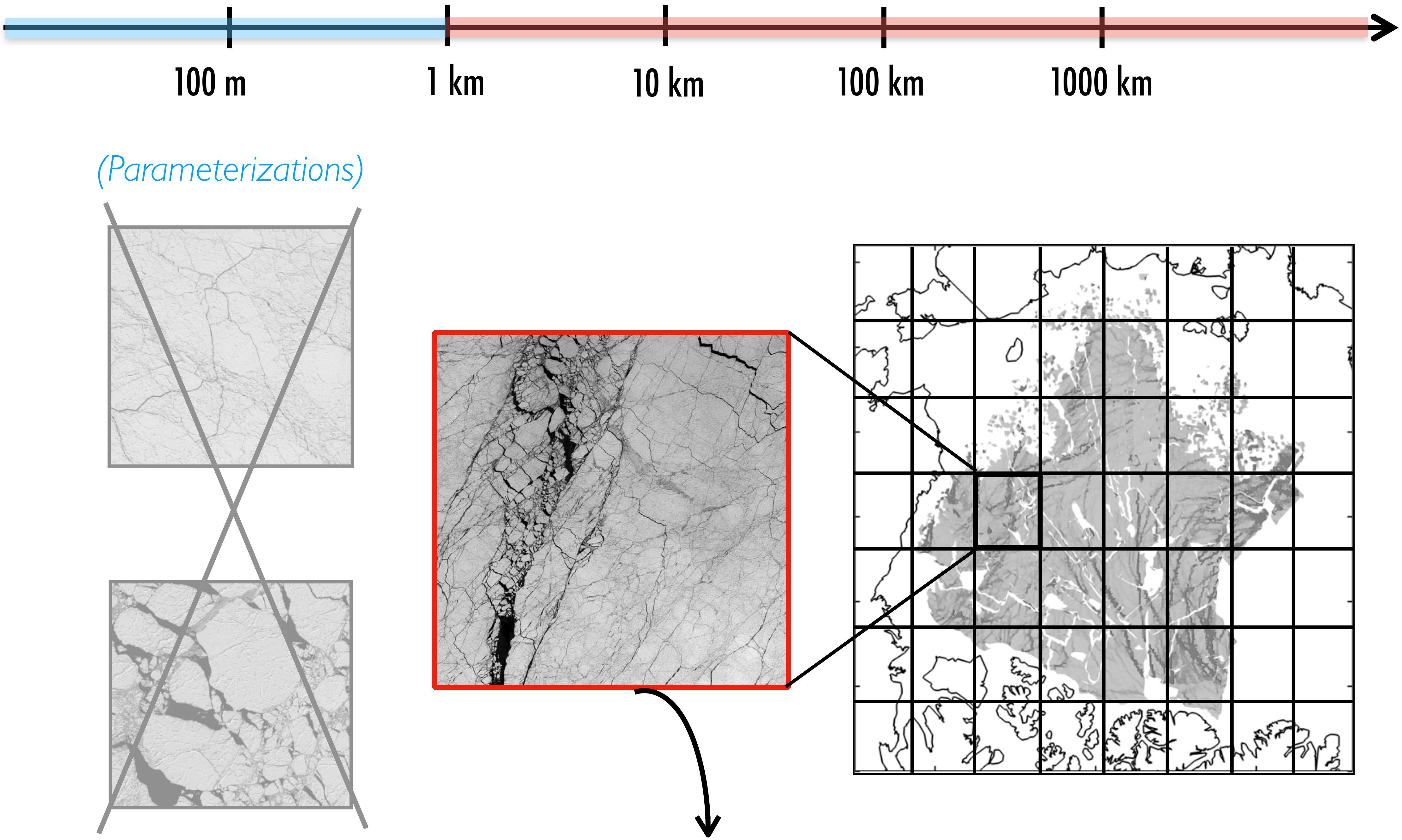
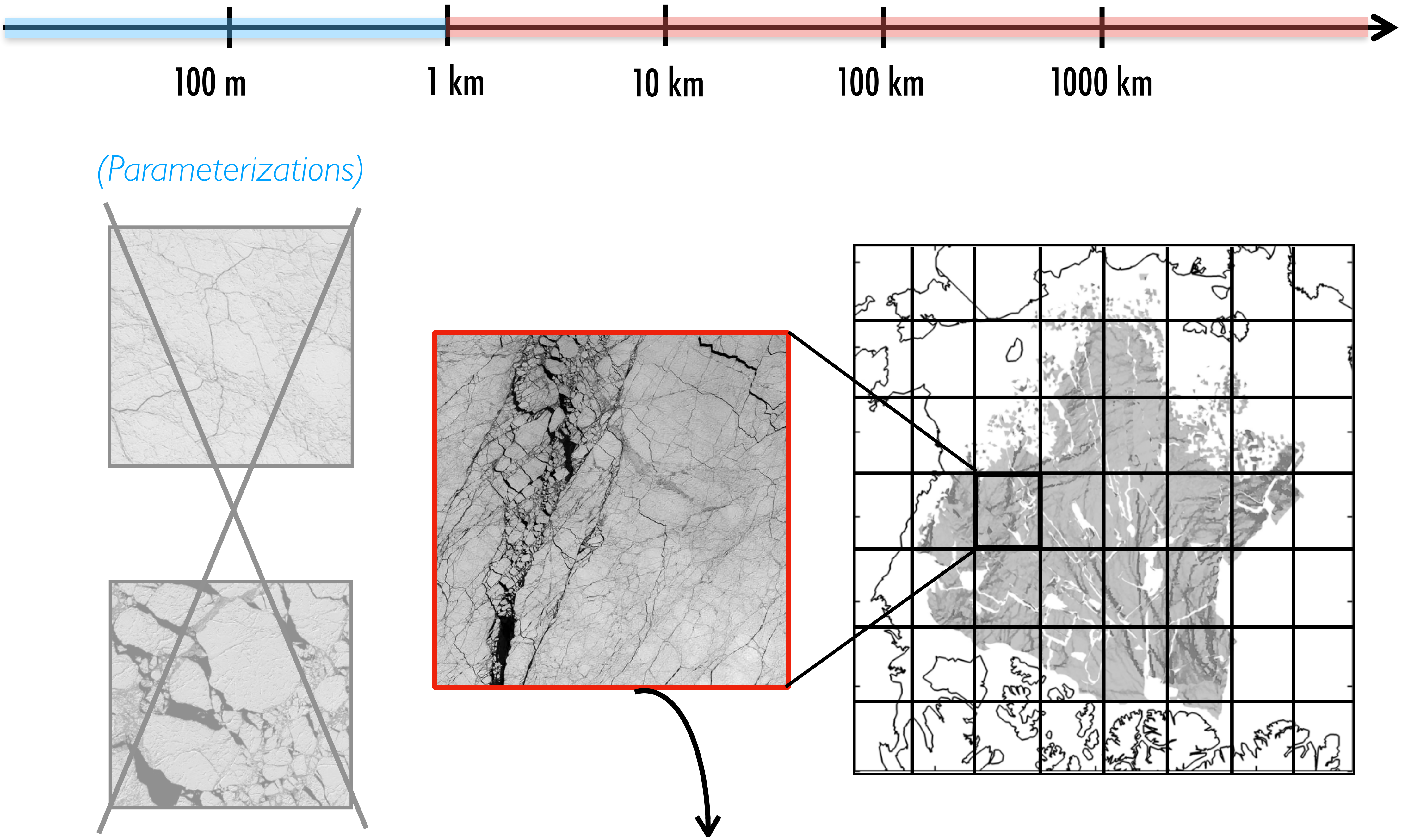


$$\rho h \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right] = \mathbf{F}_{ext} + \nabla \cdot (h\sigma)$$

mean quantities

How do we **model** sea ice deformation?



$$\rho h\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = \mathbf{F}_{ext} + \nabla\cdot(h\sigma)$$

rheology : links the internal stress, $\boldsymbol{\sigma}$, to the resulting deformation, $\boldsymbol{\varepsilon}$

How do we **model** sea ice deformation?

"Visco-Plastic" rheology (*Hibler, 1977 - present*)

https://www.amazon.se/-/en/Glass-Container-Dispenser-Storing-Approx/

$$\rho h \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right] = \mathbf{F}_{ext} + \nabla \cdot (h\sigma)$$

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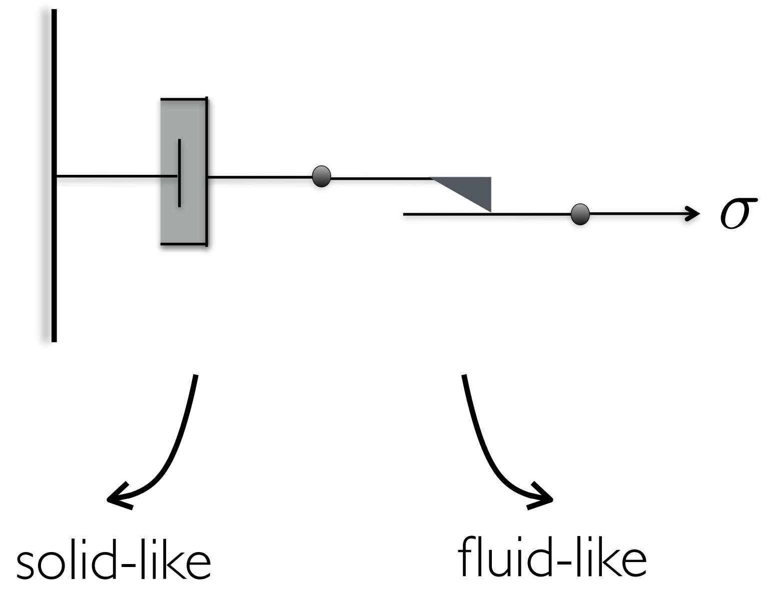

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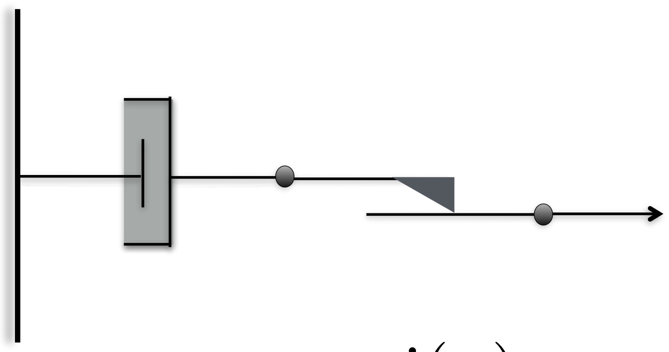
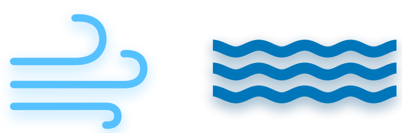


$$\sigma = \eta \dot{\varepsilon}(\mathbf{u})$$

Developed by: 

➡ Questionable treatment of the brittle solid behavior

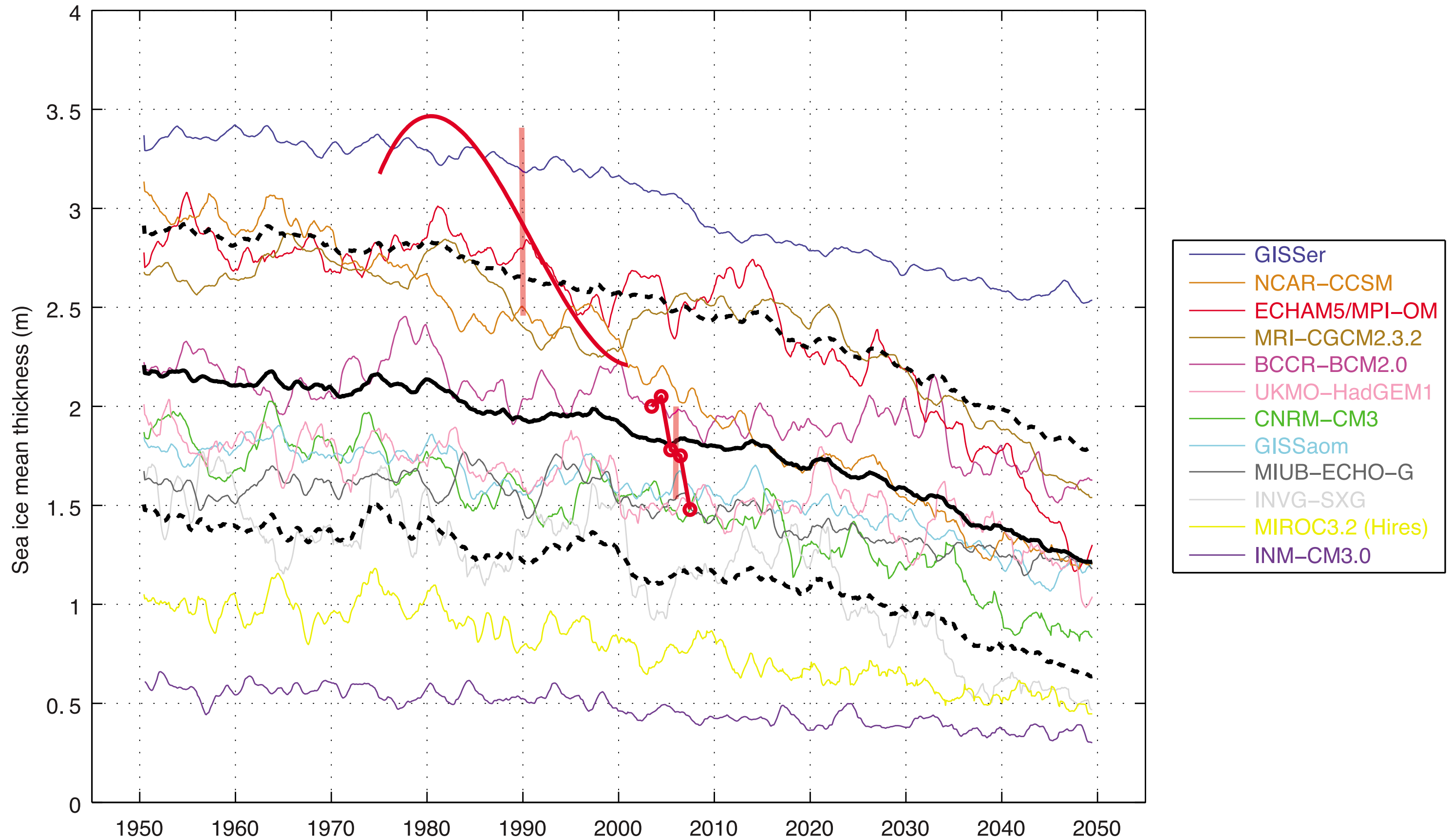
✓ Compatible with treatment of the atmosphere+ocean

$$\rho h \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right] = \mathbf{F}_{ext} + \nabla \cdot (h\sigma)$$

How do we **model** sea ice deformation?

"Visco-Plastic" rheology (*Hibler, 1977 - present*)

''IPCC climate models do not capture Arctic sea ice drift acceleration: Consequences in terms of projected sea ice thinning and decline'' *Rampal et al., 2011*



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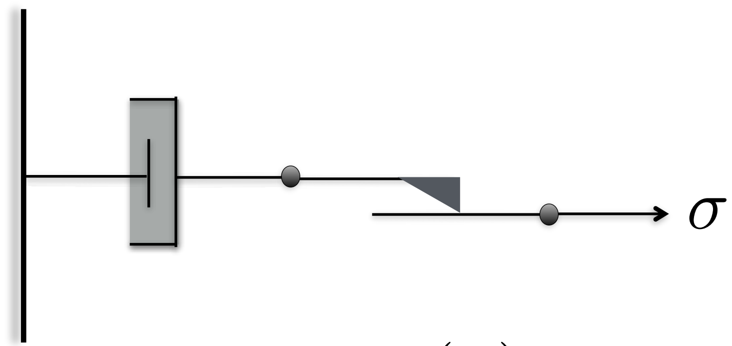


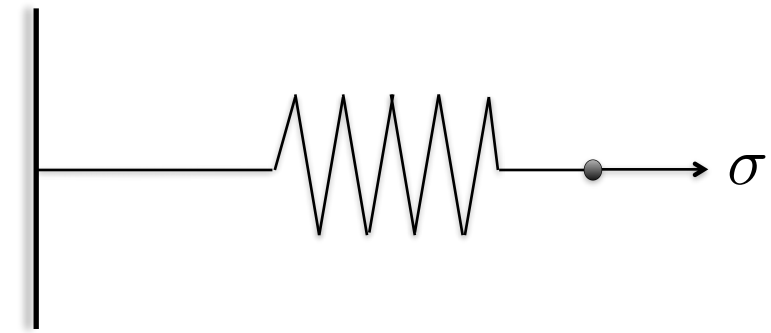
$$\sigma = \eta \dot{\varepsilon}(\mathbf{u})$$

Developed by:

➡ Questionable treatment of the brittle solid behavior

✓ Compatible with treatment of the atmosphere+ocean

Elasto-Brittle rheology (*Girard et al., 2011*)



$$\sigma = EK(\nu) : \varepsilon(\mathbf{U})$$

Developed by:

✓ Good treatment of the brittle solid behavior

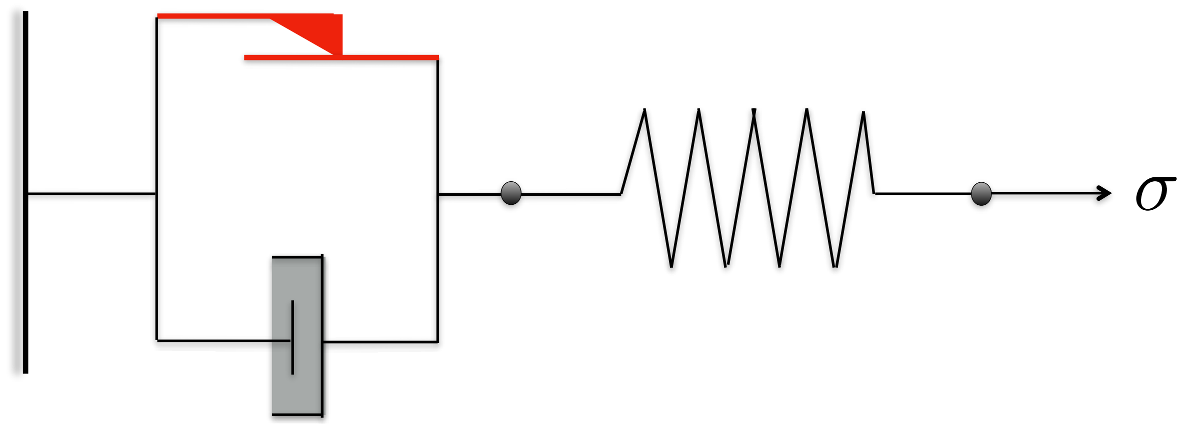
➡ Treats ONLY the brittle solid behavior

$$\rho h \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right] = \mathbf{F}_{ext} + \nabla \cdot (h\sigma)$$

How do we **model** sea ice deformation?

The (Maxwell) Visco-Elasto-Brittle rheology

(Dansereau et al., 2015; 2016; 2017, Olason et al., 2022)



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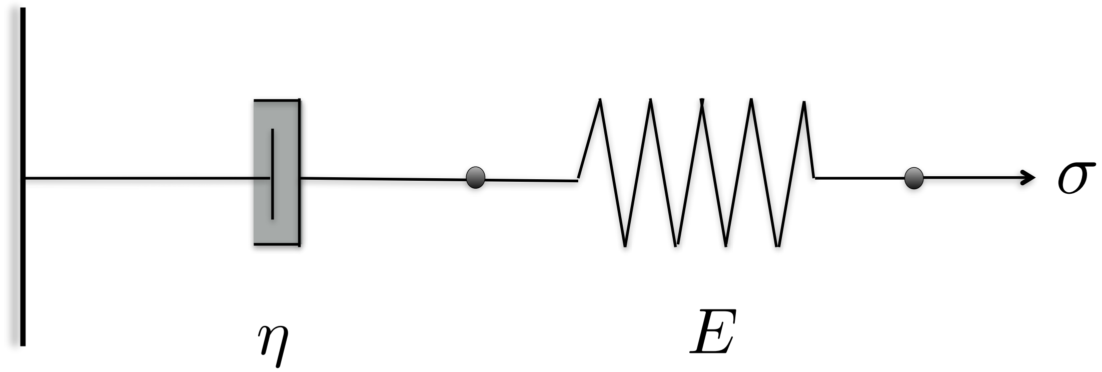
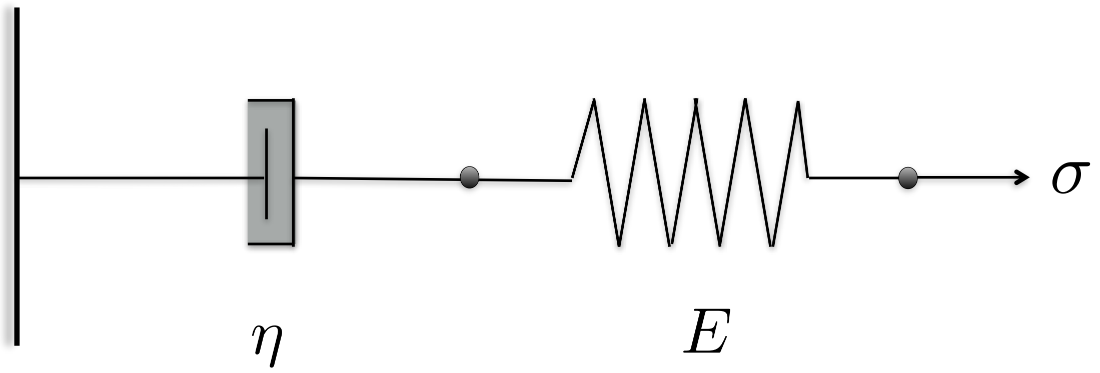


Permanent deformations
("fluid-like")

Reversible deformations
("solid-like")

How do we **model** sea ice deformation?

The (Maxwell) Visco-Elasto-Brittle rheology



$$\lambda = \frac{\eta}{E}$$

$$\frac{D\sigma}{Dt} + \frac{1}{\lambda}\sigma = E\mathbf{K}(\nu) : \dot{\varepsilon}(\mathbf{u})$$

How do we **model** sea ice deformation?

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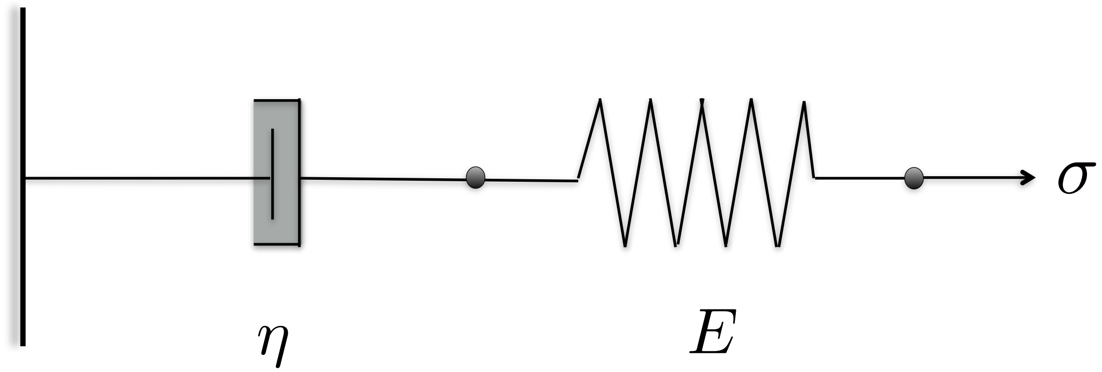

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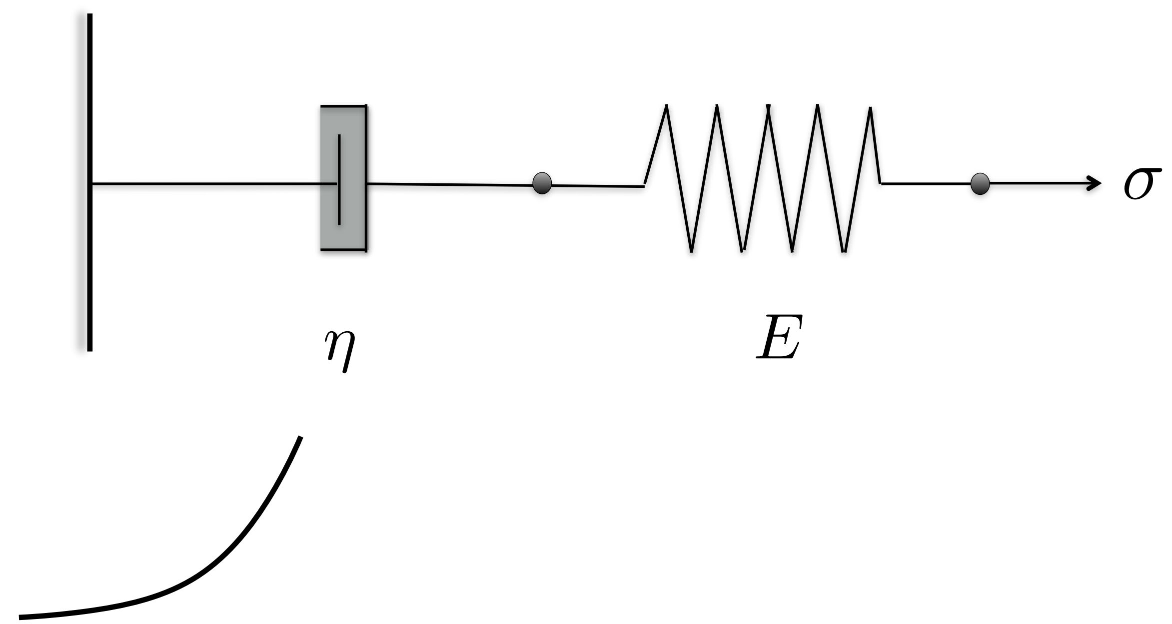

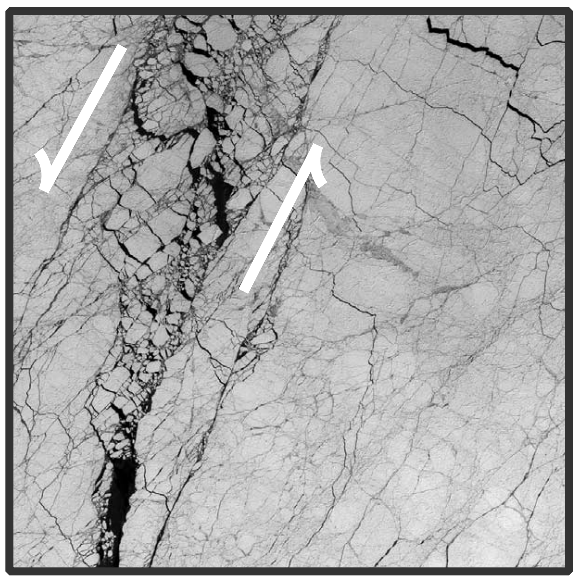

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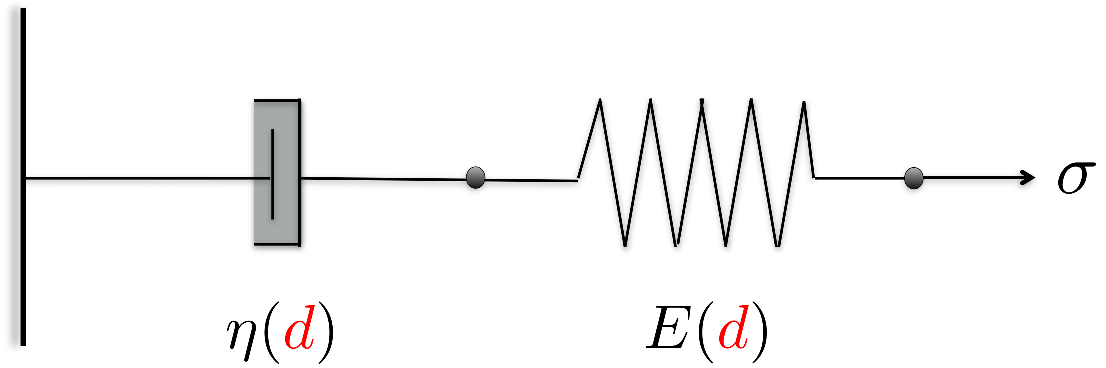
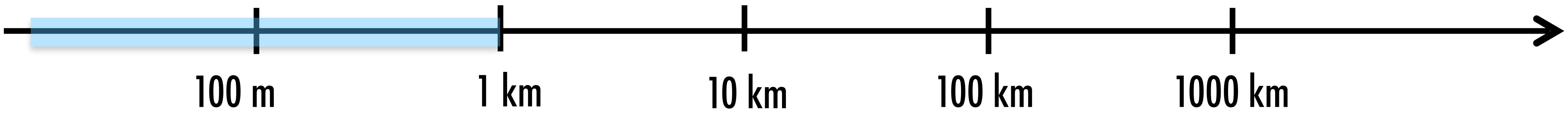


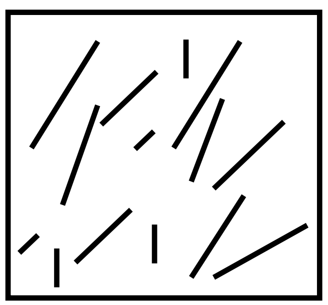
$$\frac{D\sigma}{Dt} + \frac{1}{\lambda(d)}\sigma = E(d)\mathbf{K}(\nu) : \dot{\varepsilon}(\mathbf{u})$$

How do we **model** sea ice deformation?

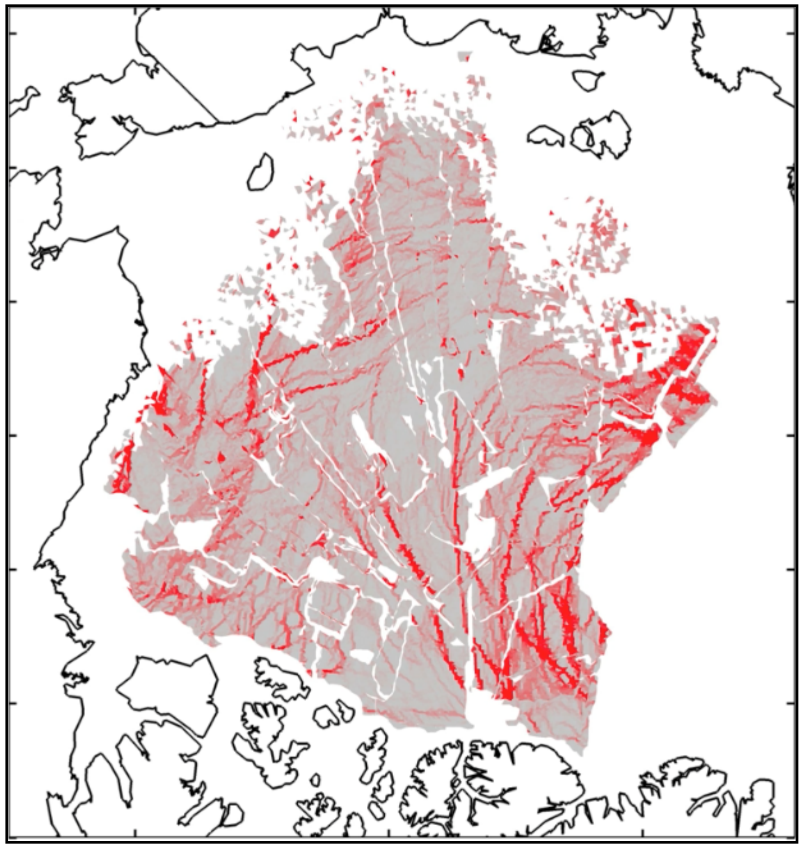


(Scalar) damage variable

$$0 \leq d \leq 1$$



Kachanov, 1958



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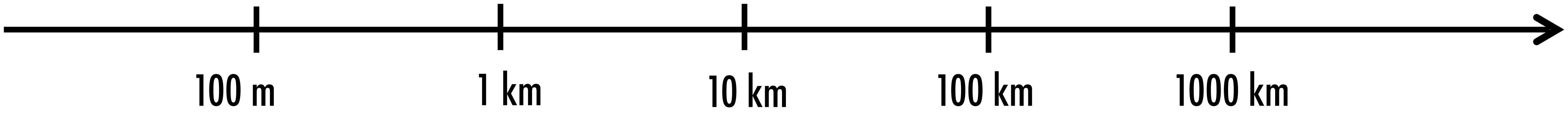

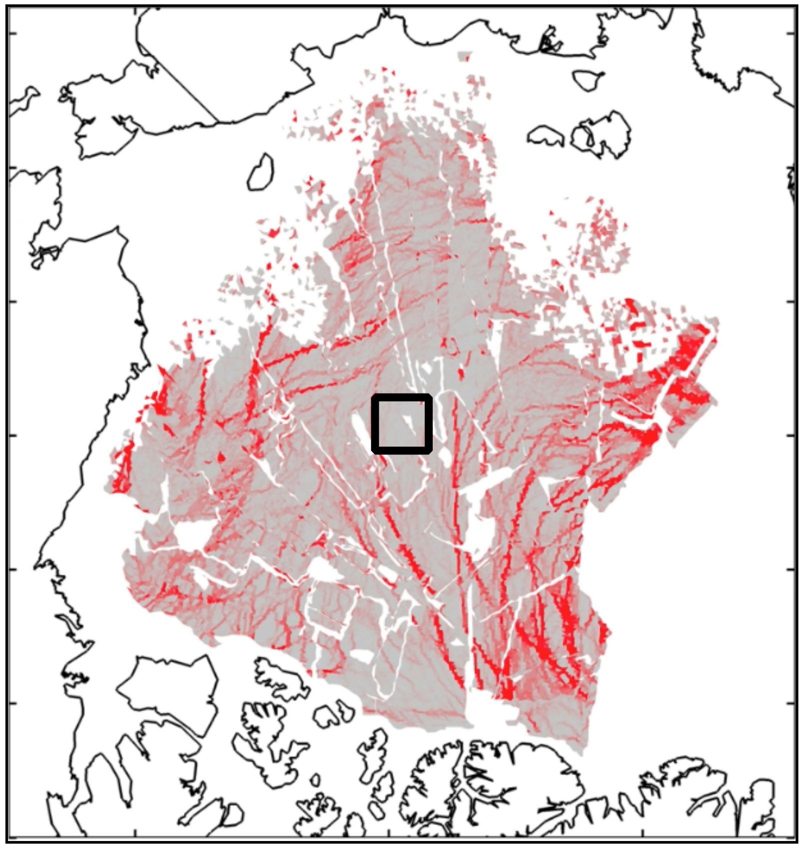

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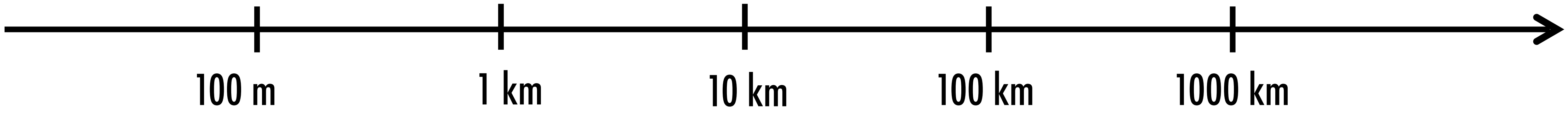
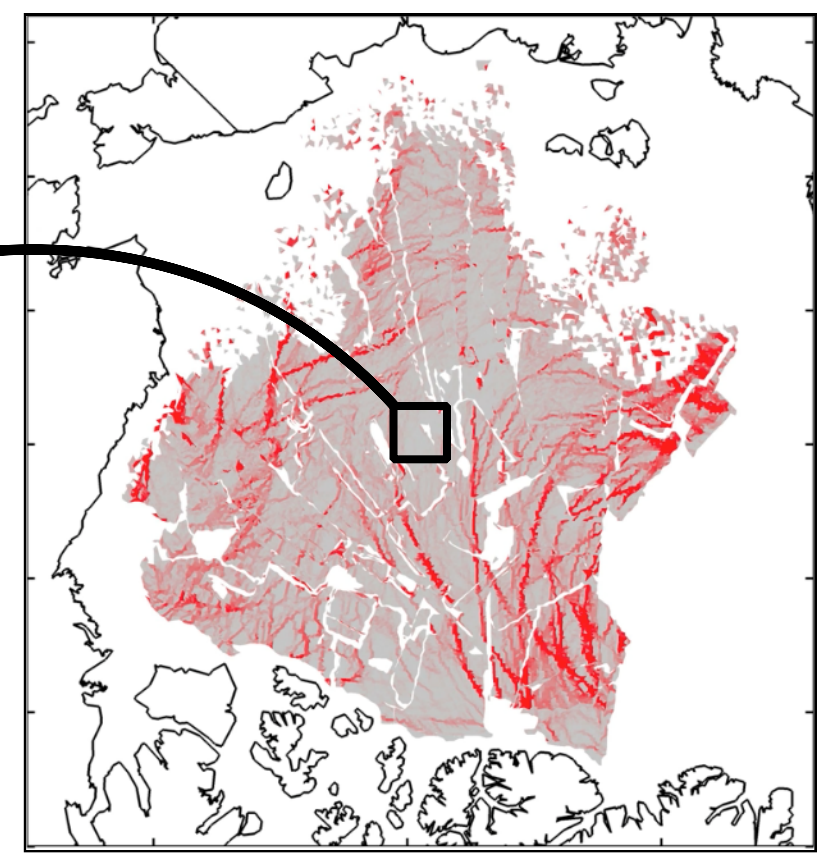


$$d = 0$$

$$E = E_0$$

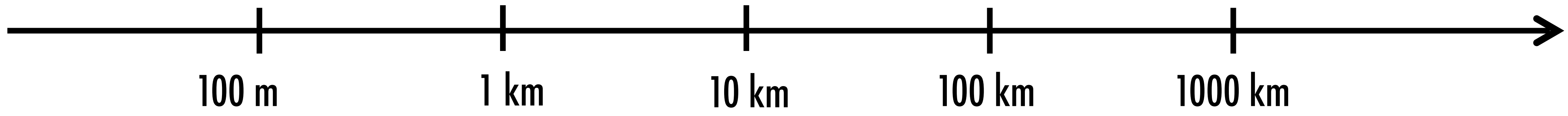
$$\eta_0 \to \infty$$

$$\lambda_0 \to \infty$$

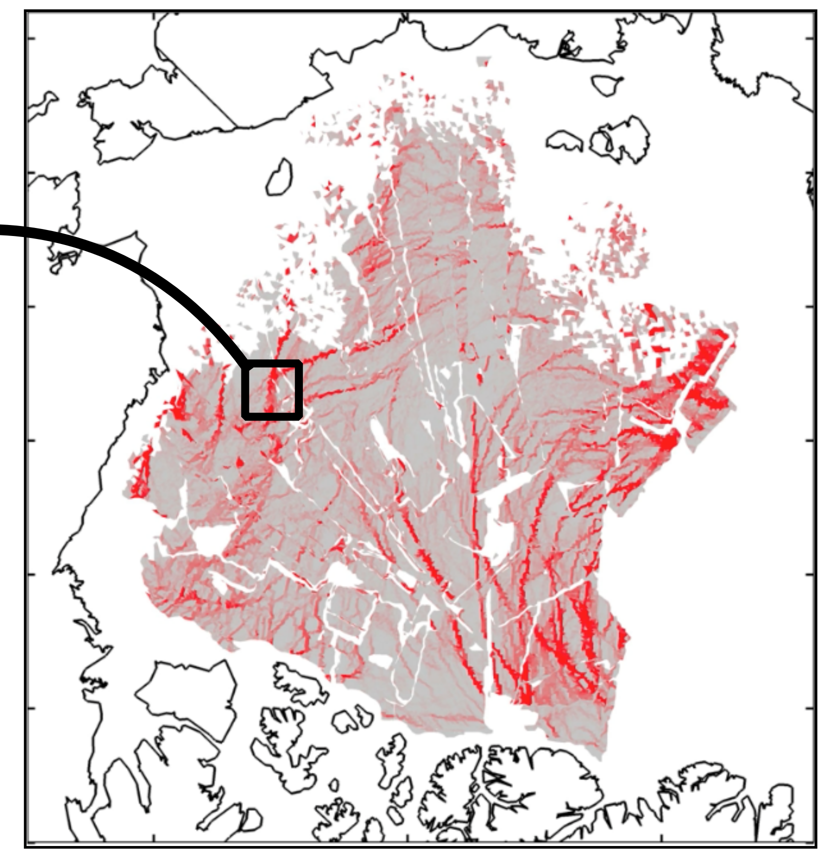


$$\frac{D\sigma}{Dt} + \cancel{\frac{1}{\lambda(d)}}\sigma = E(d)\mathbf{K}(\nu) : \dot{\varepsilon}(\mathbf{u})$$

How do we **model** sea ice deformation?



$$d \longrightarrow 1$$
$$E \longrightarrow 0$$
$$\eta \longrightarrow 0$$
$$\lambda \longrightarrow 0$$



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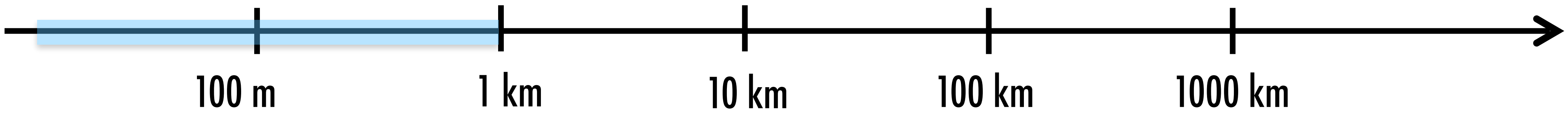
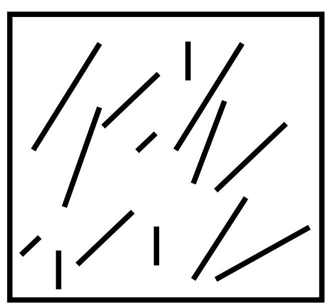


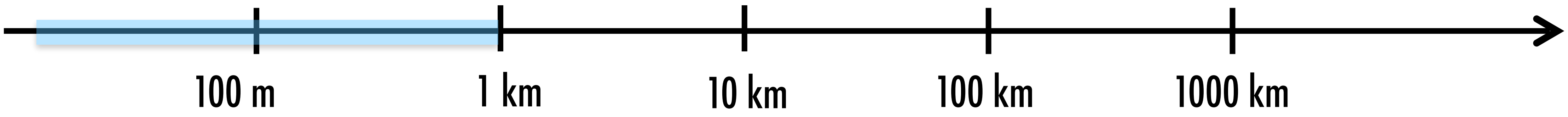
Damage evolution



Parameterization

$$\frac{Dd}{Dt} = \text{fracturing} + \text{healing}$$

How do we **model** sea ice deformation?



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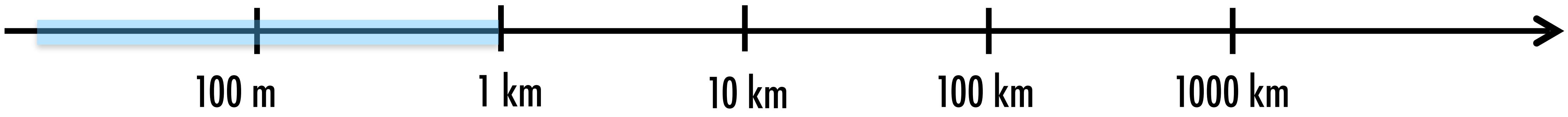
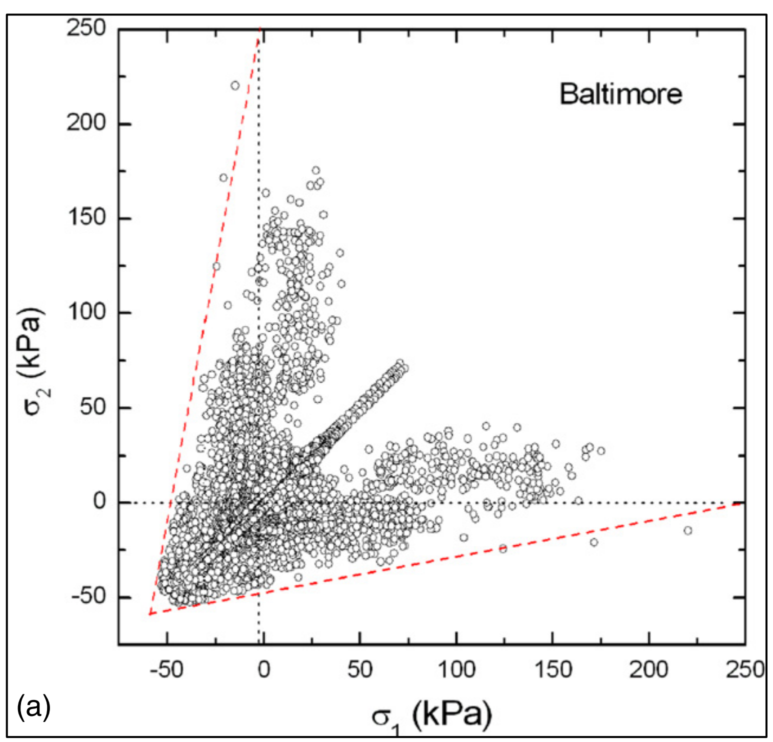


Damage evolution

$$\frac{Dd}{Dt} = \boxed{\text{fracturing}} + \text{healing}$$

In-situ stress measurements from stress-meters

Credit: J. Richter-Menge, Weiss and Schulson, 2009



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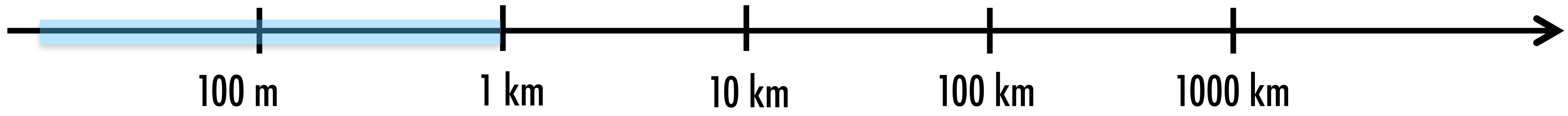

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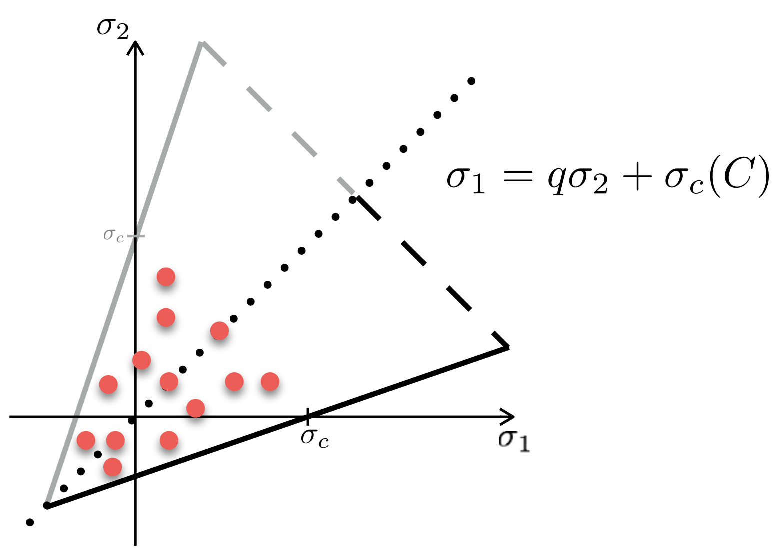

$$\frac{Dd}{Dt} = 0$$

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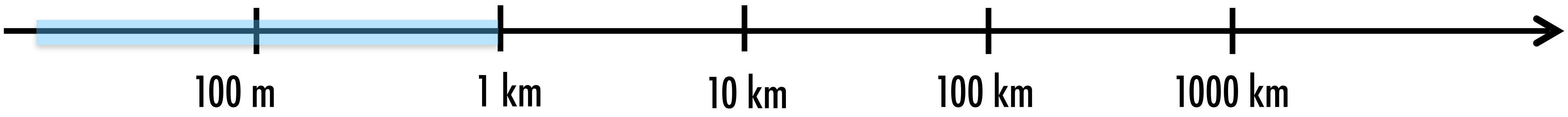

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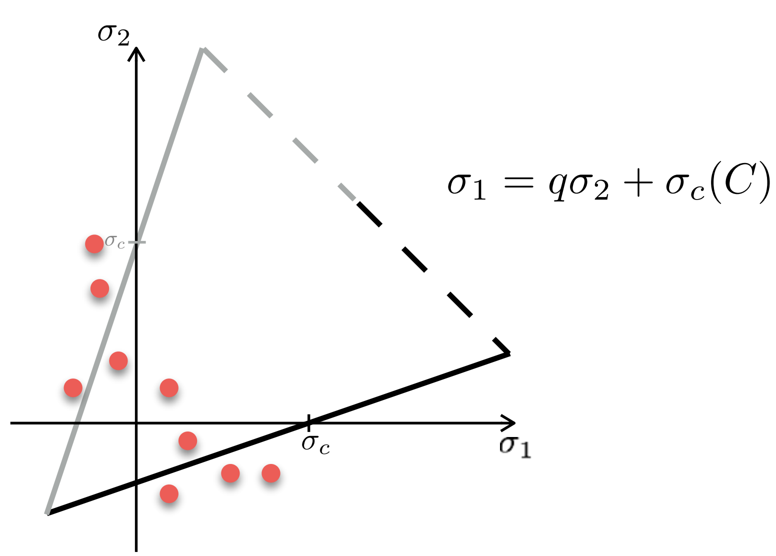
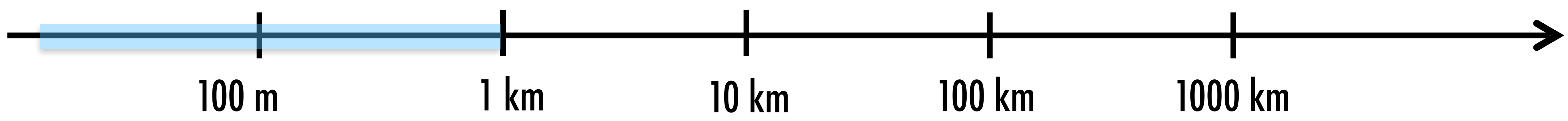


$$\frac{Dd}{Dt} > 0$$

How do we **model** sea ice deformation?



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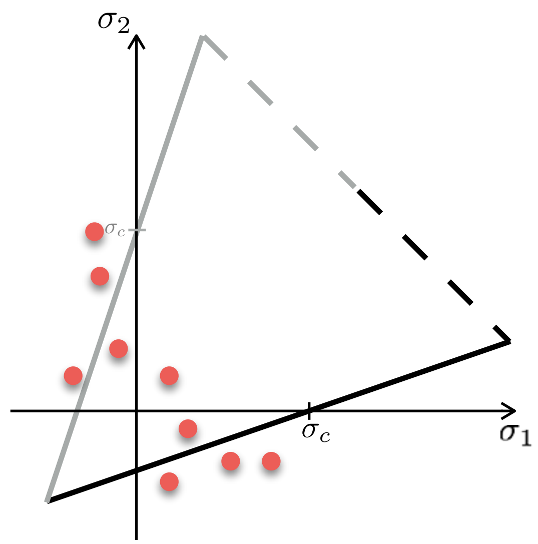

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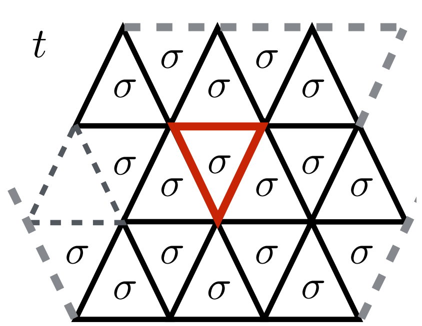

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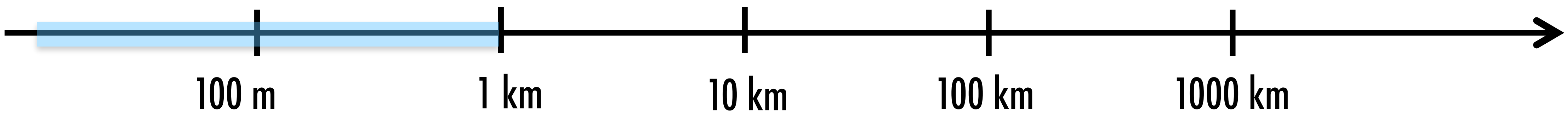

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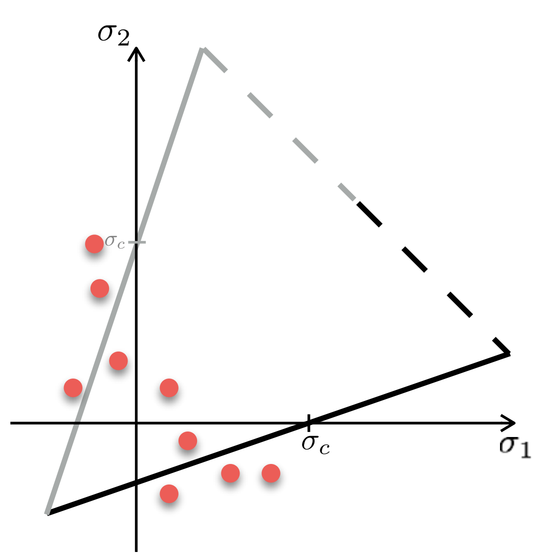

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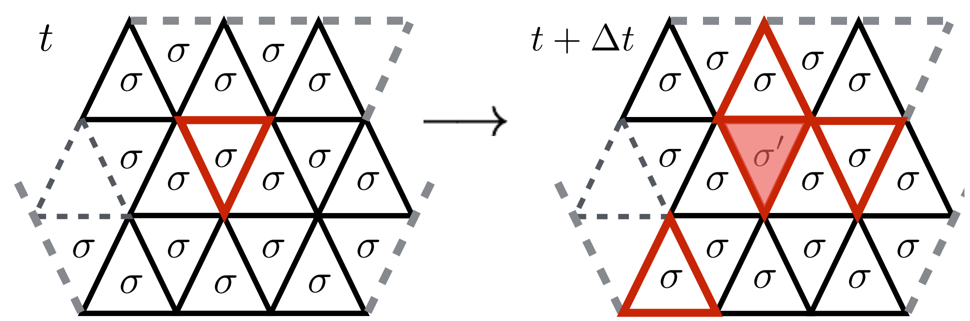

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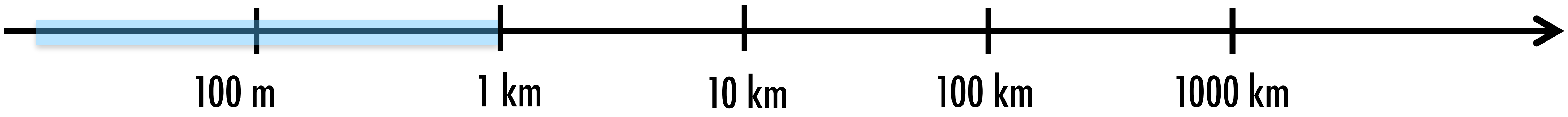

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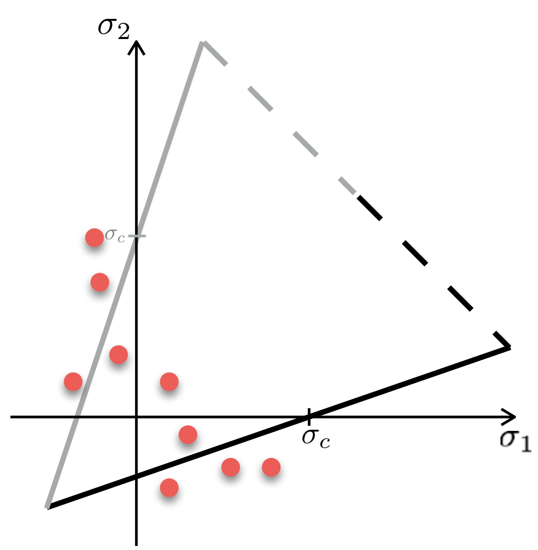

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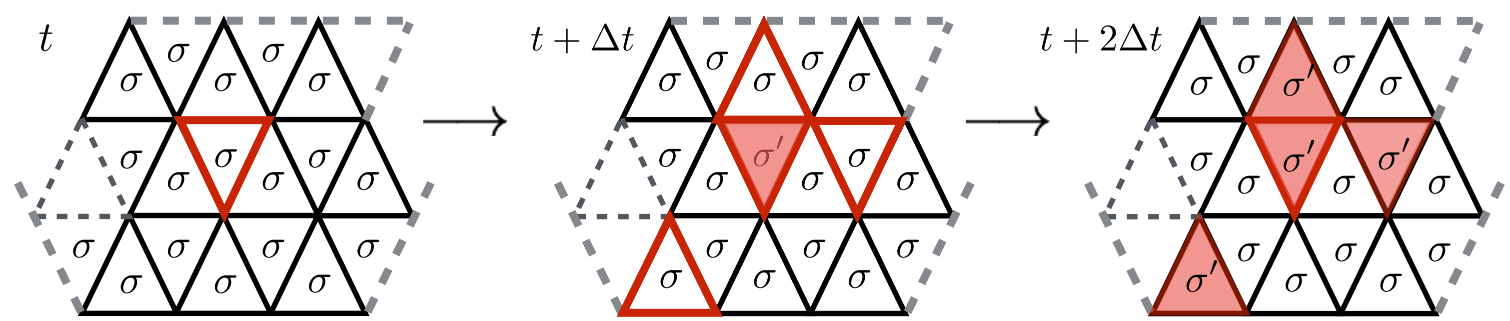

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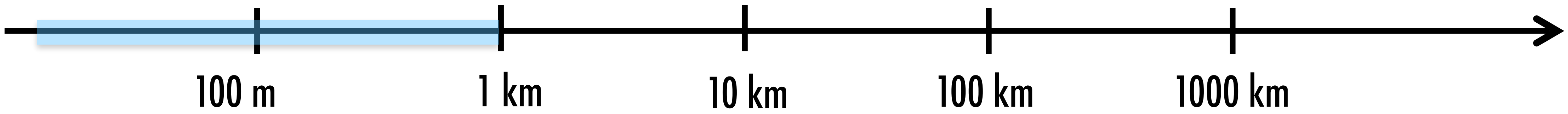

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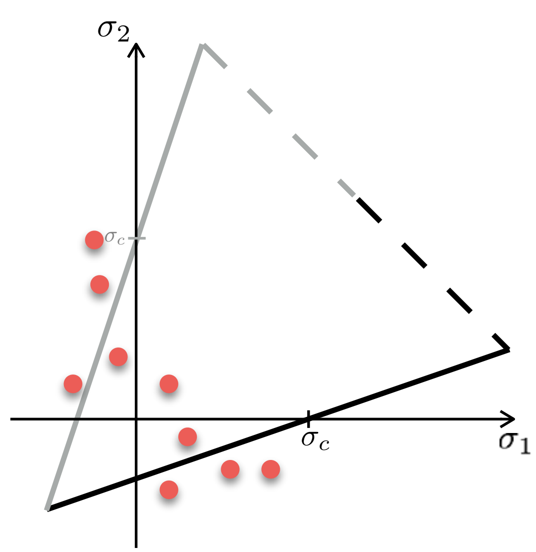
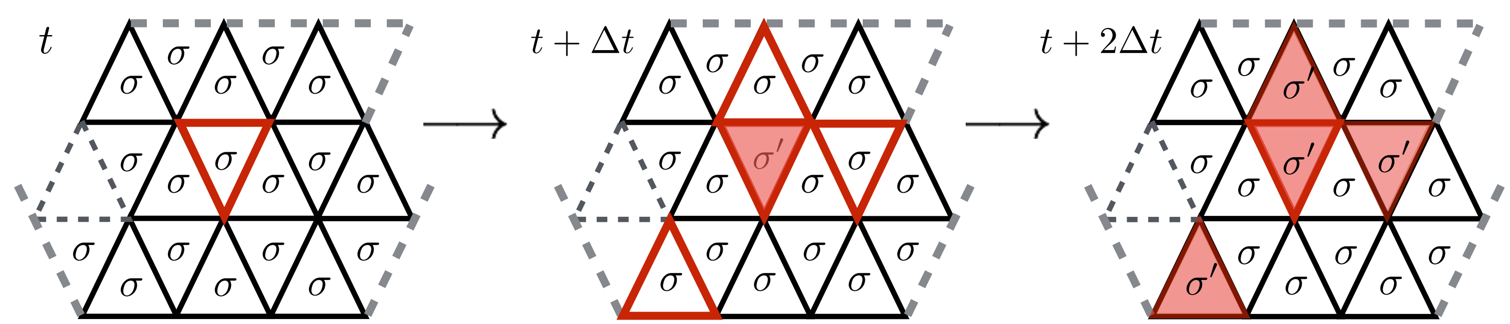


$$\frac{Dd}{Dt} > 0$$

=

https://www.programme-television.org/news-tv/Domino-Effect



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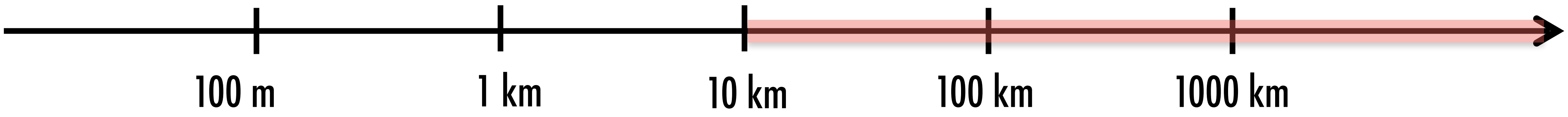

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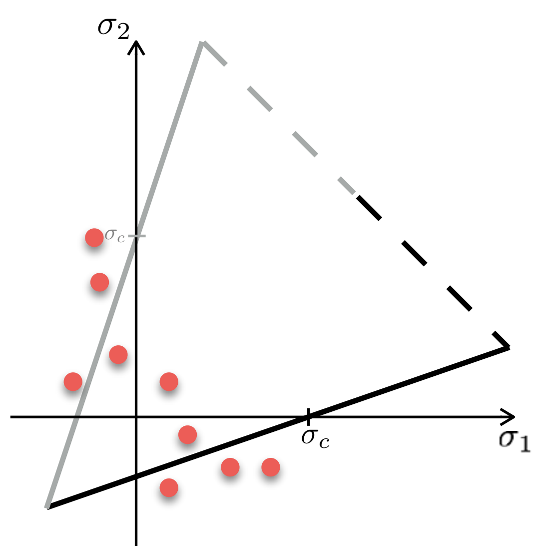

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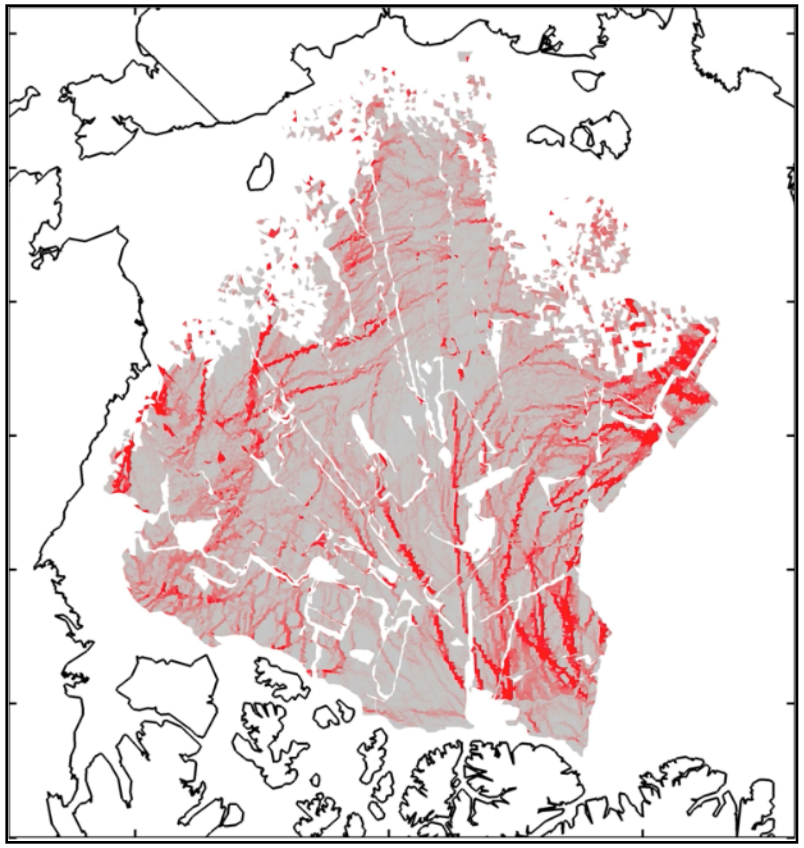

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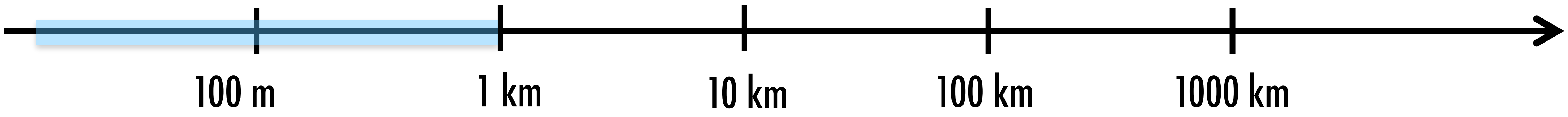

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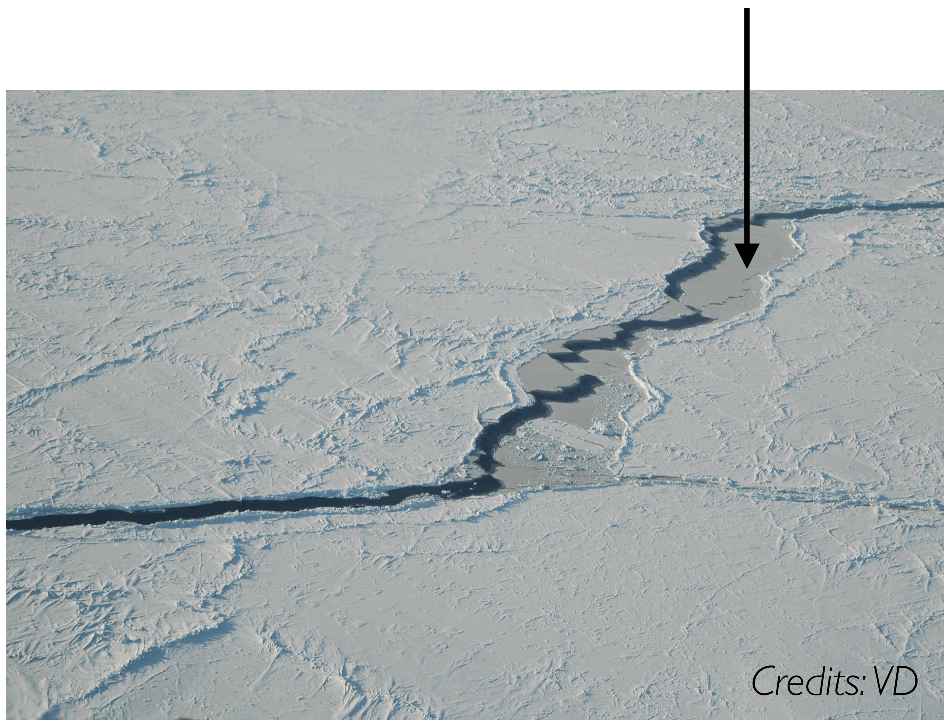

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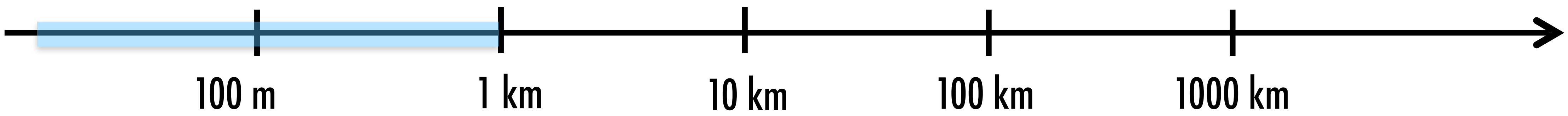
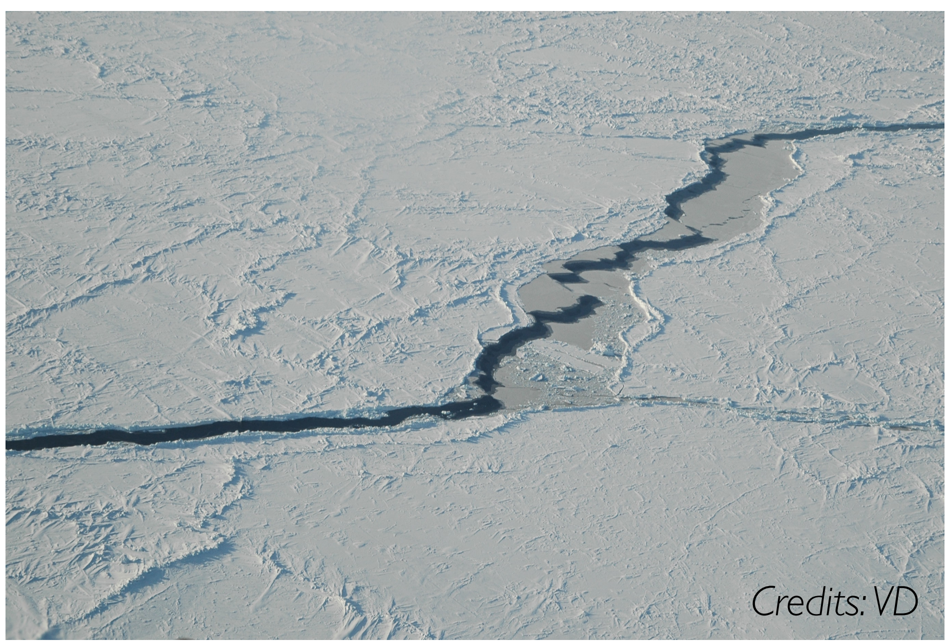


Mass conservation

h, thickness
A, concentration



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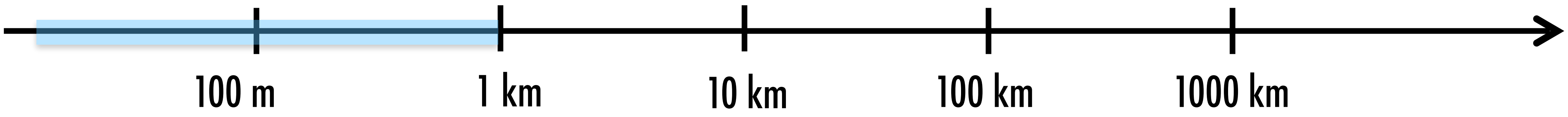

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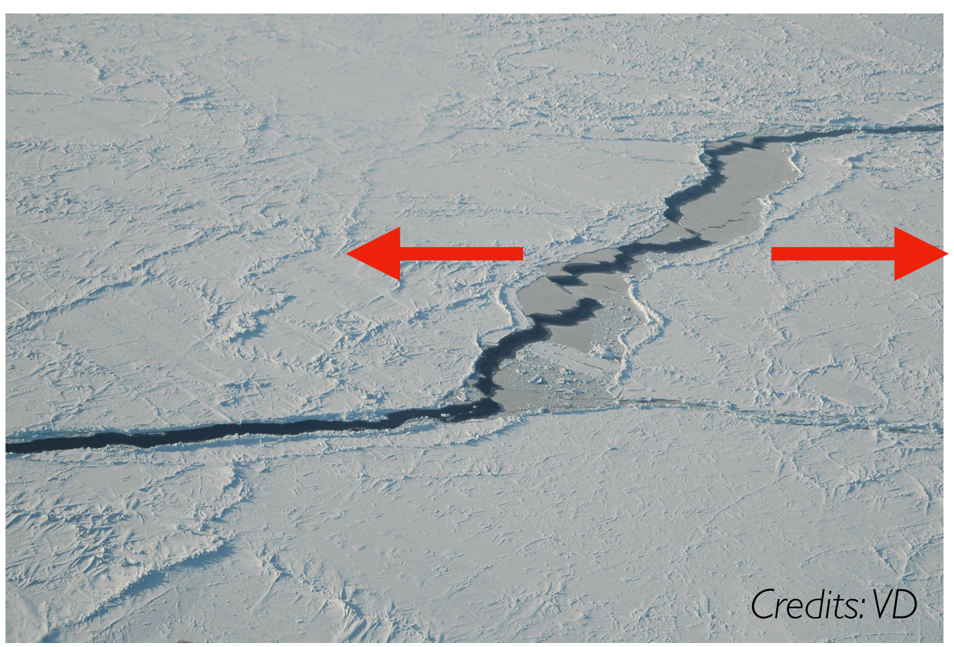

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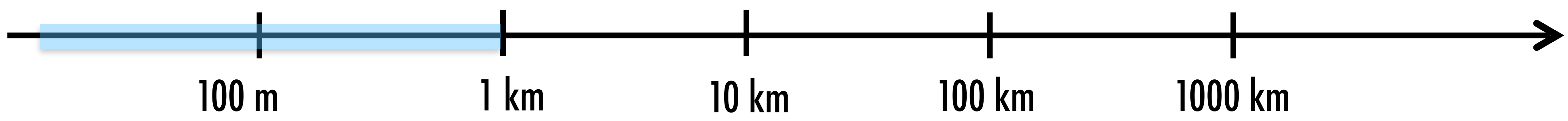

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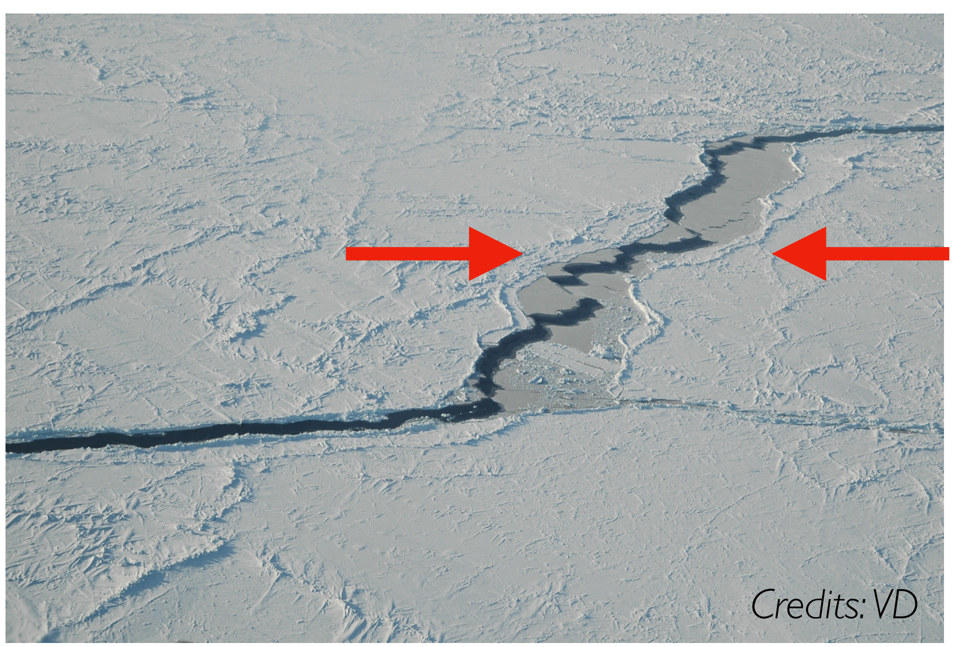


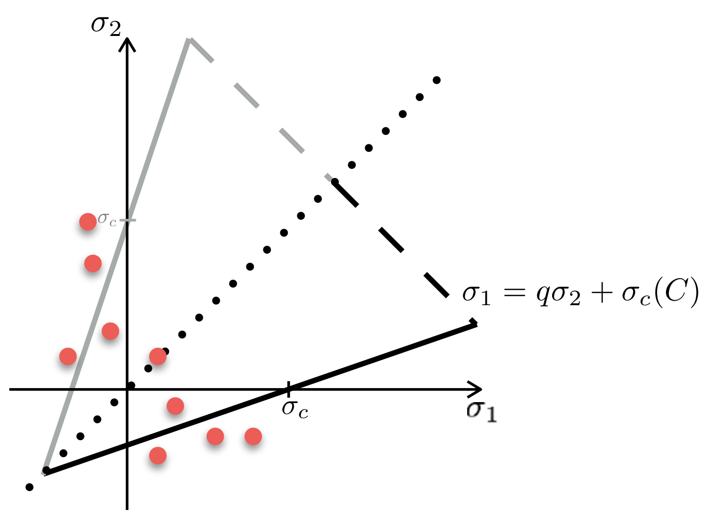
How do we **model** sea ice deformation?

COMPONENTS

Constitutive law

$$\frac{D\sigma}{Dt} + \frac{1}{\lambda(\lambda_0, d)}\sigma = E(E_0, d)\mathbf{K}(\nu) : \dot{\varepsilon}(\mathbf{u})$$

Failure criterion



Evolution equation for *d*

$$\frac{Dd}{Dt} = \text{fracturing}\left(\frac{1}{t_d}\right) + \text{healing}\left(\frac{1}{t_h}\right)$$

Dansereau et al., 2016

How do we **model** sea ice deformation?

COMPONENTS | INGREDIENTS

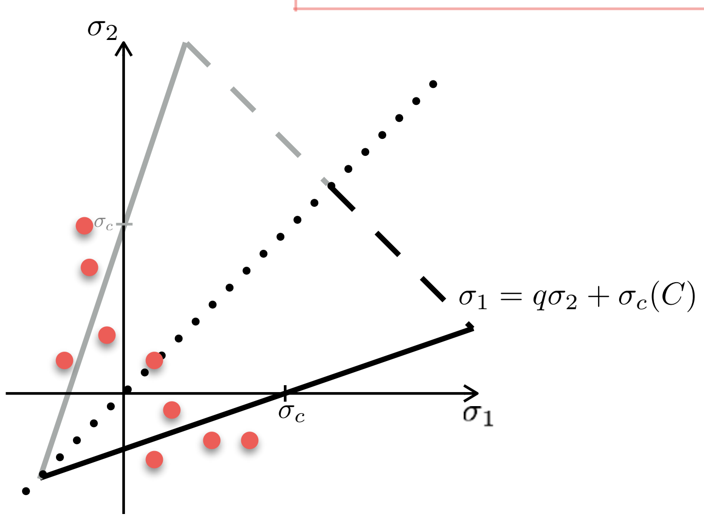
Constitutive law

$$\frac{D\sigma}{Dt} + \frac{1}{\lambda(\lambda_0, d)}\sigma = E(E_0, d)\mathbf{K}(\nu) : \dot{\varepsilon}(\mathbf{u})$$

ELASTIC SOLID

FLUID
(stress dissipation)

Failure criterion



Evolution equation for *d*

$$\frac{Dd}{Dt} = \text{fracturing}\left(\frac{1}{t_d}\right) + \text{healing}\left(\frac{1}{t_h}\right)$$

THRESHOLD MECHANISM
(brittle fracturing)

RECOVERY MECHANISM
(refreezing)

Dansereau et al., 2016
Weiss and Dansereau, 2017

Momentum equation

$$\rho h \frac{D\mathbf{u}}{Dt} = \boxed{\mathbf{F}_{\text{ext}}} + \nabla \cdot (h\sigma)$$

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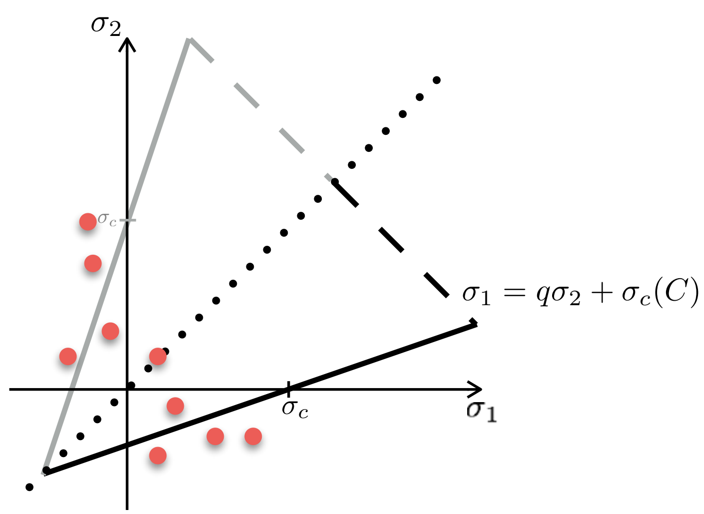

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Mass conservation

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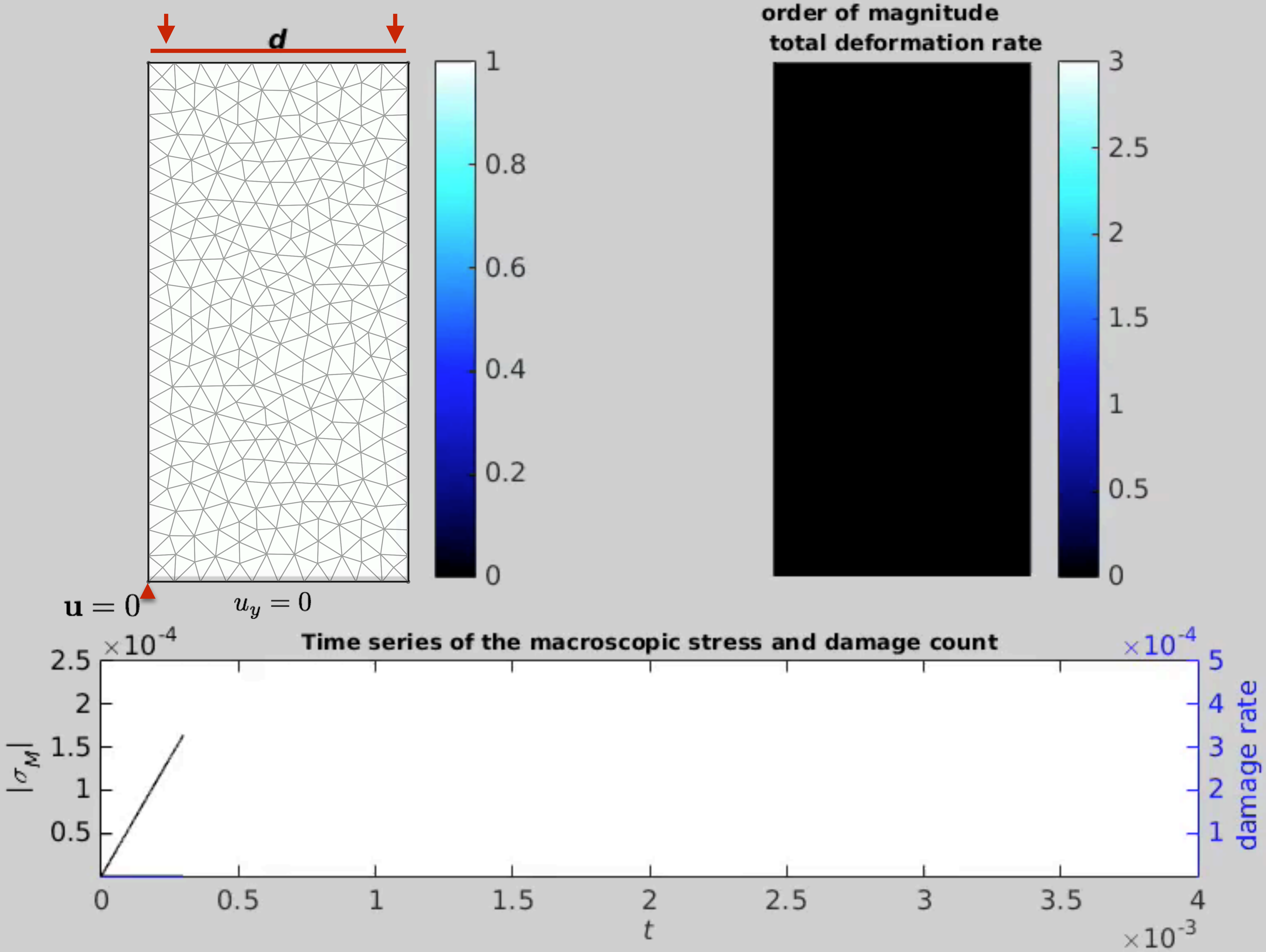
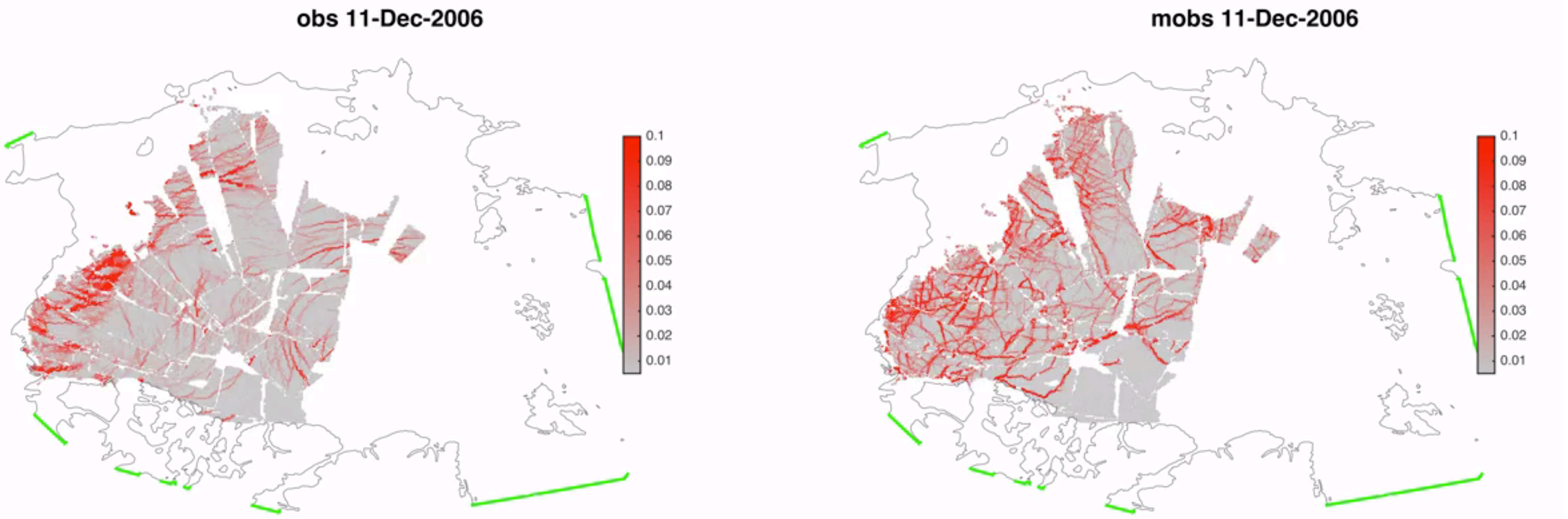
A very idealized test case



A realistic test case



Credit: S. Bouillon

NERSC

neXtSIM

Bouillon et al., 2015, Rampal et al., 2016, 2019, …

- FEM model, Lagrangian framework + dynamical remeshing
- Includes thermodynamics
- Forced with realistic winds
- Stand-alone or coupled to an ocean component (NEMO)

How do we **validate** models?

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Against observations of:

- ice **deformation,**
- **lead fraction,**
- ice concentration,
- ice **thickness.**

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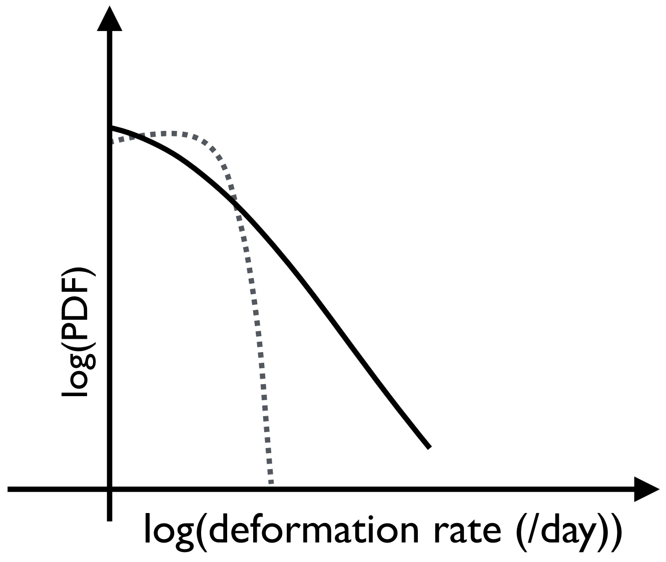
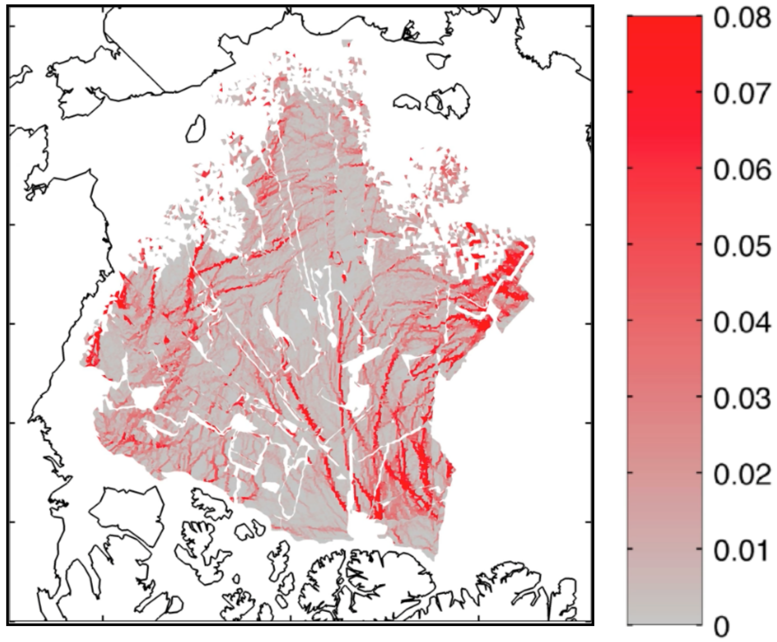
Probability Density Function (PDFs)

- Indication of scale-invariance
- **Low predictability skills, not well described by the mean**



Martin and Thorndike, 1985
Marsan et al., 2004
Rampal et al., 2008
Girard et al., 2009, 2010
Spreen et al., 2016
Bouchat and Tremblay., 2017

Deformation rate invariant



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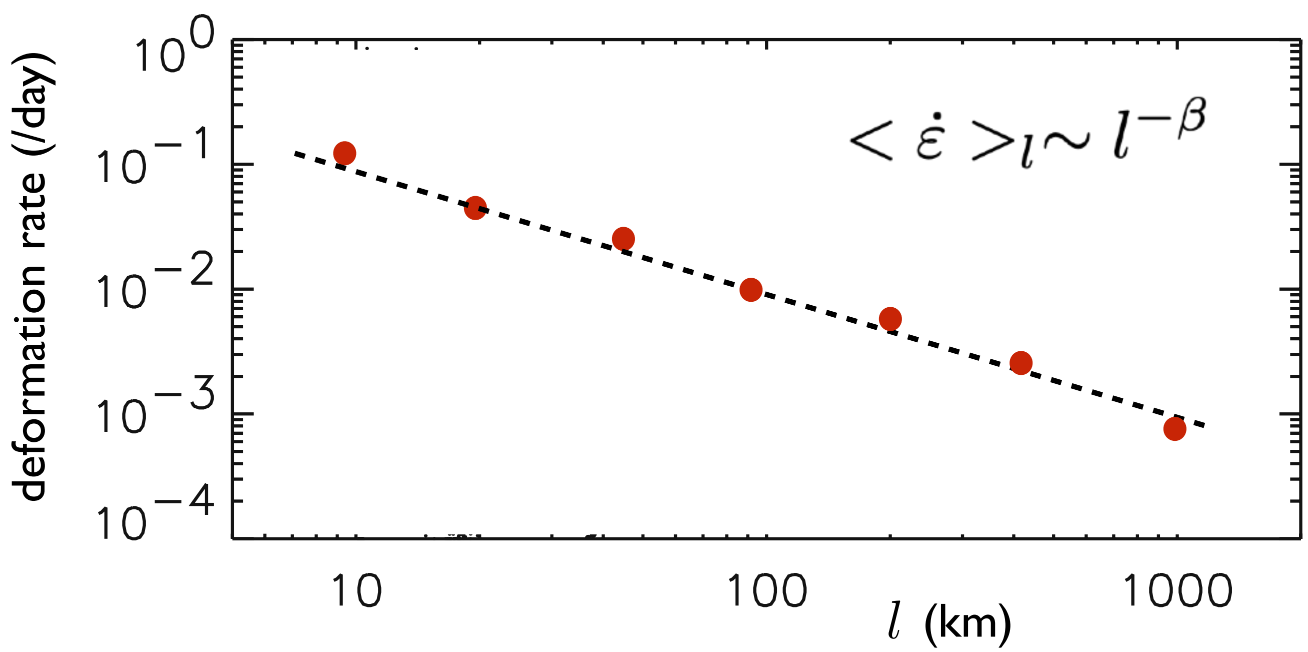
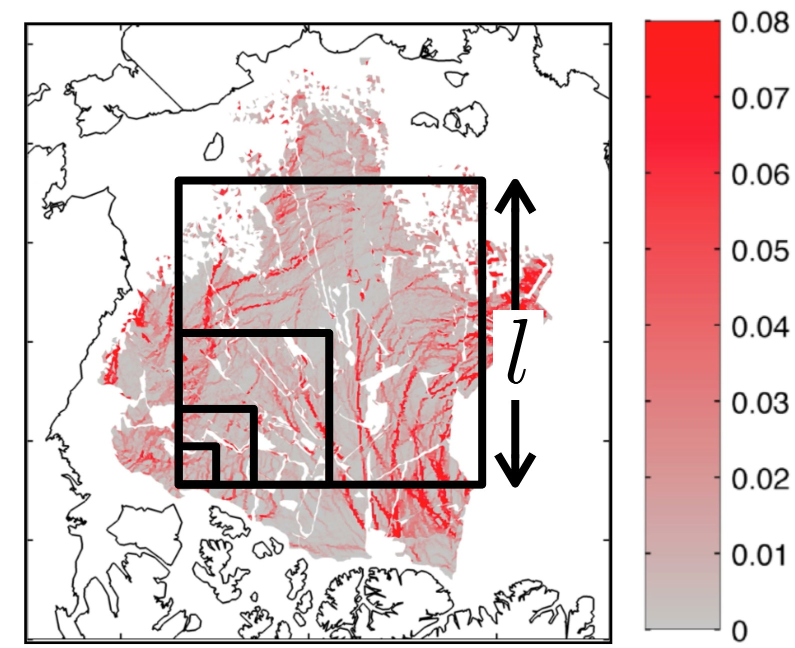
Scaling analyses ("coarse-graining")

- Indication of the amount of localization in space and time



Lindsay et al., 2003
Marsan et al., 2004
Rampal et al., 2008,
Hutchings et al. 2011
Oikkonen et al., 2017
And many others…

Deformation rate invariant



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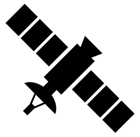

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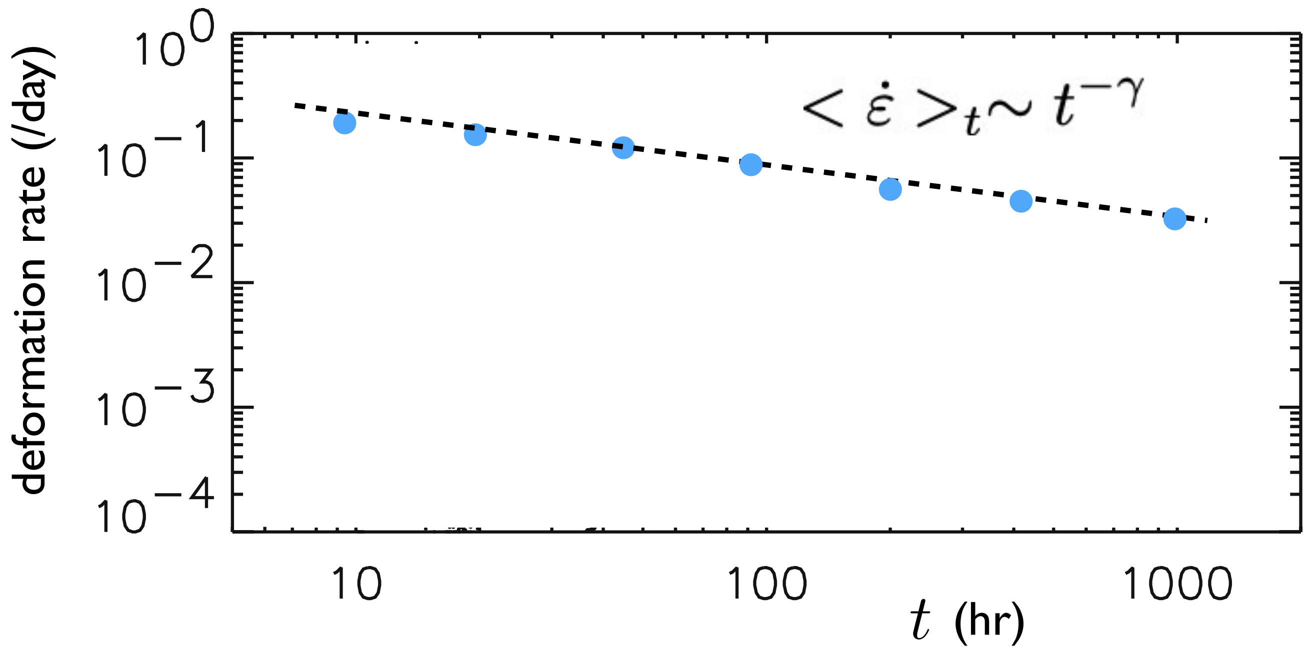

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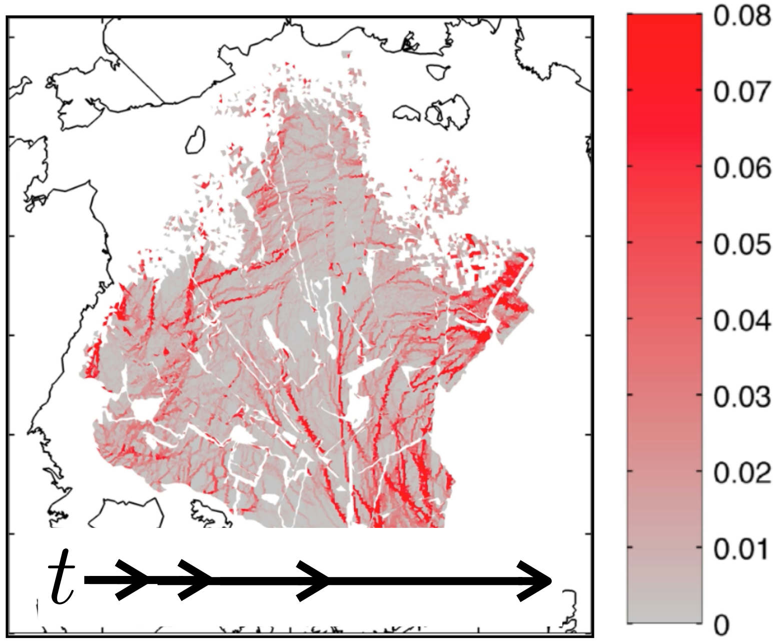

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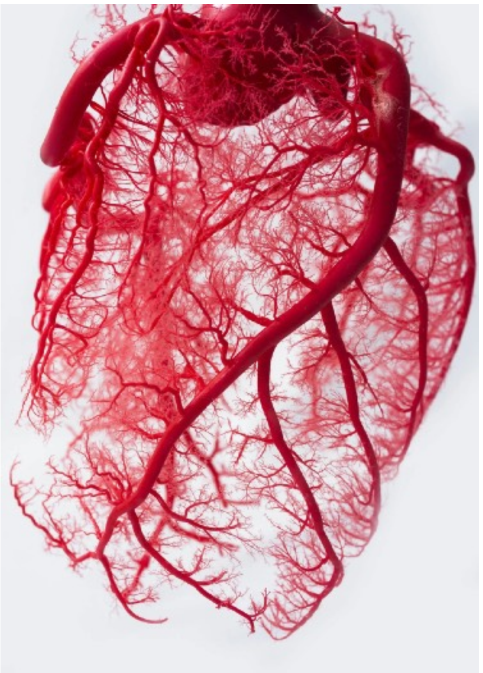

https://iternal.us/what-is-a-fractal/

How do we **validate** models?

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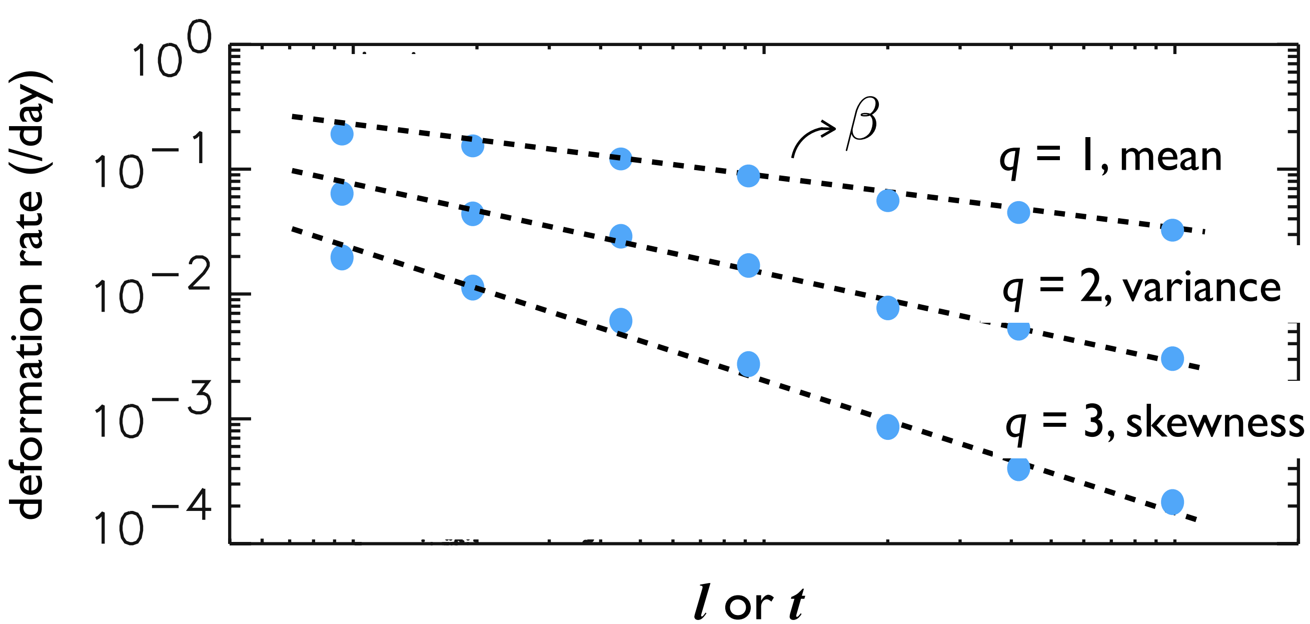
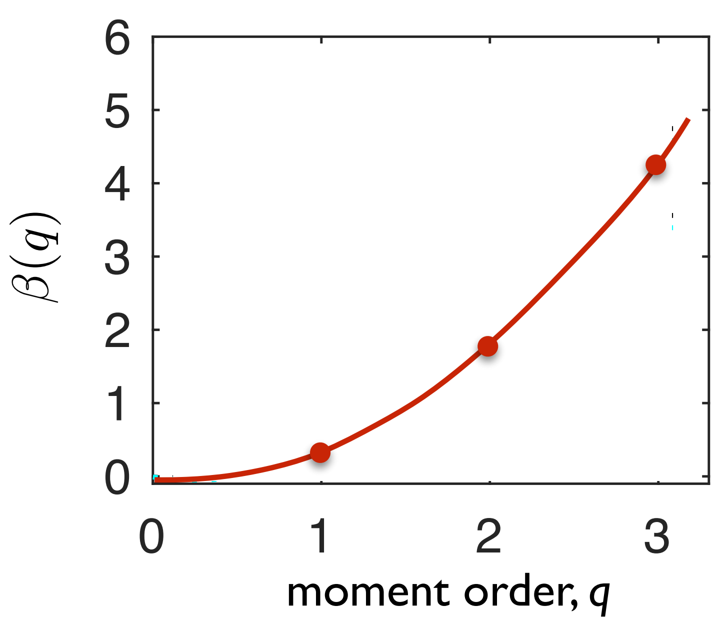
Multi-fractal scaling analyses

- Indication that the deformation is **heterogeneous and intermittent**





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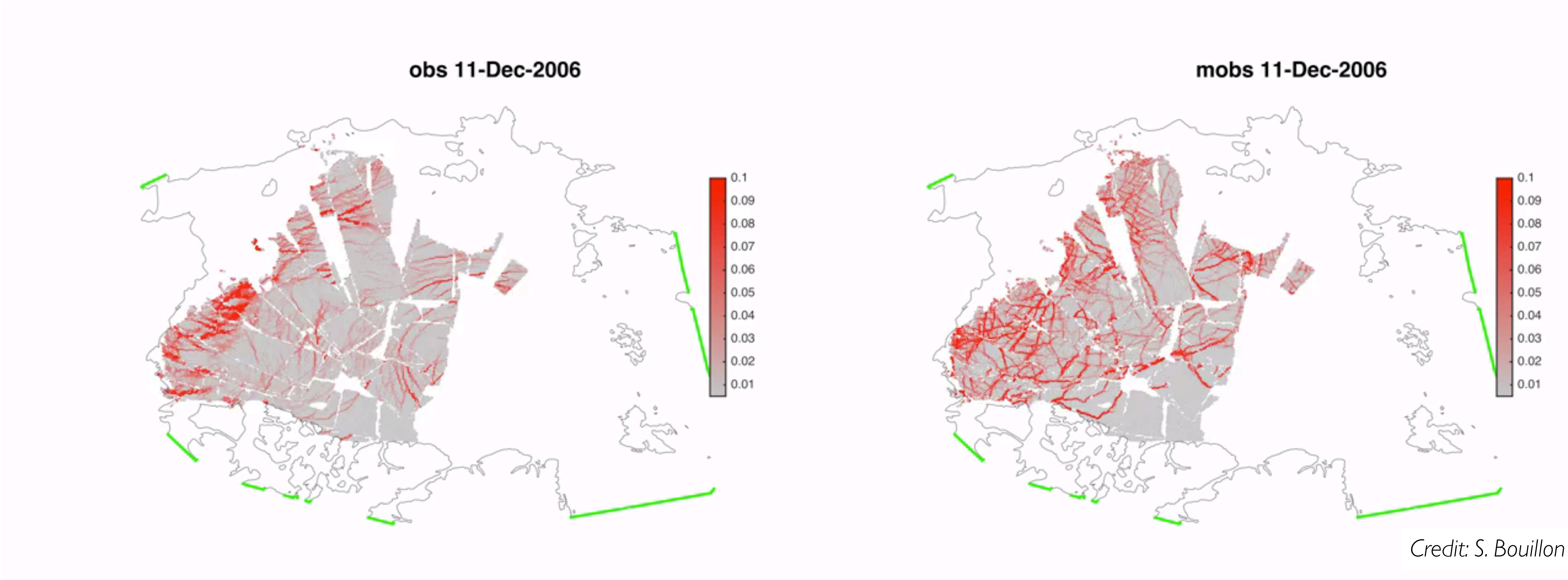
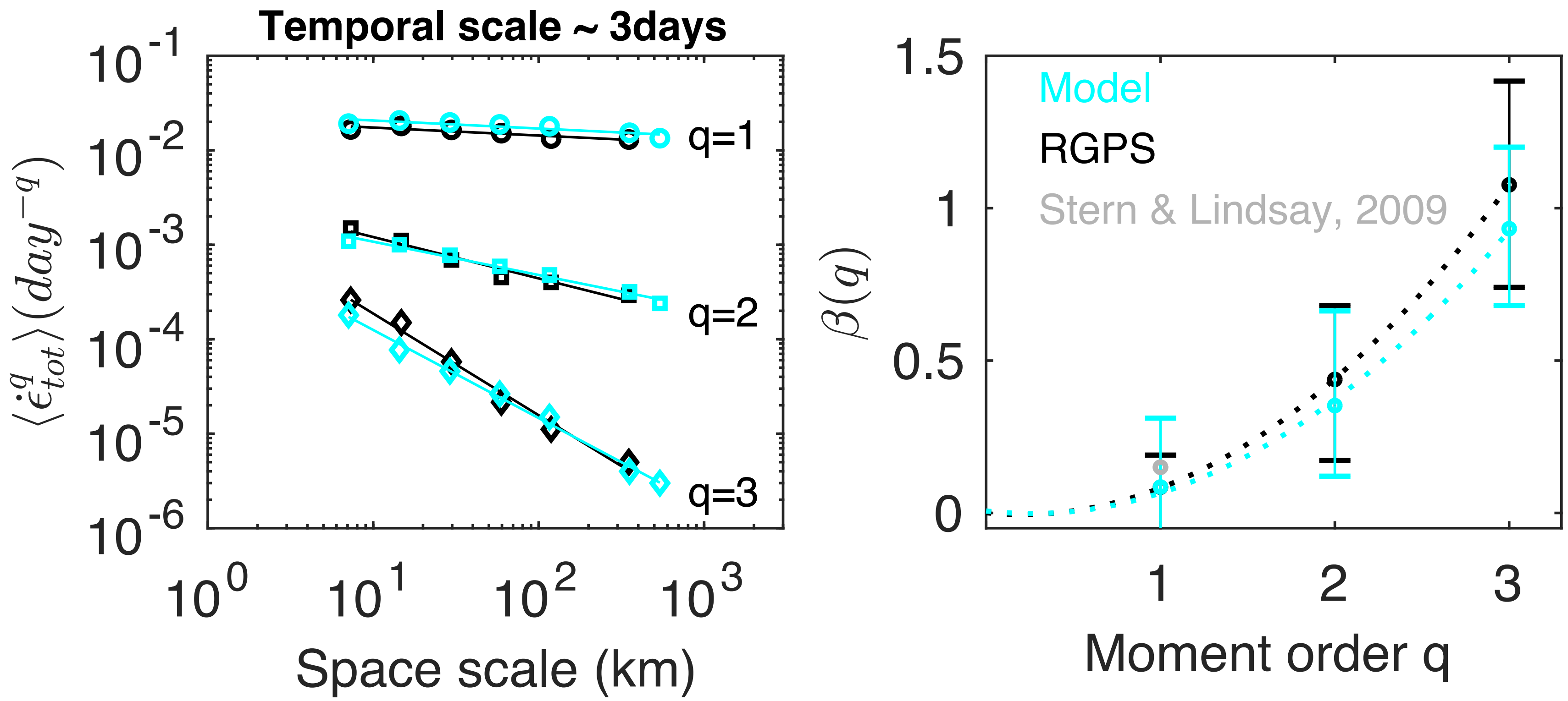


Credit: S. Bouillon



Rampal, Dansereau et al., 2019

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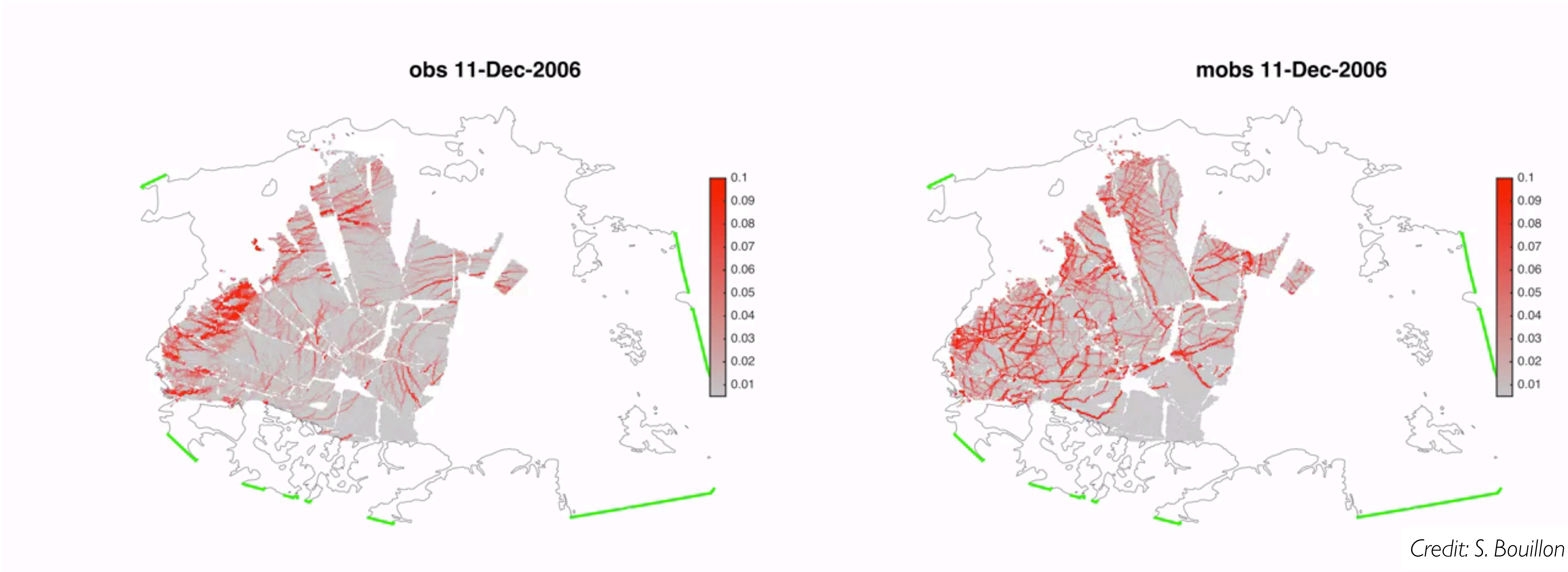

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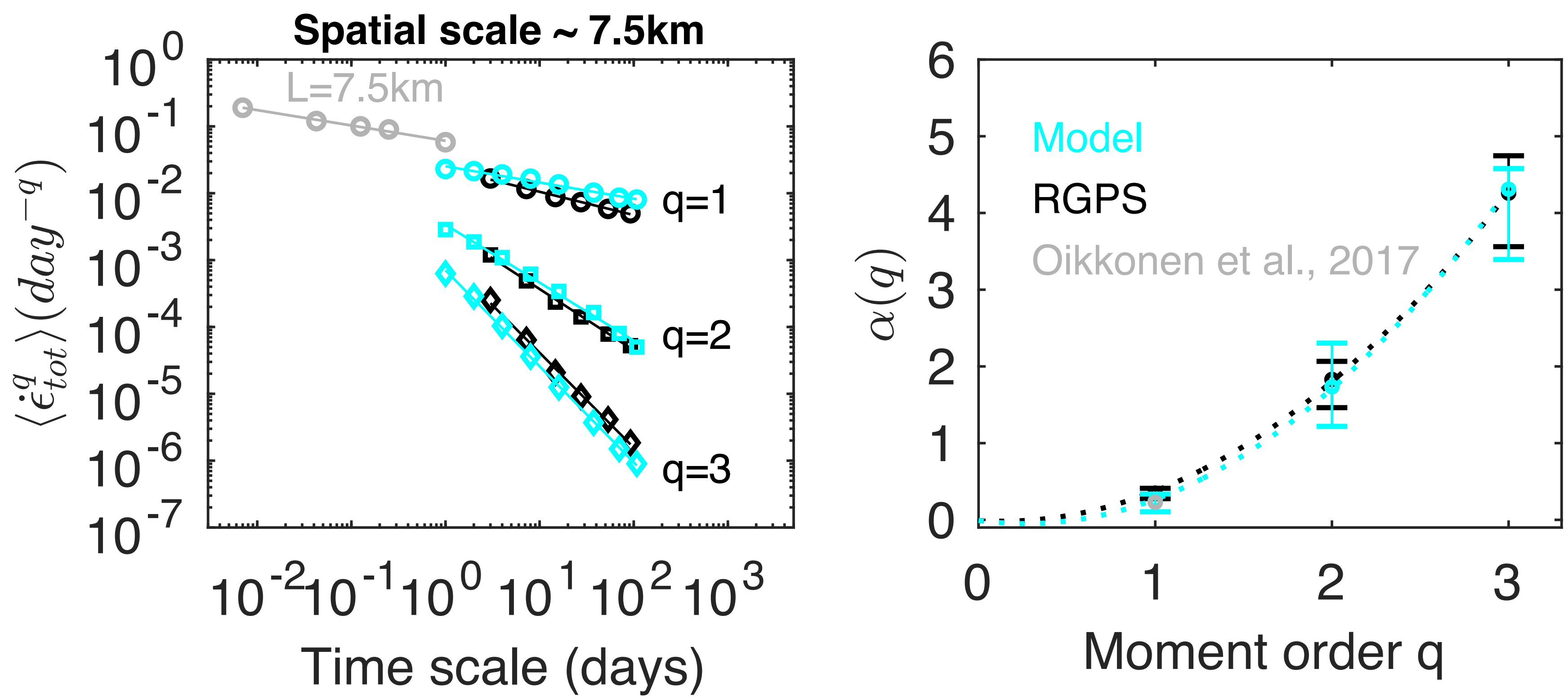

Rampal, Dansereau et al., 2019

How do we **use** models?

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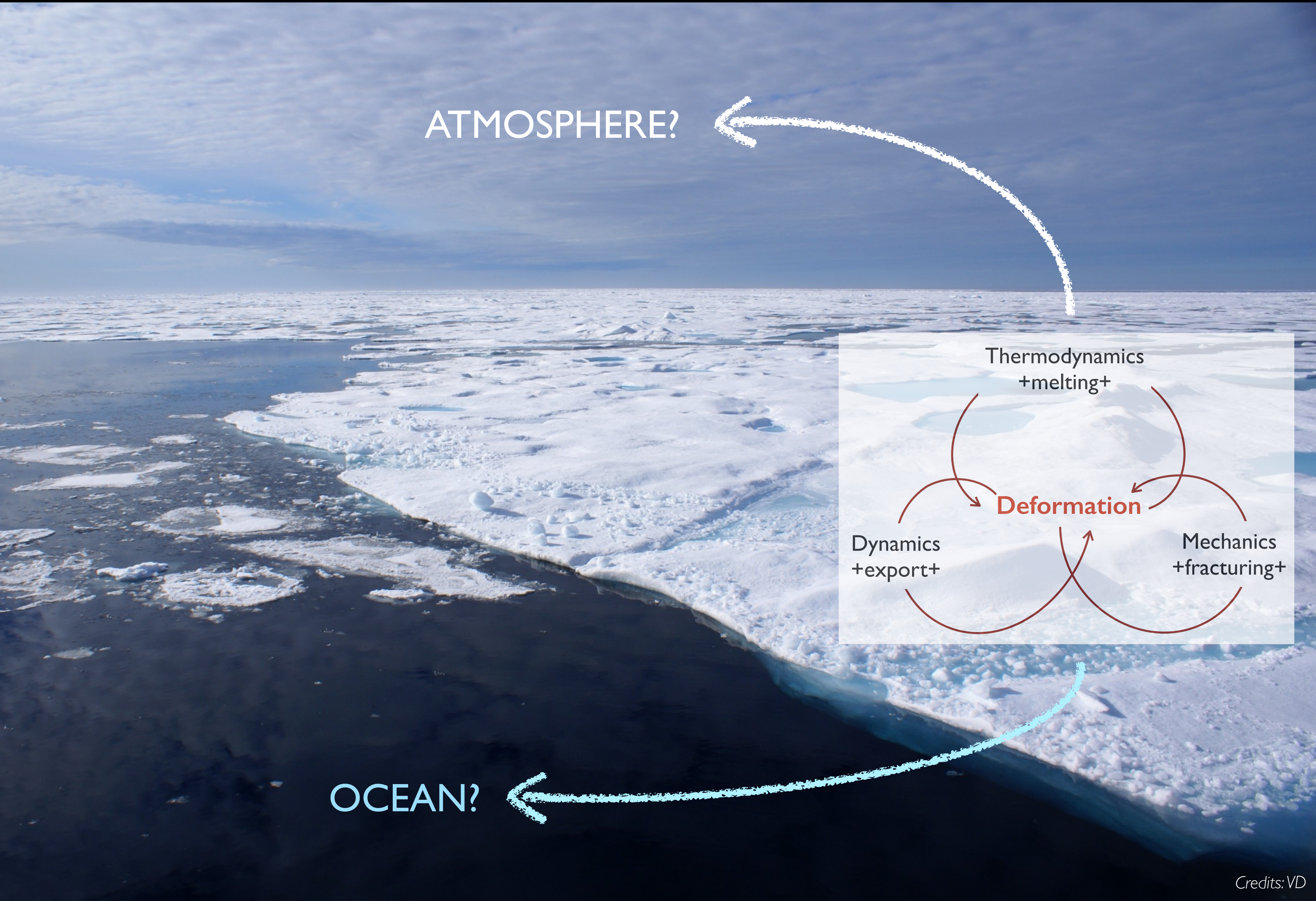

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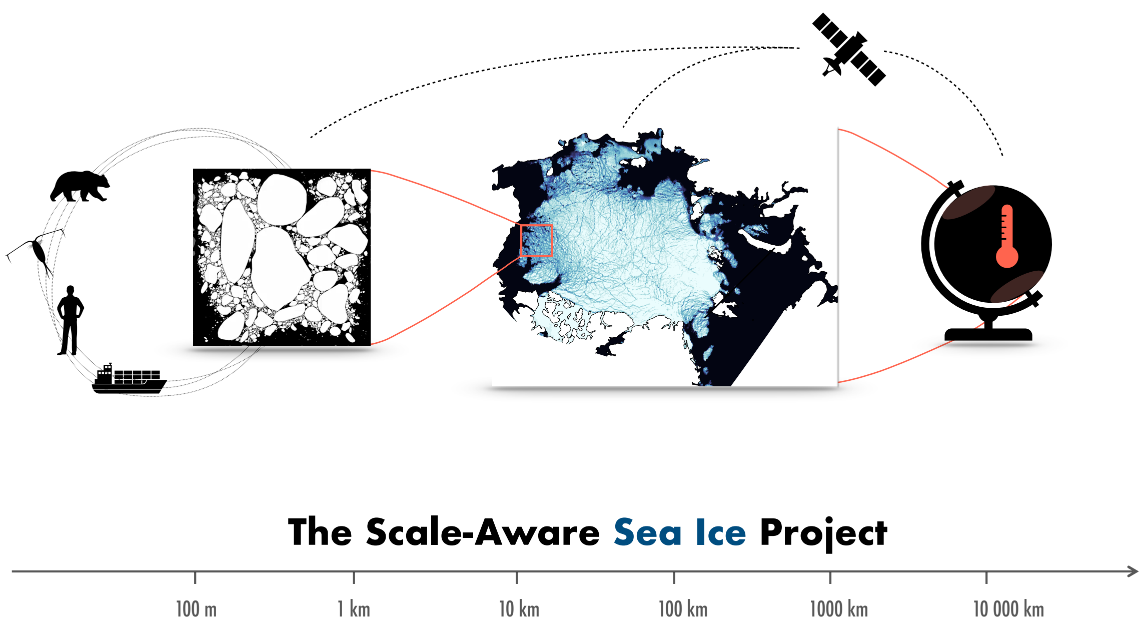

"An international collaborative project to better understand the impact of amplified warming in polar regions, through the development of a new (COUPLED) sea ice modelling paradigm, **neXtSIM**-DG"

https://sasip-climate.github.io/


P. Rampal


E. Olason


V. Dansereau


C. Horvat


A. Carassi


R. Msadek

- 6 Co-investigators
- 60 participants (12 institutions, 7 countries)
- 2021-2027

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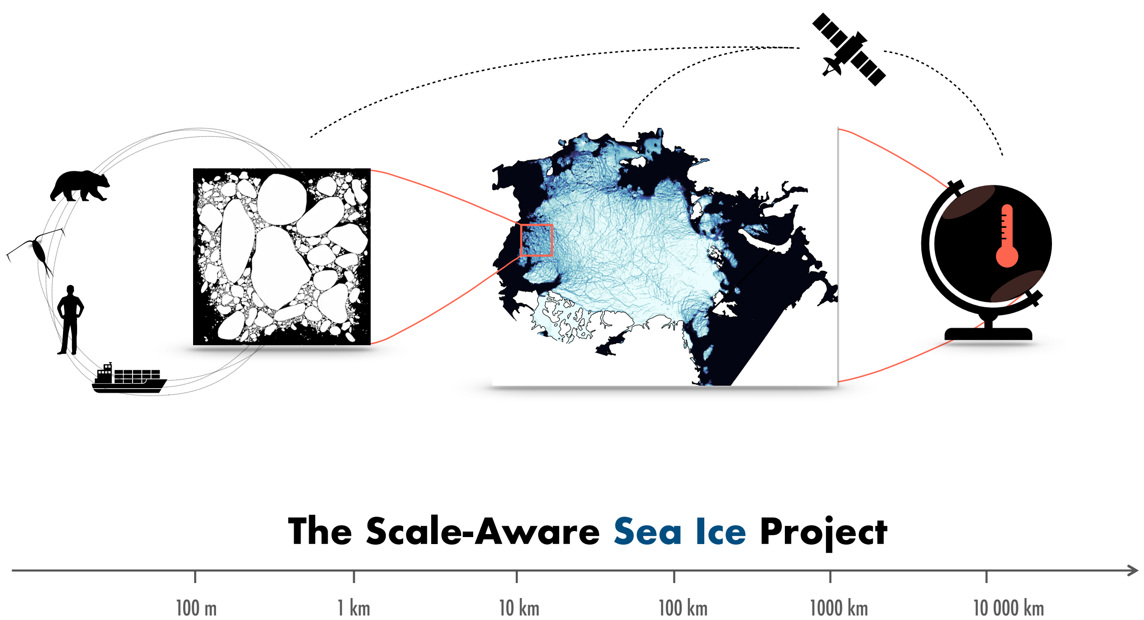



S. Leroux


L. Brodeau

datlas






- 6 Co-investigators
- 60 participants (12 institutions, 7 countries)
- 2021-2027

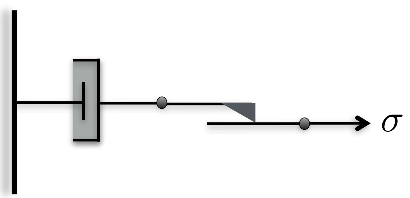
ISTerre NERSC IGE BROWN

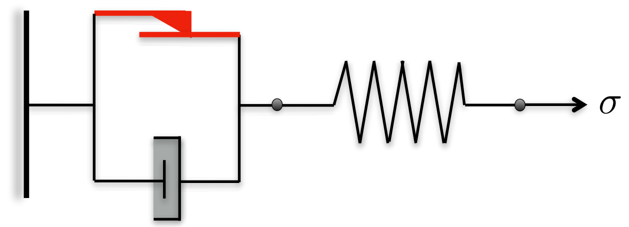
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

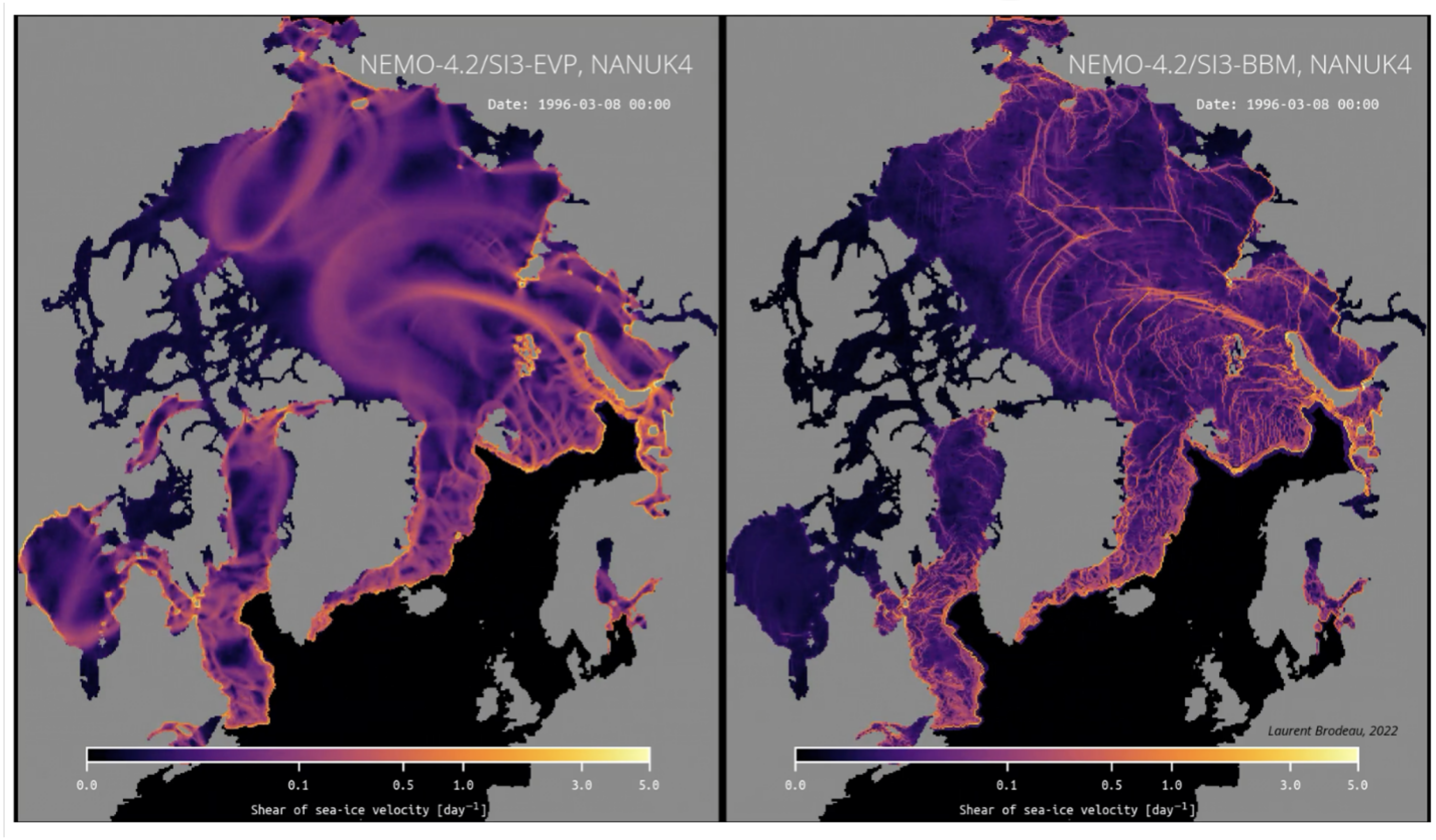
CERFACS

A taste of the challenge

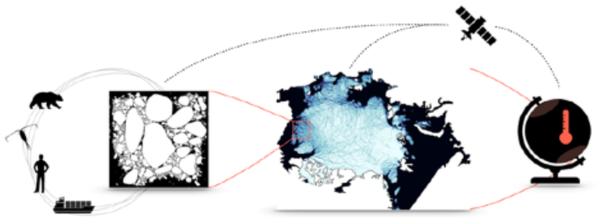
Brodeau, L., Rampal, P., Òlason, E., and Dansereau, V.: Implementation of a brittle sea-ice rheology in an Eulerian, finite-difference, C-grid modeling framework: Impact on the simulated deformation of sea-ice in the Arctic, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2023-231, in review, 2024.







How do we **use** models?



Sea ice deformation in a coupled sea ice-ocean model

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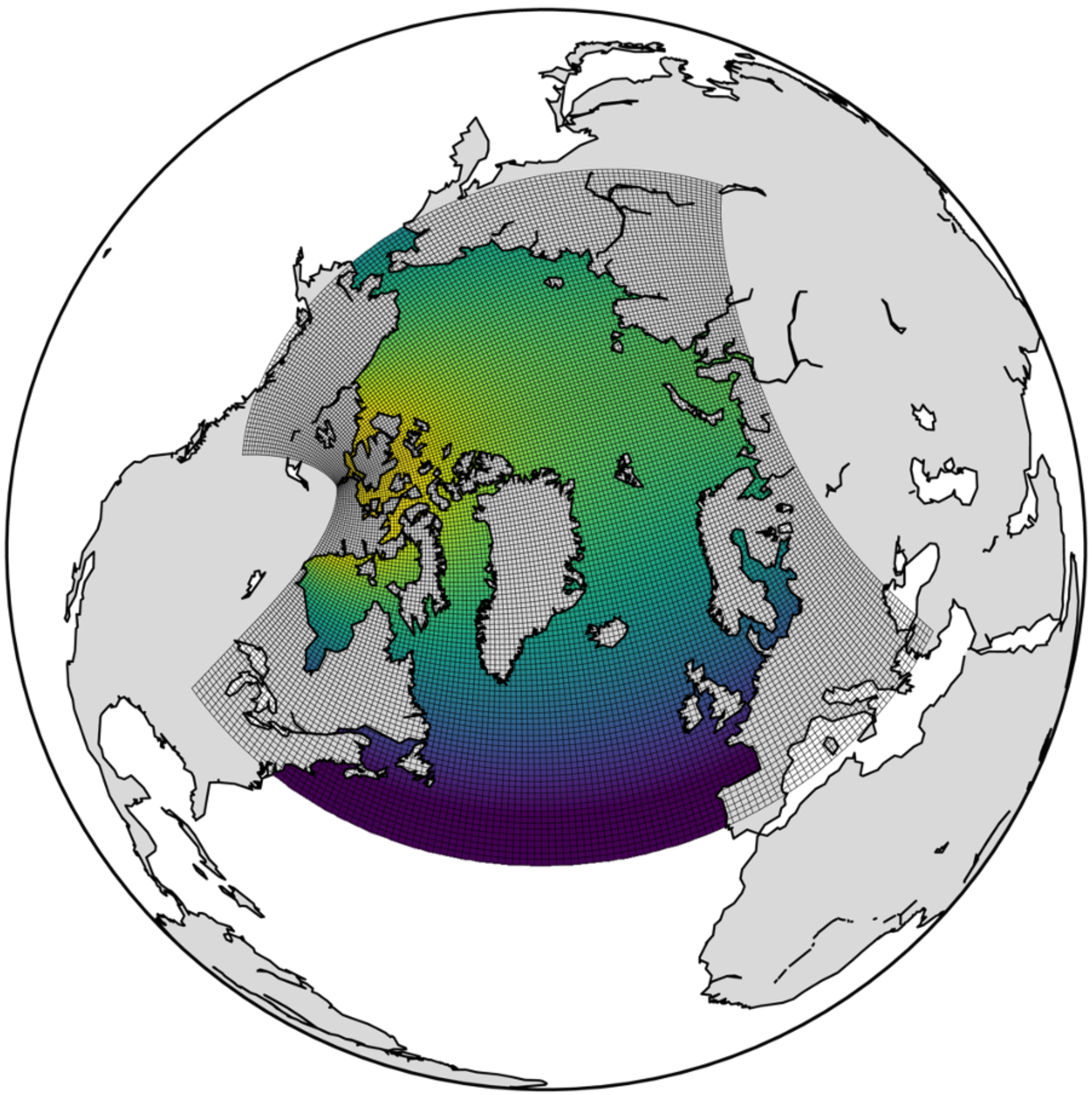
A few words on NEMO-SI3

Credit: P. Rampal, L. Brodeau



Regional coupled ocean/sea-ice experiments:

- NEMO version 4.2.1 (
- Ocean: 31 levels (z* coordinate)
- Δt: 720s (OPA, SI3, coupling frequency)
- Atmo forcing: **hourly ERA5**
- Lateral BCs: Glorys2v4 reanalysis
- Output frequency: 1 hour
- # **itterations** for **aEVP**: 180
- **Time-splitting** for **BBM**: 180 → Δt_s = 4 s

The **NANUK4 or 12** NEMO configuration
- ☆Nominal resolution: 1/4°
- ☆Horizontal points: 492 × 566
- ☆Staggered *Arakawa* C-grid

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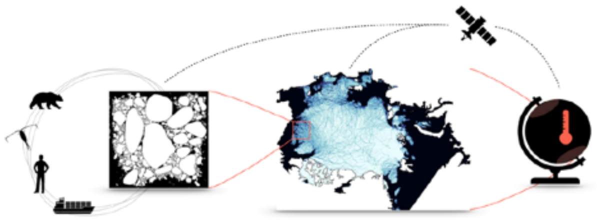
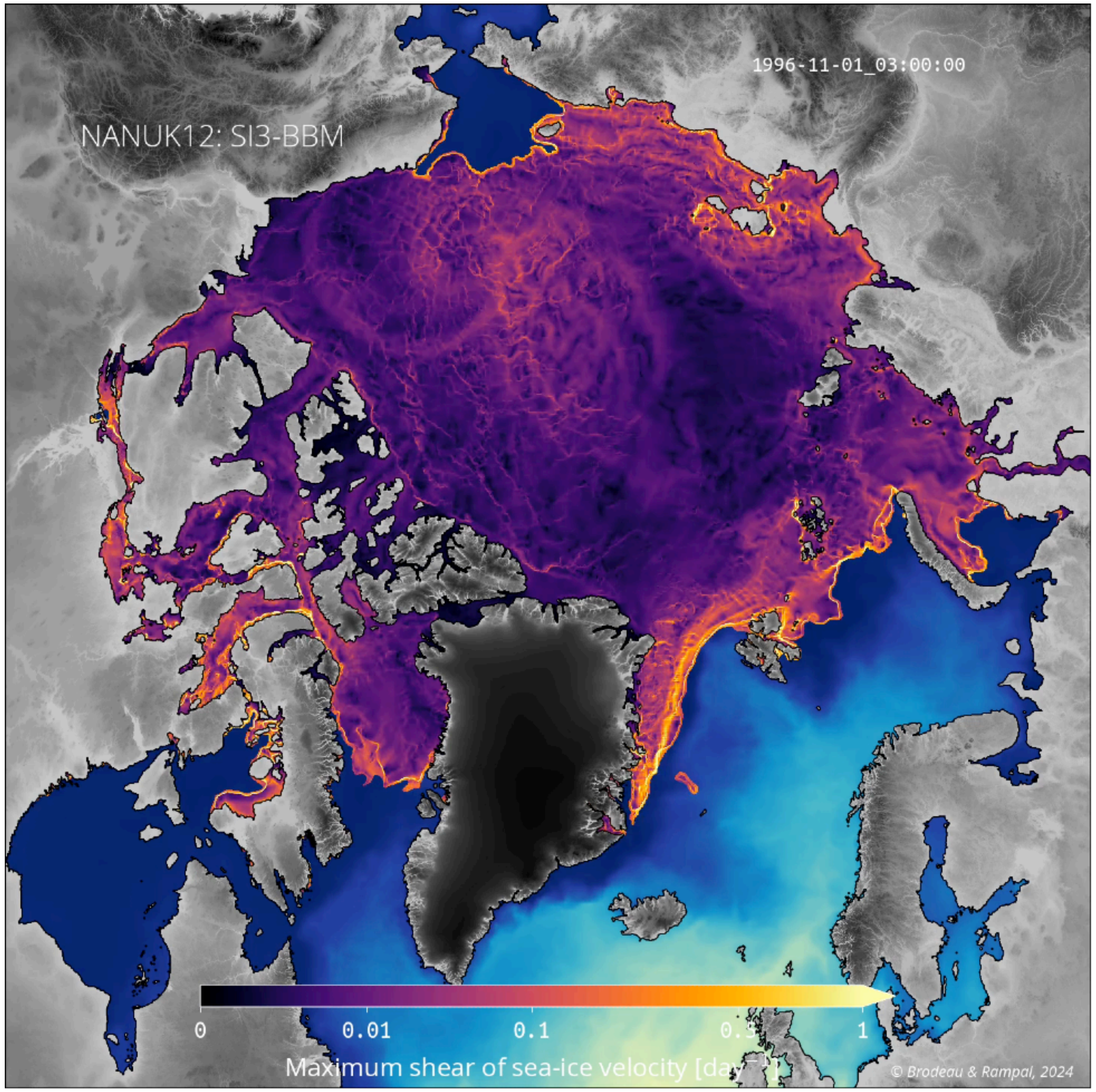
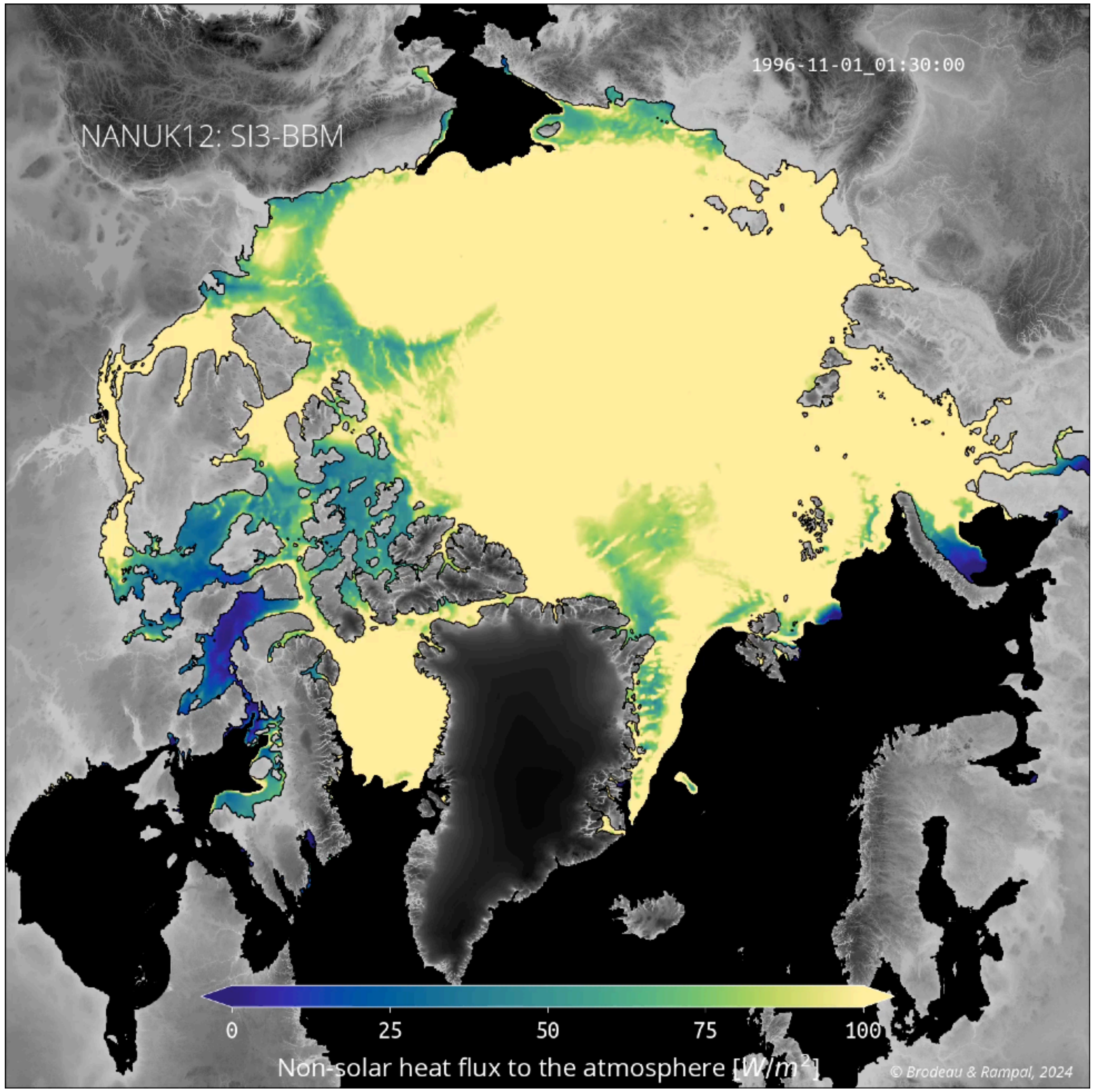


Sea ice deformation in a coupled sea ice-ocean model

Credit: Laurent Brodeau





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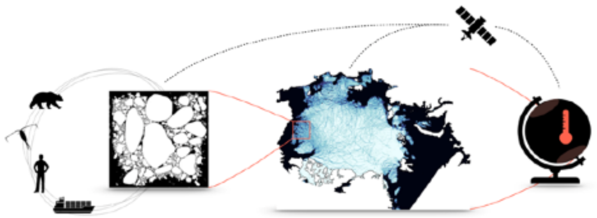

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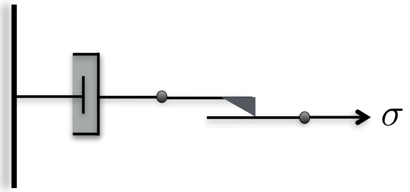
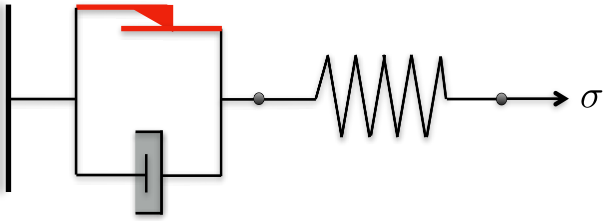
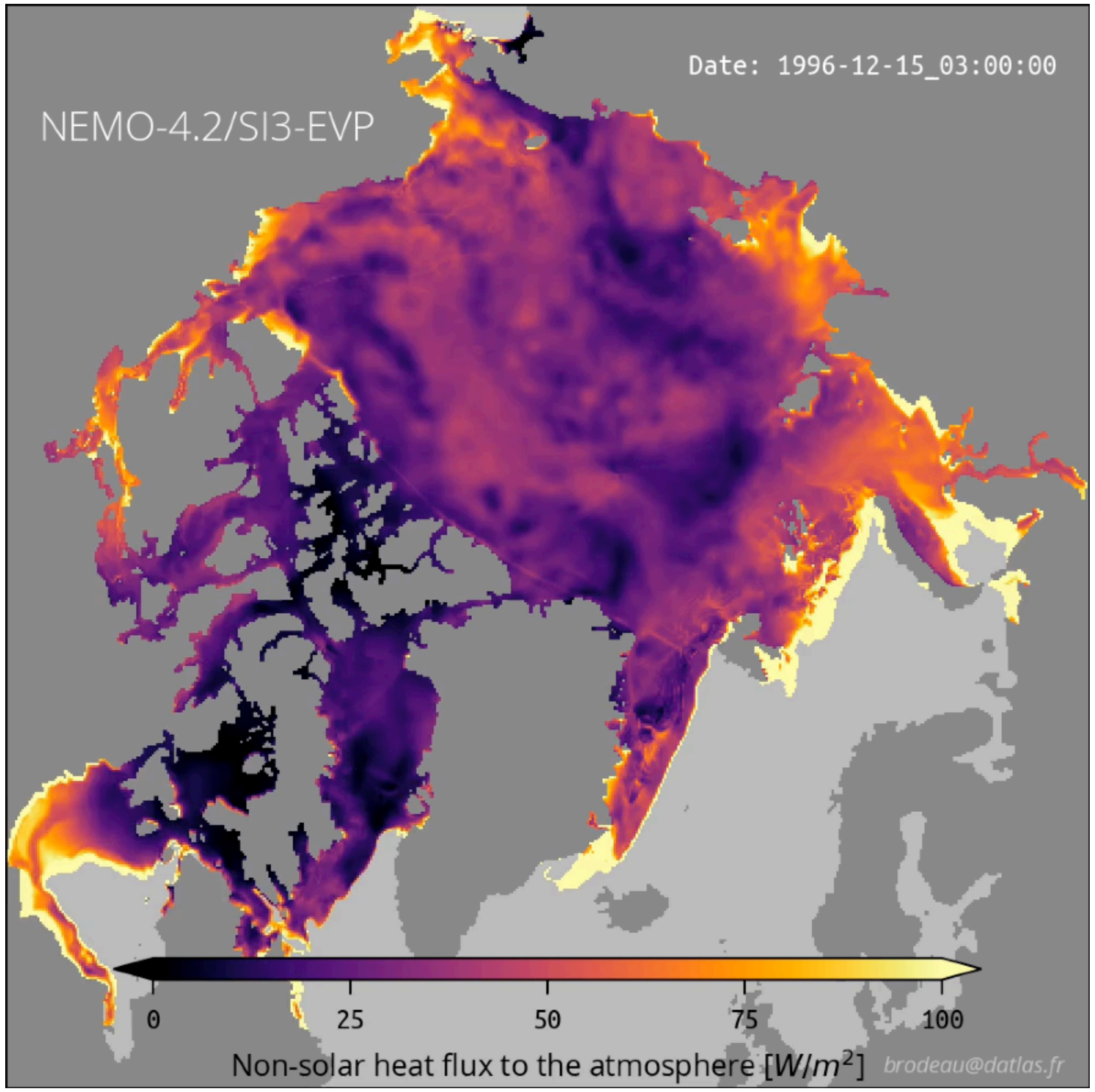
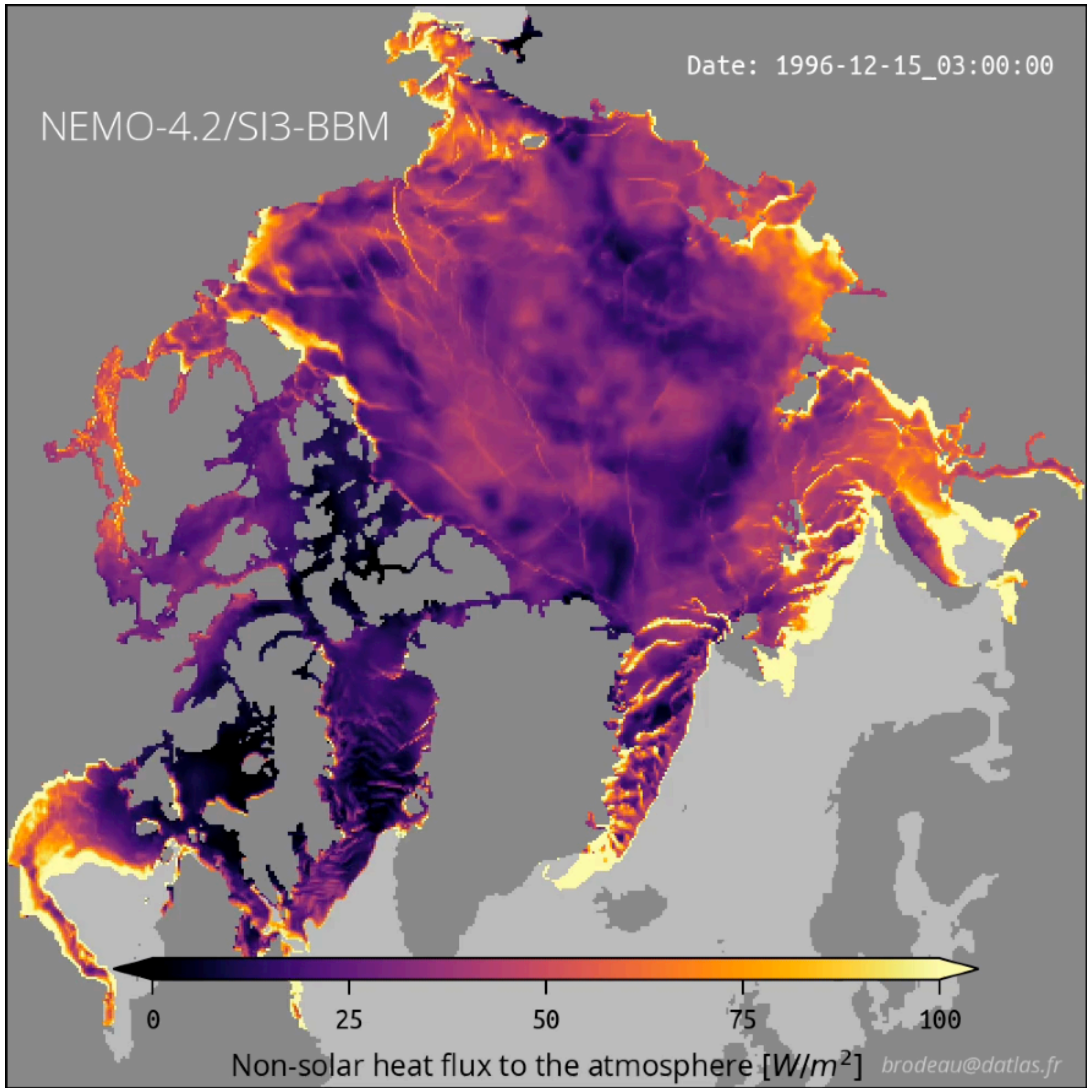
Credit: Laurent Brodeau









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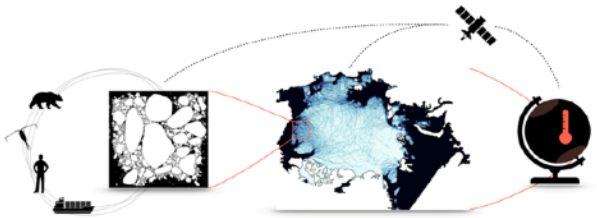
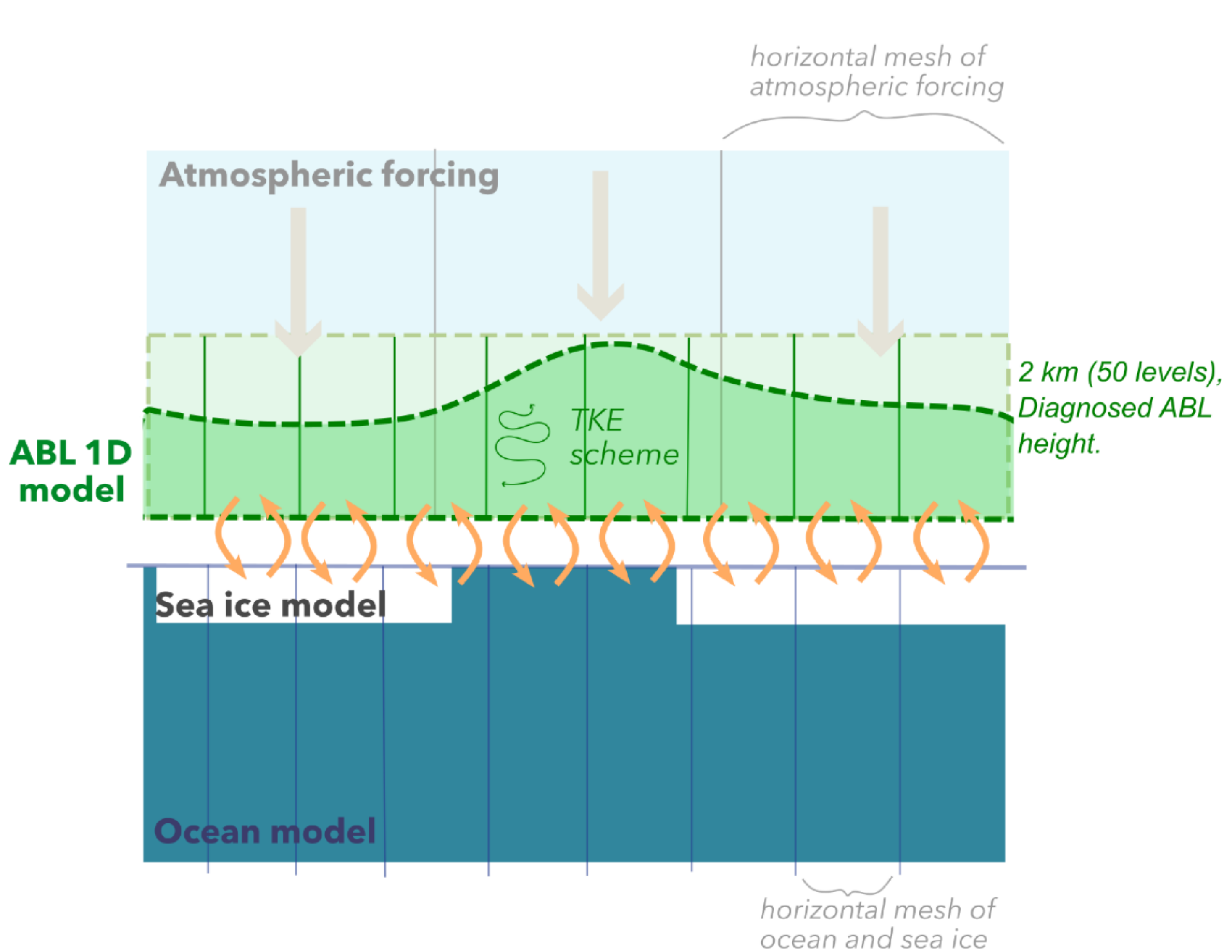


Sea ice deformation in a coupled sea ice-ABL model

Credit: Stéphanie Leroux

Available in NEMO-SI3:
1D-column ABL model *(Lemarié et al., 2021)*



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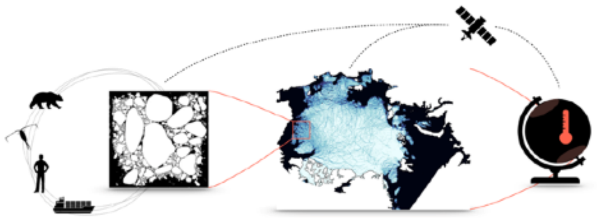

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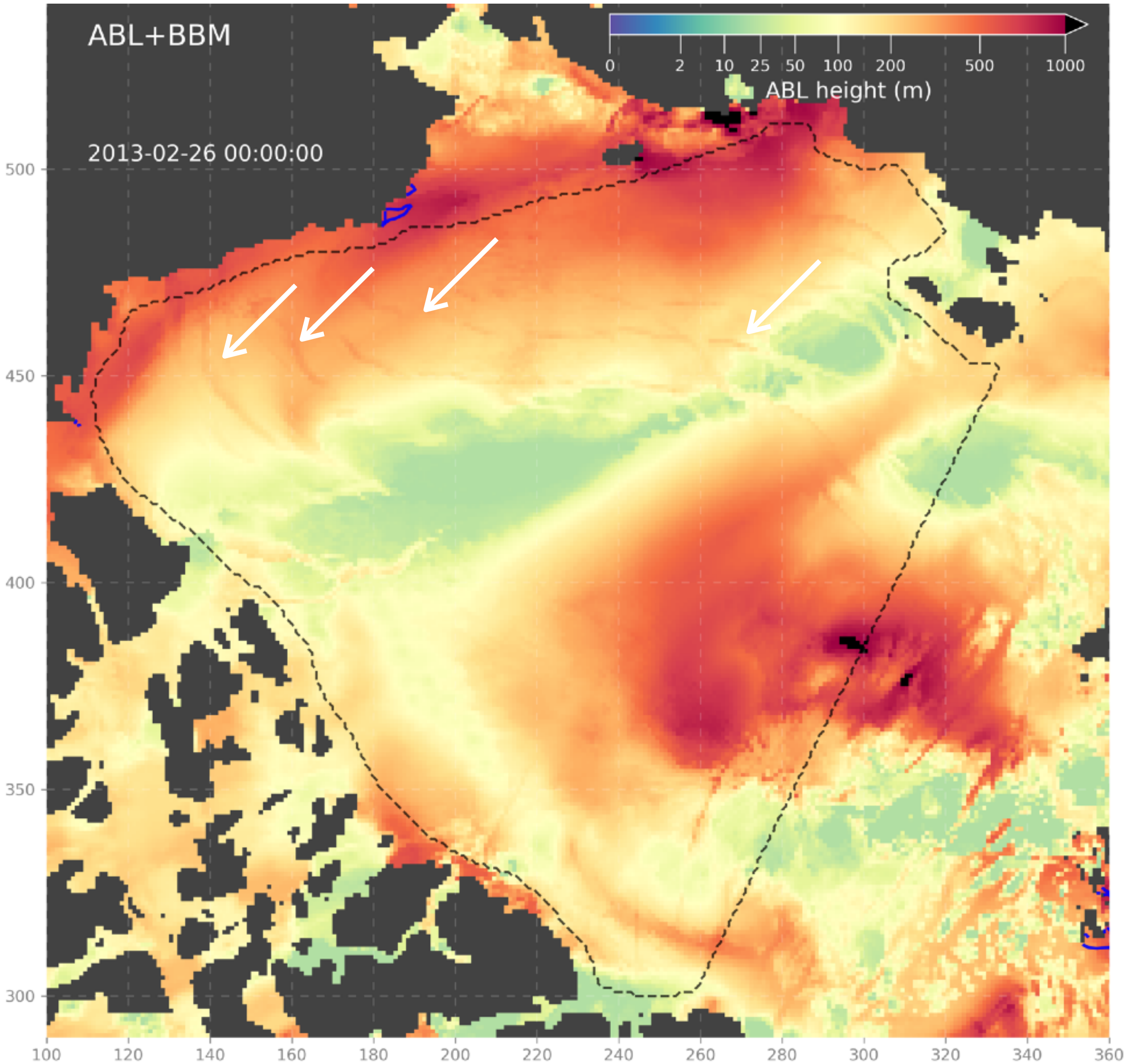
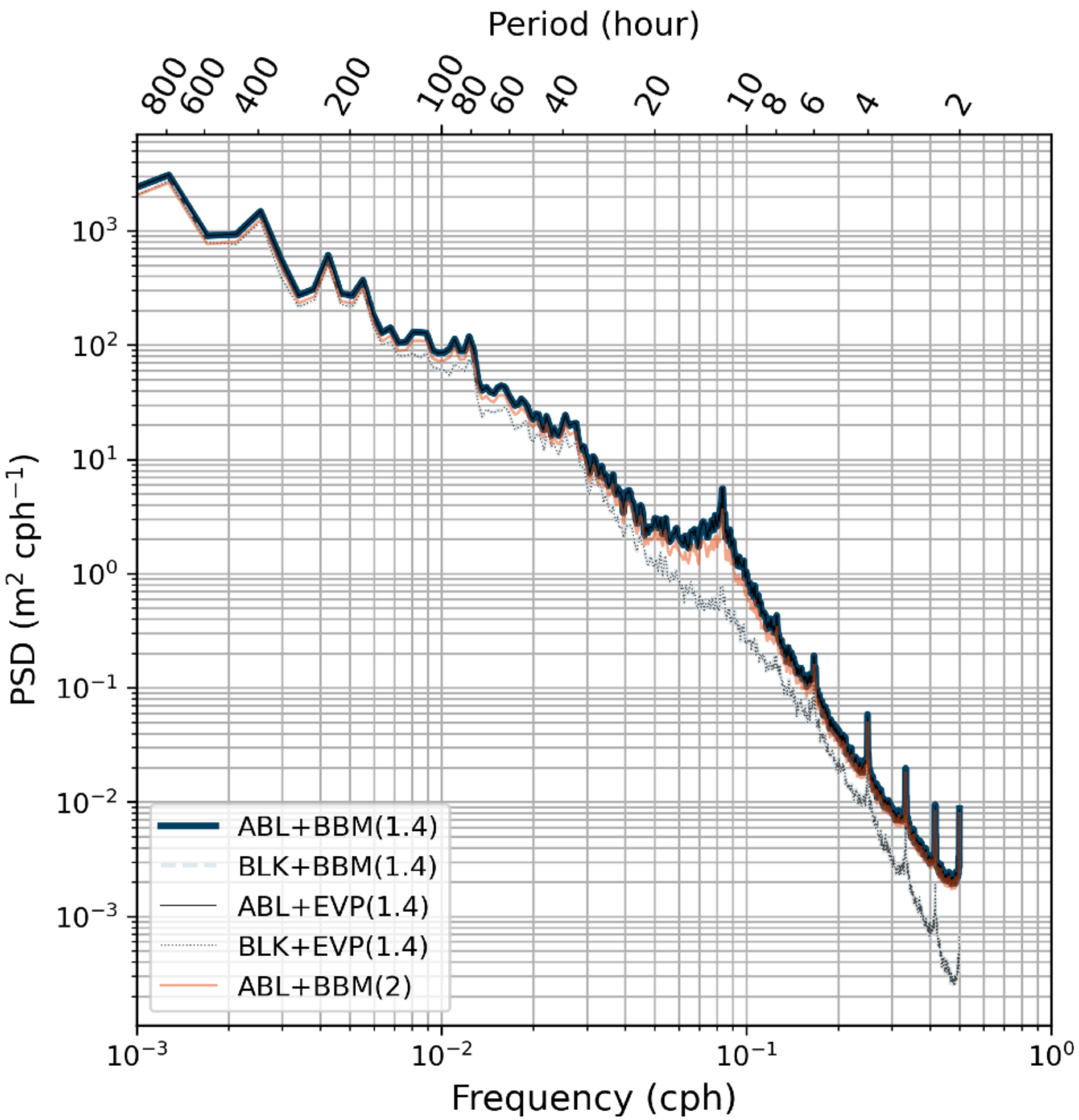




Conclusions

- On propose/développe un modèle dynamique plus intuitif pour le comportement mécanique solide-fluide-granulaire de la banquise.

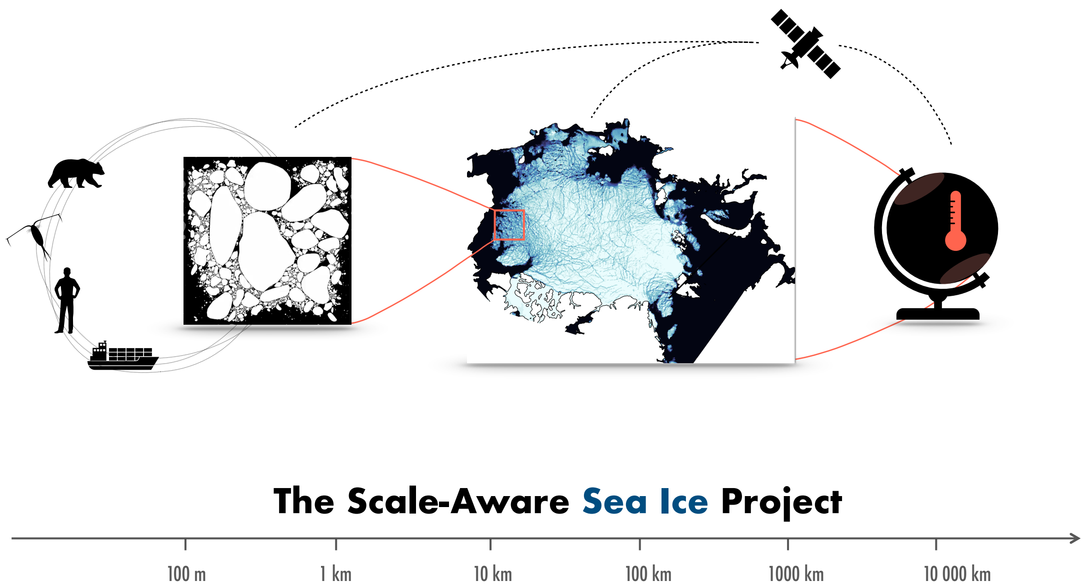
- Le modèle simule bien la déformation de la banquise, *du point de vue statistique.*

- Couplage ocean-banquise-atmosphère en cours.

  Le modèle dynamique a un impact
  - sur les flux de chaleur océan → atmosphère,
  - sur la hauteur de l'ABL,
  - sur les vents simulés.

- Questions ouvertes:

  - Quelle rétro-action sur la banquise?
  - Est-ce que ce nouveau modèle dynamique améliore nos prédictions climatiques?



https://sasip-climate.github.io/

Many thanks!

Questions?

Schmidt Sciences

This research received support through Schmidt Sciences, LLC.