On the Simulation of the Brittle Nature of Sea Ice in Future Earth System Models: Why and How?

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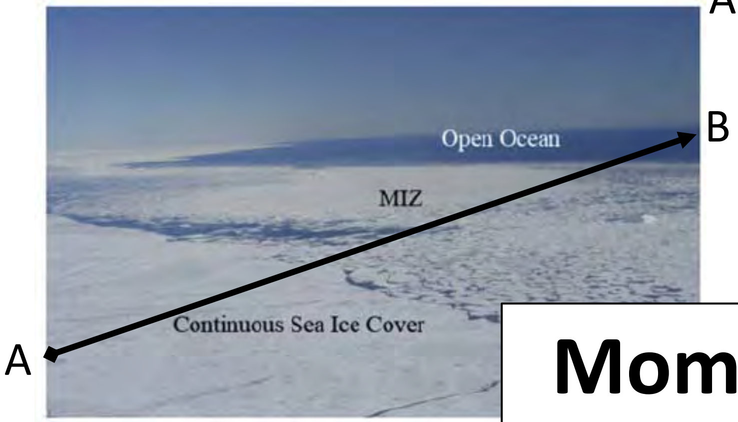
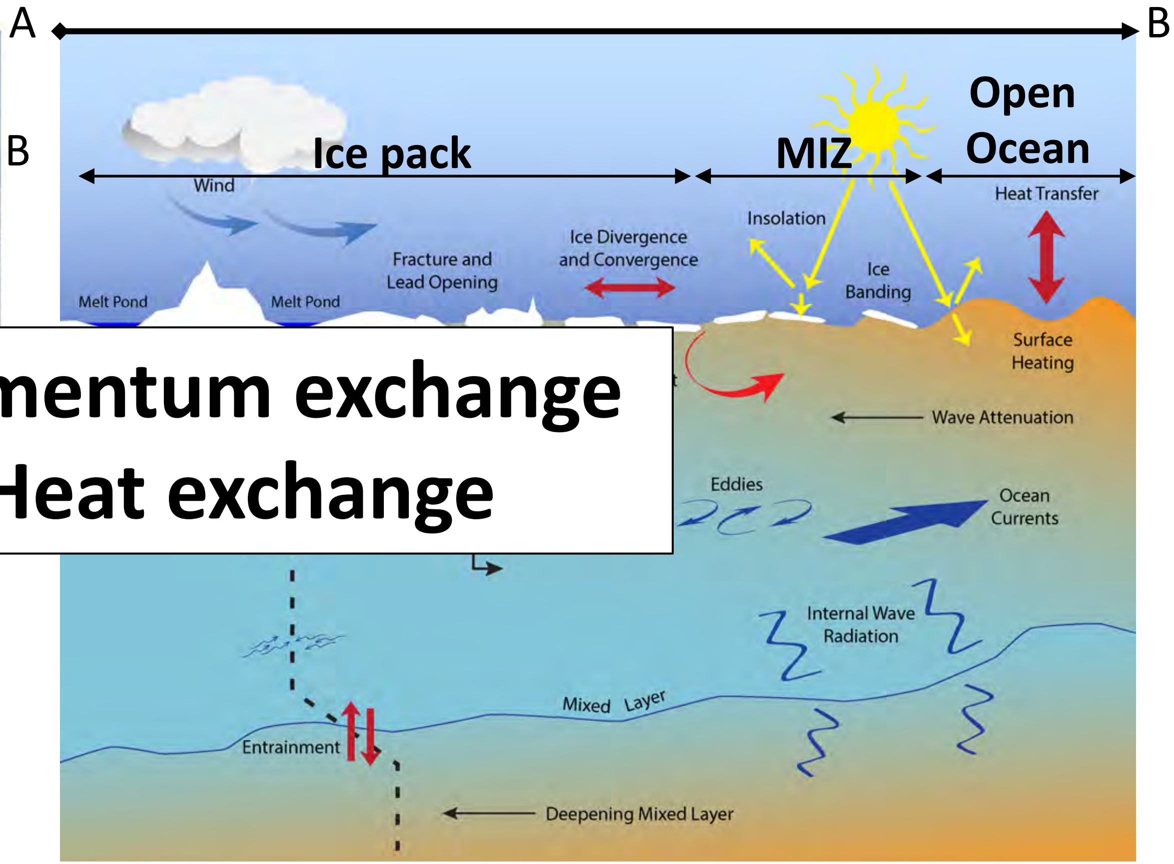
Acknowledgements: E. Olason, V. Dansereau, T. Williams, A. Samaké, P. Itkin

Why to simulate the brittle nature of sea ice?

A brittle solid interface that controls energy exchanges





Momentum exchange
Heat exchange

Source: apl.washington.edu

The sea ice dynamics feedback: impact on the sea ice itself

A more fragile sea ice cover

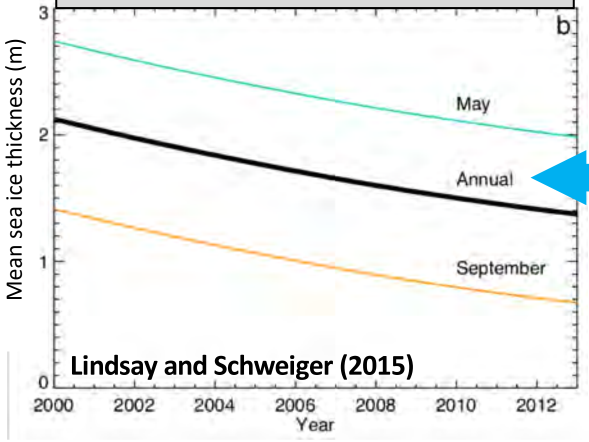
sea ice thickness

-60 cm per decade
2000-2012
(data: in-situ, submarines, airborne, satellites)

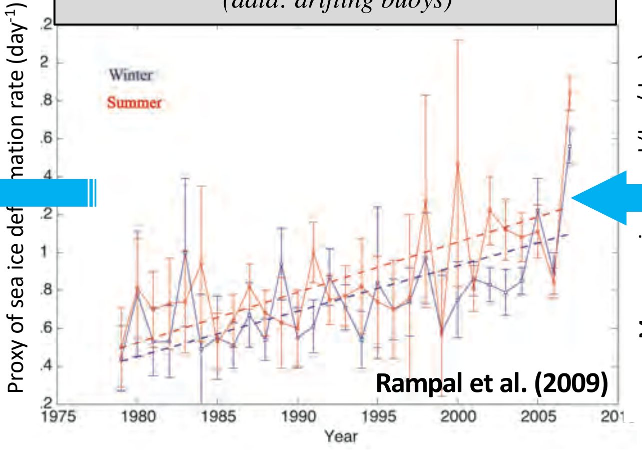
sea ice deformation **and** **sea ice drift**

50% ±10 per decade
1979-2007
(data: drifting buoys)

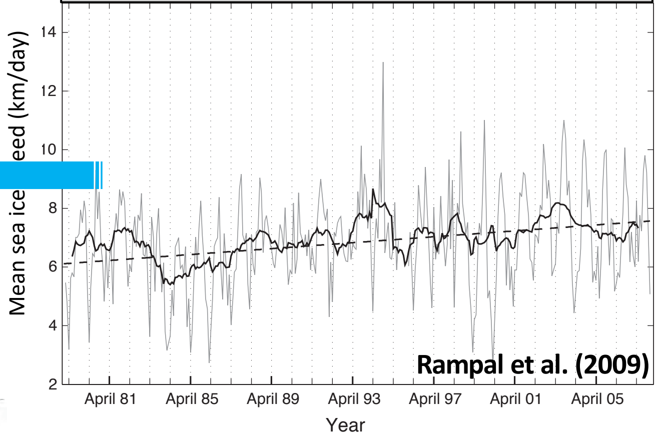
12% ±3 per decade
1979-2007
(data: drifting buoys)



Lindsay and Schweiger (2015)



Rampal et al. (2009)

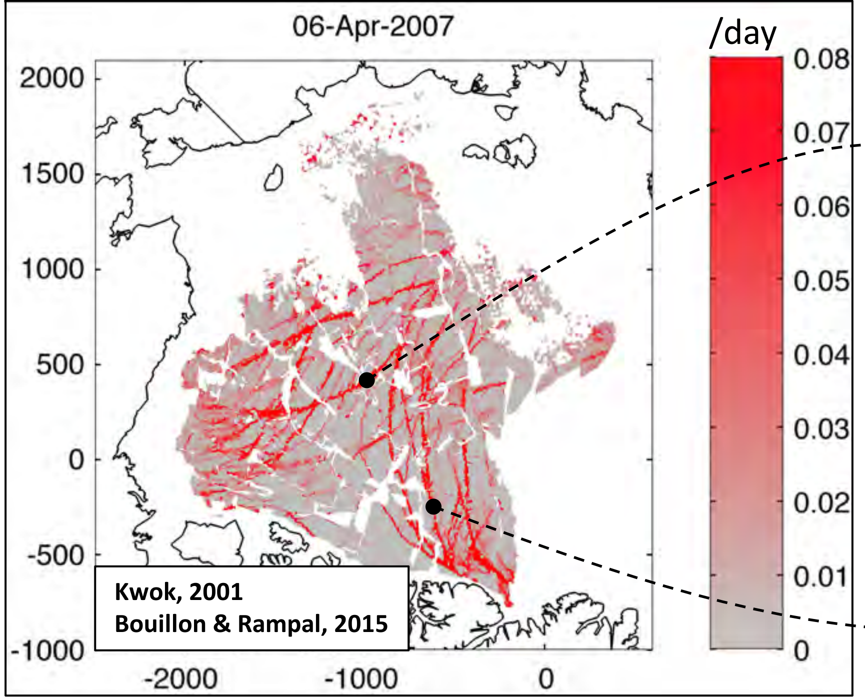


Rampal et al. (2009)

The complex response of sea ice to external forcing

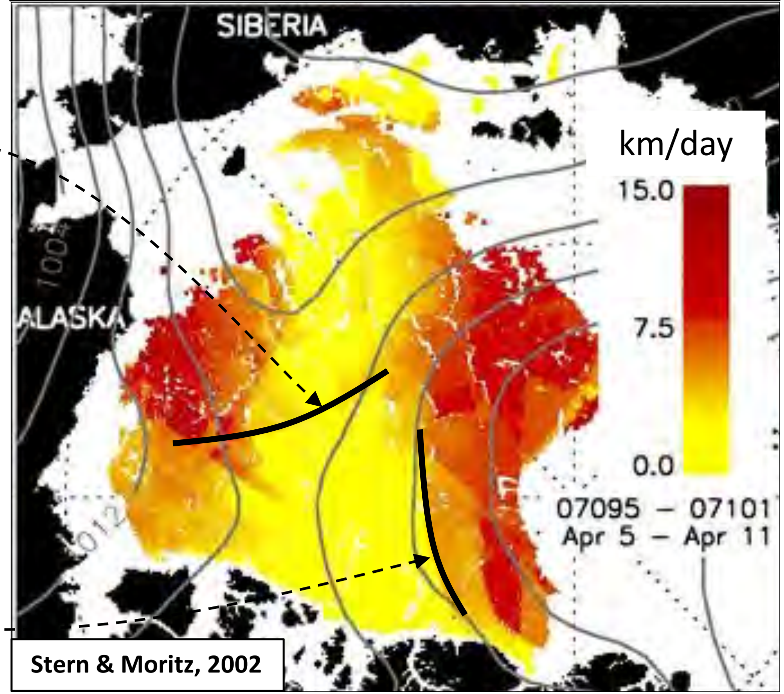
"LKF: Heterogeneous and intermittent"

sea ice deformation rate (Data: SAR - Radarsat)



"Piecewise rigid motion"

sea ice drifting speed (Data: SAR - Radarsat)



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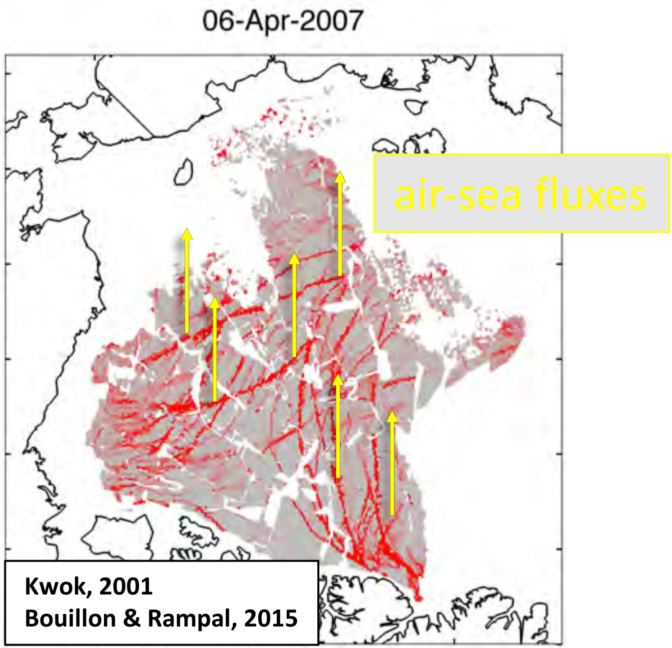

Kwok, 2001
Bouillon & Rampal, 2015

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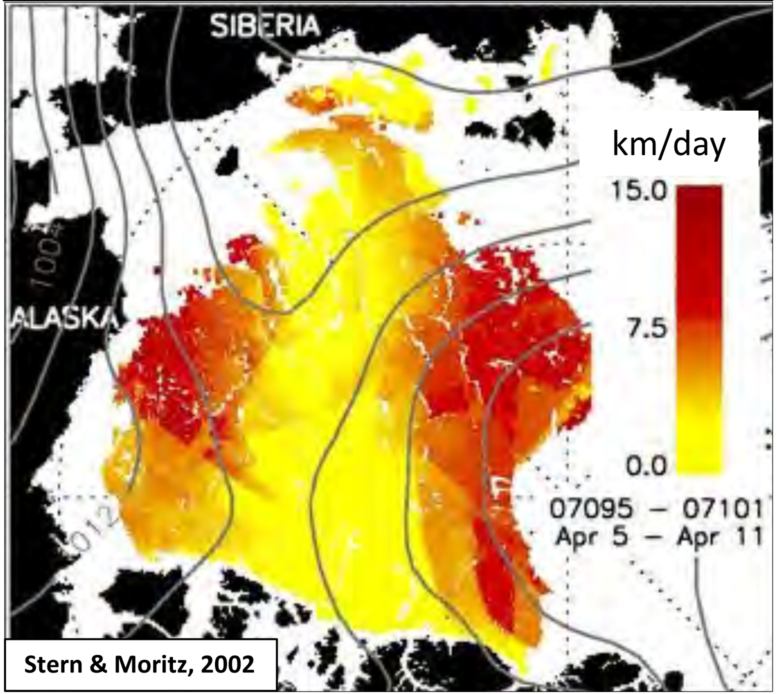
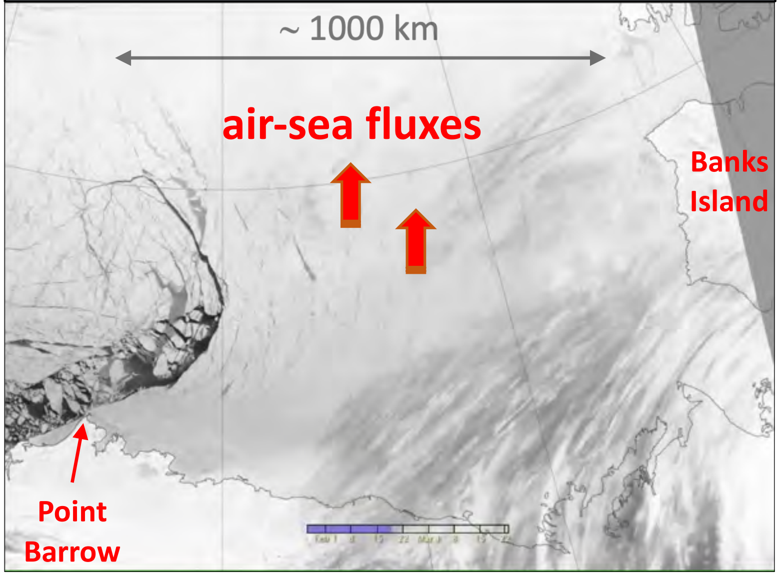


Stern & Moritz, 2002

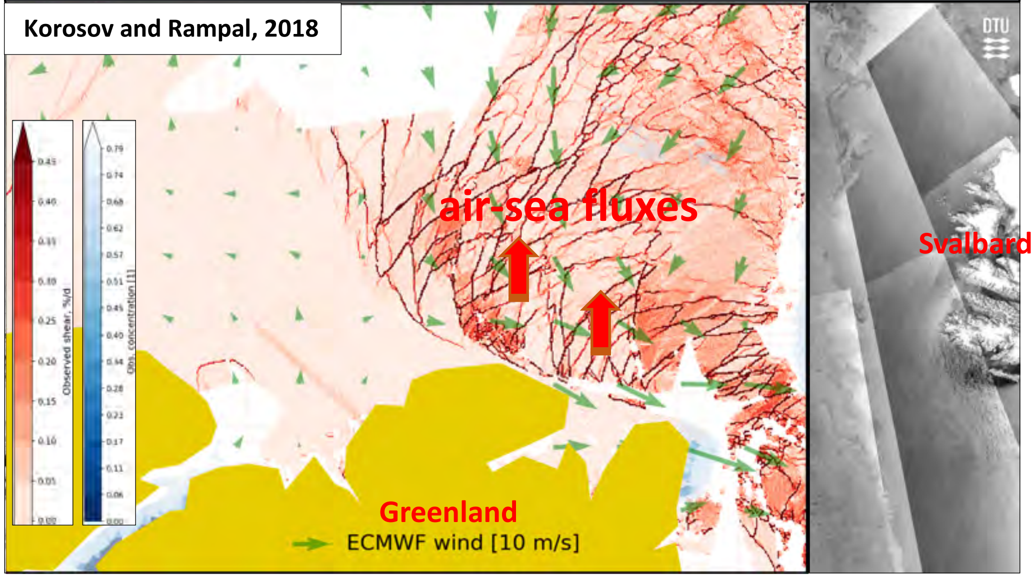
A more fragile sea ice cover … more extreme events

Massive breakup event in Beaufort Sea (Mar 2015)



data: Visible Infrared Imaging Radiometer Suite (VIIRS)

Polynya opening in Lincoln Sea (Feb 2018)



data: Sentinel SAR images

We should simulate the brittle nature of sea ice …

Because this is how sea ice behaves !!!

- *To reproduce properly the* ***temporal and spatial heterogeneity of the energy exchanges*** *in polar regions (momentum and heat)*

- *To characterize and quantify the* ***impact of small scales processes on the climate at larger scales***

- *To better evaluate the* ***causes of recent trends in polar regions*** *(e.g. polar amplification, sea ice retreat)*

- *To reduce uncertainties of future climate projections*

How to simulate the brittle nature of sea ice?

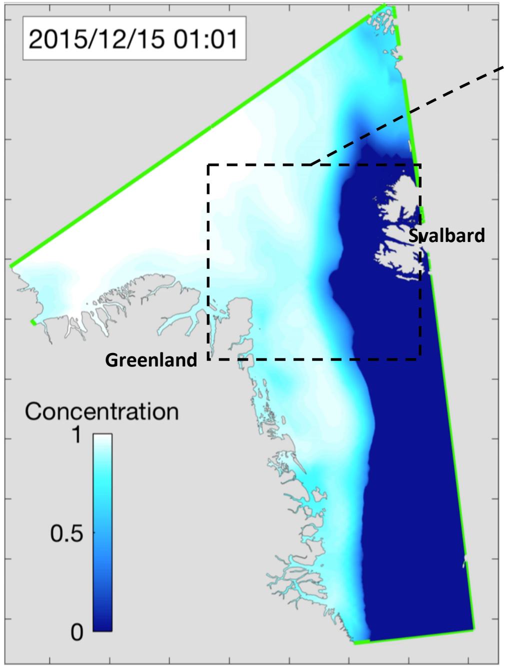
The neXtSIM model

(Rampal et al., 2016)

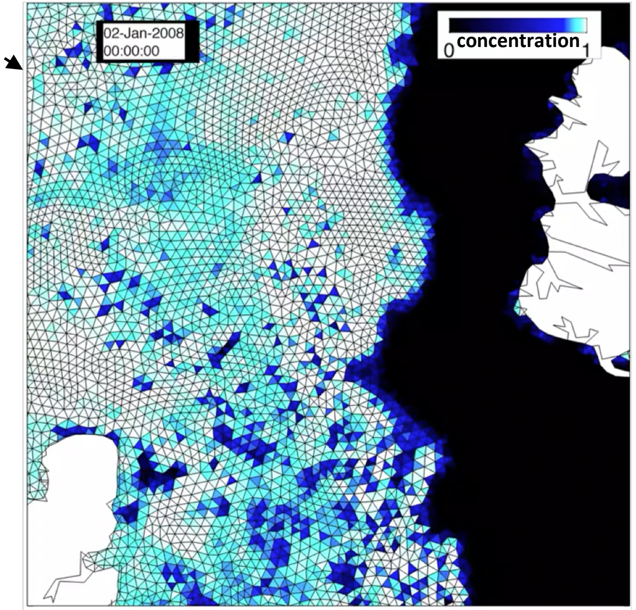
combines the concepts of
elastic memory, progressive damage mechanics and stress relaxation

- Dynamics: Maxwell-Elasto-Brittle rheology
  (Dansereau et al., 2016)

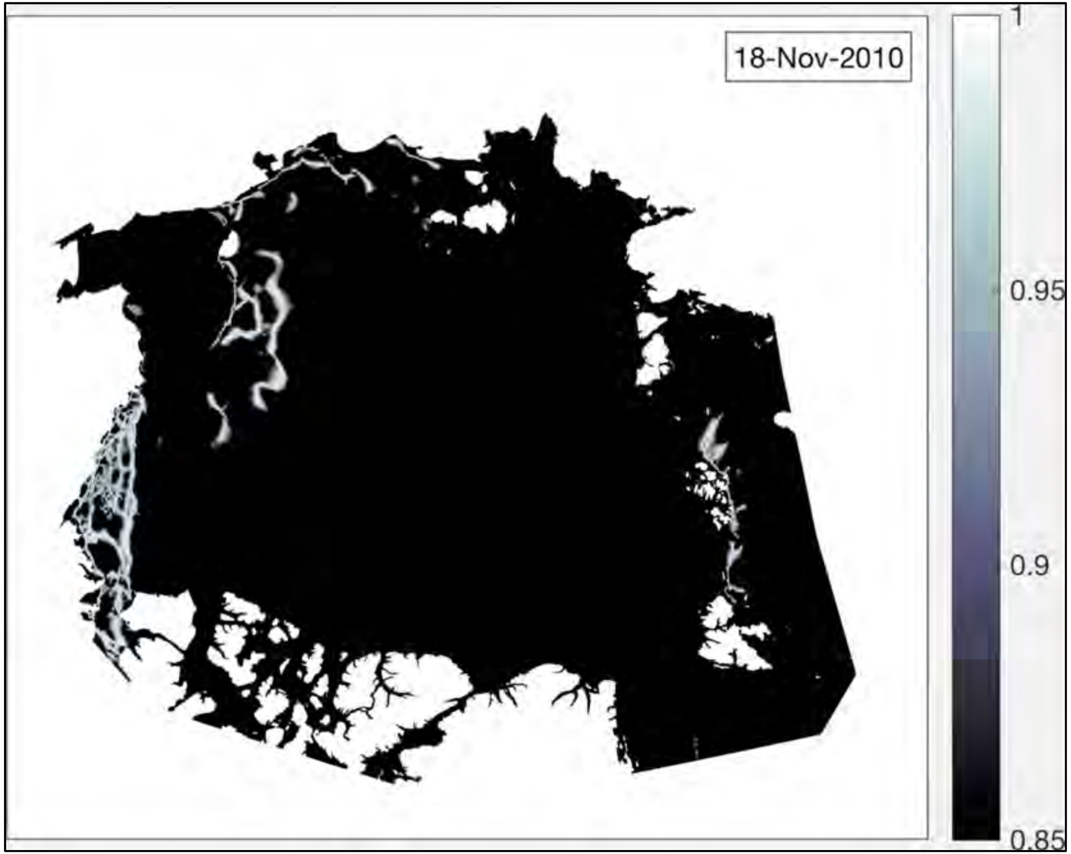
- Lagrangian, finite-element (triangular mesh)



- **stand-alone (ocean slab)**
- **forcing:**
  - CFSR reanalysis
  - TOPAZ reanalysis



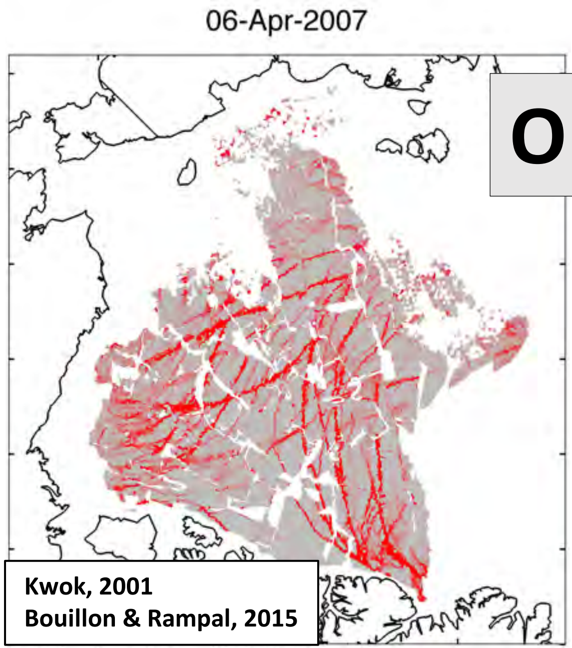
Sea ice damage: a key/new state variable for sea ice



The complex response of sea ice to external forcing

"LKF: Heterogeneous and intermittent"

sea ice deformation rate



Kwok, 2001
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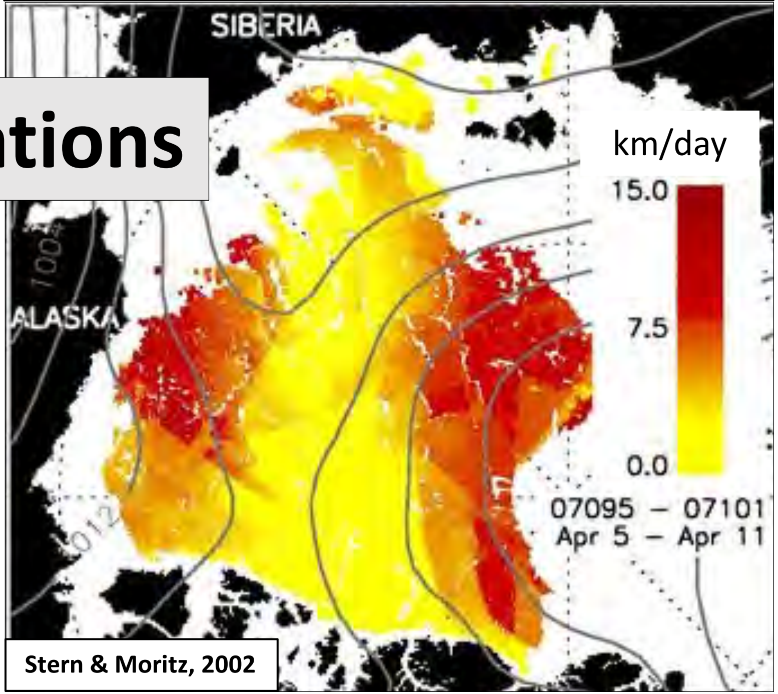
"Piecewise rigid motion"

sea ice drifting speed



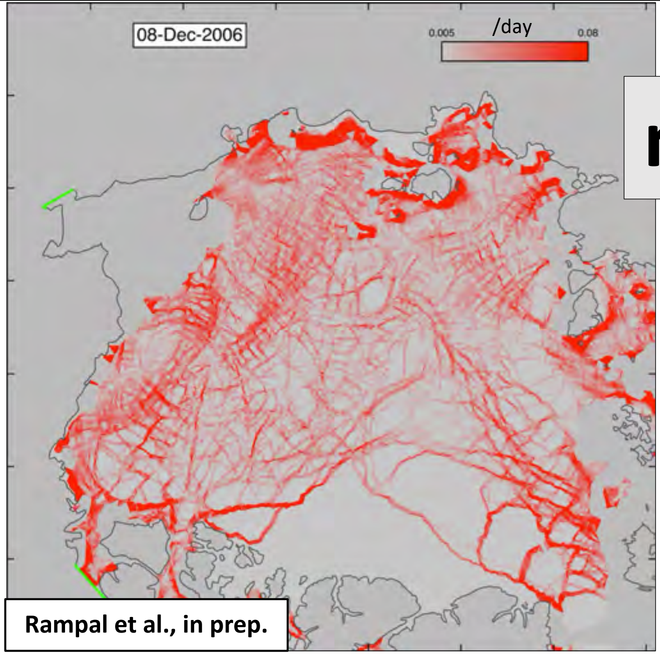
Stern & Moritz, 2002

Observations

The complex response of sea ice to external forcing

"LKF: Heterogeneous and intermittent"

sea ice deformation rate

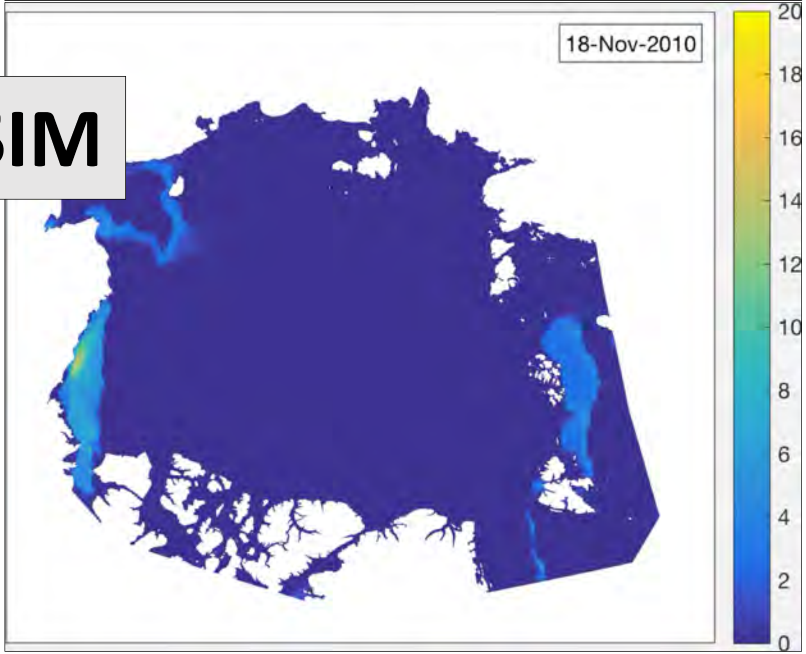


Rampal et al., in prep.

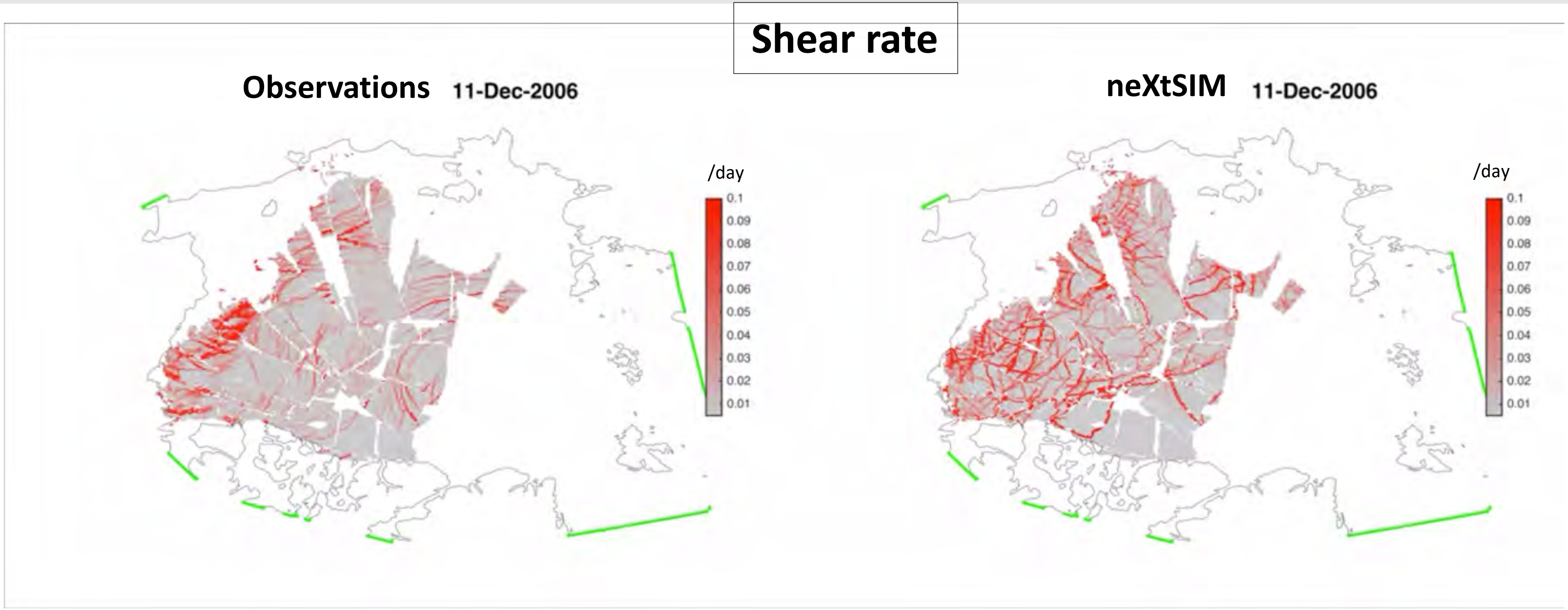
neXtSIM

"Piecewise rigid motion" or fish scale pattern

sea ice drifting speed



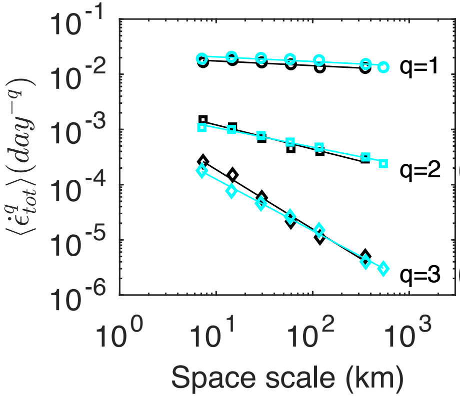
Sea ice deformation rate: model vs observations



Sea ice deformation rate: model vs SAR observations

Rampal et al., in prep.

Space



(mean)

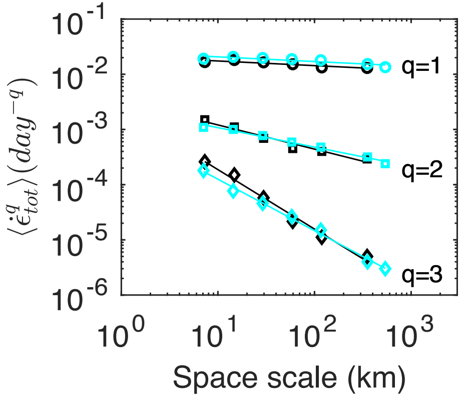
(variance)

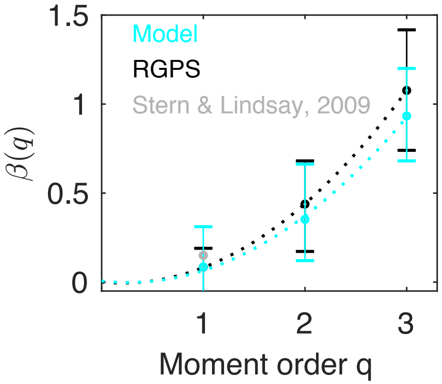
(skewness)

Sea ice deformation rate: model vs SAR observations

Rampal et al., in prep.

Space





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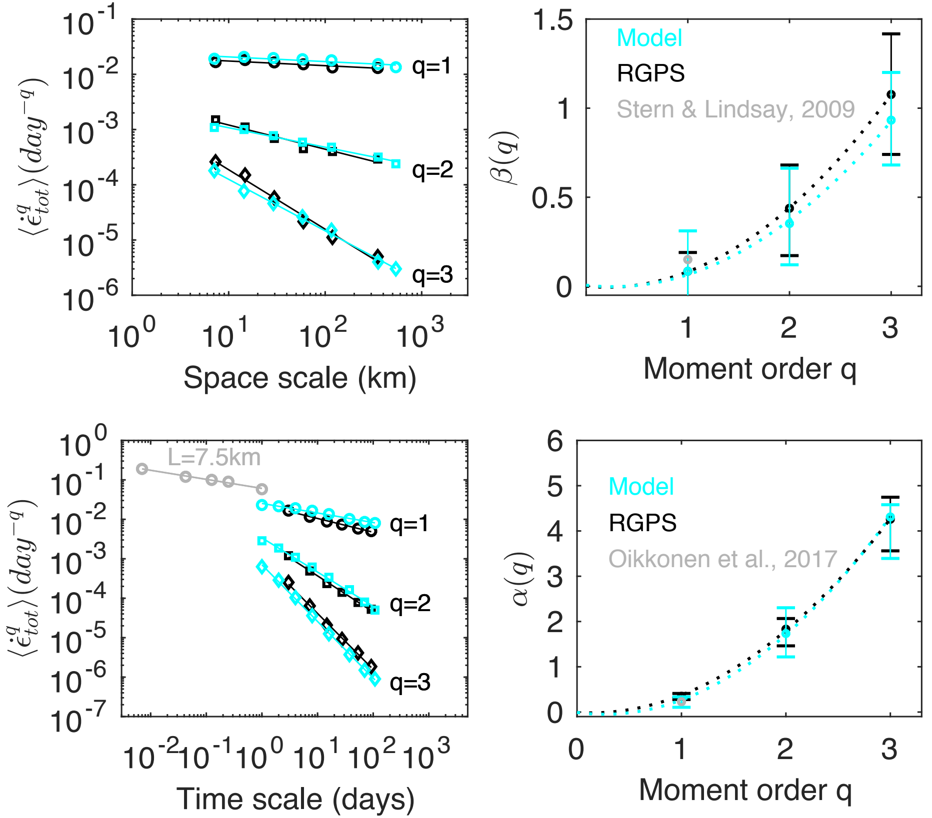
Rampal et al., in prep.

Space

Time



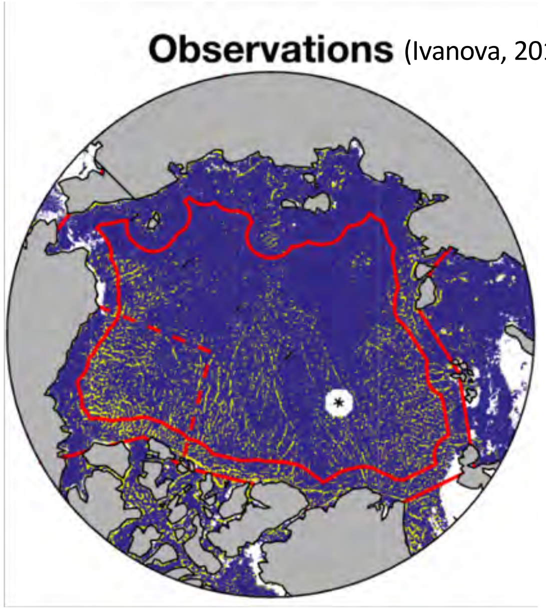
Multifractal scaling

Multifractal scaling

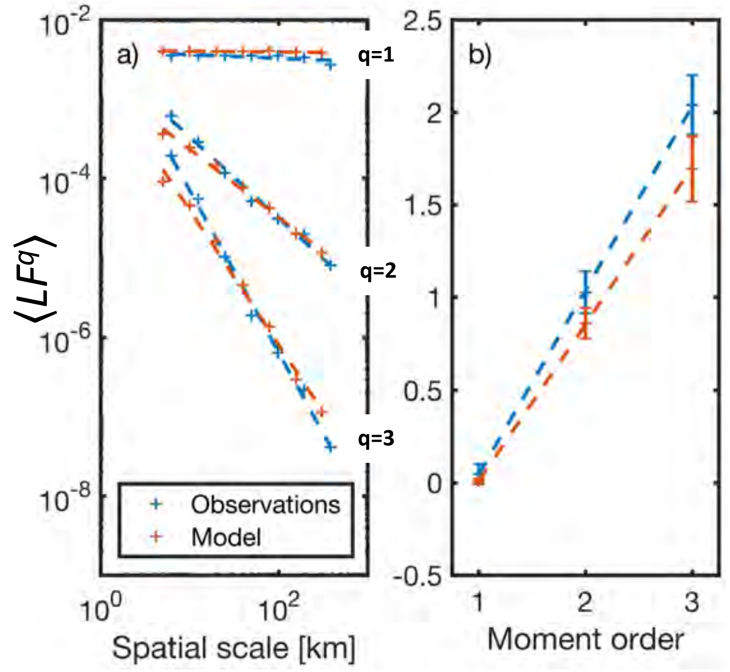
Sea ice lead fraction : model vs P-M observations

Olason et al., in prep.

Lead fraction (= fraction of open water + thin ice)



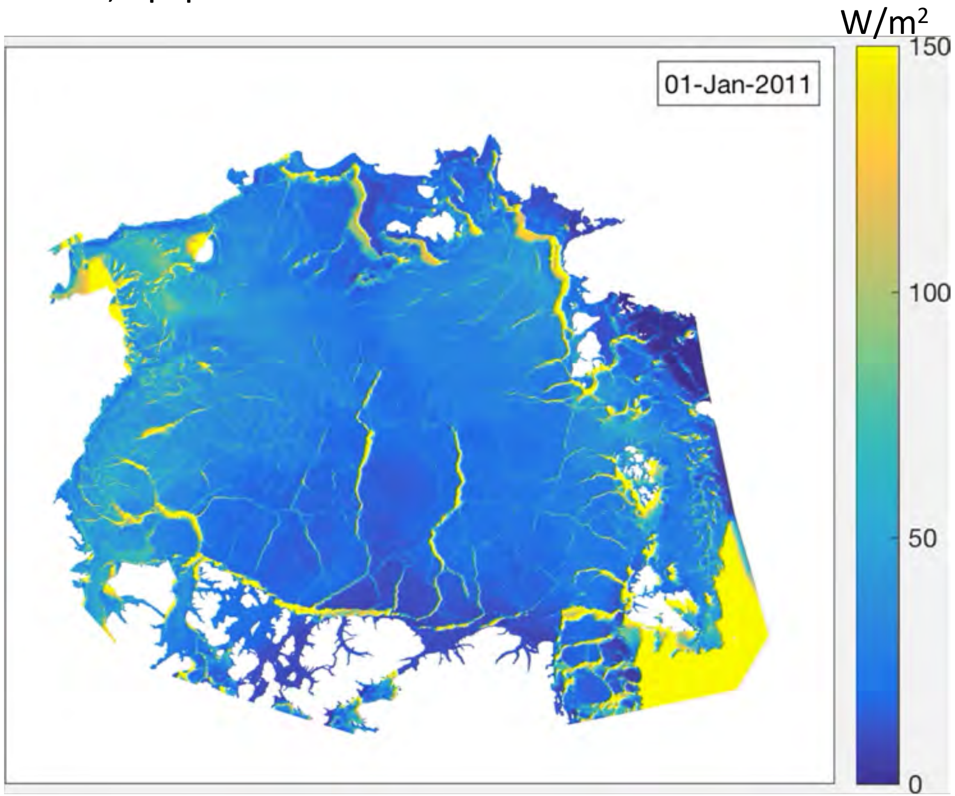
Winter 2010-2011



- Lead fraction scales with space (mono-fractal)
- Model reproduces well the observations

Simulated heat fluxes statistics

Olason et al., in prep.



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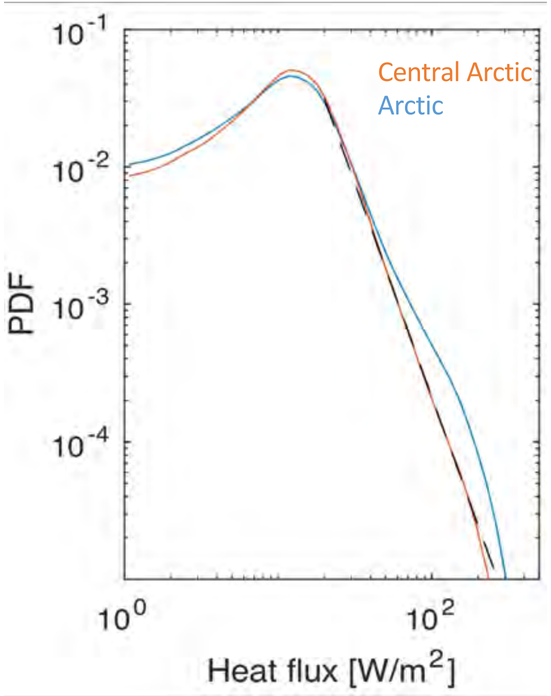
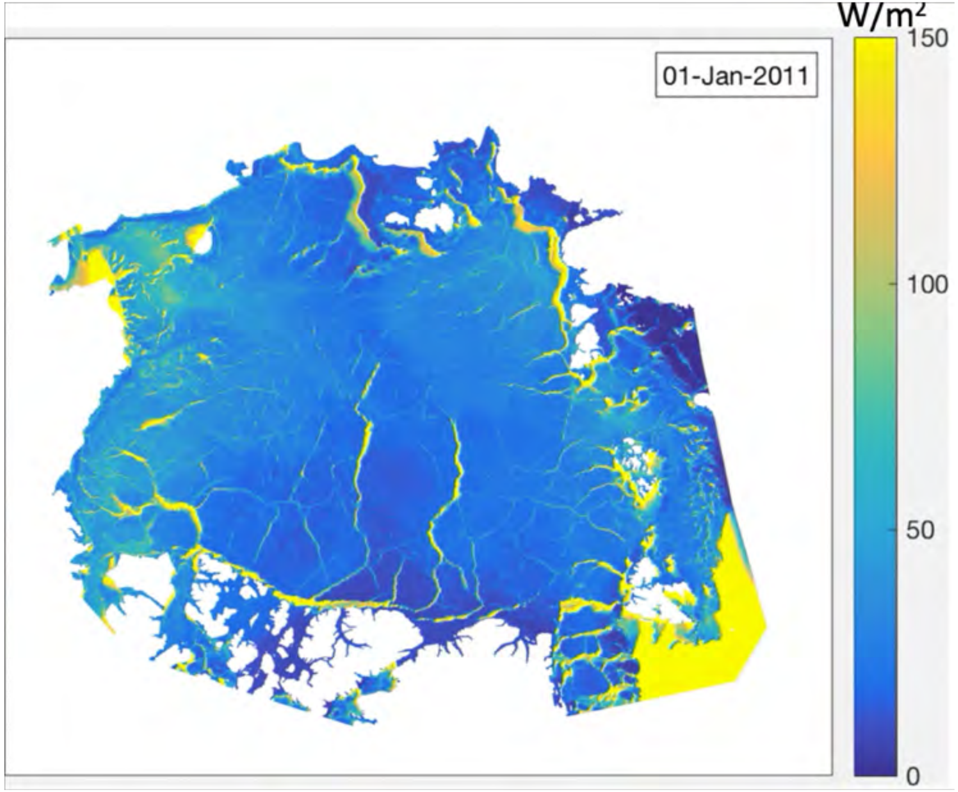


Simulated heat fluxes (resolution dependance)

Olason et al., in prep.



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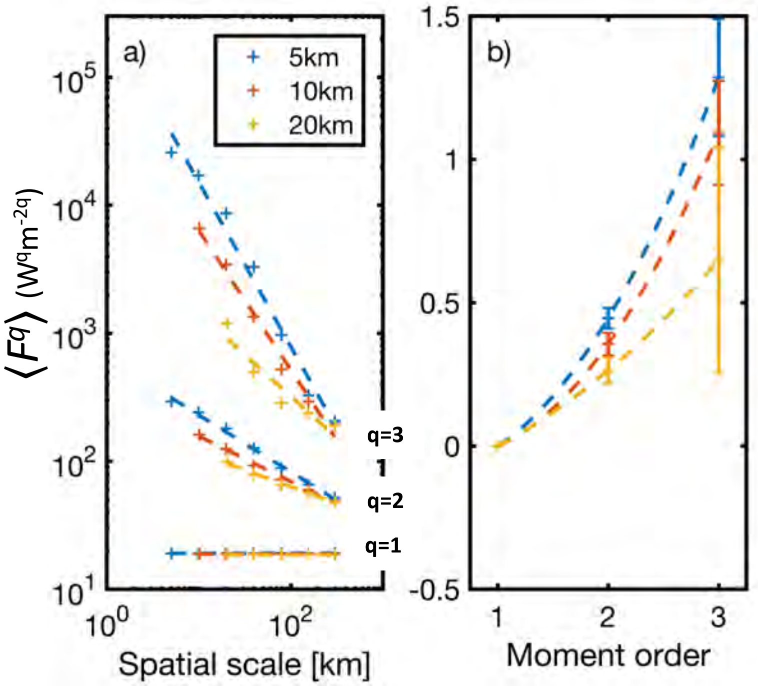


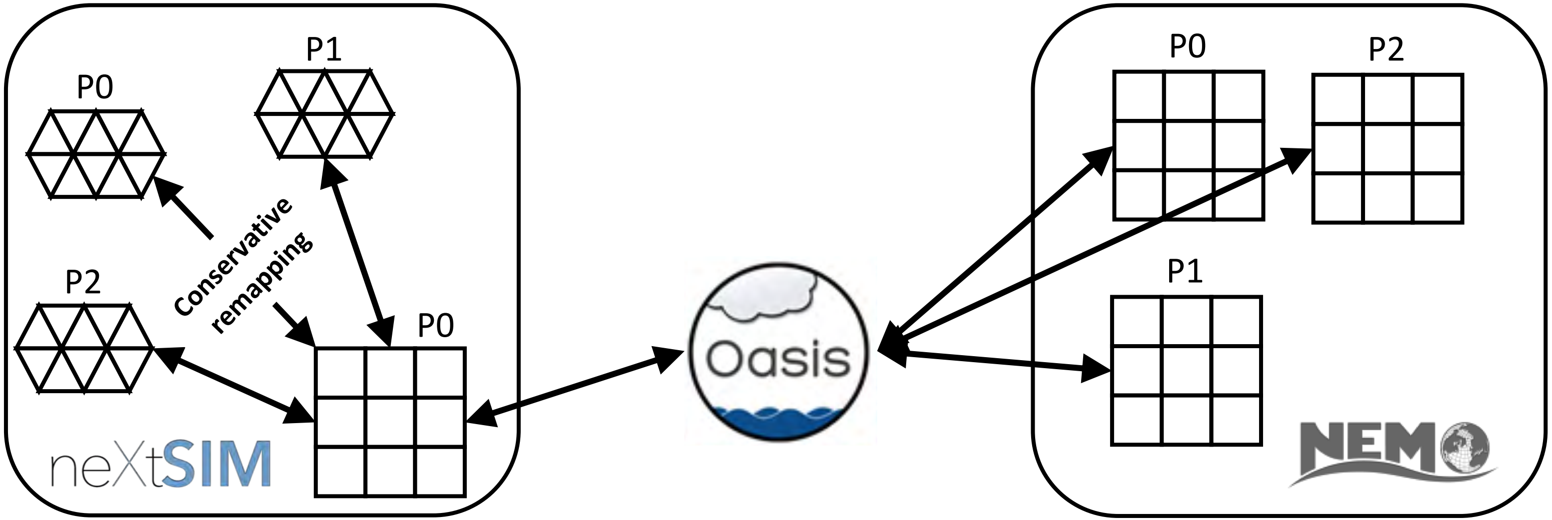
How to take the brittle mechanical behavior of sea ice into account in future Earth System Models?

On integrating neXtSIM into a climate model

- C++
- Parallel (MPI/openMP)
- Light and efficient: **~1day for 1 year on a laptop**
- Designed as an independent / pluggable module
- Lives in Github

- Lagrangian:
  - **Natural approach for brittle solids, excellent to preserve strong gradients**
  - Potential for data-driven approach and assimilation of new satellites data based on feature tracking methods

- Coupled to NEMO ocean model via the OASIS coupler



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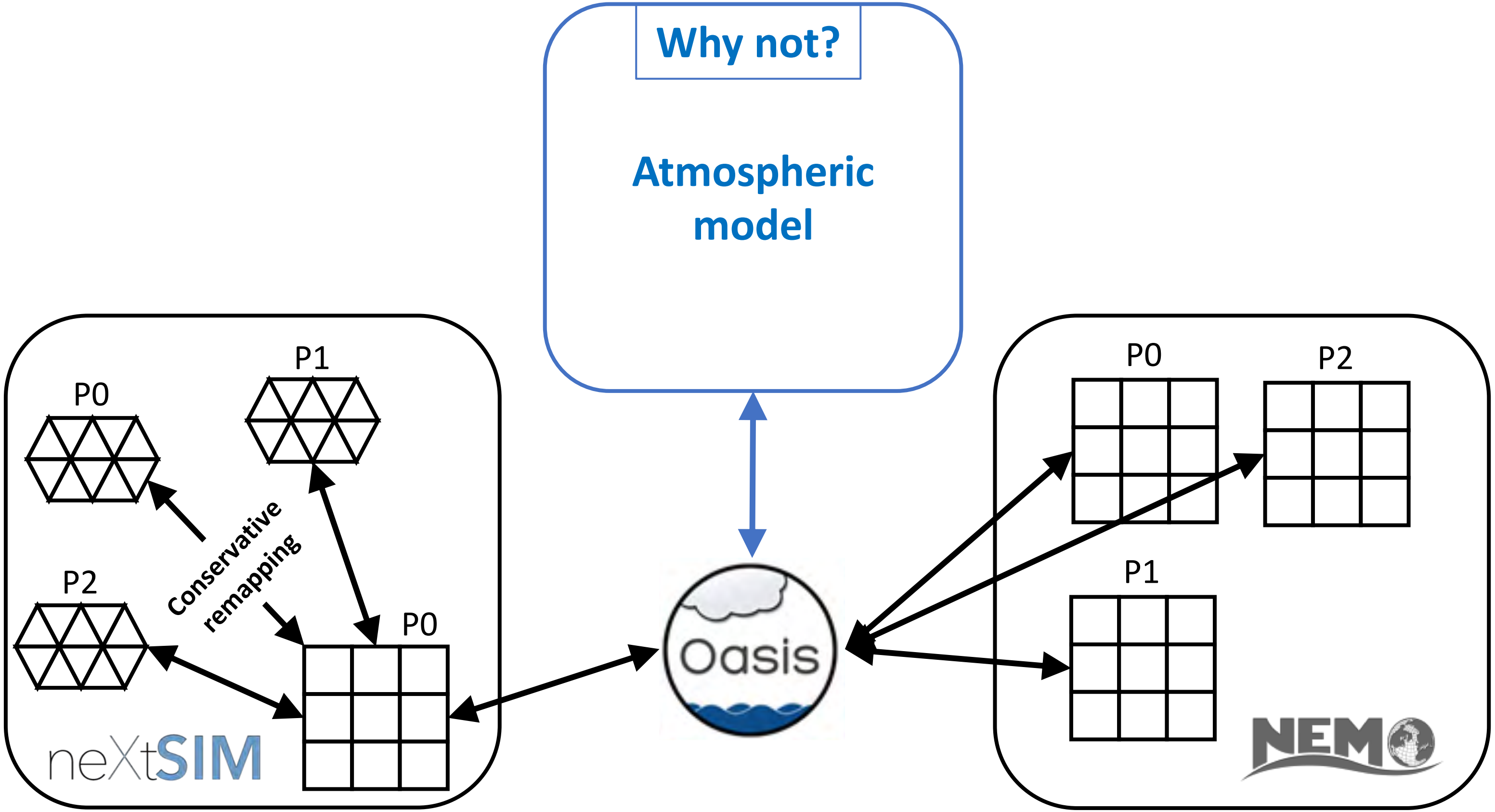

Towards an Eulerian neXtSIM using DG methods?

DG “Discontinuous Galerkin”:

- Becoming more popular
- Easier parallelization and coupling (compared to the Lagrangian approach)
- Excellent scalability properties
- Adapted to conserve strong gradients when advecting fields (reduced diffusion)

- MEB has been originally coded using DG methods on a finite element triangular mesh
- It has been tested (PhD thesis of V. Dansereau) and it works (Dansereau et al. 2017)
- But this solution would require additional efforts and investigation before any conclusions

Conclusions

- Simulating the **brittle sea ice cover** is relevant in the context of **climate change in polar regions** (e.g. leads in Arctic, coastal polynyas in Antarctica)
- neXtSIM is unique and **capable of reproducing the complex dynamics associated to the brittle nature of sea ice**
- The **coupling of neXtSIM** with an ocean just done and **can be extended to the other components of a climate model**
- Both neXtSIM Lagangian and Eulerian versions have their pros and cons, and seem **relevant for being included in future generation Earth System Models**


Thank you