Sea-ice role in Earth-system models

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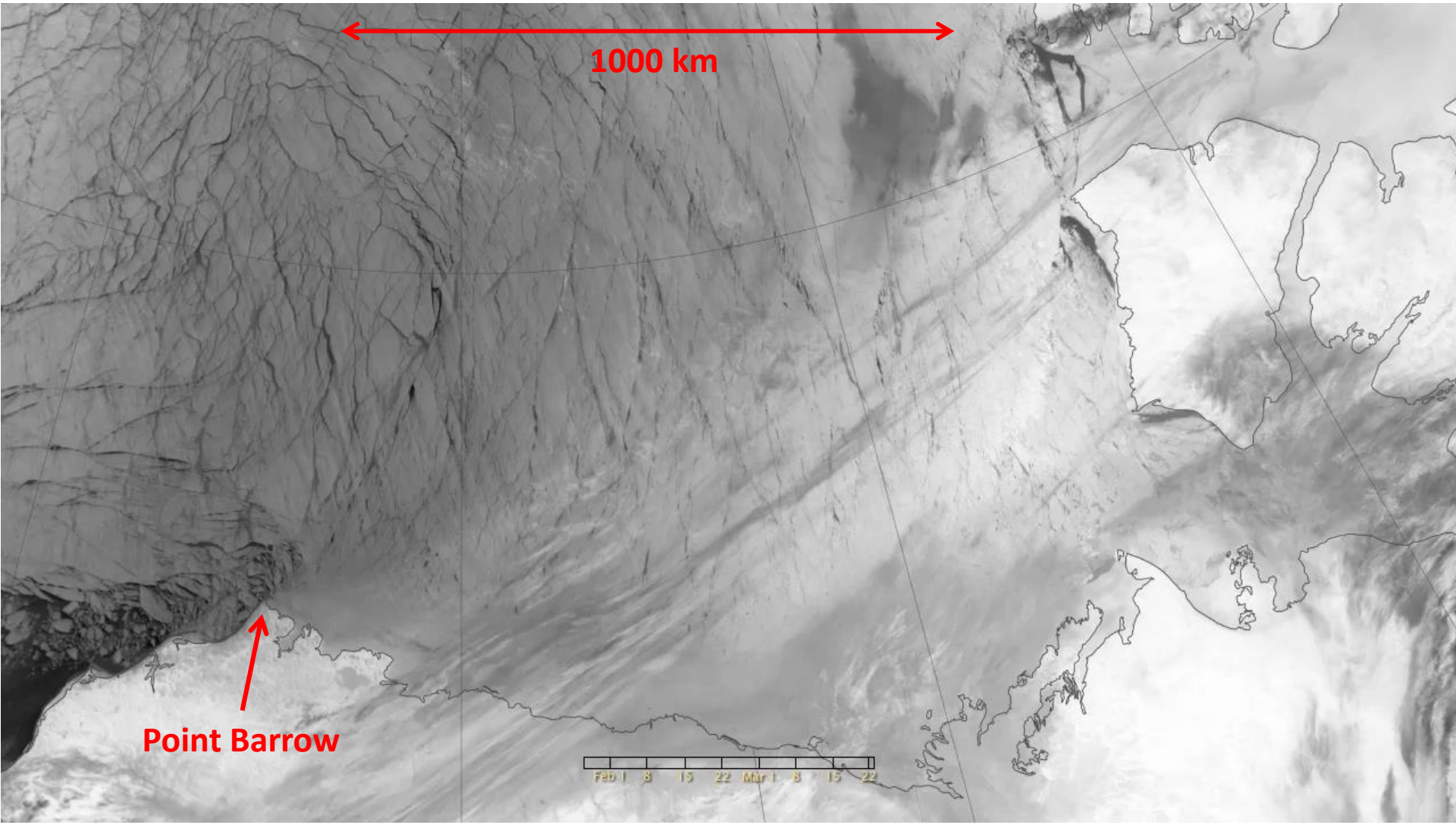
Coastal polynia along the Canadian Arctic Archipelago
Courtesy: Véronique Dansereau

Why modeling sea ice is a real challenge?



In this example: Large **breaking event** in Beaufort Sea , February-March 2013

"Seamless prediction"?

"What Earth system processes are needed, and what level of complexity is required to further **extend atmospheric predictive skill**?"

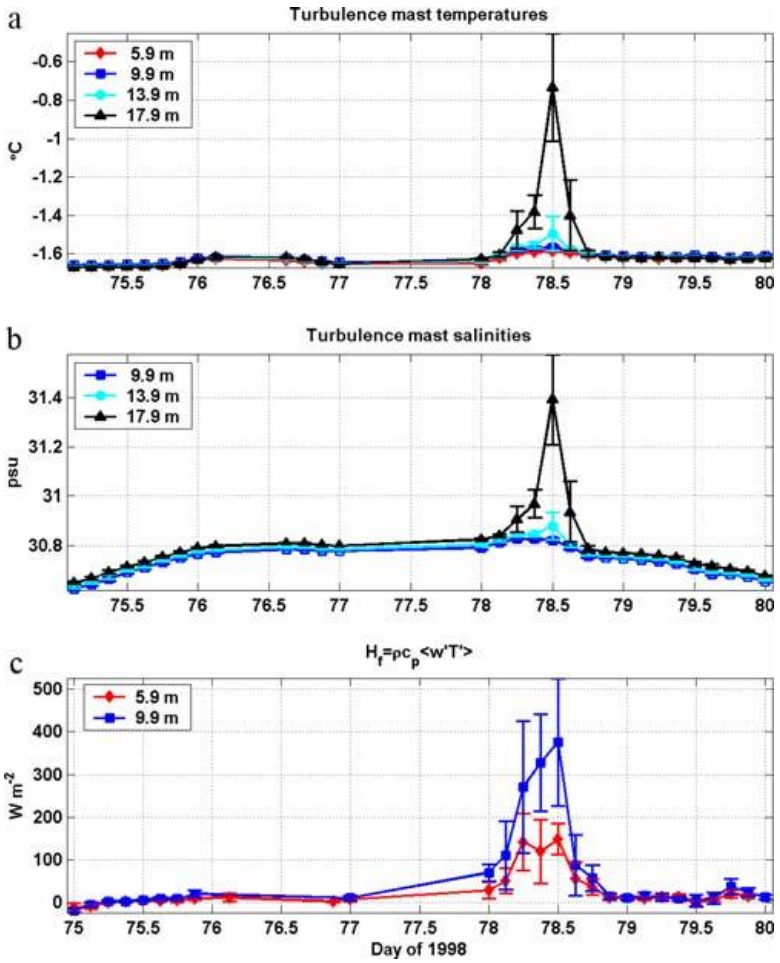
"…Earth system **modelling** and **assimilation** as the way to improve further skill in the **1-day to 1-year forecast** range covered by the ECMWF forecasts."

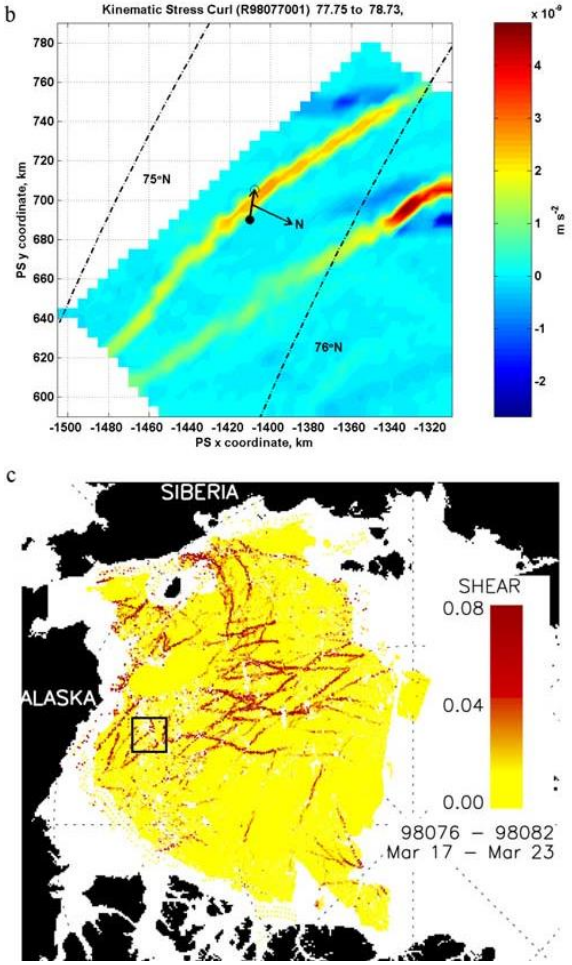
"If a model cannot **simulate a phenomena**, it cannot **predict that phenomena**."

*"…climate prediction at **the model resolutions and levels of complexity considered essential** for the most advanced and reliable representations of the climate system that **technology and our scientific understanding of the problem** can deliver…"*

- Intense oceanic heat fluxes occur where sea ice is deforming.

Example from observation

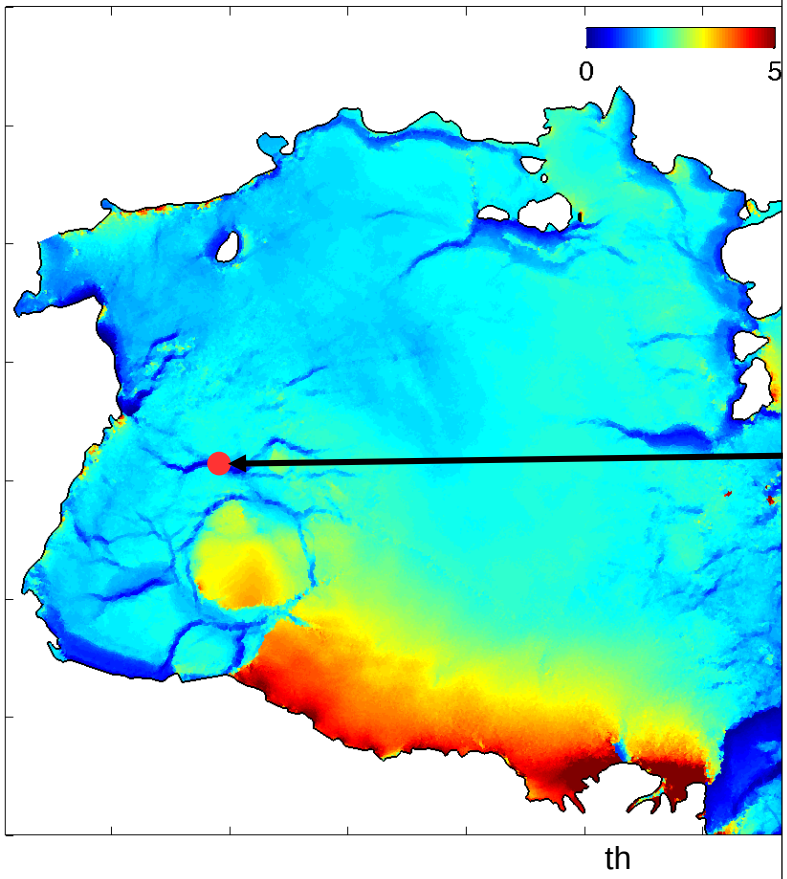




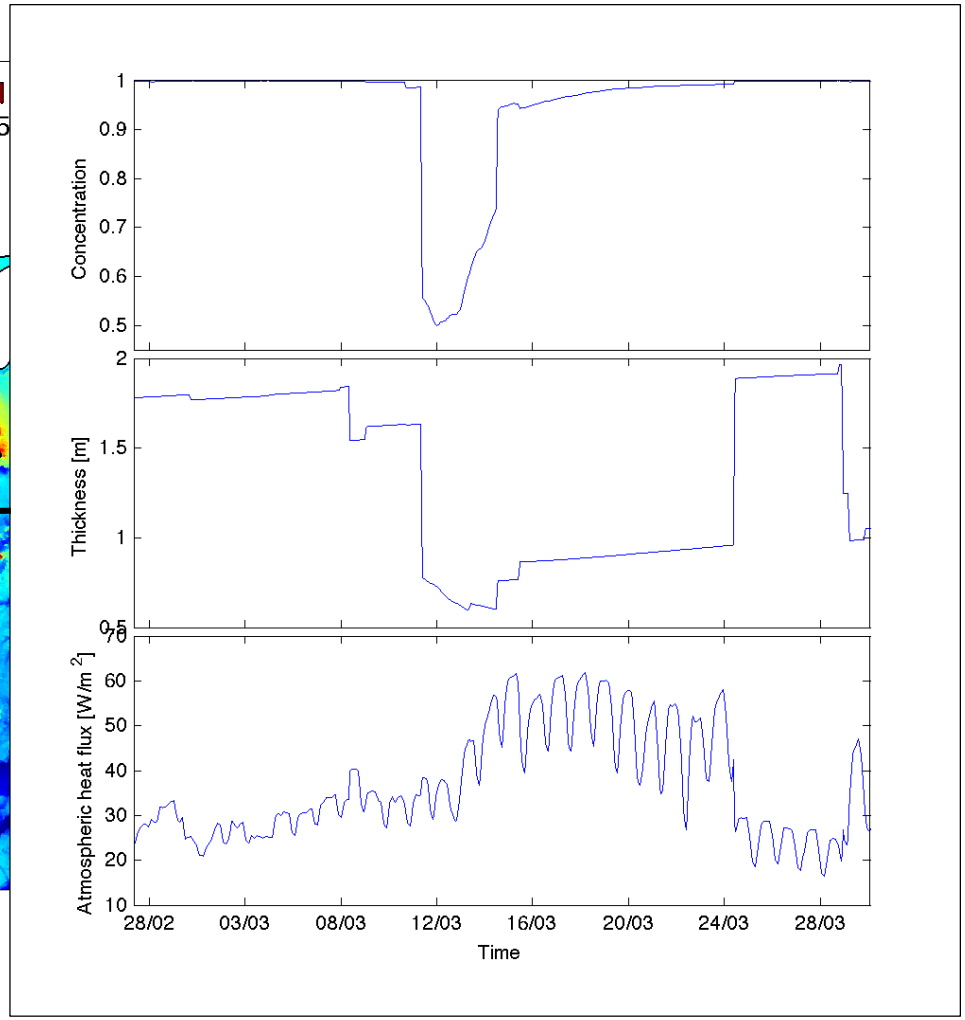
McPhee *et al*, GRL (32) 2005

- Intense atmospheric heat fluxes occur where sea ice opens.

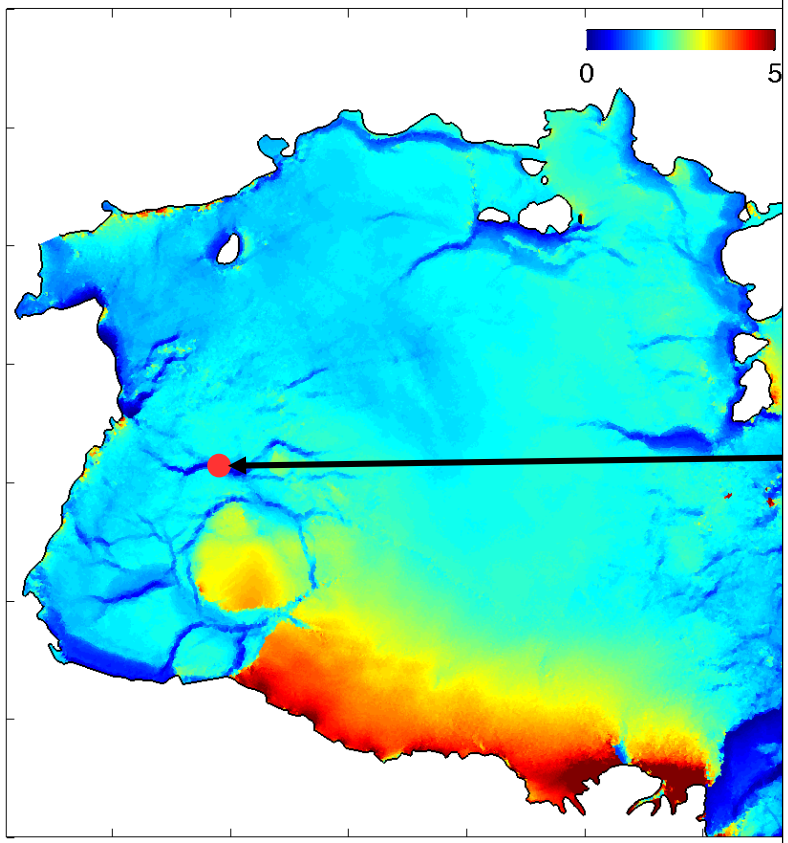
Example from simulation



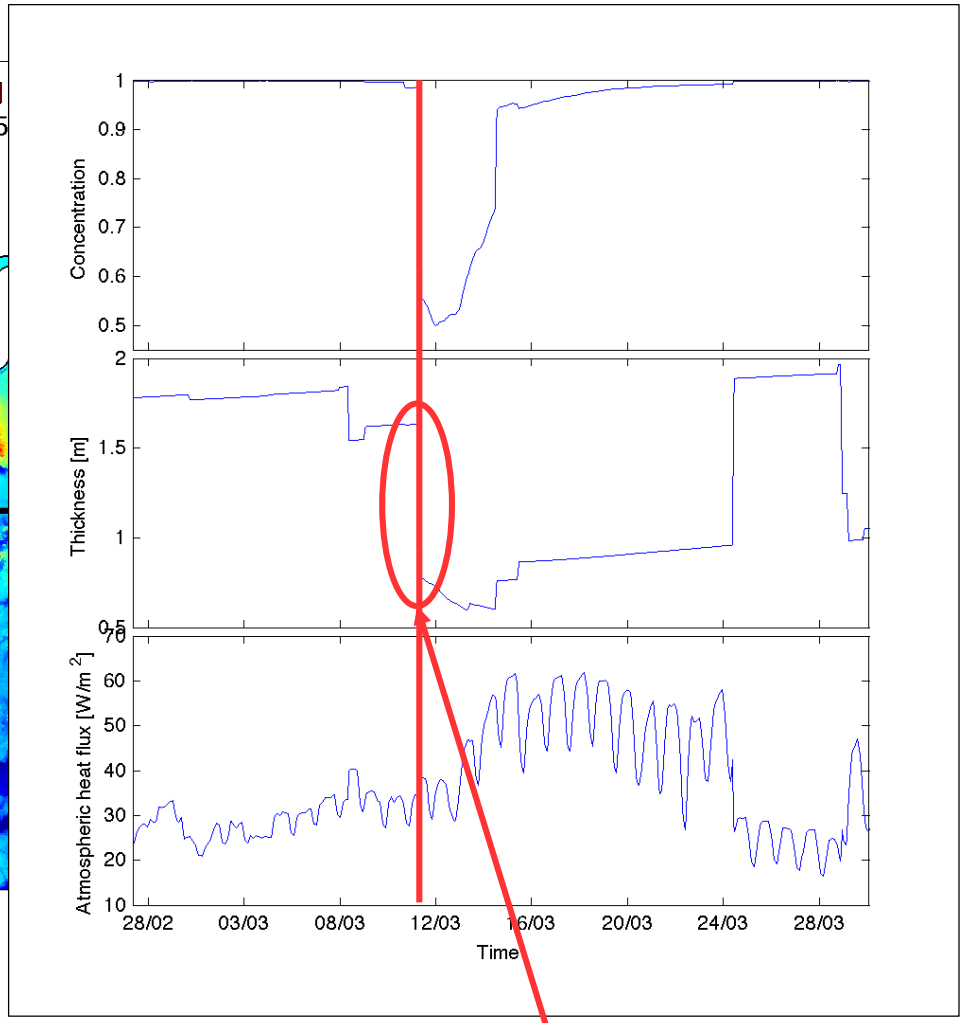
Ice thickness [m] (March 12th 2008)



Example from simulation



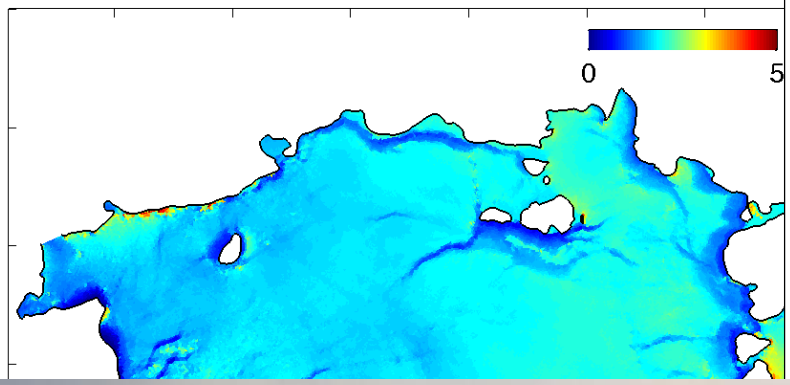
Ice thickness [m] (March 12th 2008)

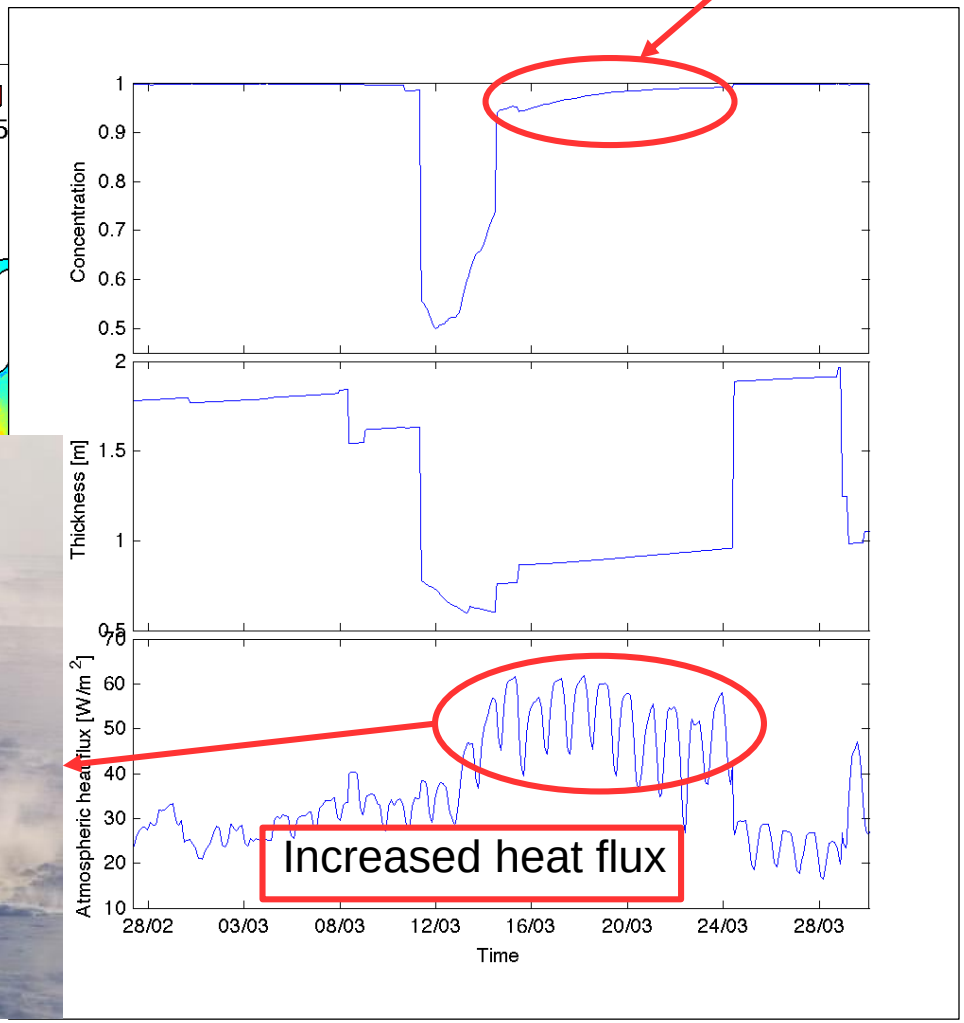


Mechanical opening

Example from simulation

Thermodynamical closing





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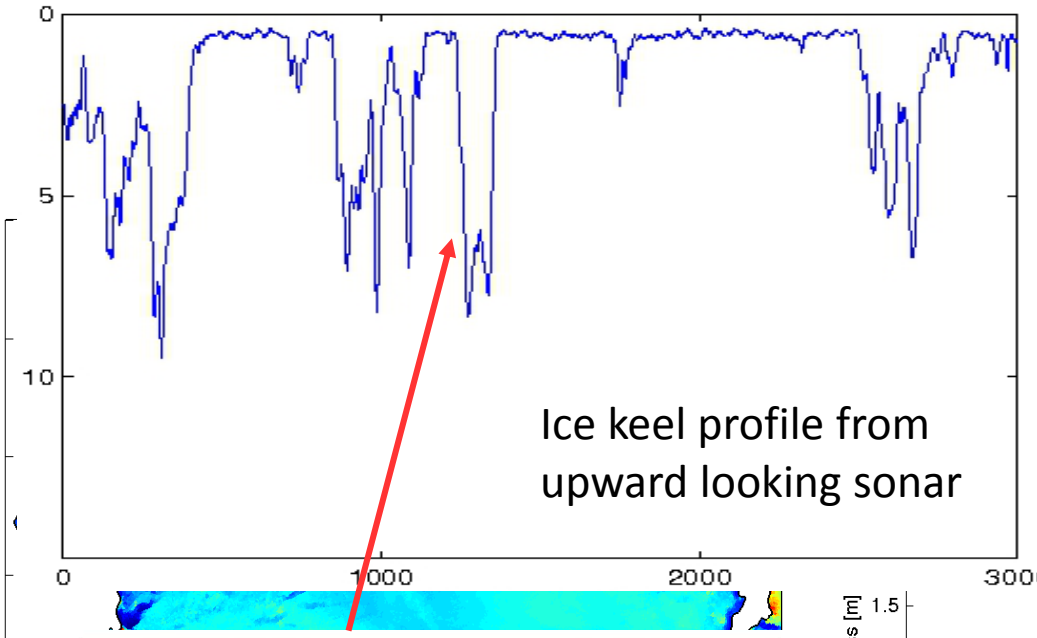
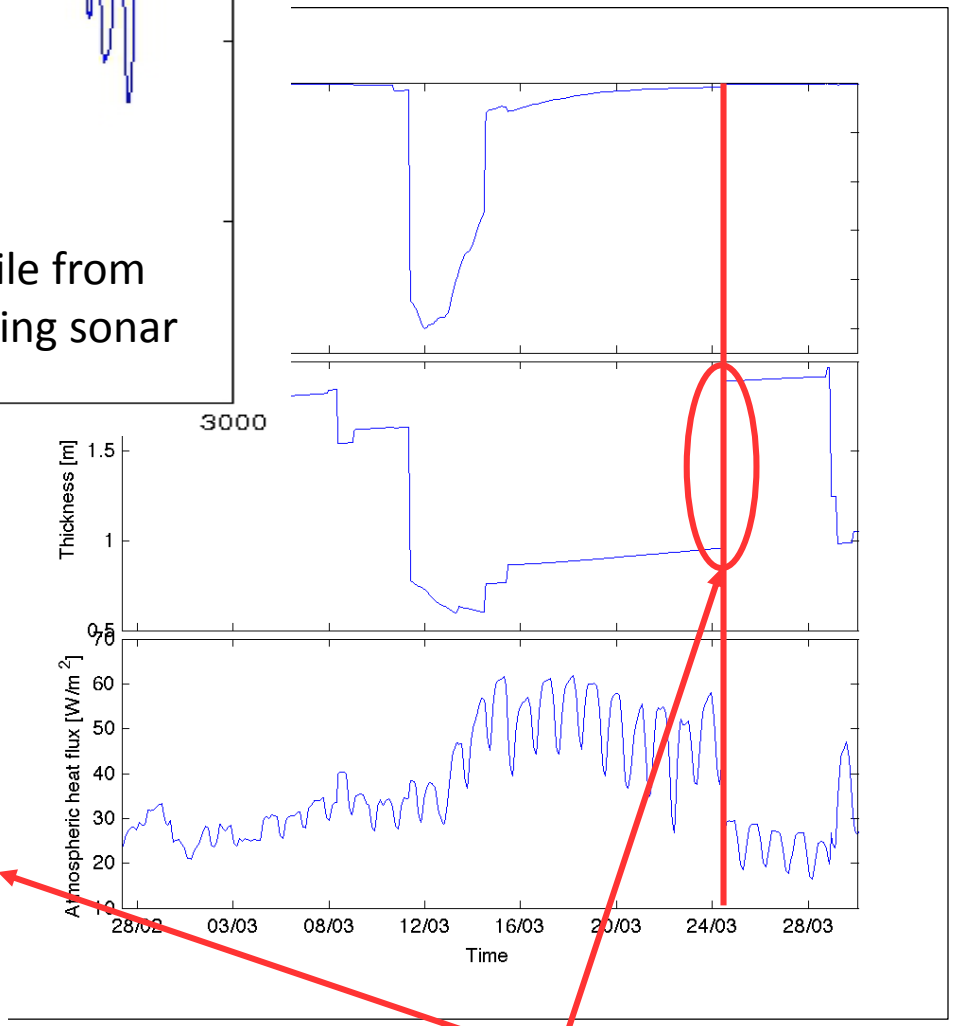


Ice keel profile from upward looking sonar

Ice



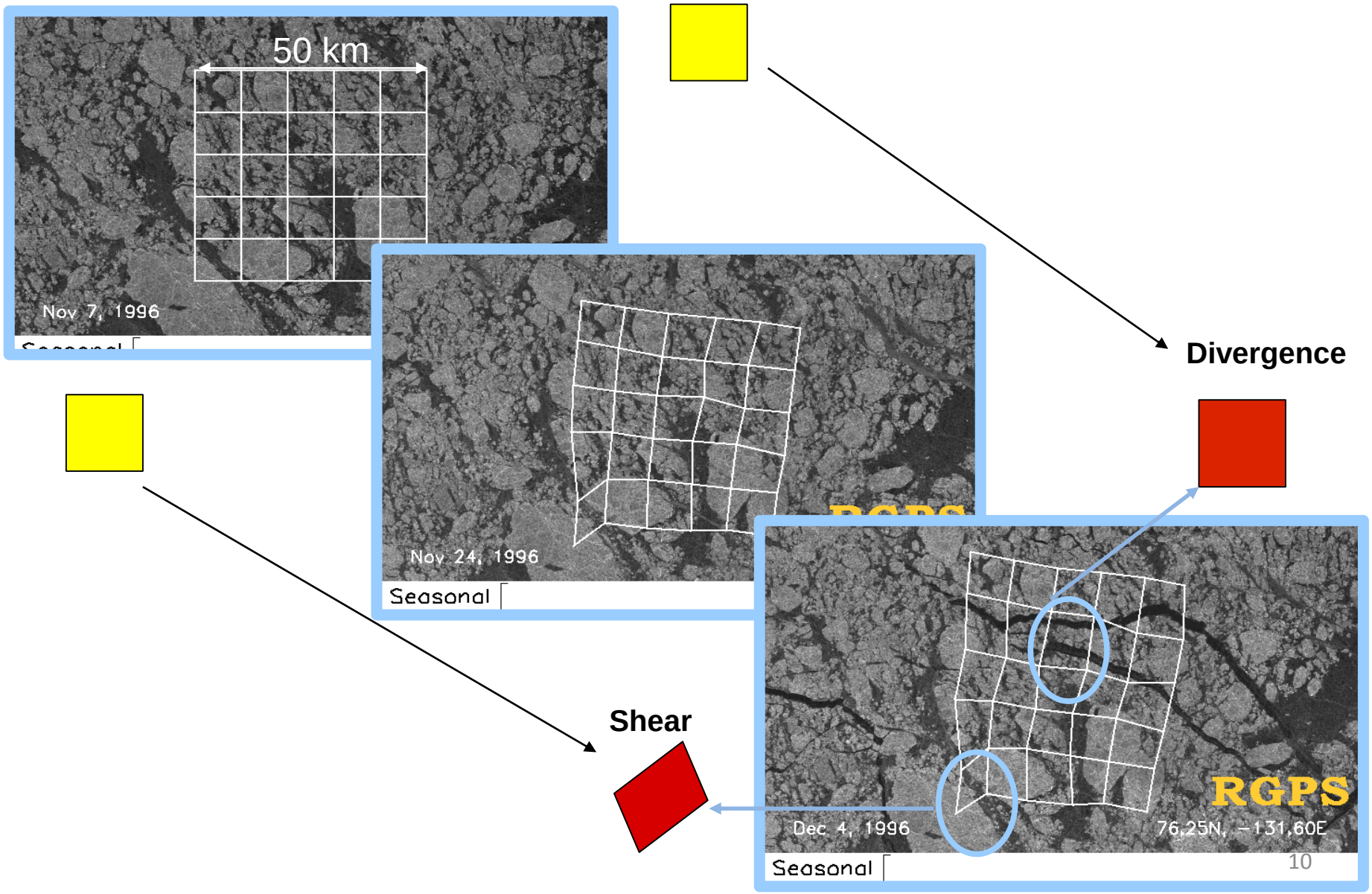
Mechanical closing

Physical processes :

Sea ice drift and deformation

1. **Observations** from SAR-derived drift
2. **Simulations** from the neXtSIM sea ice model
3. **Assimilation** for operational forecasts

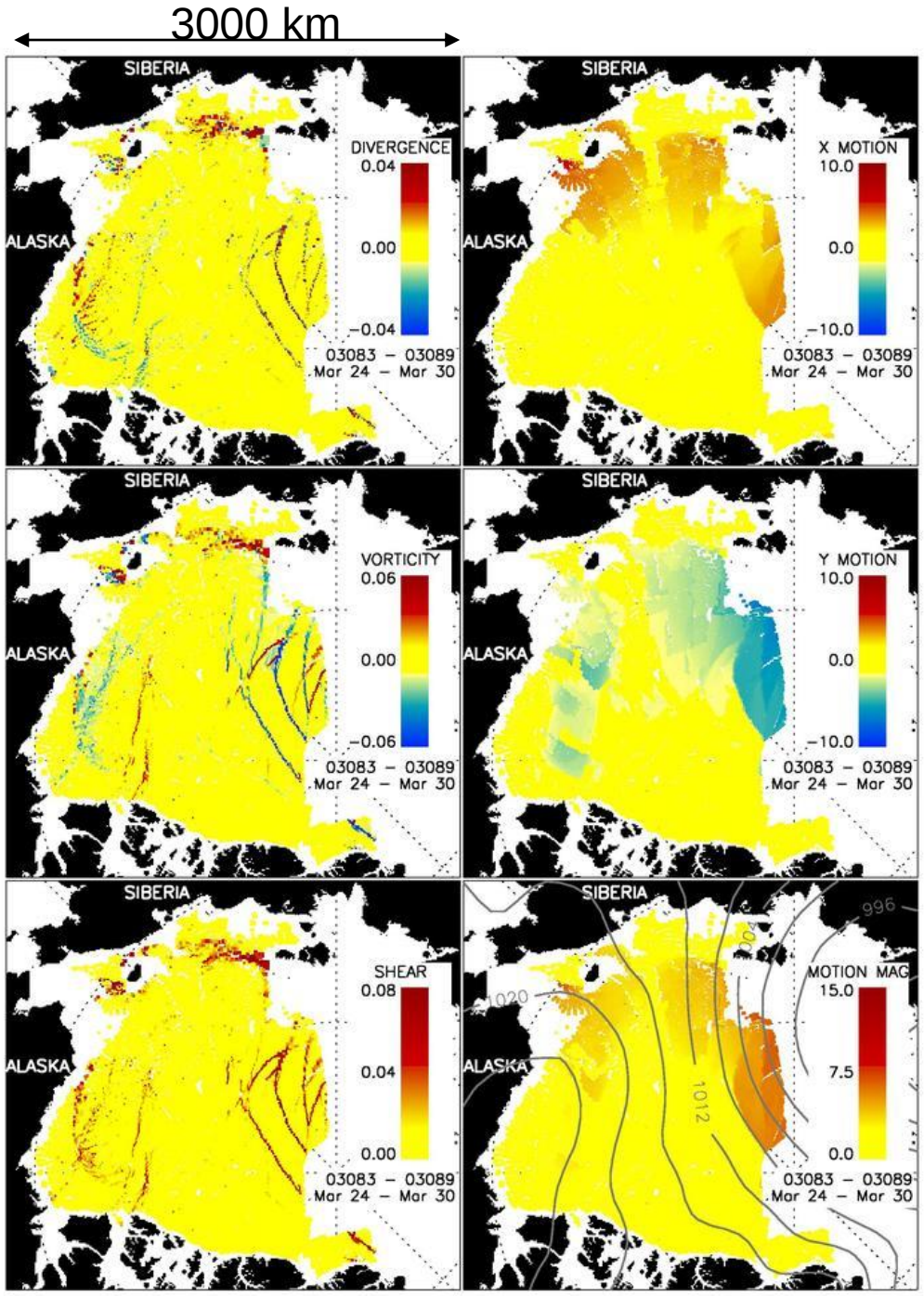
Observations from SAR-derived drift



Divergence rate (/day)

Vorticity (/day)

Shear rate (/day)

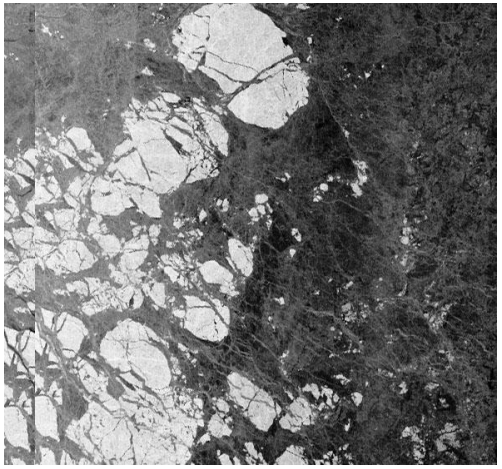


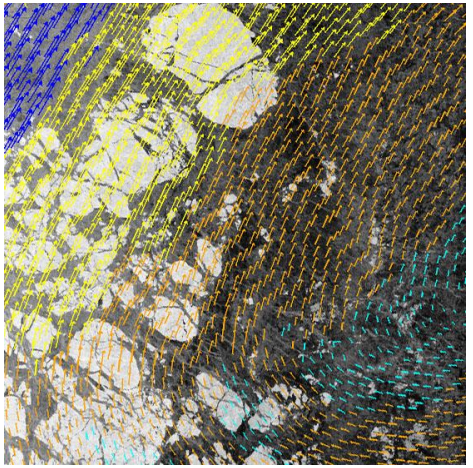
Velocity (km/day)

Kwok, 2001

Observations from SAR-derived drift

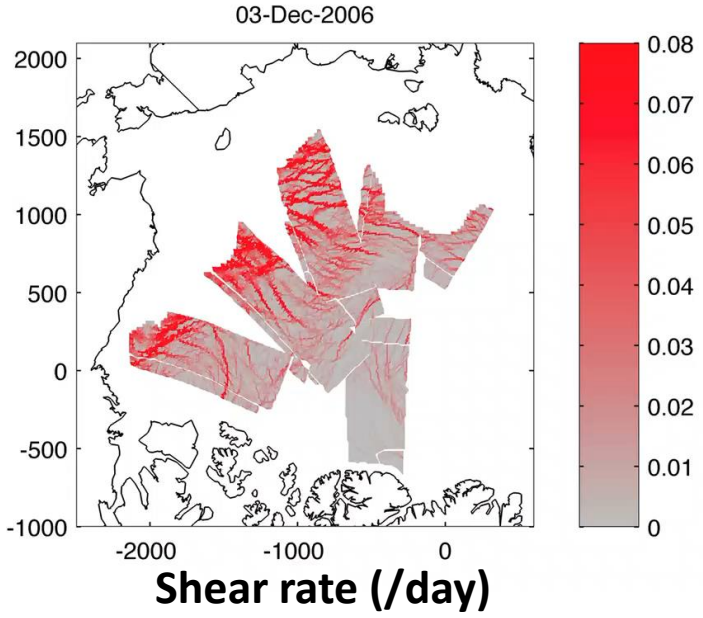
Level 1 product:
Drift





Images courtesy: University College London

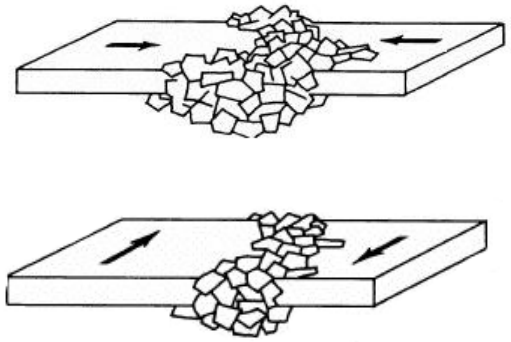
Level 2 product:
Deformation



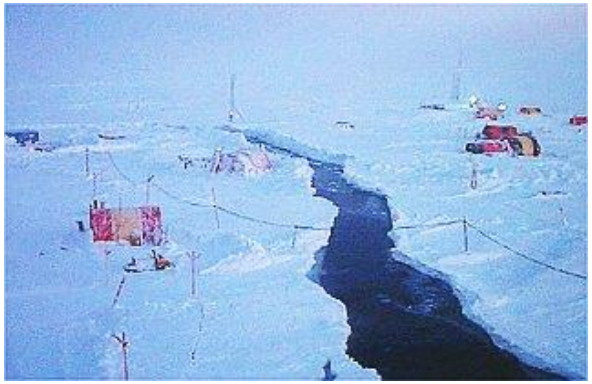
“The sea **ice thickness distribution** is controlled by **localized deformation events**”

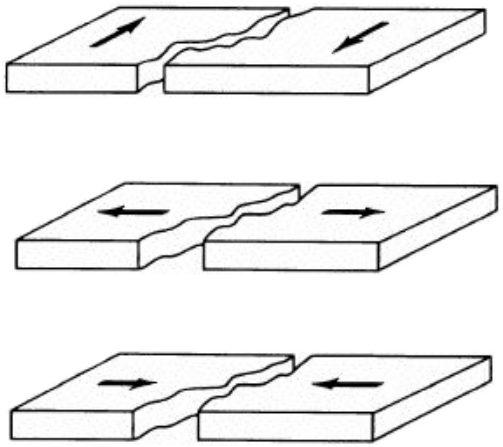
(Hutchings and Hibler, 2008)

Ridging (a few hours)



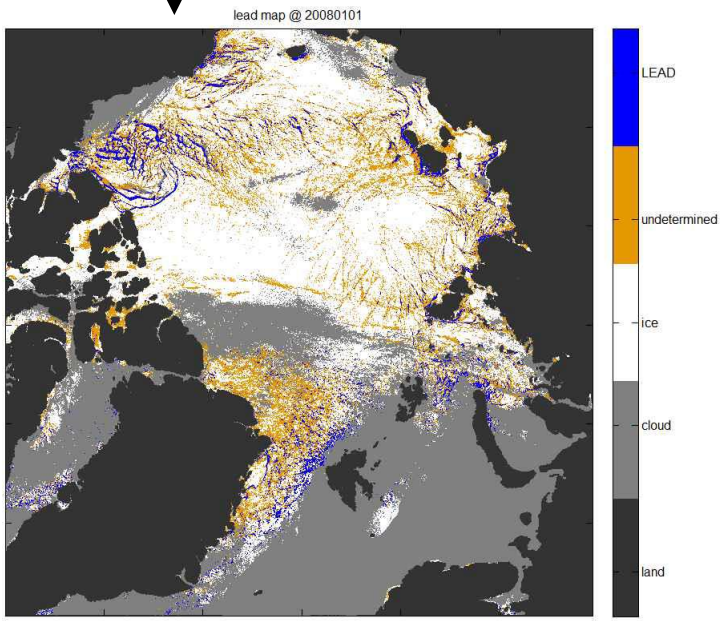
Lead opening/closing (a few hours)





"**a change of the lead fraction** by 1% could cause a **near-surface air temperature signal** of up to 3.5K"
(Lüpkes et al., 2008b)

Leads or fractures (from 1 m to 50 km)



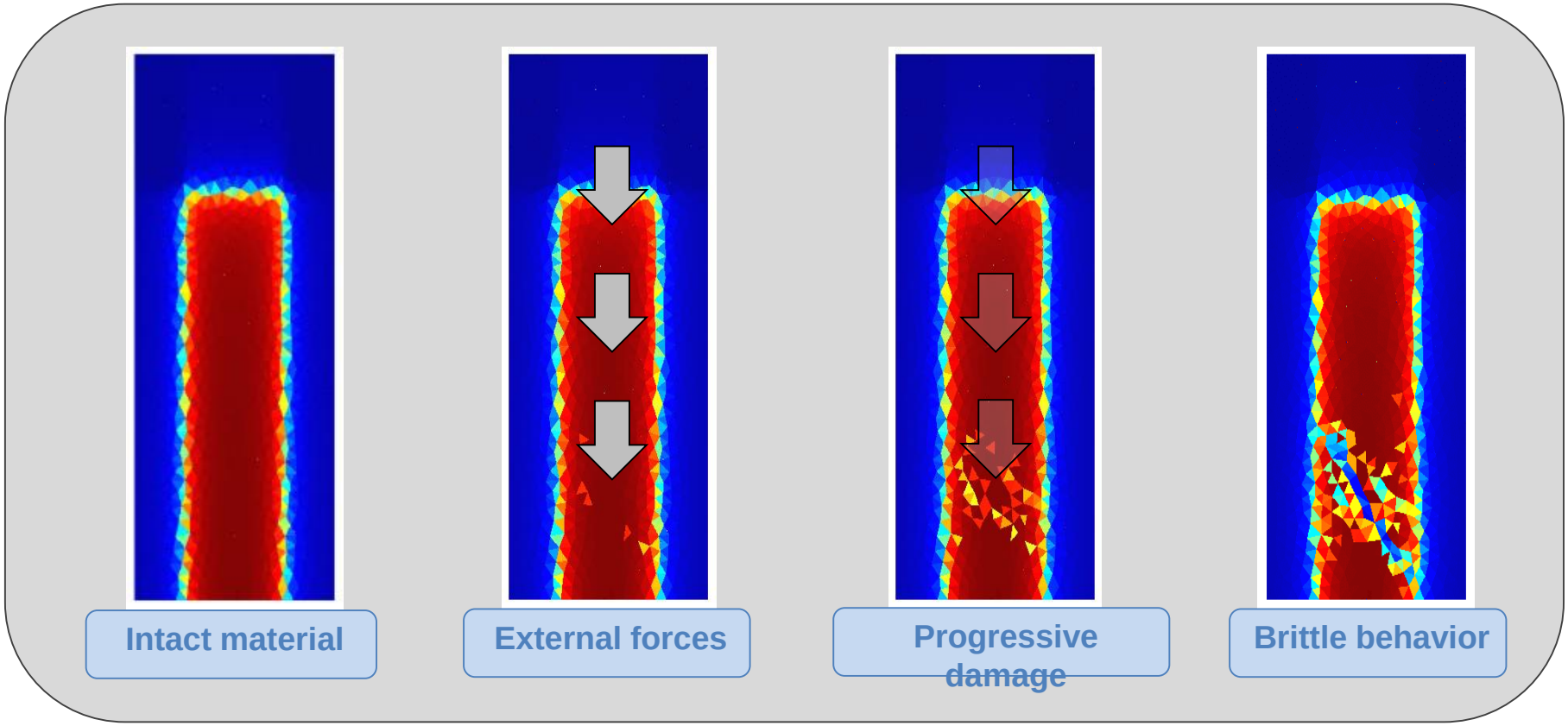
Willmes, S. and Heinemann, G. (2015)
"Pan-Arctic lead detection from MODIS thermal infrared imagery"

What is neXtSIM ?

A simple approach…

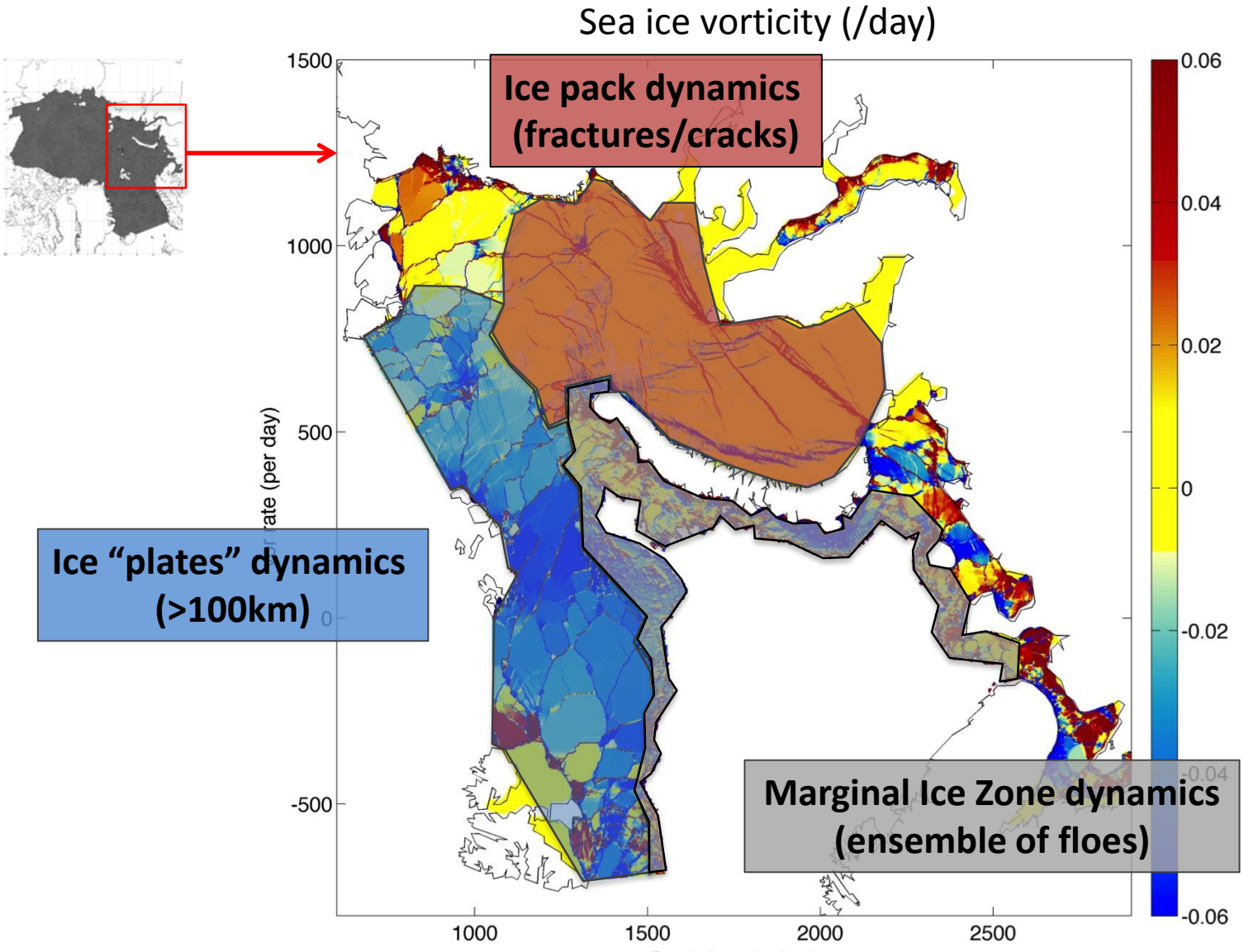
Mechanical modeling framework **inherited from solid mechanics**

Concept:



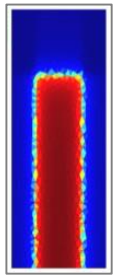
Inspired from Amitrano et al. (1999)

… to produce complex behaviors



neXtSIM at a glance

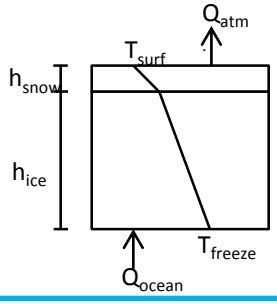
Physics



- **Dynamics: EB rheology**

  localize the deformation

  simulate ice failure

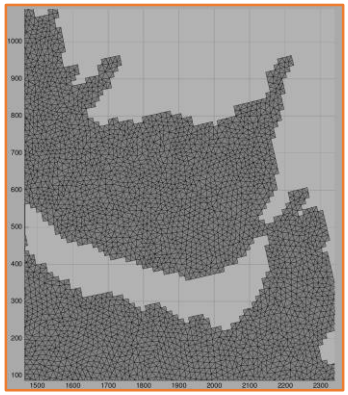


- **Thermodynamics:**

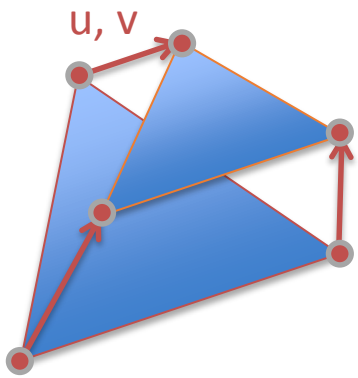
  2 ice categories, zero layer thermodynamics (3 categories also available)

Numerics

- **Unstructured grid**

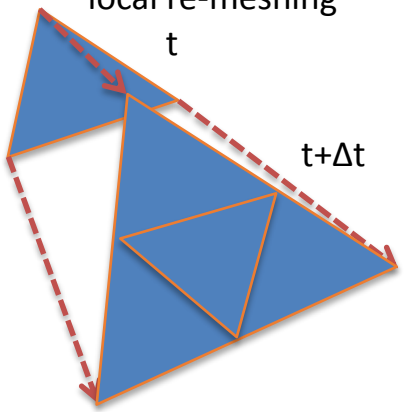


- **Fully Lagrangian**

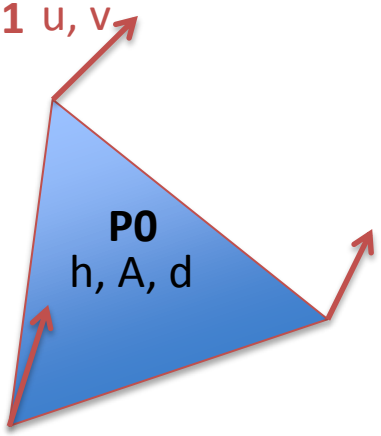


- **Adaptive mesh**

  local re-meshing



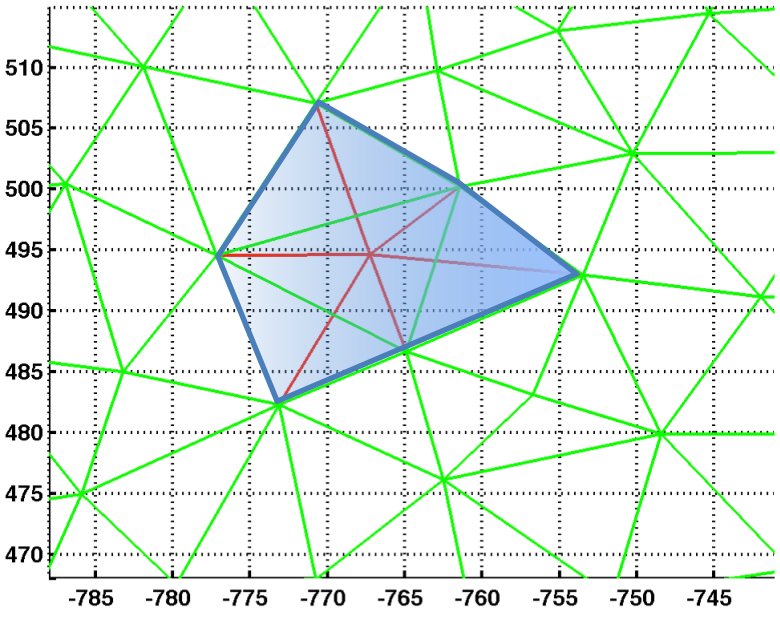
- **Finite element method**

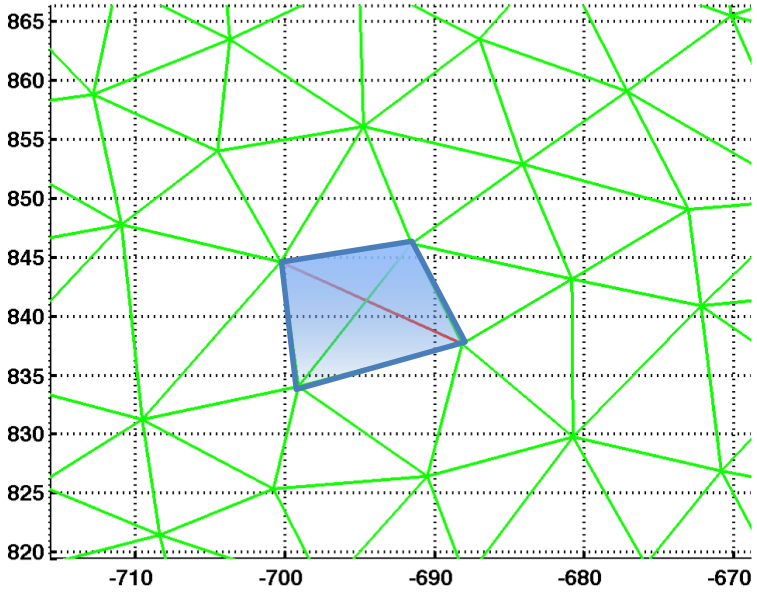


Conservation after the mesh adaptation

- Examples of mesh adaptation with BAMG

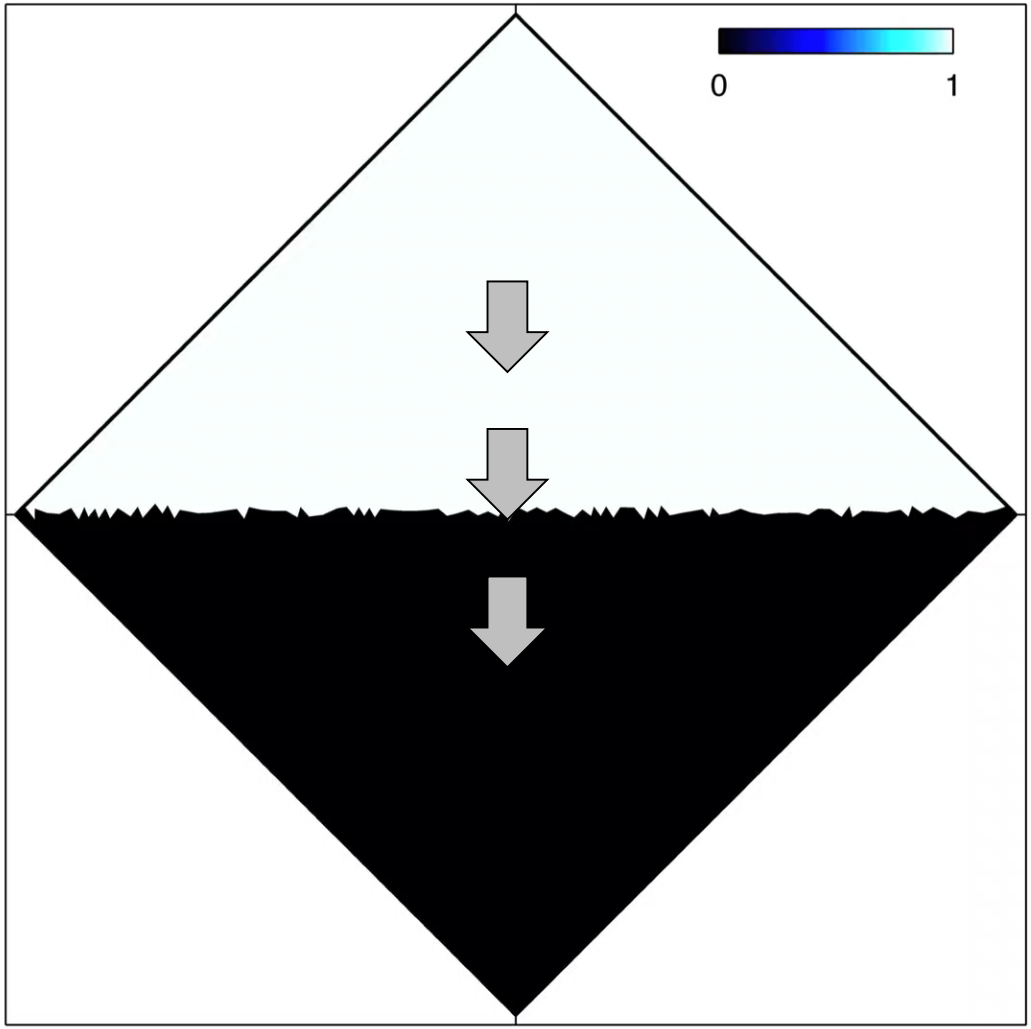
Adaptation are limited to small cavities



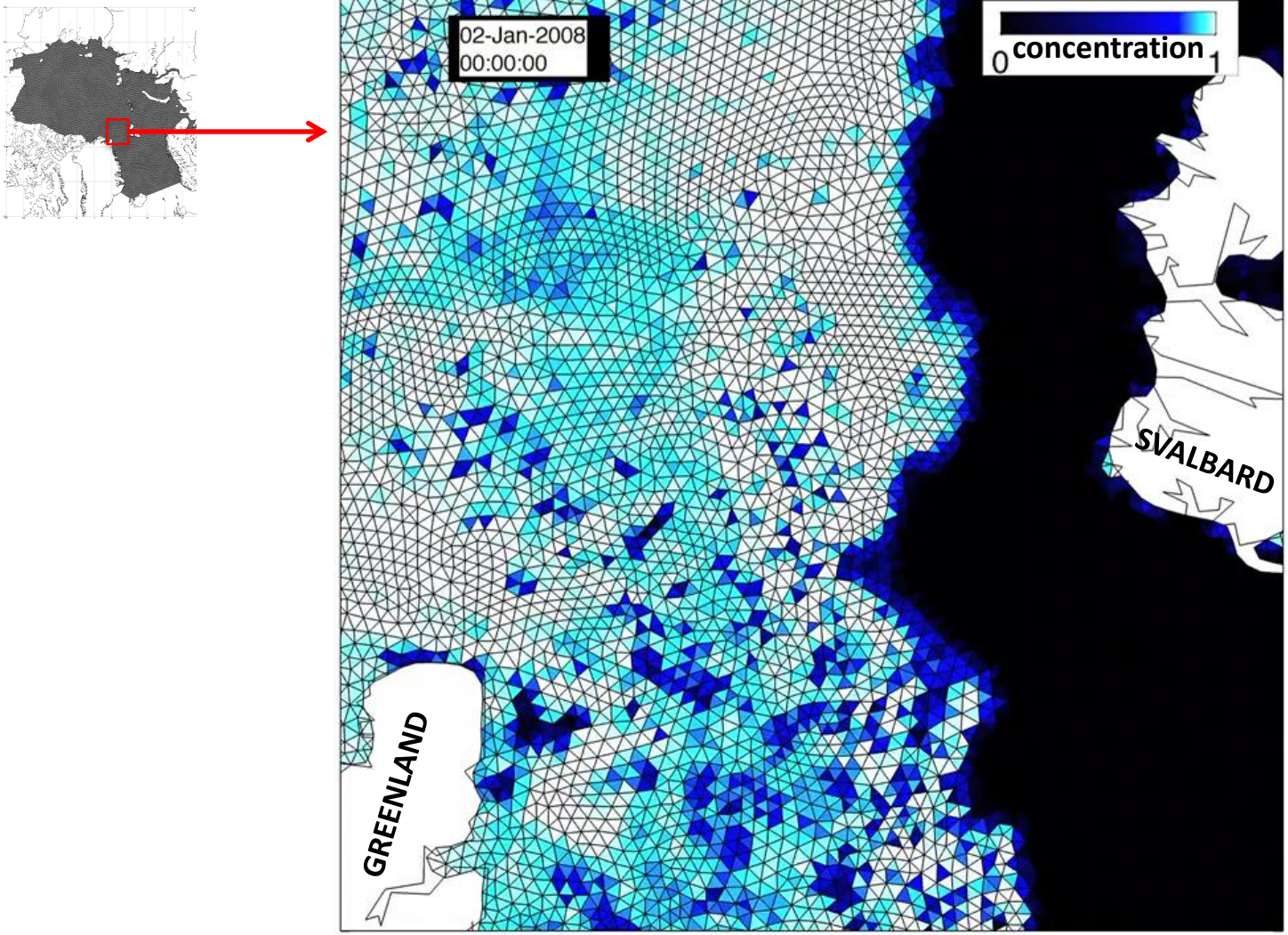


Conservation after the mesh adaptation

- Numerical diffusion is limited

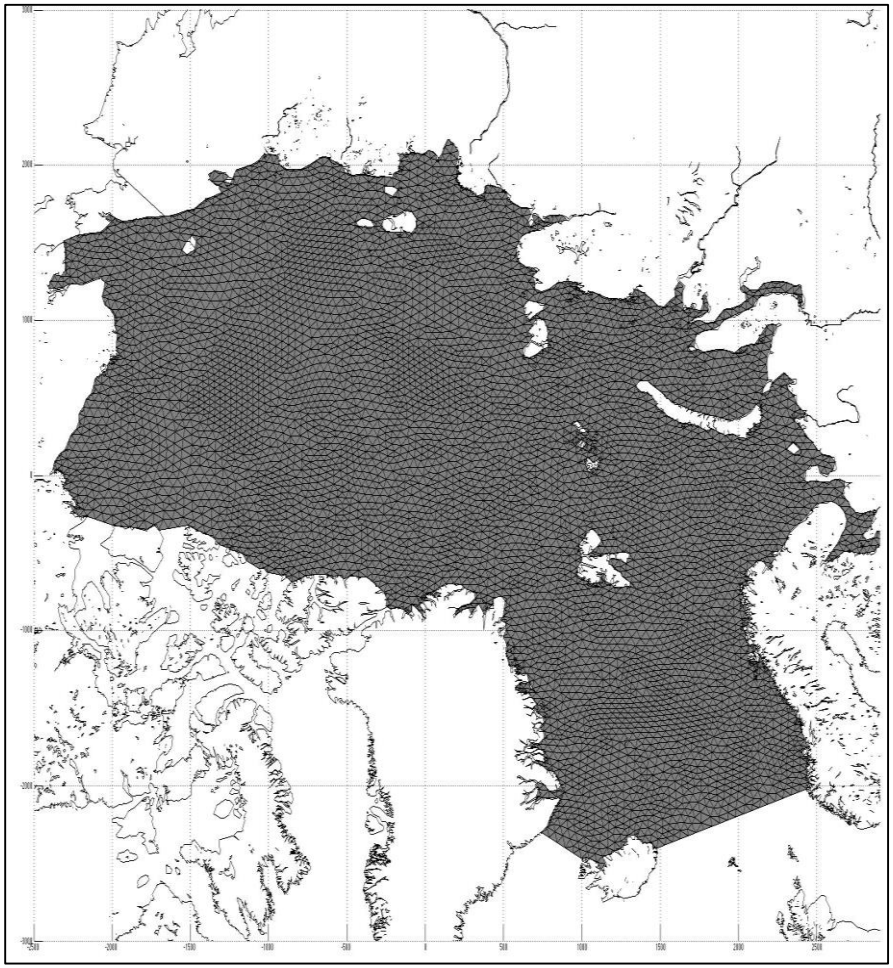


Simulating cracks/leads in the Fram Strait (with local remeshing)



pan-Arctic configuration

Resolution: 7km



stand-alone simulation

Jan 1st – Apr 15th 2008

Boundary conditions:
No slip at coasts
open at straits

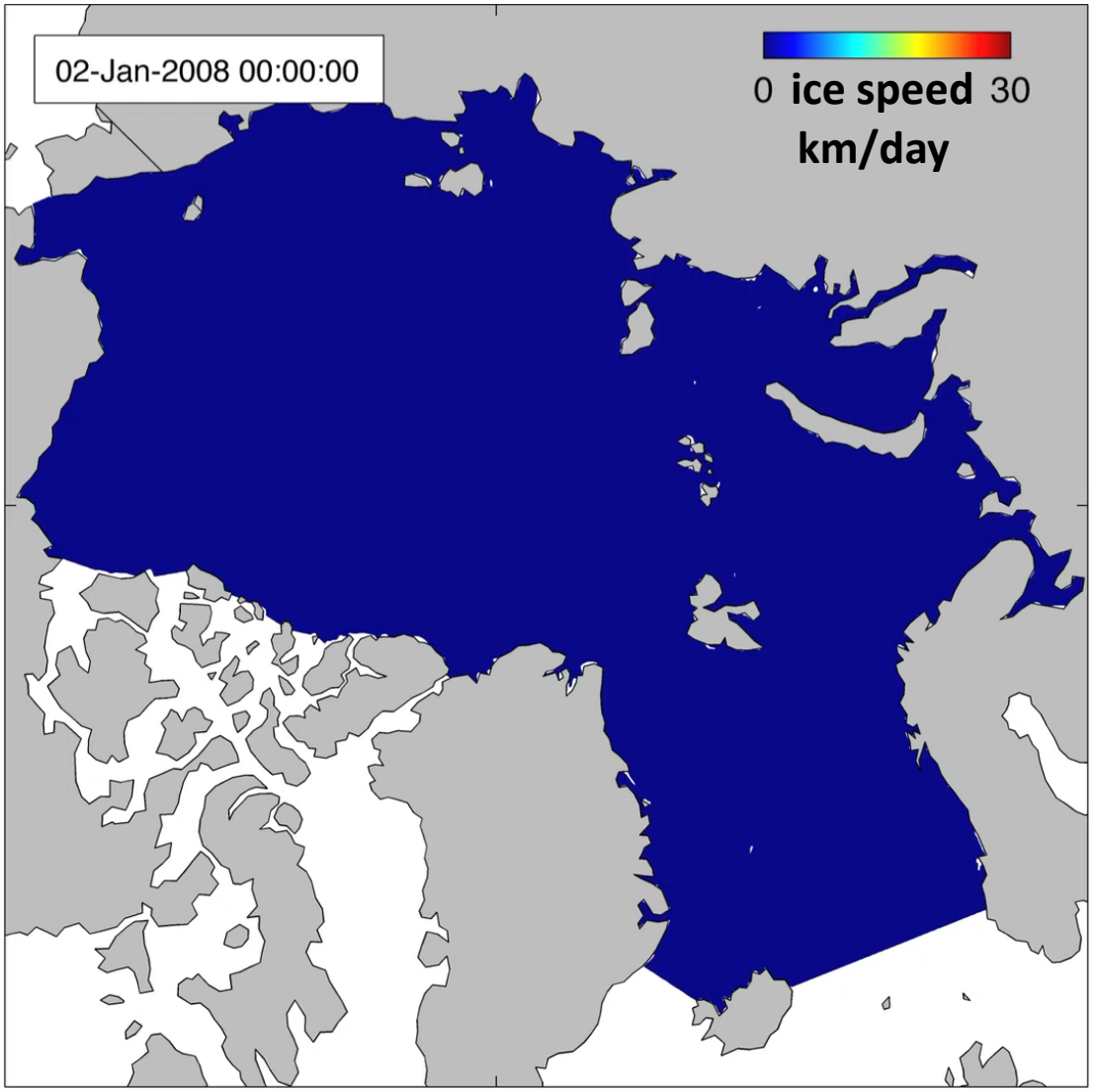
External forcing:
ASR winds (30km, 3-hourly)
TOPAZ ocean currents at 30m (10km, daily)

Initial conditions:
Combined AMSR-E ice concentration and **lead fraction**
TOPAZ ice thickness (modulated)

Undamaged ice cover!

1 year simulation ➔ 2days with a 2.7GHz Intel quad core i7 processor

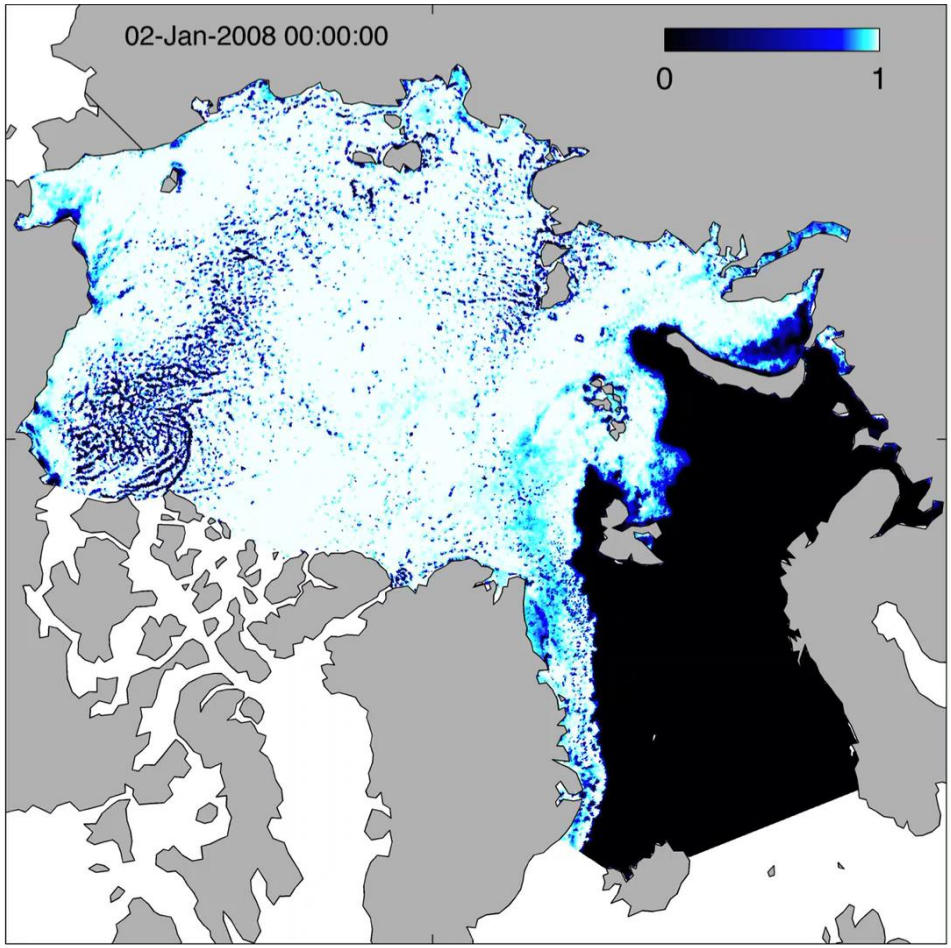
In neXtSIM, the ice motion looks like this…



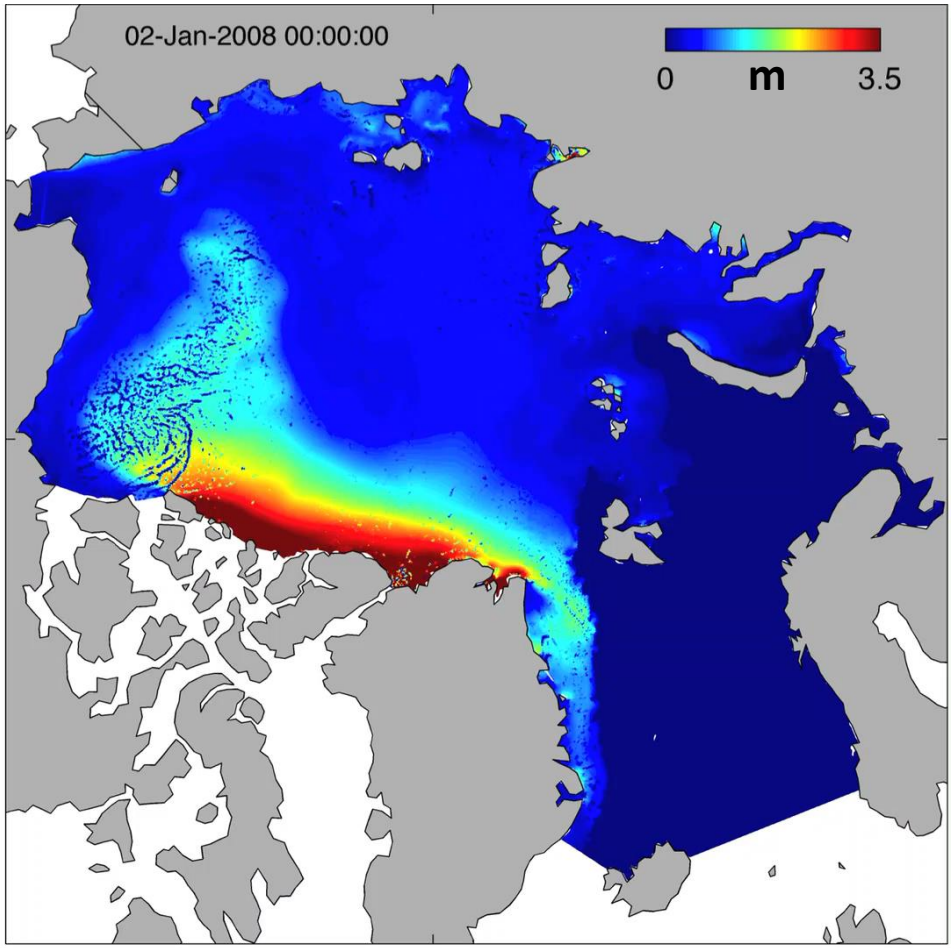
"the **ice cover concentrates gradients** in the forcing wind field into narrow bands of intense shear" (Mac Phee et al., 2005)

Sea ice concentration and thickness simulated by neXtSIM

ice concentration



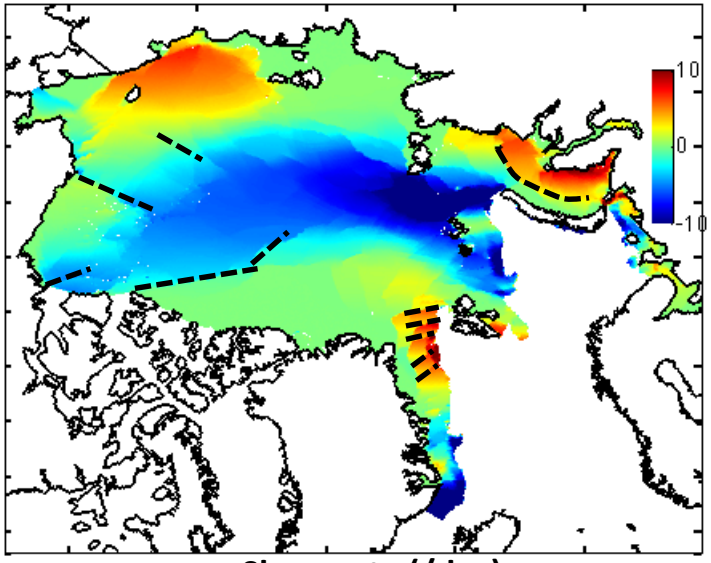
ice thickness



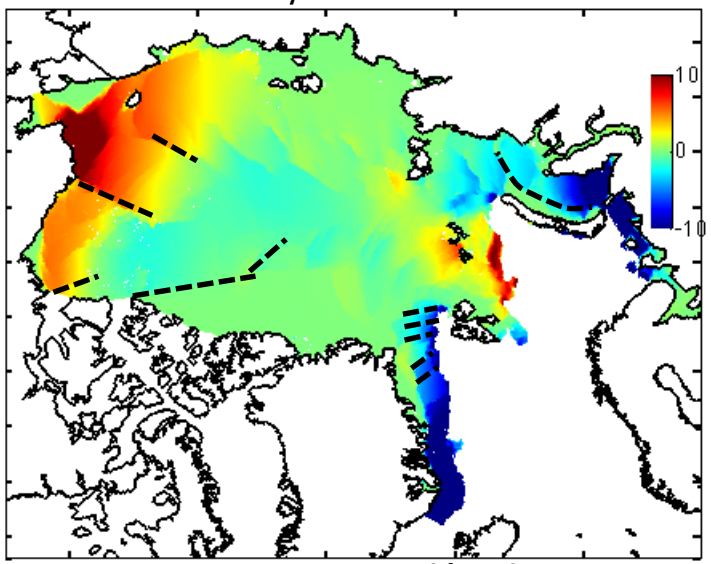
Sea ice drift and deformation simulated by neXtSIM

Ice velocity

U_x (km/day)

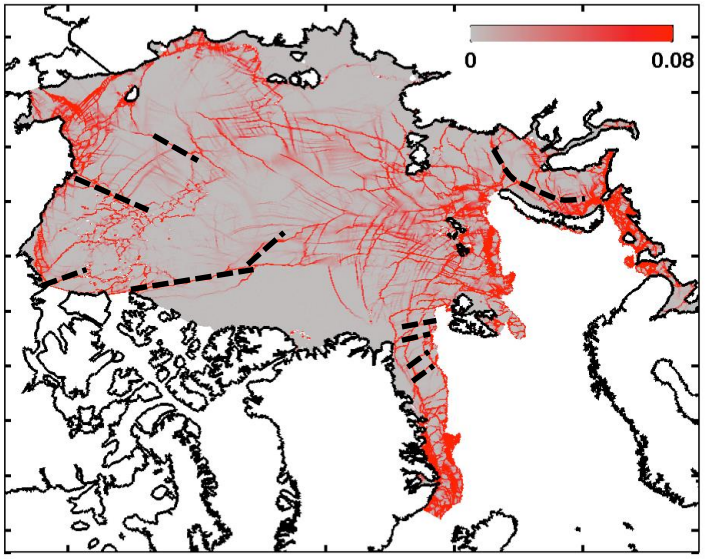


U_y (km/day)

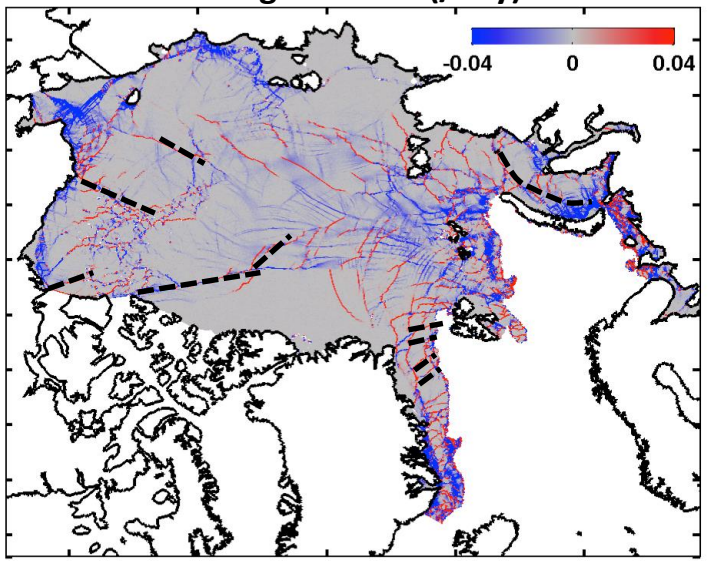


Ice Deformation

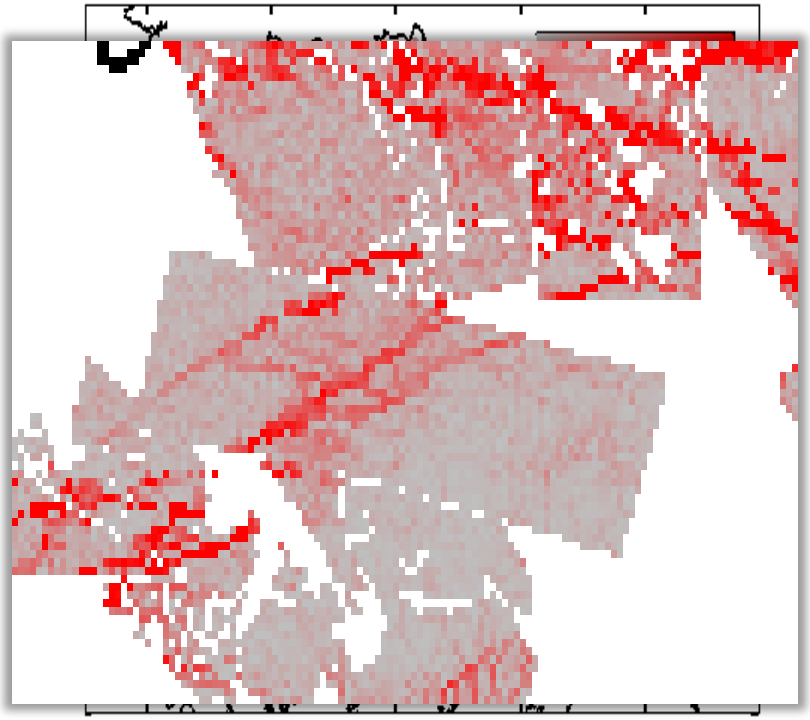
Shear rate (/day)



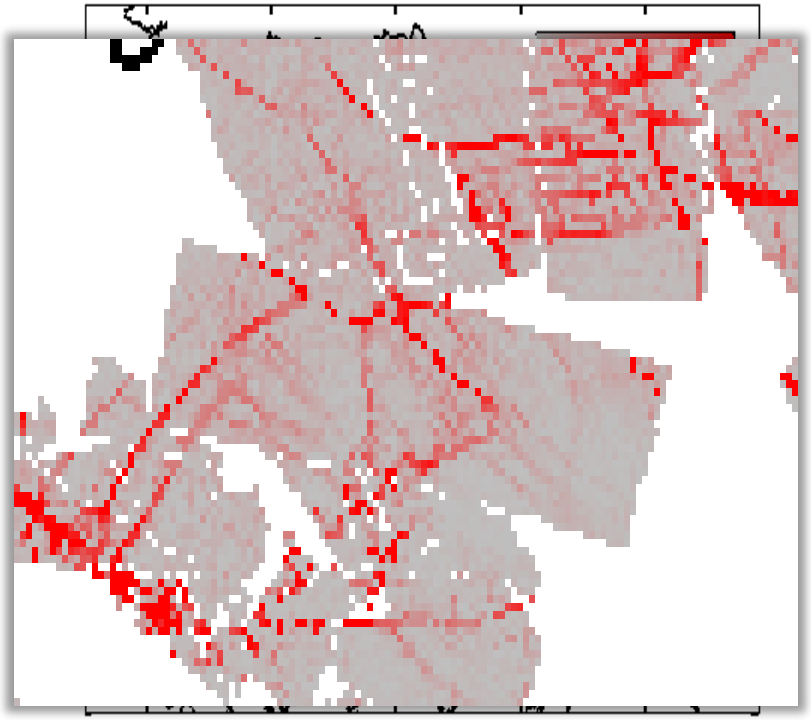
Divergence rate (/day)



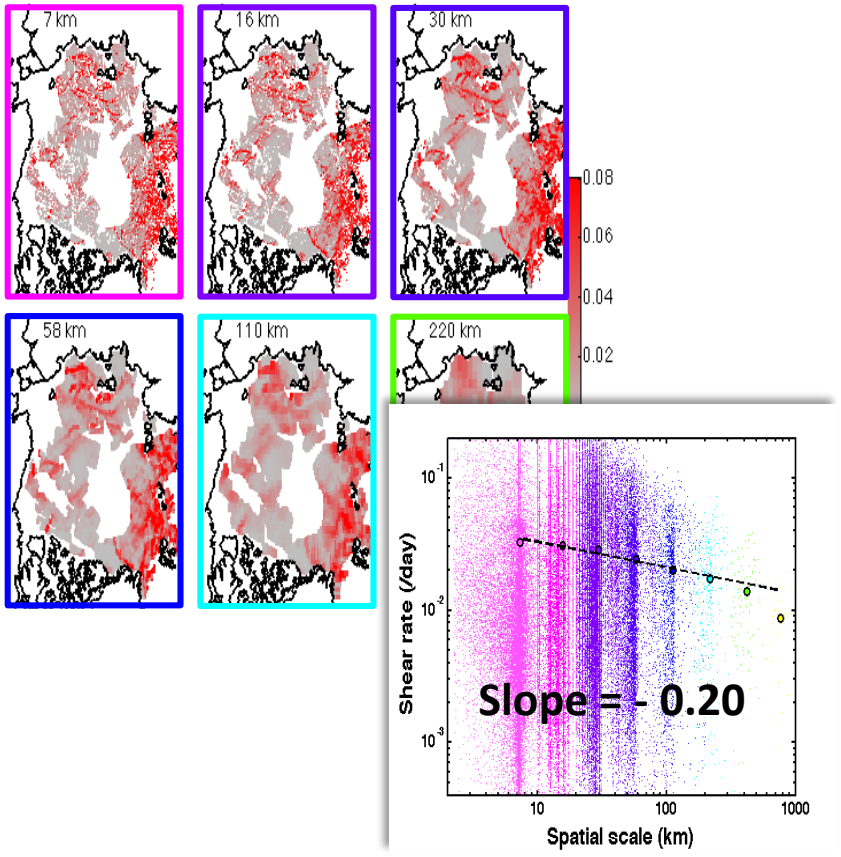
SAR (ENVISAT & RADARSAT)



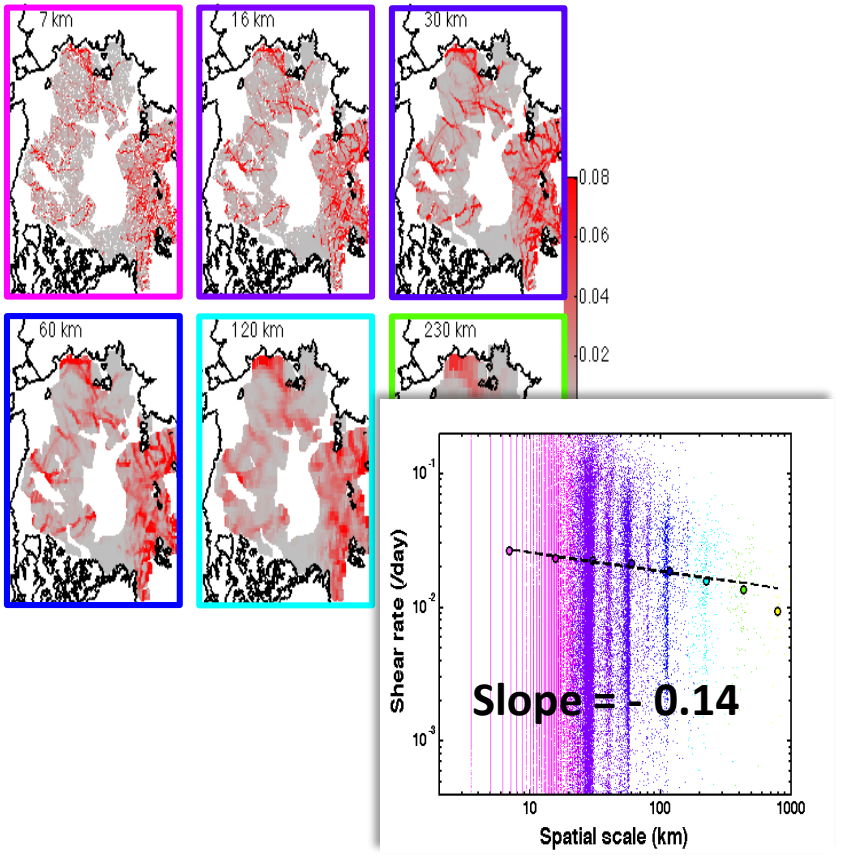
neXtSIM



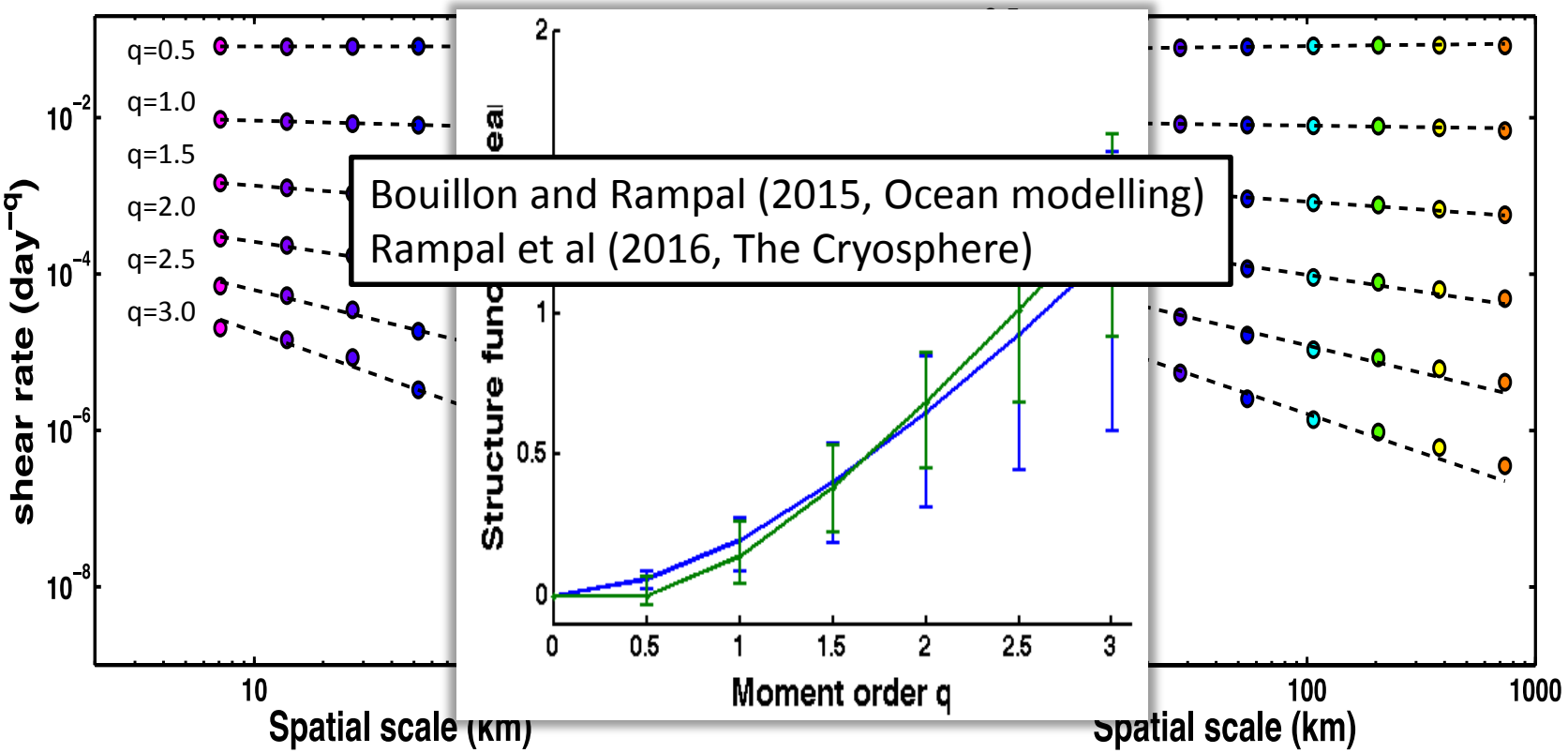
SAR (ENVISAT & RADARSAT)



neXtSIM

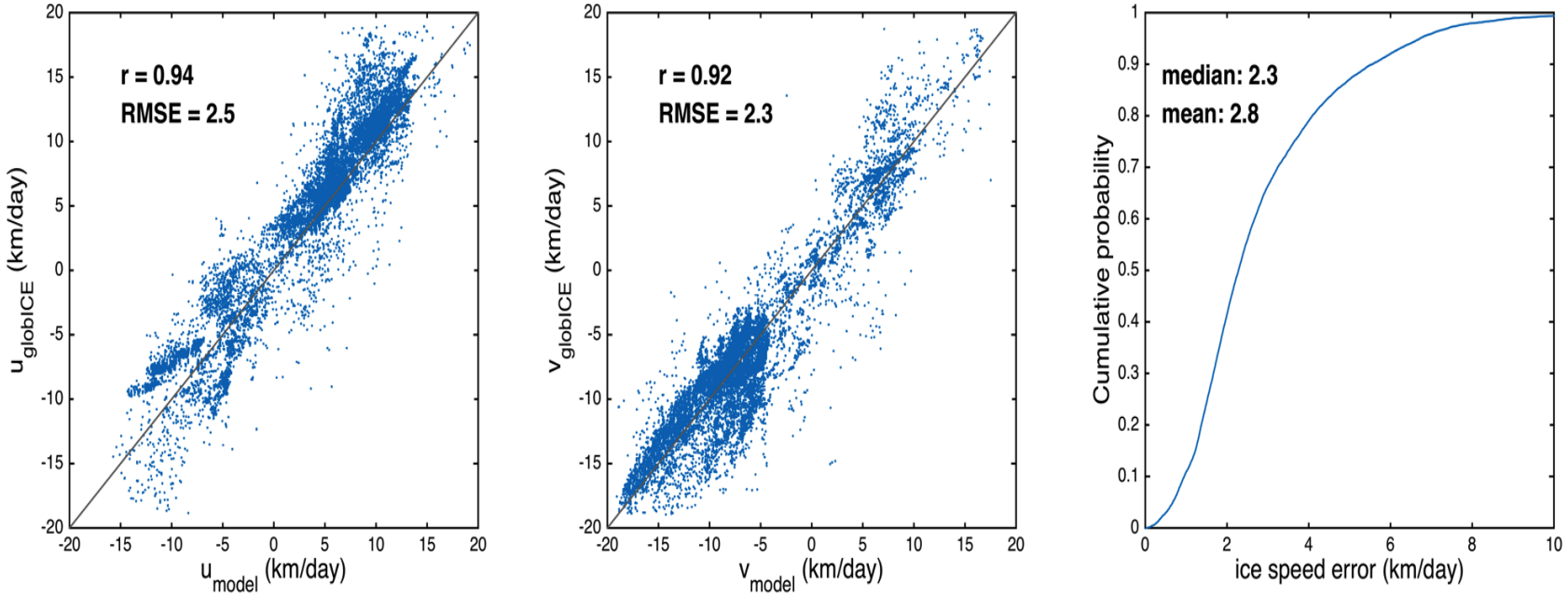


SAR (ENVISAT & RADARSAT) neXtSIM



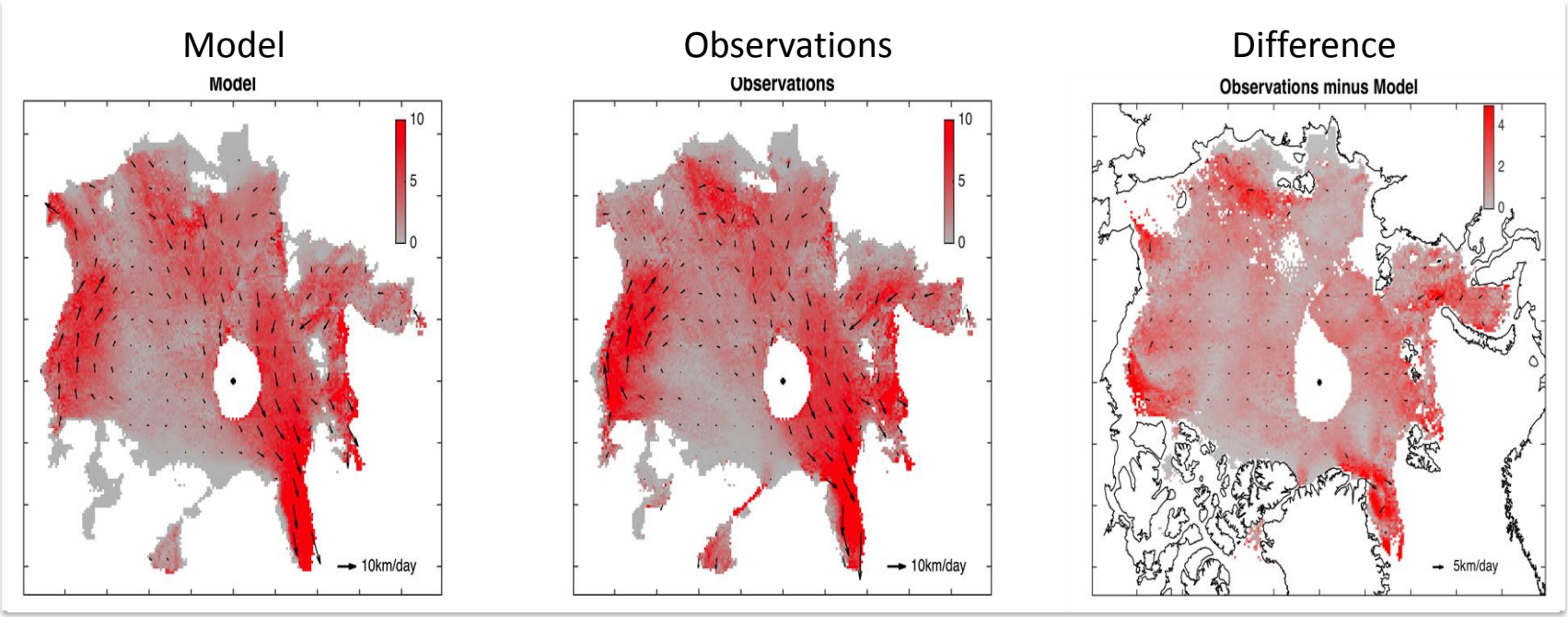
Bouillon and Rampal (2015, Ocean modelling)
Rampal et al (2016, The Cryosphere)

Simulated vs. observed drift



- High correlation between simulated and observed drift
- Holds for comparison done over the entire model domain, not just free drift cases.
- No bias
- RMSE 2.4 km/day for ASR and 3.6 km/day for ERA-Interim

Winter mean drift

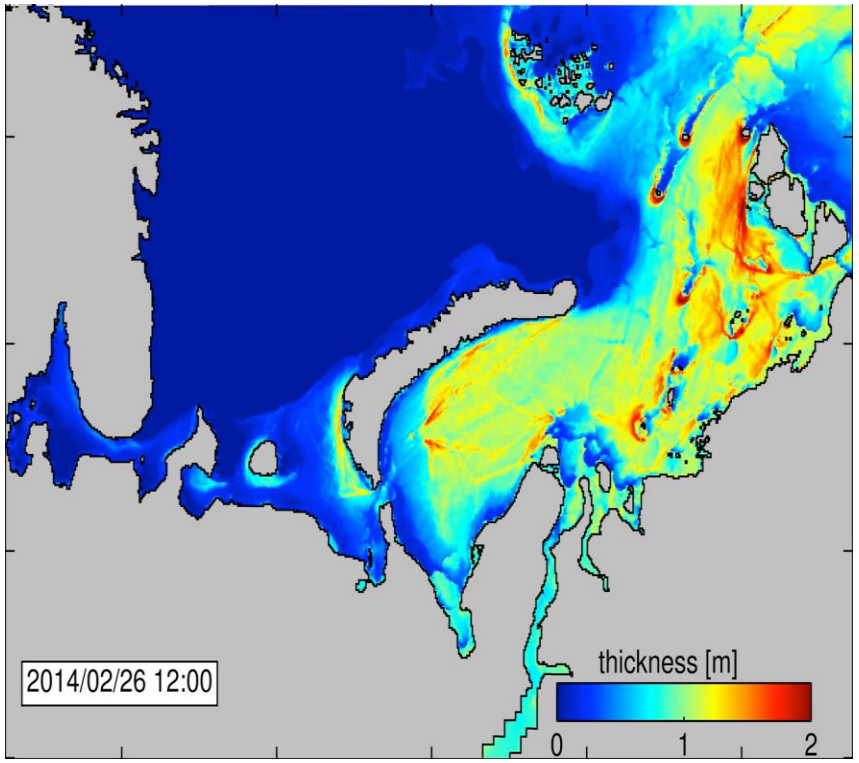


- Error below 1 km/day in most of the area
- Areas of large errors may be related to model/forcing short comings

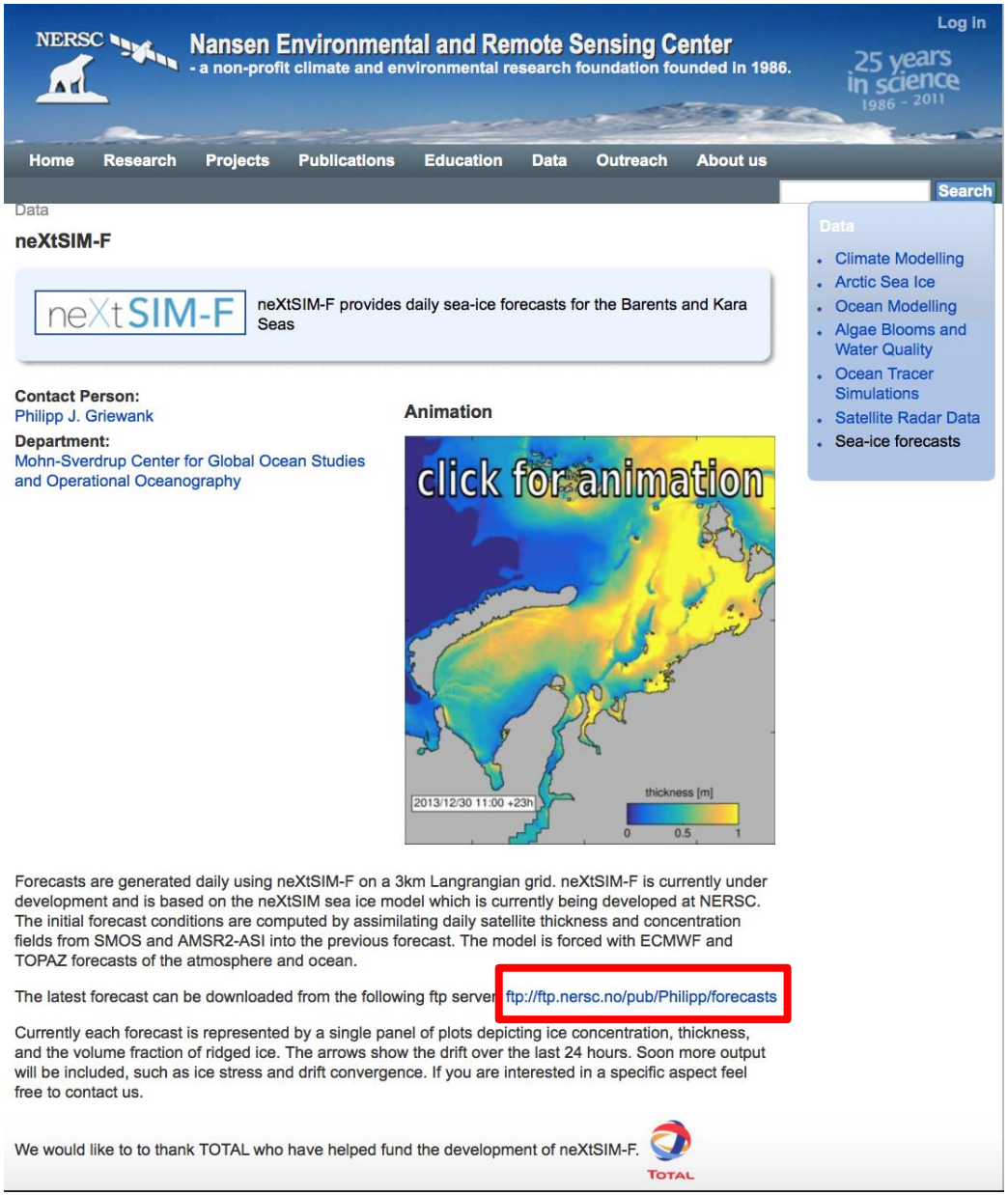
Rampal et al (2016, The Cryosphere) for details

Application for operational forecast

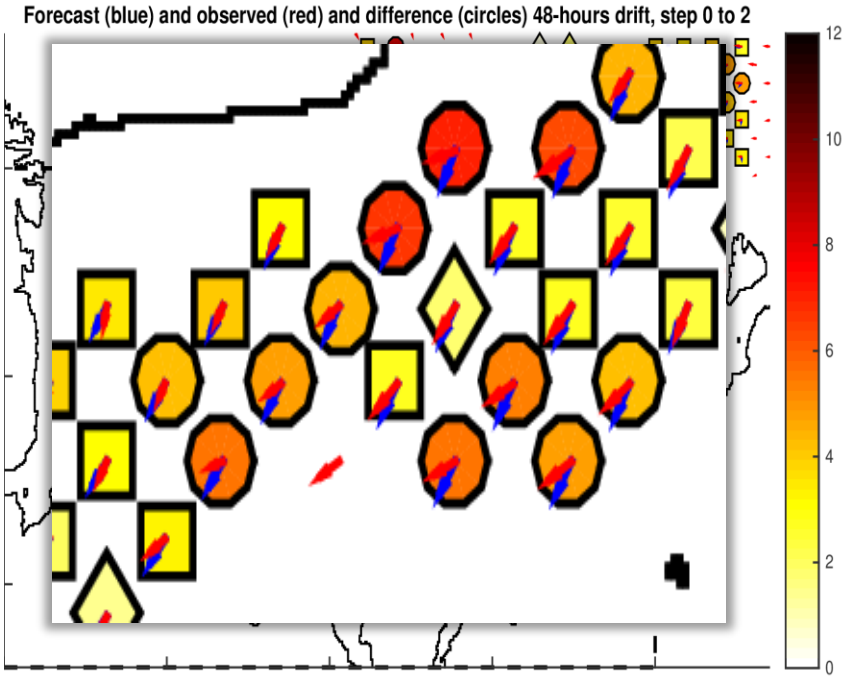
- neXtSIM-F is a sea ice forecast platform for the Kara Sea
- Forced by ECMWF and ARC MFC forecasts
- Assimilates
  - Concentration (AMSR2)
  - Thin ice thickness (SMOS)
- www.nersc.no/data/neXtSIM-F



http://www.nersc.no/data/nextsim-f



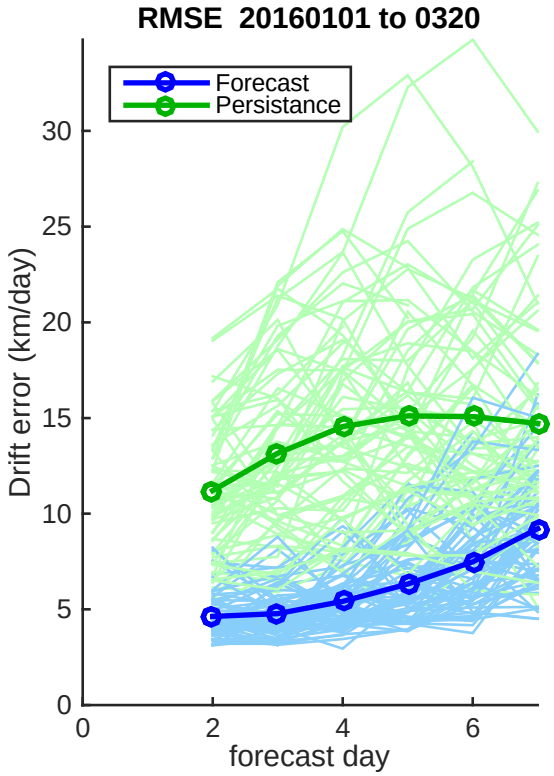
OSI SAF drift comparison

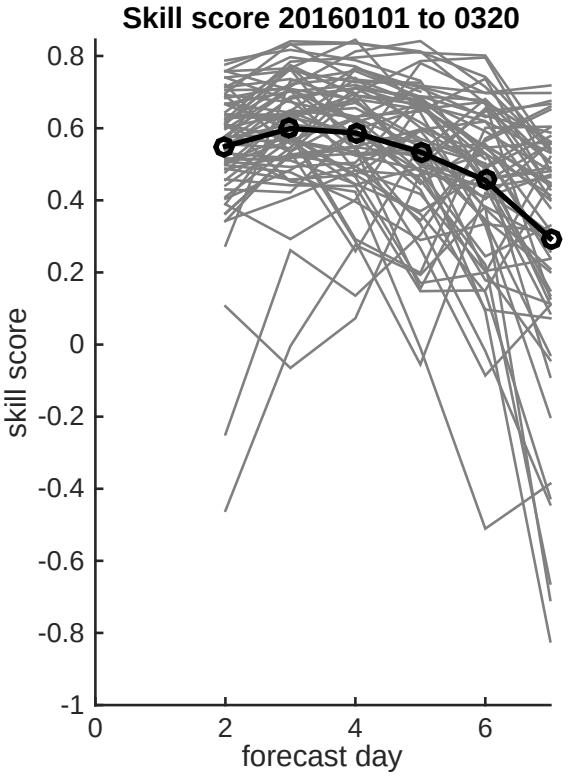


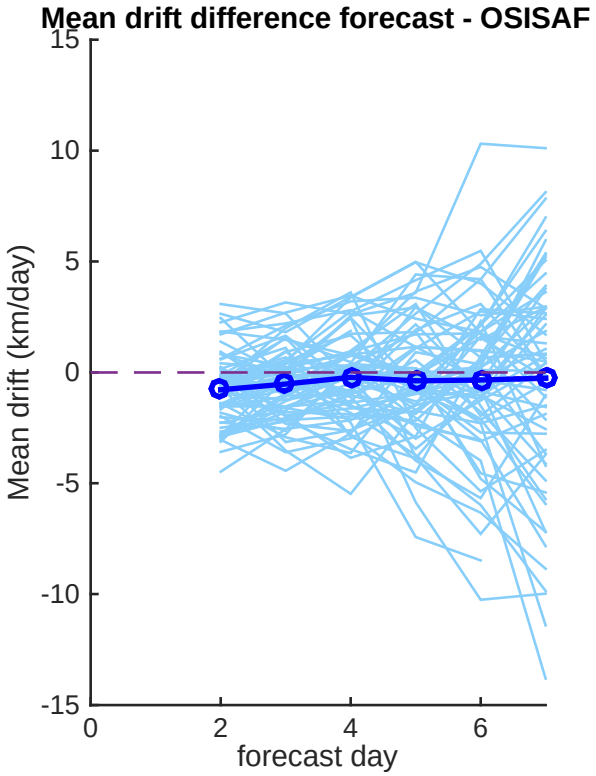
- Forecast evaluation
  - AMSR2 concentration
  - SMOS thin ice thickness
  - OSI SAF ice drift
- Daily forecast and evaluation

www.nersc.no/data/nextsim-f

OSI SAF drift comparison



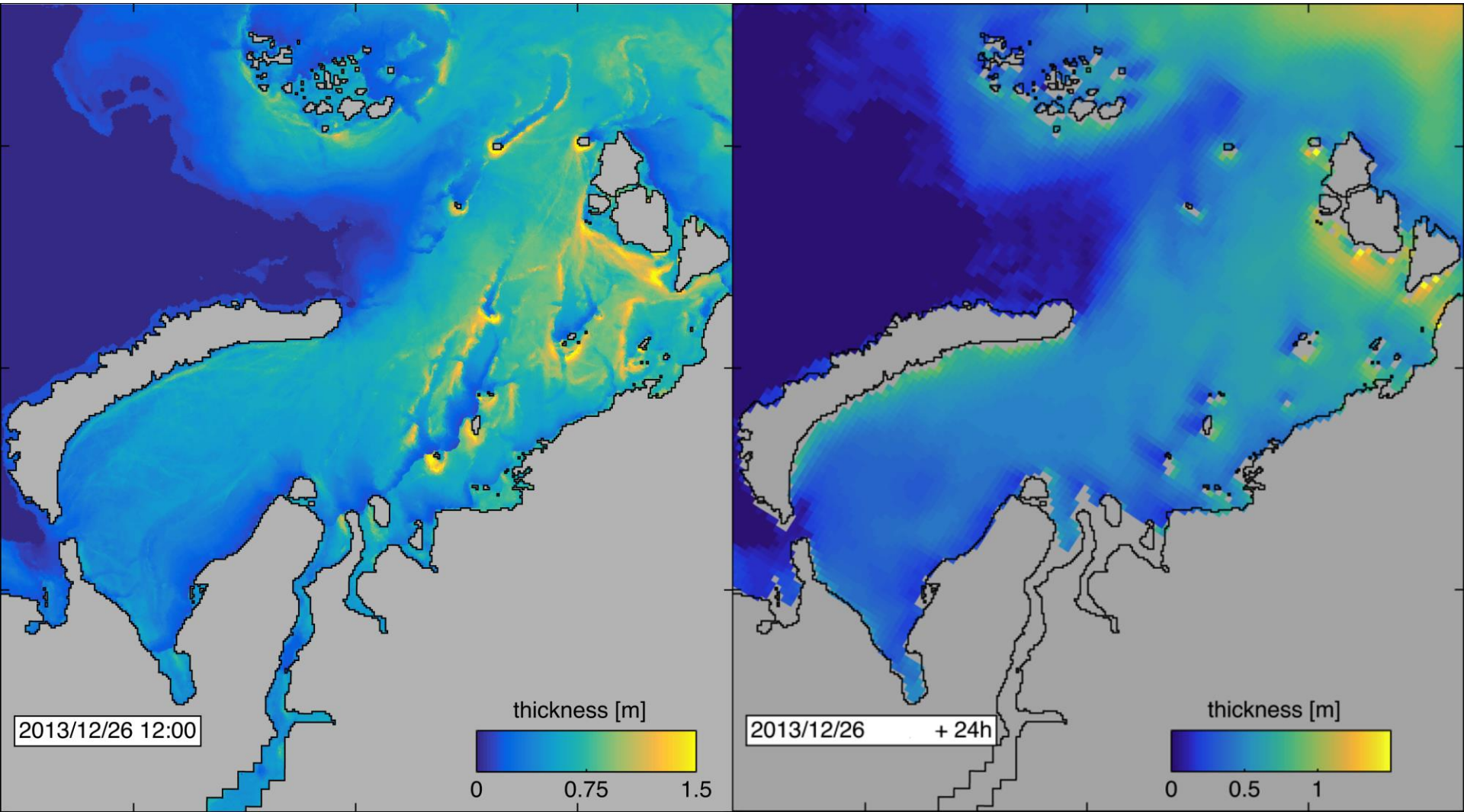




- Forecast has skill throughout forecast period, partially thanks to weak persistence forecast.
- Time increase in forecast error is mostly due to errors of ECMWF forecast
- Mean drift speed matches well

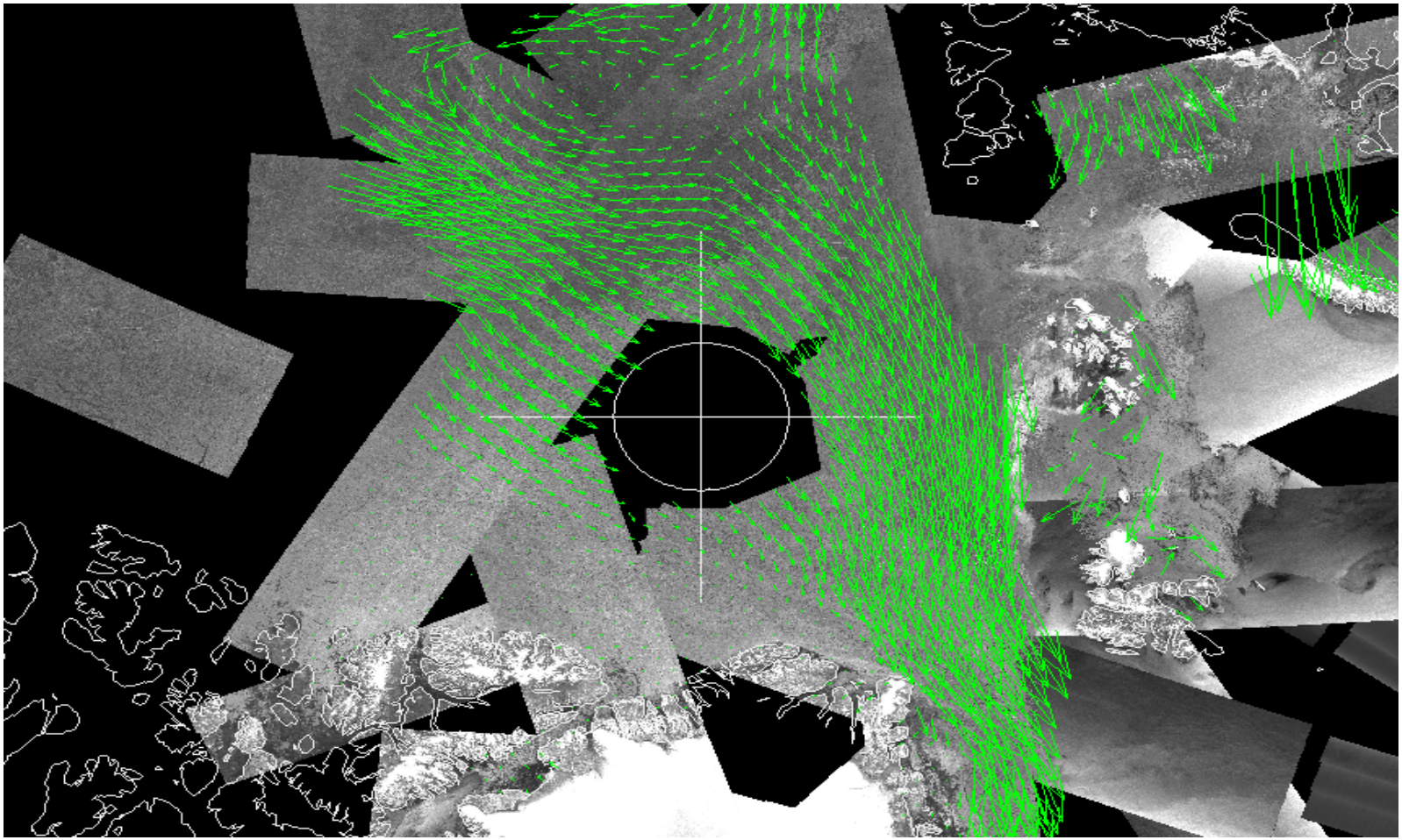
neXtSIM-F vs TOPAZ

neXtSIM-F thickness is more heterogeneous than TOPAZ.



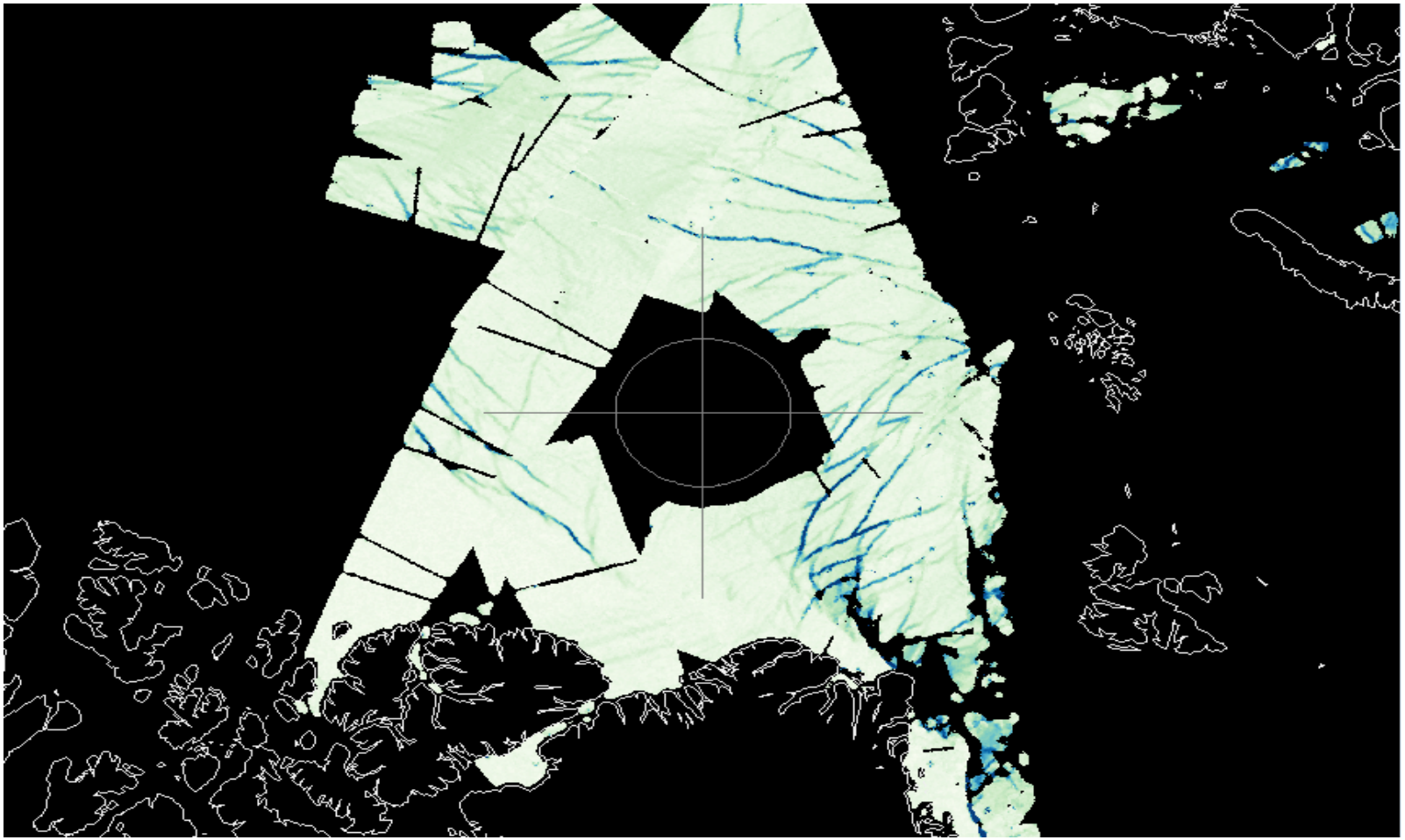
Data assimilation of sea ice drift and deformation

Operational products: daily sea ice drift from Sentinel satellites
(DTU, Copernicus Marine Service)



2016-02-28

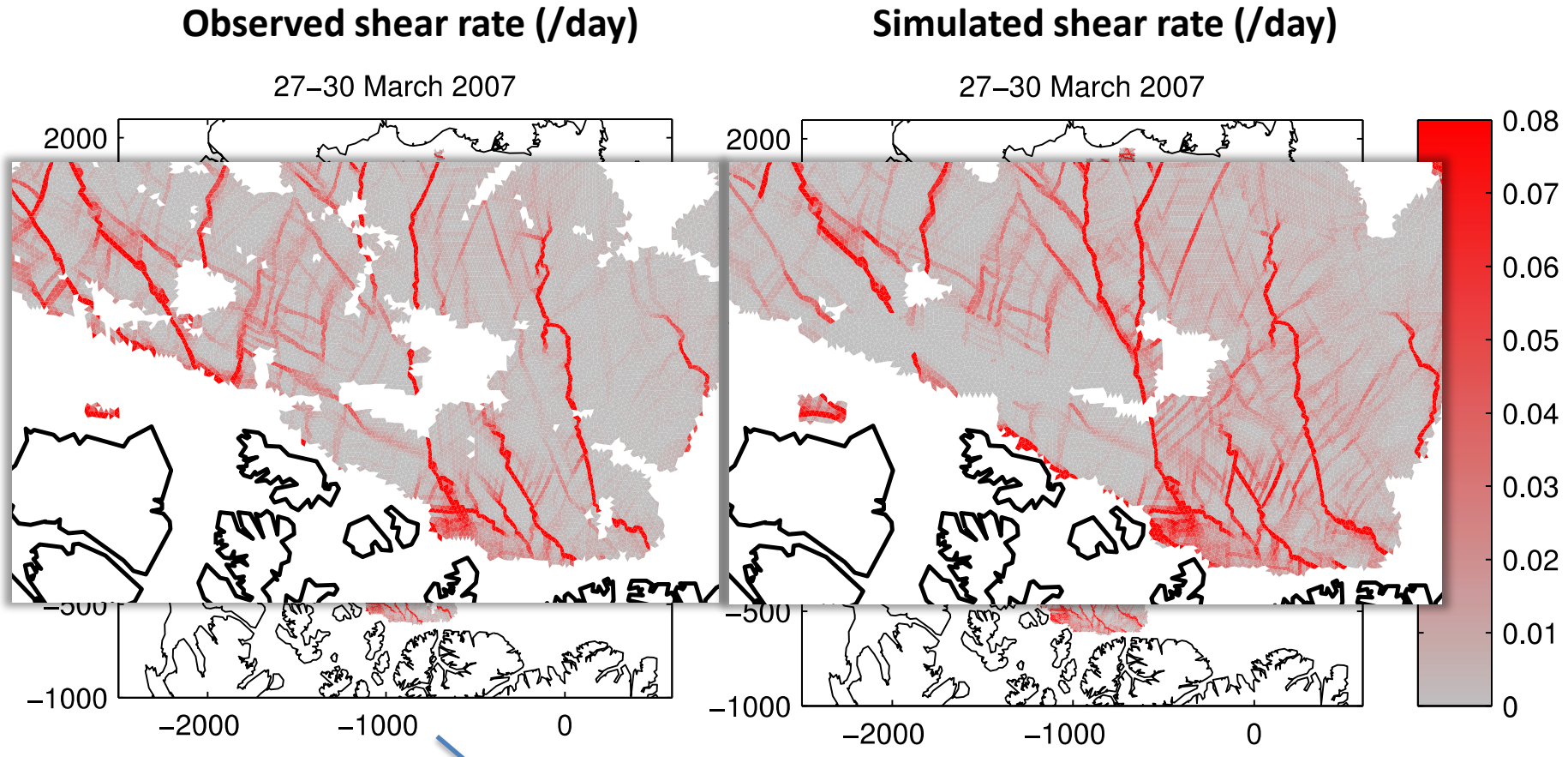
Data assimilation of sea ice drift and deformation



2016-02-27 ->28 Shear rate

From more than 500.000 ice drift vectors at 2 km spacing

Data assimilation of sea ice drift and deformation



"Only damaged sea ice deforms"

Damage field

Initial conditions for the simulation

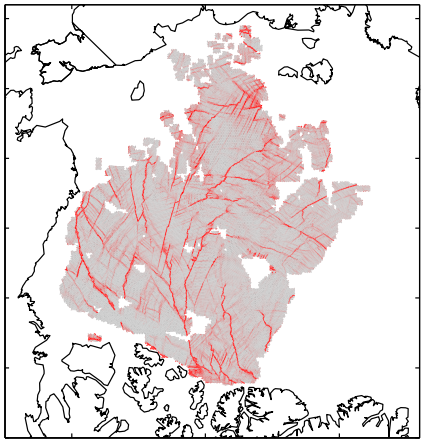
Conclusions and perspectives

Modelling

- Coupling with the atmosphere (weather forecast, feedback,…)
- Coupling with the ocean (inertial oscillation, enhanced fluxes, waves…)
- Sub-grid scale parameterizations

Observations

- Operationalization
- Track the discontinuities
- Link deformation, thickness and lead datasets



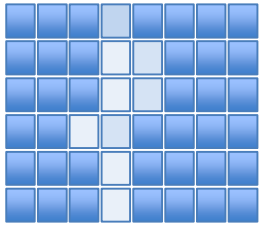
Data assimilation

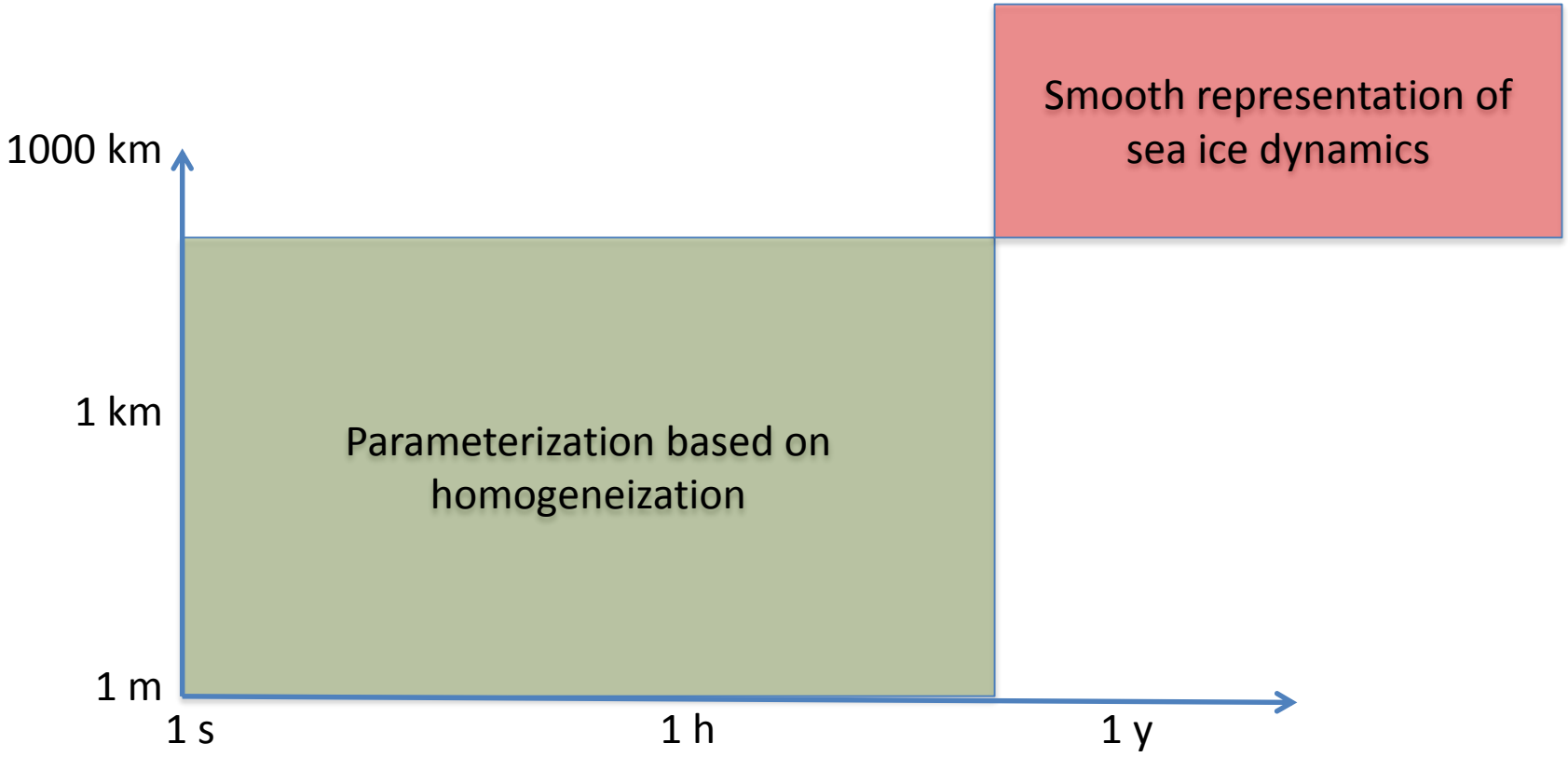
- Assimilation of sea ice drift and deformation
- Assimilation of sea ice thickness data (CrySat and SMOS)

List of the on-going projects on: www.nersc.no/group/sea-ice-modelling
www.nersc.no/group/data-assimilation

Classical sea ice models parameterize most of the processes of interest.

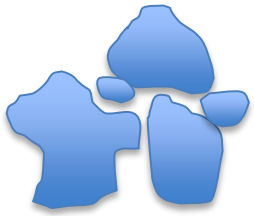
- **Classical continuous Eulerian model**
  with increased resolution

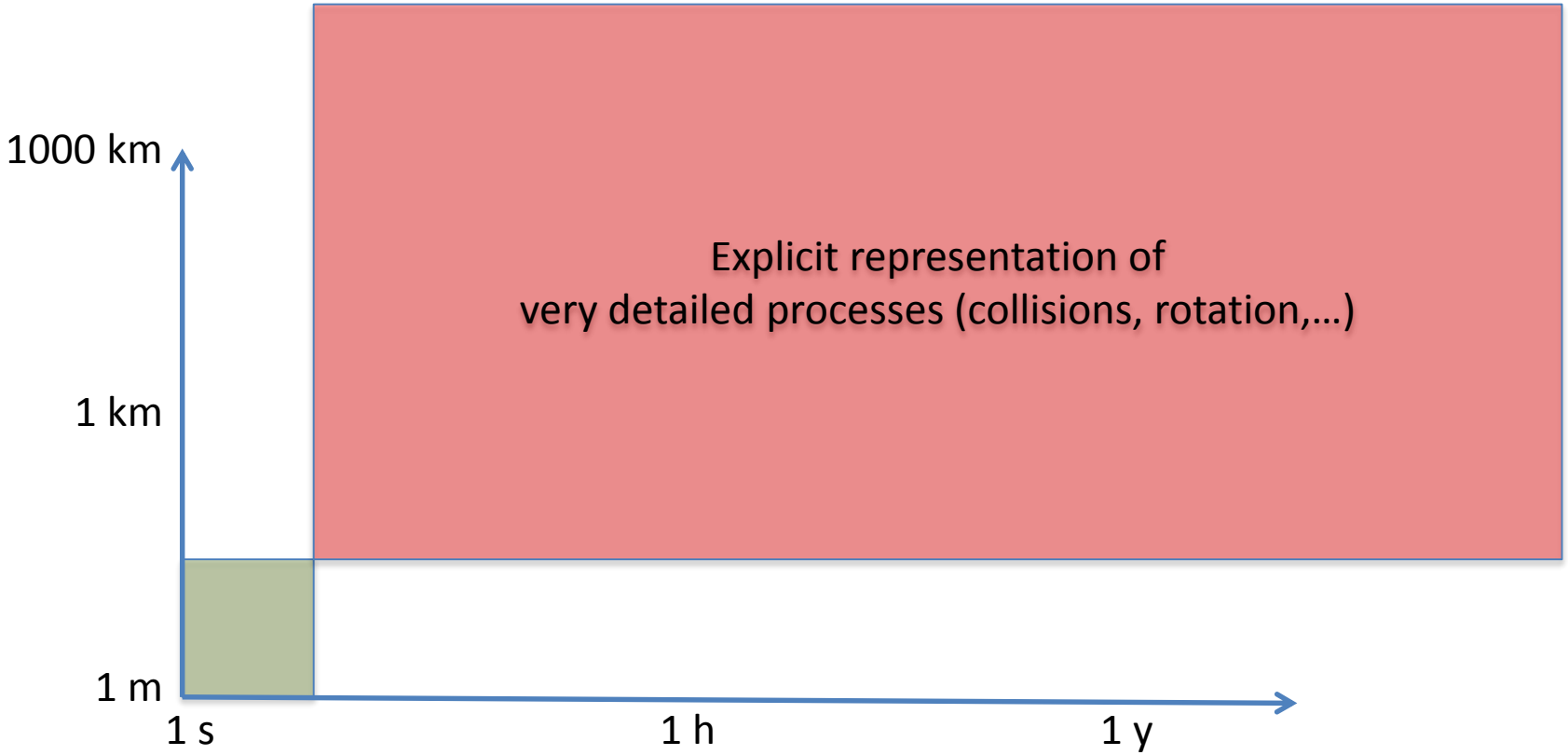




Discrete sea ice models are maybe not suited for long simulations on large domains.

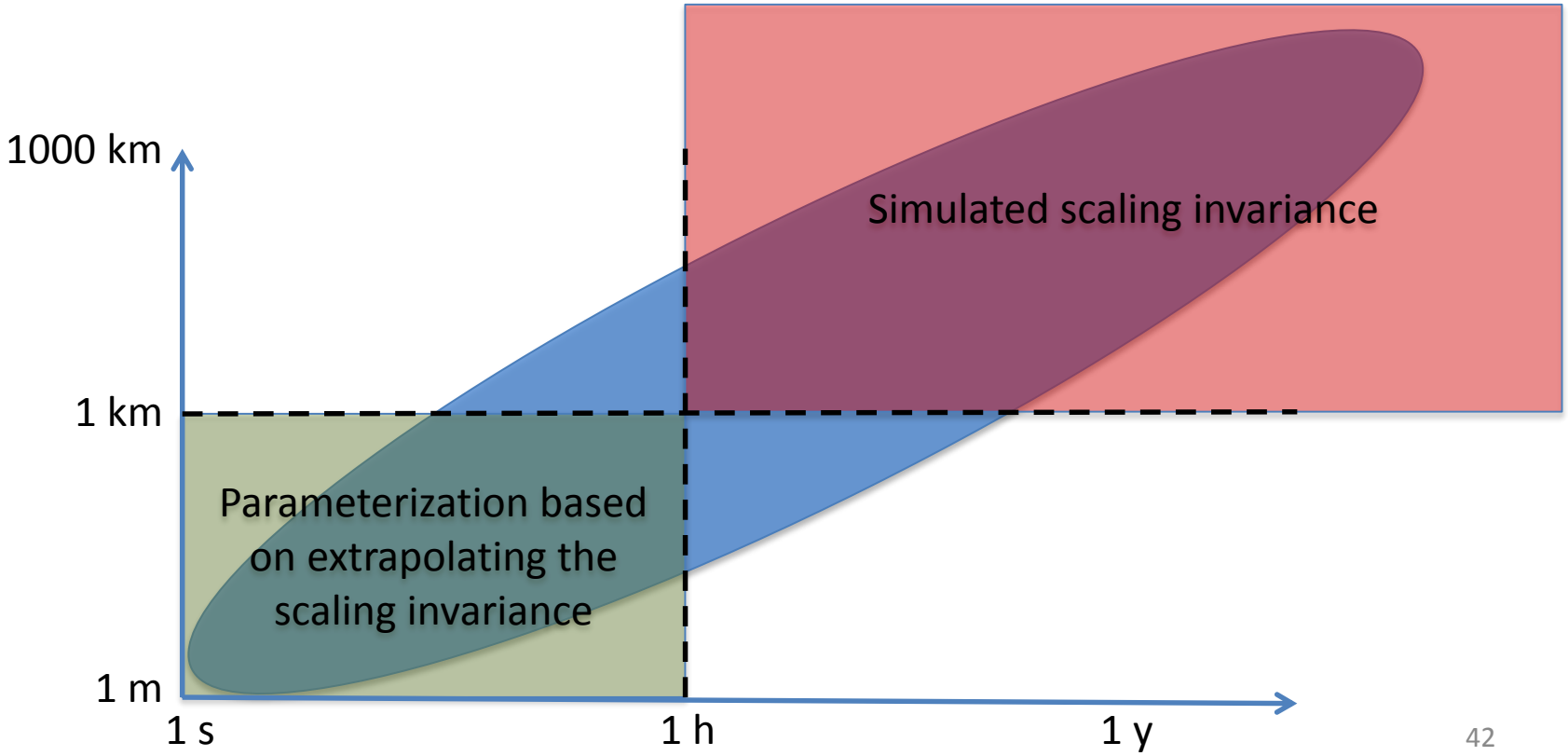
- **Discrete model**
  with simplistic or realistic shapes
  with refreezing/breaking of the floes
  with a precise representation of the collisions





neXtSIM reproduces the scaling invariance down to its nominal resolution

- Sea ice models should **simulate and/or parameterize** deformation scaling.



Drag optimisation

- The momentum equation of sea ice is

$$\rho_i h \frac{D\boldsymbol{u}_i}{Dt} = \nabla \cdot (\boldsymbol{\sigma} h) + A(\boldsymbol{\tau}_\mathrm{a} + \boldsymbol{\tau}_\mathrm{w}) - \rho_i h f \boldsymbol{k} \times \boldsymbol{u}_i - \rho_i h g \nabla \eta$$

Inertial term | Internal force | Drag terms | Coriolis force | Ocean tilt term

- In free drift we can ignore most terms, giving:

$$\boldsymbol{u}_i = \boldsymbol{u}_w + \boldsymbol{u}_a Na$$

$\boldsymbol{u}_i$ is ice velocity
$\boldsymbol{u}_w$ is water velocity
$\boldsymbol{u}_a$ is wind velocity

Nansen number