ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

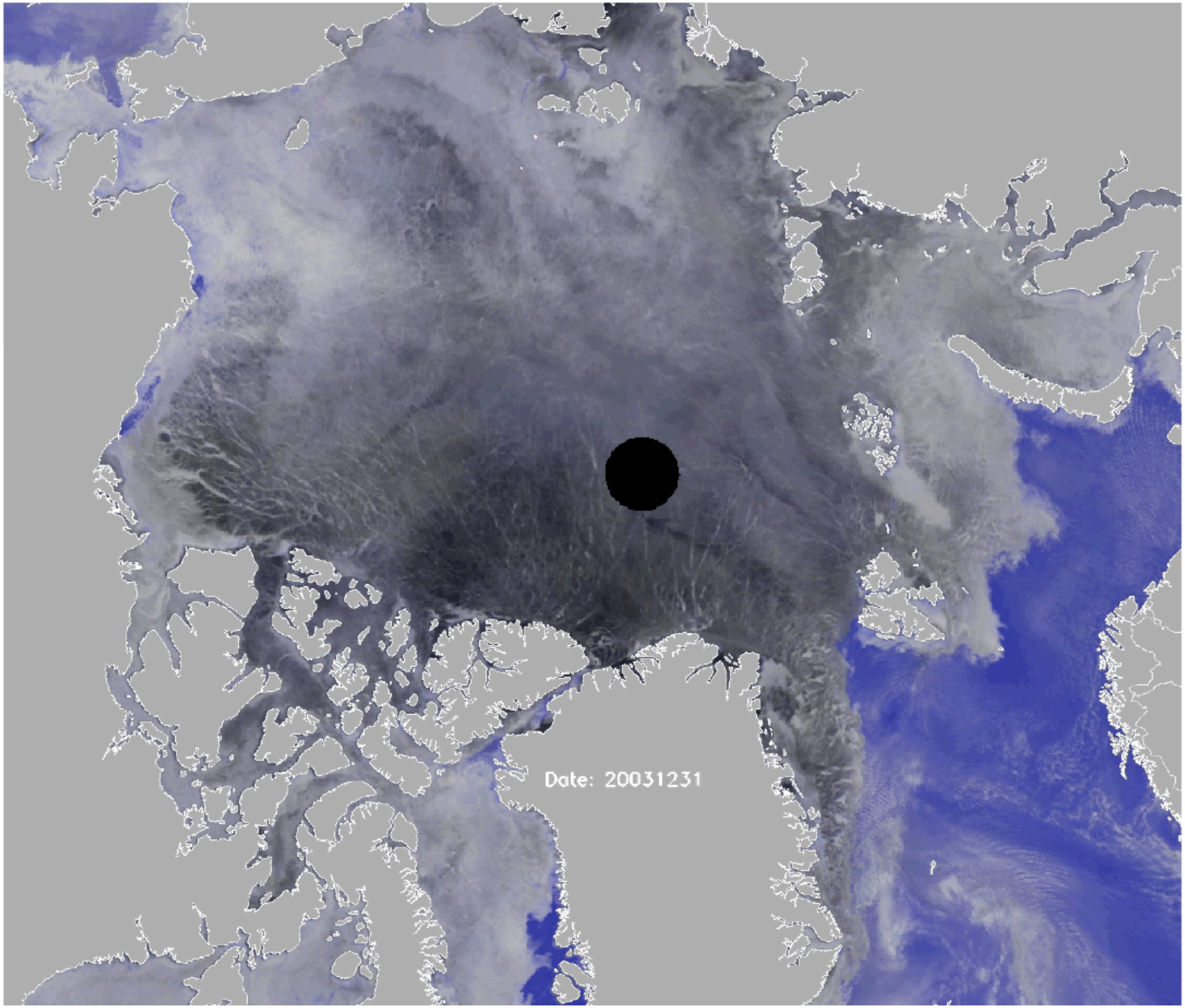
Simulating sea ice dynamics at high resolution

Martin Losch

with contributions from Nils Hutter (AWI),
Dimitris Menemenlis (JPL, NASA),
and Jean-François Lemieux (EC)

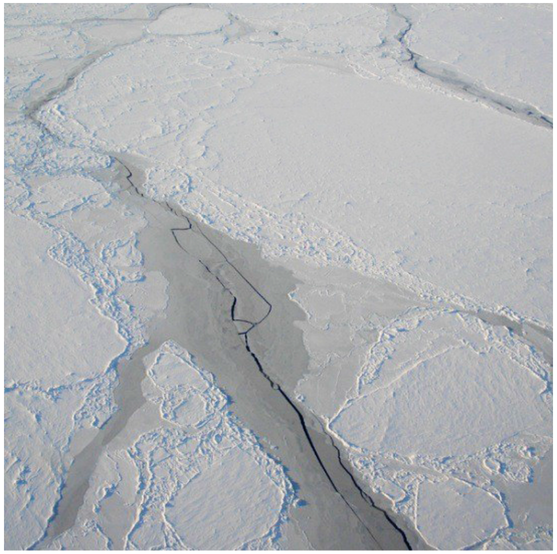
HELMHOLTZ
ASSOCIATION

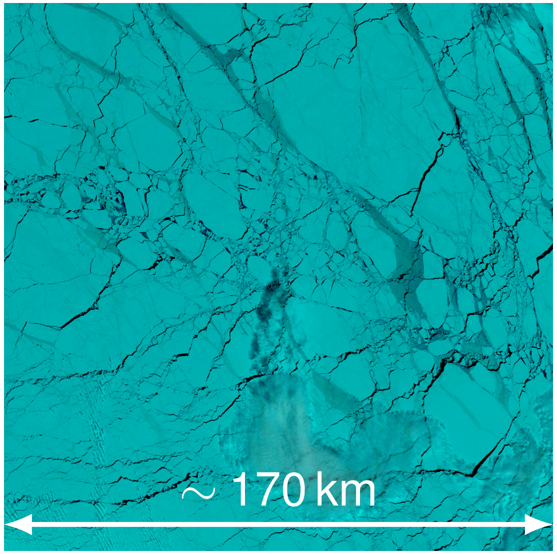
Arctic Sea ice from space

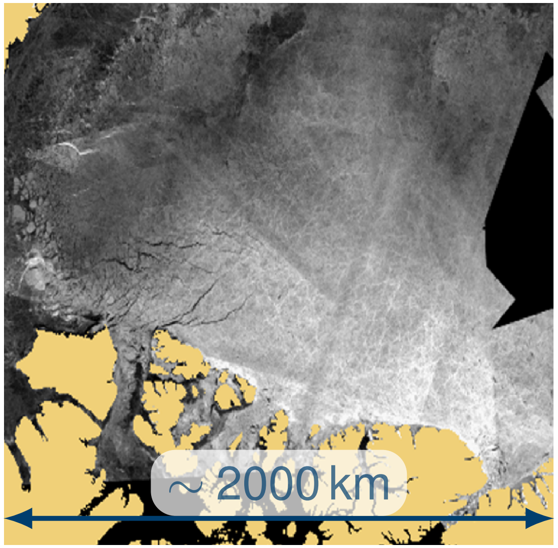


Animation by T. Agnew

Multiple scales of sea ice deformation







A different kind of satellite

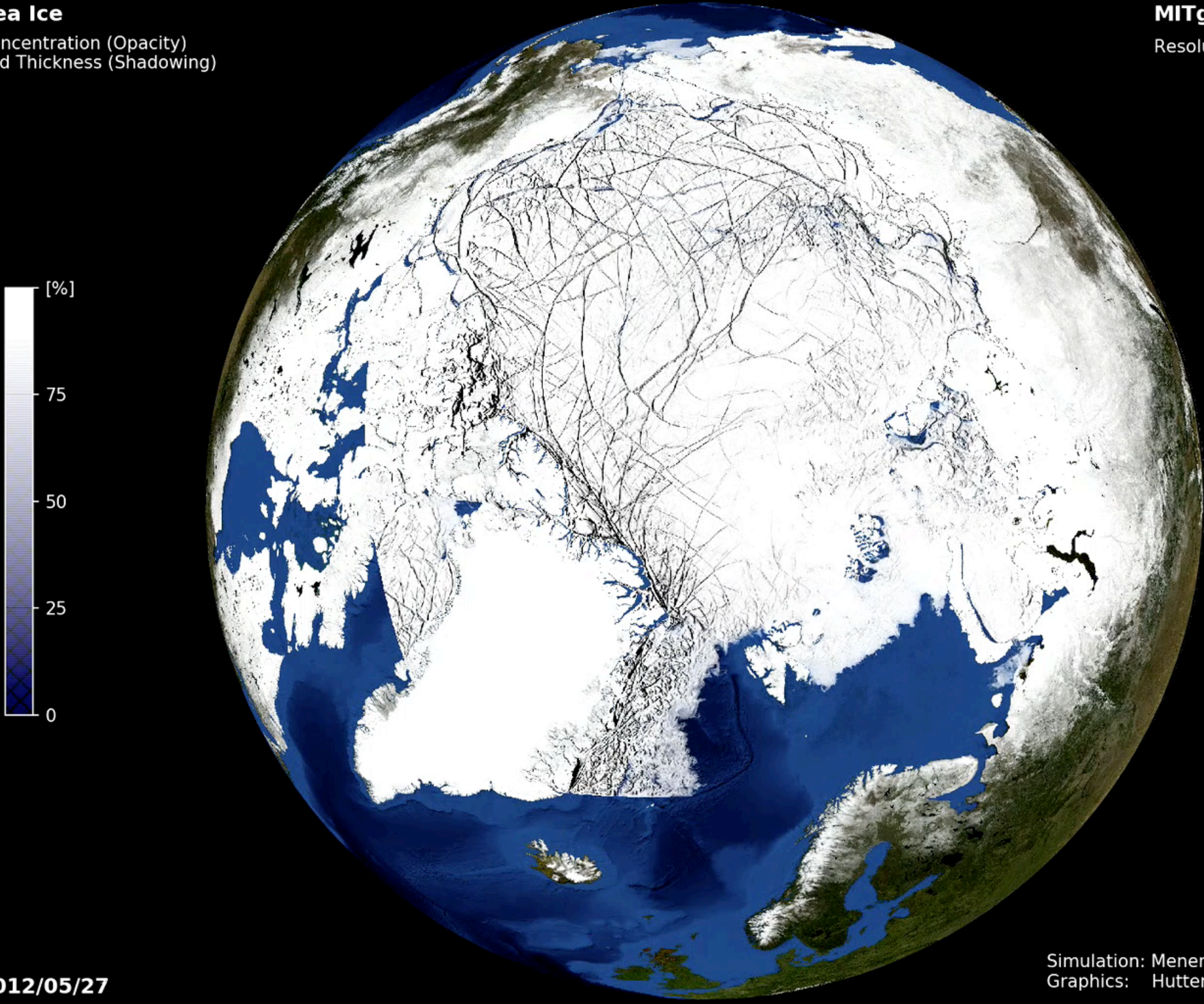
MITgcm at <1km grid spacing, Simulation: D. Menemenlis (JPL)

Sea Ice

Concentration (Opacity)
and Thickness (Shadowing)

MITgcm

Resolution (1km)



Simulation: Menemenlis (JPL)
Graphics: Hutter (AWI)

2012/05/27

this talk

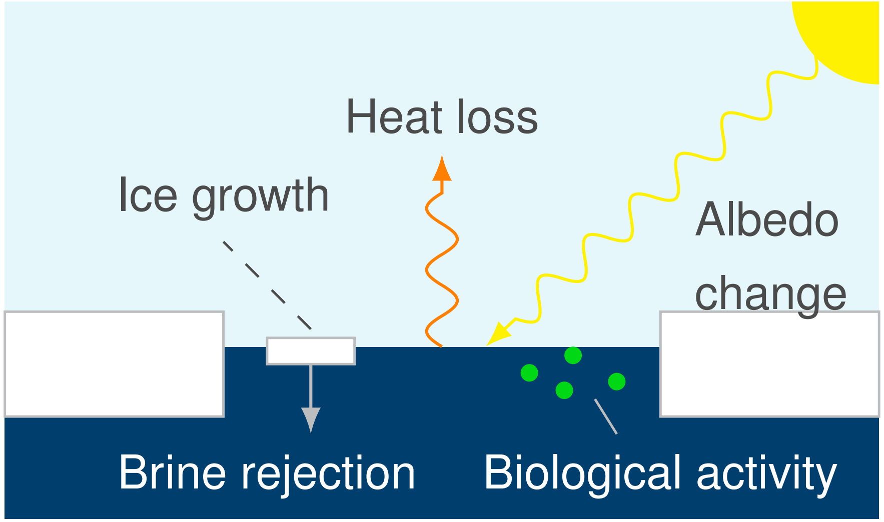
- are these new high-res simulations with old VP-rheology useful? realistic? (Hutter et al. 2018)

- explore properties of high-res VP dynamics: example land-fast ice

Why sea ice at high resolution?

Climate Modeling:

- Sea ice acts as an insulator between ocean and atmosphere
- Leads cover 5% of area but accommodate 50% of heat loss



Economic interest:

- exploration/exploitation of natural resources
- intensified shipping in the Arctic
- LKF forecast?

Why sea ice at high resolution?

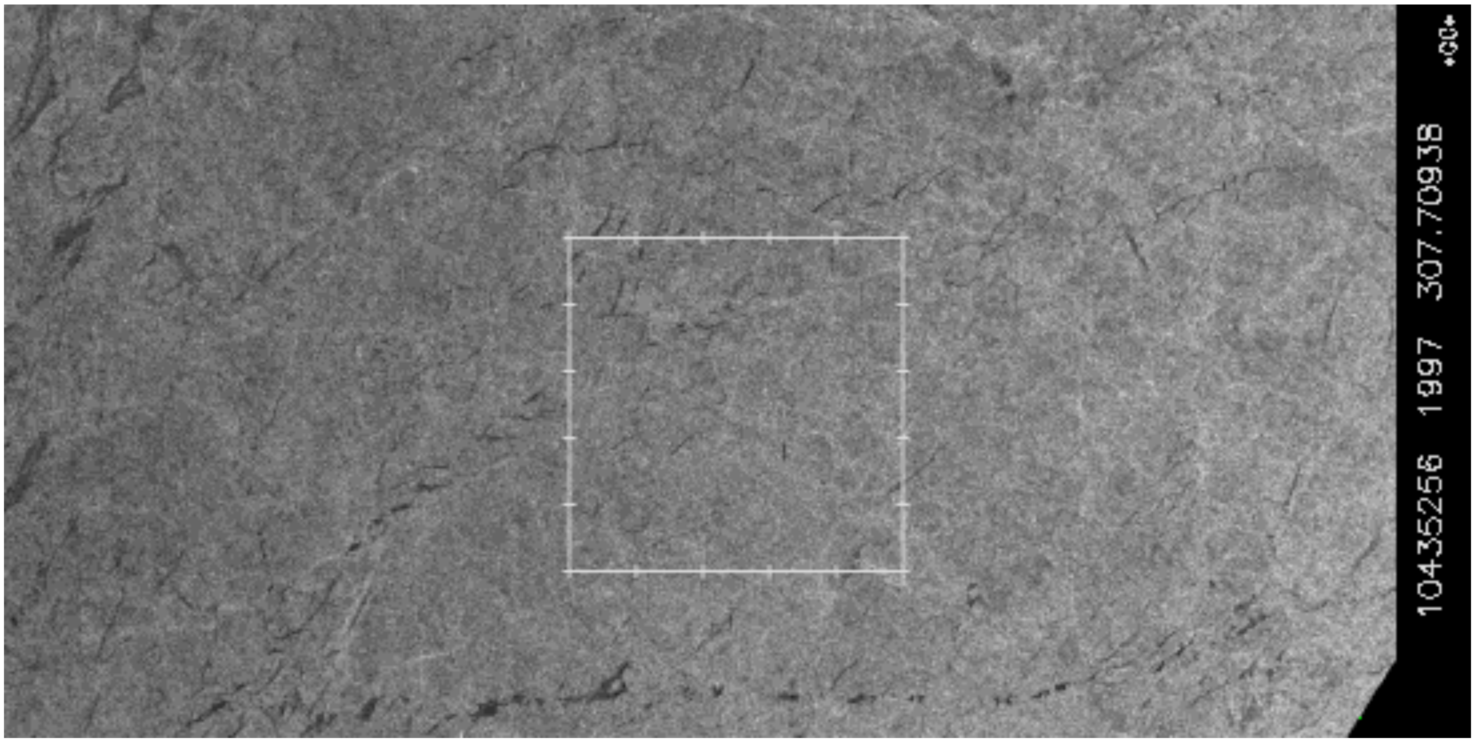
Climate Modeling:

- Sea ice acts as an insulator between ocean and atmosphere
- Leads cover 5% of area but accommodate 50% of heat loss

Economic interest:

- exploration/exploitation of natural resources
- intensified shipping in the Arctic
- LKF forecast?

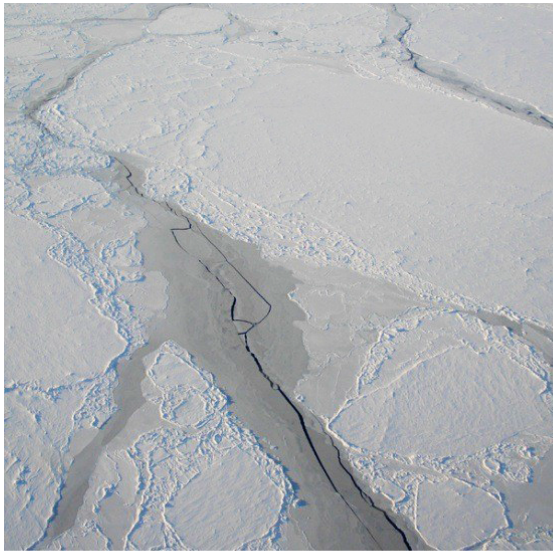
Sea Ice Deformation

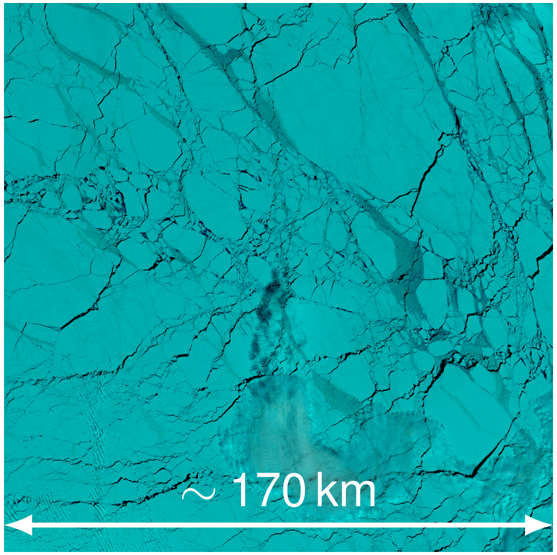


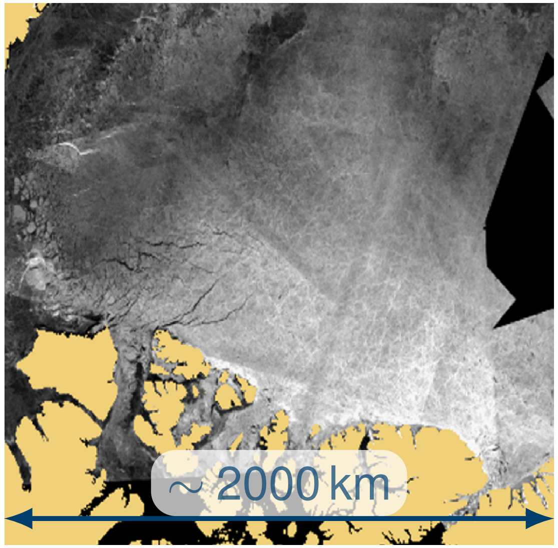
- RADARSAT sequence in the Beaufort Sea with focus on SHEBA camp (1997/1998)

Sea Ice Deformation

Linear Kinematic Features (LKFs):







What induces the stress in the ice cover?

Wind

Tides, Swell & Ocean Circulation

Sea ice as a quasi-continuous fluid with Viscous-Plastic (VP) rheology

2D momentum equations for sea ice (Hibler 1979):

$$m\frac{D\mathbf{u}}{Dt} = -m\, f\, \mathbf{k} \times \mathbf{u} + \boldsymbol{\tau}_a - \boldsymbol{\tau}_o + m\, g\, \nabla H + \nabla \cdot \boldsymbol{\sigma}$$

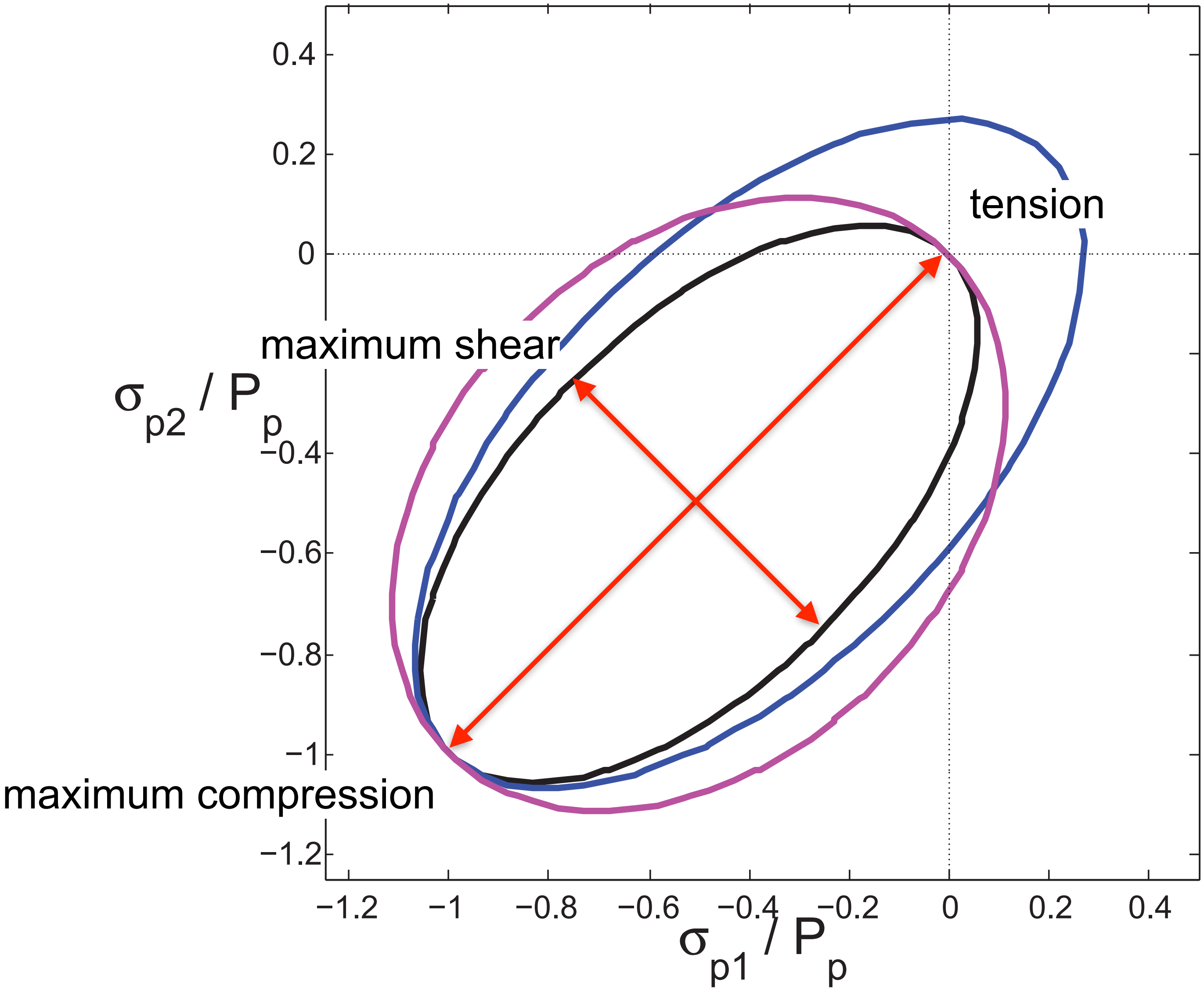
requires relation between internal stress tensor and velocity vector ⇒ Rheology $\boldsymbol{\sigma}(\boldsymbol{\epsilon})$

Material properties of sea ice:

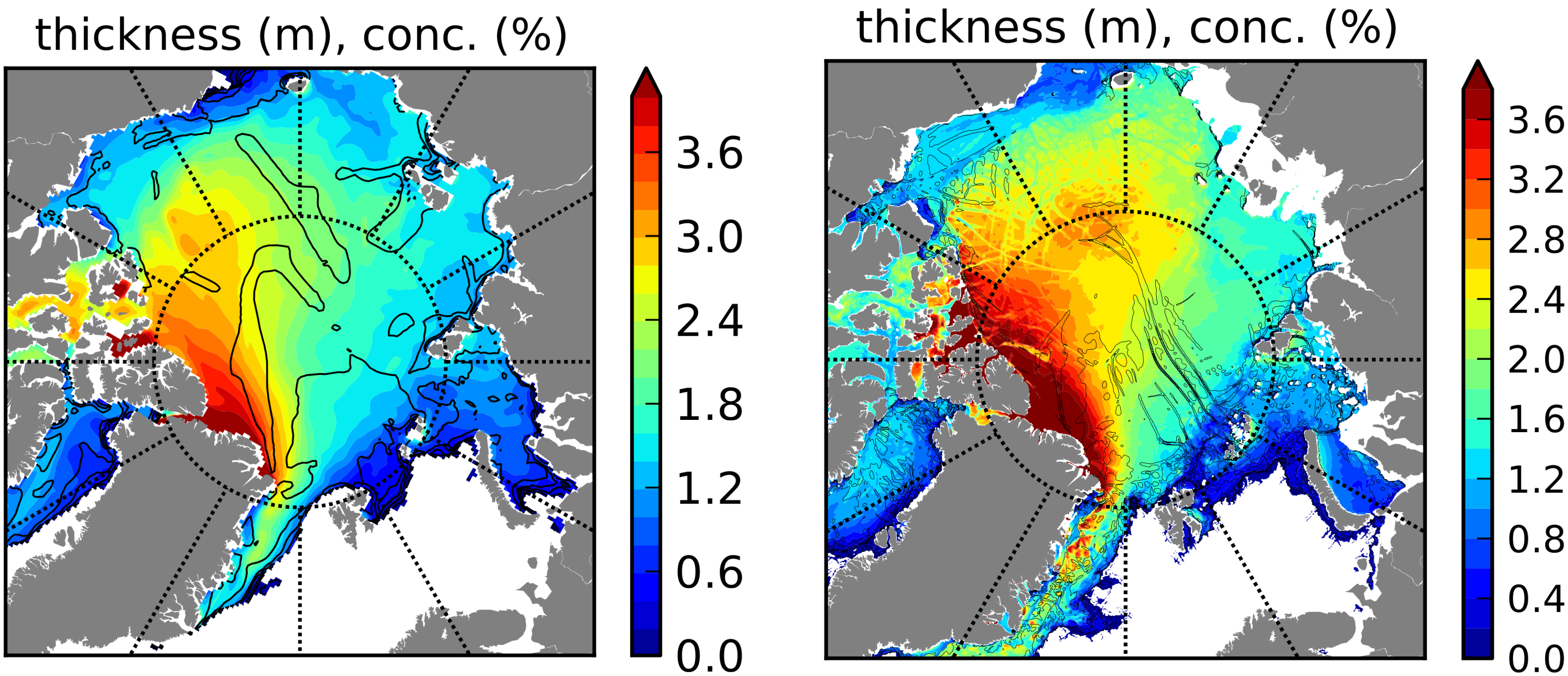
- weak in tension (divergence)
- strongest in compression (convergence)
- strong in shear

Collection of plastic ice floes leads to on average viscous behavior (Hibler, 1977)

principle stress plane



Increasing the resolution

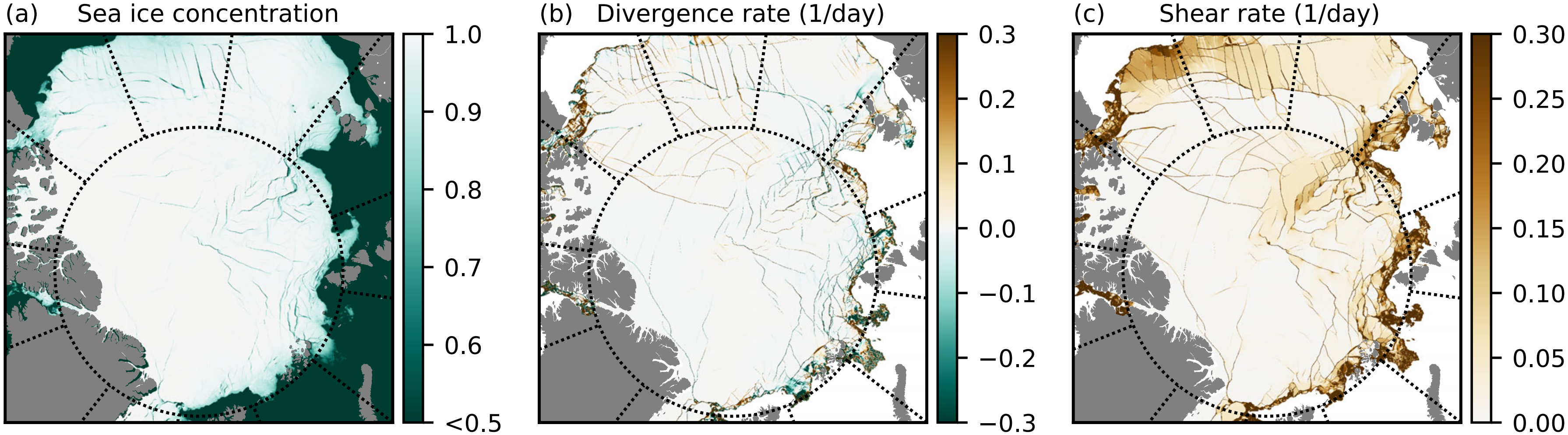


(a) resolution: 27 km

(b) resolution: 4.5 km

Sea ice thickness (color) and sea ice concentration (contour lines) from a sea ice model (Losch et al., 2014)

1km-model snapshots on Sep21, 2011



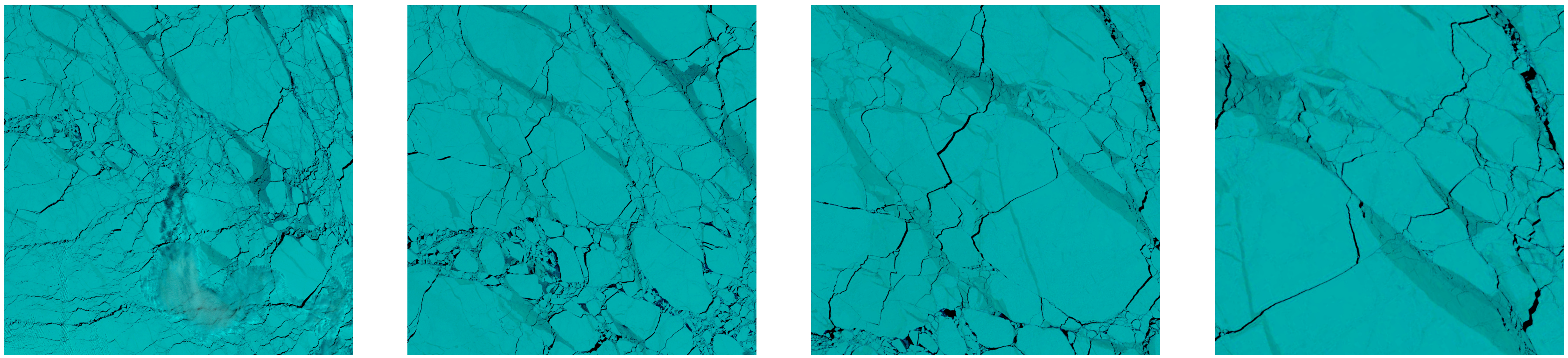
strain rate tensor components $$\dot{\epsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\text{divergence rate} = \dot{\epsilon}_{11} + \dot{\epsilon}_{22}$$

$$\text{shear rate} = \sqrt{(\dot{\epsilon}_{11} - \dot{\epsilon}_{22})^2 + 4\dot{\epsilon}_{12}^2}$$

Spacial Scaling of Sea Ice Deformation

Figure: LANDSAT 8 false color image showing sea ice in the Beaufort Sea in spring (U.S. Geological Survey)

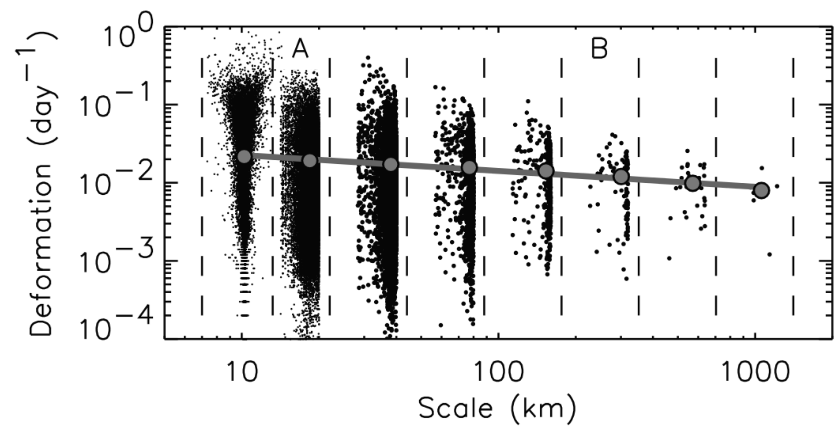


(a) 170 km (b) 85 km (c) 42.5 km (d) 21.25 km

- **Multi fractal** characteristics
- Spatial scaling laws (Marsan et al., 2004):

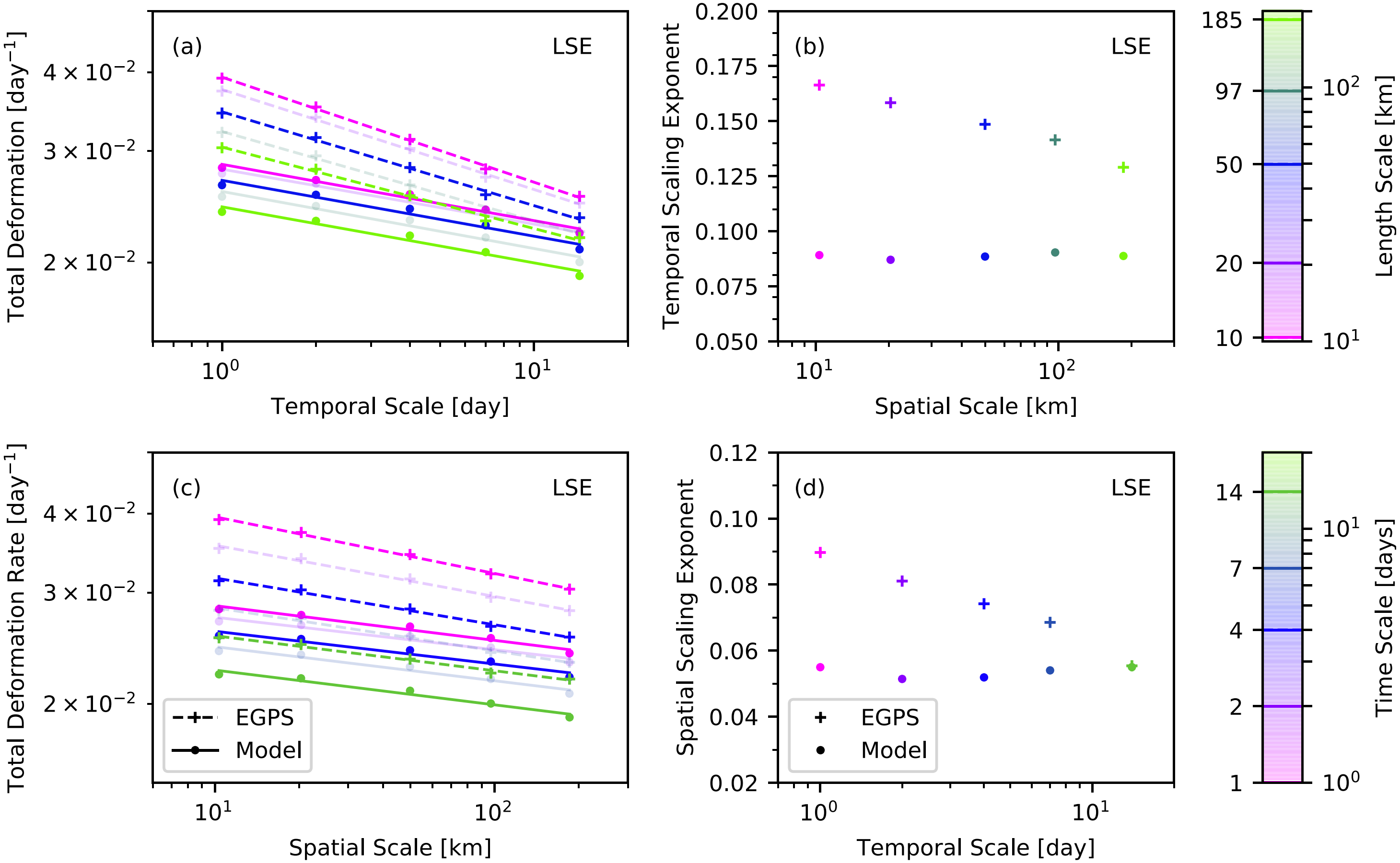
$$\langle \dot{\varepsilon}_L \rangle \sim L^{-H} \qquad (3)$$

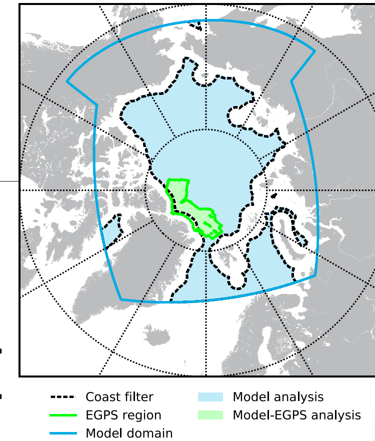
with $H = 0.20 \pm 0.01$



in comparison to EGPS data

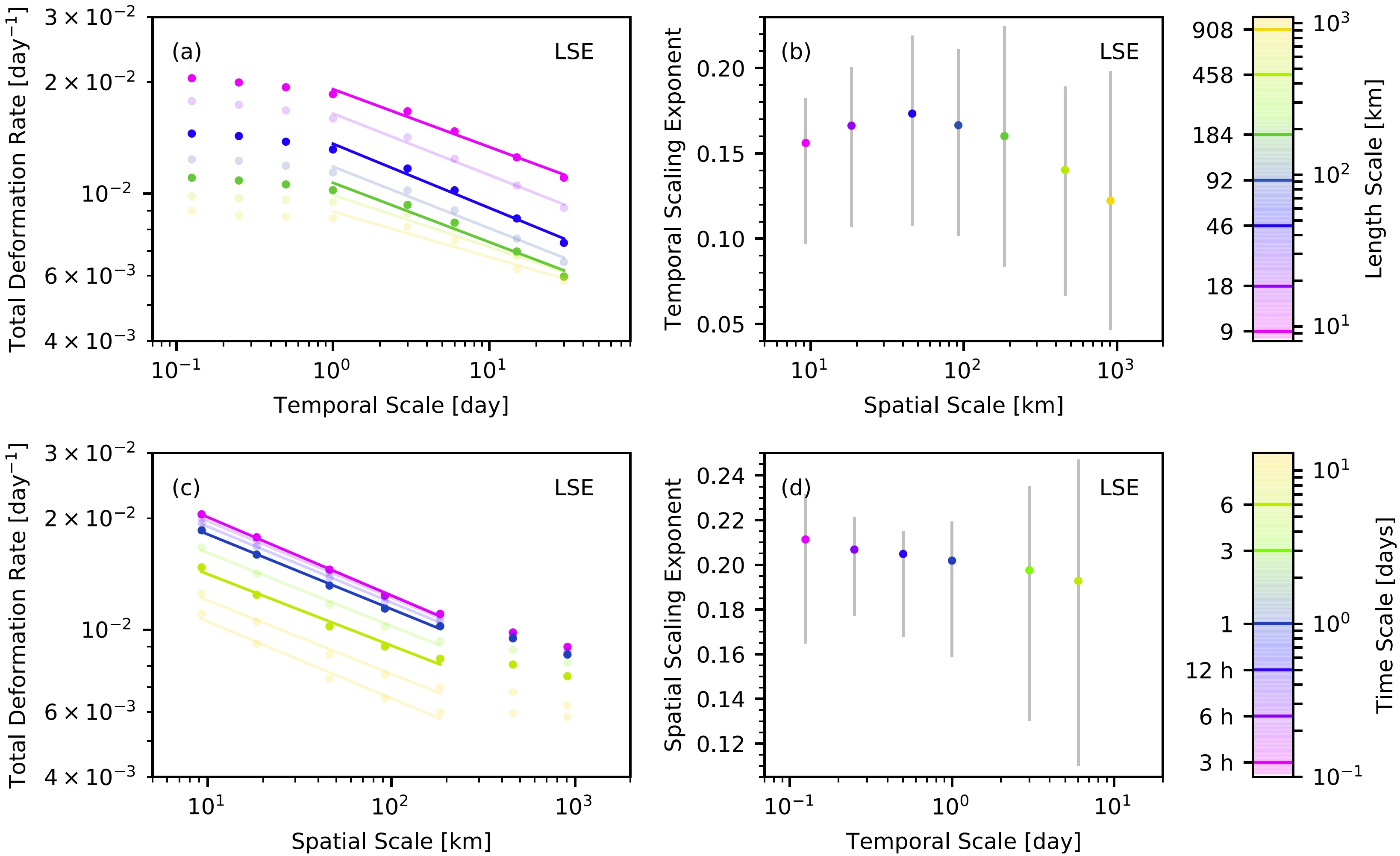
Hutter et al. (2018)





- heterogeneity OK for large (10day) time scales
- low intermittency (Hutter et al., 2018)

Pan-Arctic model data



- coupling of spatial and temporal scaling (Hutter et al., 2018)

Summary so far

- Sea ice deformation localizes along lines in high-resolution viscous-plastic sea ice models

- The model reproduces spatial scaling properties as observed in satellite data (heterogeneity OK)

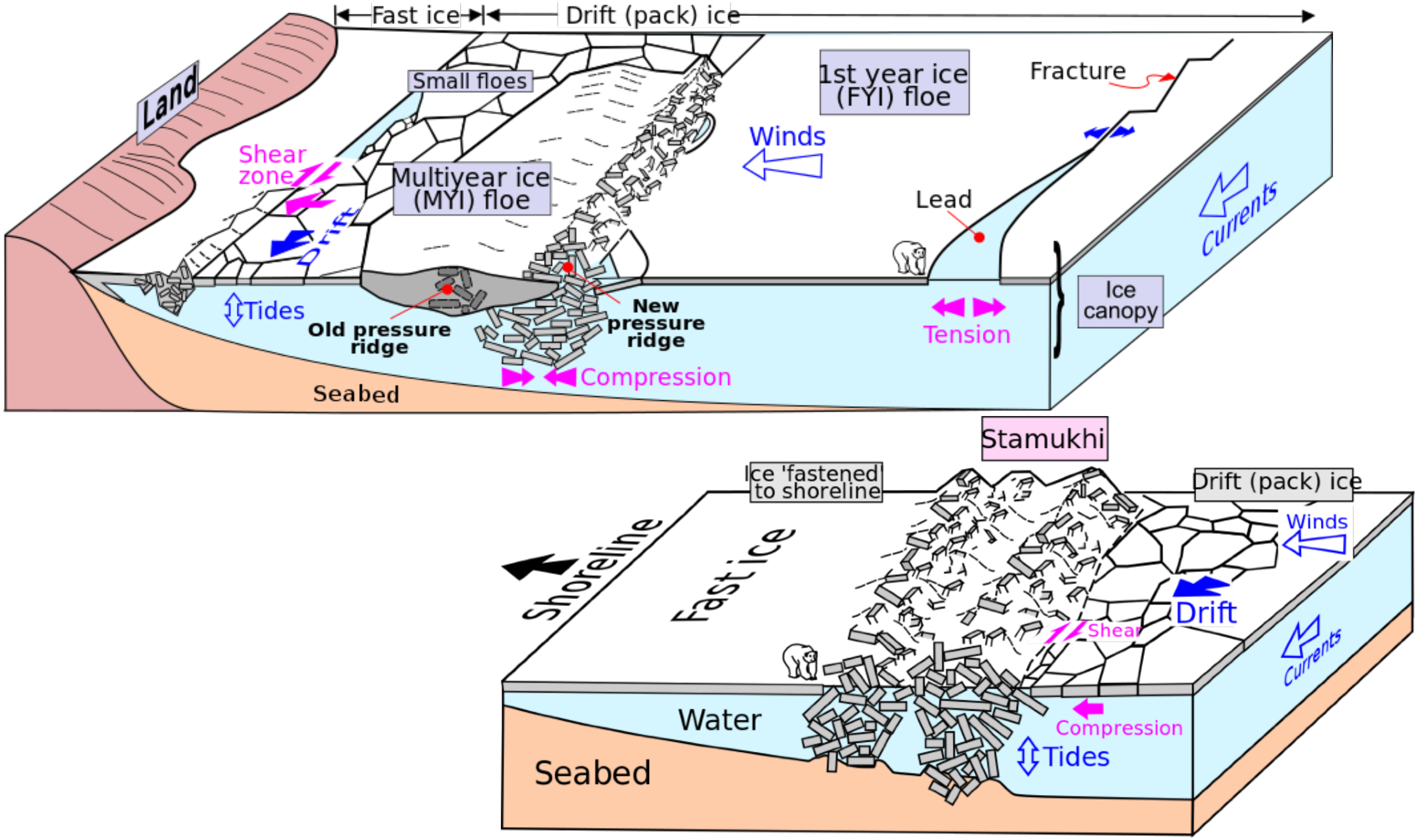
- The model underestimates temporal scaling compared to satellite data (intermittency of deformation events too low)

Land-fast ice at high resolution

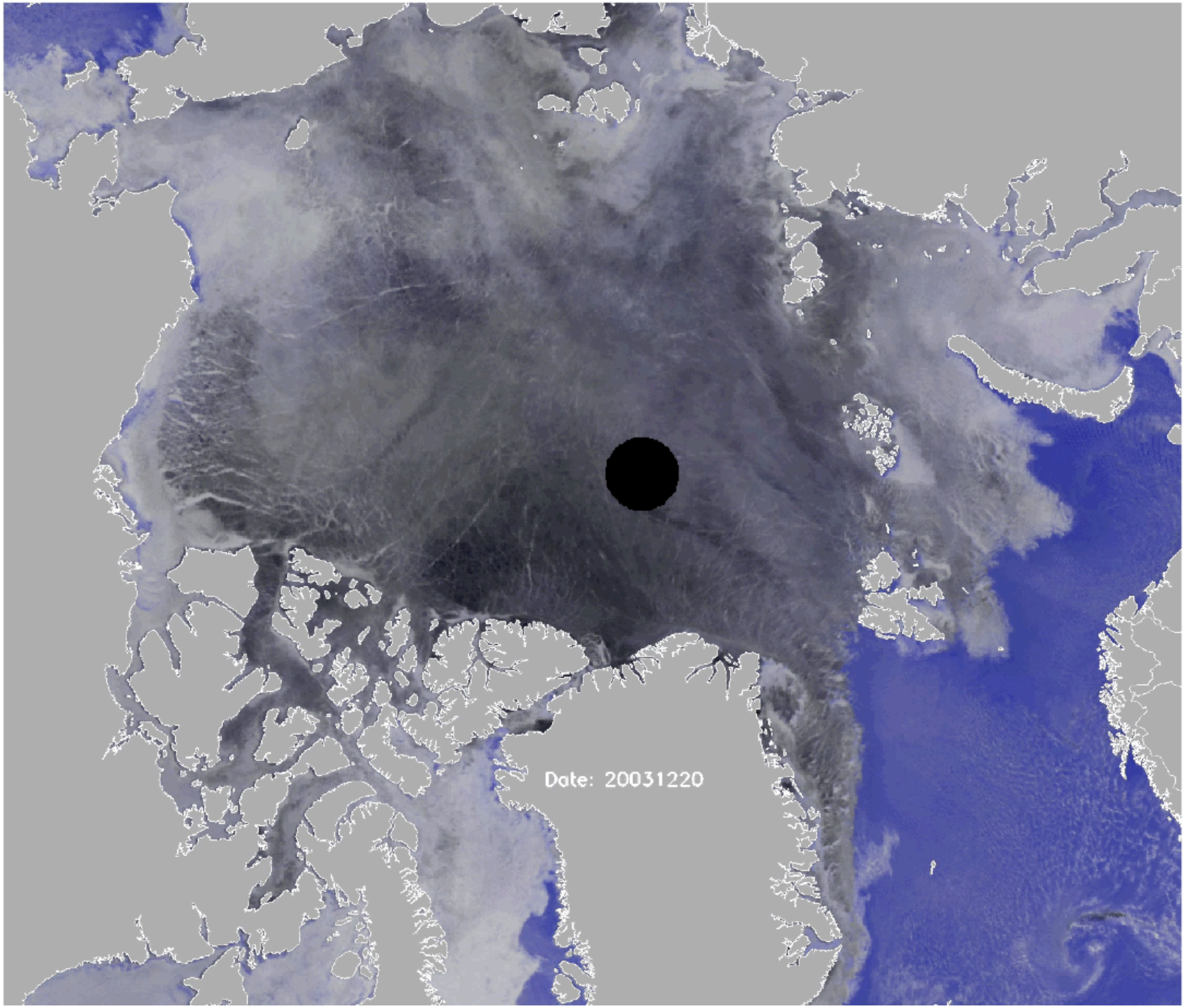
Martin Losch (AWI)
Jean-François Lemieux (EC)

- What is land-fast ice? Why is it important?
- land-fast ice and models, problems and solutions
- parameterizations and resolution

What is fast ice? Why is it important?

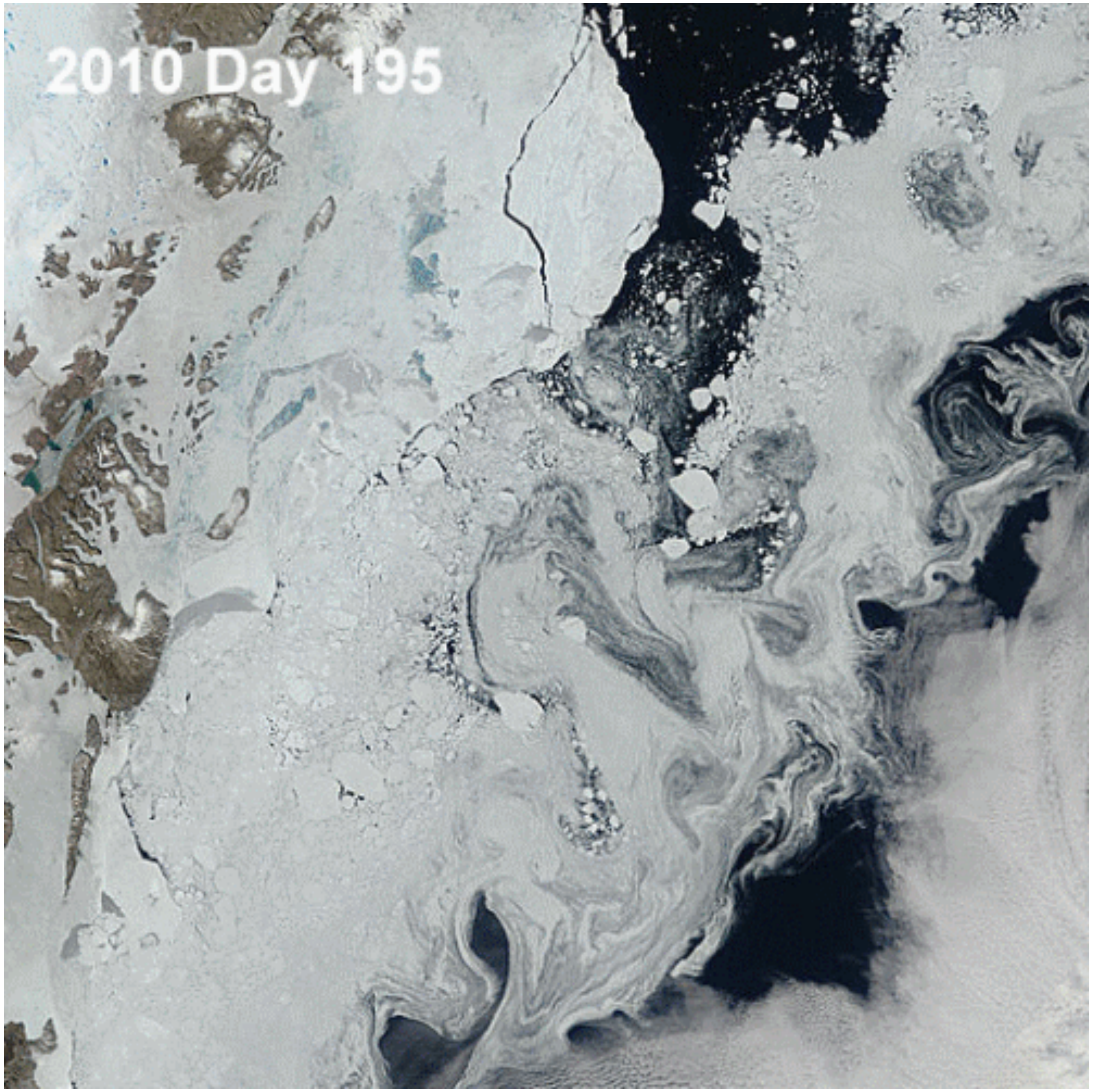


Arctic Sea ice from space



Animation by T. Agnew

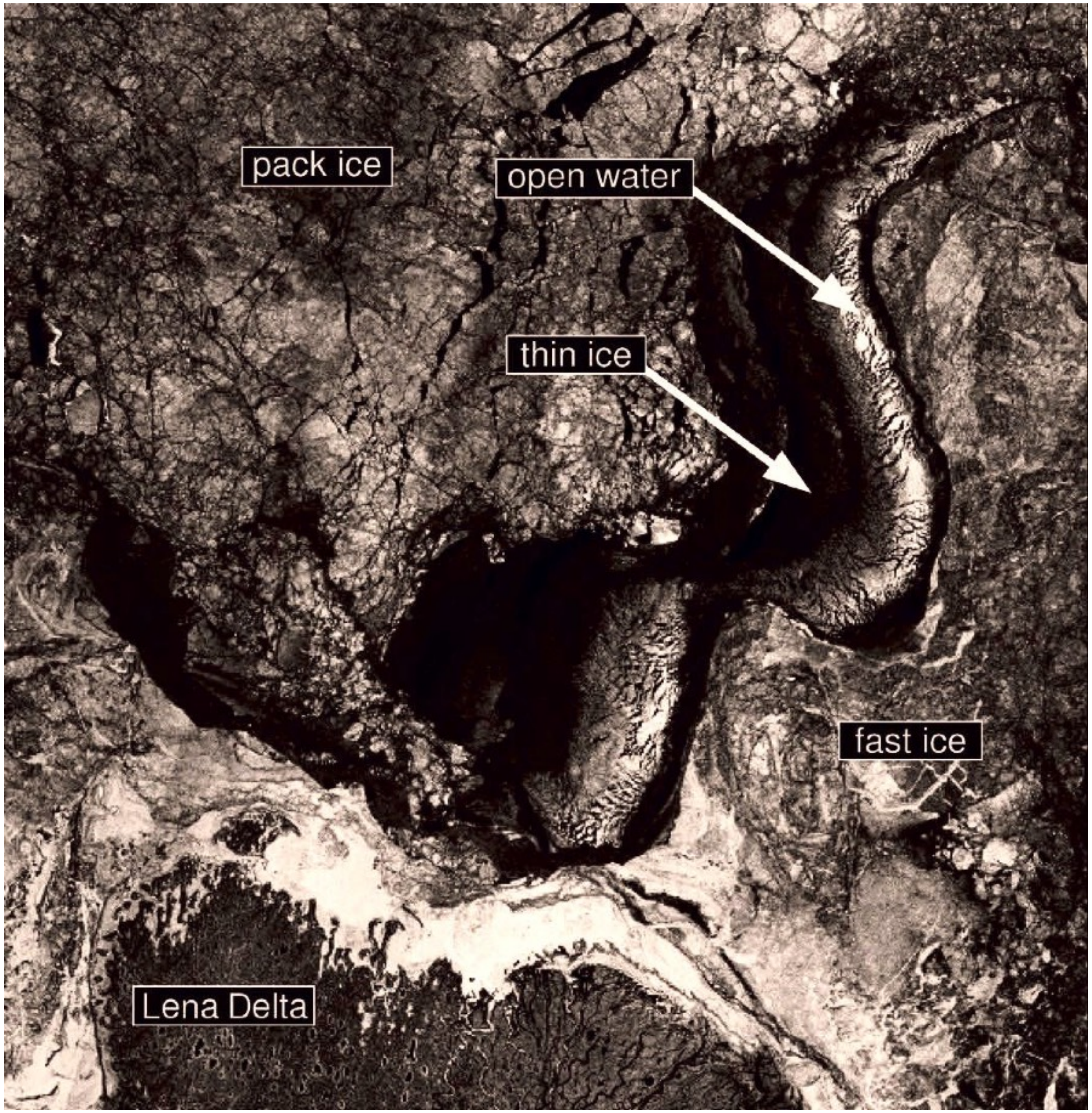
Fast ice example



Greenland's east coast near Zachariae and 79N Glaciers

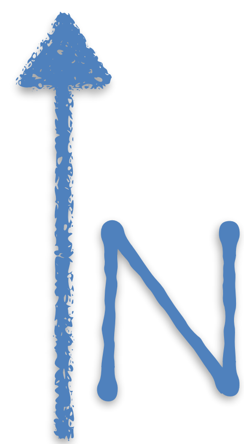
(Source: Arctic Sea ice blog)

False Polynyas



ASAR satellite image
(30 April 2008),
south-eastern Laptev Sea

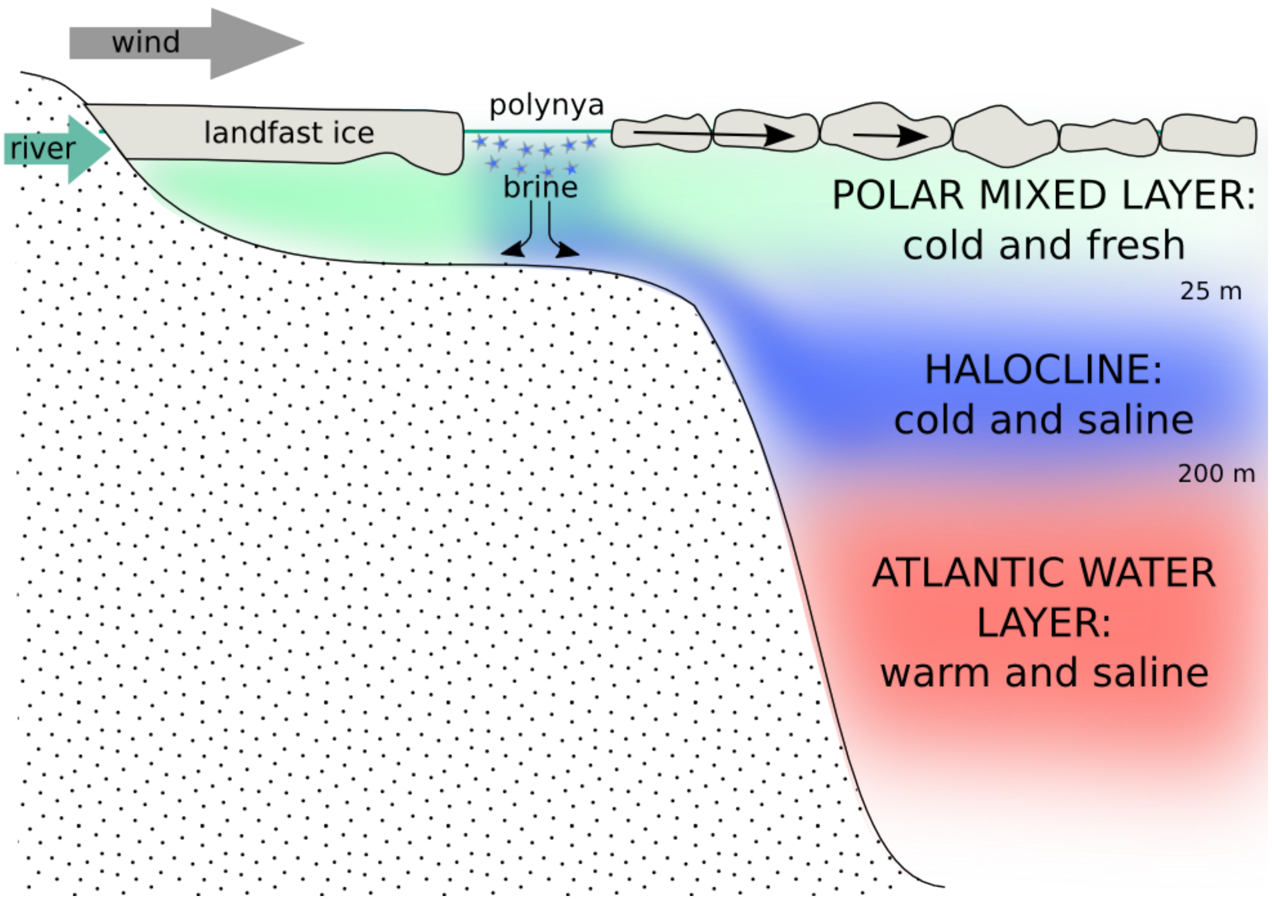
(from Rozman et al. 2011)



It matters: example fluxes

Photo: Christof Lüpkes, AWI

False Polynyas matter



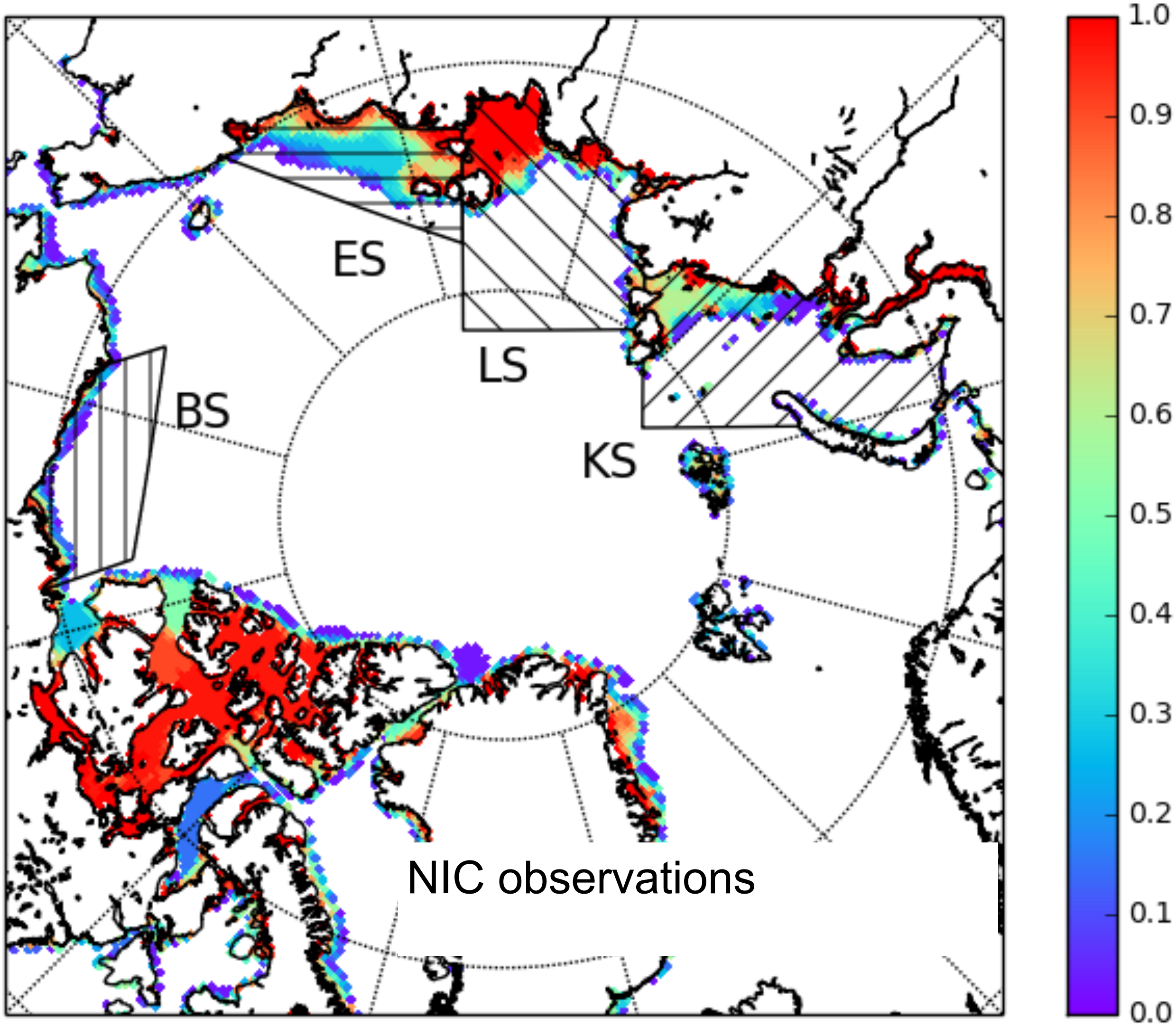
Itkin et al. (2015): position of false polynya in Laptev Sea has an effect on the water mass distribution in the central Arctic

mechanisms

- grounding (in shallow shelf seas)
- static arching (pinned between coastlines and islands or shallows?)

- how much of this is in standard visco-plastic models (Hibler 1979)?
- (usually models don’t get it right)

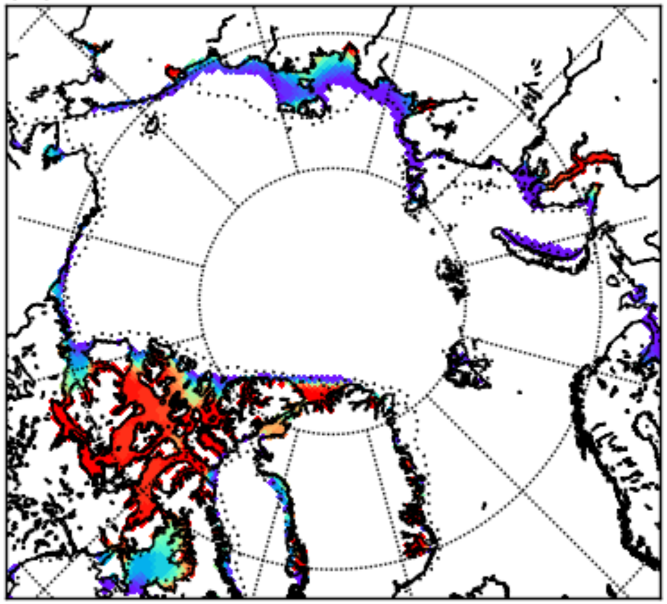
Observations and model



http://nsidc.org/data/docs/noaa/g02172_nic_charts_climo_grid/

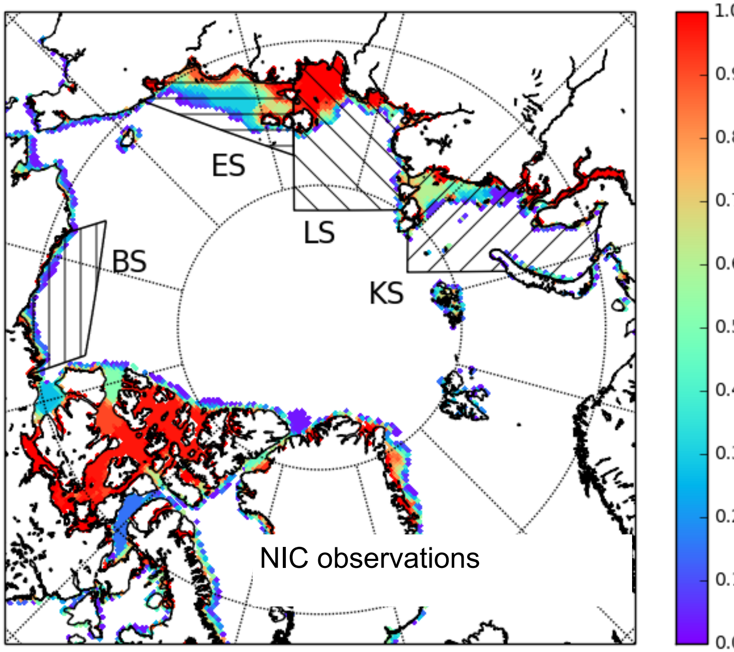
Observations and model

(a) default



numerical model (MITgcm)
36km grid spacing

Frequency of occurrence of land-fast ice for January-May for the years 2005, 2006 and 2007, reproducing Lemieux et al. (2016).



http://nsidc.org/data/docs/noaa/g02172_nic_charts_climo_grid/

Sea ice as a quasi-continuous fluid with Visous-Plastic (VP) rheology

2D momentum equations for sea ice (Hibler 1979):

$$m\frac{D\mathbf{u}}{Dt} = -m\,f\,\mathbf{k}\times\mathbf{u} + \boldsymbol{\tau}_a - \boldsymbol{\tau}_o + m\,g\,\nabla H + \nabla\cdot\boldsymbol{\sigma}$$

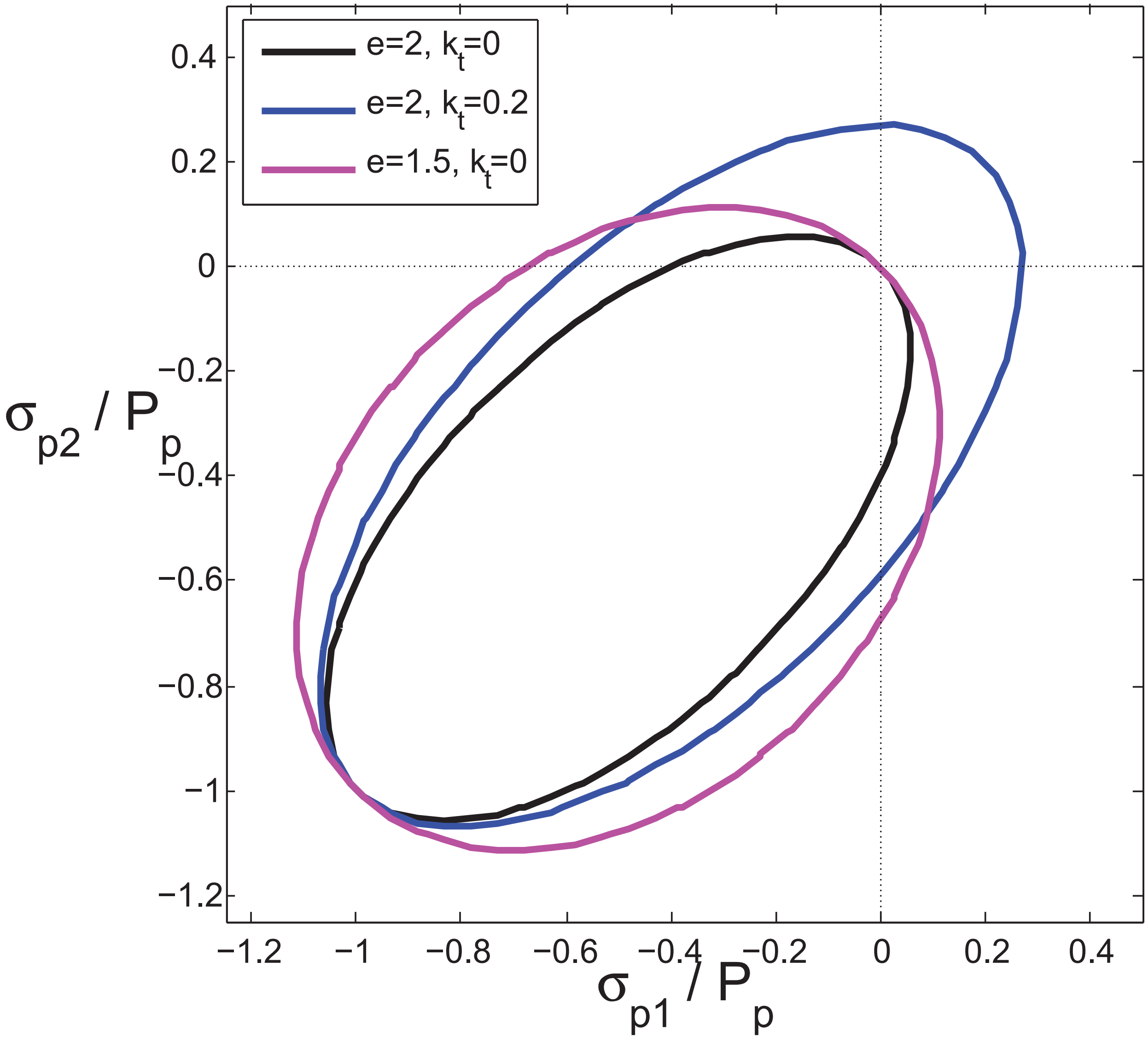
requires relation between internal stress tensor and velocity vector ⇒ Rheology $\boldsymbol{\sigma}(\boldsymbol{\epsilon})$

Material properties of sea ice:

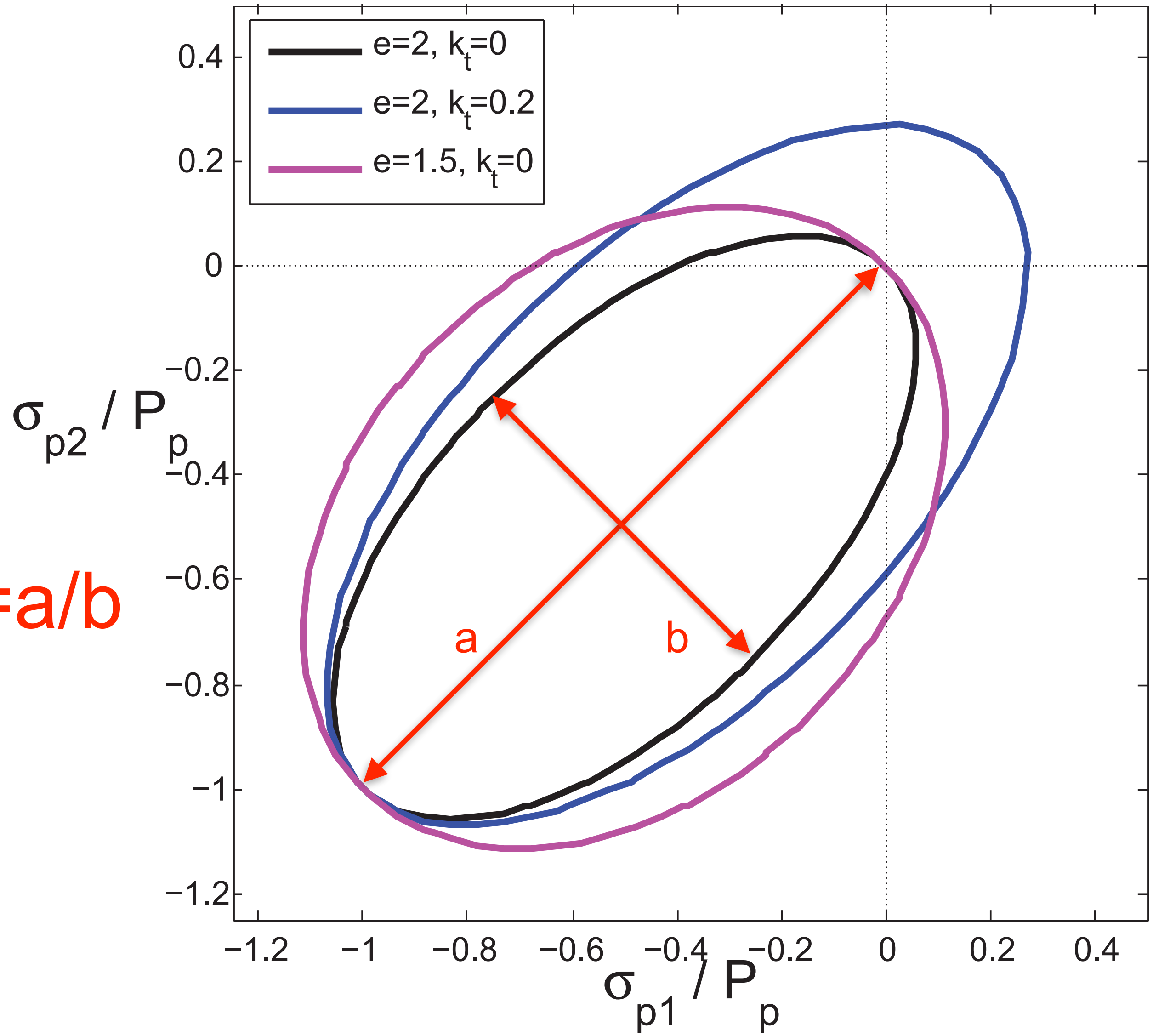
- weak in tension (divergence)
- strongest in compression (convergence)
- strong in shear

Collection of plastic ice floes leads to on average viscous behavior (Hibler, 1977)

previous work



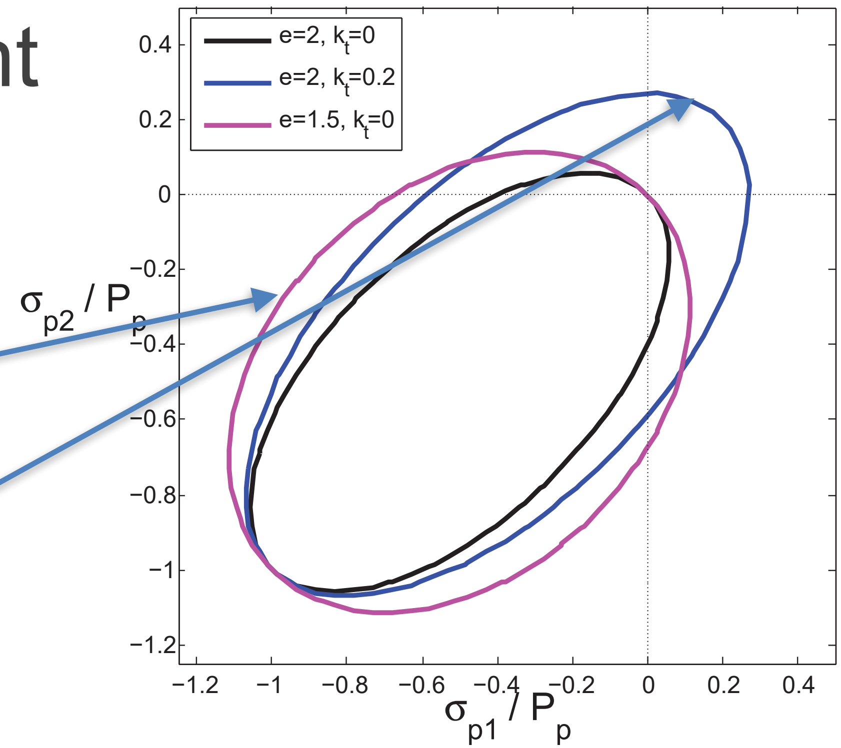
previous work



e=a/b

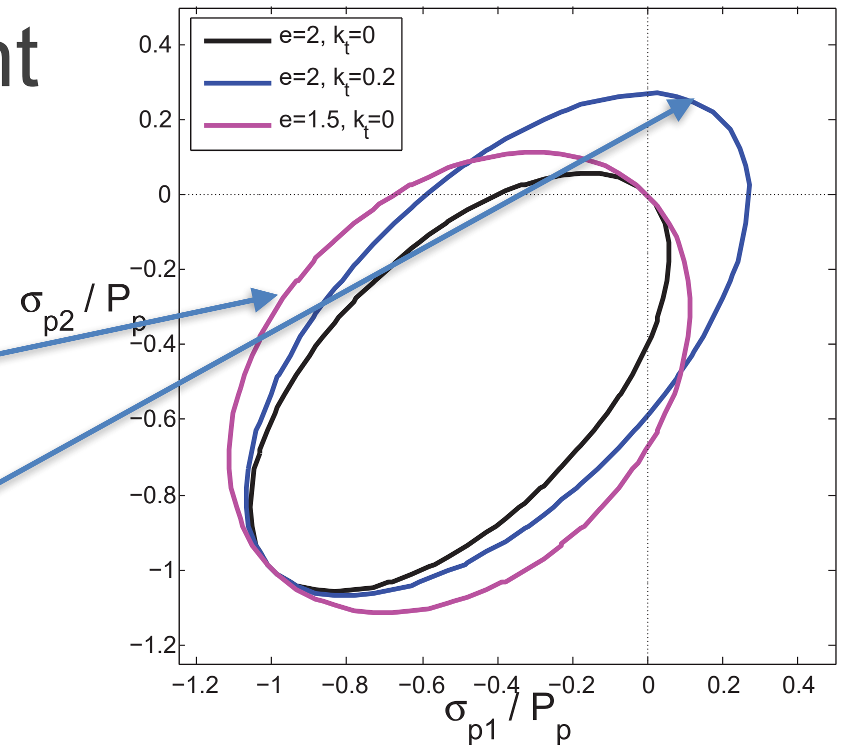
previous work

- tensile strength (Dumont et al. 2007, Itkin et al 2015, Olason 2016)
  - uniaxial (param *e*)
  - isotropic (param k_t)



previous work

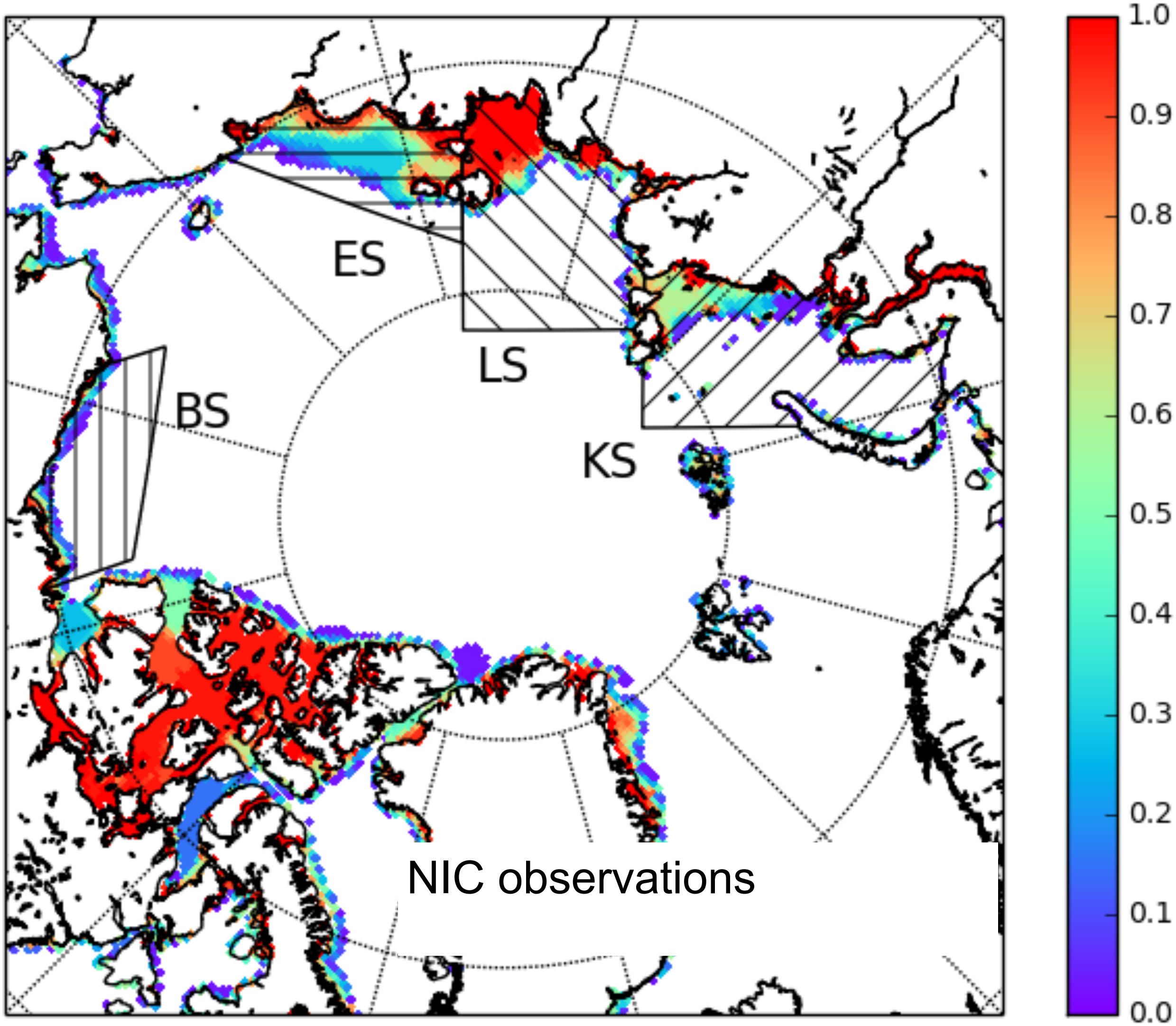
- tensile strength (Dumont et al. 2007, Itkin et al 2015, Olason 2016)
  - uniaxial (param *e*)
  - isotropic (param k_t)



- bottom drag (Lemieux et al 2015)

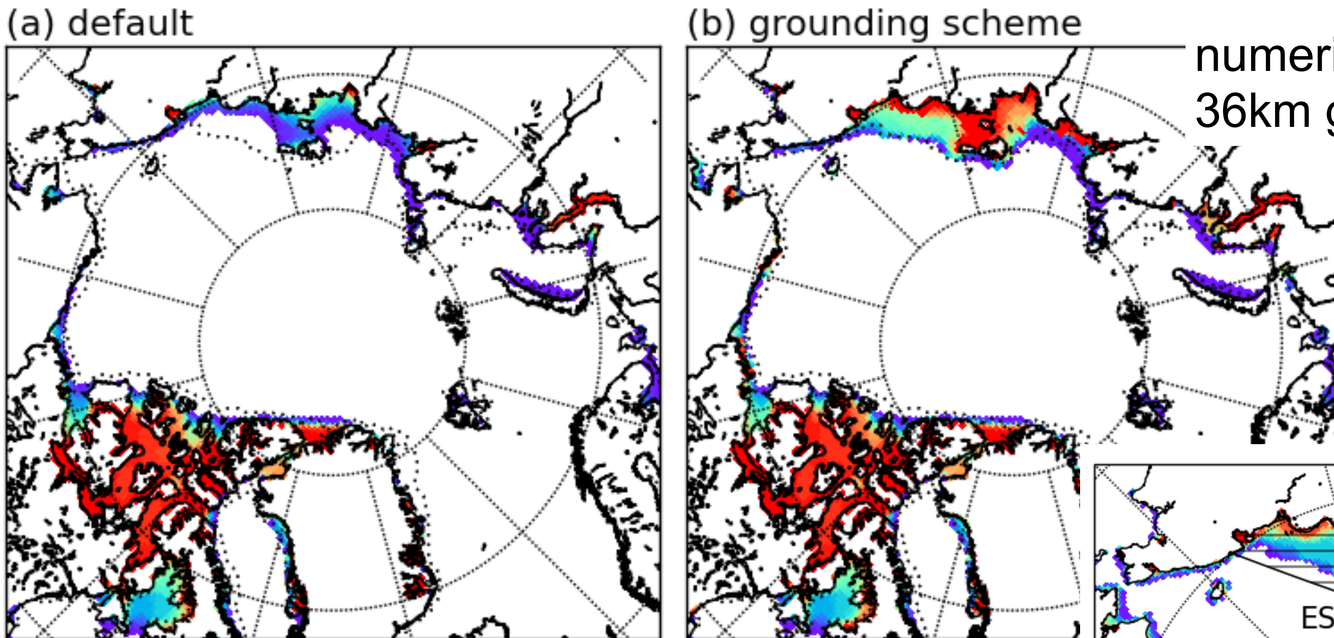
$$\tau_{\mathbf{b}} = \begin{cases} 0 & \text{if } h \leq h_c, \\ k_2 \left(\frac{-\mathbf{u}}{|\mathbf{u}|+u_0} \right) (h - h_c) \exp^{-\alpha_b(1-A)} & \text{if } h > h_c, \end{cases}$$

Observations and model



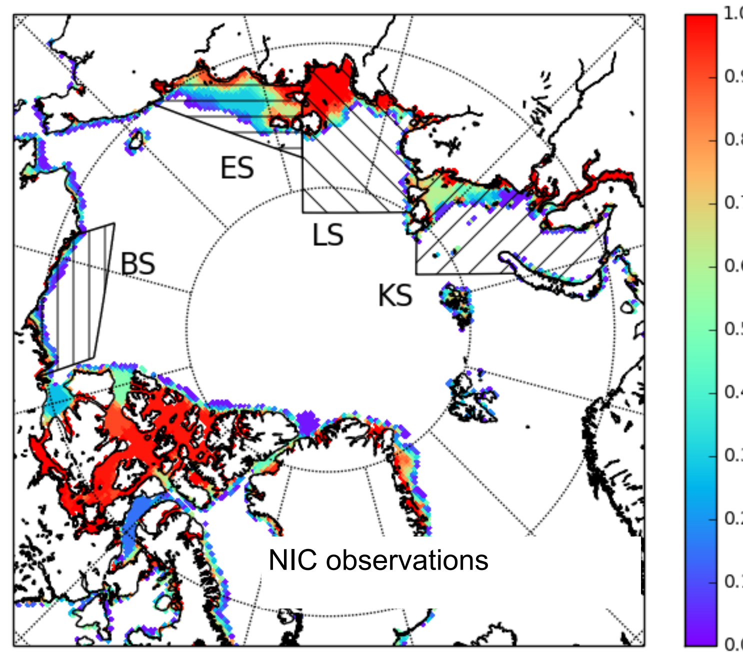
http://nsidc.org/data/docs/noaa/g02172_nic_charts_climo_grid/

Observations and model



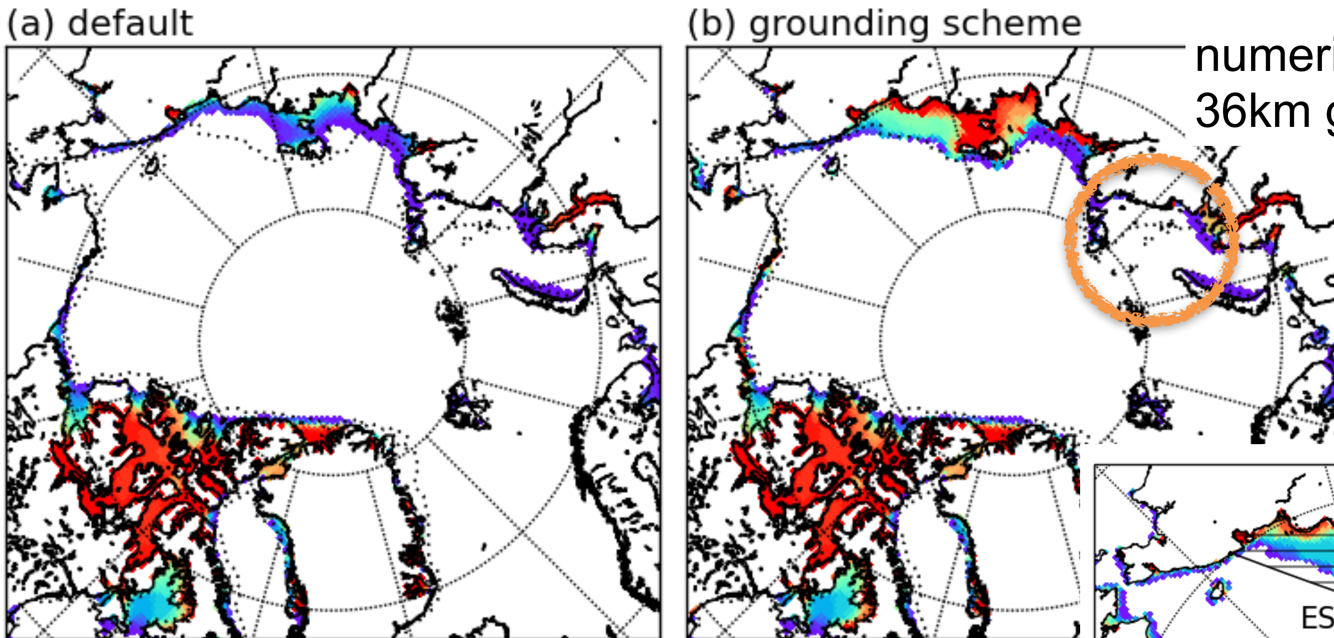
numerical model (MITgcm)
36km grid spacing

Frequency of occurrence of land-fast ice for January-May for the years 2005, 2006 and 2007, simulation without and with explicit parameterization of grounding (Lemieux et al., 2015), reproducing Lemieux et al. (2016).

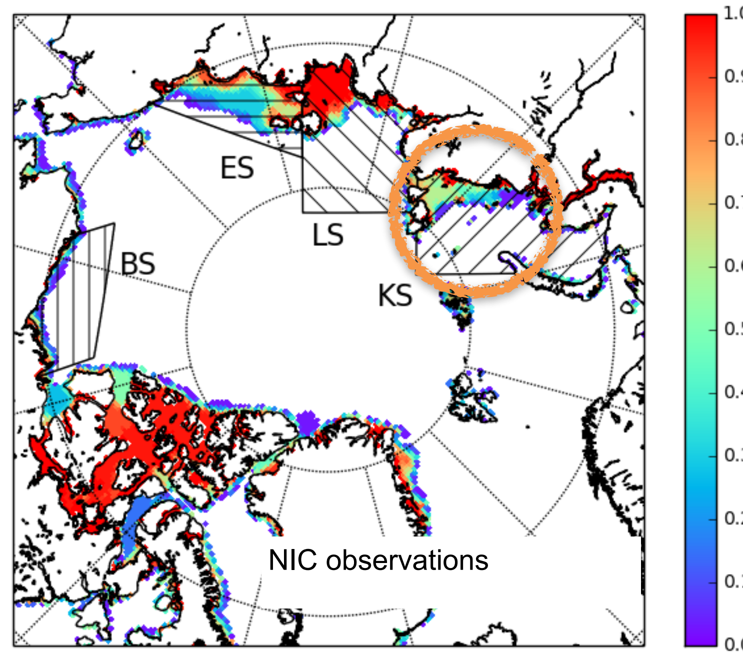


http://nsidc.org/data/docs/noaa/g02172_nic_charts_climo_grid/

Observations and model



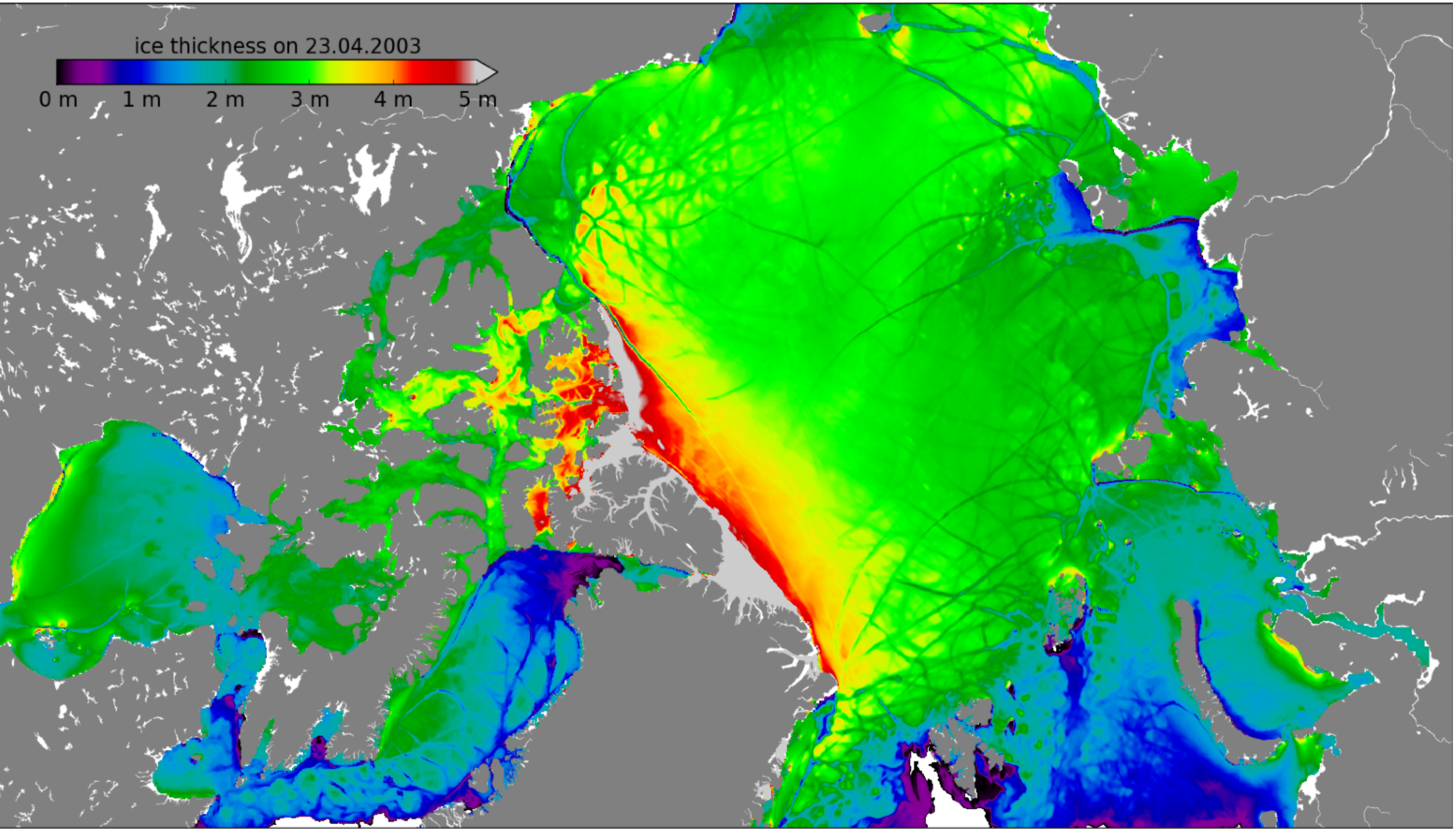
numerical model (MITgcm)
36km grid spacing



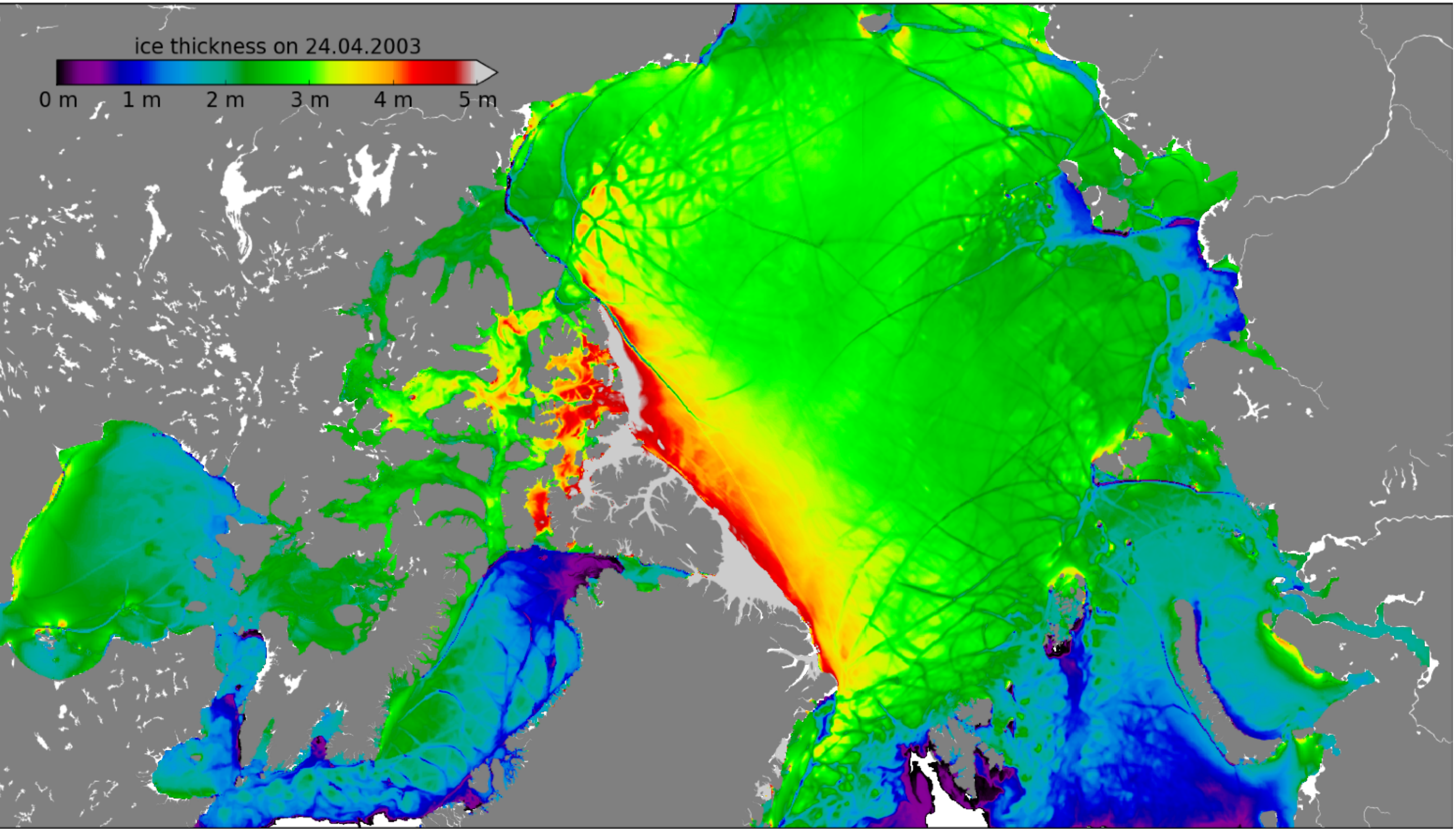
Frequency of occurrence of land-fast ice for January-May for the years 2005, 2006 and 2007, simulation without and with explicit parameterization of grounding (Lemieux et al., 2015), reproducing Lemieux et al. (2016).

http://nsidc.org/data/docs/noaa/g02172_nic_charts_climo_grid/

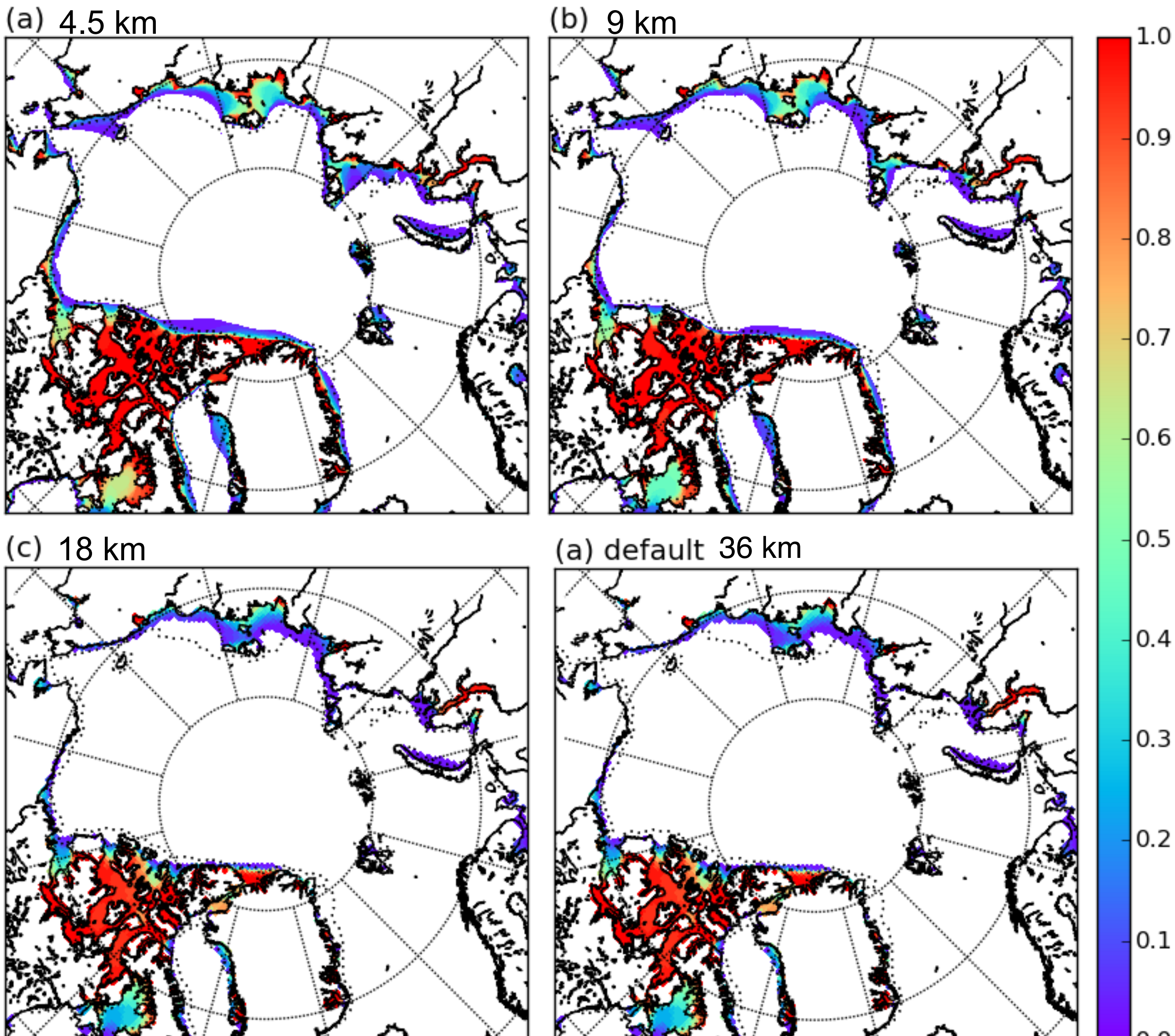
4.5km VP simulations

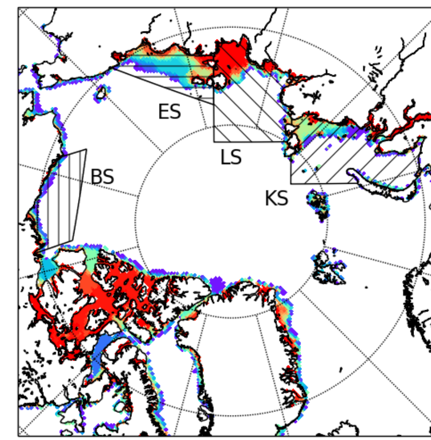


4.5km VP simulations



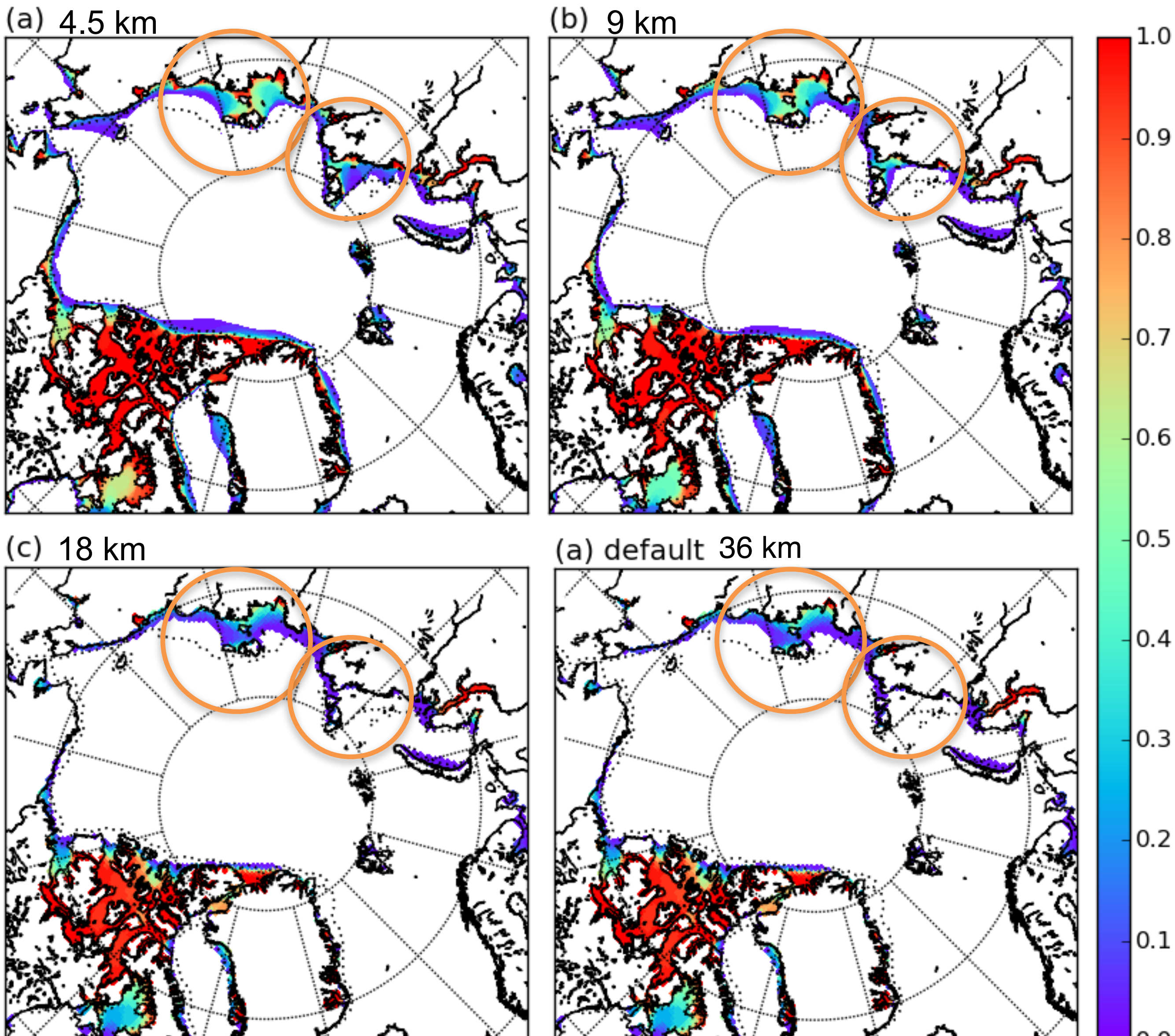
Resolution (w/out parameterization)

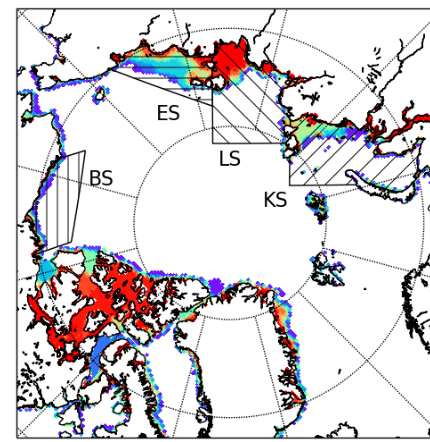




NIC observations

Resolution (w/out parameterization)

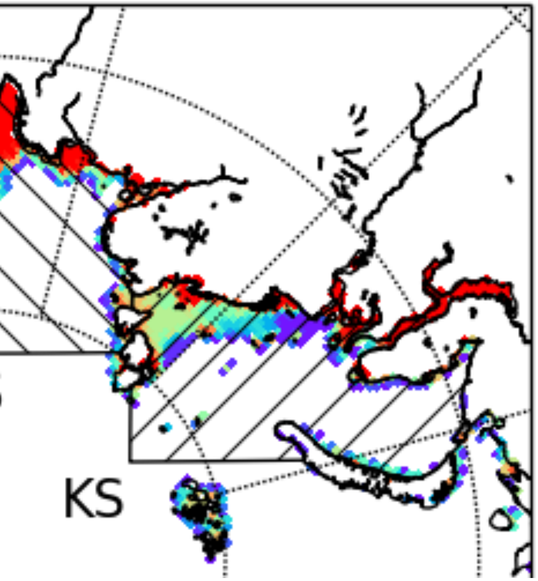


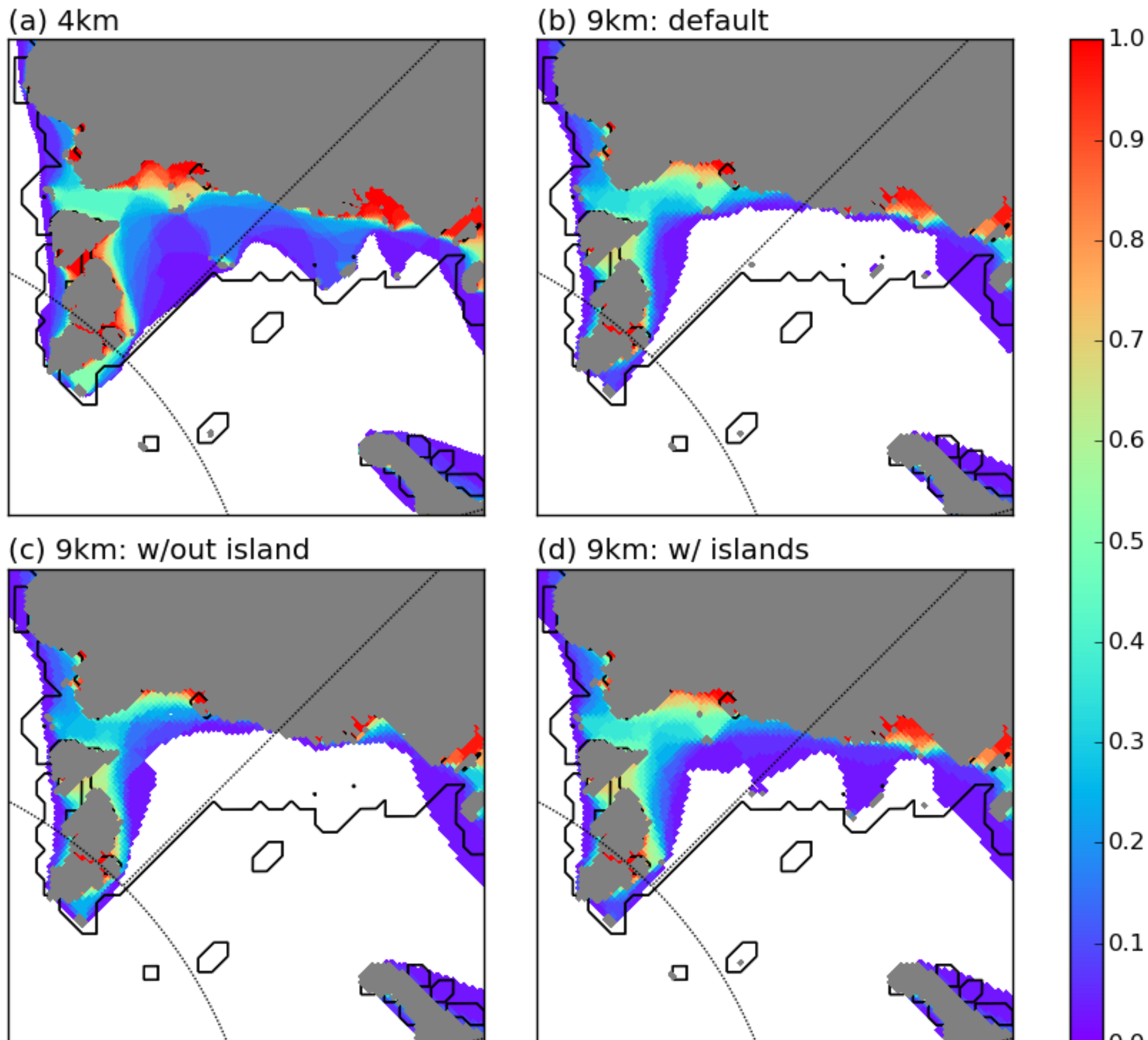


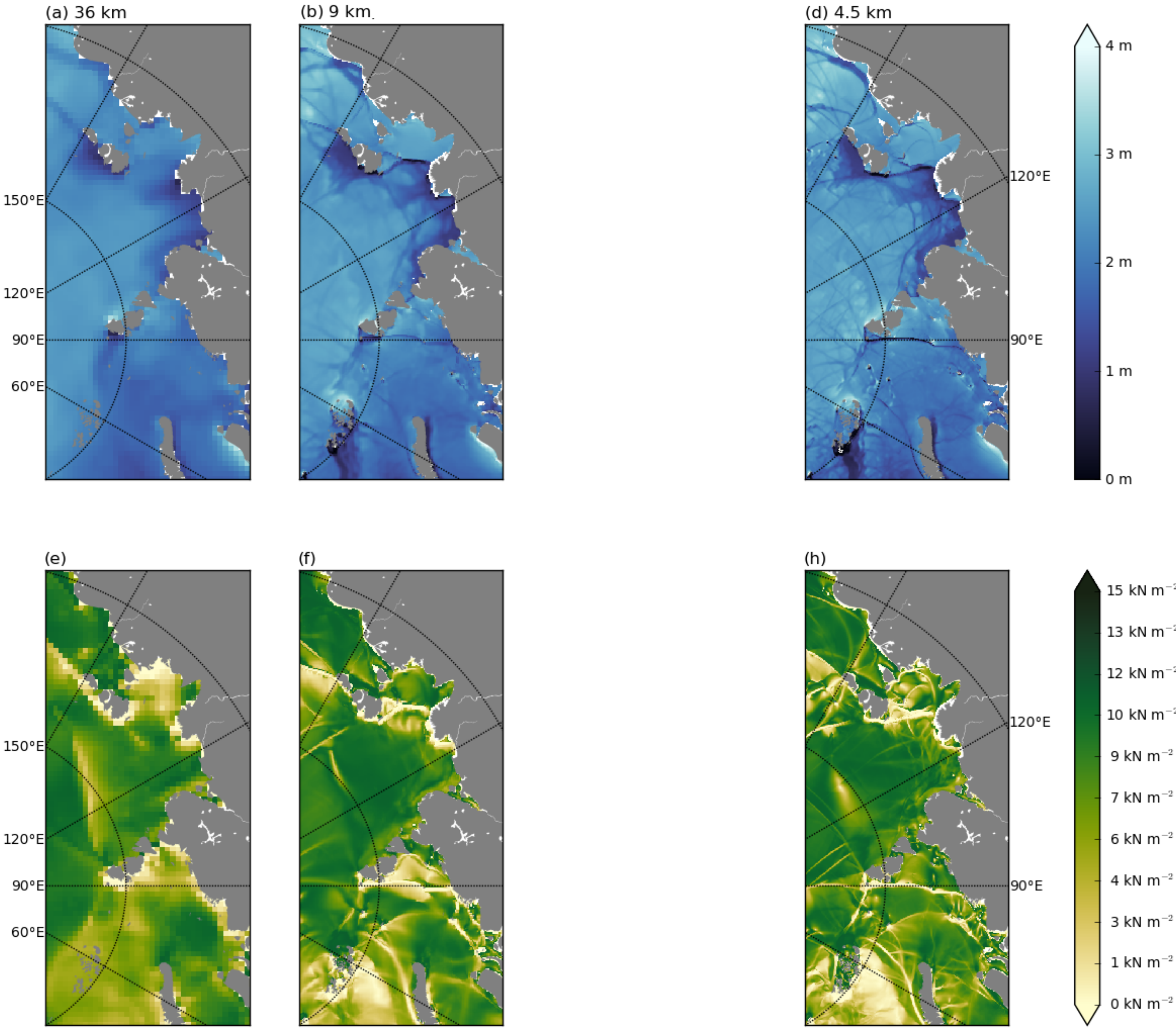
NIC observations

HELMHOLTZ ASSOCIATION

Islands in the Kara Sea







thickness

shear stress

Conclusions: Fast ice

- Parameterizations can improve land fast ice
- resolution of VP model also improves the land fast ice representation probably because of increased "effective shear strength", and resolved topography (islands)
- results depend on regions implying different mechanisms in different regions:
  - topographic anchors
    - bottom (grounding)
    - islands (arching)
  - static arching:
    - shear strength of sea ice
    - general strength of sea ice (changes with resolution?)

Conclusions

challenges high resolution sea ice modeling:

- continuity assumption
- VP-rheology assumptions (new rheologies)
- more nonlinearity: solvers don't converge

but:

- simulations more realistic in comparison to observations
- for the right/wrong reasons?
- …