Sea Ice Deformation in a Coupled Sea Ice-Ocean Model and in Satellite Remote Sensing Data

Gunnar Spreen, Ron Kwok,
Dimitris Menemenlis, An T. Nguyen

Jet Propulsion Laboratory, California Institute of Technology

Outline

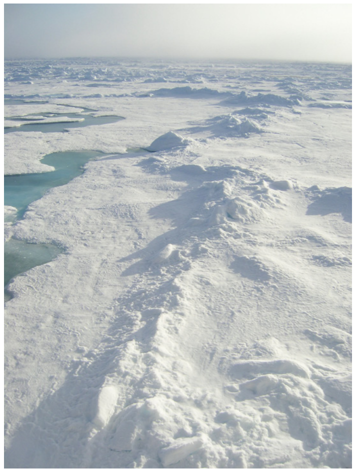
Comparison of observed RGPS SAR sea ice deformation fields to results from a traditional viscous-plastic sea ice model

- Motivation
- Data and Model
- Comparison
    - Dependence on model resolution
    - Power law scaling of sea ice deformation
    - Dependence on model sea ice strength formulation
- Conclusions

Motivation (1)

Sea ice deformation in the Arctic climate system:

- Divergence creates open water
  → new ice growth in winter
- Convergence creates pressure ridges
  → thicker ice



- Controls heat and gas fluxes to the atmosphere and brine rejection to the ocean
- Alters the air and water drag coefficients

➔ Correct modeling of sea ice kinematics important for sea ice mass balance and ocean – air energy fluxes

Motivation (2)

Sea ice model evaluation with ice deformation fields:

- Even simple models with wrong sea ice physics can simulate the mean sea ice velocity field correctly [e.g. Rampal et al., 2009].
- Comparisons with first order mean velocity fields therefore **not sufficient**. Second order **sea ice deformation should be used**.

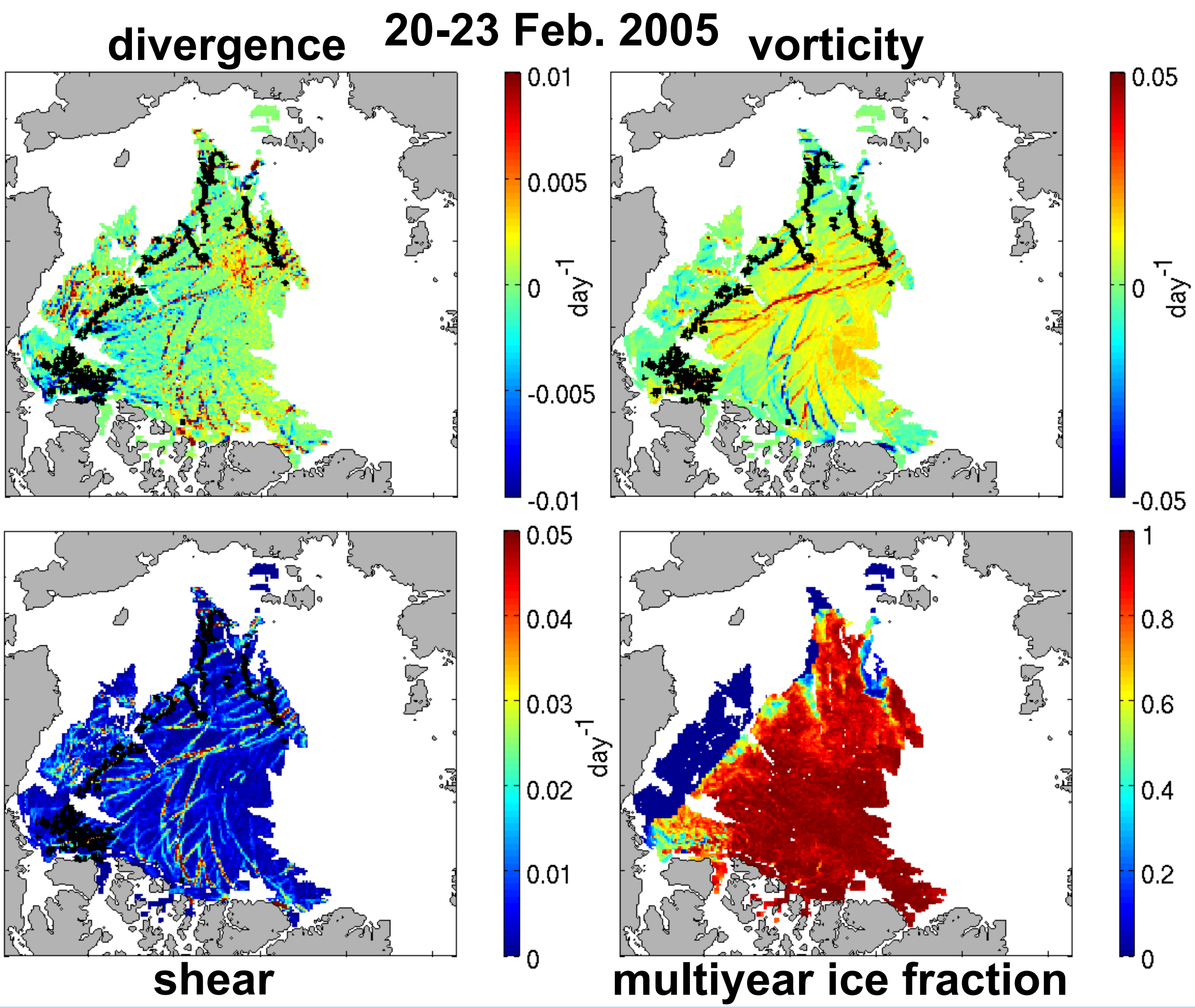
Tuning a traditional Hibler-type viscous-plastic sea ice model with elliptical yield curve

- Sea ice deformation field is not represented correctly in all details
- But it is widely used in climate research.

➔ Tune model to best represent observed sea ice kinematics

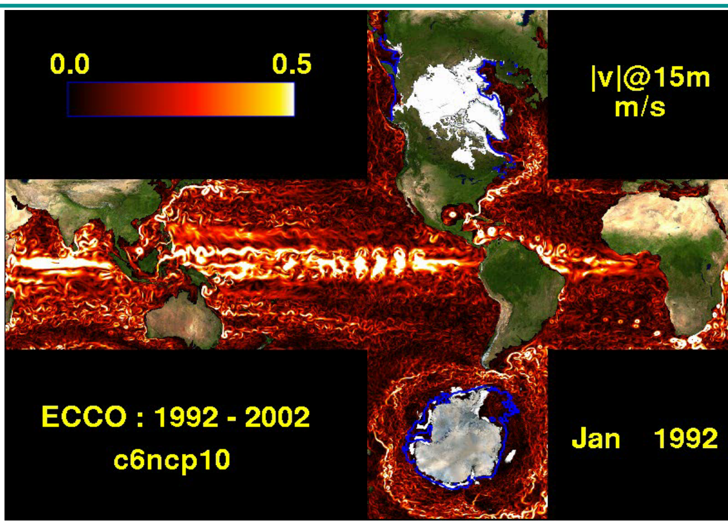
RGPS Satellite Data

- RADARSAT Synthetic Aperture Radar (SAR) data
- Same region covered approx. every 3 days
- Spatial cross-correlation of patterns → ice movement

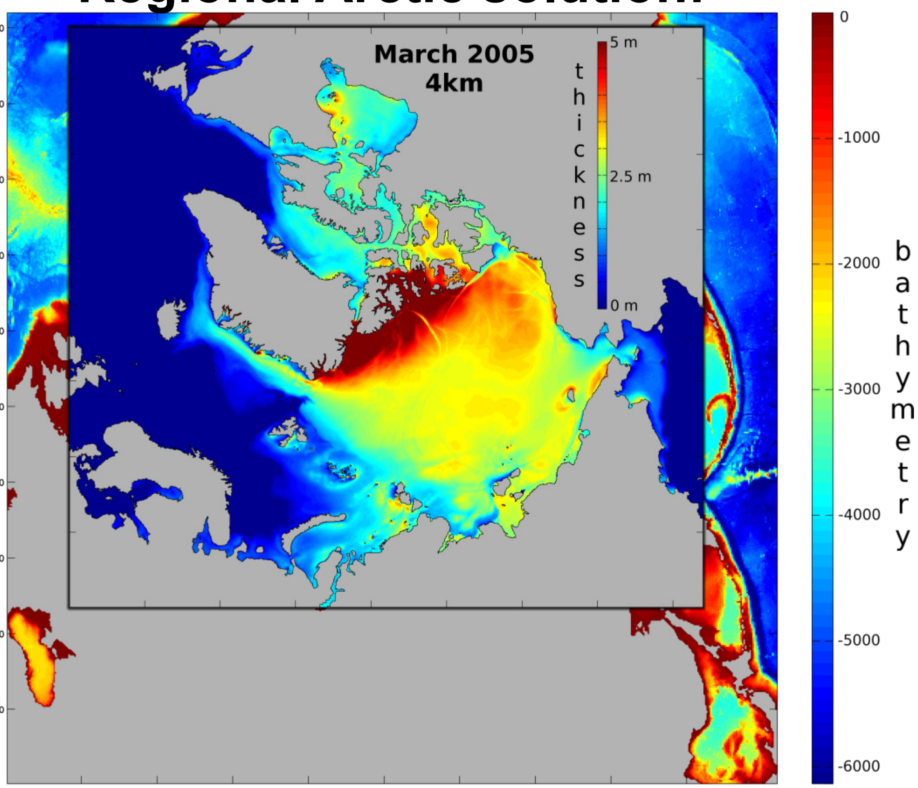


- Initial grid spacing 10 km
- Calculation of deformation (divergence, vorticity, shear) from Lagrangian cells
- 3 daily gridded (12.5 km)
- Accuracy of ice velocities in the order of 100 m (SAR pixel size)
- Discrimination between first- and multiyear ice

ECCO2 Coupled Sea Ice-Ocean Model



Regional Arctic solution:



ECCO2: High-resolution global ocean and sea ice model constrained by least squares fit to available satellite and in-situ data (Green's function approach).

<u>Ocean model</u>

- 50 vertical levels, volume-conserving, C-grid
- Surface boundary conditions: JRA-25
- Initial conditions: WOA05

<u>Sea ice model</u>

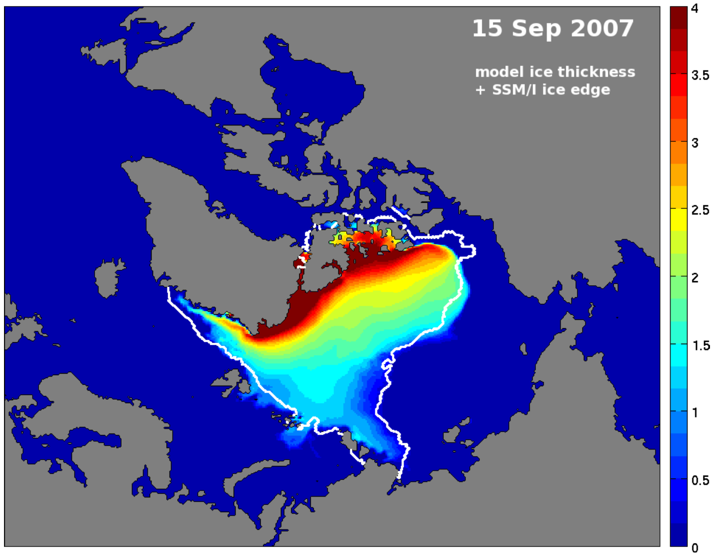
- 2-category zero-layer thermodynamics [Hibler, 1980]
- Viscous plastic dynamics [Hibler, 1979]
- Initial conditions: Polar Science Center
- Snow simulation: [Zhang et al., 1998]

<u>Regional Arctic solution</u>

- 4.5, 9 and 18 km horizontal grid spacing.
- Boundary conditions from global solution.
- Bathymetry: IBCAO
- Time: 1992 – 2009 (18 years)

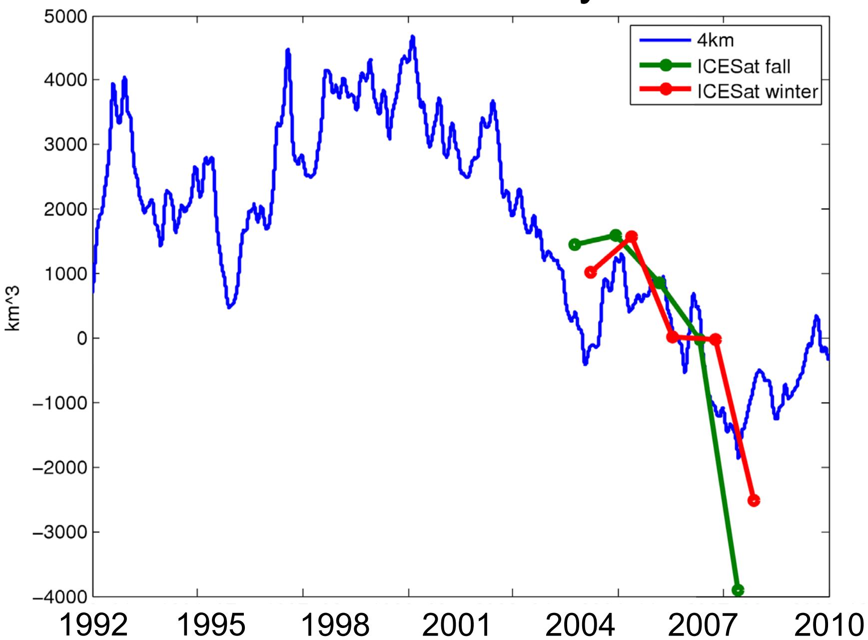
Model Performance

Sea ice minimum 2007

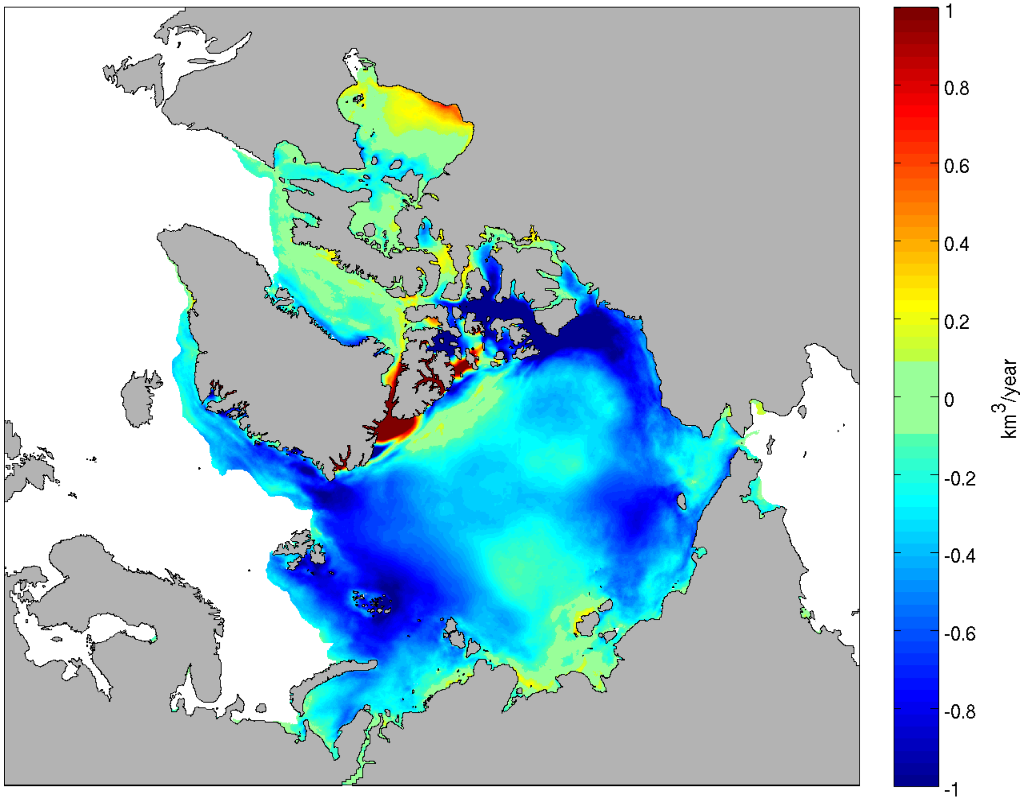


- Model is doing well in terms of sea ice extent but is tuned to do so ☺
- Changes in ice volume are comparable to observed ones using ICESat data (Kwok et al., 2009)

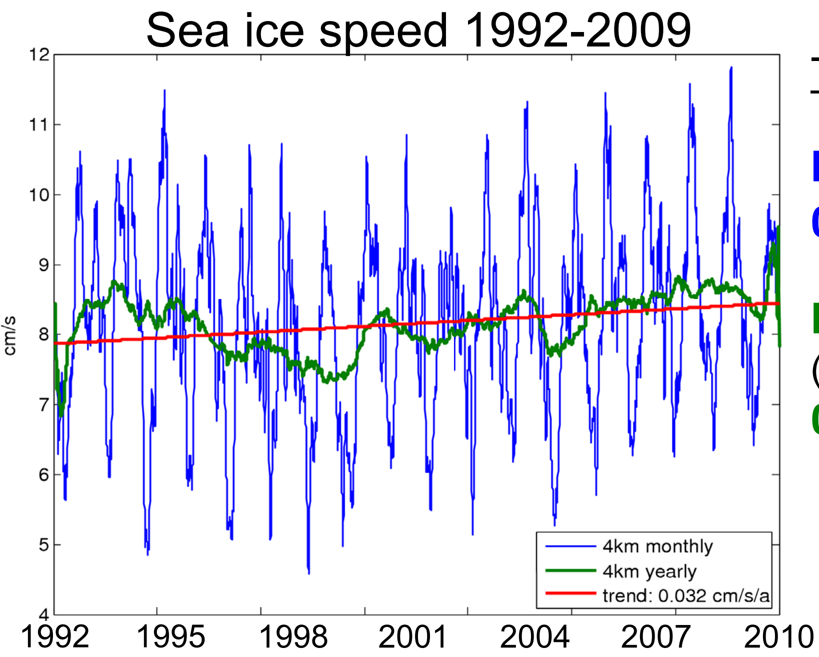
Sea ice volume anomaly 1992-2009



Trend in sea ice volume (1992-2009)



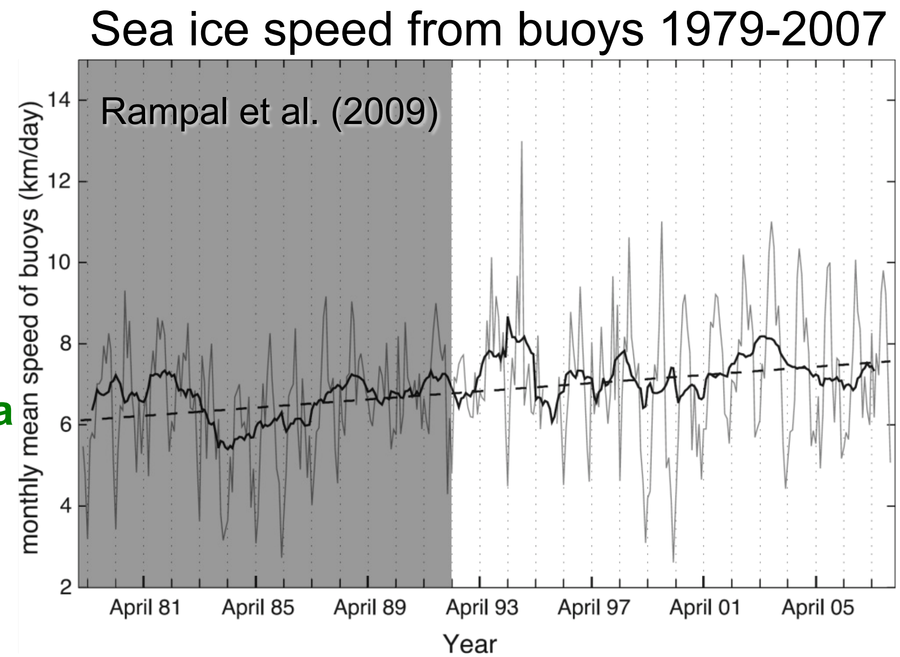
Sea Ice Speed

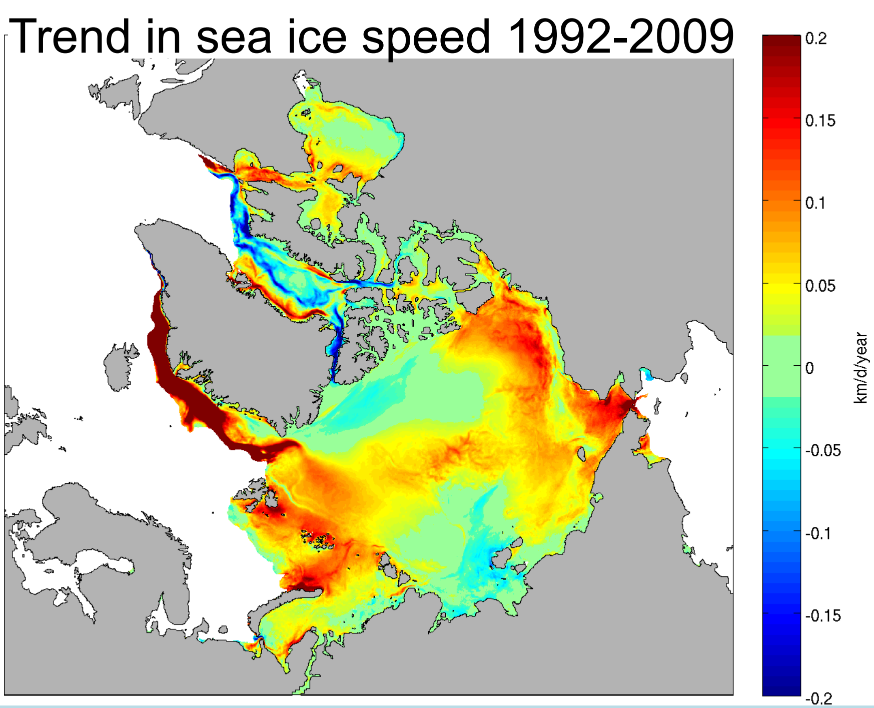


Trend sea ice speed

Model 1992-2008:
0.028 km/d/a

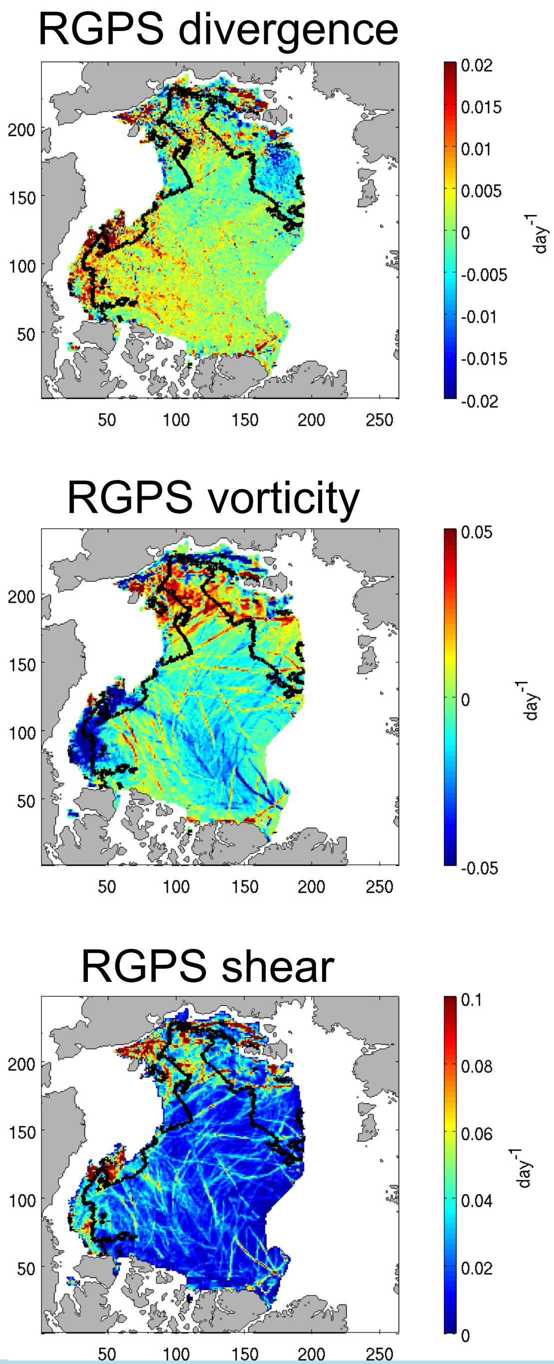
Buoy 1979-2007
(Rampal et al., 2009):
0.056 ± 0.011 km/d/a





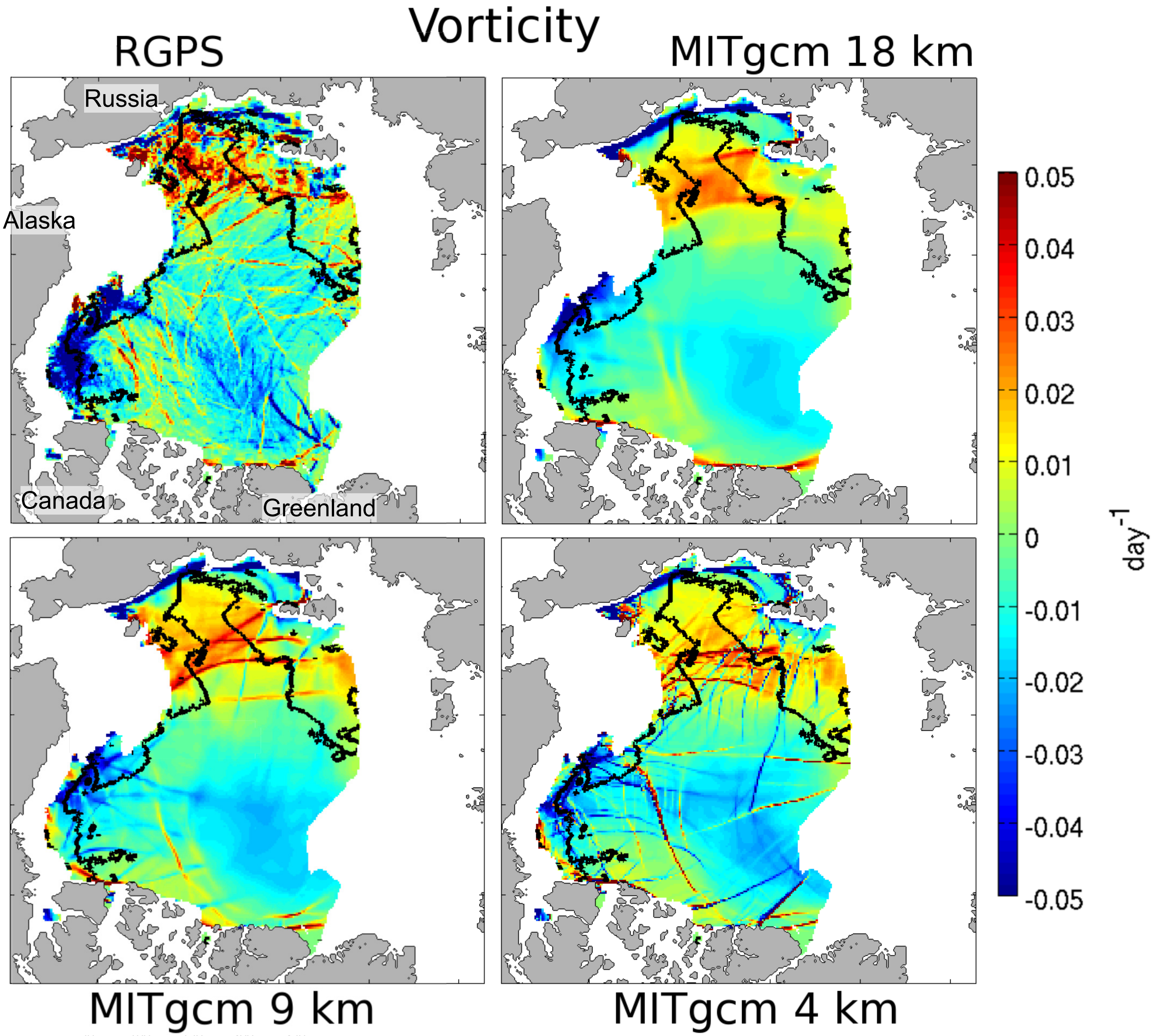
- Buoy observations and model show increase in mean sea ice speed
- Increase in speed is higher for buoys but different regions and periods are considered
- Strongest increase in west Beaufort Sea and Transpolar Drift

RGPS and Model Sea Ice Deformation

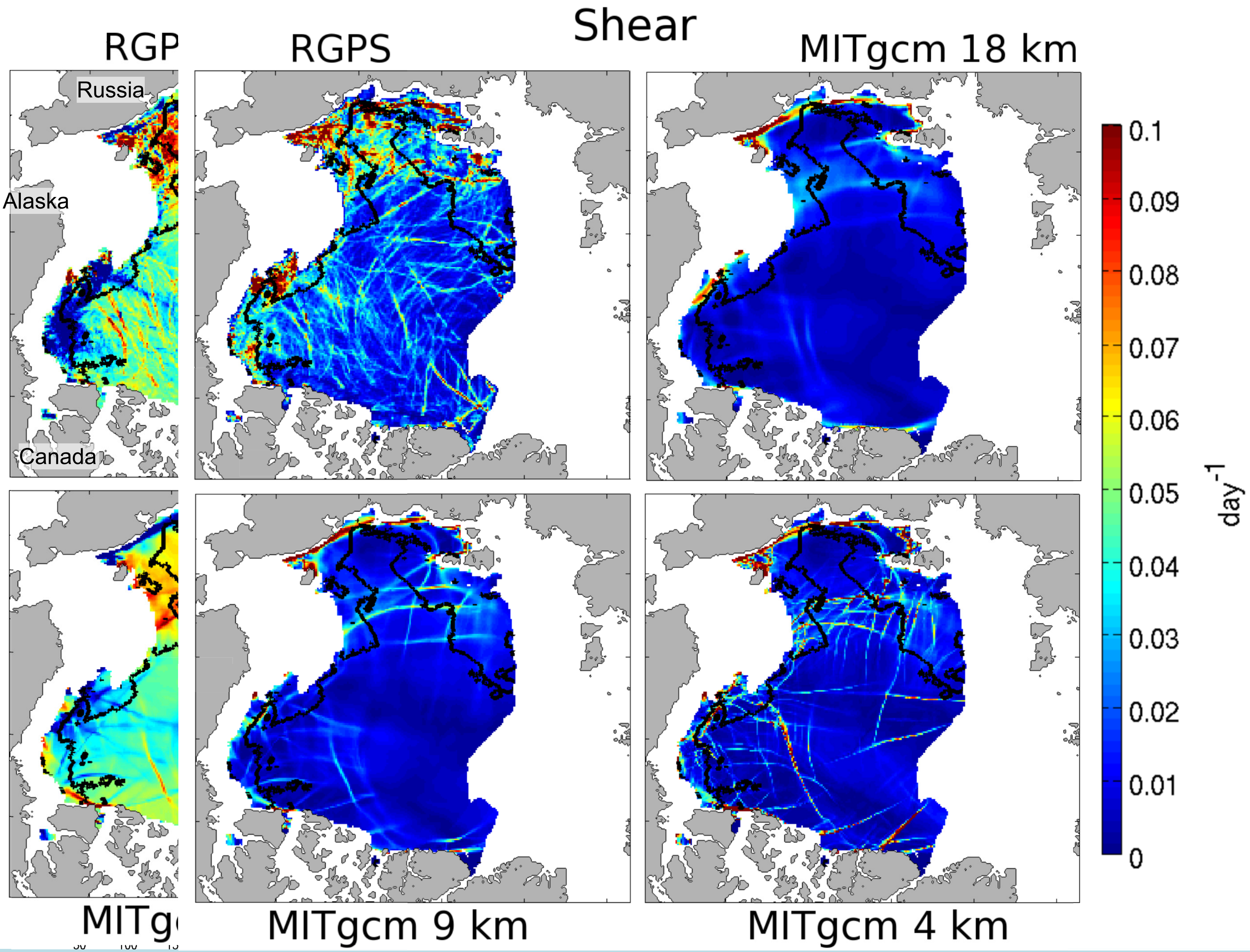


- Sea ice deformation parameters: divergence, vorticity and shear
- Example: November 1997
  black line: perennial ice

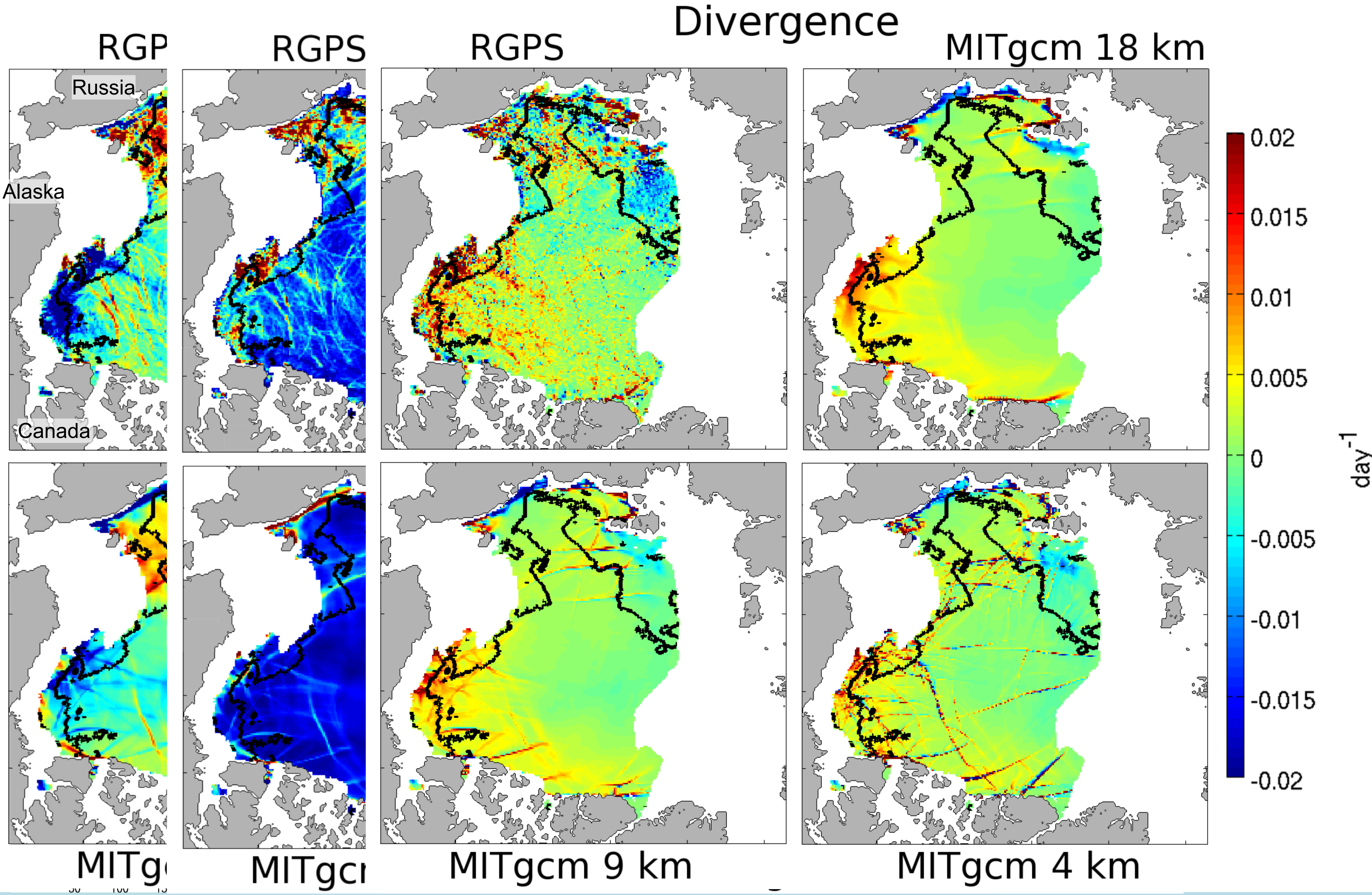
RGPS and Model Sea Ice Deformation



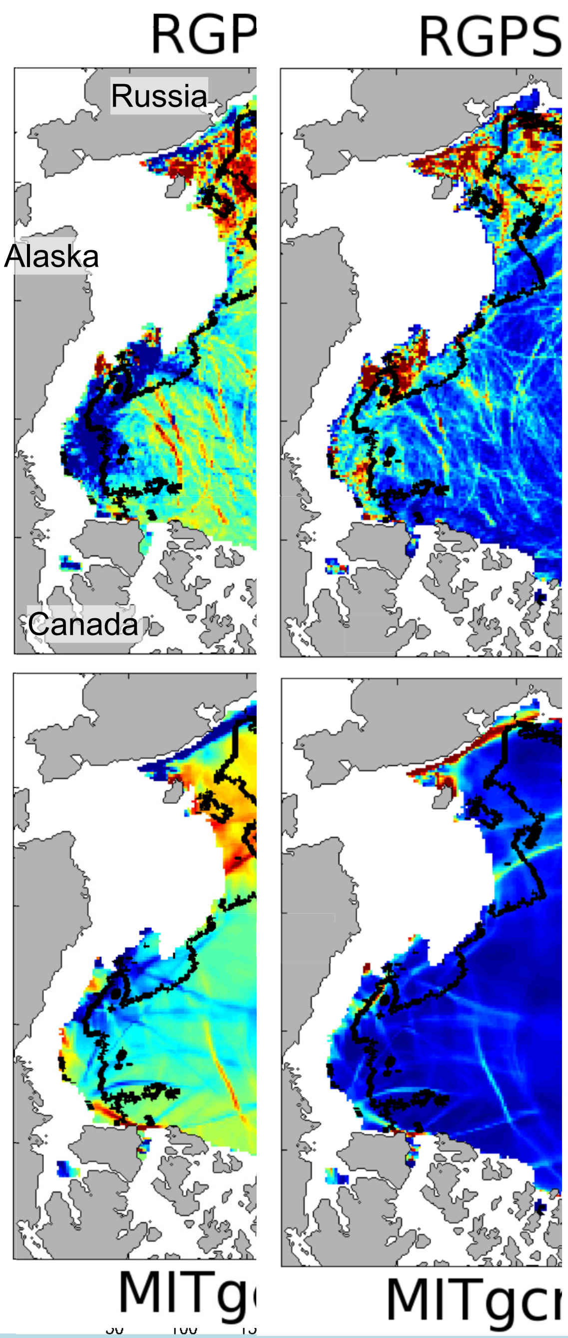
RGPS and Model Sea Ice Deformation



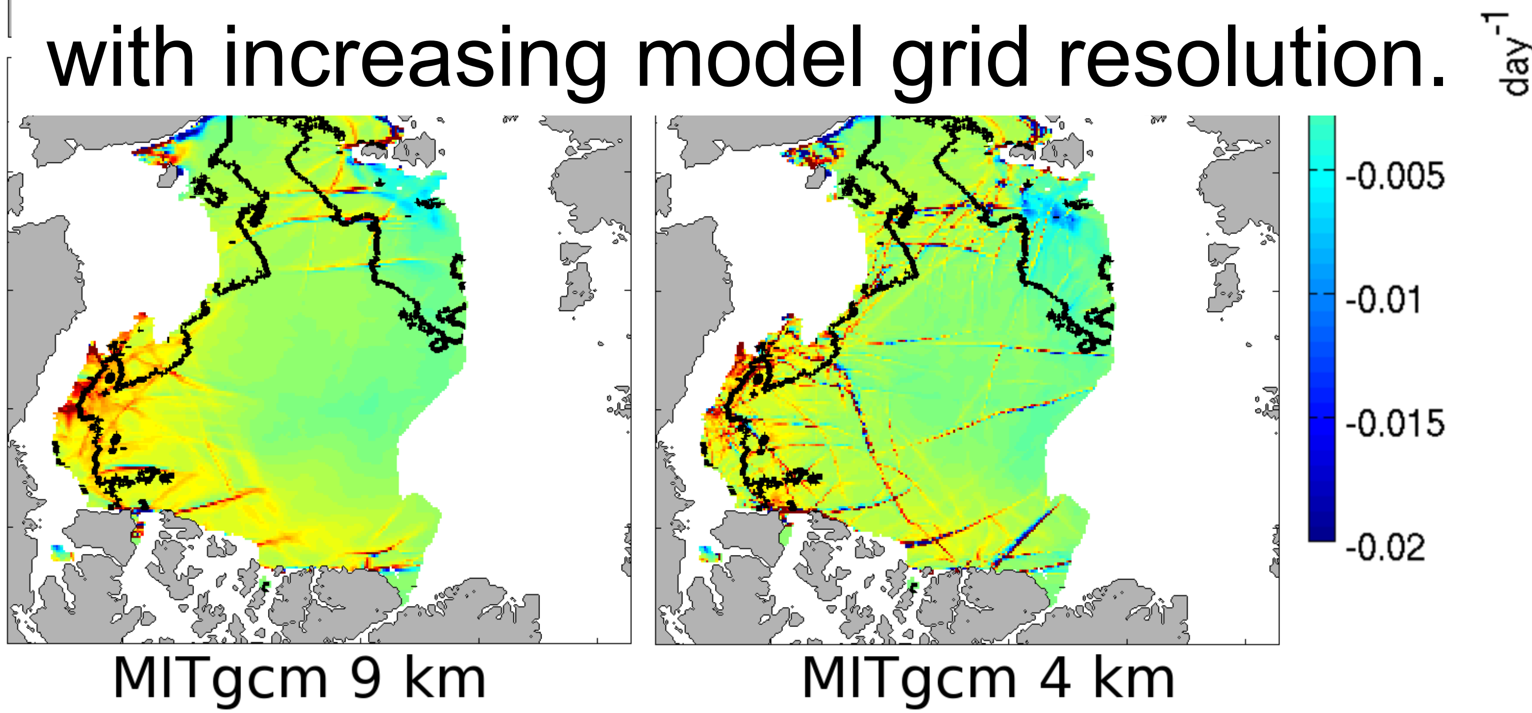
RGPS and Model Sea Ice Deformation



RGPS and Model Sea Ice Deformation



- Sea ice deformation parameters: divergence, vorticity and shear
- Example: November 1997
  black line: perennial ice
- Number and distribution of linear kinematic features (LKF) improve with increasing model grid resolution.



Spatial Scaling of Deformation Rate

- Deformation rate *D*:

$$D = \sqrt{\mathrm{div}^2 + \mathrm{shear}^2}$$

- follows power law with dependence on spatial scale *L*: $D \approx d\, L^b$
- Scaling exponent *b* from RGPS observations:

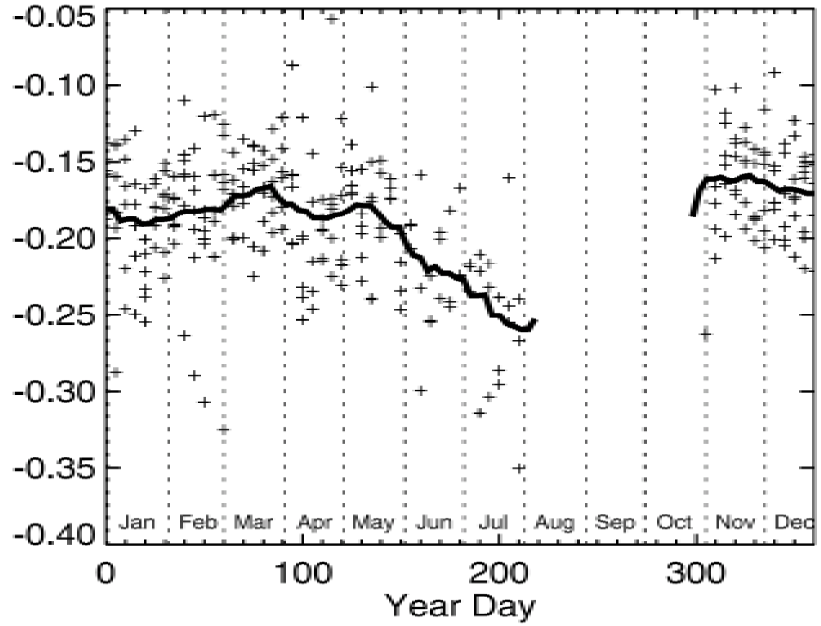
  b = -0.2 (winter)

  b = -0.3 (summer)

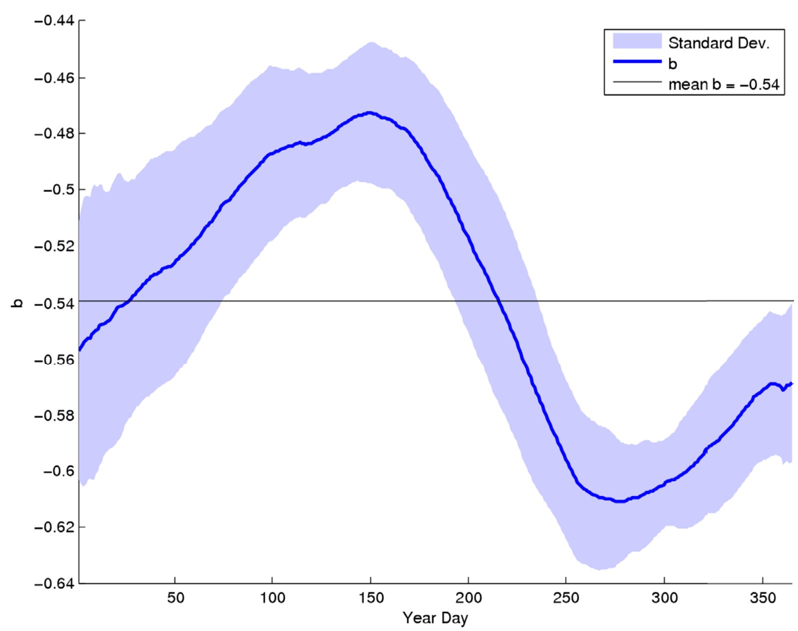
  (Stern & Lindsay, 2009)

- Power law also found in model: *b* = -0.5
- Similar seasonal cycle

Seasonal Cycle Scaling Exponent *b*

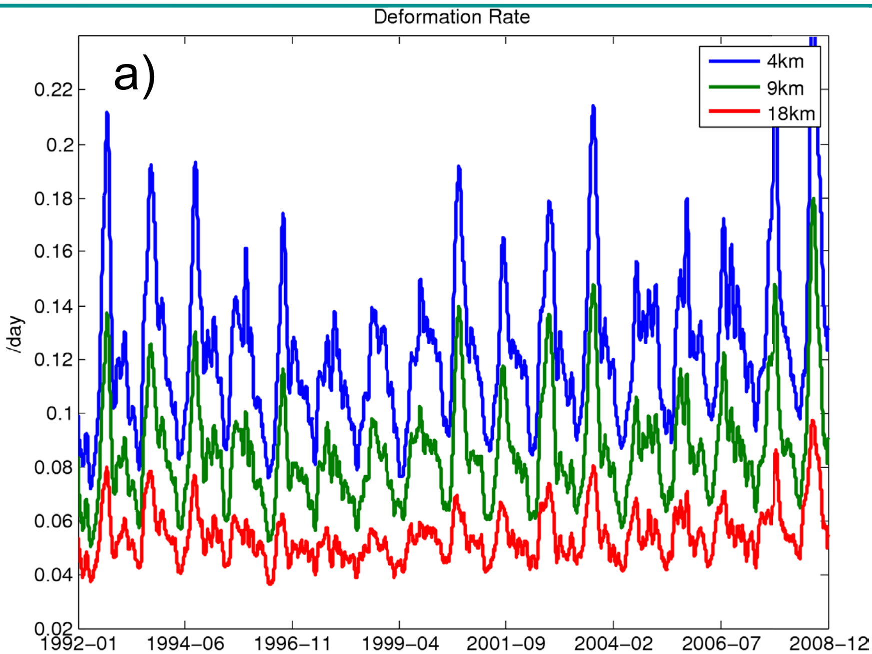


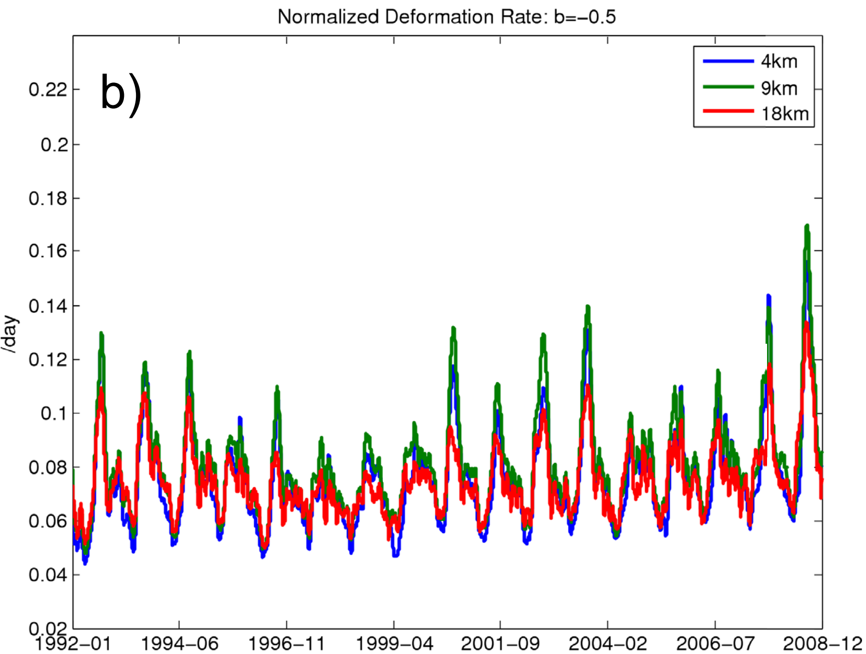
RGPS (Stern & Lindsay, 2009)



Model

Power Law Scaling of Deformation Rate

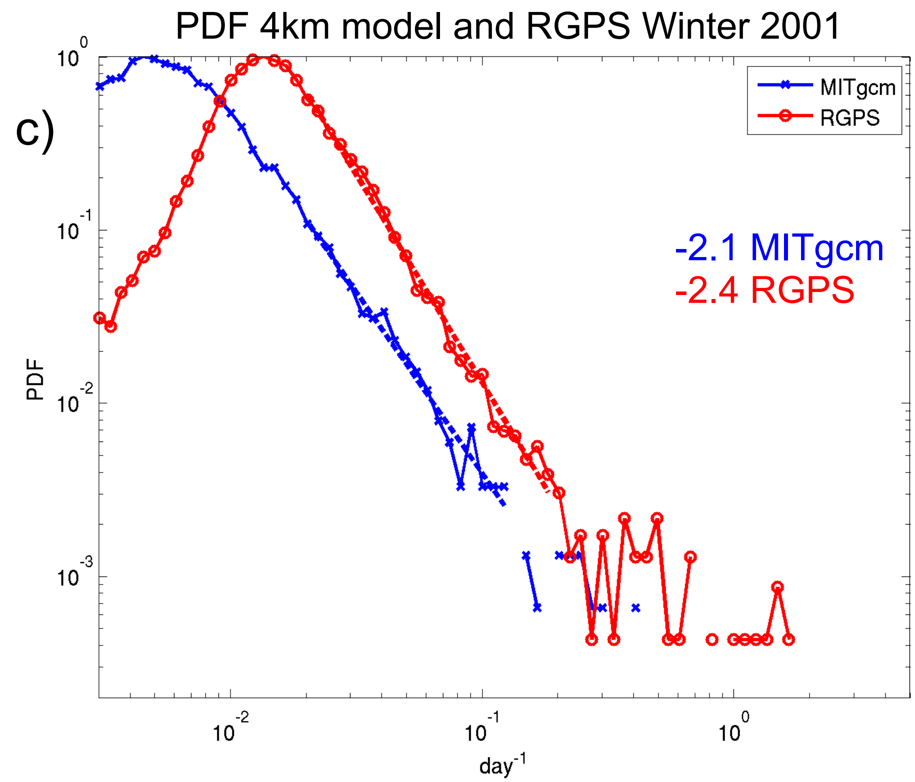




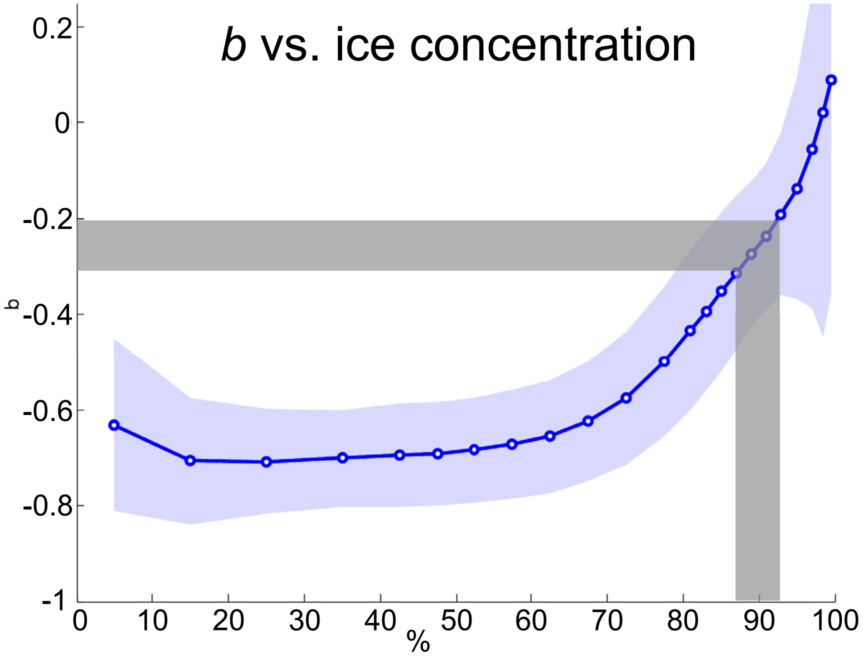
a) Original deformation $D=\sqrt{\text{div}^2+\text{shear}^2}$ for three model resolutions (18, 9 and 4.5 km).

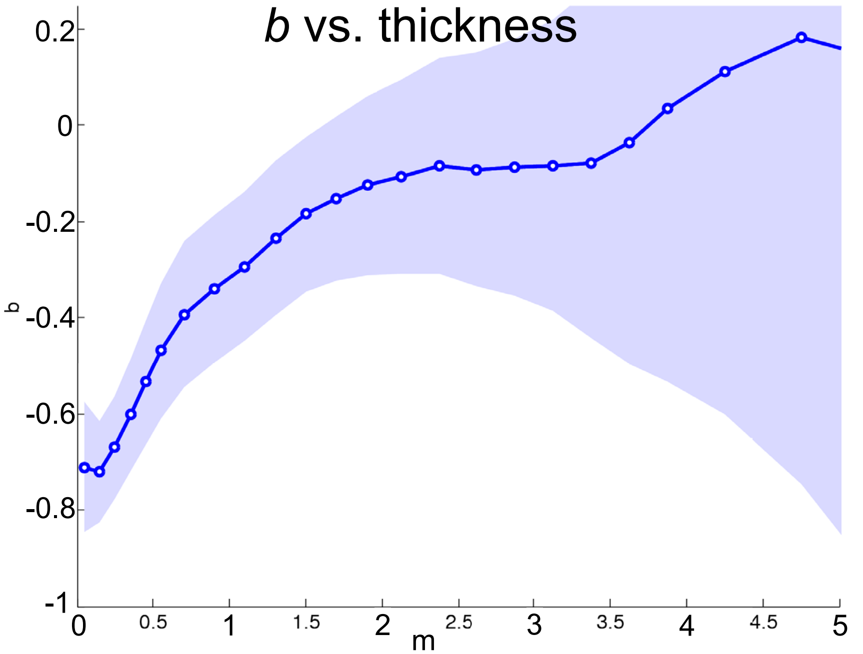
b) By power law scaling with exponent *b* = -0.54 deformation rates of three model runs become similar.

c) Probability density function of model shows similar power law scaling as RGPS data.



Scale factor vs. ice concentration & thickness





- Model power law scaling factor *b* strongly depends on ice concentration.
- For ice concentrations of 90% *b* becomes similar to the observed RGPS scaling factor (-0.3 to -0.2).
- RGPS data is only obtained in high ice concentration regions.
- Ice concentrations near 100% do not show power law scaling.
- Stronger power law scaling for thin than for thick ice but very variable.

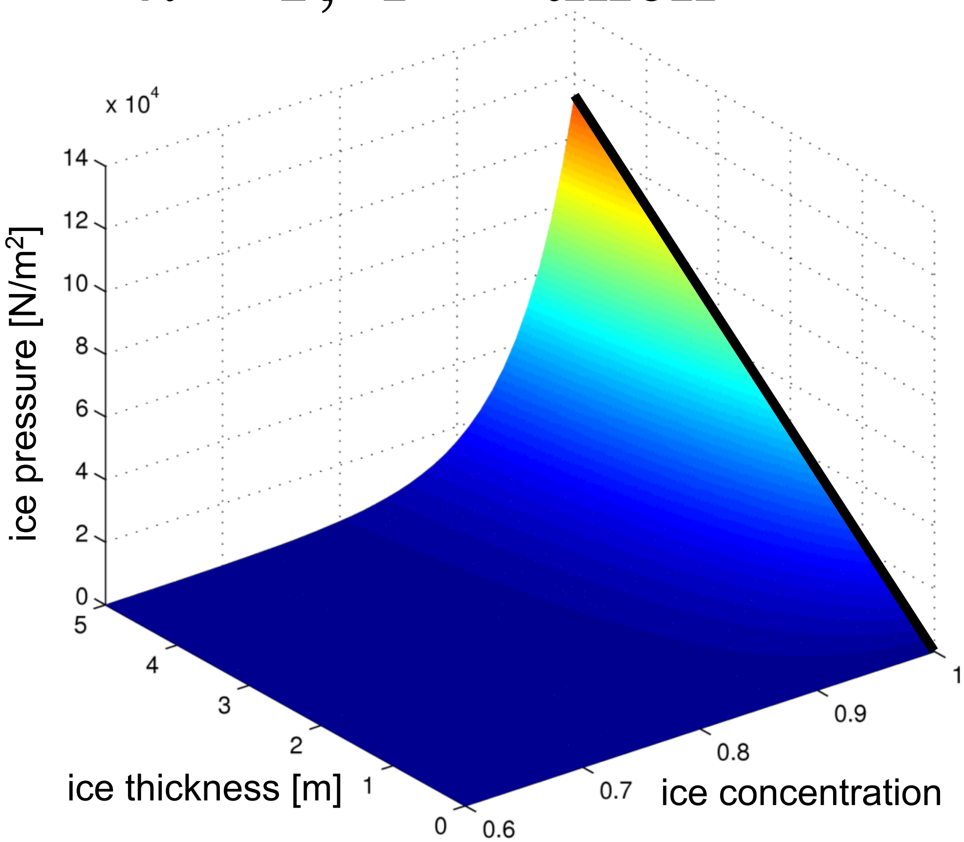
Ice Pressure (Strength)

Sea ice pressure formulation: $P_{max} = P^* h^n e^{[C^*(1-a)]}$

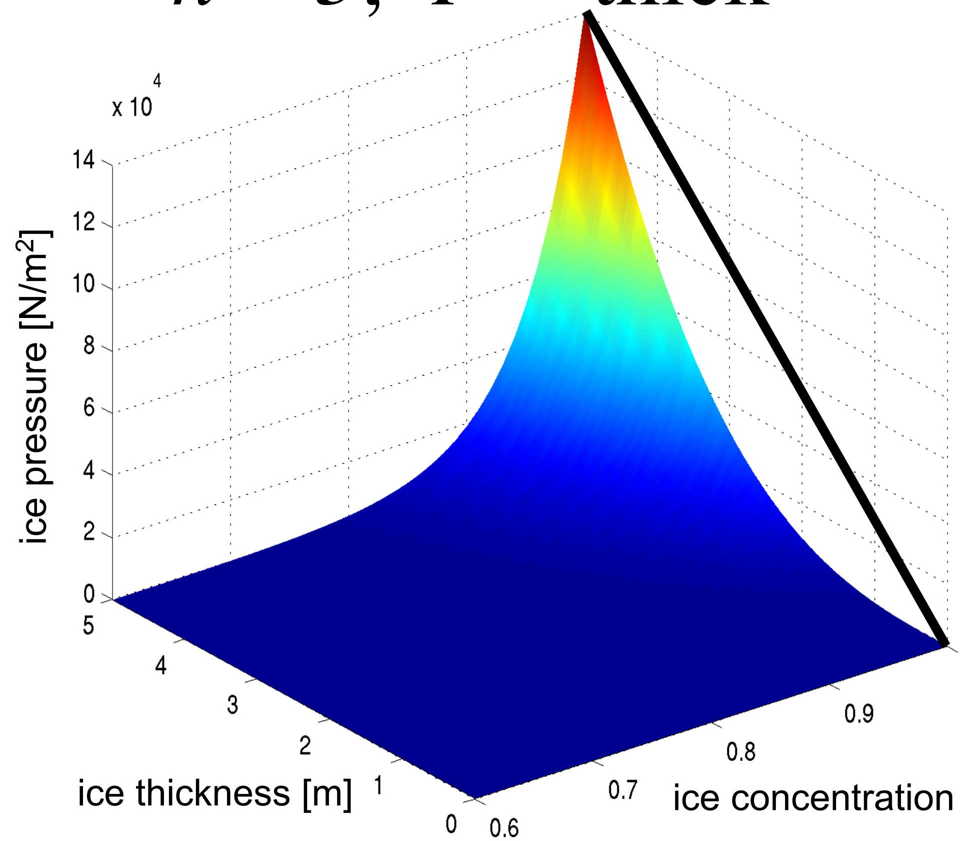
h : ice thickness, $C^* = -20$

a : ice concentration

Linear parameterization:
$n = 1,\ P \propto \text{thick}$



Cubic parameterization:
$n = 3,\ P \propto \text{thick}^3$

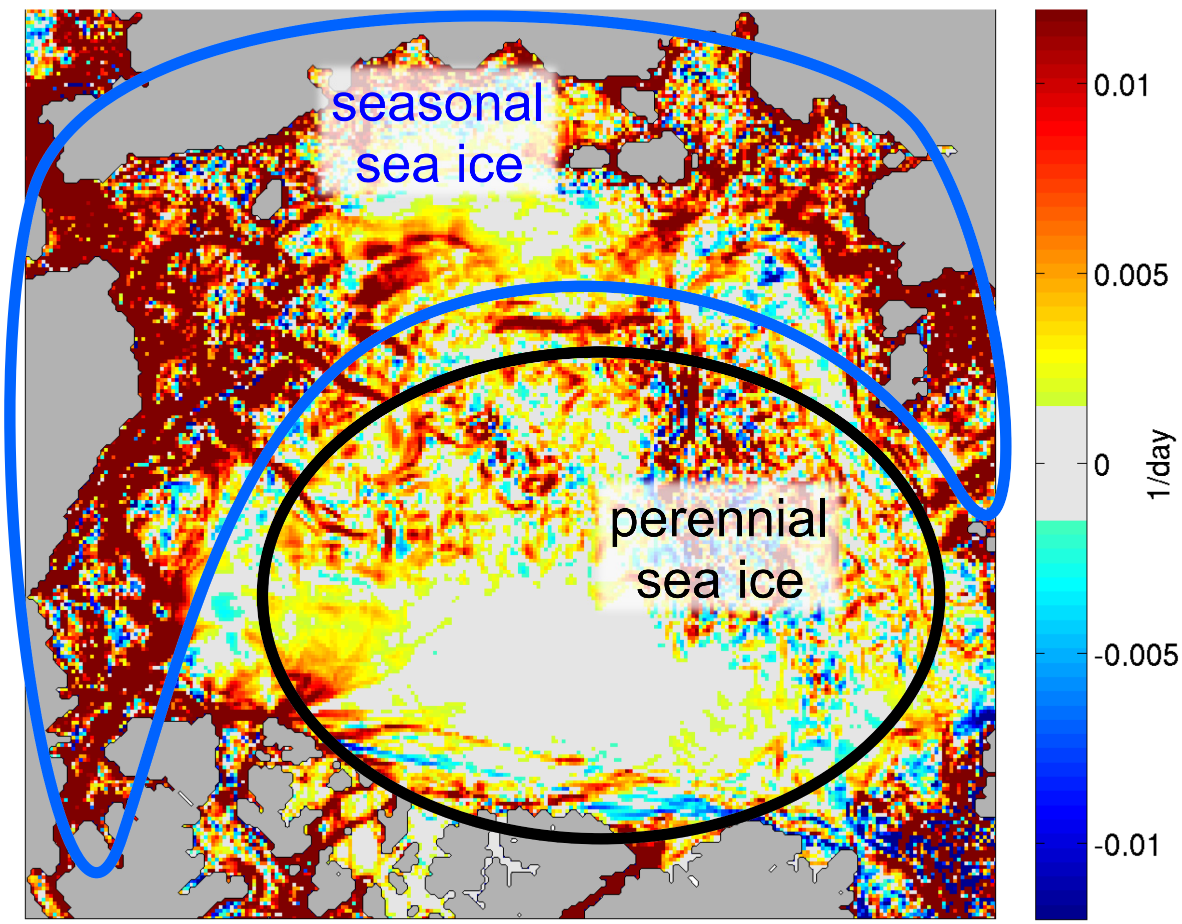


Cubic – Linear Parameterization Difference

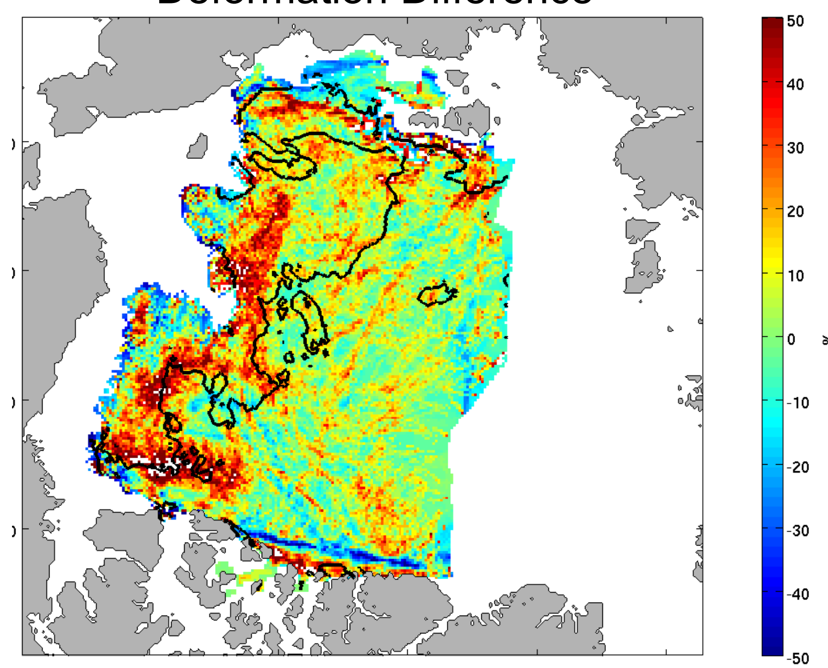
- Difference in deformation rate:
  Test – Control ice strength formulation

➔ More deformation, especially in seasonal ice zone.

Deformation Rate Difference 1996-2000: Cubic – Linear

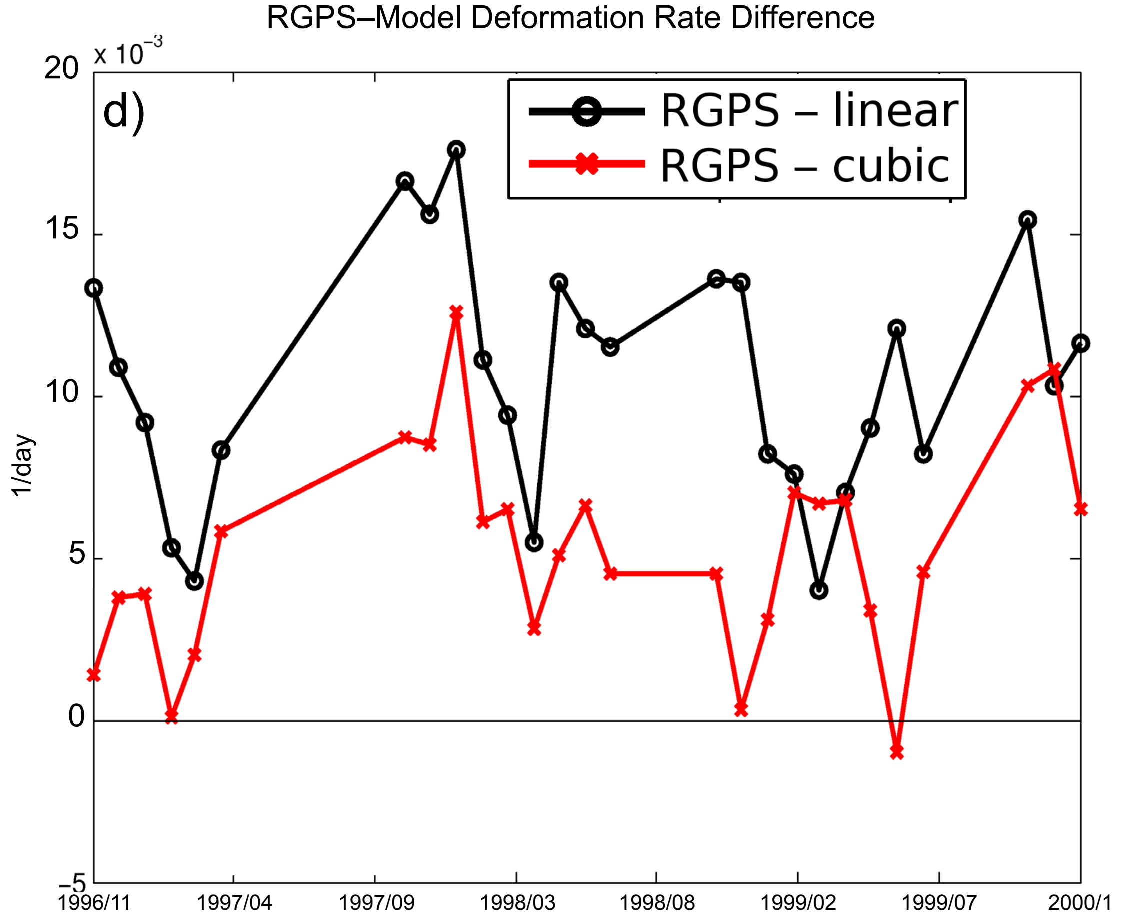


Original RGPS – Model
Deformation Difference



Time Series of Deformation Rate Difference

difference observation – model



Time series of deformation rate 1996-2000.

Difference RGPS–MITgcm

	mean [10^{-3}/day] all	MY	FY	st. dev. all
9km linear	11	7	14	22
9km cubic	5	5	4	16

➔ New ice pressure formulation improves sea ice deformation distribution

➔ Independent of model resolution.

Conclusions

- Compared to RGPS observations, the model does not adequately reproduce small scale deformation and linear kinematic features (LKFs). Also the overall modeled deformation rate is lower than the observed one.
- Increase in model resolution produces more and clearer confined ice deformation features.
- The observed power law scaling of sea ice deformation can also be found in the model. Noticeable is that the scaling exponent *b* is not constant but strongly depends on sea ice concentration, thickness and time of year.
- By changing the model sea ice strength formulation from a linear to a cubic dependence on ice thickness, the modeled and observed deformation fields become more consistent.

Conclusions

- Compared to RGPS observations, the model does not adequately reproduce small scale deformation and linear kinematic features (LKFs). Also the overall modeled deformation rate is lower than the observed one.
- Increase in model resolution produces more and clearer confined ice deformation features.
- The  power law scaling of sea ice de  can also be found in the model. Noticeable is that the scaling exponent *b* is not constant but strongly depends on sea ice concentration, thickness and time of year.
- By changing the model sea ice strength formulation from a linear to a cubic dependence on ice thickness, the modeled and observed deformation fields become more consistent.

Thank you!