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

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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
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

![divergence](20-23 Feb. 2005) ![vorticity](20-23 Feb. 2005)

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

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

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

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

- 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 Speed

- 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

Trend in sea ice speed 1992-2009

- Model 1992-2008: 0.028 km/d/a
- Buoy 1979-2007 (Rampal et al., 2009): 0.056 ± 0.011 km/d/a

Trend sea ice speed

Sea ice speed from buoys 1979-2007

Rampal et al. (2009)
• Sea ice deformation parameters: divergence, vorticity and shear
• Example: November 1997
  black line: perennial ice
RGPS and Model Sea Ice Deformation

RGPS divergence
RGPS vorticity
RGPS shear

Greenland
Alaska
Canada

MITgcm 18 km
MITgcm 9 km
MITgcm 4 km
RGPS and Model Sea Ice Deformation

RGPS divergence
RGPS vorticity
RGPS shear
RGPS divergence

Greenland
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RGPS and Model Sea Ice Deformation
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- RGPS vorticity
- RGPS shear
- Greenland
- Russia
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• 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 $D$:
  \[ D = \sqrt{\text{div}^2 + \text{shear}^2} \]
  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
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.

PDF 4km model and RGPS Winter 2001

-2.1 MITgcm
-2.4 RGPS
- 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:

\[ P_{\text{max}} = P^* h^n e^{[C^*(1-a)]} \]

- \( h \): 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.
Time Series of Deformation Rate Difference


Difference RGPS–MITgcm

<table>
<thead>
<tr>
<th></th>
<th>mean [10^{-3}/day]</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>all</td>
<td>MY</td>
</tr>
<tr>
<td>9km linear</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>9km cubic</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

→ 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.
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Thank you!