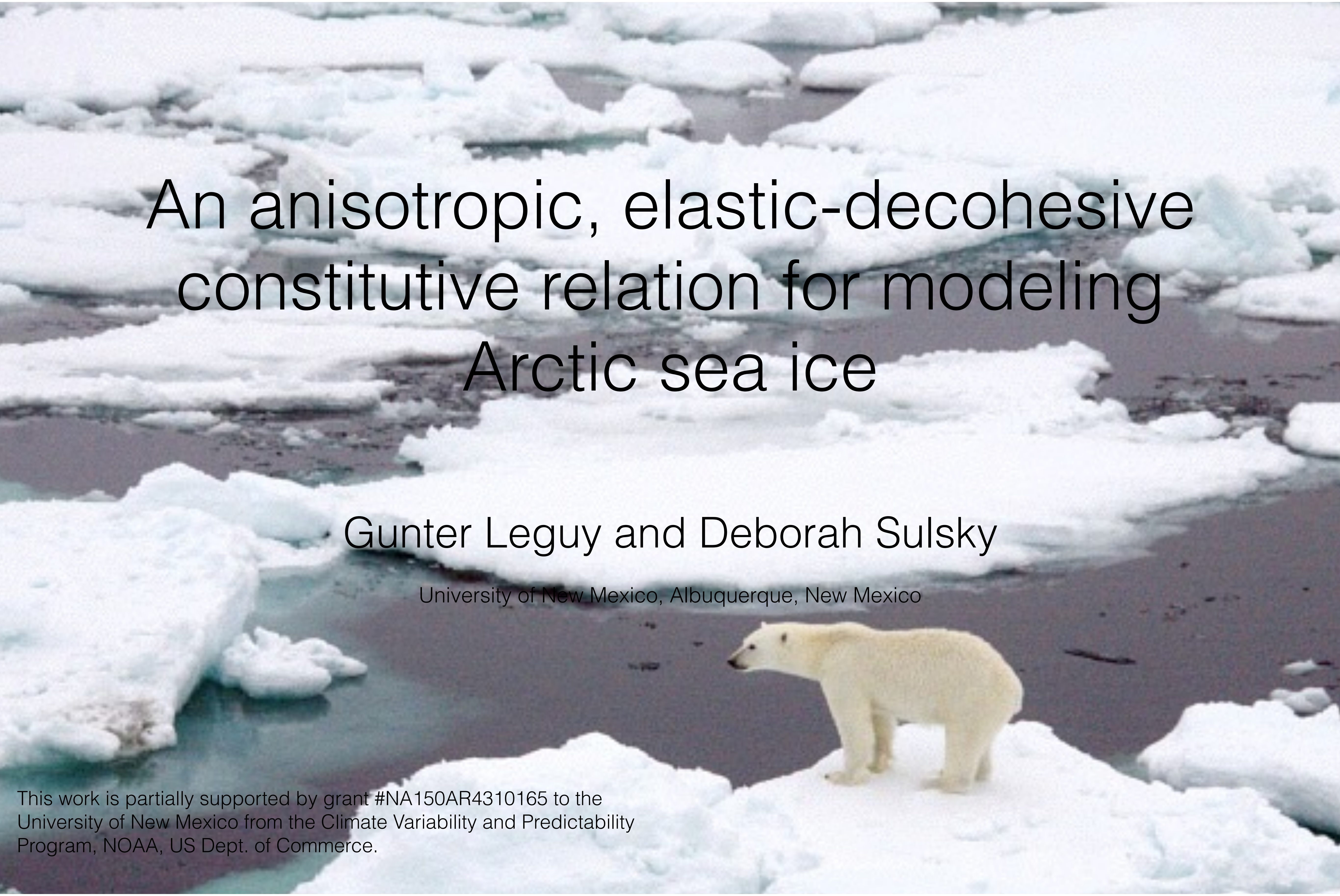

An anisotropic, elastic-decohesive constitutive relation for modeling Arctic sea ice

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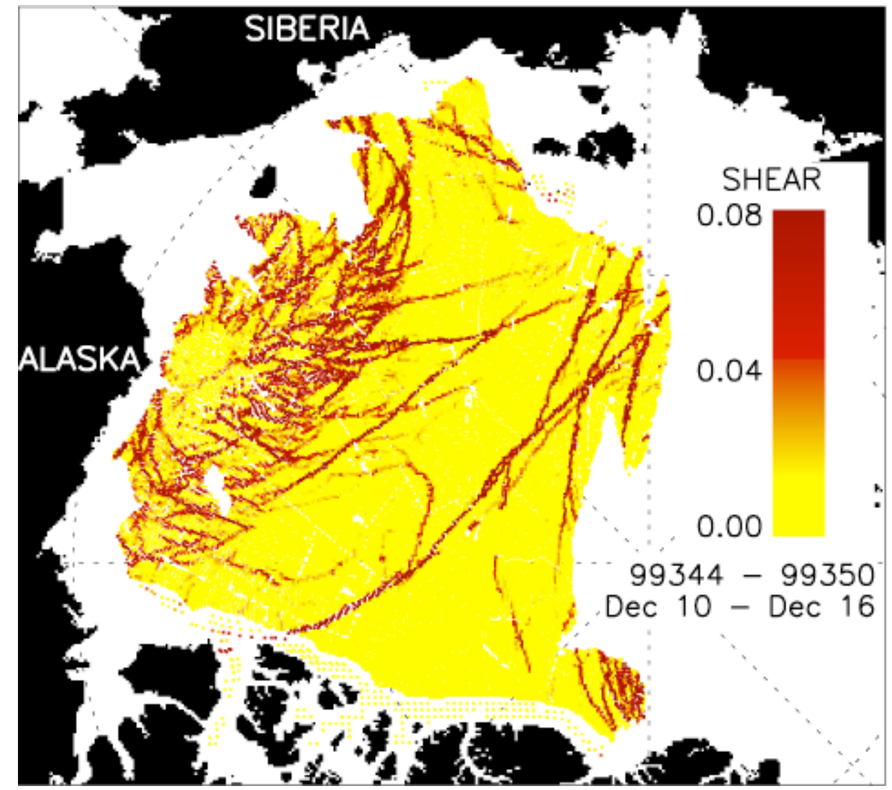
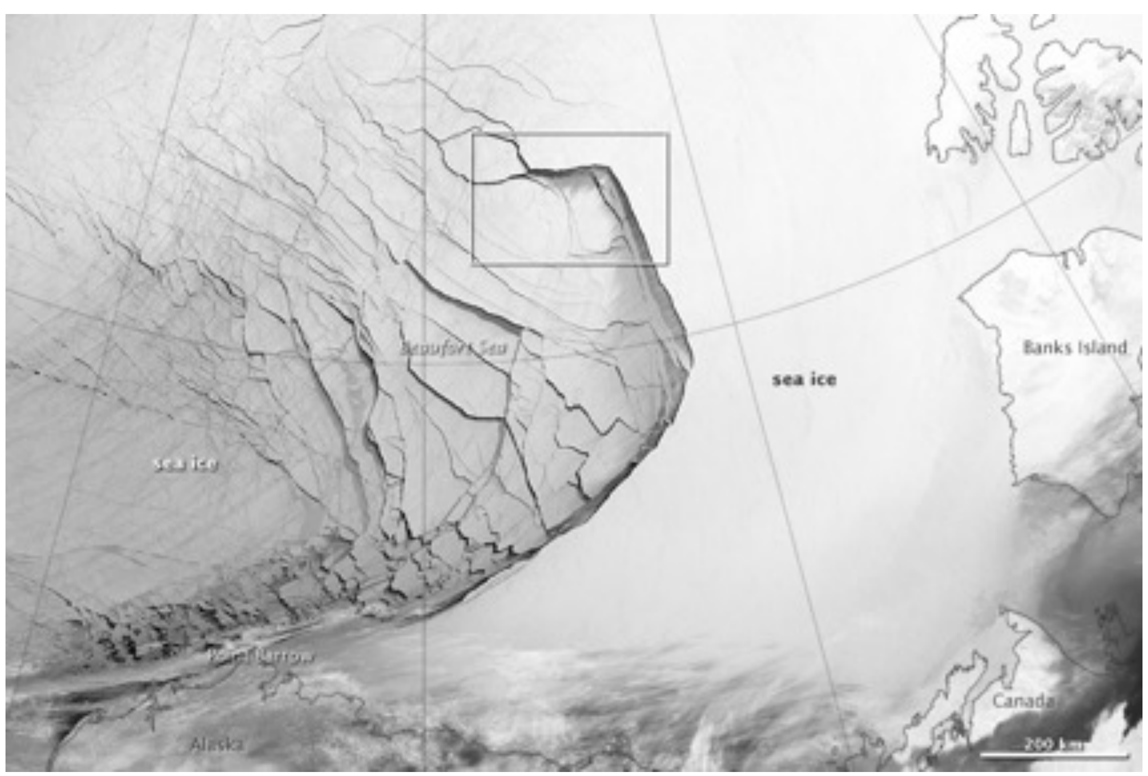
Motivation

Explicitly represent lead formation

RGPS (Kwok, 1998) analysis of satellite images shows large ice deformation events occurring in long-lasting linear features that appear to correspond to displacement (or velocity) discontinuities in the deformation field due to leads.





Cracks in the ice (leads) occupy 1-2% of the ice cover in winter but account for half of the ocean-air heat flux. Heat flux through intact ice is 2-5 Wm^2 compared with 300-500 Wm^2 through leads.

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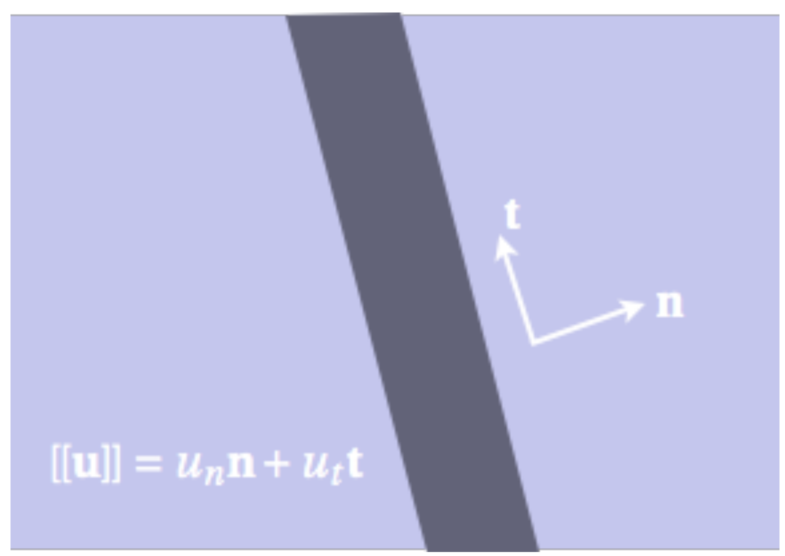
Model

- Ice dynamics (horizontal momentum equation) is solved using the material point method (Peterson and Sulsky, 2012)
- Mass is conserved for each material point (continuity equation)
- Each material point solves column thermodynamics equations and tracks ice thickness distribution
- The sea ice code is coupled to the MITgcm (Marshall et al., 1997) ocean code through fluxes
- Atmospheric forcing is JRA-25 reanalysis data (Onogi et al., 2007)
- Use of an elastic-decohesive constitutive model for the ice

The Elastic-Decohesive Constitutive Model

- Intact ice is modeled as elastic
- Leads (cracks) are modeled as discontinuities
- Model predicts initiation, orientation and opening of leads
- Traction is reduced with lead opening until a complete fracture forms



The model introduces a jump in displacement as a crack is initiated in the simulation. Crack initiation is governed by a curve in stress space. What is that curve?

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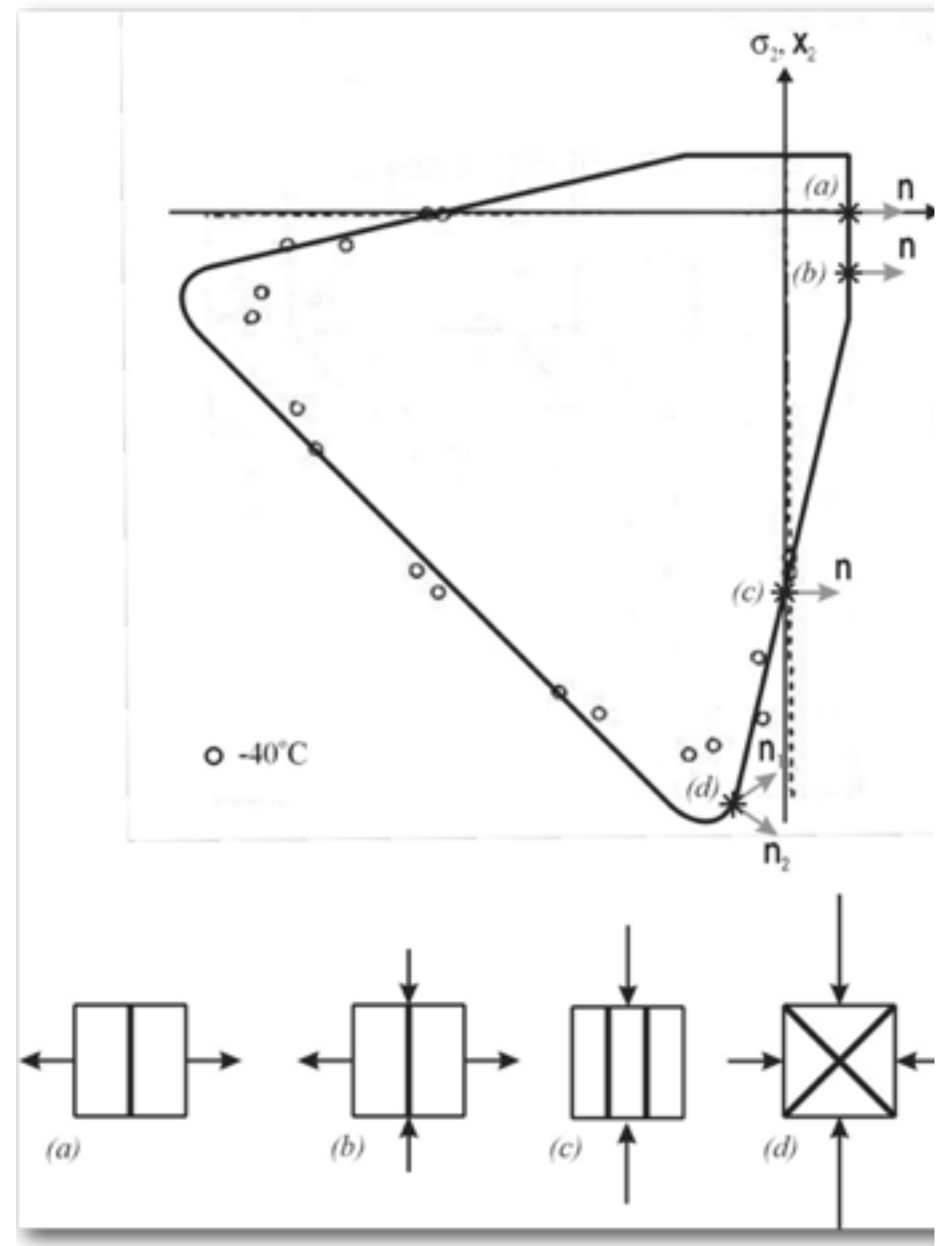
Laboratory data

Measurement by Schulson (2001) show the stress state when a crack forms and the orientation of the crack. The observed failure envelope in stress space that describes initiation of failure could be described mathematically by a function $F(\sigma) = 0$.

What is F?



(a) Loading is purely tensile.
(b) Biaxial loading - tension and compression.
(c) Axial loading - pure compression.
(d) Biaxial compression.

In (a-c) the crack has a normal in the direction of maximum principal stress. (d) transitions to shear failure with two possible crack orientations.

Corresponding Model

F is a function of stress (Schreyer et al. (2005), Sulky et al. (2006)).

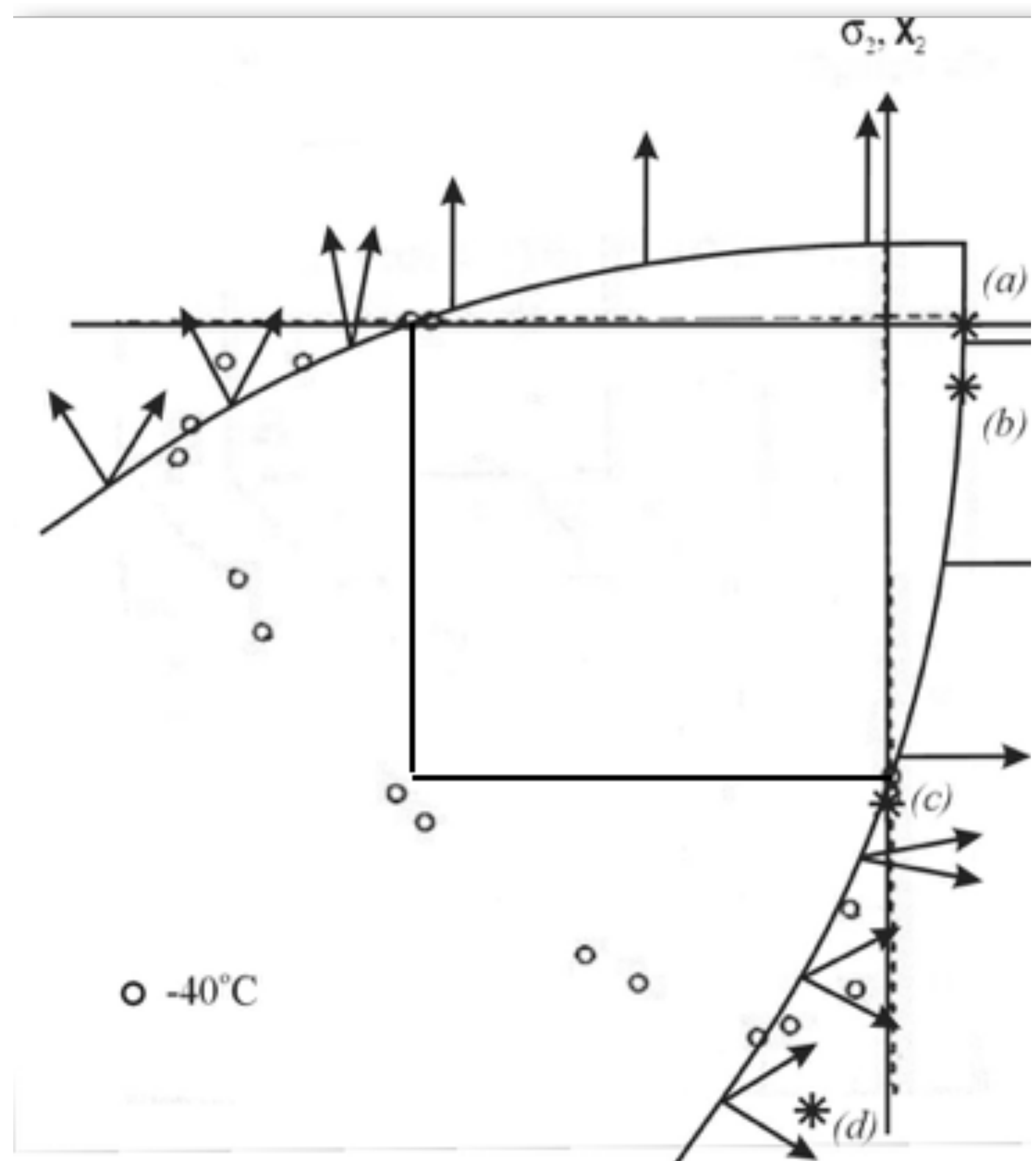
$$F = \max_n F_n(\sigma), \quad [\sigma] = \begin{pmatrix} \tau_n & \tau_t \\ \tau_t & \sigma_{tt} \end{pmatrix}$$

$$F_n = \left(\frac{\tau_t}{s_m \tau_{sf}}\right)^2 + e^{\kappa B_n} - 1$$

$$B_n = \frac{\tau_n}{\tau_{nf}} + \frac{\langle -\sigma_{tt} \rangle^2}{f_c'^2} - 1$$

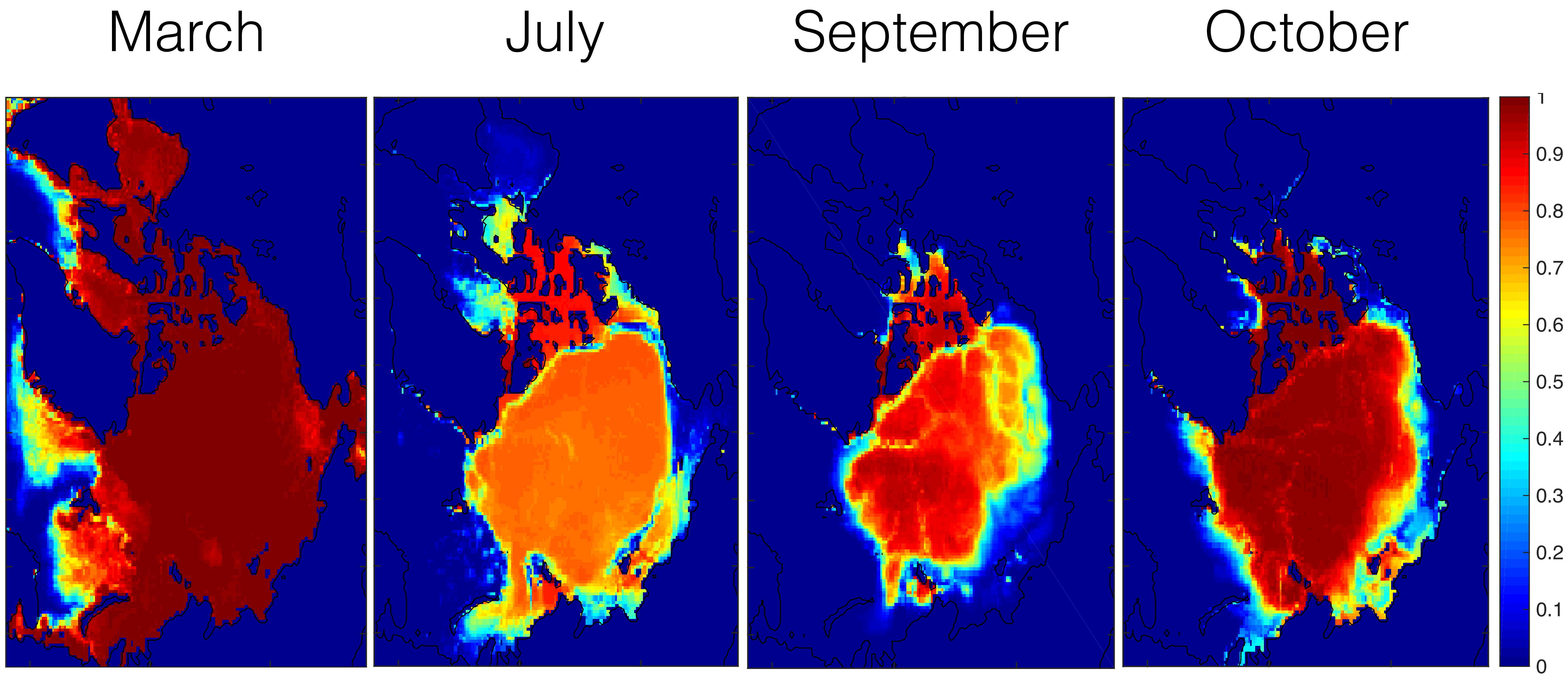
Model parameters:

$$\begin{aligned} \tau_{nf} &= \text{tensile strength} \\ \tau_{sf} &= \text{shear strength} \\ f_c' &= \text{compressive strength} \\ s_m &= \text{shear magnification} \end{aligned}$$



Modeled failure envelope F=0. Arrows show the predicted direction of the normal to the crack surface. Directions match experiments at (a-d).

Sea ice concentration 2003



Grid resolution = 36km

Metrics

Multi-category contingency table

		Observed category				
	ij	1	2	$\cdots$	K	Total
Forecast category	1	$n(F_1, O_1)$	$n(F_1, O_2)$	$\cdots$	$n(F_1, O_K)$	$N(F_1)$
	2	$n(F_2, O_1)$	$n(F_2, O_2)$	$\cdots$	$n(F_2, O_K)$	$N(F_2)$
	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
	K	$n(F_K, O_1)$	$n(F_K, O_2)$	$\cdots$	$n(F_K, O_K)$	$N(F_K)$
	Total	$N(O_1)$	$N(O_2)$	$\cdots$	$N(O_K)$	N

$$hits[i] = n(F_i, O_i),$$ event forecast to occur and did occur

$$false\ alarm[i] = \sum_{j \neq i} n(F_i, O_j),$$ event forecast to occur, but did not occur

$$misses[i] = \sum_{j \neq i} n(F_j, O_i).$$ event forecast not to occur, but did occur

Name	Perfect	Definition	Interpretation
Bias	1	$\frac{h + fa}{h + m}$	How did the forecast frequency of ‘yes’ events compare to the observed frequency of ‘yes’ events?
POD	1	$\frac{h}{h + m}$	What fraction of the observed ‘yes’ events were correctly forecast?
SR	1	$\frac{h}{h + fa}$	What fraction of the forecast ‘yes’ events were correctly observed?
TS	1	$\frac{h}{h + m + fa}$	How well did the forecast ‘yes’ events correspond to the observed ‘yes’ events?

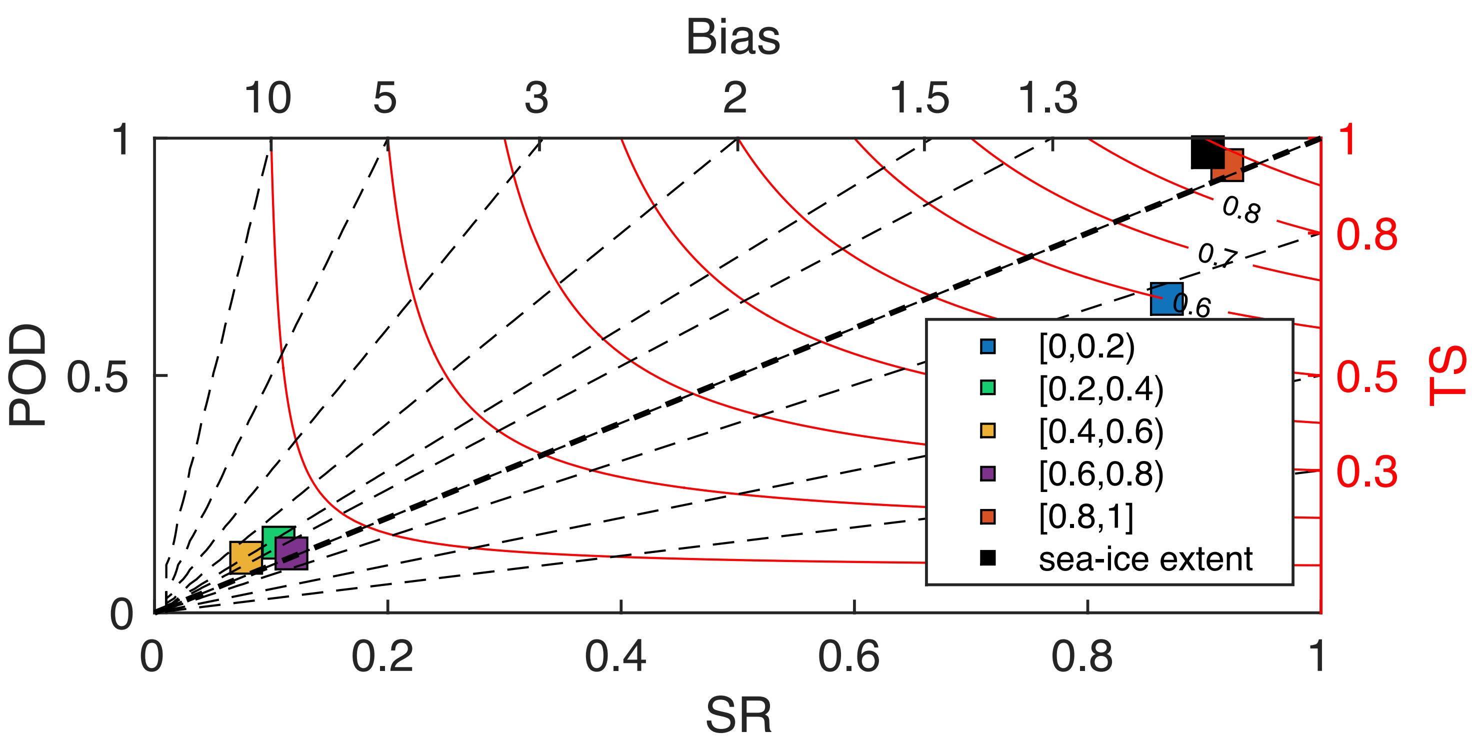
Performance diagram

- Roebber (2009)

- Use geometric relationship of 4 metrics:

$$\text{bias} = \frac{\text{POD}}{\text{SR}},$$

$$\text{TS} = \frac{1}{\frac{1}{\text{SR}} + \frac{1}{\text{POD}} - 1}.$$



- Easy to read and display

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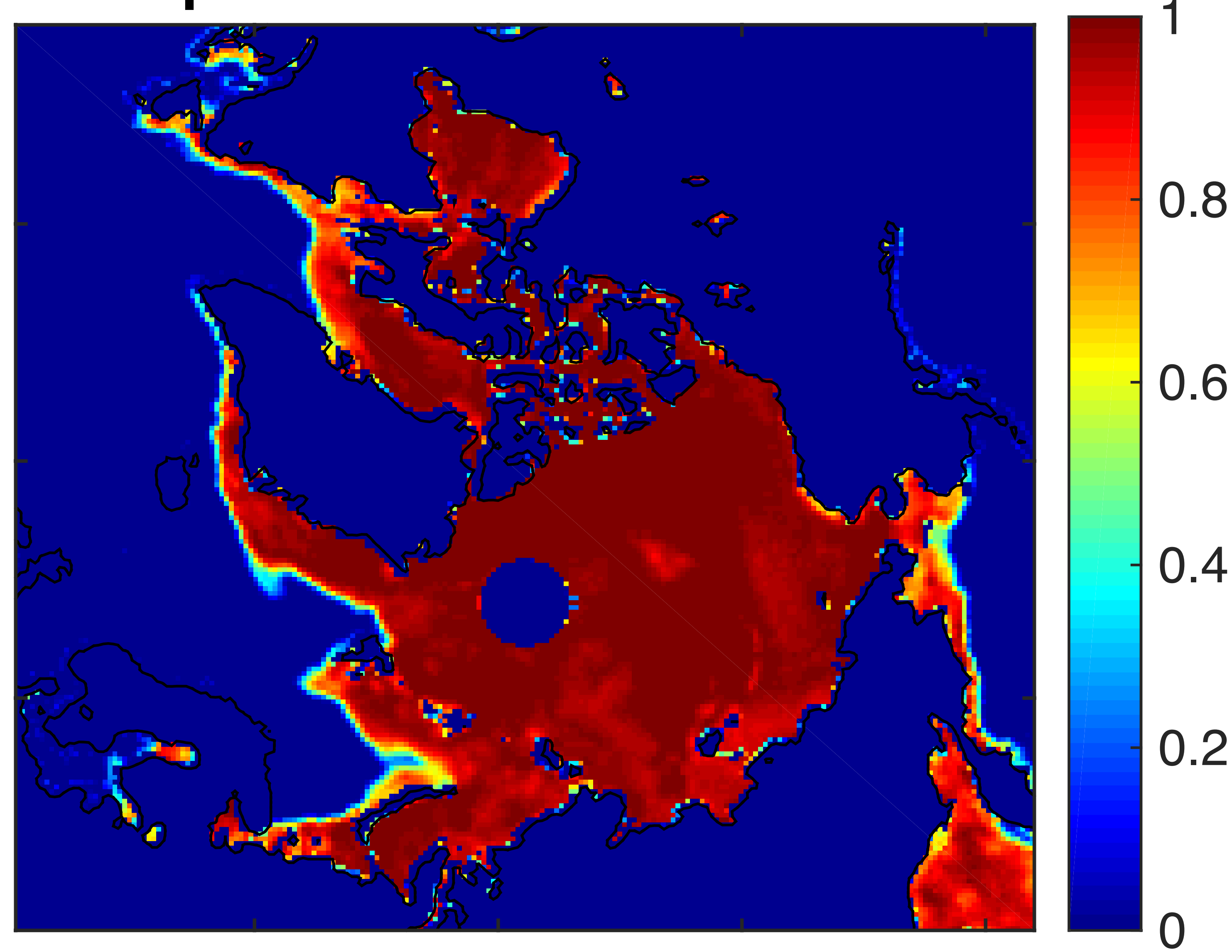
Model comparison

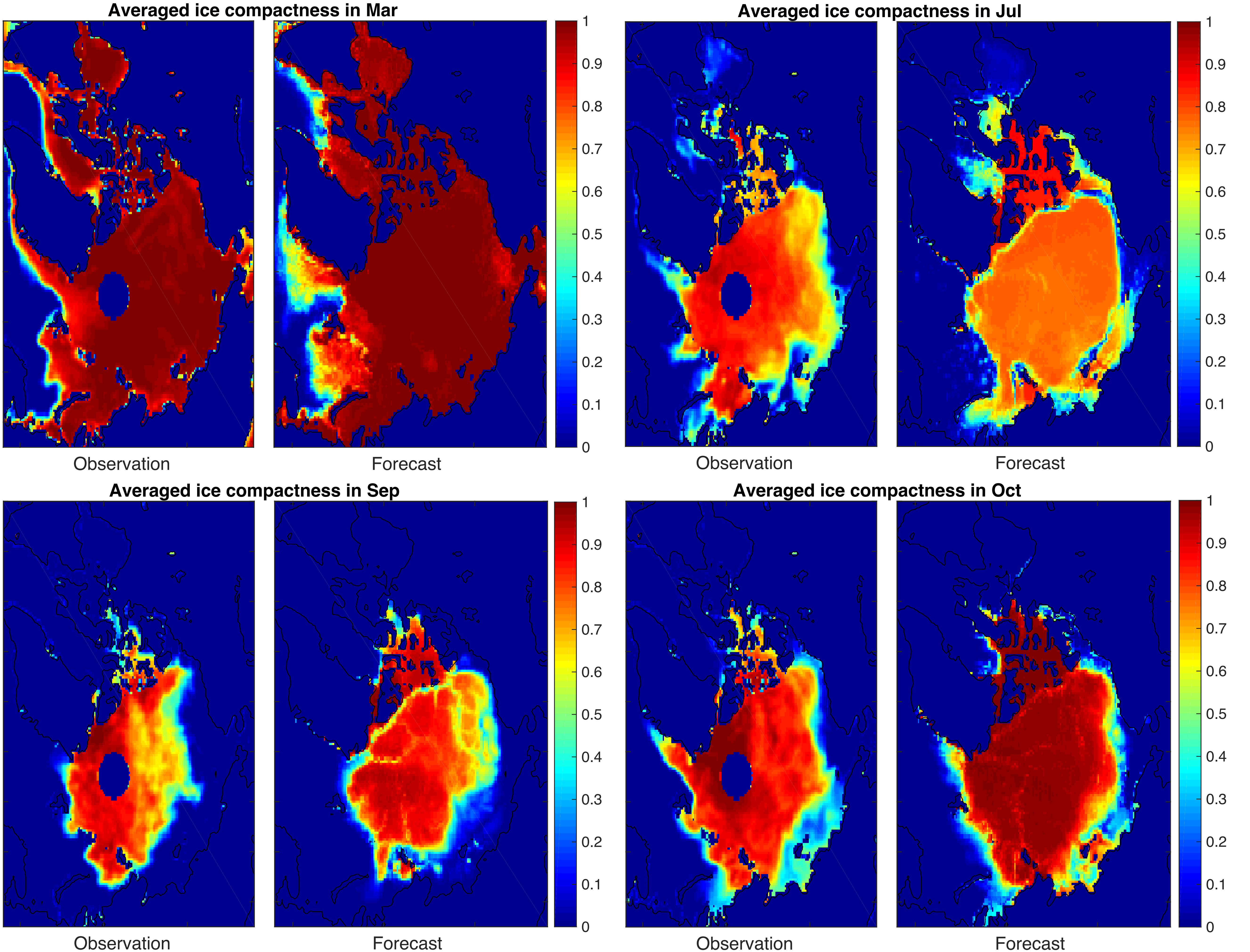
Sea ice concentration

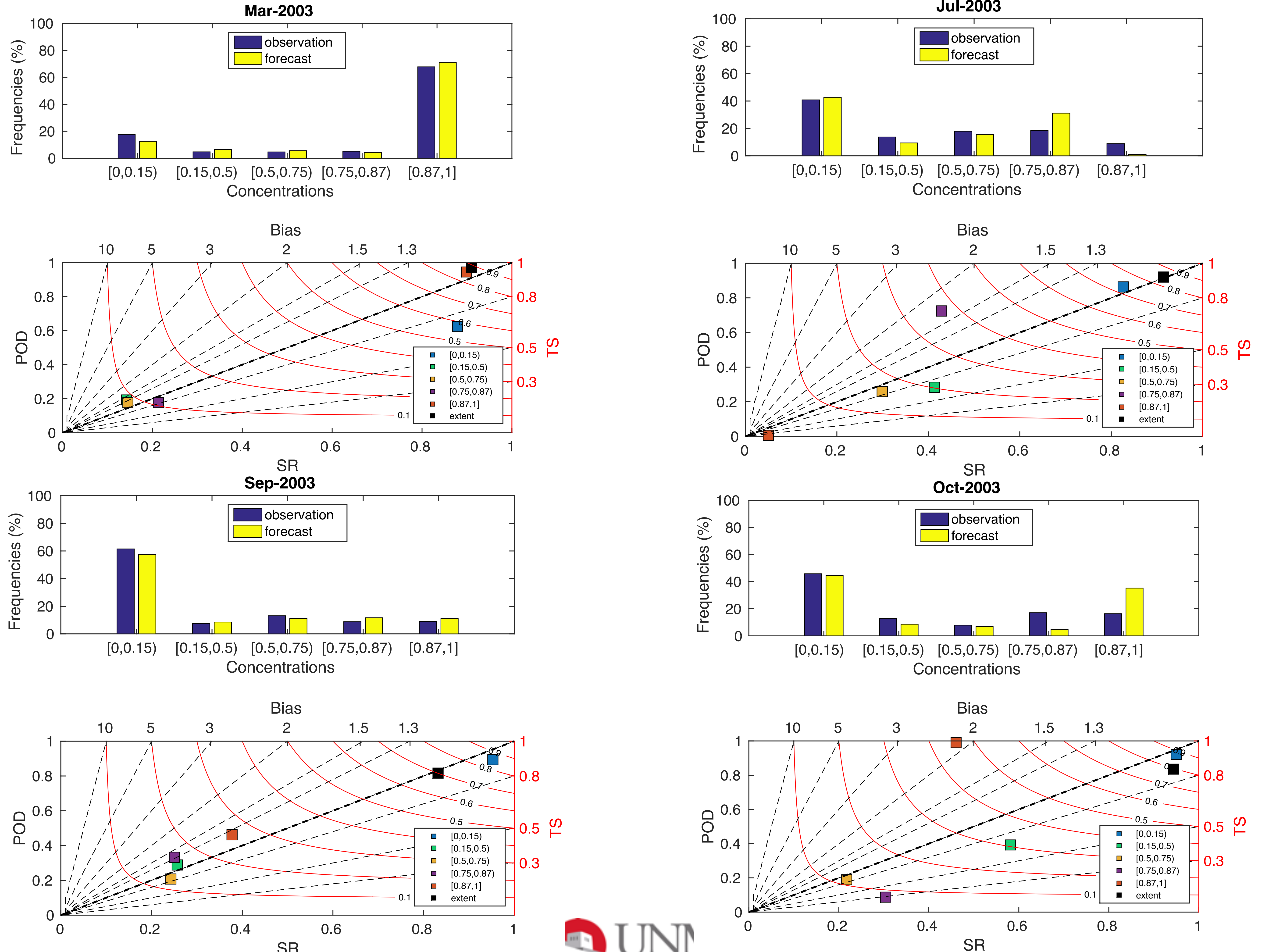
Observations

- Nimbus-7 passive microwave data (Cavalieri et. al, 1996)
- Gridded resolution: 25 km * 25 km
- Sensitivity: ±5% in winter and ±15% in summer

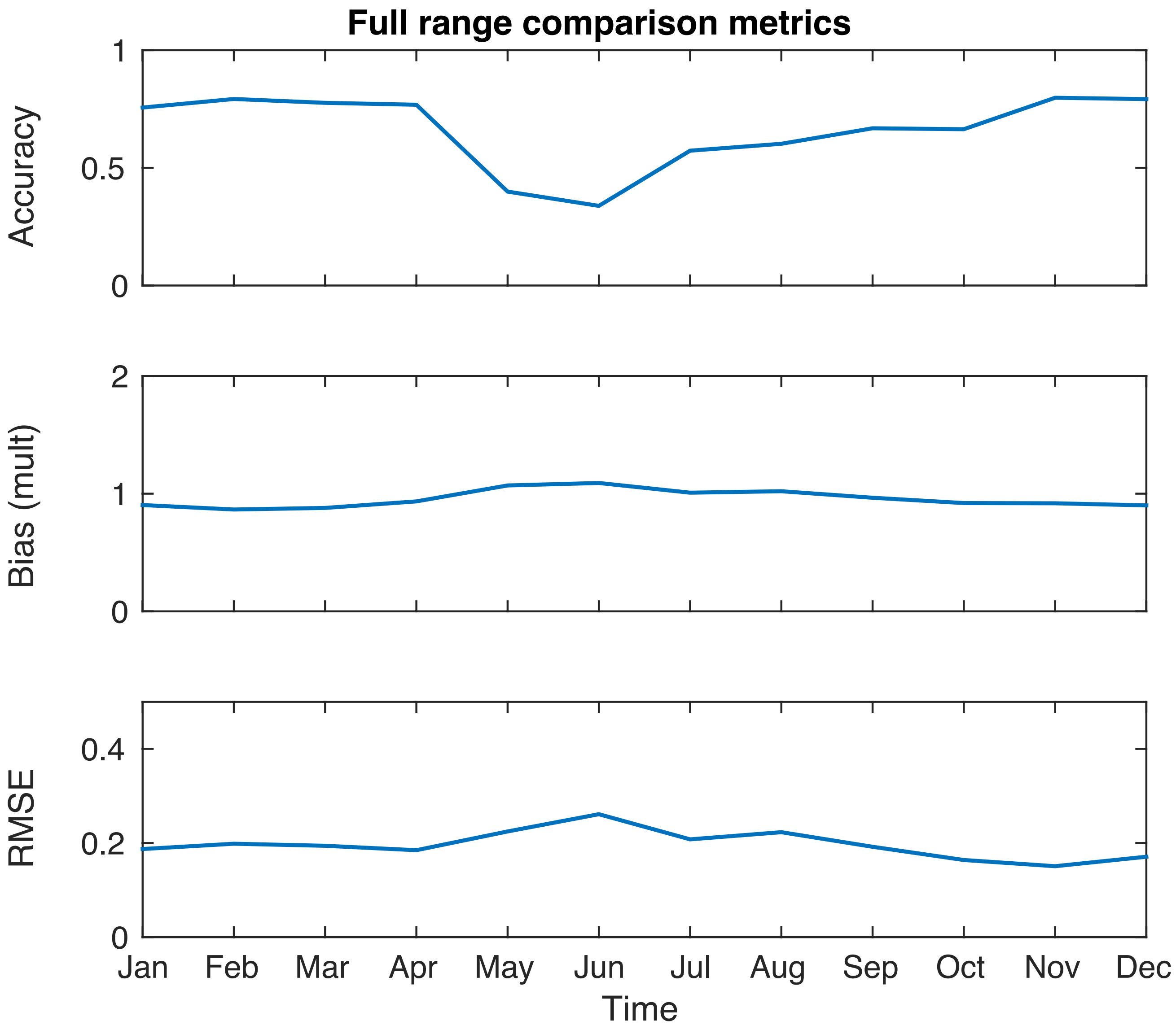
Ice compactness on Mar-15-2001




Averaged ice compactness in Mar
Observation
Forecast
Averaged ice compactness in Jul
Observation
Forecast
Averaged ice compactness in Sep
Observation
Forecast
Averaged ice compactness in Oct
Observation
Forecast
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

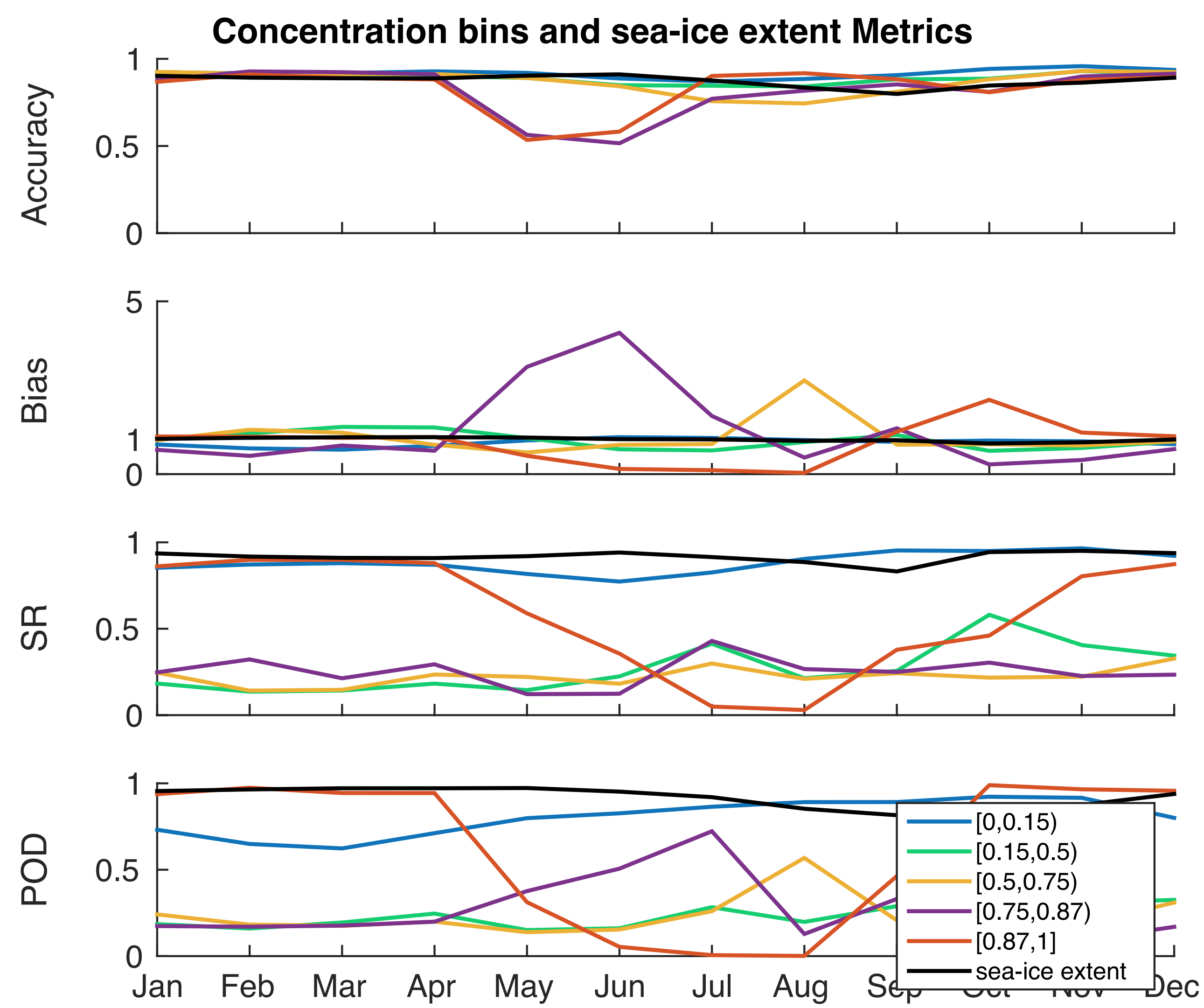


Mar-2003
Jul-2003
Sep-2003
Oct-2003
observation
forecast
Frequencies (%)
Concentrations
[0,0.15)
[0.15,0.5)
[0.5,0.75)
[0.75,0.87)
[0.87,1]
extent
Bias
10
5
3
2
1.5
1.3
POD
SR
TS
0.1
0.3
0.5
0.6
0.7
0.8
0.9
1



- Late spring and summer months are the least accurate and have the highest RMSE
- Bias (mult) alone does not provide useful information

- Bad accuracy is driven by high concentration inaccuracy
- The bias shows the disparity of each bin (the mult Bias looks good because of compensation)
- SR and POD confirm the model's inaccuracy in late spring and summer months



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Conclusion from sea ice concentration comparison

- Sea-ice extent is well matched all year long
- Concentration is well matched year round besides in the summer during which forecast is weaker (larger error in observations as well though)
- Thermodynamics needs to be improved? (can't wait for the column physics package release)
- A similar analysis with different bin size (e.g. equal bin size) provides similar conclusions

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Conclusion

- We developed a sea-ice model capable of representing sea-ice fractures and lead openings.

- The model is running and simulates reasonable results.

- Performance and frequency diagrams provide quantitative insight into the validation of multi-category variables. It has the advantage to be easy to read, interpret and implement

- We created a git repository with the code performing the comparison. It is easy to adapt for any model and is available for sea-ice concentration and thickness

- Work in progress for sea ice displacement validation and higher resolution runs