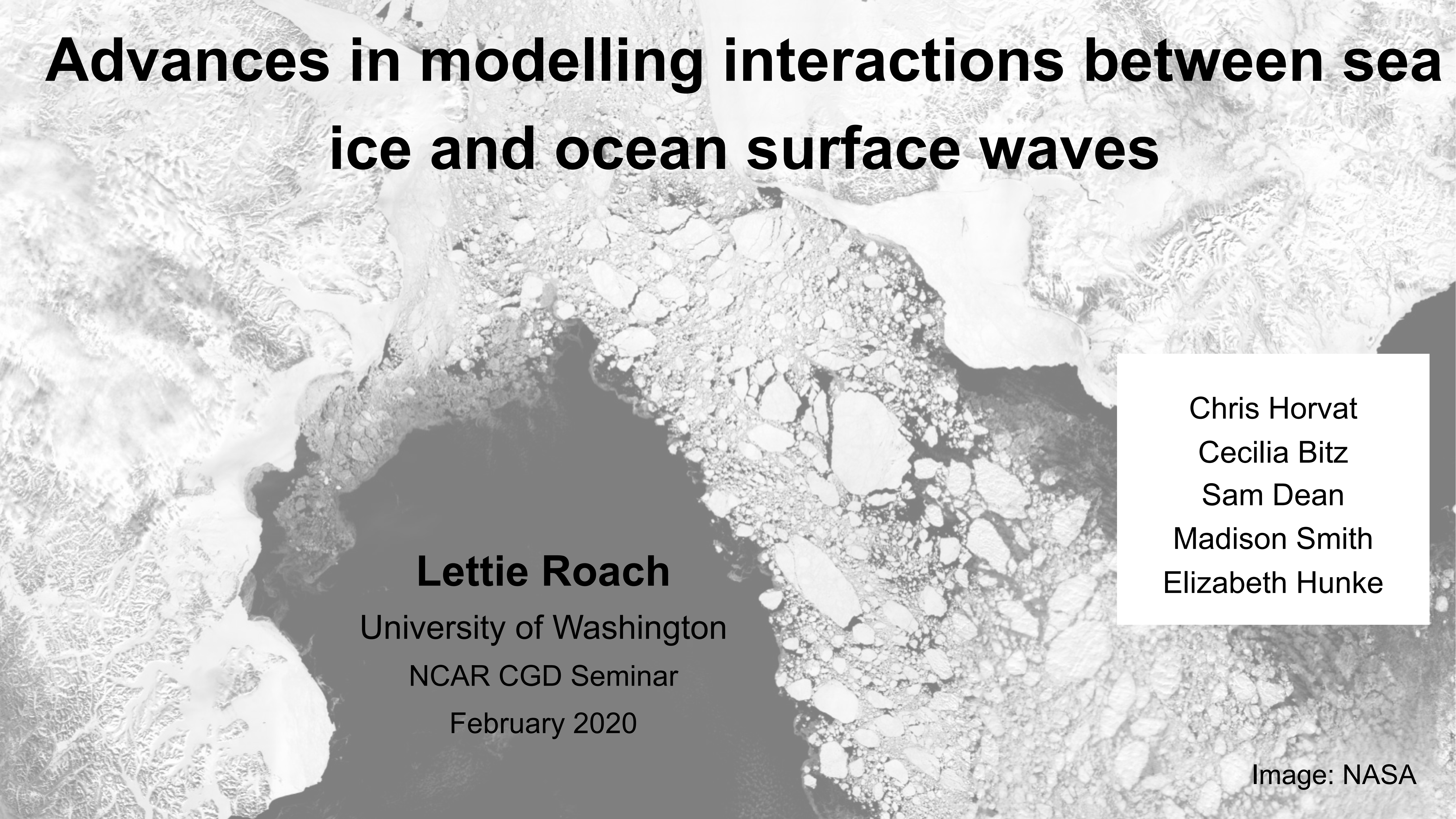

Advances in modelling interactions between sea ice and ocean surface waves

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University of Washington

NCAR CGD Seminar

February 2020

Chris Horvat

Cecilia Bitz

Sam Dean

Madison Smith

Elizabeth Hunke

Image: NASA

CICE

- Recent release: CICE v6.1.0 and Icepack v1.2.0

CICE documentation » 2. Science Guide »

Previous topic

2.1. Coupling With Other Climate Model Components

Next topic

2.3. Tracers

This Page

Show Source

2.2. Fundamental Variables

The Arctic and Antarctic sea ice packs are mixtures of open water, thin first-year ice, thicker multiyear ic
thick pressure ridges. The thermodynamic and dynamic properties of the ice pack depend on how much i
in each thickness range. Thus the basic problem in sea ice modeling is to describe the evolution of the ice
ness distribution (ITD) in time and space.

In addition to an ice thickness distribution, CICE includes an optional capability for a floe size distribution.

- Interactions between waves and sea ice occur via the floe size distribution
- Modelling work has advanced our understanding of the evolution of the floe size distribution
- We still need observations for overall model validation – in progress
- There are number of ways that wave-ice interactions may influence the polar climate system

Motivations

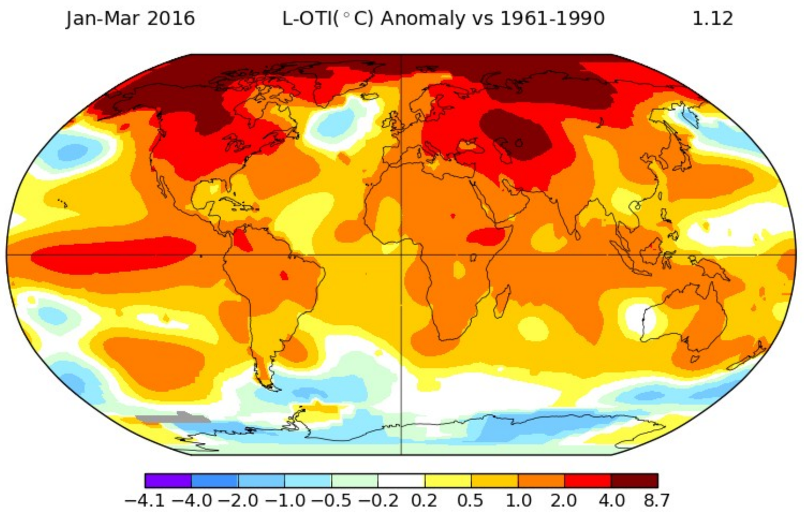
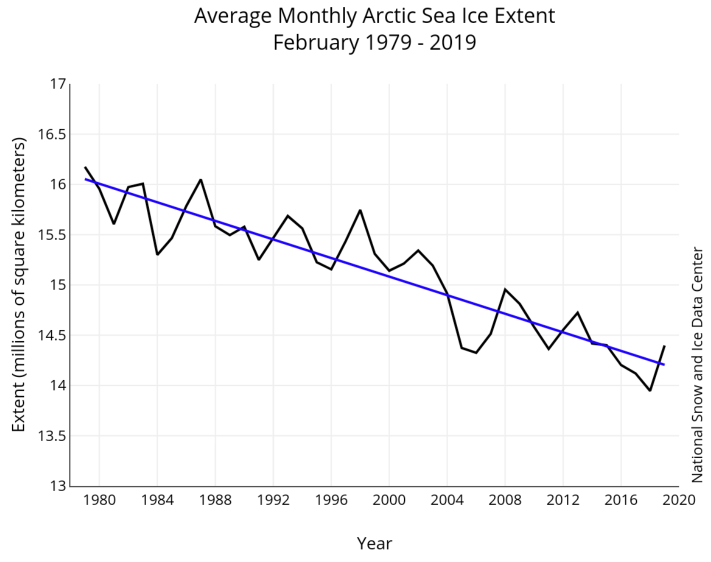
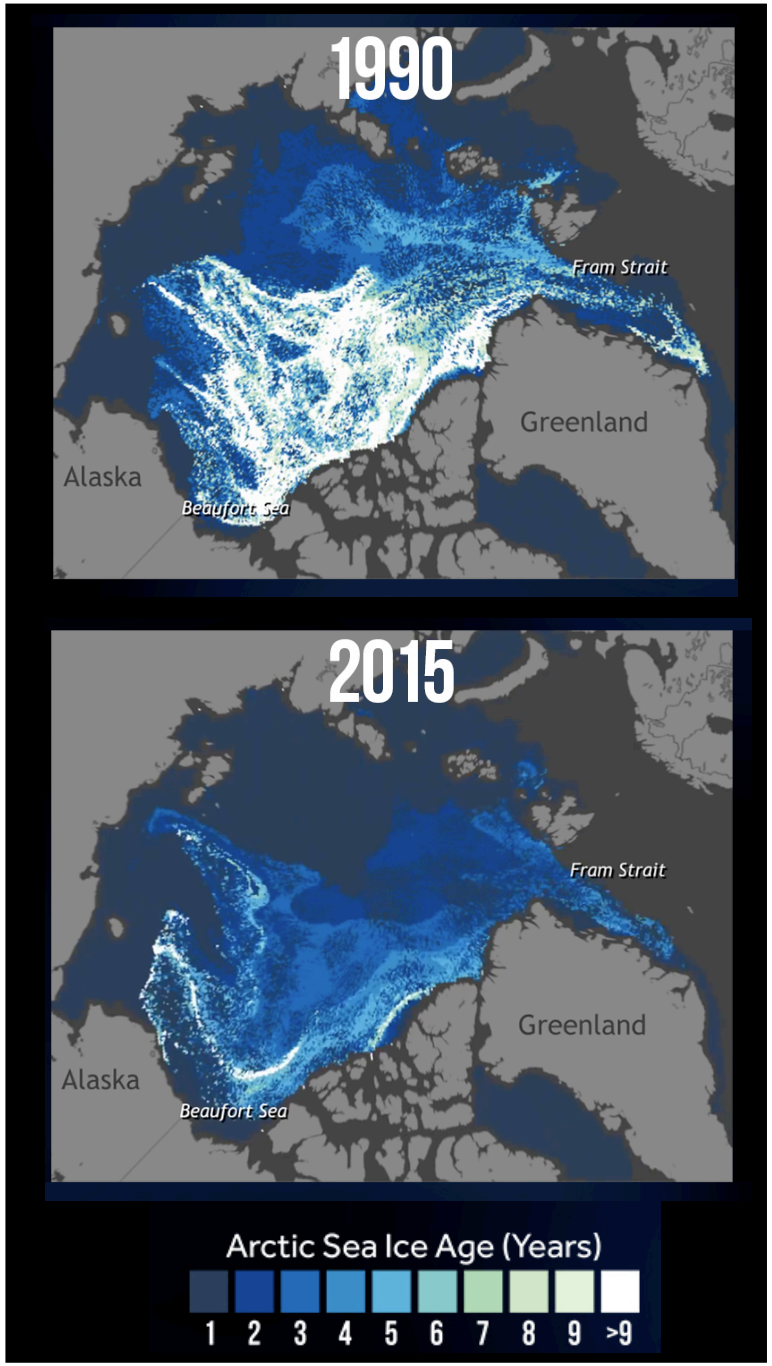


Figure: Surface temperature anomalies (in °C) for Jan-Mar (2016) with respect to a 1961-1990 baseline. [Credit: NASA — GISTEMP (accessed 2016-10-15) and Hansen et al., 2010]





The New Arctic

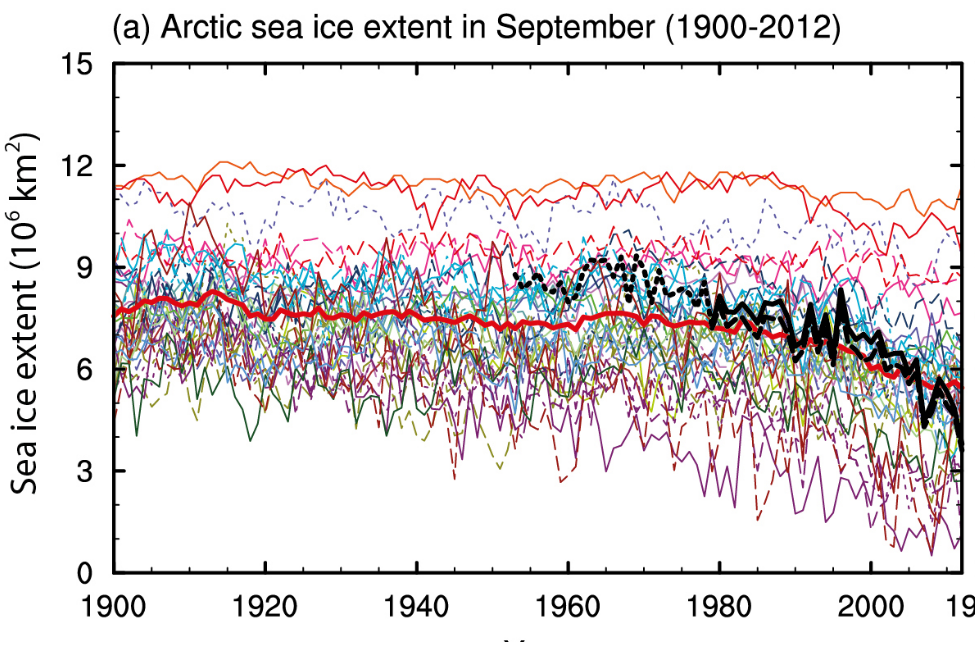
Sea ice is

- Less extensive
- Thinner
- Younger
- Darker
- More seasonal

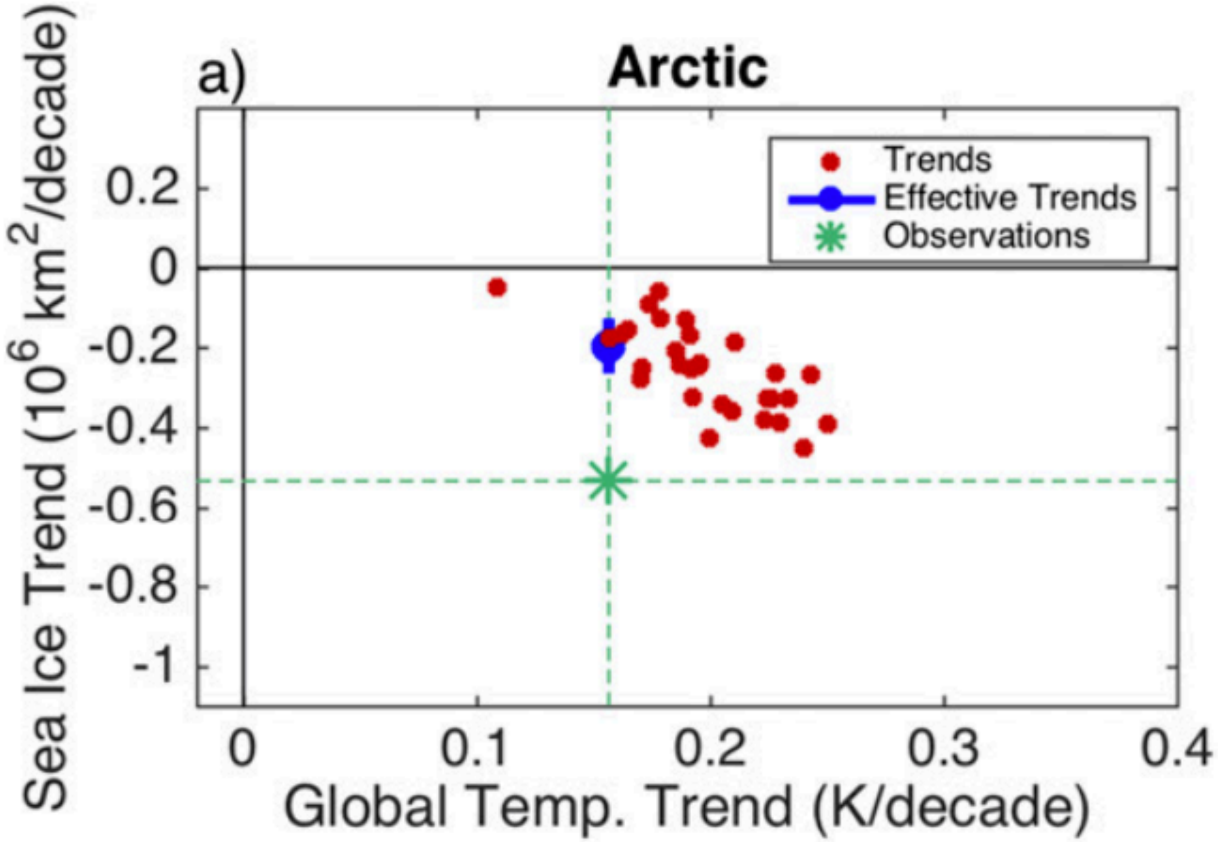
Are models suitable for the 'new Arctic'?

CMIP5

‘Faster than forecast’



Flato et al. (2013) *IPCC WG1 AR5 Ch. 9*

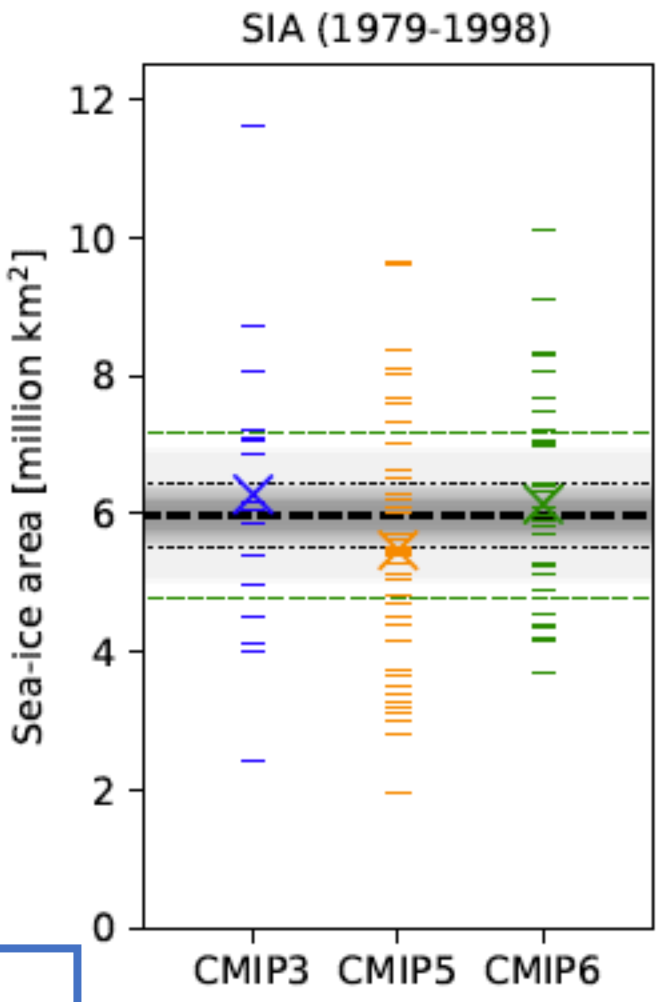


Rosenblum & Eisenman (2017) *J. Clim*

Are models missing feedbacks relevant for sea ice?

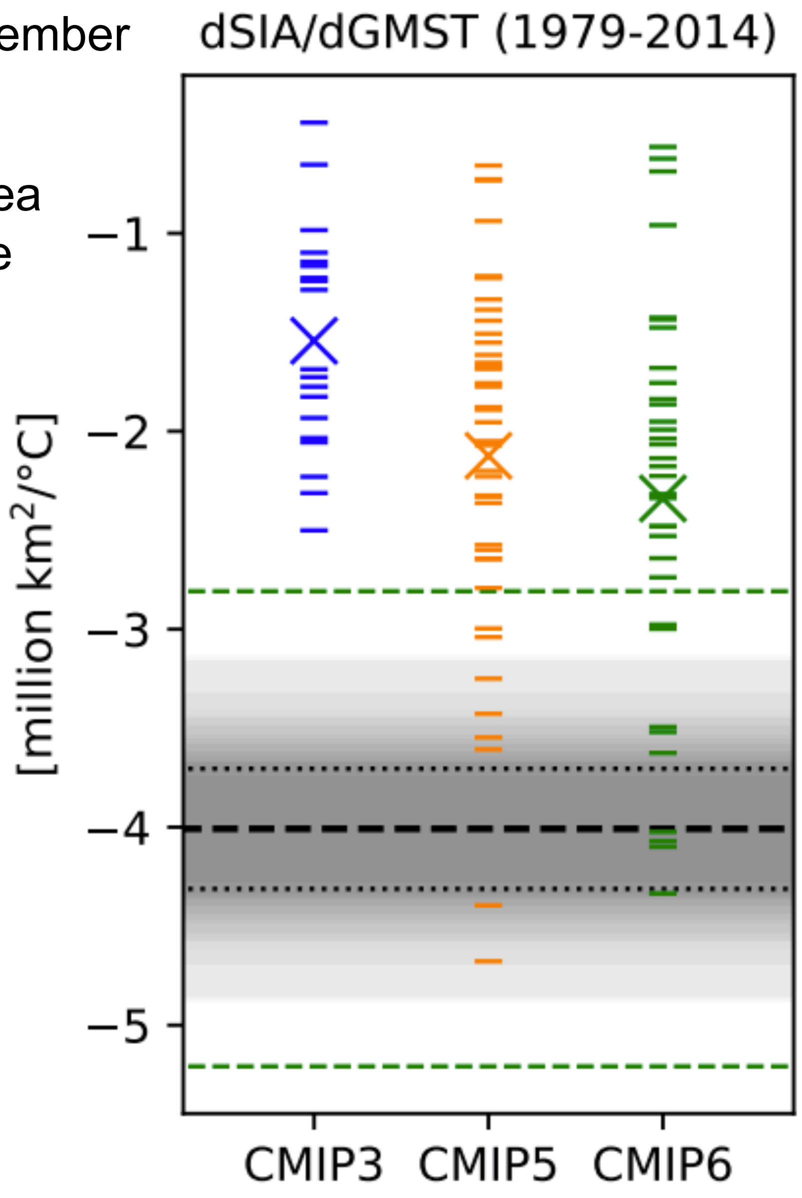
CMIP6

September



September

Change in sea ice area per degree of global warming



NB: Antarctic sea ice – Thursday!

SIMIP Community (2020, in review) *GRL*

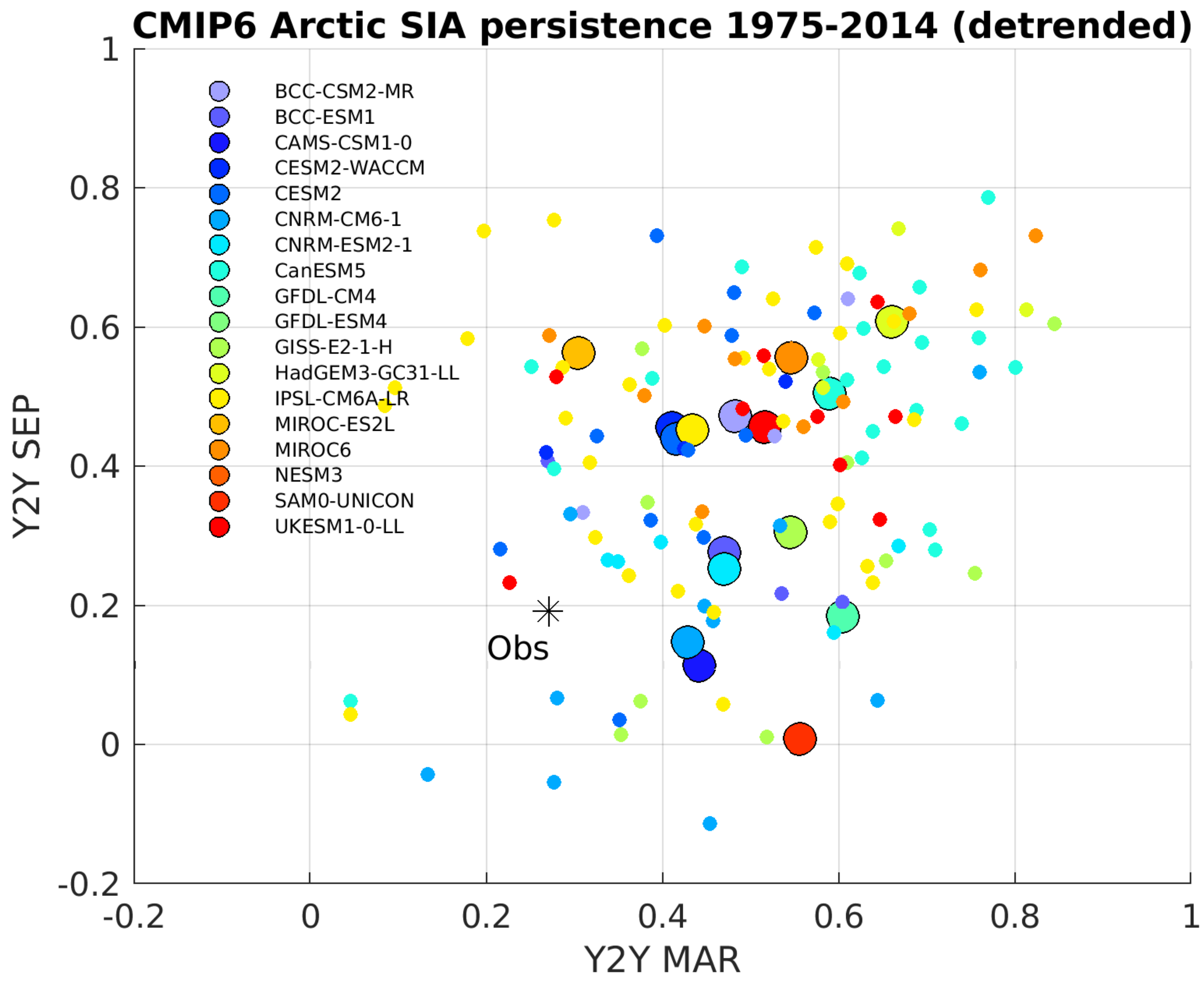
Blanchard-Wrigglesworth & Bushuk (2019) *Clim Dyn*
New figure here courtesy Ed. BW

Sea ice persistence

Y2Y SEP: Year-to-year September autocorrelation

Y2Y MAR: Year-to-year March autocorrelation

Models more persistent than observations



Are sea ice models missing short timescale physics?

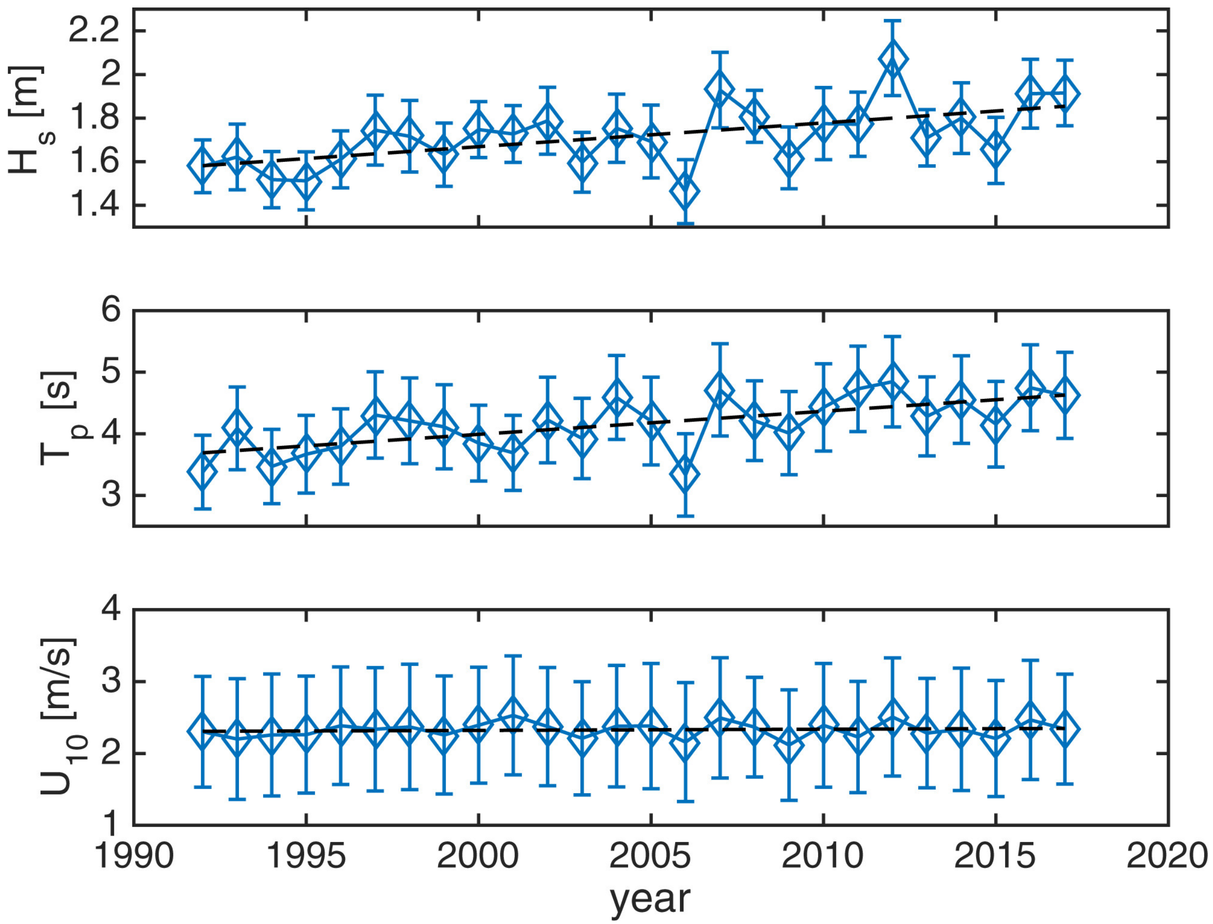
Are models suitable for the ‘new Arctic’?

Are sea ice models missing short timescale physics?

Are models missing feedbacks relevant for sea ice?

Ocean surface waves and sea ice

Enhanced wave activity in the Arctic



Significant wave height

Wave period

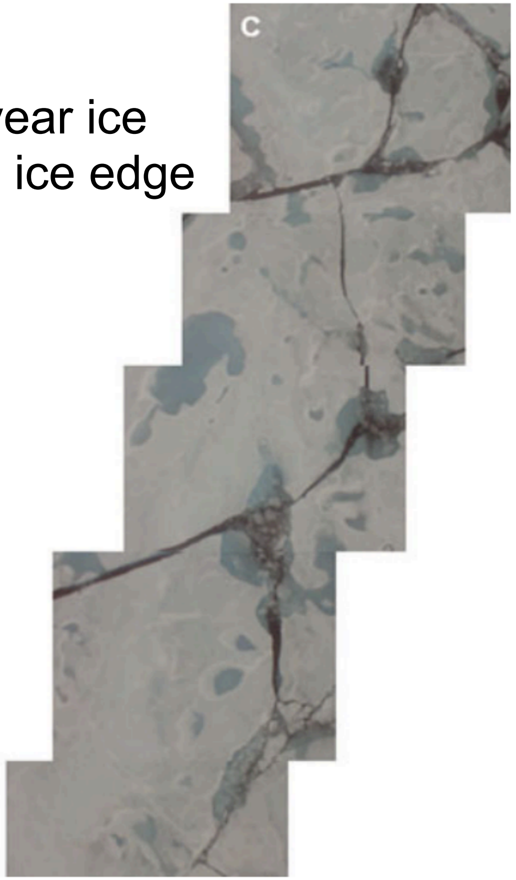
Wind speed

enhanced wave activity due to increased fetch

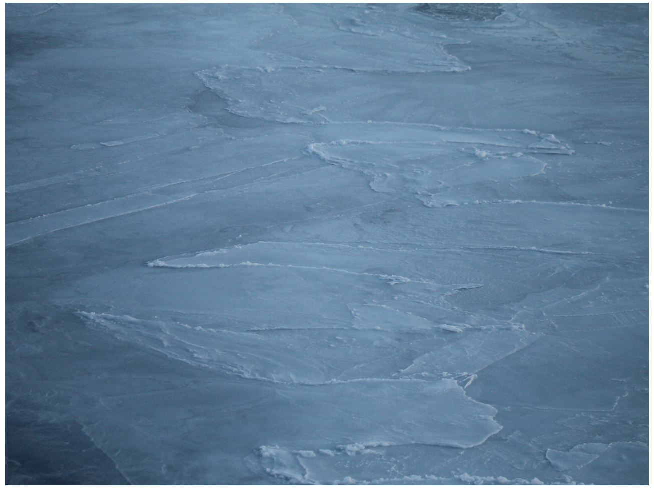
Thomson et al. (2018) *JGR: Oceans*

Waves break up sea ice and influence sea ice growth

Thick multi-year ice
350 km from ice edge



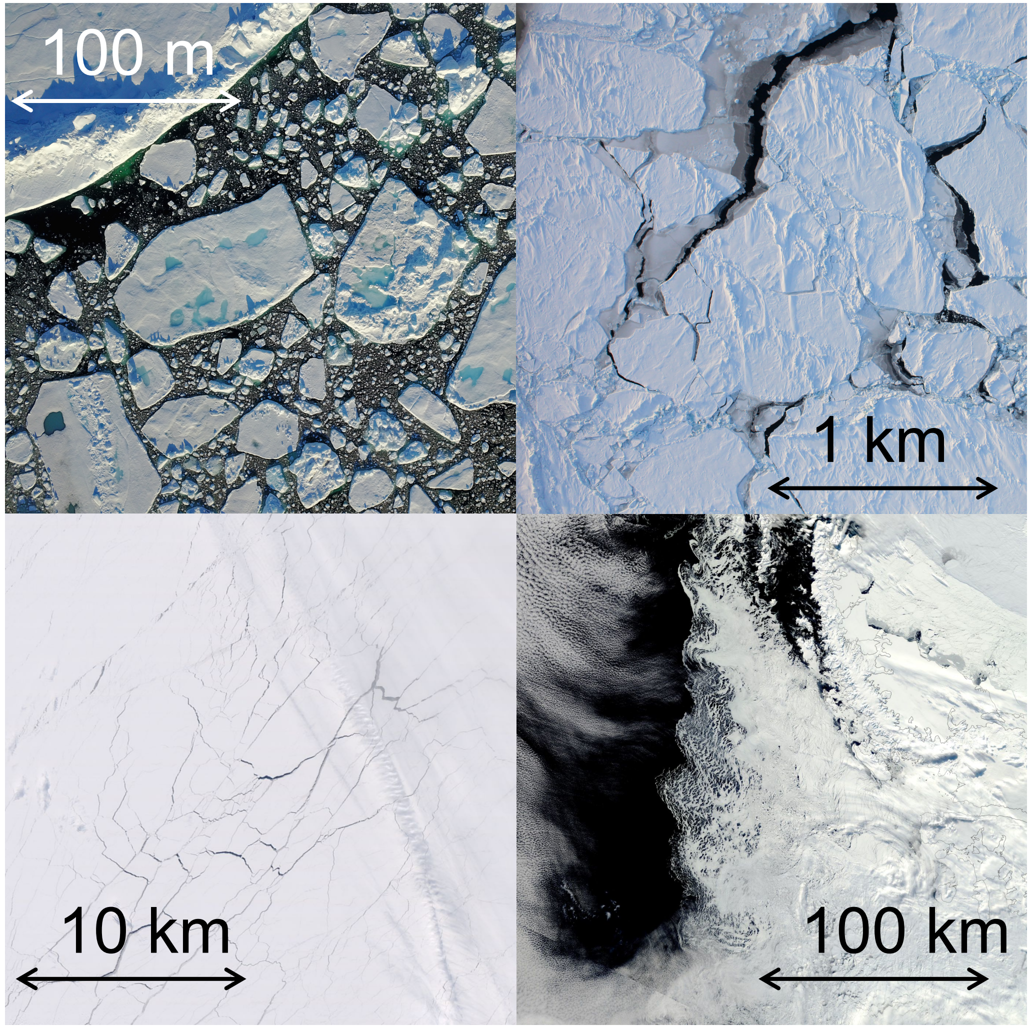
Pancakes



Nilas

Prinsenberg & Peterson (2011) *Ann. Glaciol.*

Floe size distribution (FSD)



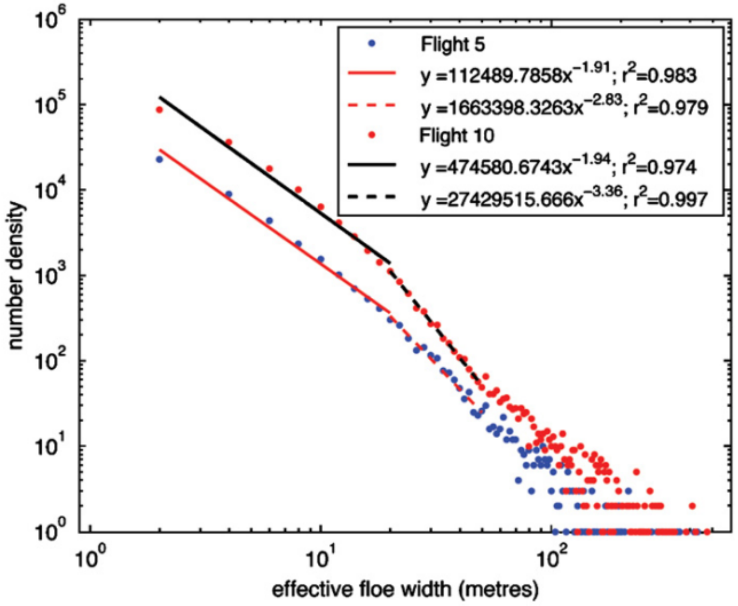


Fig: Steer et al. (2008) *Deep Sea Res. II*

Representative radius

Perimeter per unit ice area

$$\bar{r} \equiv \frac{\langle r^1 \rangle}{\langle r^0 \rangle}$$

- Weighted towards larger floe sizes
- Determines wave attenuation

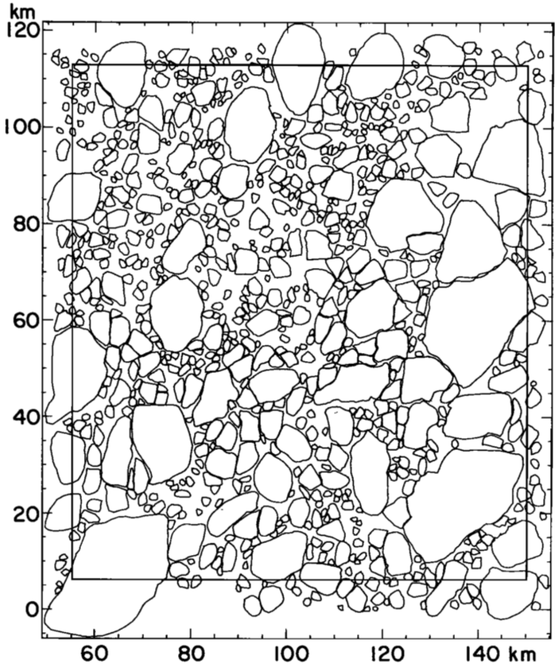
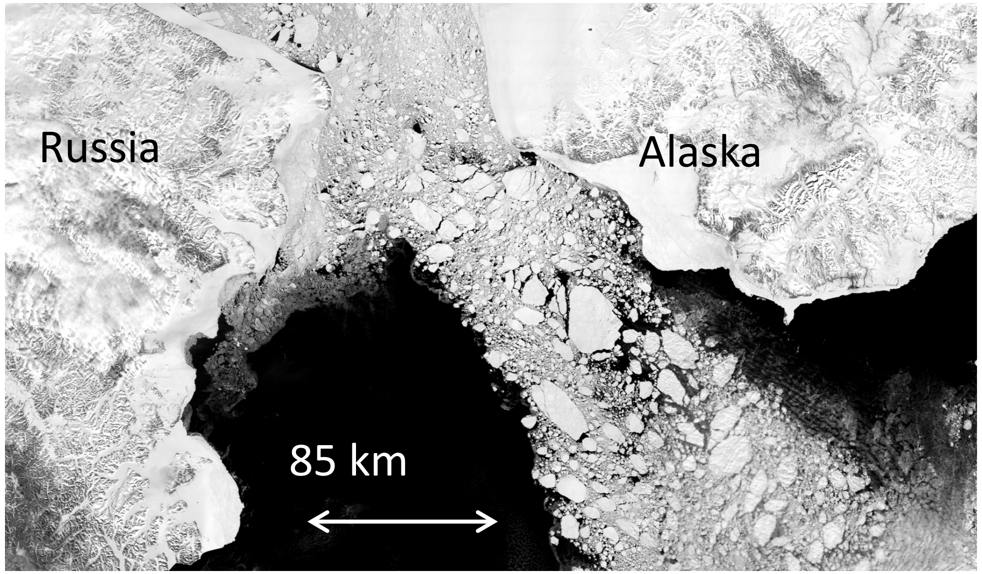


Fig: Rothrock & Thorndike (1984)

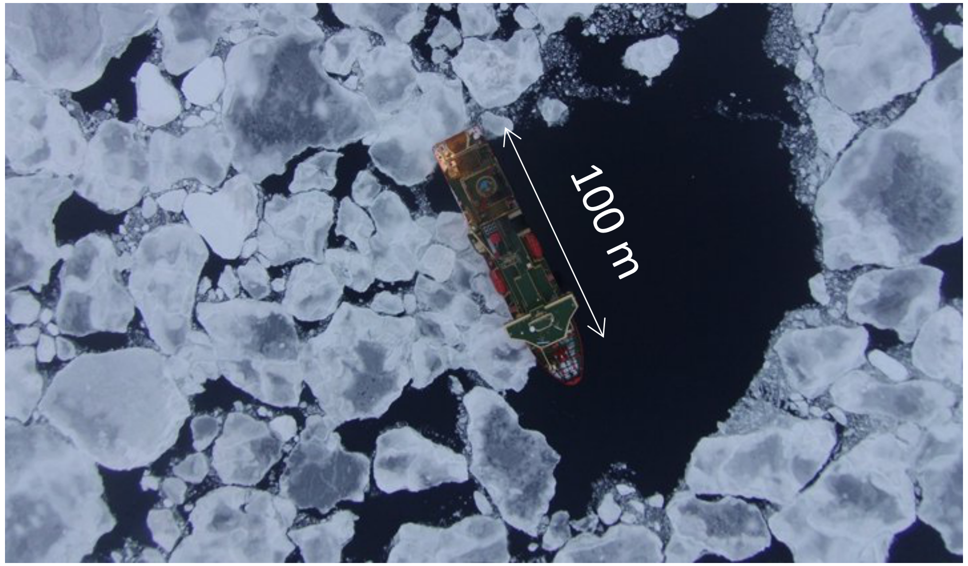
$$P_i \equiv 2\frac{\langle r^{-1} \rangle}{\langle r^0 \rangle} = 2\frac{\langle r^1 \rangle_N}{\langle r^2 \rangle_N}$$

- Weighted towards smaller floe sizes
- Determines lateral melt

- Need to represent FSD to
  - (a) describe impact of waves on ice
  - (b) describe impact of ice on waves



- Coupled climate models
  - don't typically contain wave models
    - if they do, they stop at the ice edge
  - don't represent changes in floe size
    - CICE5: all floes are 300 m in diameter

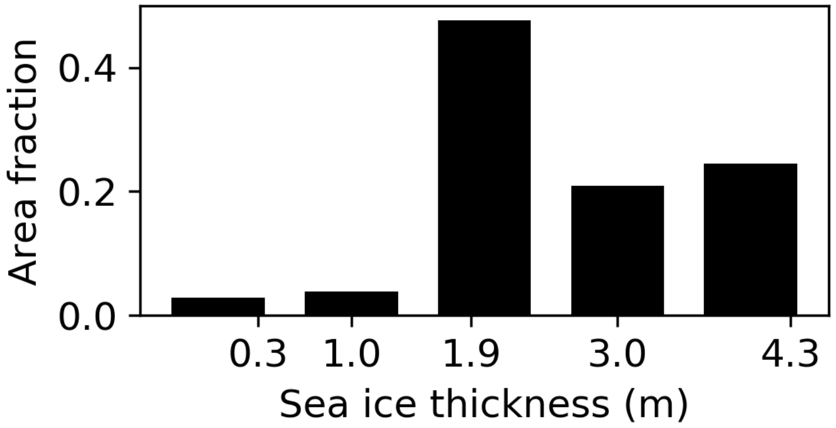


New modelling capability

Horvat & Tziperman (2015) *The Cryosphere*

Roach, Horvat et al (2018) *JGR: Oceans*

Ice thickness distribution



Advection

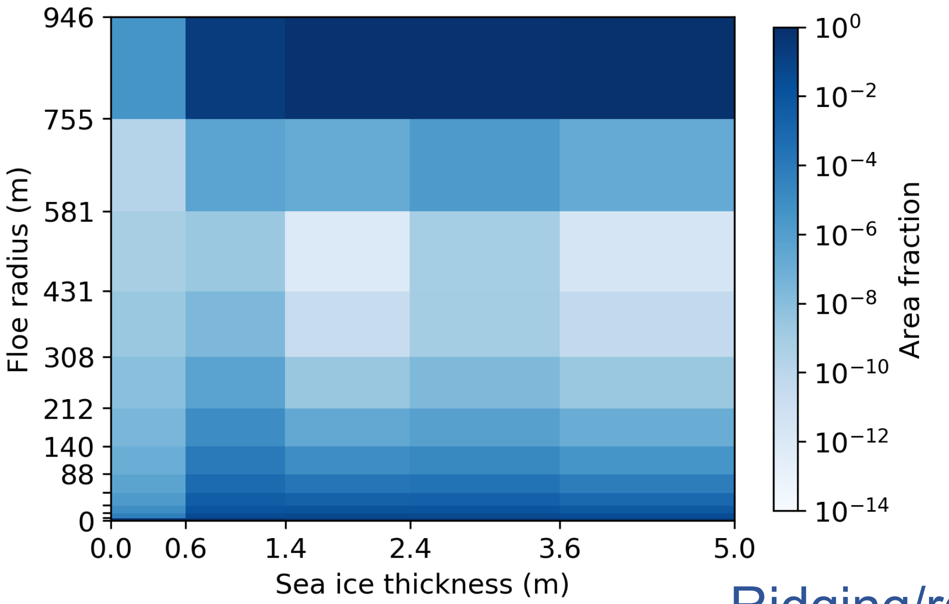
Ridging/rafting

$$\frac{\partial g}{\partial t} = -\nabla.(g\vec{v}) - \frac{\partial}{\partial h}(fg) + \psi$$

Thermodynamics

- Vertical, lateral

Joint floe size and thickness distribution



Ridging/rafting

Advection

Thermodynamics

- Lateral

$$\frac{\partial f}{\partial t} = -\nabla \cdot (f(r,h)\mathbf{u}) + \mathcal{L}_T + \mathcal{L}_M + \mathcal{L}_W$$

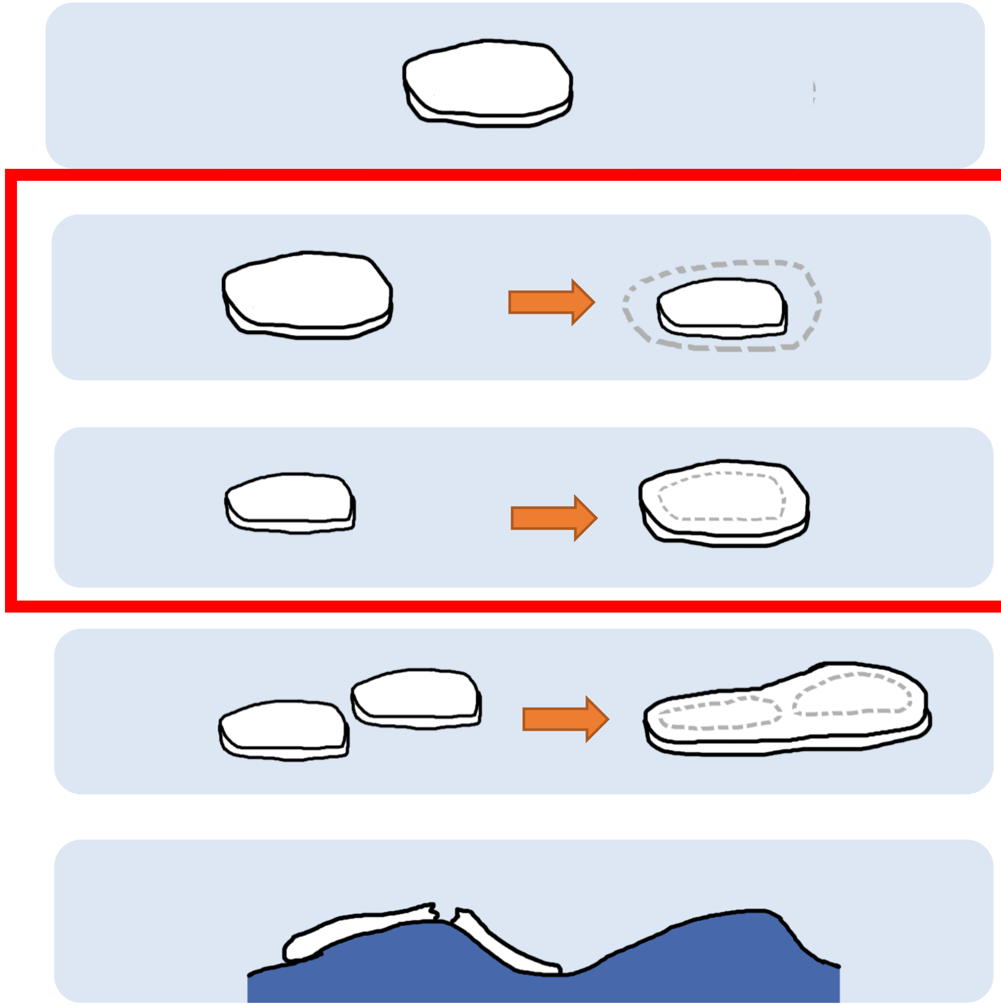
Thermodynamics

- Vertical

Wave fracture

Horvat & Tziperman (2015) *The Cryosphere*
Roach, Horvat et al (2018) *JGR: Oceans*

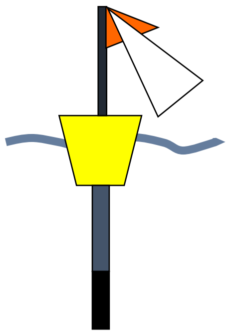
The FSD emerges due to the interaction of physical processes

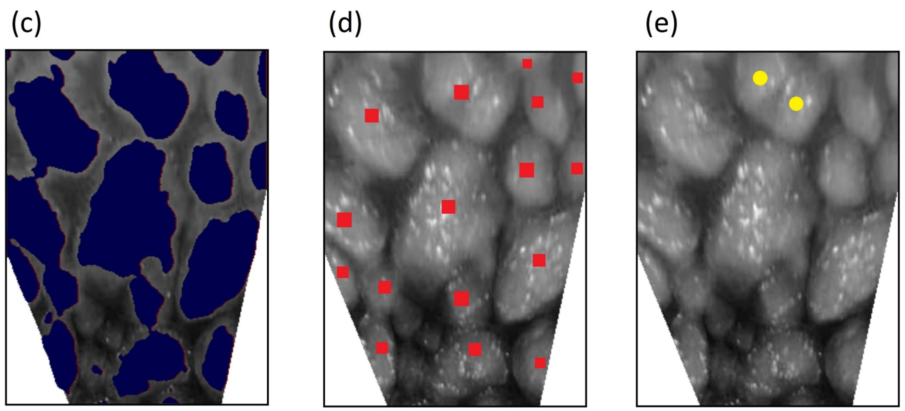


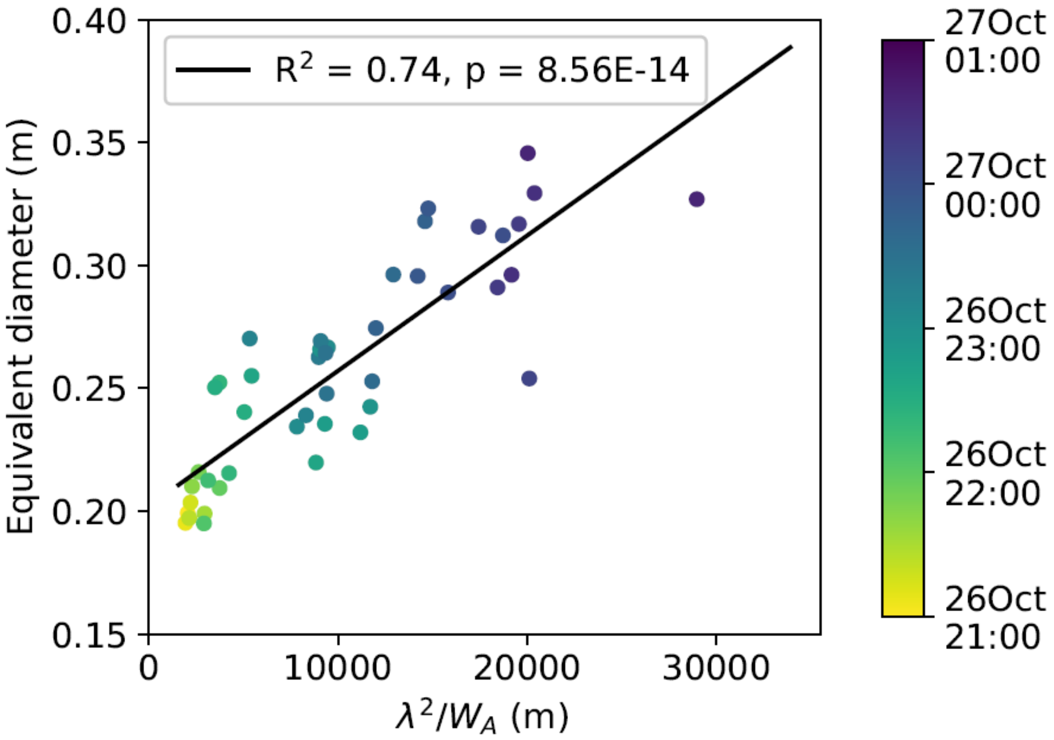
- New ice formation
- Lateral melt
- Lateral growth
- Floe welding
- Wave fracture

Roach, Smith & Dean (2018) *JGR: Oceans*
Roach, Bitz et al. (2019) *JAMES*

In-situ observations of floe growth processes







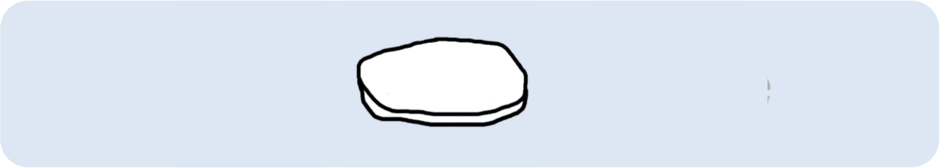
- SWIFT wave buoys (APL) – Lagrangian drifters – in the Arctic
- Compared lateral growth and floe welding
- Tensile stress limitation on floe sizes imposed by the wave field (Shen et al. 2001)

Horvat & Tziperman (2015) *The Cryosphere*
Roach, Horvat et al (2018) *JGR: Oceans*
Roach, Bitz et al. (2019) *JAMES*

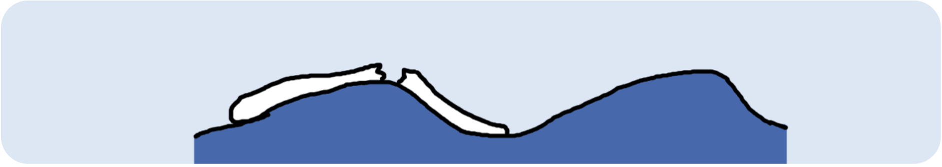
Wave-ice interactions

Input: 1D ocean surface wave spectrum, E(f)

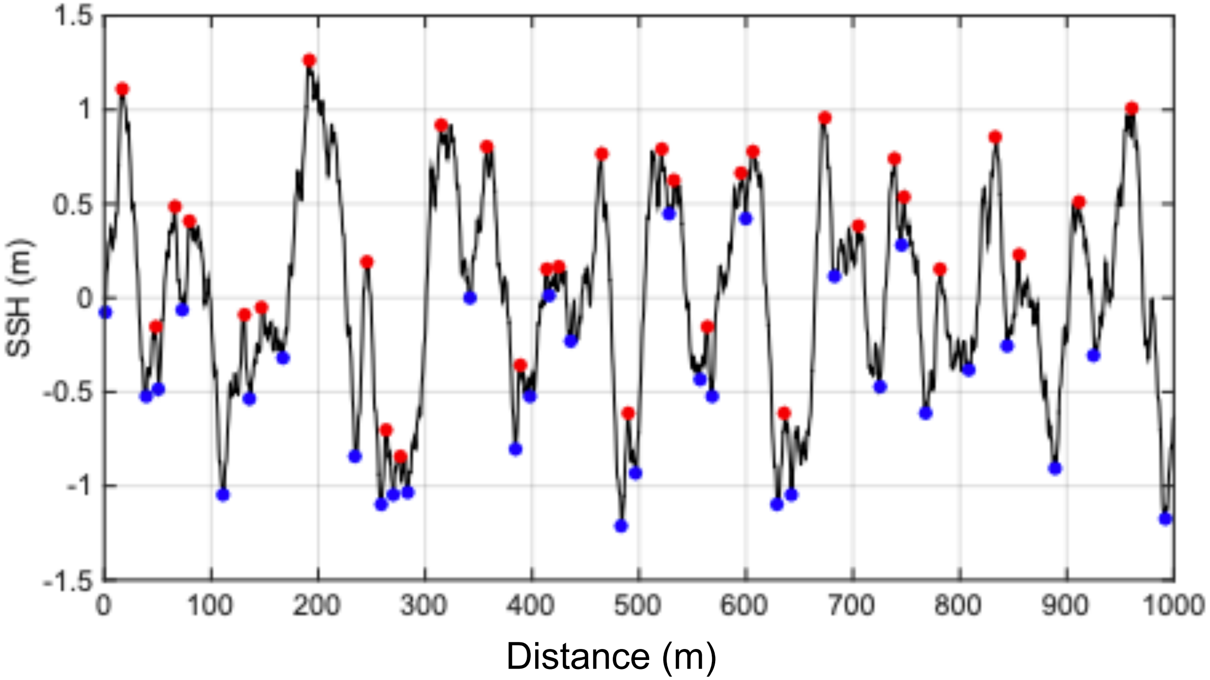
- e.g. coupling with Wavewatch III; empirical expression for wave attenuation as a function of ice thickness, concentration and floe size (Meylan et al. 2020, in prep)



1. Compute wavelength and amplitude for tensile stress → size of newly formed floes

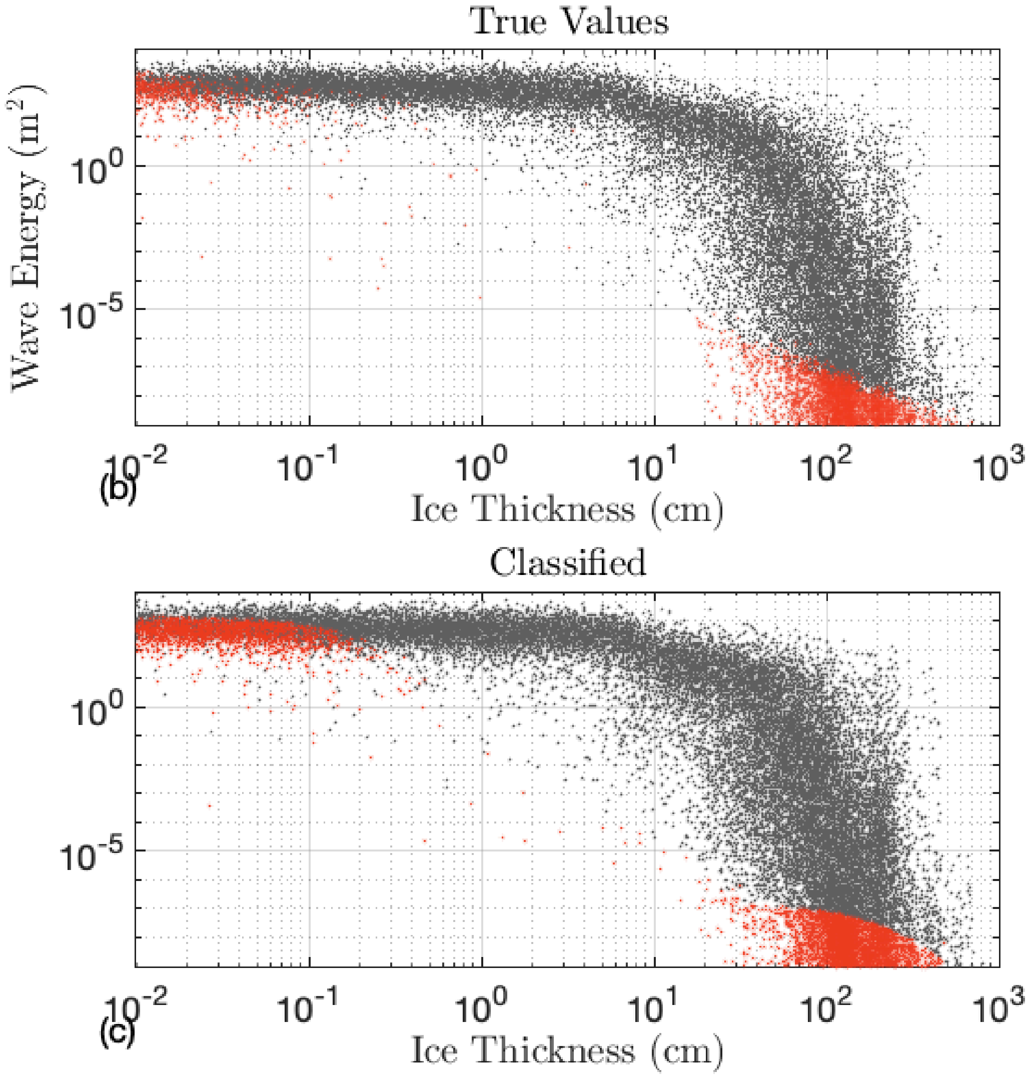


2. Use E(f) to generate realizations of the sea surface height field → strain between extrema in SSH → generate fractures i.e. a super-parametrization



Horvat & Roach (2020, in prep)

Machine-learning-aided parametrization of wave fracture



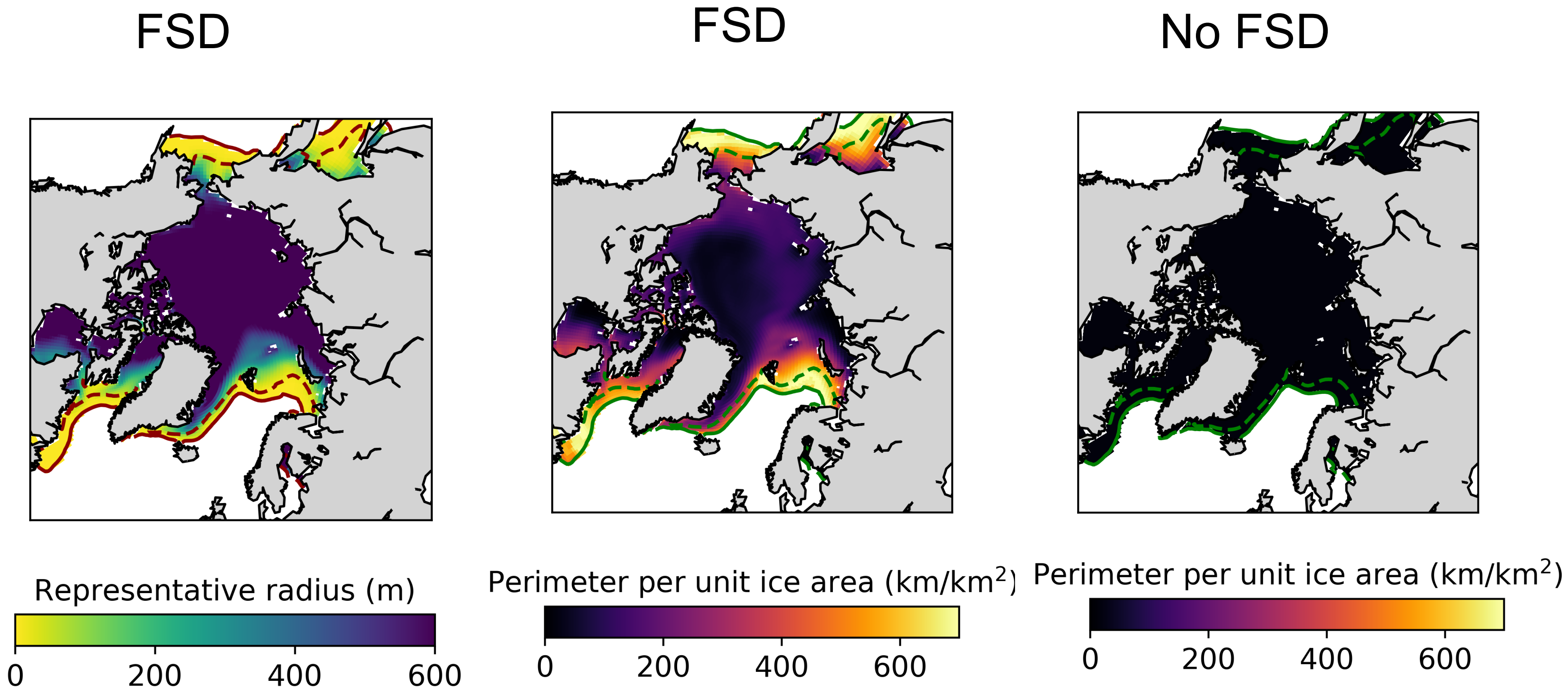
Red is no fracture, grey is fracture.

- **When the model runs, it often doesn't cause fracture.**
  - We train a classifier to recognize when input won't lead to fracture.
  - Shallow (100x100) network trained on 4 million input wave spectra and ice fields
- **The output data is also reasonably well-captured by a deep network**
- Hopefully coming soon to CICE code

Roach, Bitz et al. (2019) *JAMES*

Wave-sea ice coupled results

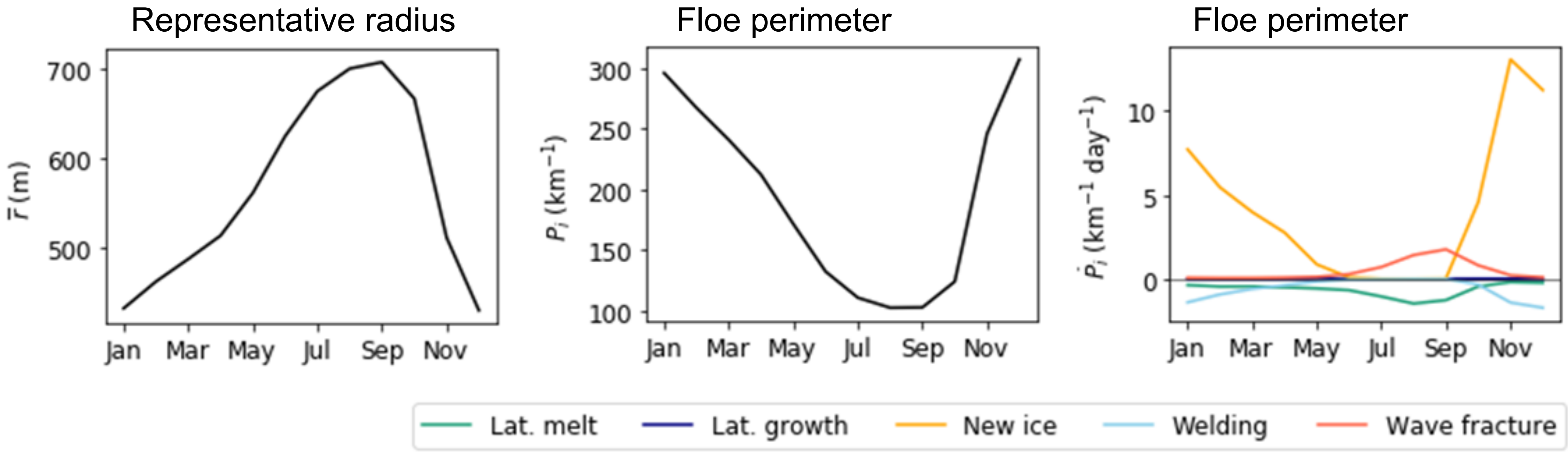
CICE5-WW3 coupled, JRA55 reanalysis, slab ocean, nominal 1 degree, 2000-2014



Roach, Bitz et al. (2019) *JAMES*

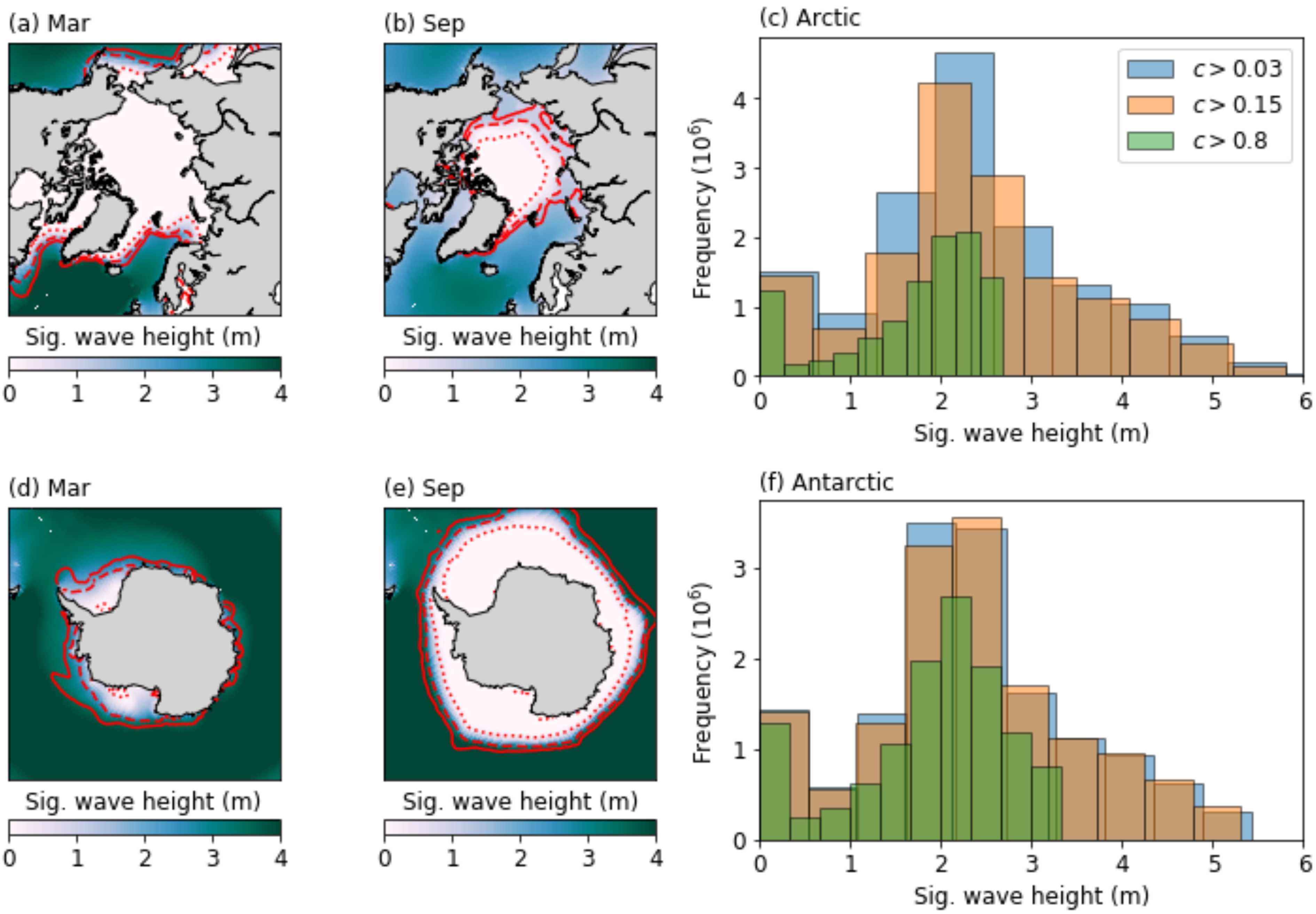
Seasonal cycle in floe size statistics

- Arctic average



- Highlights role of wave-ice interactions

Roach, Bitz et al. (2019) *JAMES*

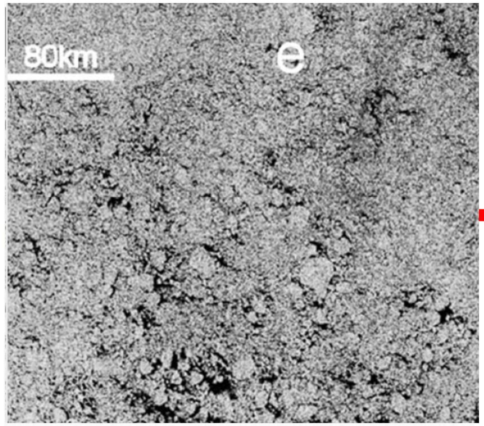


- Significant wave heights in ice can be large
- Need observations for validation

Observations

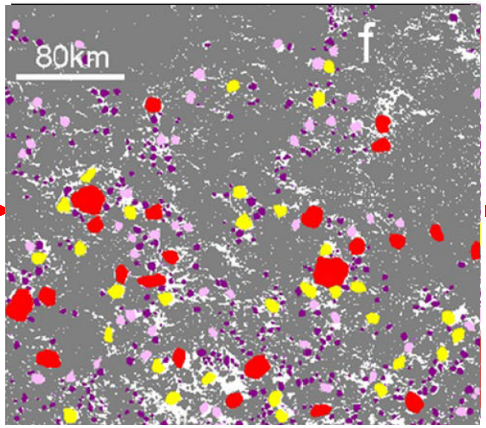
Floe size observations are sparse

(1) Acquire image

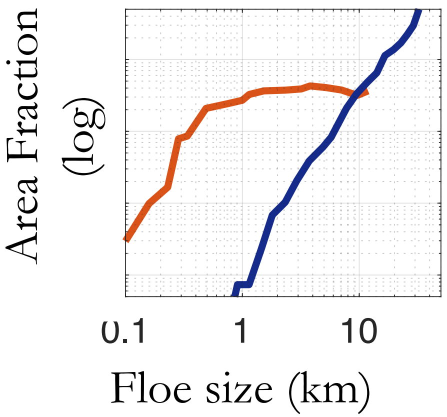


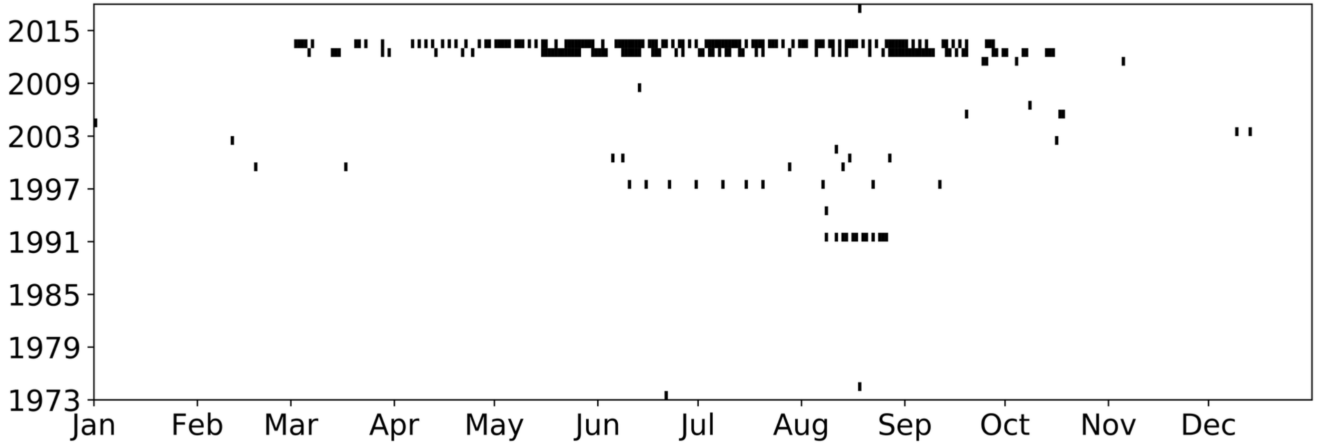
Images from Wang et al, 2016

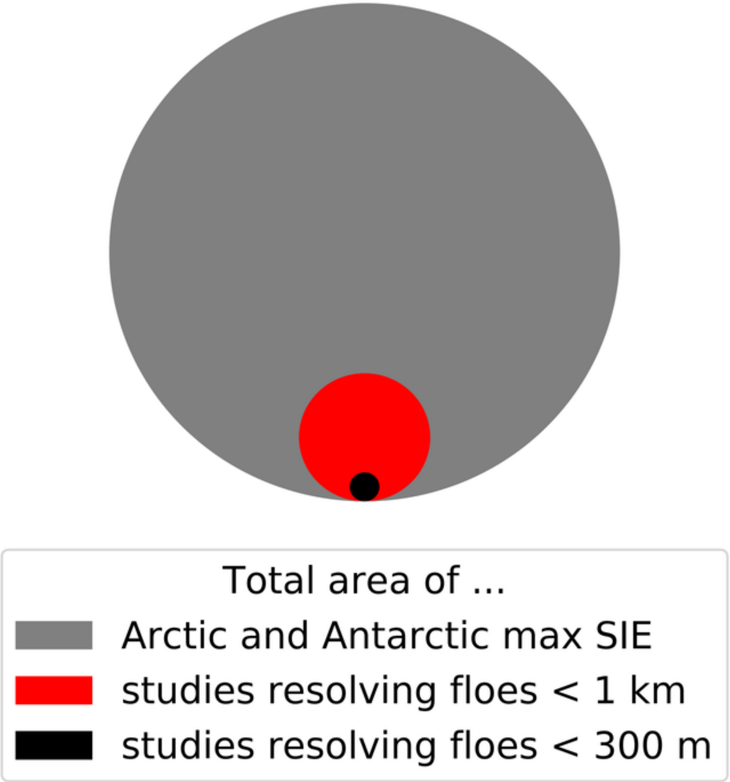
(2) Pick out floes



(3) Plot the FSD







But there is cause for optimism!

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2

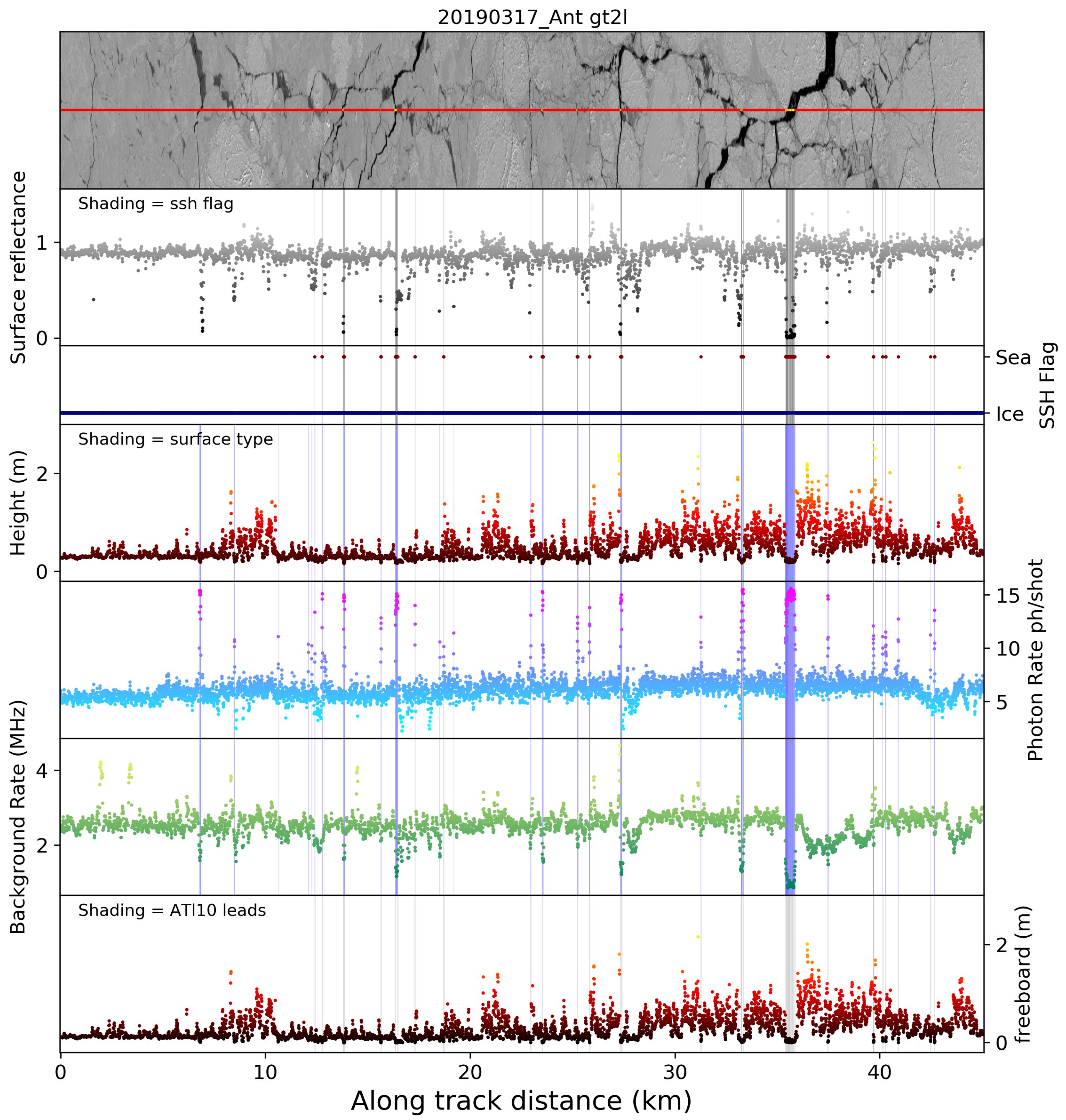
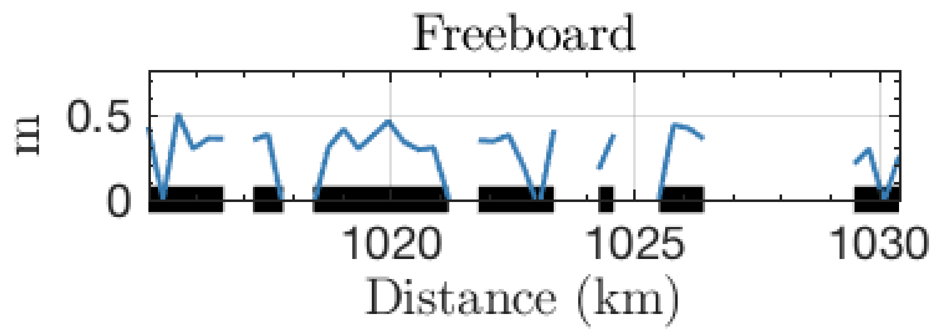


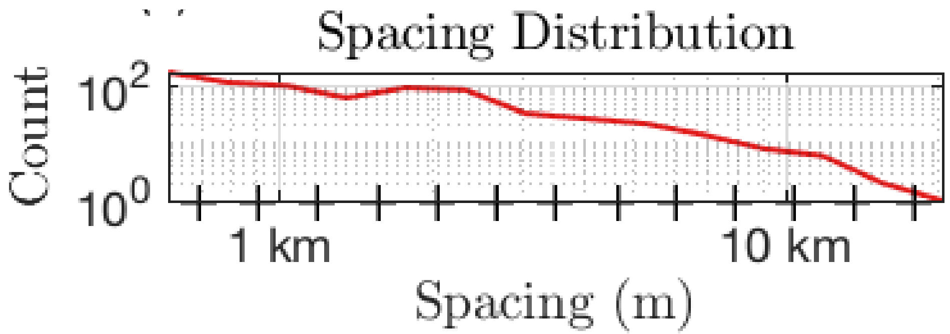
Figure produced by Marco Bagnardi c/o the ICESat-2 Project Science Office

Horvat, Roach et al. (2019) *The Cryosphere*

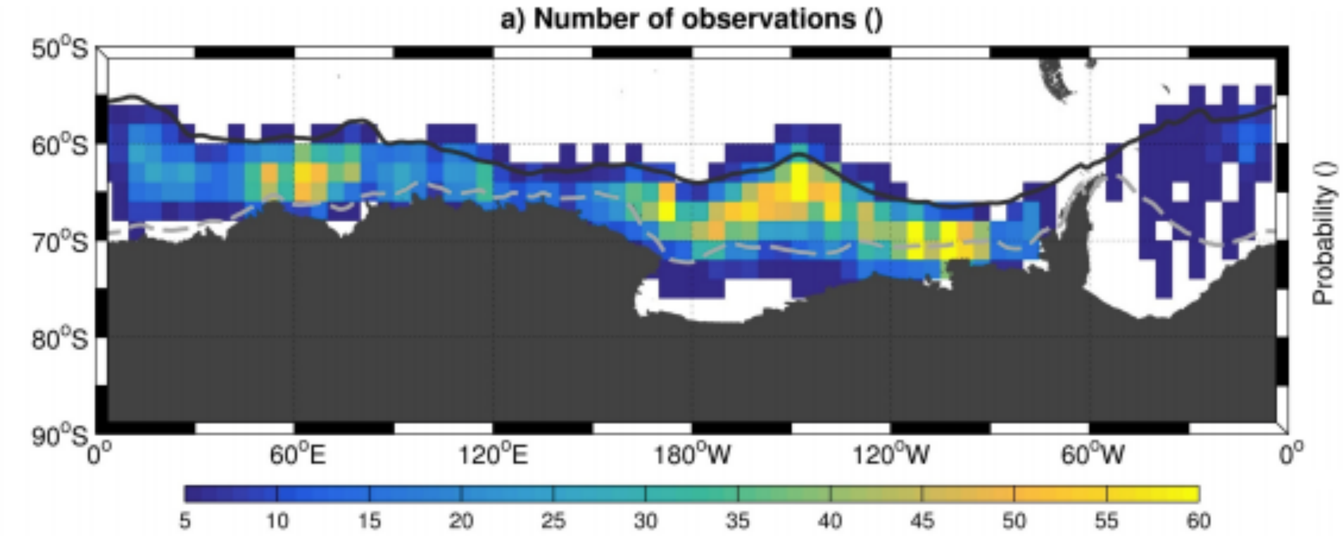
Inferring floe sizes from altimetry

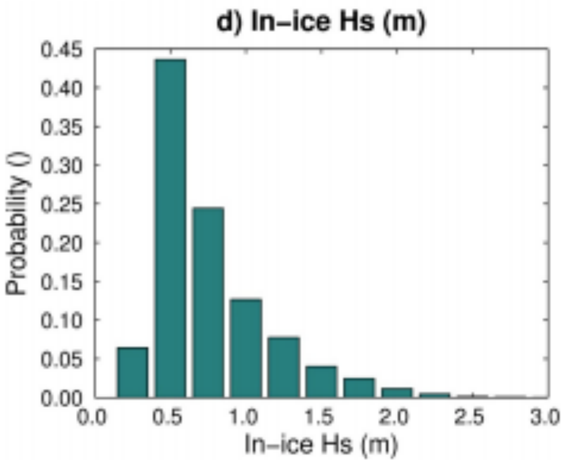
- Identify a continuous segment of ice points
- Define the "spacing distribution" in an area by accumulating floe chords over repeat passes.
- Chord lengths are not floe sizes!
- Use Bayes' theorem to infer the most likely distribution of floe sizes that would lead to the observed chord distribution.
- Can use this to find out:
  - When the FSD/CLD have the same scaling properties.
  - The relationship between moments of the CLD and FSD.



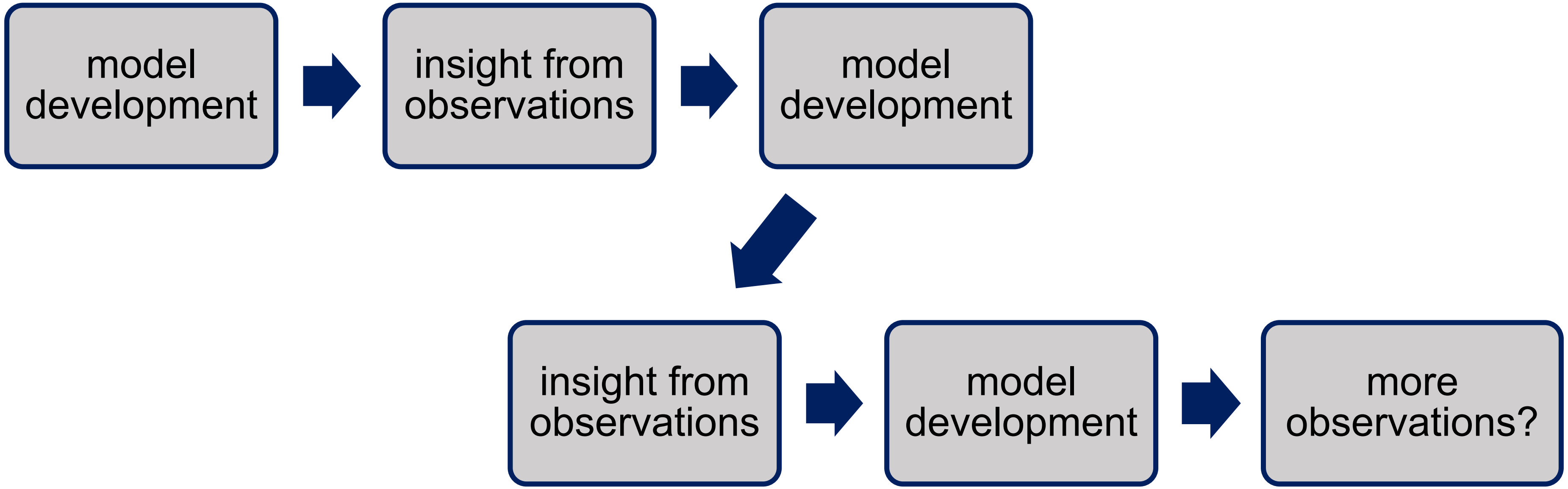


Few observations of waves in sea ice





Stopa et al. (2018) *PNAS*


model
development
insight from
observations
model
development
insight from
observations
model
development
more
observations?

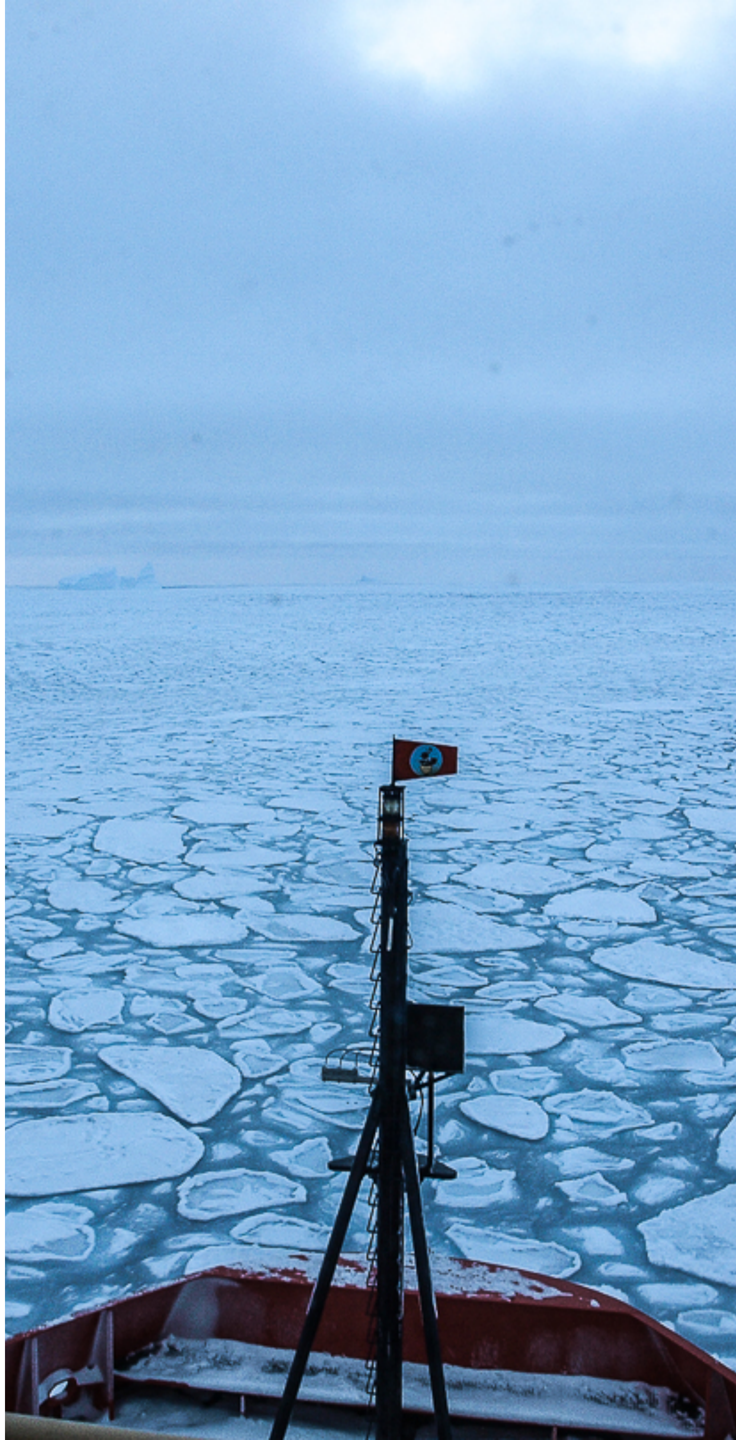
Impacts and opportunities

1. Forecasting waves and the fragmentation of sea ice for stakeholders

2. Process-level: understanding how different processes drive the floe size distribution, how do waves interact with sea ice?

3. Short-timescale: how does sea ice respond to storms?

4. Long-timescale: how does sea ice respond to a changing climate?



Wave attenuation in sea ice

- Many ice source terms available in Wavewatch III
- Some based on field observations
  - limited environmental/ice conditions
- Others based on theory
  - may limit processes
- Our current choice: empirical
- Future model-observation comparisons will advance understanding

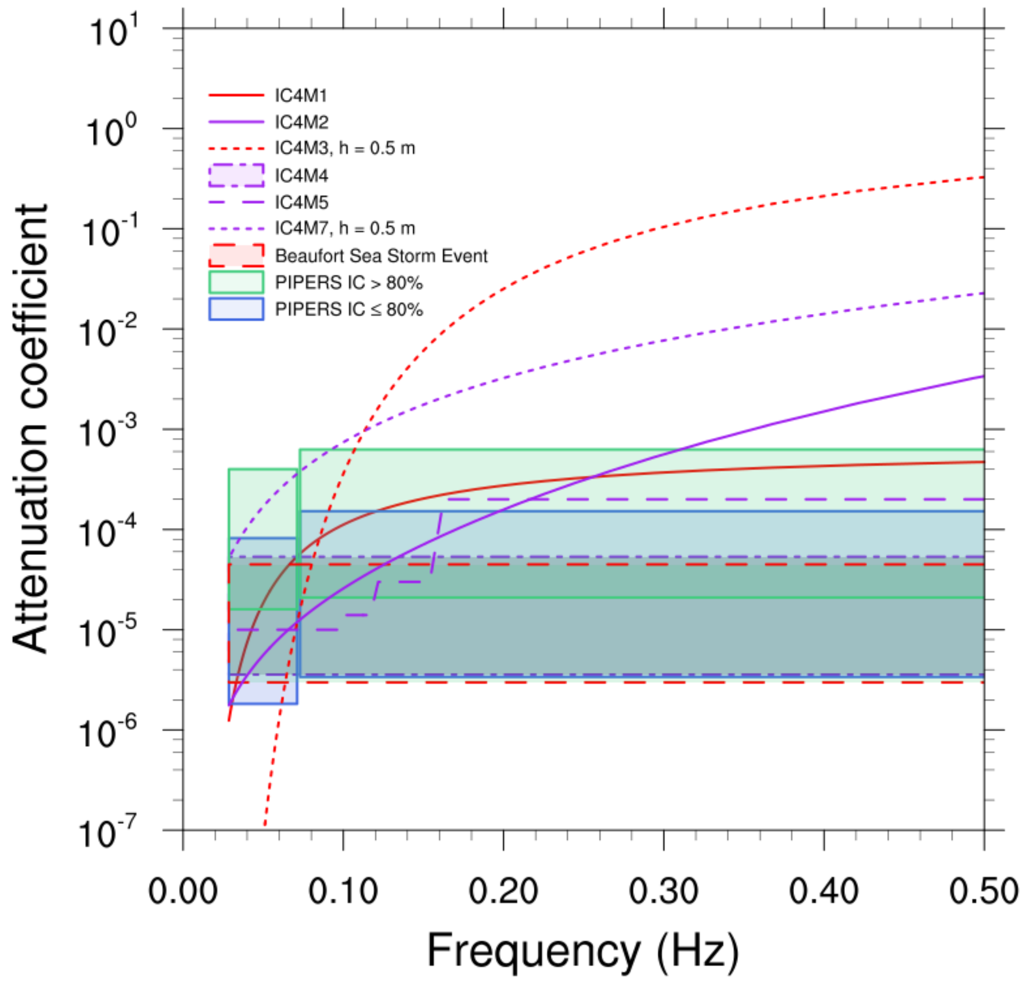
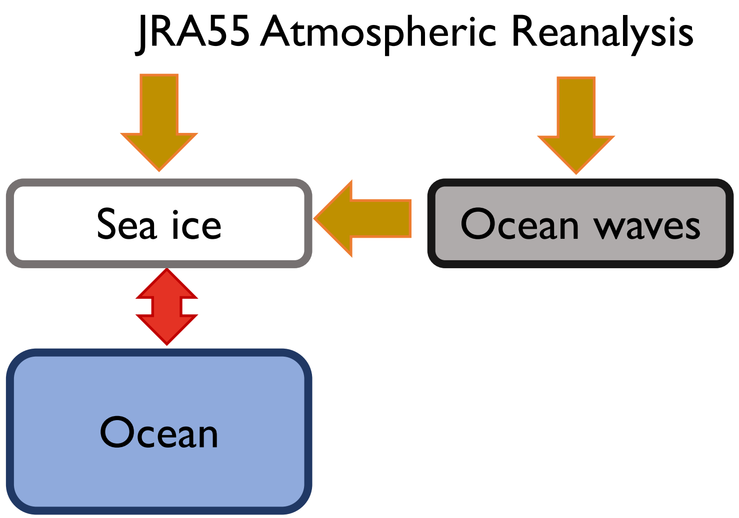
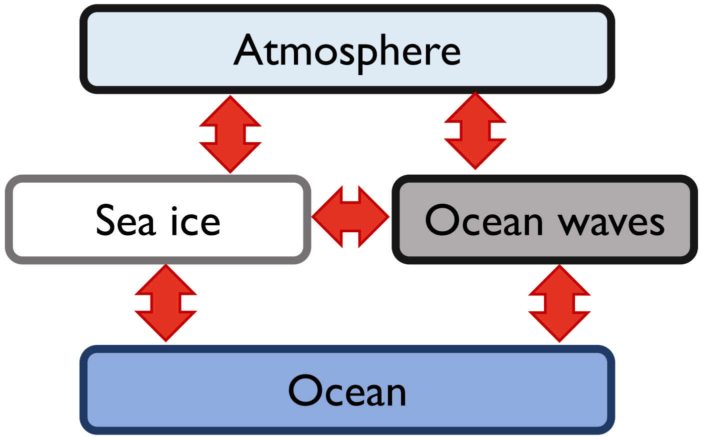
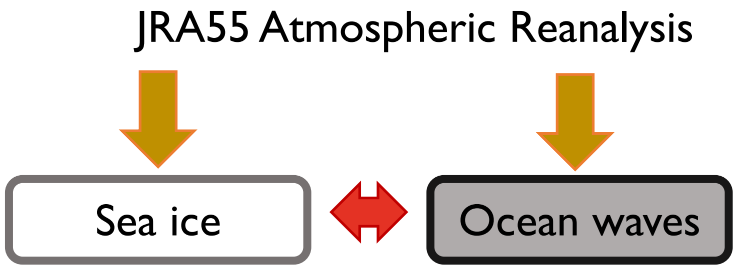


Figure: Kohout et al. (2020, in prep)



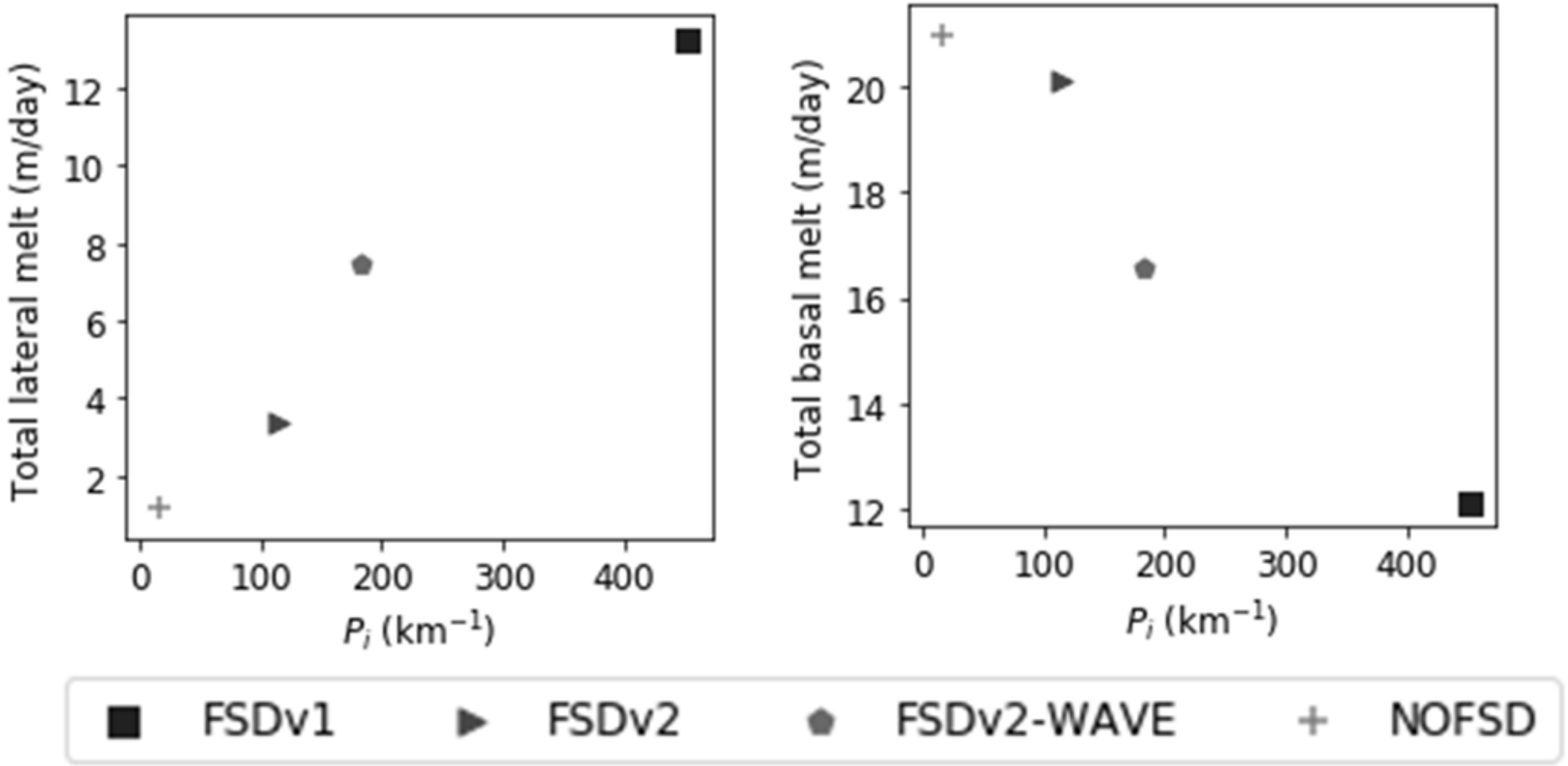


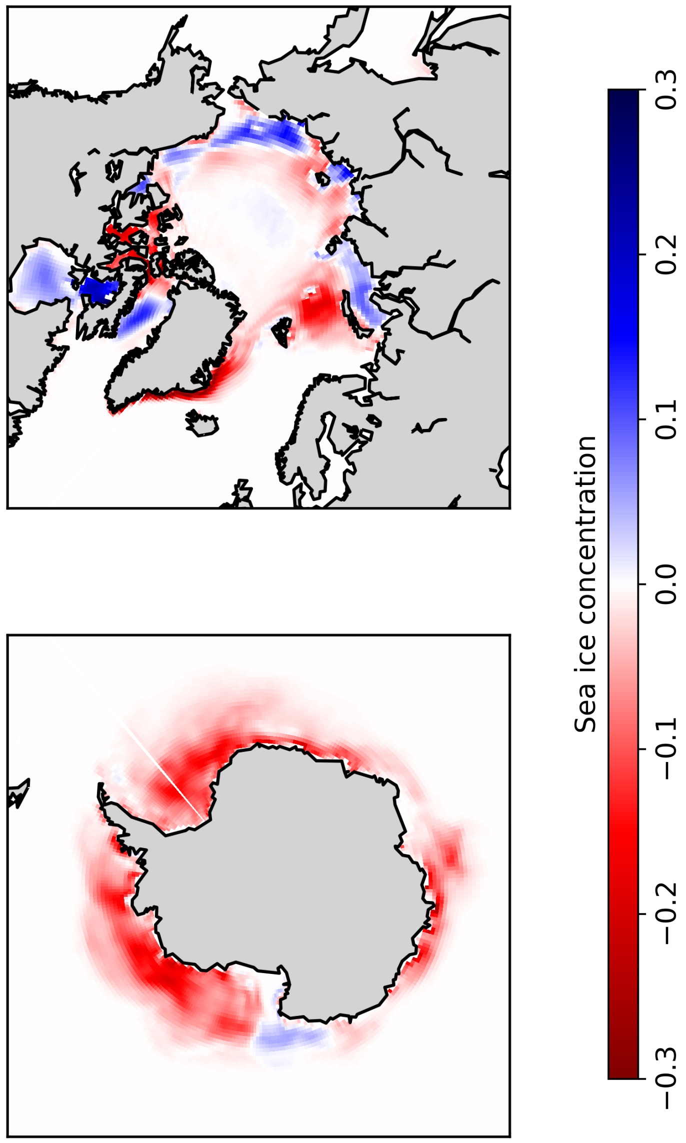
Helen Kershaw & Baylor Fox-Kemper, Brown University



Roach, Bitz et al. (2019) *JAMES*

Lateral melt





- Large changes in lateral melt with changes in FSD and wave physics, reduction in basal melt
- Need to investigate in fully-coupled system

Heat transfer through fragmented sea ice

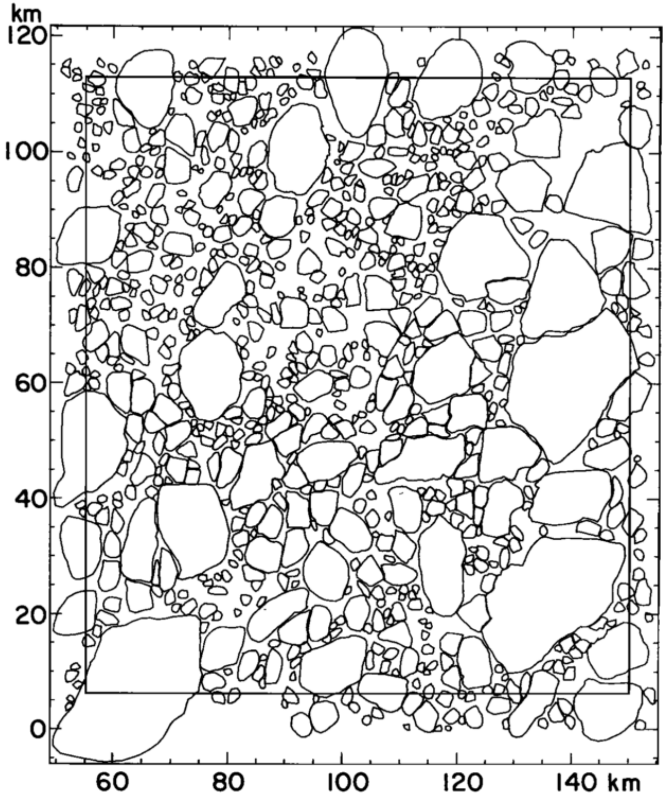


Figure: Rothrock & Thorndike (1984)

- In current climate models, ocean-atmosphere heat fluxes are computed by aggregating the ice-covered and non-ice-covered portions of a grid cell
- Observations show that turbulent heat transfer is much more efficient for smaller leads (Marcq & Weiss, 2012)
- Infer lead widths from FSD
- How will sea ice moderate ocean-atmosphere heat fluxes in a changing climate?

Sea ice dynamics

- Wave radiation stress on sea ice increases sea ice drift velocity (Boutin et al., 2019)

- Fragmentation results in decrease in internal ice stress (Boutin et al. 2020, in review)

Form drag, eddy generation at floe edges, wave-induced mixing ….

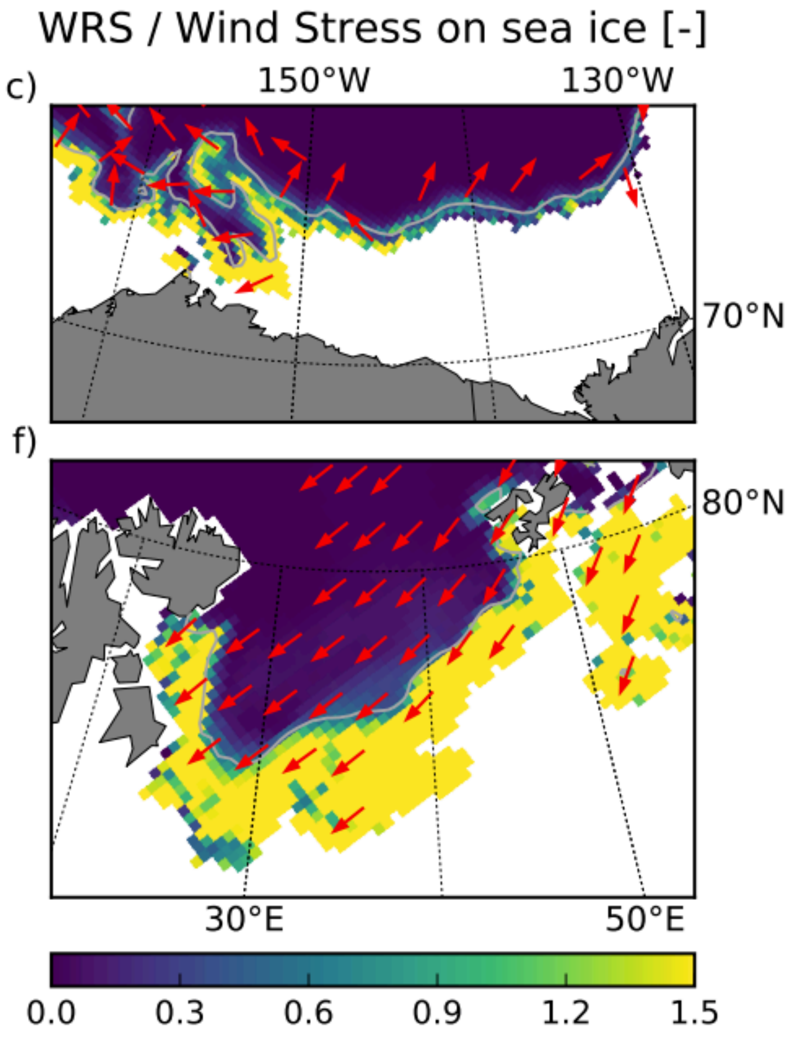


Figure: Boutin et al. (2019) *The Cryosphere*

… a number of sea ice-climate interactions that may become more important in the new Arctic

Summary

- Discussed reasons to reconsider the physics in sea ice models
- Developed a new model for sea ice floe sizes compatible with existing climate models and allowing sea ice-wave coupling – now in CICE6/Icepack
- Worked on integrating observations with modelling of different physical processes
- Gained initial insights on what drives evolution of the floe size distribution and what impact it may have on polar climate
- Lots more future work!