

# Wave-Ice Interactions in the Community Earth System Model

Cecilia Bitz

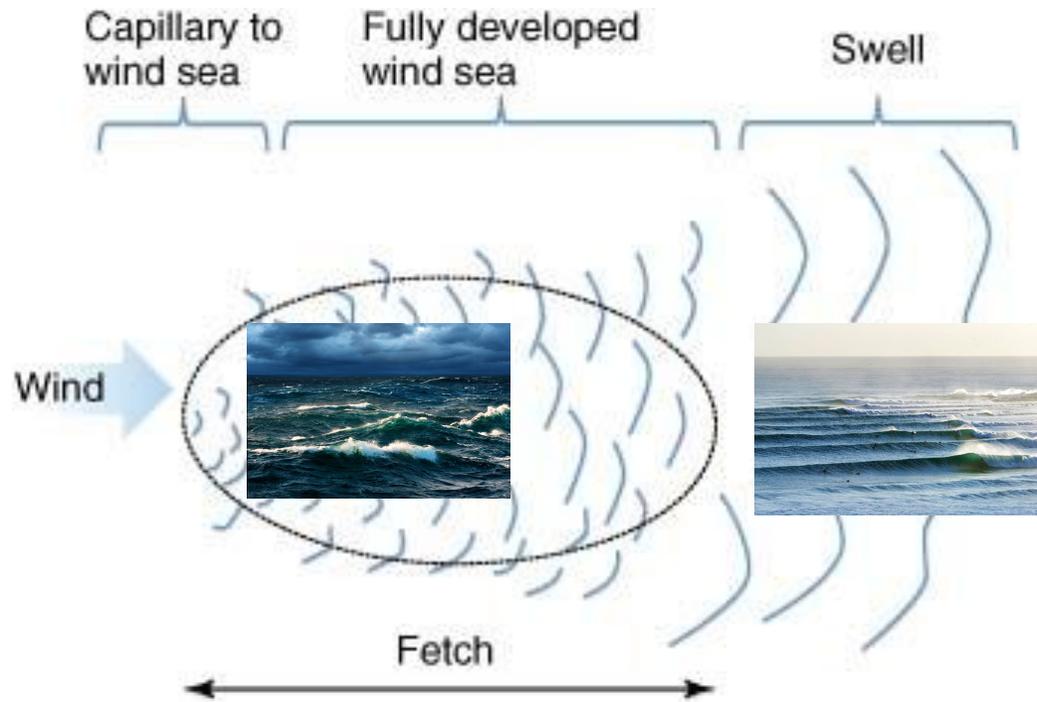
Atmospheric and Climate Science  
University of Washington

~100 km

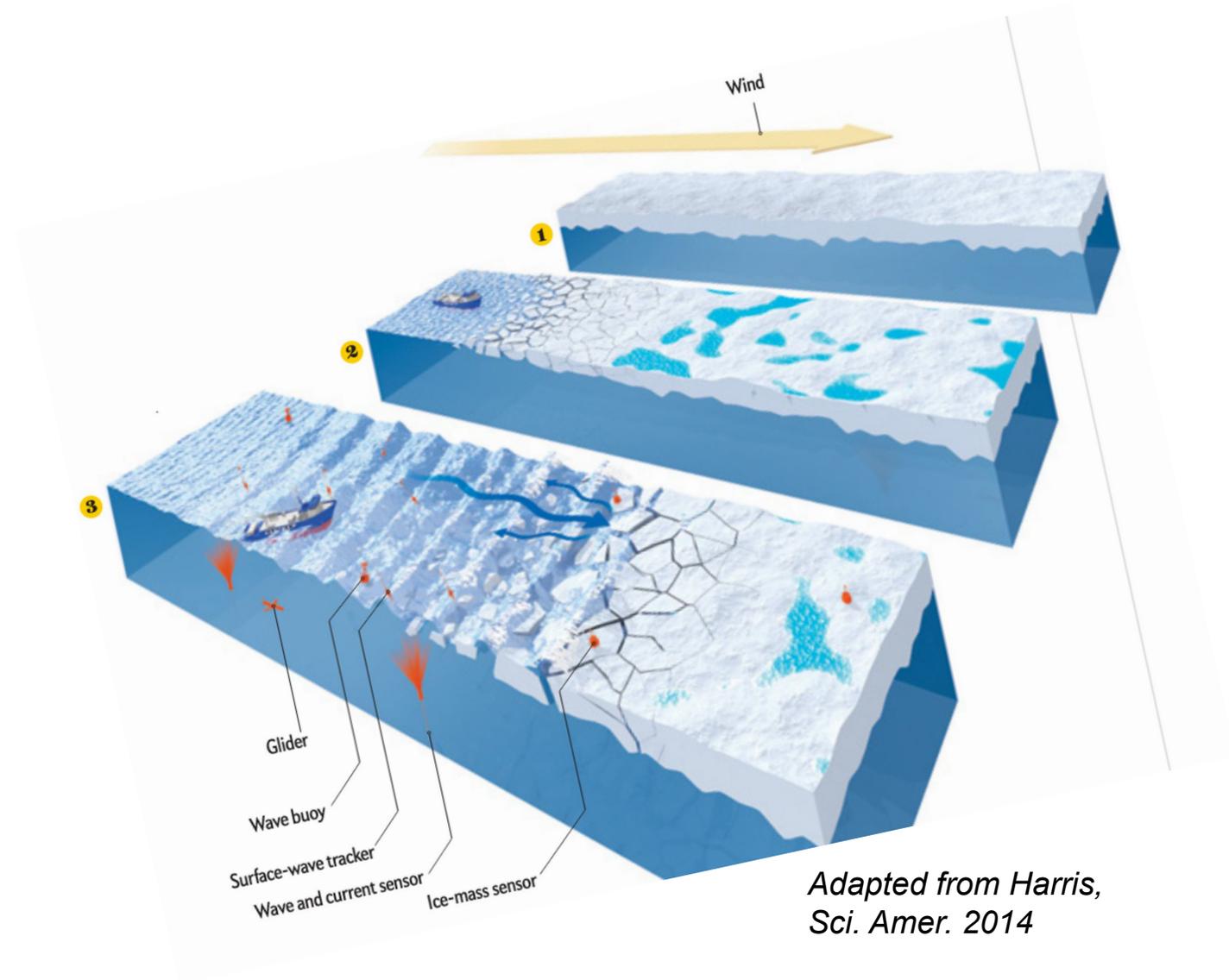
Geraint Webb (UW)  
Lettie Roach (AWI)  
Dave Bailey (NCAR)  
Nils Hutter (GEOMAR)  
Chris Horvat (Brown)  
Mirjam Bourgett (AWI)



# Overview of ocean surface waves in sea ice

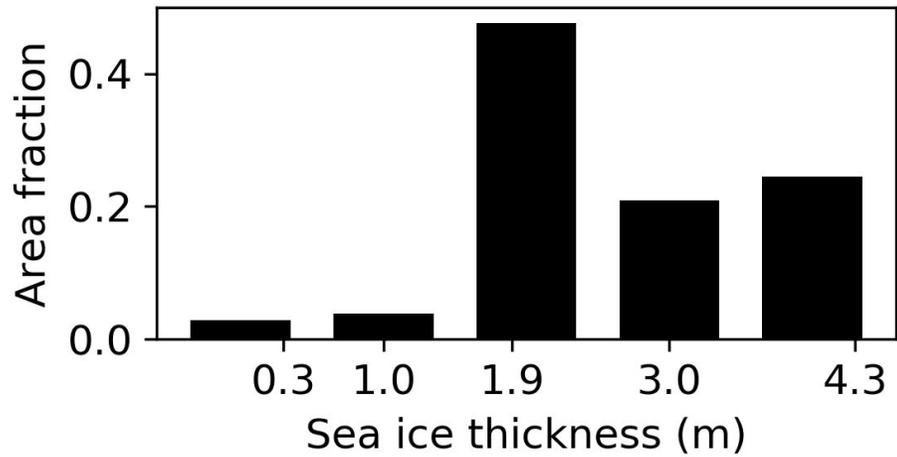


Source: Spire



Adapted from Harris, Sci. Amer. 2014

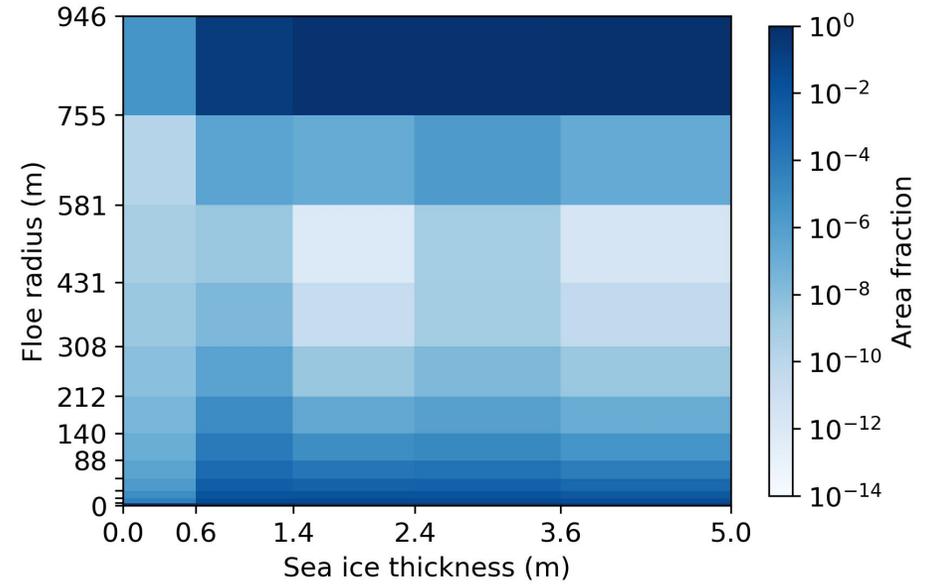
## Ice thickness distribution - ITD



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

Transport (points to  $-\nabla \cdot (g\vec{v})$ )  
Ridging/rafting (points to  $-\frac{\partial}{\partial h}(fg)$ )  
Thermodynamics (points to  $\psi$ )  
▪ Vertical, lateral

## Joint floe size and thickness distribution - FSDT



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

Transport (points to  $-\nabla \cdot (f(r, h)\mathbf{u})$ )  
Mechanical Deformation (points to  $\mathcal{L}_M$ )  
Thermodynamics (points to  $\mathcal{L}_T$ )  
▪ Vertical, lateral  
Wave fracture (points to  $\mathcal{L}_W$ )

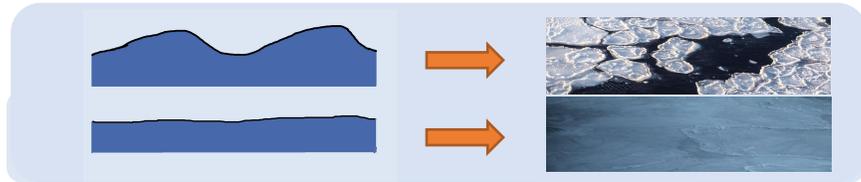


e.g. CICE  
<https://github.com/CICE-Consortium/CICE>  
 E

# Processes that influence joint floe-size thickness distribution (FSDT)

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

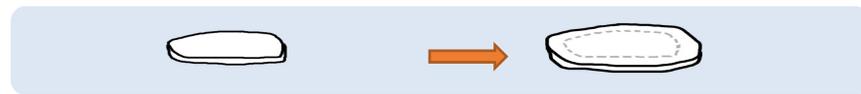
transport of  $f(r, h)$   
due to ice motion
thermo
deform  
ation
wave  
fracture



New ice formation



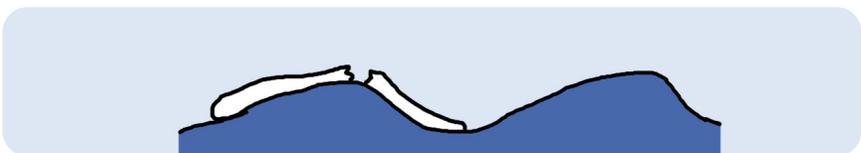
Lateral melt



Lateral growth



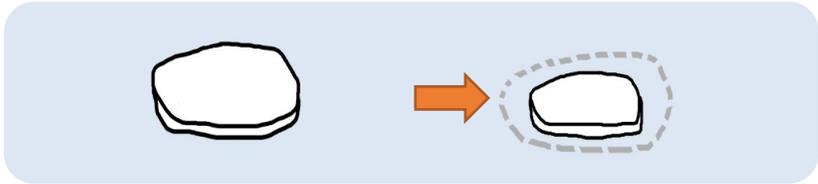
Floe welding



Wave fracture

*Horvat & Tziperman (2015)*  
*Roach, Horvat et al (2018)*  
*Roach, Smith & Dean (2018)*  
*Roach, Bitz et al (2019)*

# Why we care: Floe sizes determine lateral melt and influence sea ice dynamics



- **Lateral melt** depends on surface area on sides of floes exposed to the ocean, i.e. total perimeter
- becomes important...

During summer, if floe radius less than  $\sim 15$  m (Steele 1992)

*Schematics from L. Roach*

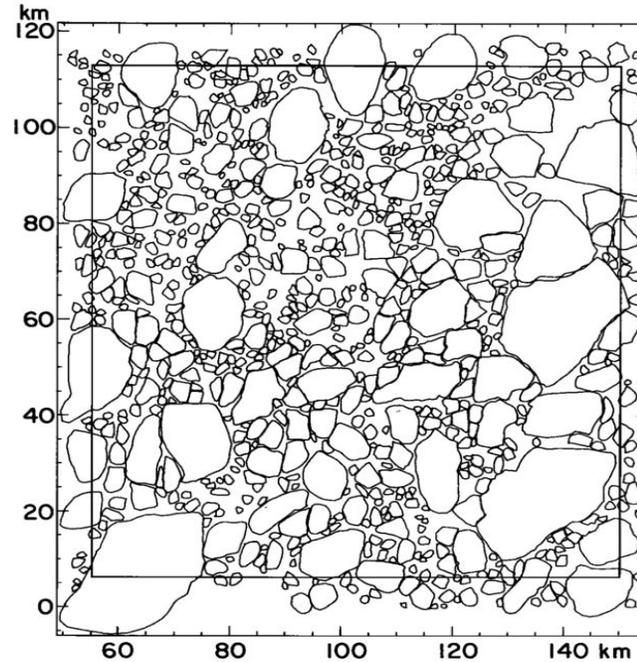


Fig: Rothrock & Thorndike (1984)

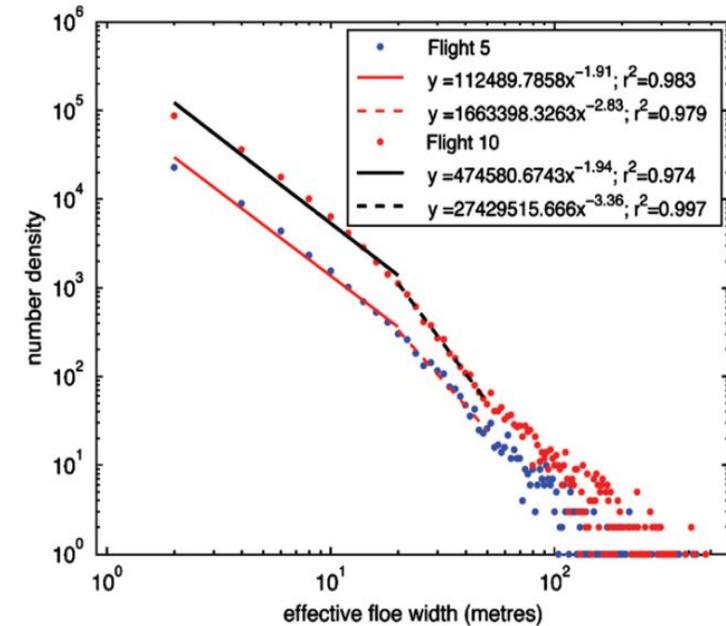
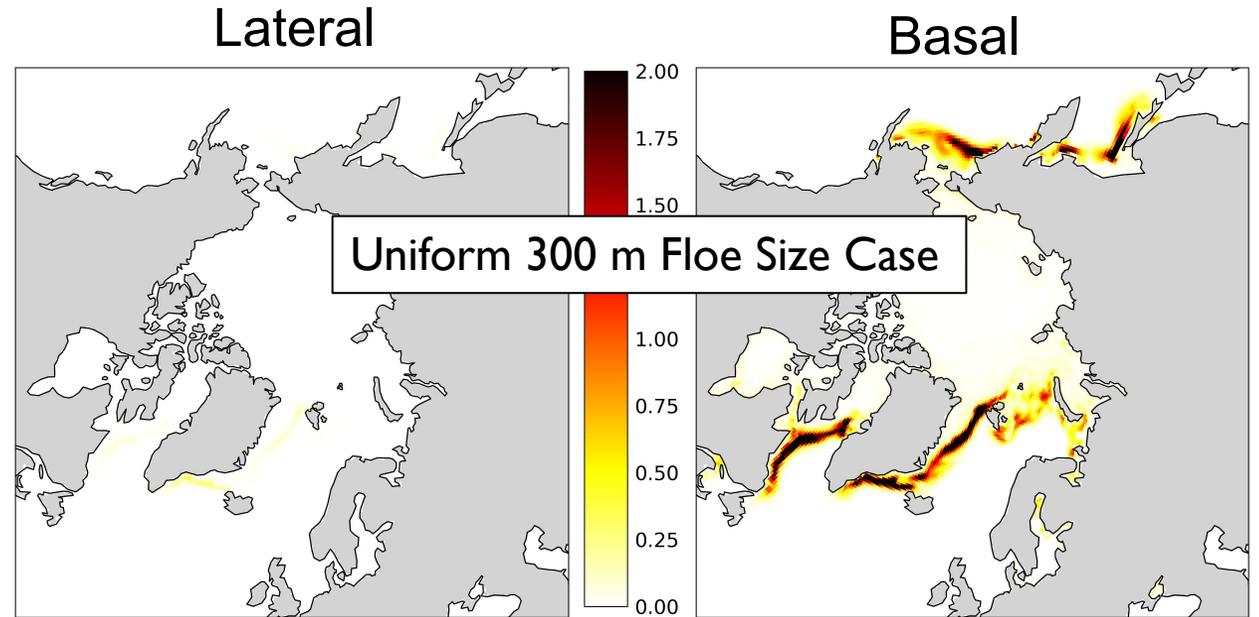


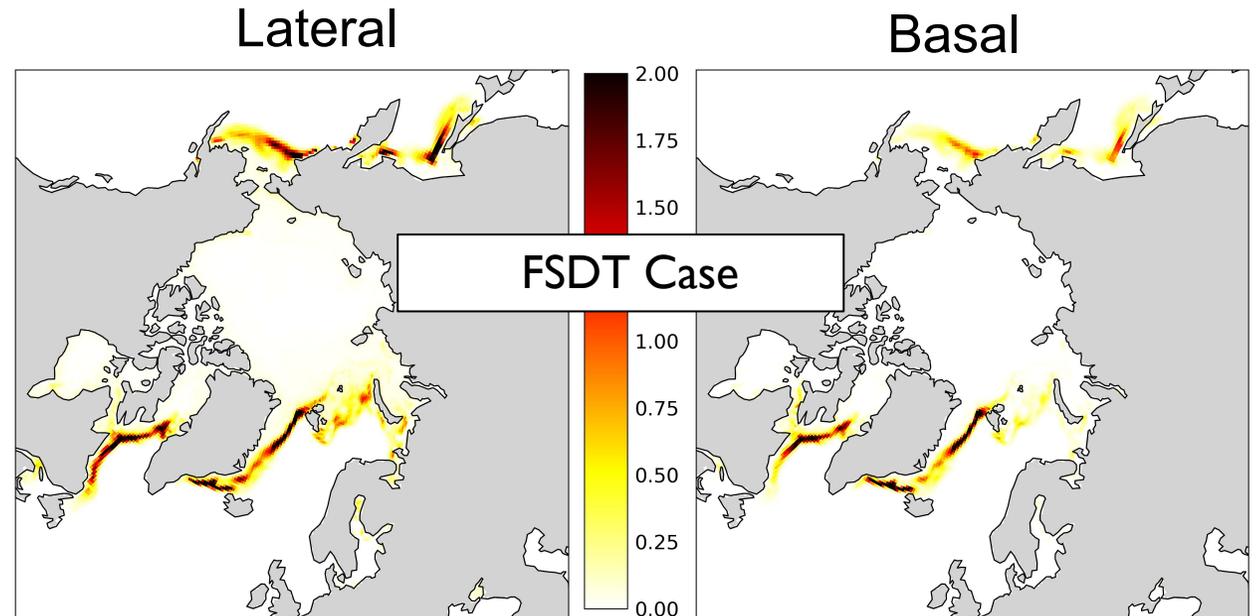
Fig: Steer et al. (2008)

## Floe size distribution (FSD)

## Lateral versus Basal Melt (cm day<sup>-1</sup>) in January

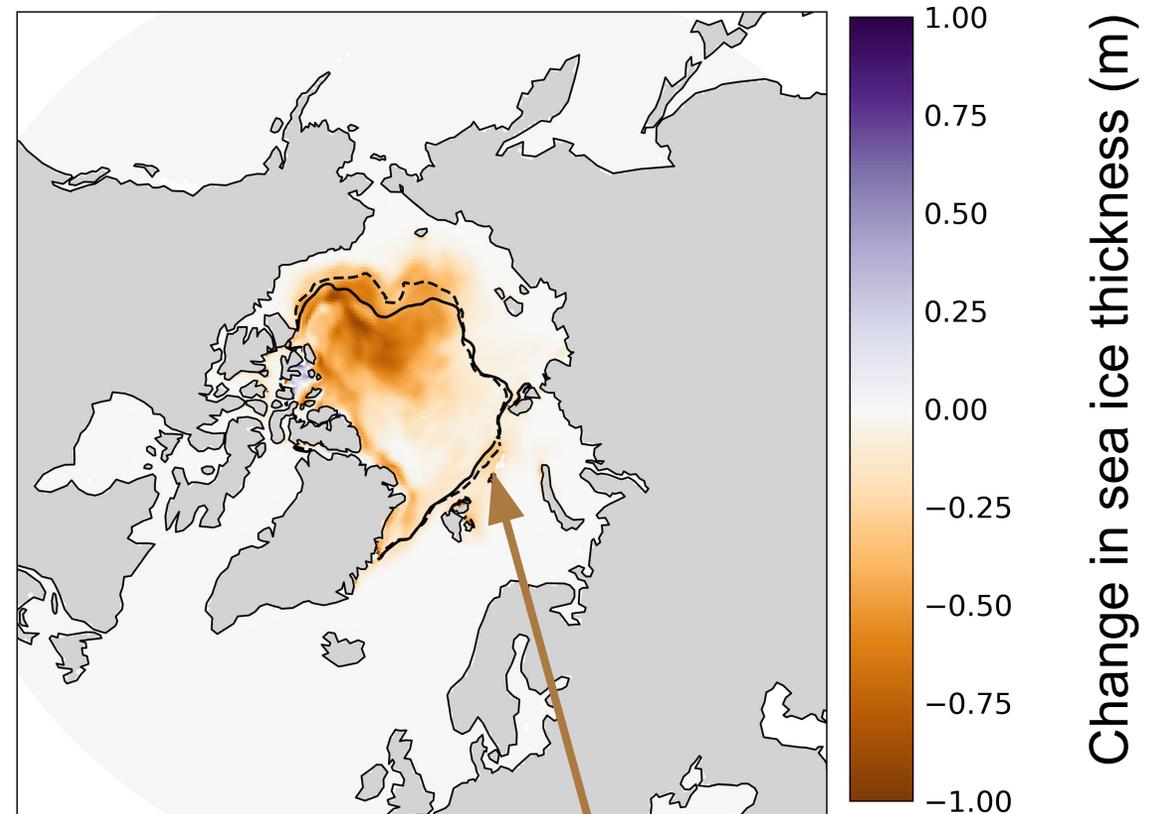


**Much more lateral melt at expense of less basal melt** in case with floe size distribution due to wave fracture making small floes and high lateral perimeter



## Response of thickness and Extent in September: Case with FSDT minus Case with Uniform 300 m Floes

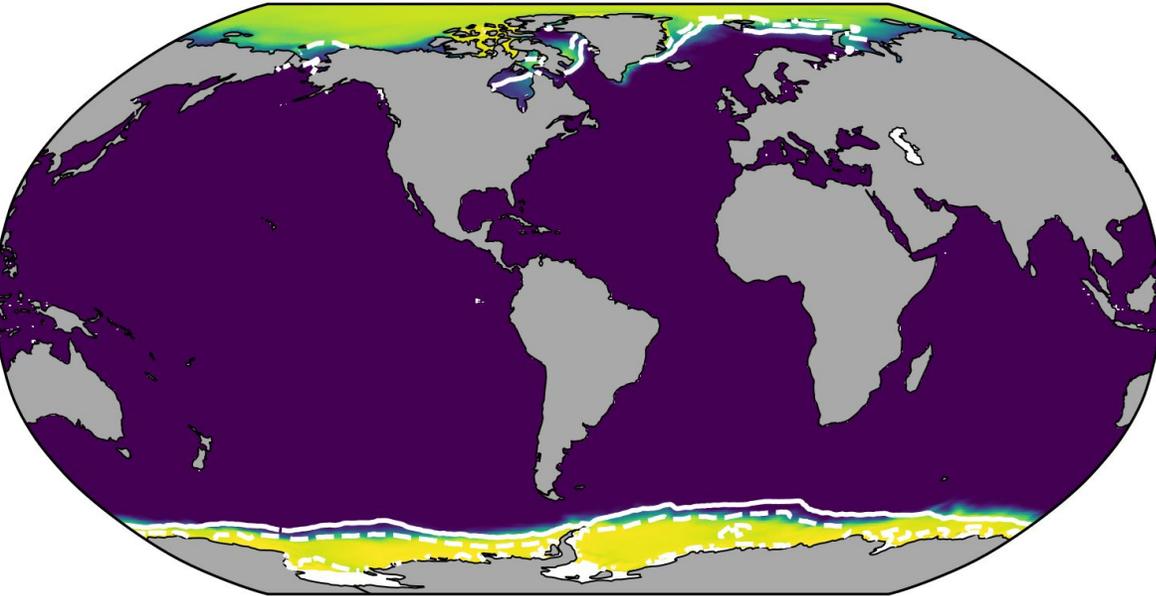
**Sea ice is thinner and less extensive** in case with FSDT due to enhanced ice albedo feedback from more lateral melt



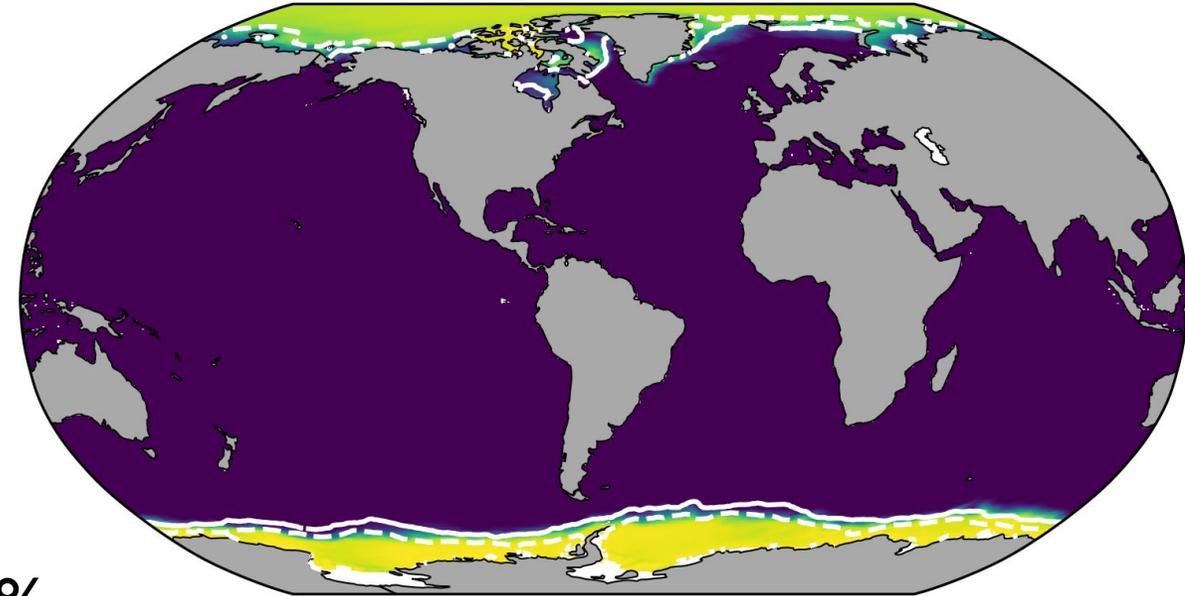
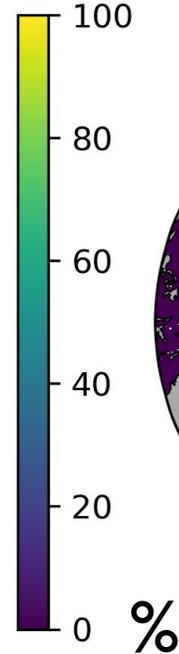
Concentration 15%  
Case with FSDT (solid)  
Case with Uniform 300 m Floes (dashed)

# CESM3 Preindustrial Control Fully Coupled with FSDT and Wave-Ice Interactions Sea Ice Concentration- Fantastic Job!

Sea Ice Concentration (%) - November



Sea Ice Concentration (%) - July

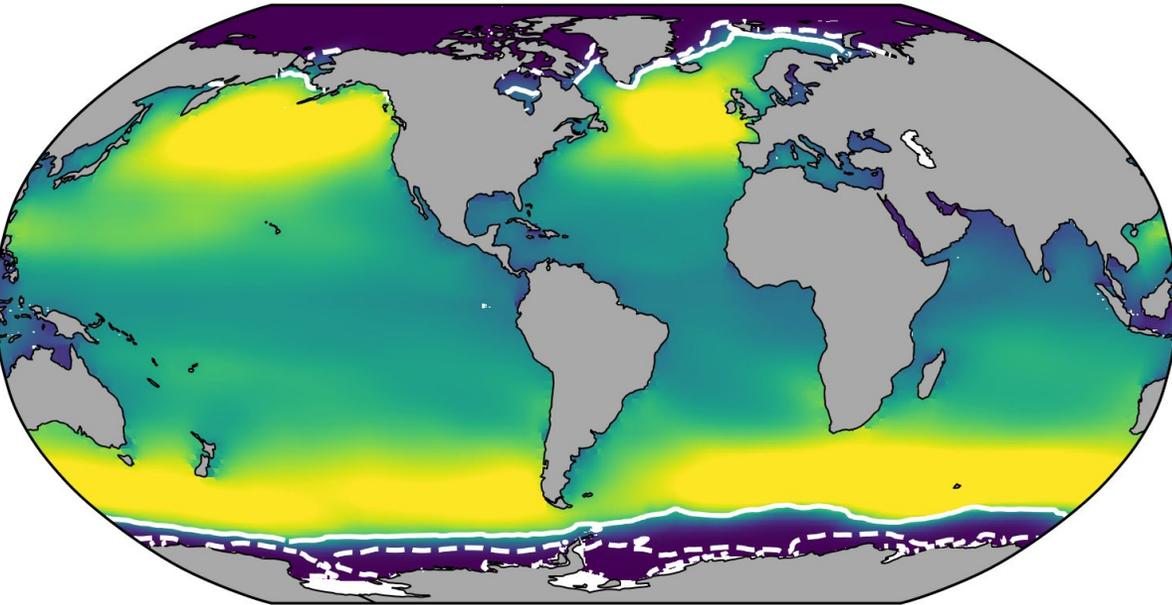


White lines 15% (solid) and 80% (dashed) from HadISST 1979-1990

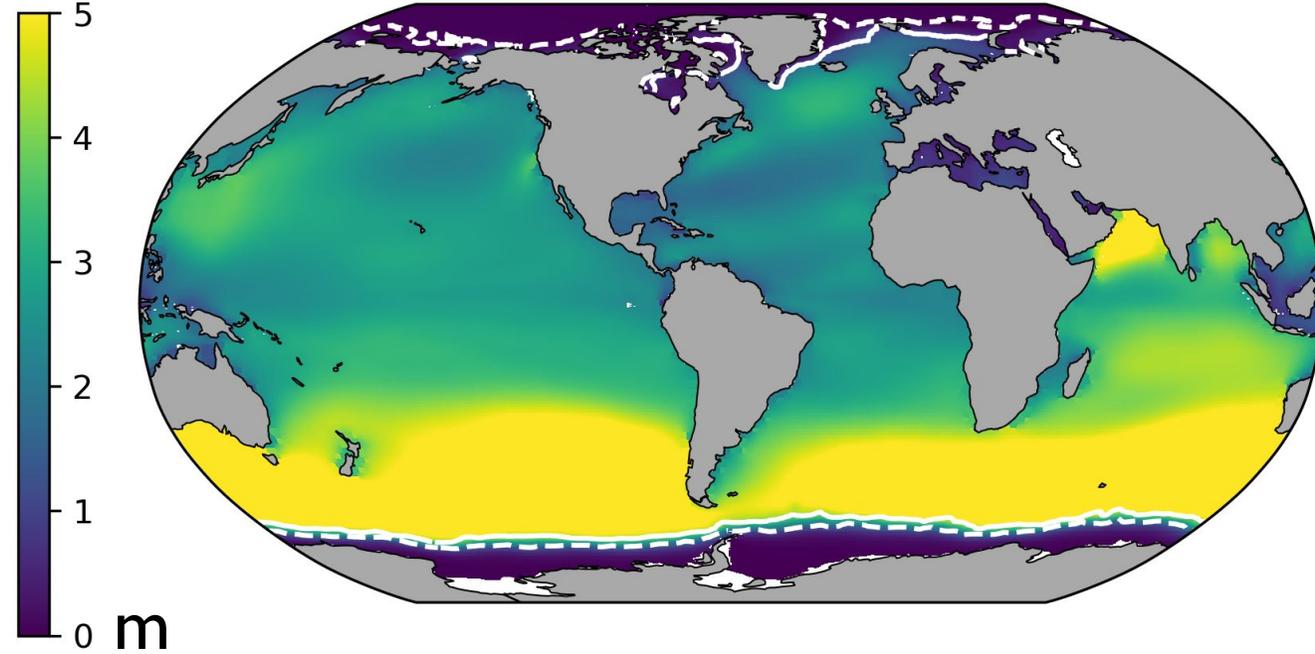
CESM3 simulation is b.e30\_alpha07g.B1850C\_LTso.ne30\_t232\_wgx3.287 10-year mean

## Significant Wave Height

Significant Wave Height - November



Significant Wave Height - July

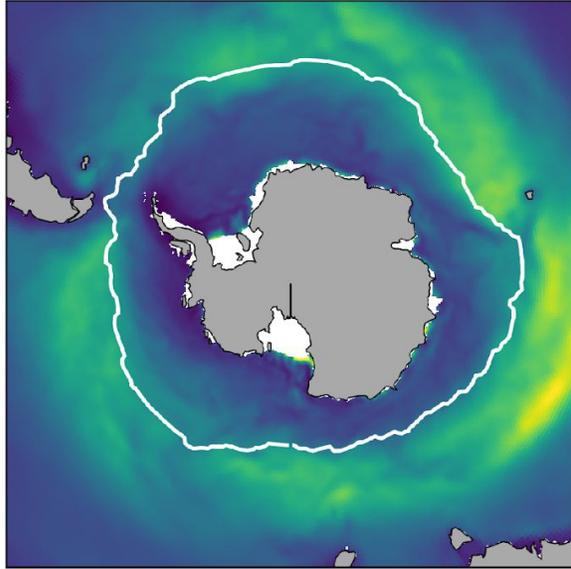


White lines 15% (solid) and 80% (dashed) Sea Ice Concentration from model henceforth

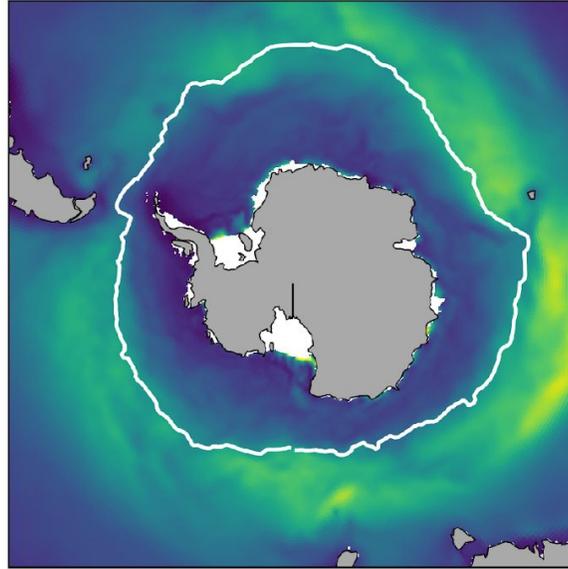
CESM3 simulation is b.e30\_alpha07g.B1850C\_LTso.ne30\_t232\_wgx3.287 10-year mean

## Ocean Mixed Layer Depth Annual Mean

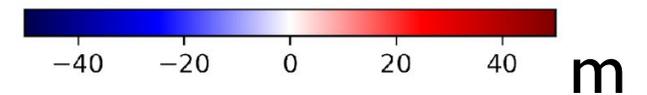
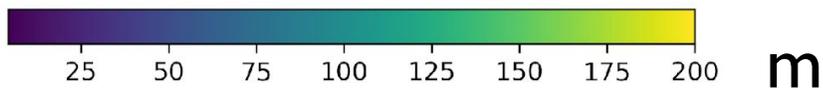
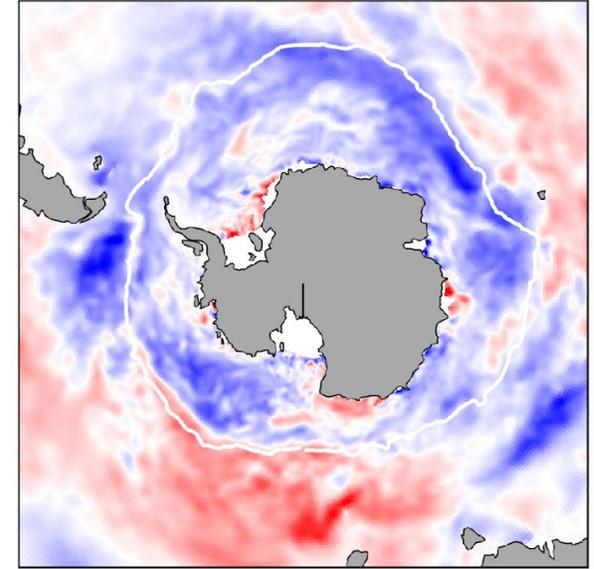
Control with wave-ice coupling



All waves damped by sea ice



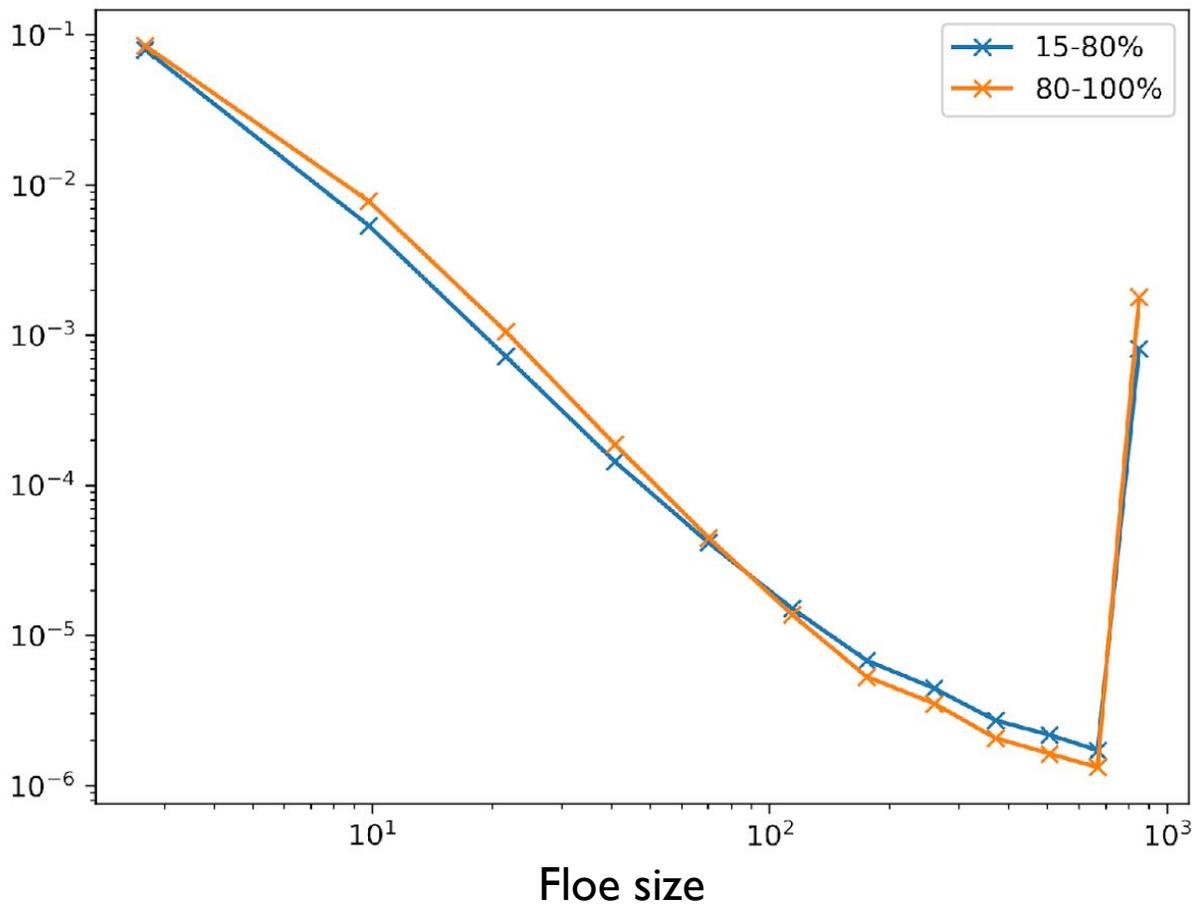
All damped minus Control



White lines 15% (solid) Sea Ice Concentration from Model

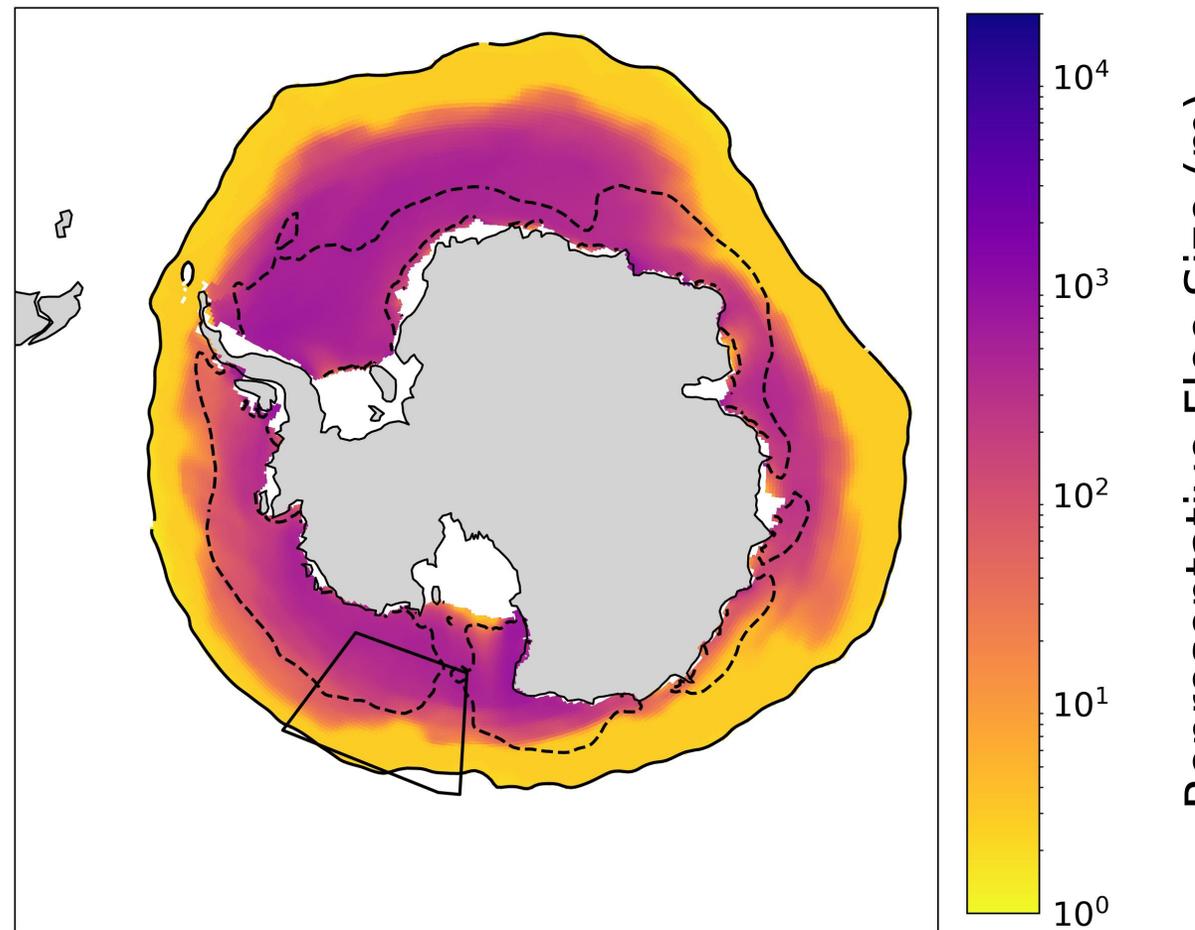
CESM3 simulation is b.e30\_alpha07g.B1850C\_LTso.ne30\_t232\_wgx3.287 5-year mean

\*Area Floe-Size Distribution (AFSD)  
Averaged over Box at right



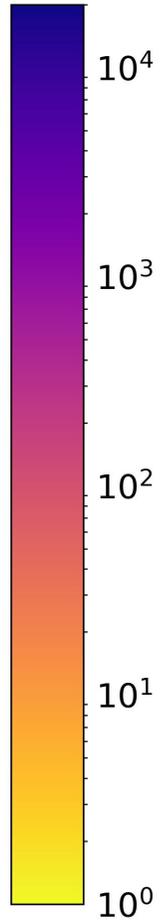
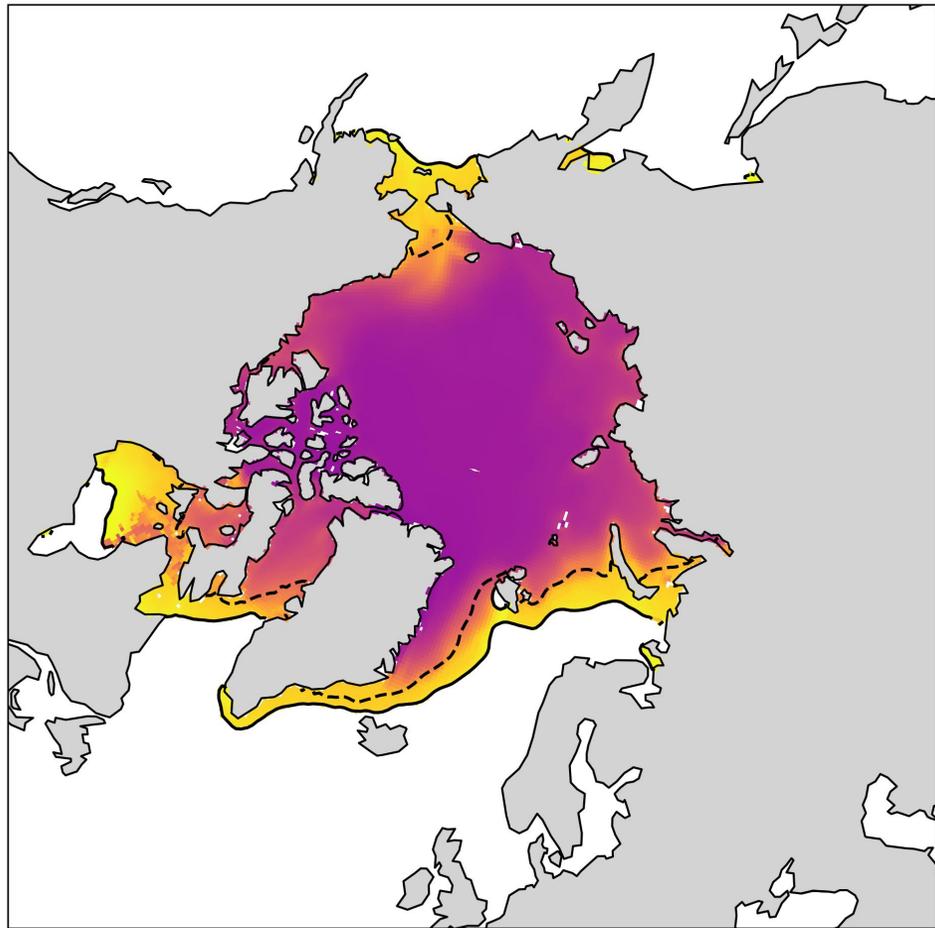
\*AFSD =  $x f(x)$  where  
 $f(x)$  = number distribution  
 $x$  = floe area

Representative Floe Size  
(aka first moment of the FSD)  
For November

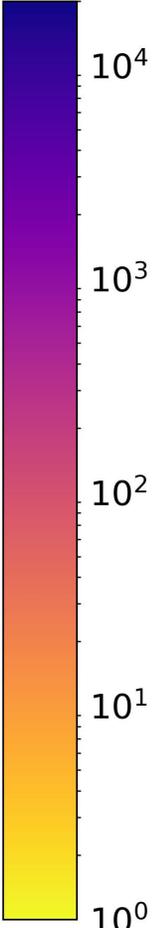
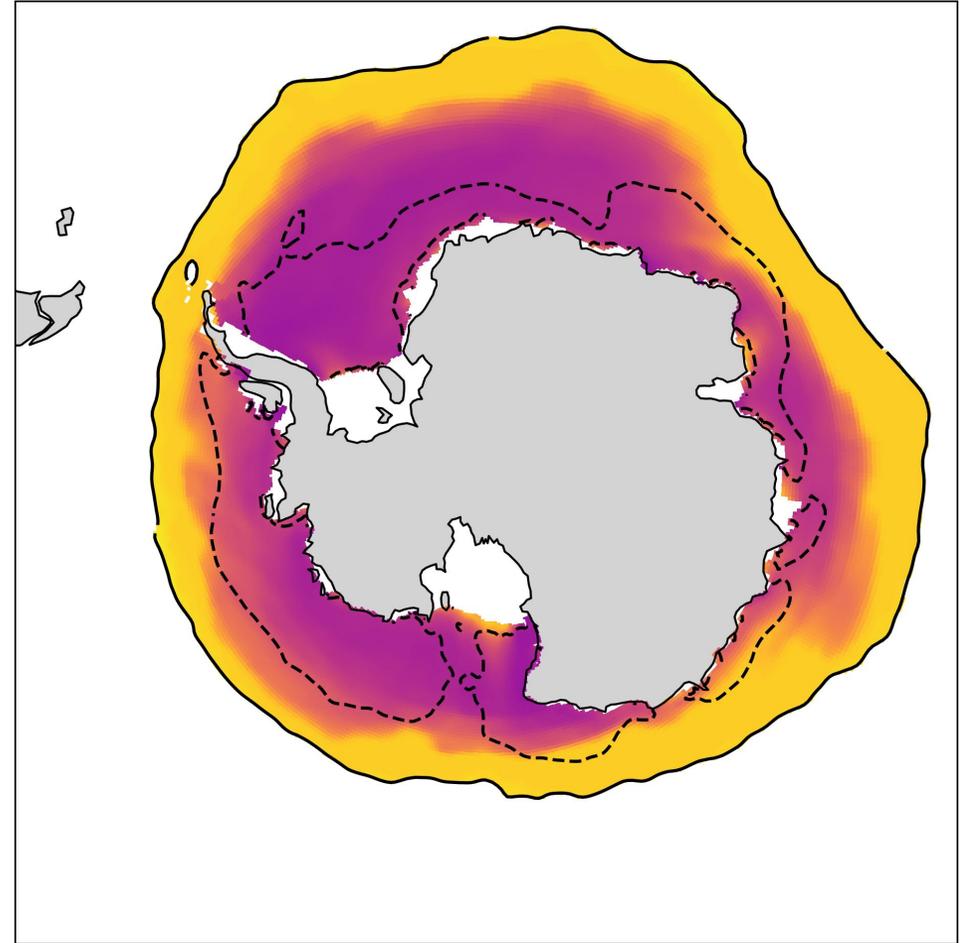


Black lines 15% (solid) and 80% (dashed) Sea Ice Concentration

# Representative Floe Size (aka first moment of the FSD) For November



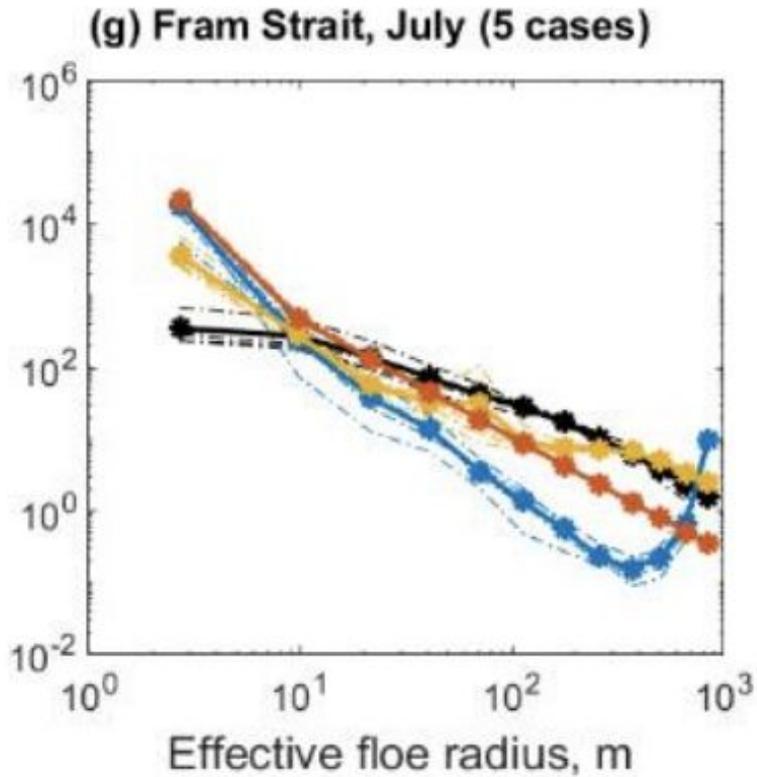
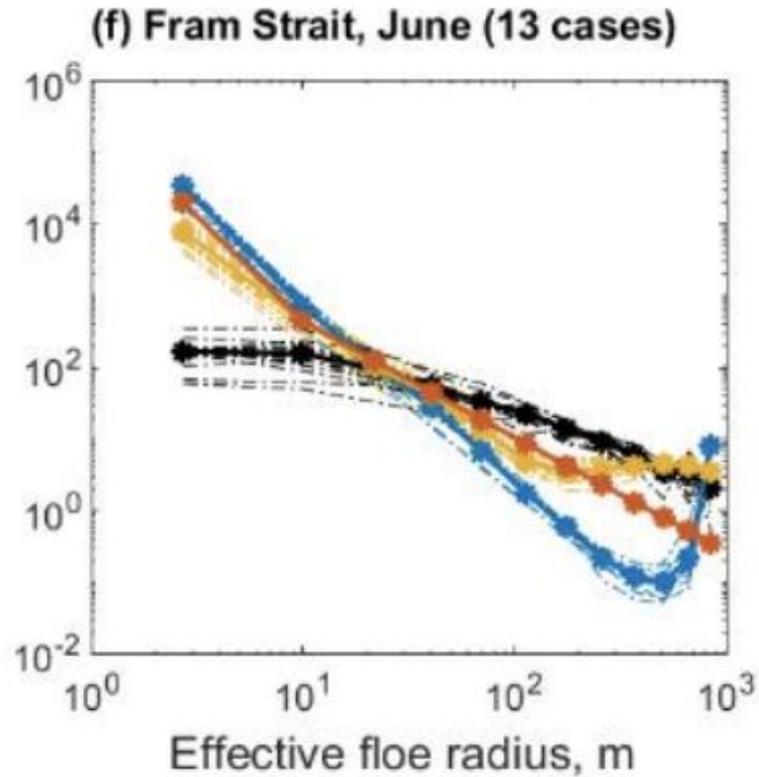
Representative Floe Size (m)



Black lines 15% (solid) and 80% (dashed) Sea Ice Concentration

CESM3 simulation is b.e30\_alpha07g.B1850C\_LTso.ne30\_t232\_wgx3.287 10-year mean

## Modeled Number Floe Size Distribution versus observations



- Observations
- Power law model (Bateson et al. 2020)
- Roach et al. (2019)
- Roach et al. (2019) + CPOM 'brittle fracture'

AFSD =  $x f(x)$  where  
 $f(x)$  = number distribution  
 $x$  = floe area

Bateson, Feltham, Schroeder, Wang, Hwang, Ridley & Aksenov (2022)  
 Wang, Hwang, Bateson, Aksenov & Horvat (2022)

## Room for Improvement

The FSD has a few key tunable parameters and a whole lot of processes that nearly cancel one another

We lack (or haven't used) a consistent set of observations to tune.

Suspected parameterizations and possible solutions (not yet in CESM3):

Wave Fracture

Accuracy

Allow floes to be larger by “extending bounds” of the FSD

Not accounting for deformation

Welding

Modify kernel

Etc.

\*our floe-size problems have minimal impact on the ocean (probably)

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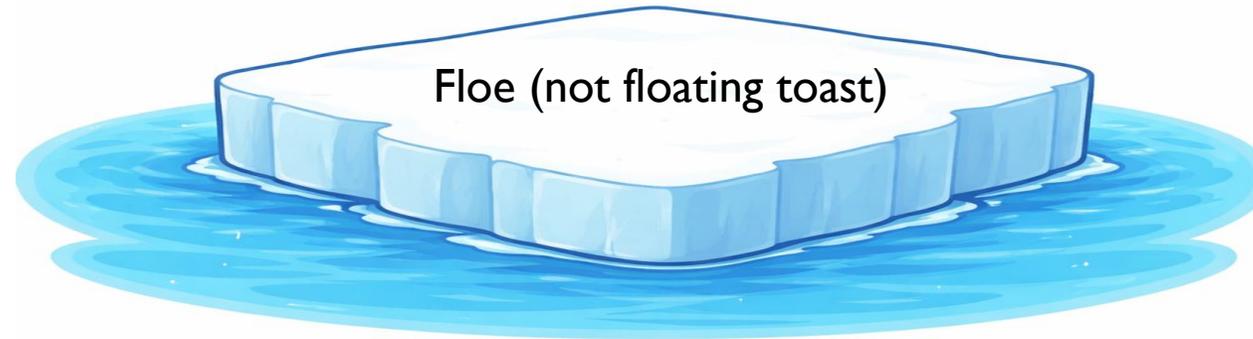
### Welding

Modify kernel

Etc. (Geraint will talk about this too)

\*our floe-size problems have minimal impact on the ocean (probably)

# Why emulate wave fracture?



11 s per model day

CESM3 now with  $dx = 4m$   
(compromise of lower accuracy for speed)

100 s per model day

Better accuracy with  $dx = 2m$

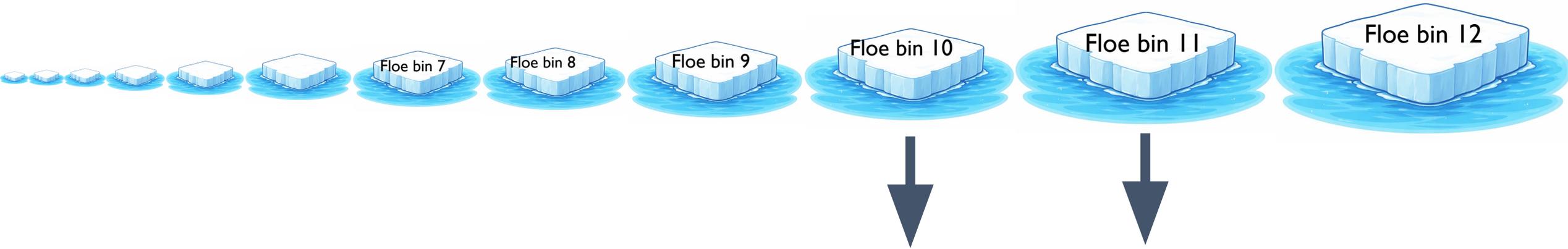
60 s per model day

Extended FSD bounds, needed for new deformation fraction

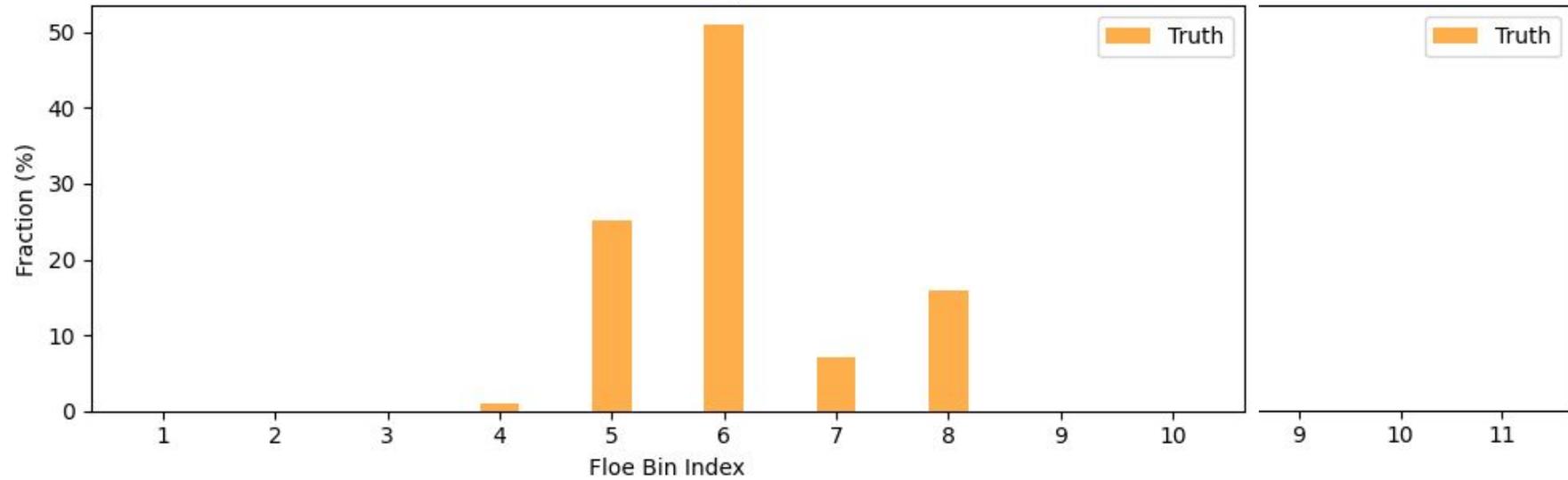
6 s per model day

AI Emulation of wave fracture trained on output with  $dx = 2m$  and extended bounds!

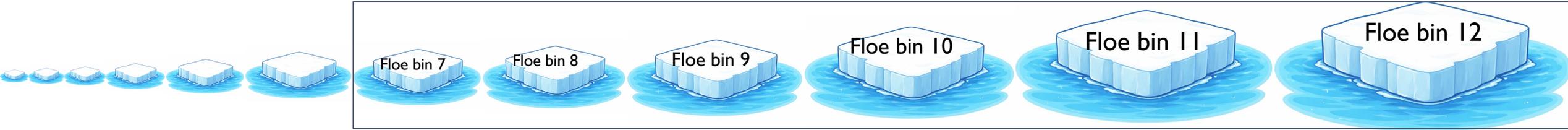
# Emulating wave fracture



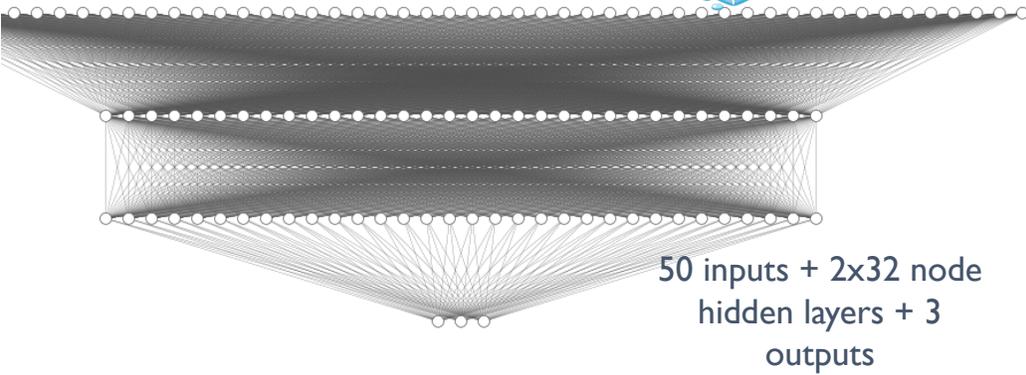
Fracture Histogram



# Emulating wave fracture



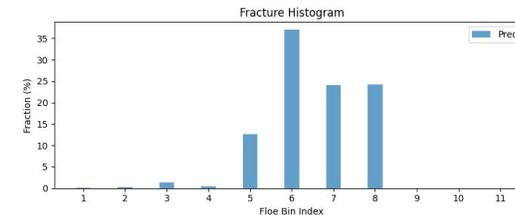
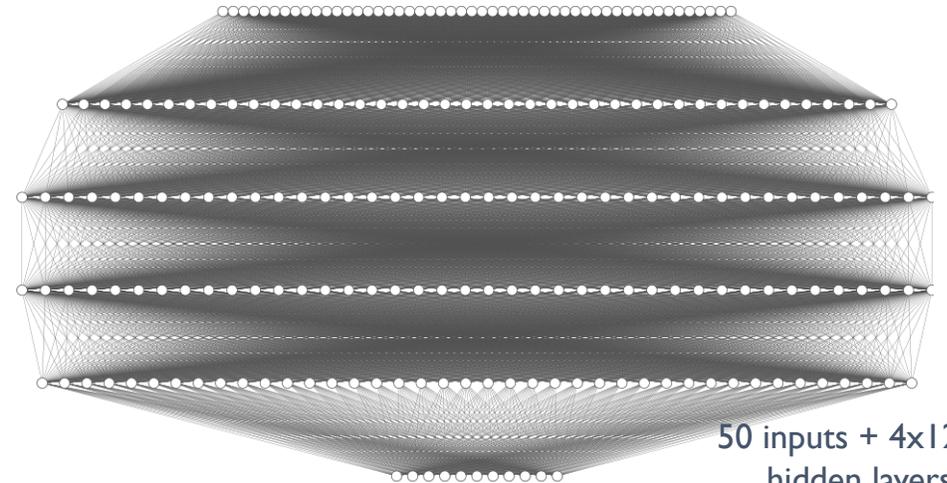
Modified methodology from Horvat and Roach (2022)  
 wave spectrum (WWIII) 🌊 +  
 sea ice thickness 🧊



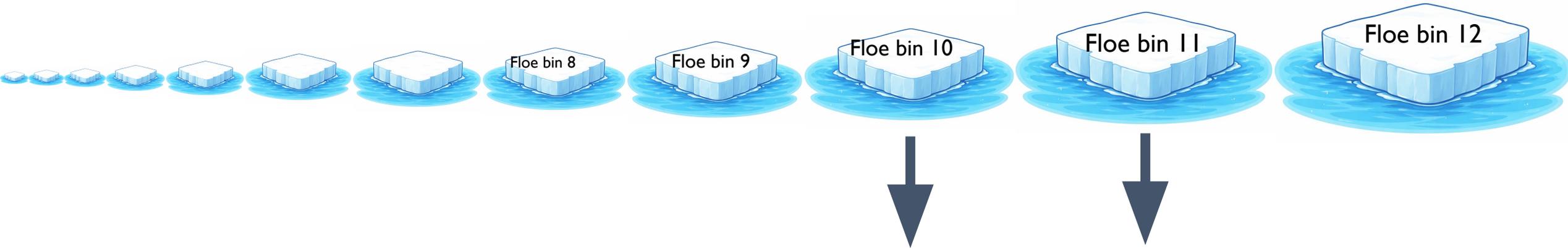
Fracture?



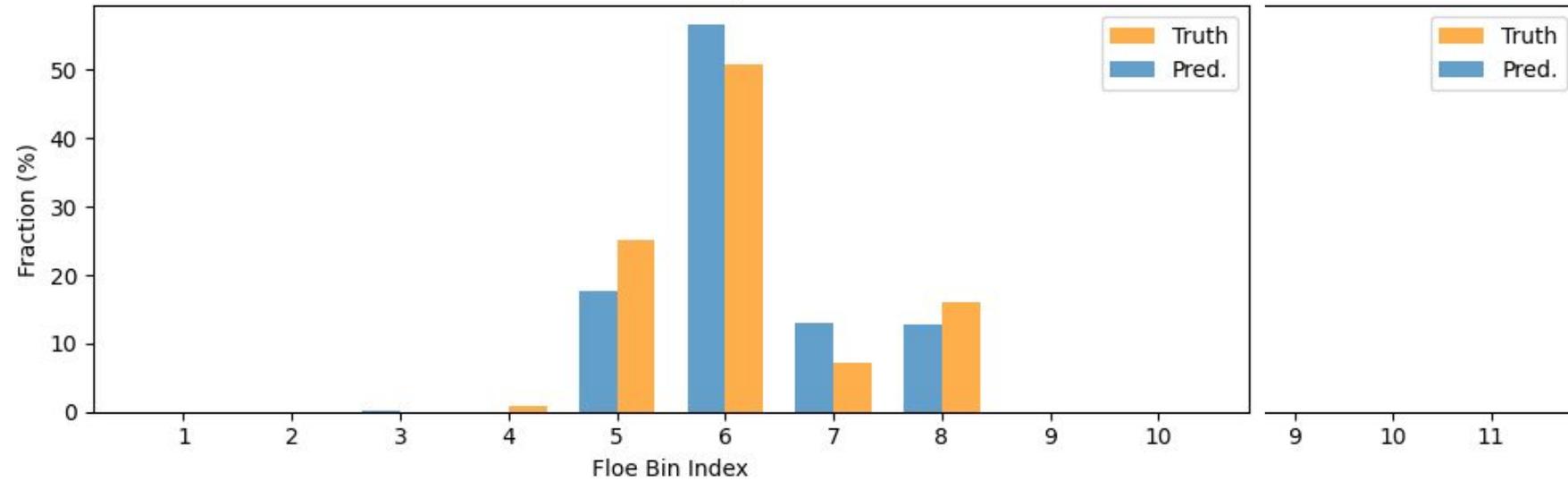
If **YES** : wave spectrum (WWIII) 🌊 +  
 sea ice thickness 🧊



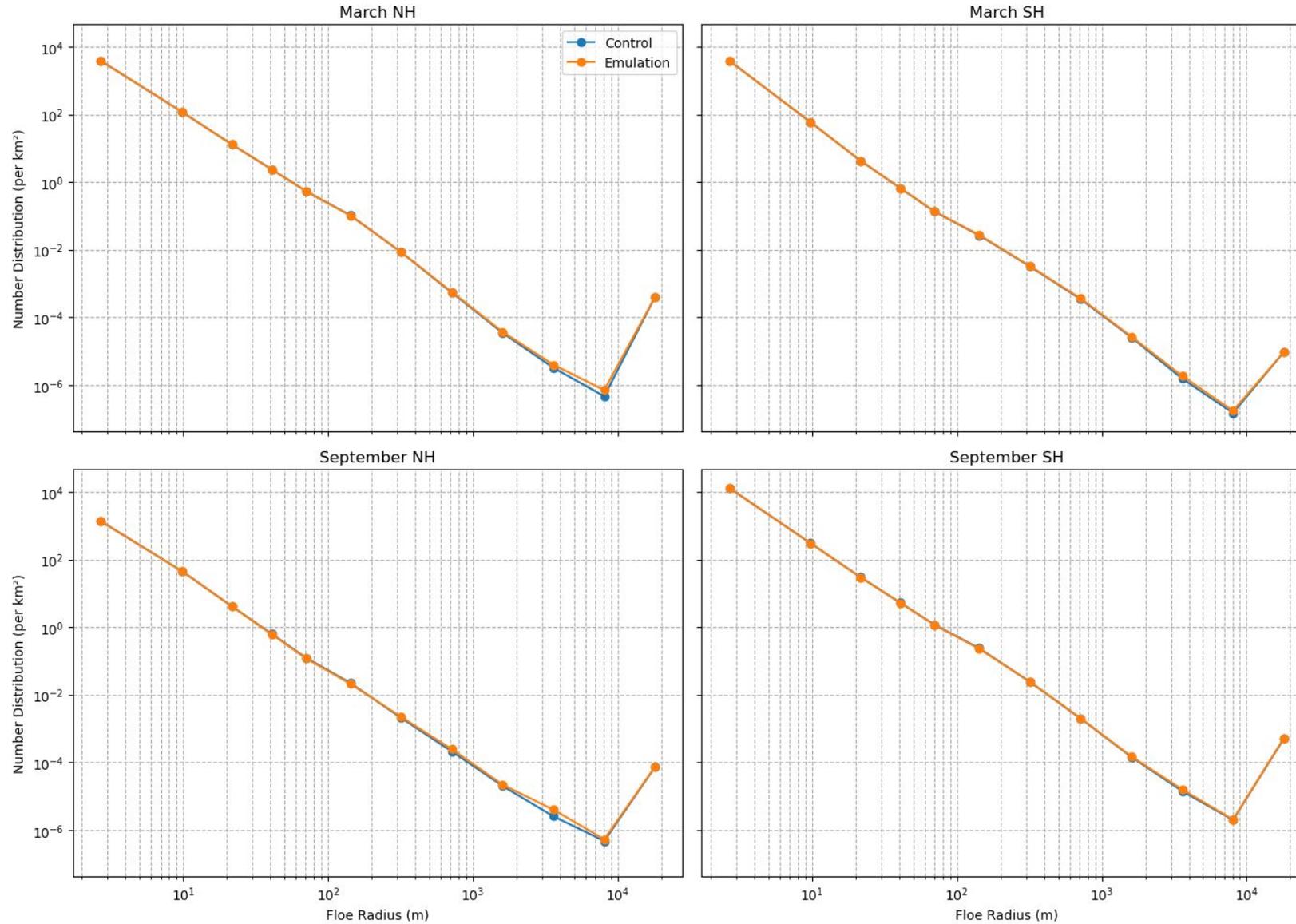
# Emulating wave fracture



Fracture Histogram



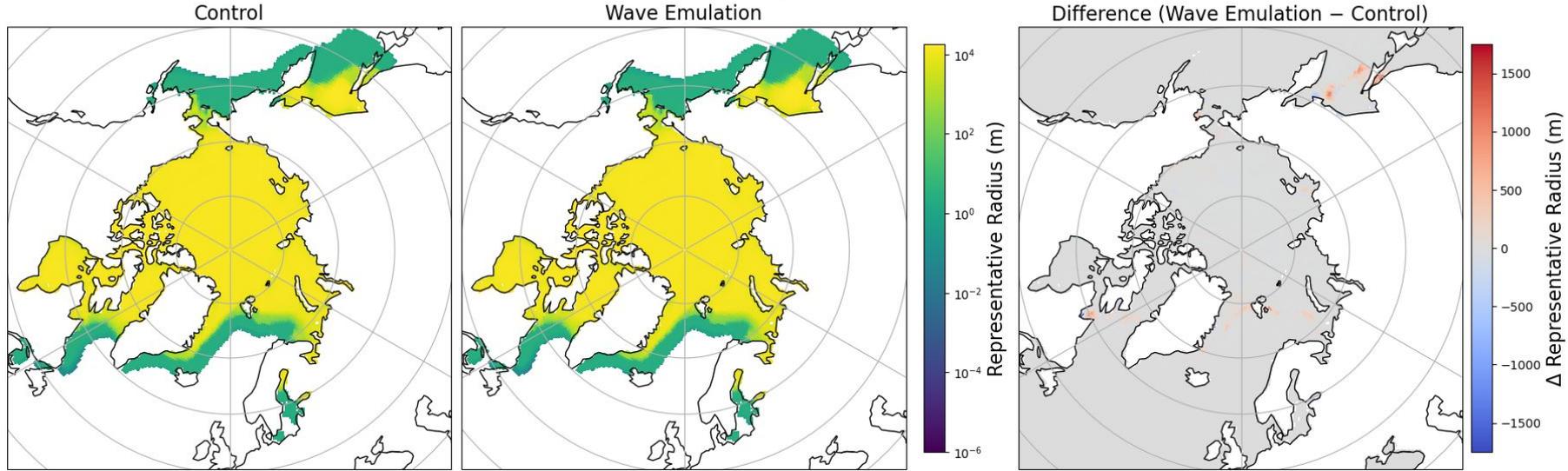
# Emulation results - FSD



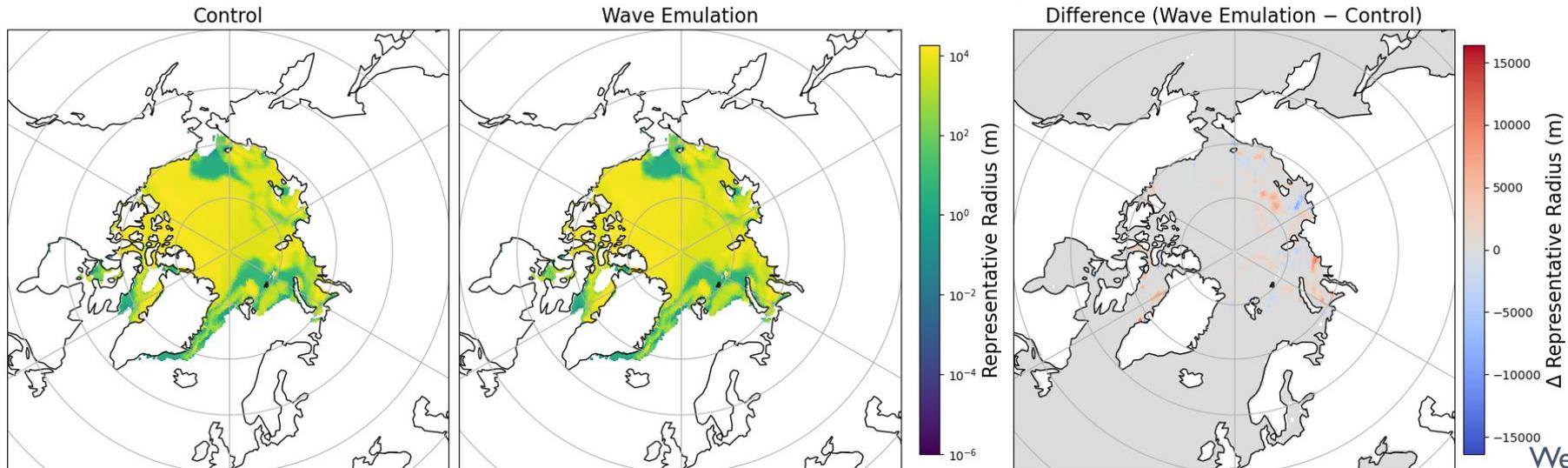
Webb et al., *in prep*

# Emulation results - representative radius (NH)

Emulation vs Control for Representative Radius in March



Emulation vs Control for Representative Radius in September



Webb et al., *in prep*

## Floe Welding in CICE6 is Governed by Coagulation Theory

Smoluchowski Coagulation Equation for a Number Distribution  $f(x)$  where  $x$  is floe area

$$\begin{aligned} \partial_t f &= Q_c(f), \quad (t, x) \in \mathbb{R}_+^2, & \text{Filbert and Laurençot (2004)} \\ f(0) &= f_0, \quad x \in \mathbb{R}_+, \end{aligned}$$

$$Q_c(f)(x) = \frac{1}{2} \int_0^x a(x', x - x') f(x') f(x - x') dx' - \int_0^\infty a(x, x') f(x) f(x') dx'$$

$a(x', x - x')$  is the coagulation kernel, describing rate of combining particles of size  $x'$  and  $x - x'$  into new size  $x$



This equation describes asteroid collisions, raindrop coalescences, blood coagulation, and sea ice floe welding!

$$Q_c(f)(x) = \frac{1}{2} \int_0^x a(x', x - x') f(x') f(x - x') dx' - \int_0^\infty a(x, x') f(x) f(x') dx'$$

This is the sum of rate of gain and loss by floe welding

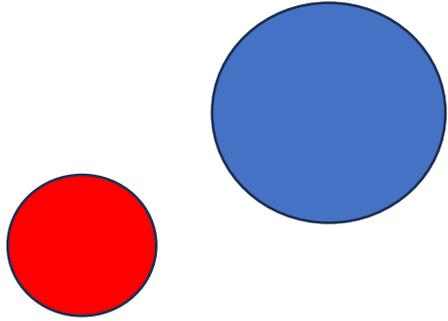
$a(x', x - x')$  is the coagulation kernel, describing rate of combining particles of size  $x'$  and  $x - x'$  into new size  $x$



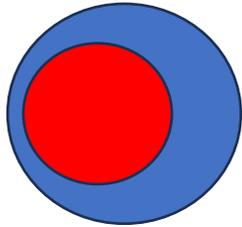
In Roach, Bitz, Horvat and Dean (2019) we let

$$a(x', x - x') \propto x(x - x')$$

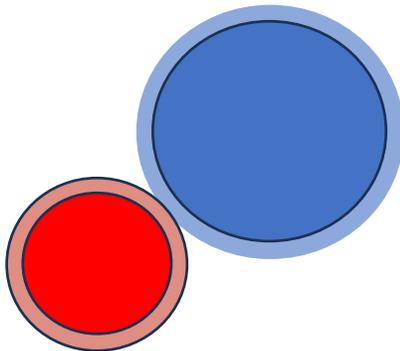
- Coefficient of proportionality determined from observations of welding pancakes X10, recently made X100
- Only allowed welding when net heat loss from open water, I recently added: or when  $T_{air} < -10$  deg C



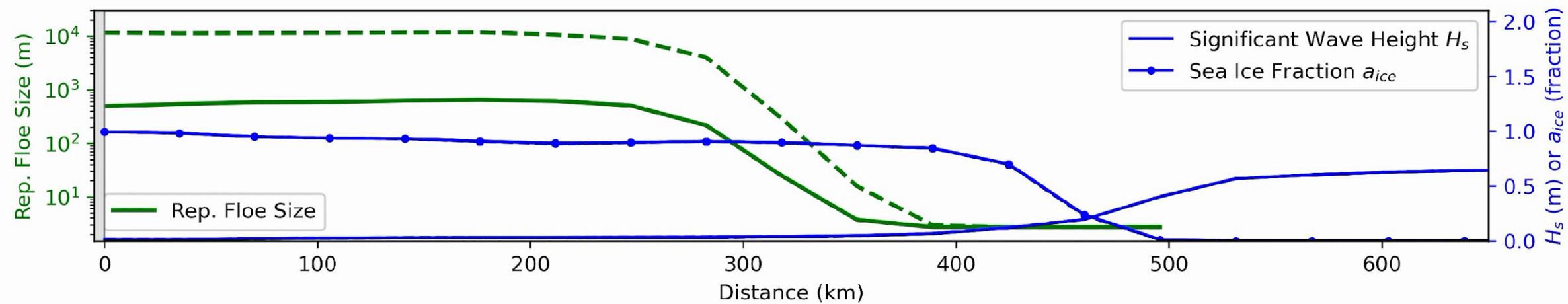
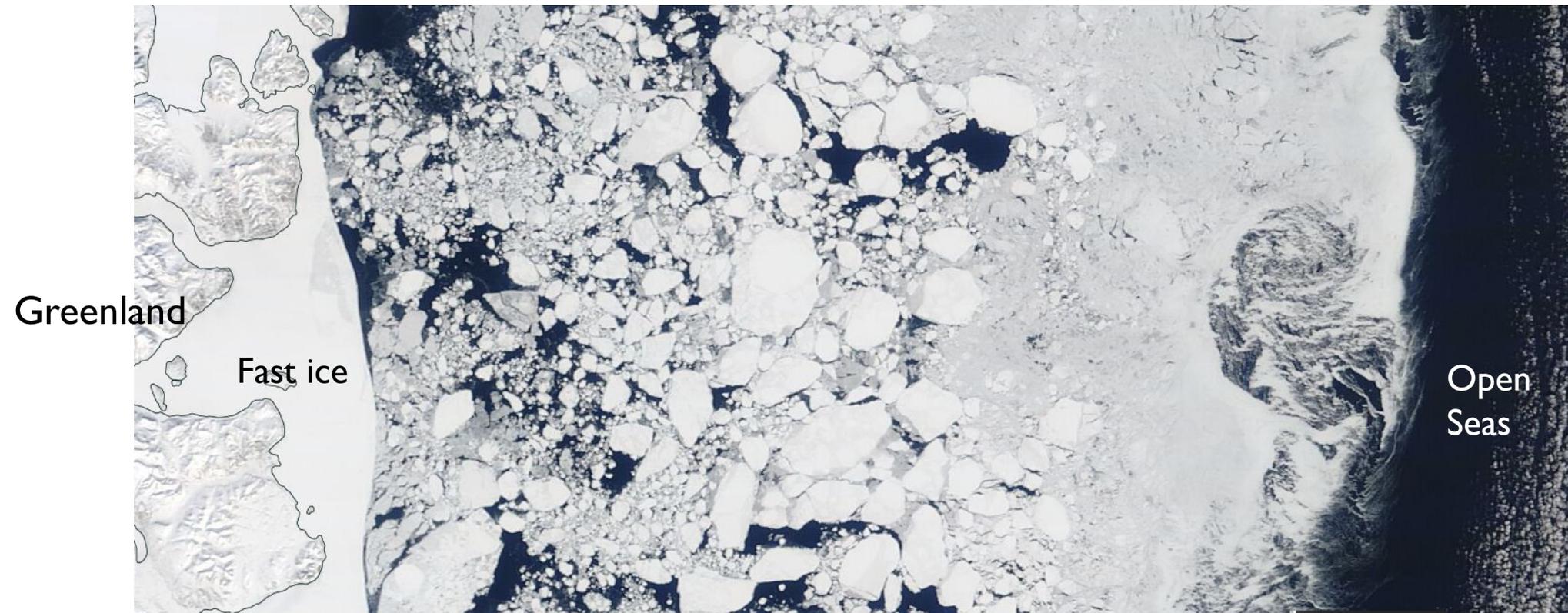
What about their geometries determines the probability of two floes welding?



The product of their areas might make sense if welding does this



The product of their perimeters makes sense if welding does this



# Summary

The FSTD model that we implemented in CICE6 gives sensible results when coupled to WW3, but the time-mean hides very fast fracture and welding, resulting in variability not seen in satellite images.

Suspect too much wave fracture and consequently too much welding. We are working on it (e.g., modification to the welding kernel)

We are working on increase spatial heterogeneity in the pack ice and coupling floe-size to the sea ice rheology to. See Geraint's talk.

We needed to extend the floe size upper bound (Geraint will say more about this), which caused wave fracture to be more computationally demanding so we implemented a wave fracture emulator.

The new wave fracture emulator can emulate more accurate wave fracture at a fraction of the cost.

FYI, we needed to improve WW3 numerics so it doesn't overdamp waves in sea ice. Easy fix already implemented in CESM3. Room for more numerical improvements in WW3, love to talk about it with those that are interested