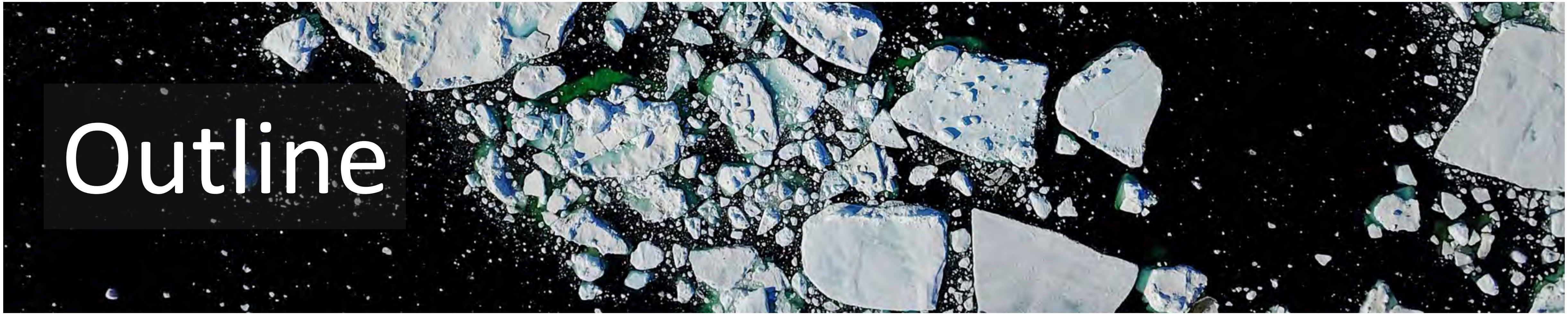
About the Sea Ice Floe Size Distribution

Christopher Horvat

Feat. Lettie Roach, CC Bitz, Sam Dean, Eli Tziperman, Baylor F-K, Kaitlin Hill, Mike Meylan, Rachel Tilling, Jacinta Clay, and others.



Outline

Sea ice is made of floes.

1. **Why do we care?** Ocean mixing energized at floe boundaries and leads.

2. **How can we model floe-scale processes?** Theory of the floe size distribution.

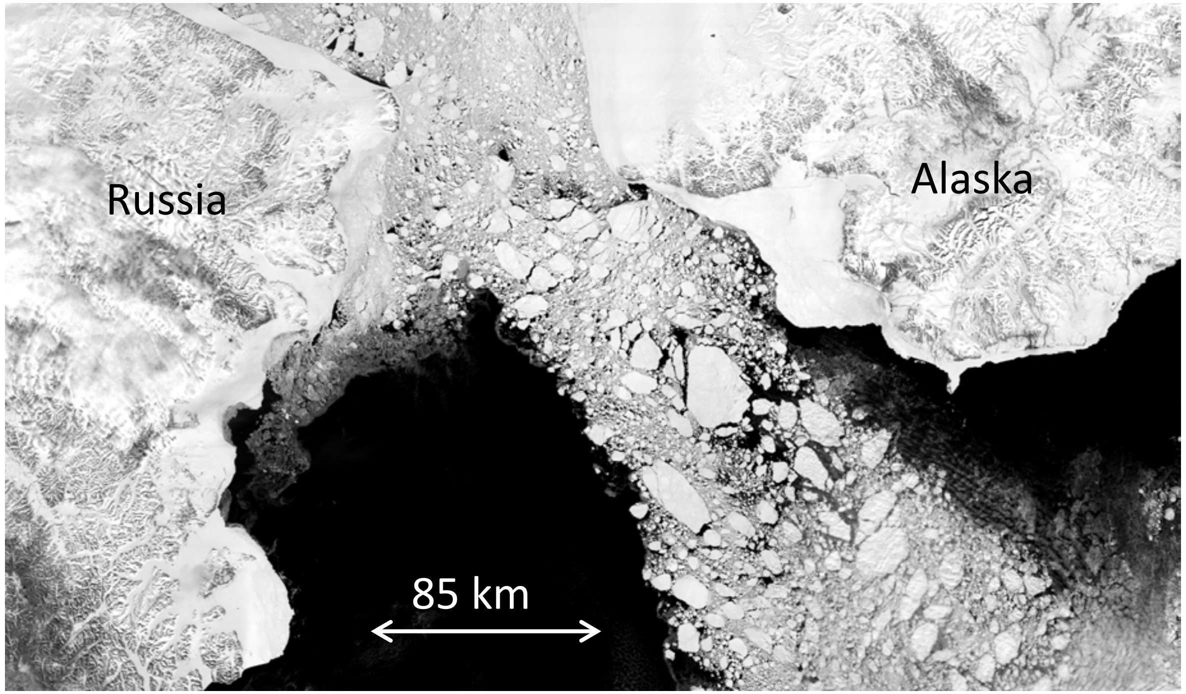
3. **How do we evaluate an FSD model?** New remote sensing ideas.

The Sea Ice Cover Is Made Up Of Floes

- Sea ice is composed of distinct pieces, known as floes.

- Floe sizes span a wide range, both above and below the climate model grid scale.

Floes surrounding the Nathaniel Palmer in Antarctica

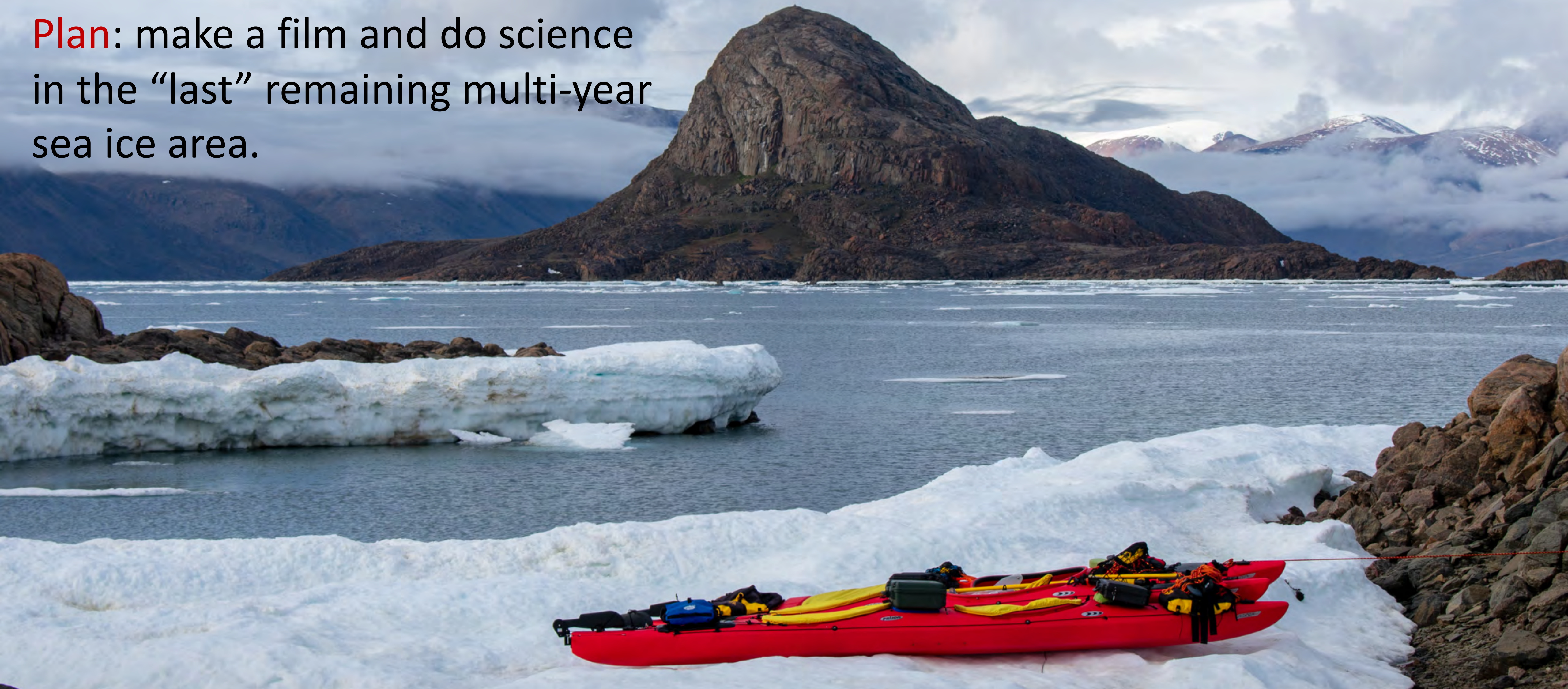


Floes in the Bering Sea (NASA)

Enduring Ice: An Film/Expedition At 82N

Summers 2017/2018 “kayaking” Nares Strait, doing science and making a film.

Plan: make a film and do science in the “last” remaining multi-year sea ice area.



Floe-Scale Fracture Controls Loss of Multi-Year Ic

Nares Strait has historically jammed with multi-year ice from Lincoln Sea, allowing passage for would-be kayakers.

Instead of jamming, fractured, first-year sea ice poured through the strait in summer.

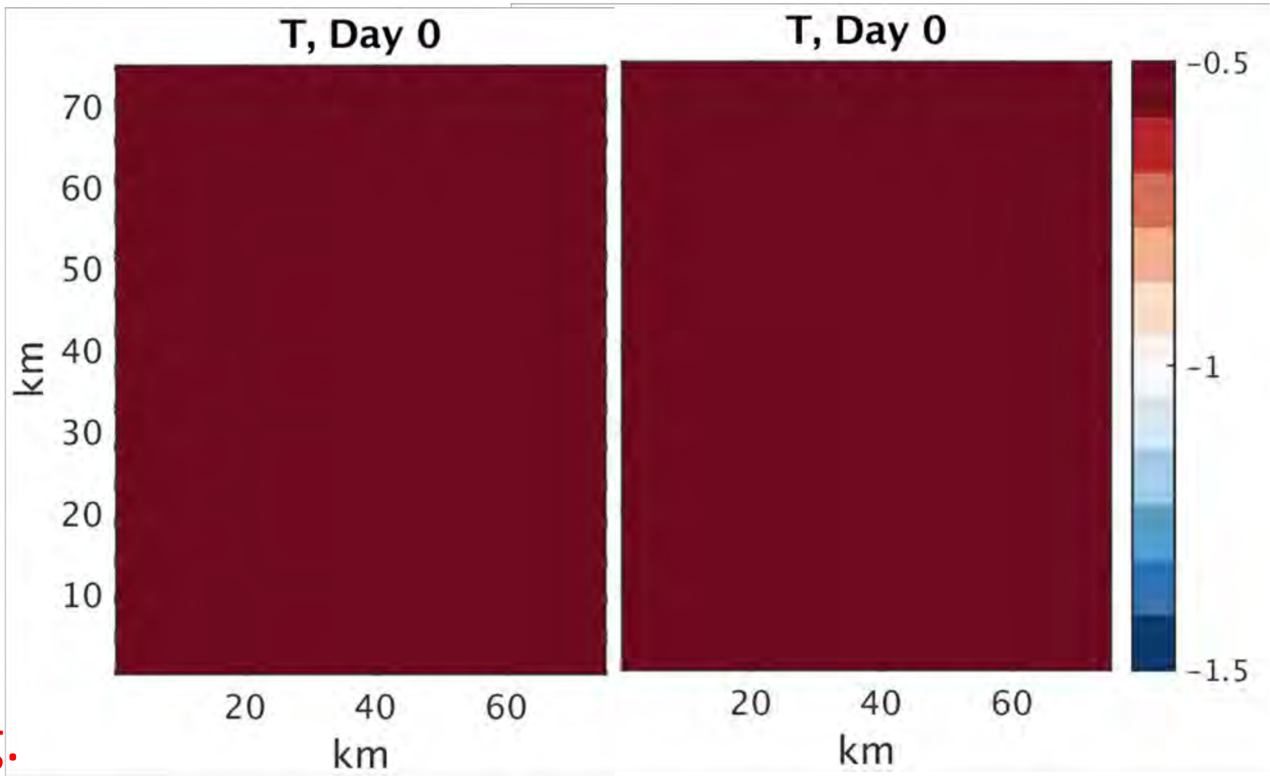
In 2017-2018, none of this streaming ice was multi-year

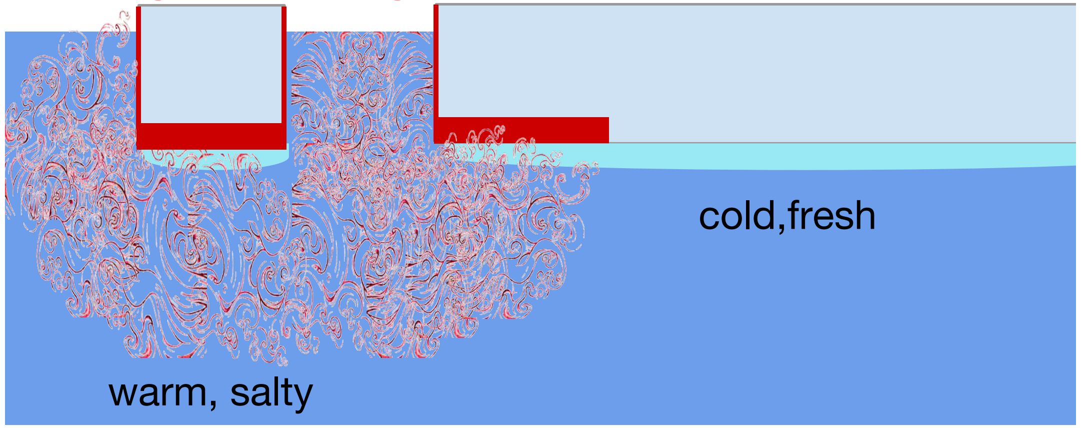
A typical image of Nares Strait in summer.

Floe-scale coupling of ice and ocean may drive sea ice evolution.

Floes force strong boundary condition gradients. Melting and freezing ice, and insulation of ice-free or open waters lead to gradients that may energize sub-mesoscale eddies.

Eddy mixing is more effective as floe and lead scale decreases, leading to FSD-dependent melting, freezing, horizontal and vertical mixing.

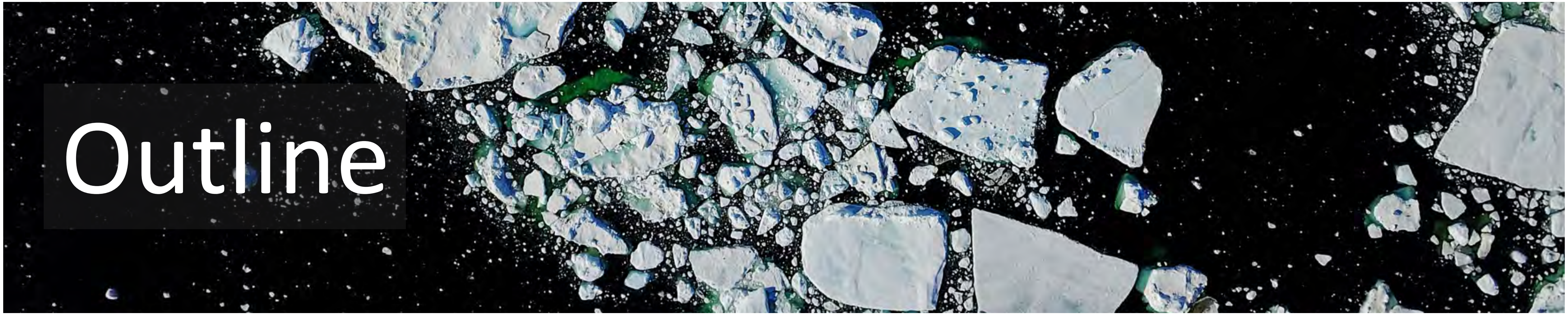




Horvat, Tziperman, & Campin (2016) Interaction of sea ice floe size, ocean eddies, and sea ice melting. GRL.

Horvat and Tziperman (2018) Understanding melting due to ocean eddy heat fluxes at the edge of sea ice floes. GRL.

Horvat and Fox-Kemper (2018) Mixing at the edge of a broken sea ice floe. *Submitted.*



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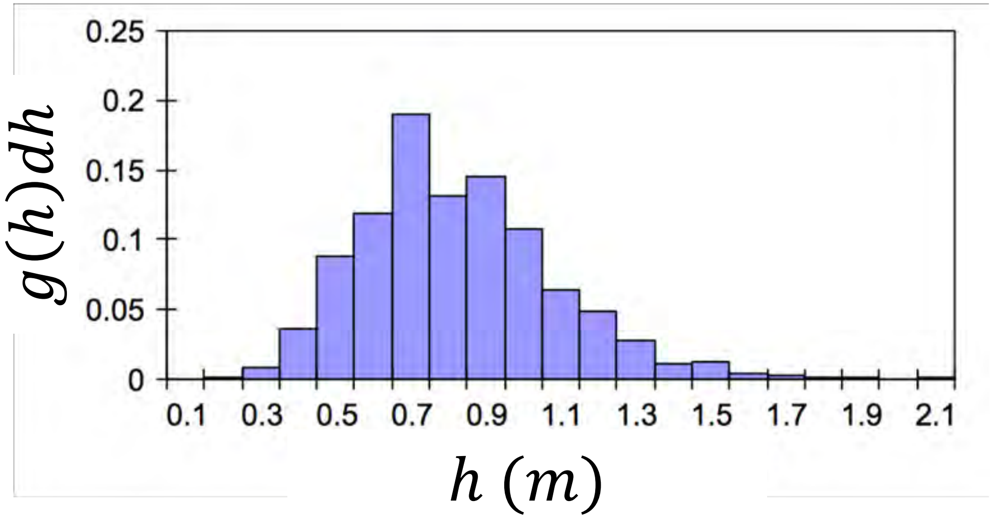
The Sea Ice Thickness Distribution (Thorndike et al 1975)

- Ice thickness distribution (ITD): g(h)dh: the fraction of an area composed of ice with thickness between h, and h+dh



ITD from Xie (2013) – Bellinghausen Sea

$$\frac{\partial g}{\partial t} = -\nabla \cdot (\mathbf{ug}) - \frac{\partial}{\partial h}(\dot{h}g) + \psi$$

Time evolution

Advection by ice motions

Melting and freezing of ice

Mechanical Interactions

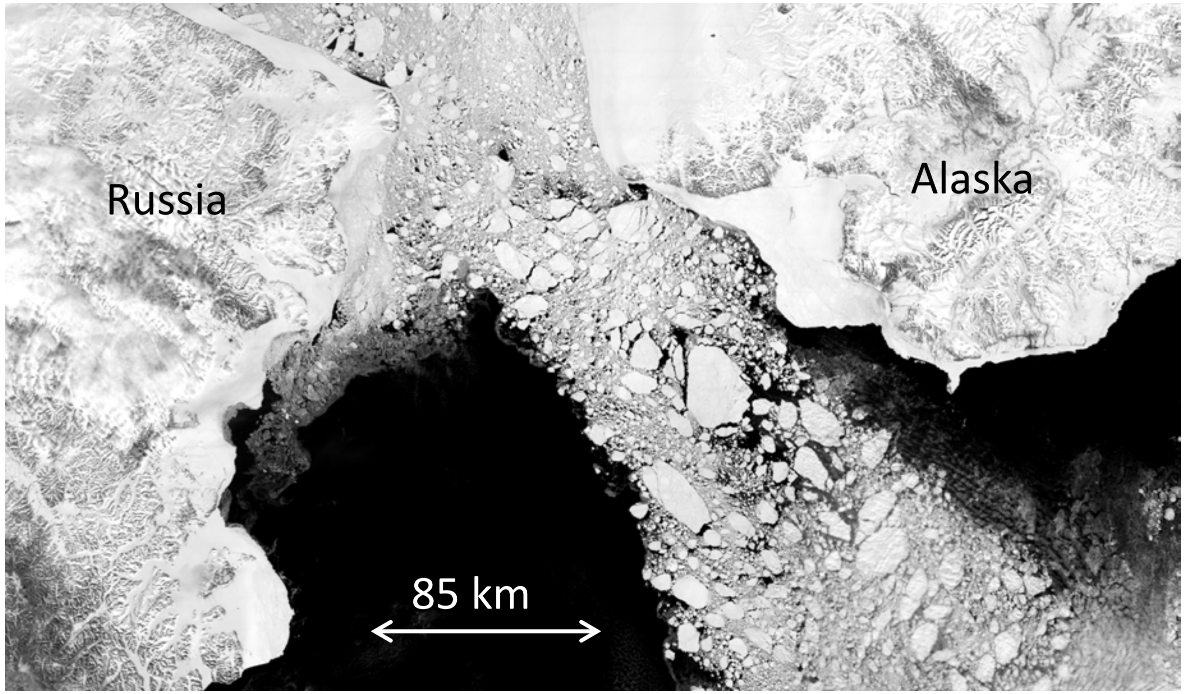

Ridged sea ice

The Sea Ice Cover Is Made Up Of Floes

- Sea ice is composed of distinct pieces, known as floes.

- Floe sizes span a wide range of scales, described statistically by their floe size distribution (FSD).

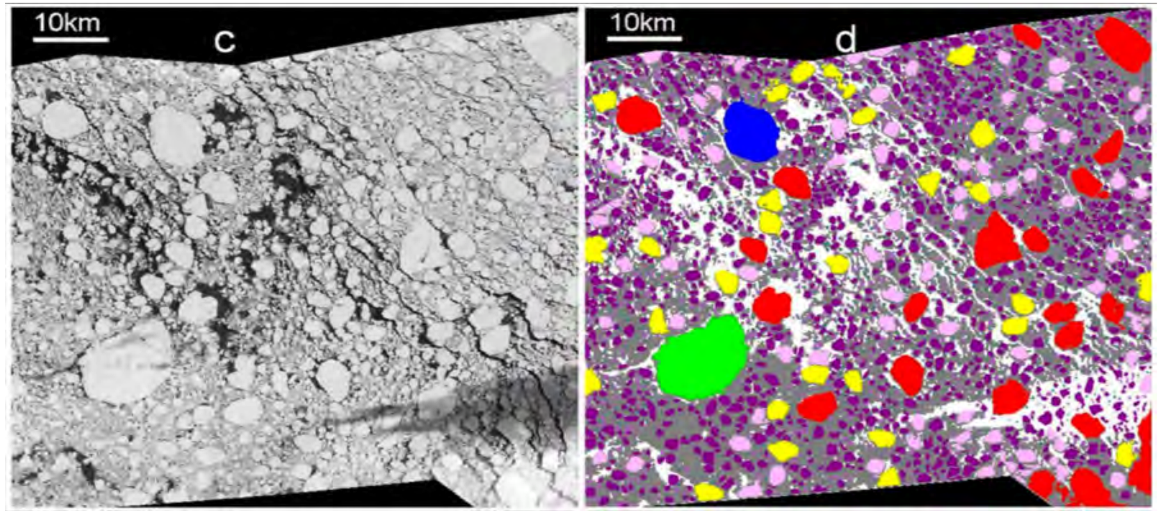
Floes surrounding the Nathaniel Palmer in Antarctica



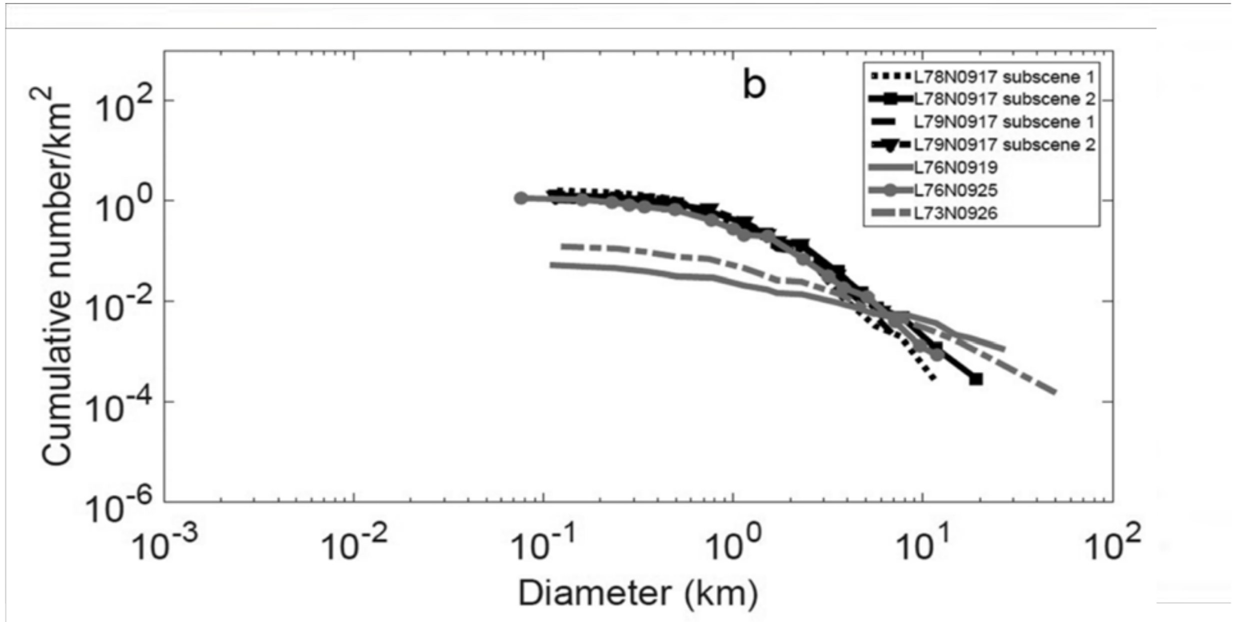
Floes in the Bering Sea (NASA)

The Sea Ice Floe Size Distribution

- A floe's "size" is the radius of a circle with the same perimeter - the "effective radius"
- Floe size distribution (FSD): $n(r)dr$: the fraction of an area composed of ice with size between r and r + dr



Landsat image of floes with a floe identifying algorithm applied (Wang 2016)



Cumulative number distribution of floes from above

The Floe Size and Thickness Distribution

Combining size and thickness, the joint FSD/ITD (FSTD) f(r,h) dr dh is defined as the fraction of the sea surface covered by ice with thickness between h and h + dh, and effective radius r and r + dr.

Floe size distribution

$$n(r)\ dr$$

Ice thickness distribution

$$g(h)\ dh$$

$$f(\mathbf{r})\ dr\ dh$$

Horvat & Tziperman (2015). A prognostic model of the sea ice floe size and thickness distribution. Cryosphere.
Horvat & Tziperman (2017). The evolution of scaling laws in the sea ice floe size distribution. JGR.
Roach, Horvat, Dean, & Bitz (2018). The sea ice floe size and thickness distribution in a coupled climate model. JGR.
Roach, Smith, and Dean (2018). Quantifying growth of pancake sea ice floes using images from drifting buoys

The FSTD Model

$$\frac{\partial f(\mathbf{r})}{\partial t} = \mathcal{L}_T + \mathcal{L}_M + \mathcal{L}_W$$

Thermodynamics:

- Ice Formation (pancakes)
- Lateral Freezing/Melting
- Basal Freezing/Melting
- Floe Welding

Mechanical Interactions:

- Ice Divergence/Convergence
- Rafting
- Ridging

Wave Fracture:

- Strain failure due to surface waves

Horvat & Tziperman (2015). A prognostic model of the sea ice floe size and thickness distribution. Cryosphere.
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Thermodynamics and Sub-gridscale Distributions

Under basal change, area is conserved, thus ITD evolution goes as: $C(h) = \int_0^h g(h')dh'$

$$\frac{\partial C(h)}{\partial t} = -\dot{h}\frac{\partial C(h)}{\partial h}$$

$$\boxed{\frac{\partial g}{\partial t} = -\dot{h}\frac{\partial g}{\partial h}}$$

Change to ITD as ice changes thickness category

Under lateral change, area is *not* conserved, but floe number is

$$\frac{\partial C_n(r)}{\partial t} = -\dot{r}\frac{\partial C_n}{\partial r}$$

$$C_n(r) = \int_0^r \frac{n(r')}{\pi r'^2}dr'$$

$$\frac{\partial n}{\partial t} = \underbrace{\boxed{-\dot{r}\frac{\partial n}{\partial r}}}_{\text{ITD-like}} + \underbrace{\boxed{\frac{2\dot{r}}{r}n(r)}}_{\text{FSD-specific}}$$

Change to FSD as floes change size category

Change to FSD as lateral melting changes ice area

Thermodynamics and the FSTD

$$\nabla_r = \left(\frac{\partial}{\partial r}, \frac{\partial}{\partial h}\right) \qquad \mathbf{G} = \left(\dot{r}, \dot{h}\right)$$

The melting/freezing of the FSTD is expressed as:

$$\overbrace{\frac{\partial f(r,h)}{\partial t} = -\nabla_r (f(r,h)\mathbf{G})}^{\text{ITD-like}} + \overbrace{\cdots}^{\text{FSD-specific}}$$

Overall, the change to area is

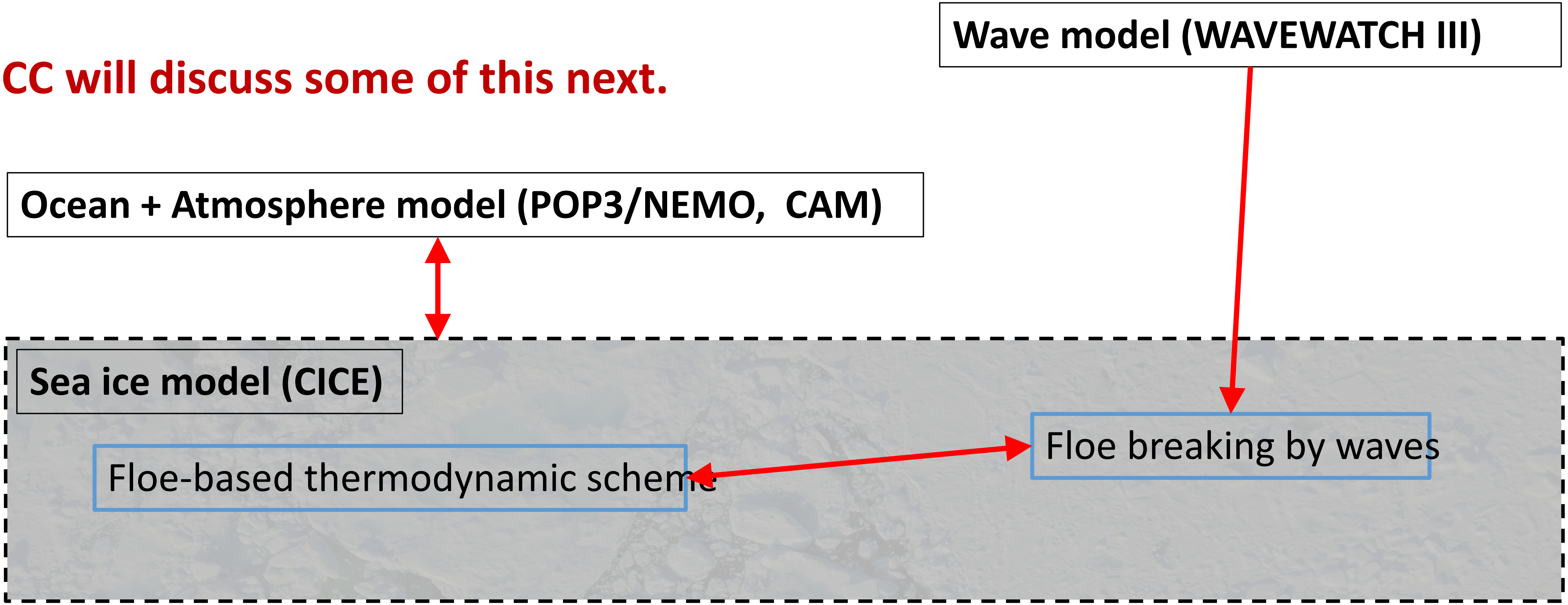
$$\frac{\partial A}{\partial t} \propto \overline{1/r}$$

This is the **whole game!** – it tells how changes to floes affect the melting of sea ice. It can be observed! Yet it is missing from most parameterizations of floe effects to date…

The Floe Size Distribution in a coupled GCM

The FSTD scheme is now being used with a hierarchy of coupled models.

CC will discuss some of this next.



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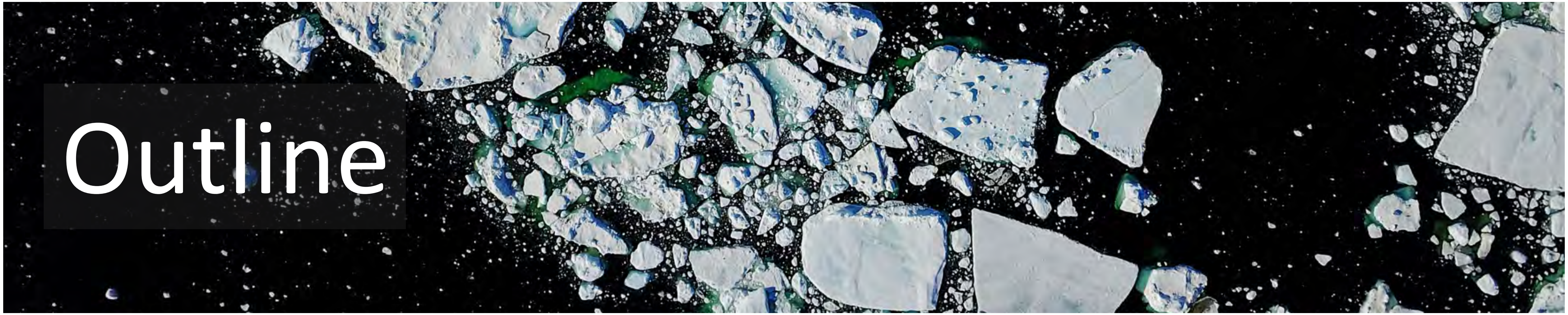

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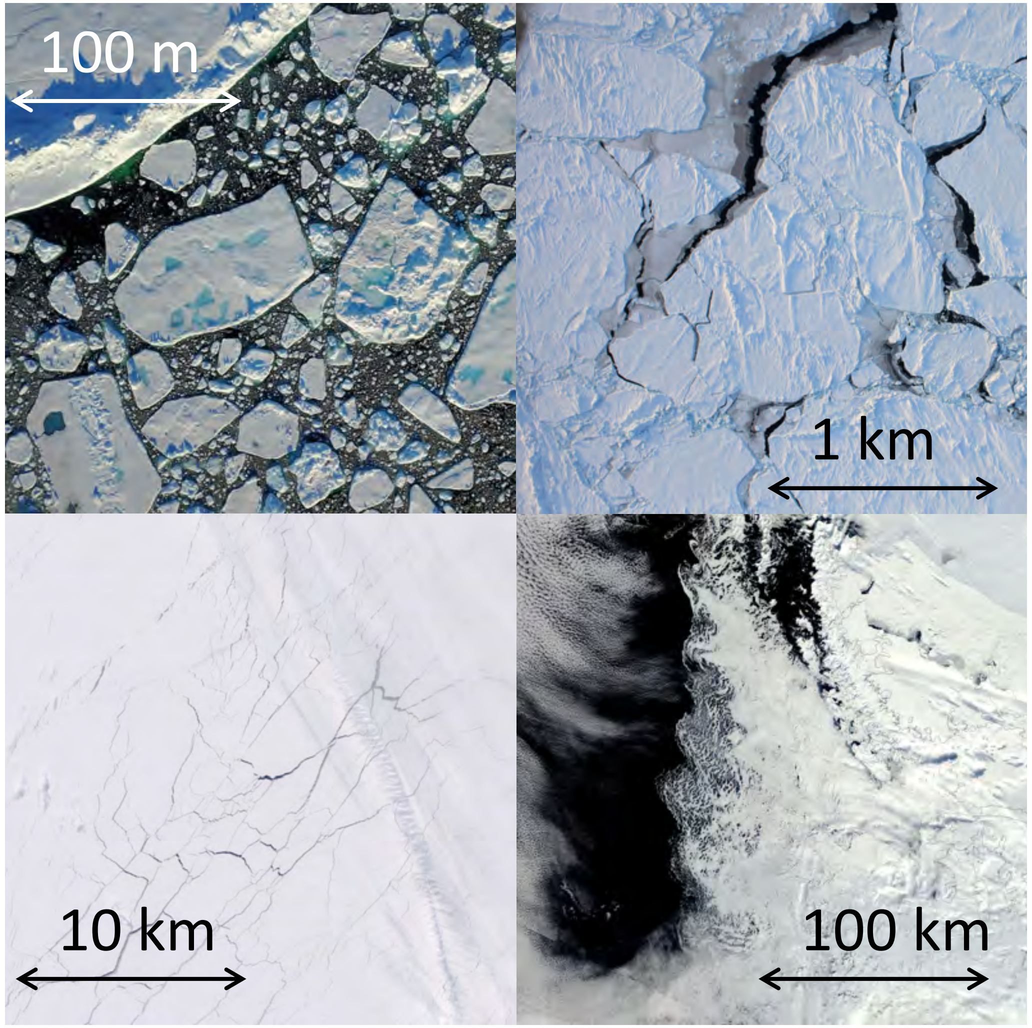
Observations and the Floe Size Distribution

What a wonderful situation!

We now have sea ice models at a variety of stages of complexity that parameterize floe-scale processes.

The sea ice surface is readily observed with many systems at multiple scales.



Observations and the Floe Size Distribution

What a frustrating situation!

We now have sea ice models at

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The sea ice surface is readily observed with many systems at multiple scales.

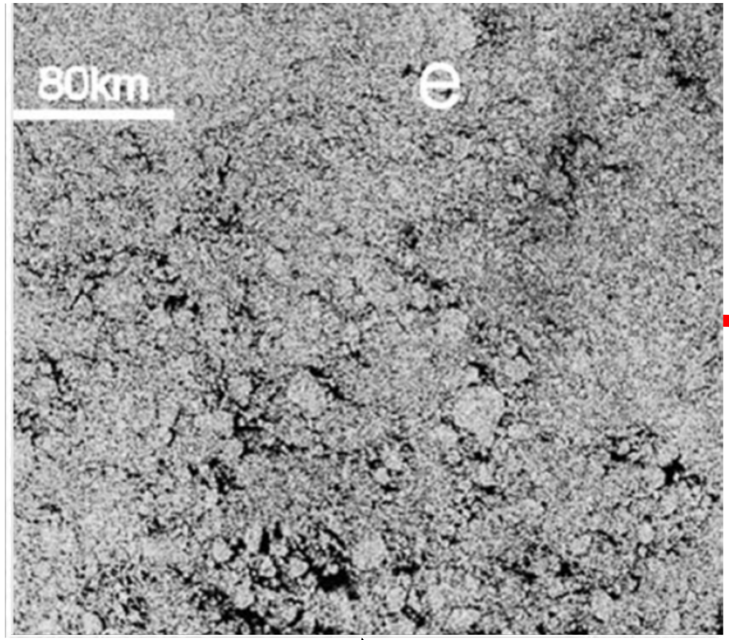
Theory, models, and observations diverged in 1984. At the moment, they don't support each other.

How is the FSD observed?

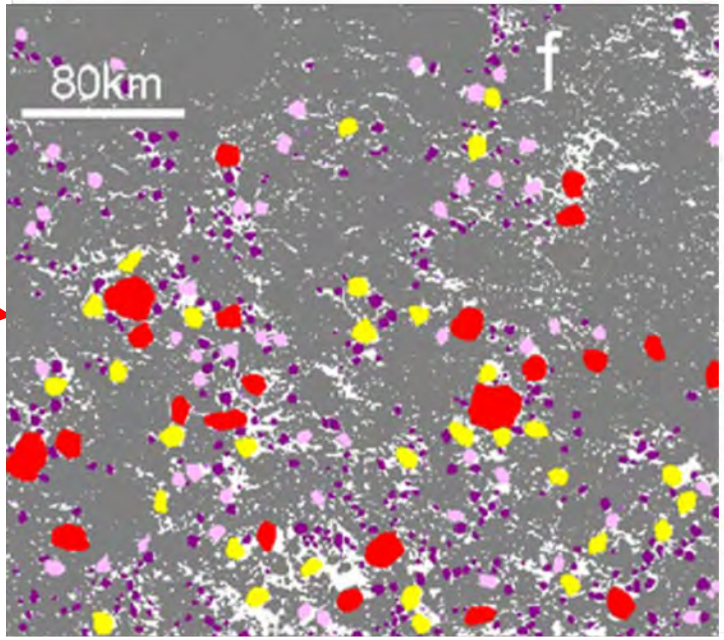
Floes in the Beaufort/Chukchi Sea (from Wang et al, 2016)

Remember: Floe size distribution (FSD): n(r)dr: the fraction of an area composed of ice with size between r and r + dr

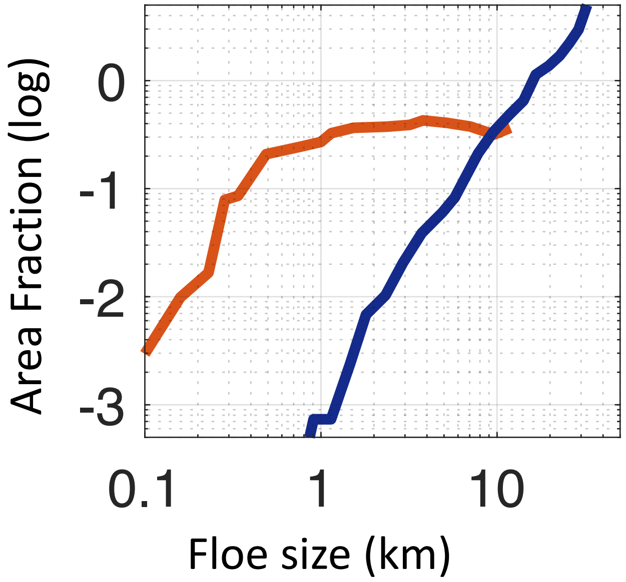
(1) Acquire image



(2) Pick out floes



(3) Plot the FSD



(4) Repeat!

Observed FSDs are fit to a power law distribution

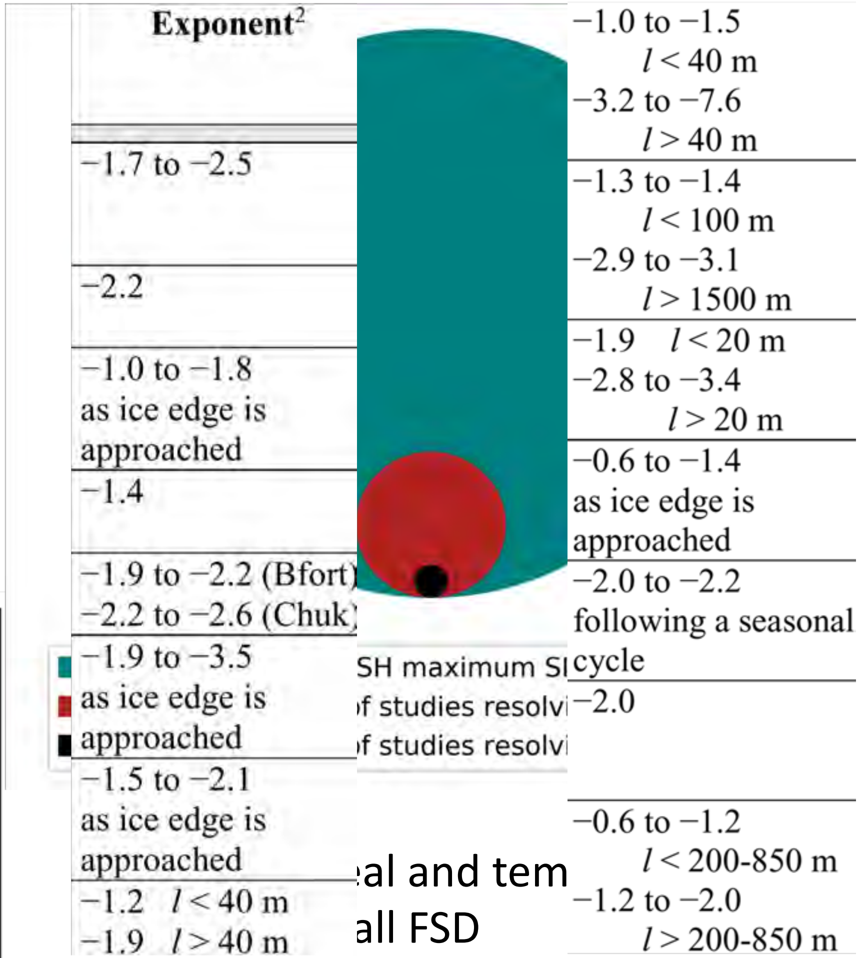
How can we constrain an FSD model?

Issues with the state of observations:

1. Object identification techniques are extremely sensitive.
2. Coverage is extremely small.
3. Output is in terms of power laws that vary wildly or don't stand up to scrutiny. (see Horvat et al, 2017, Stern et al, 2018).

Suggestion:

- Try to leverage existing, global data sets in ways specifically designed for model comparison.



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...al and tem... all FSD measurements ever taken. (From Lettie Roach)

Power law fits to those all FSD obs (Stern et al, 2018)

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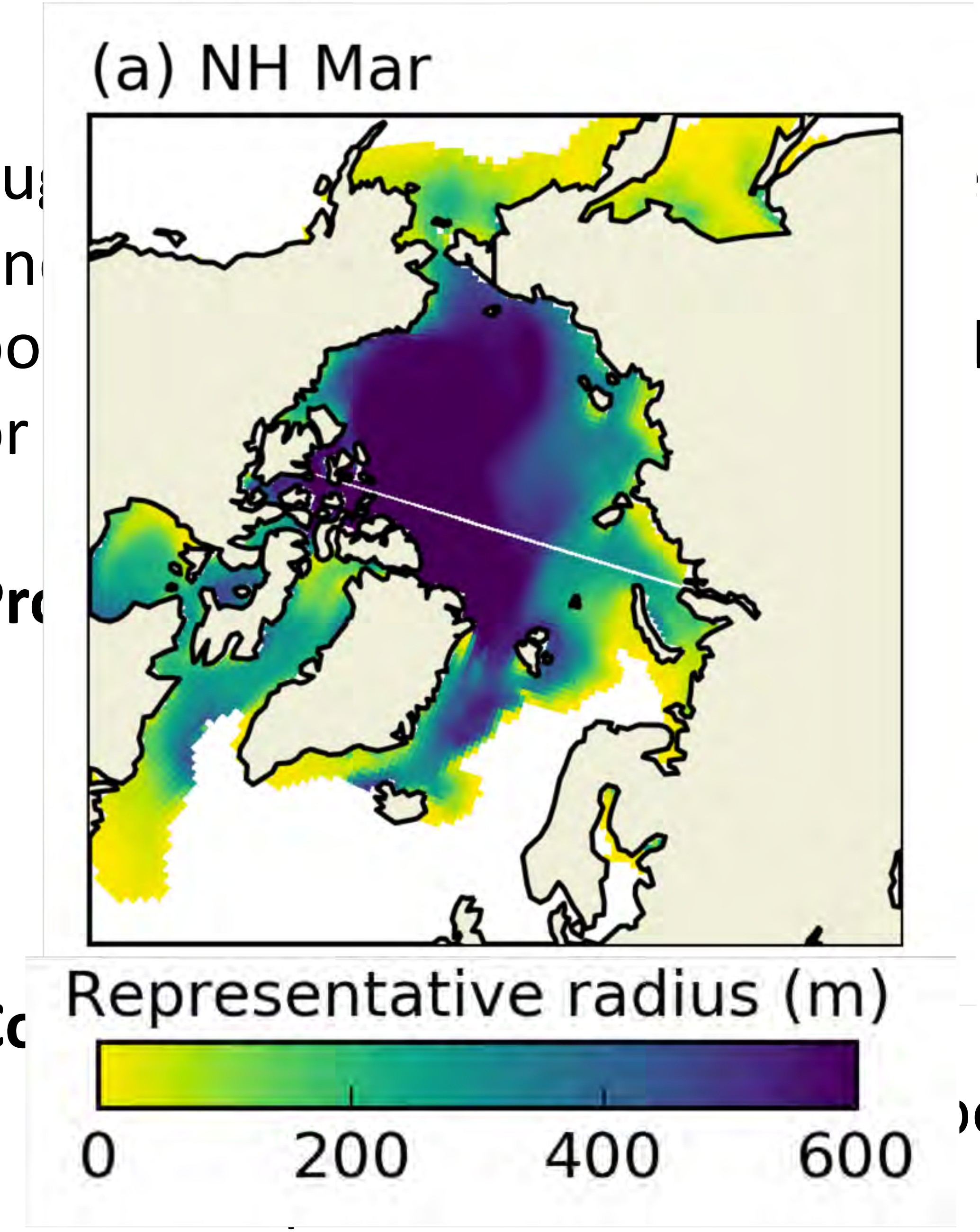
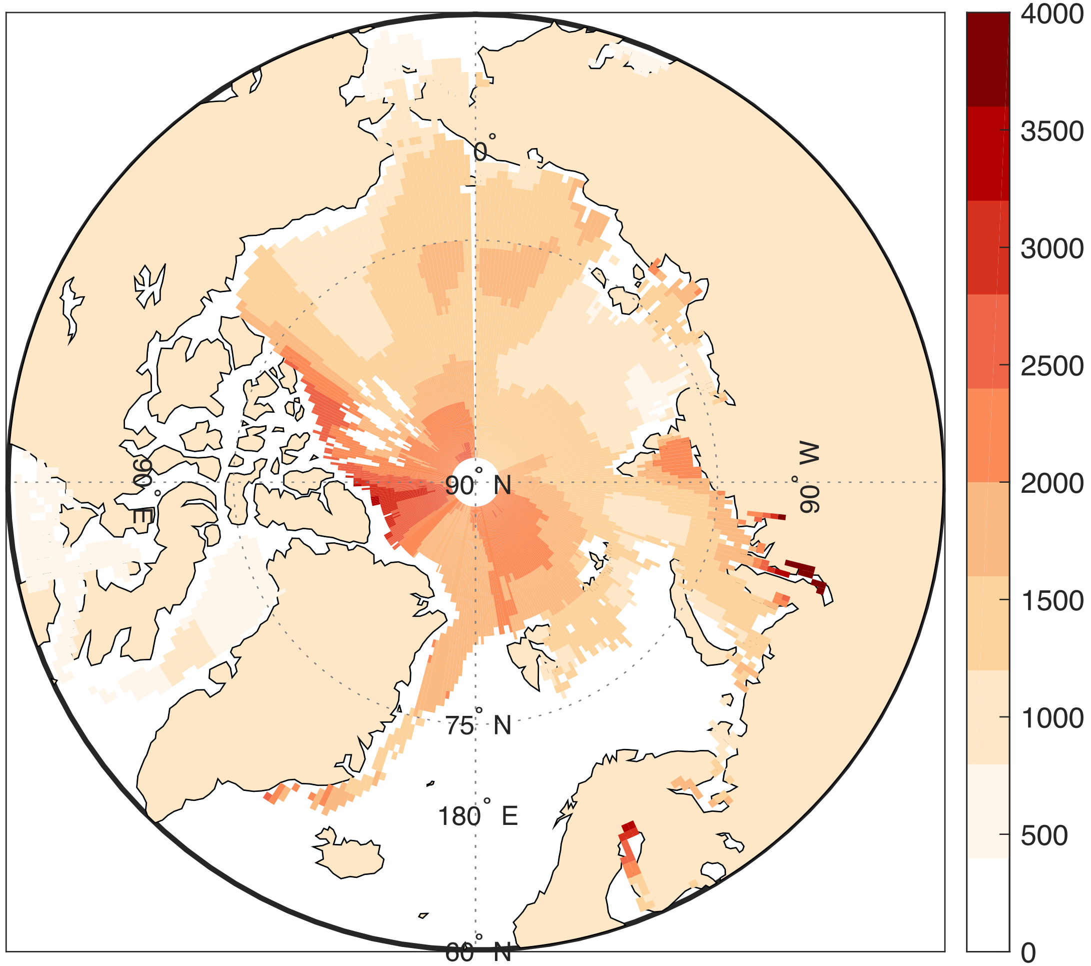
- Resolved scale still large



Climatological March floe size from FSTD-CICE



Inferred floe size from CRYOSAT in March, 2011

Constrain FSD models with Machine Learning?

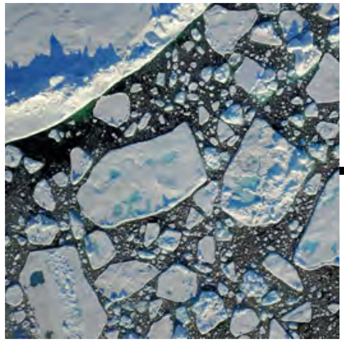
Suggestion: train a model to return FSD information using low-res imagery + met variables as input.

Pros:

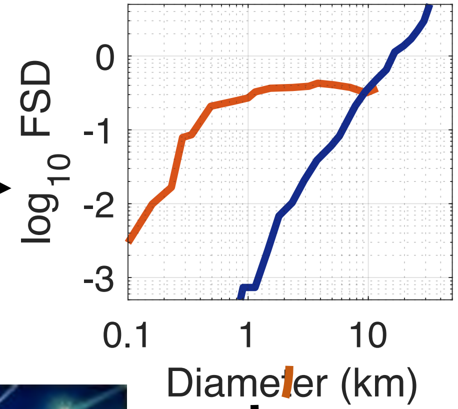
- Global record of required data products since 1990. Data for trai
  exists.
- Efficient once built.

Cons:

- Development of training data subject to same issues as before.
- Requires time, $$$, effort to produce



(x 1 million)



Bulk parameters

Bulk parameters

Constrain FSD models with SP/LES simulations?

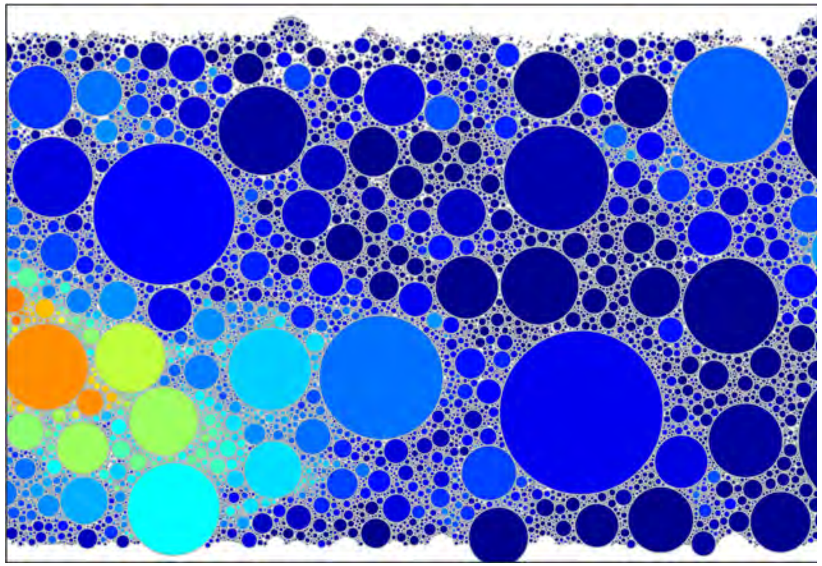
Can we run high-resolution coupled discrete element models of sea ice to obtain FSD-sensitive parameterizations?

Pros:

- Existing framework for SP

Cons:

- We don't really trust sea ice DEMs.
- Expensive to run even vs. cloud physics models



Floes in DESIGN/LAMMPS (Herman, 2015)

Summary

Sea ice is made of floes. Floes and their sizes are important for determining the evolution of ice, ocean, climate, etc, and are below resolved scales in sea ice models.

We have sub-grid scale theories for sea ice models. These include the floe size and thickness distributions, ocean mixing under ice, and others

We have included these new ideas in coupled climate models. See next talk.

But…. We don't yet have the tools to validate models against observations.