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Fracture of sea ice by ocean surface waves in CESM3

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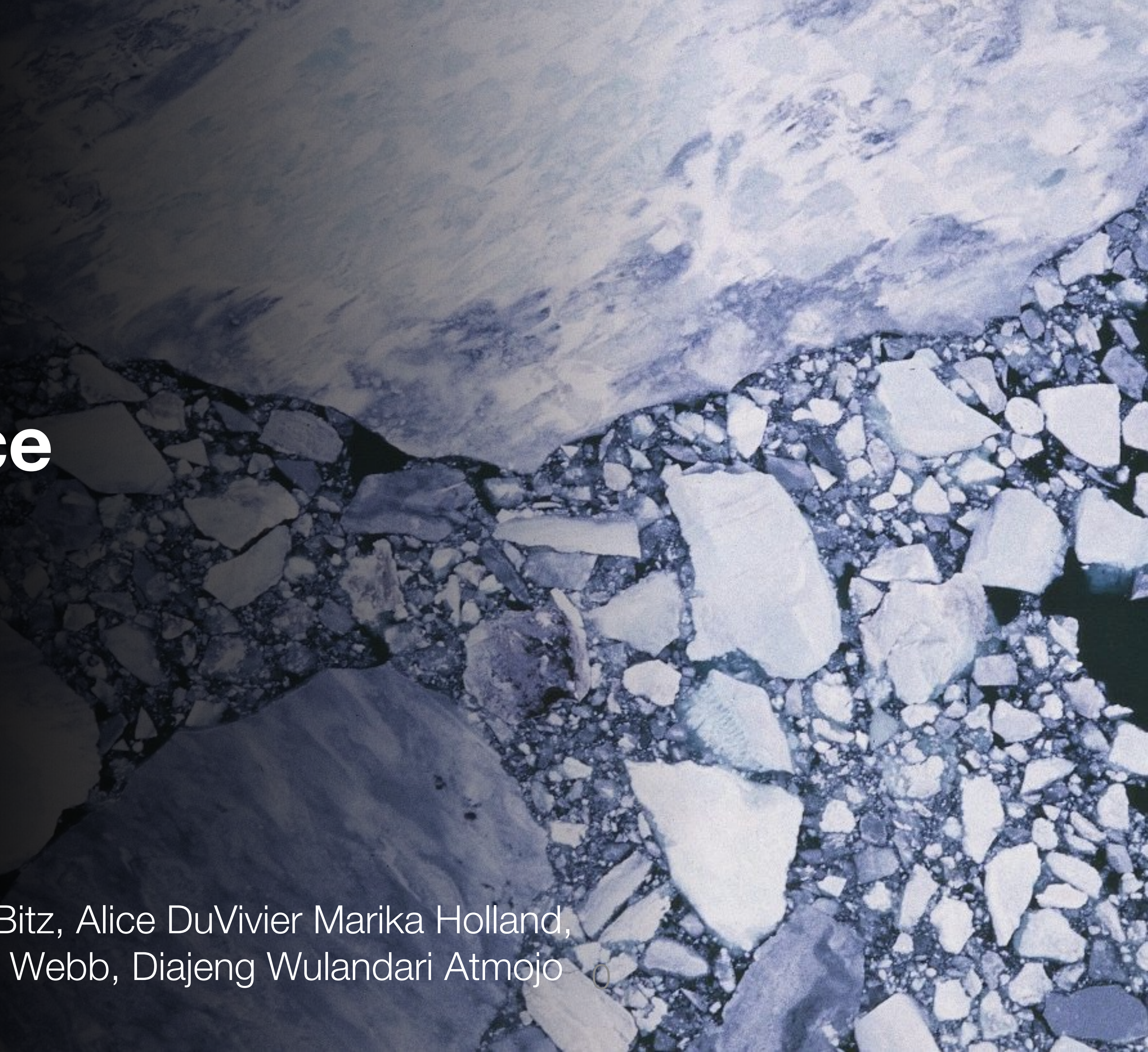
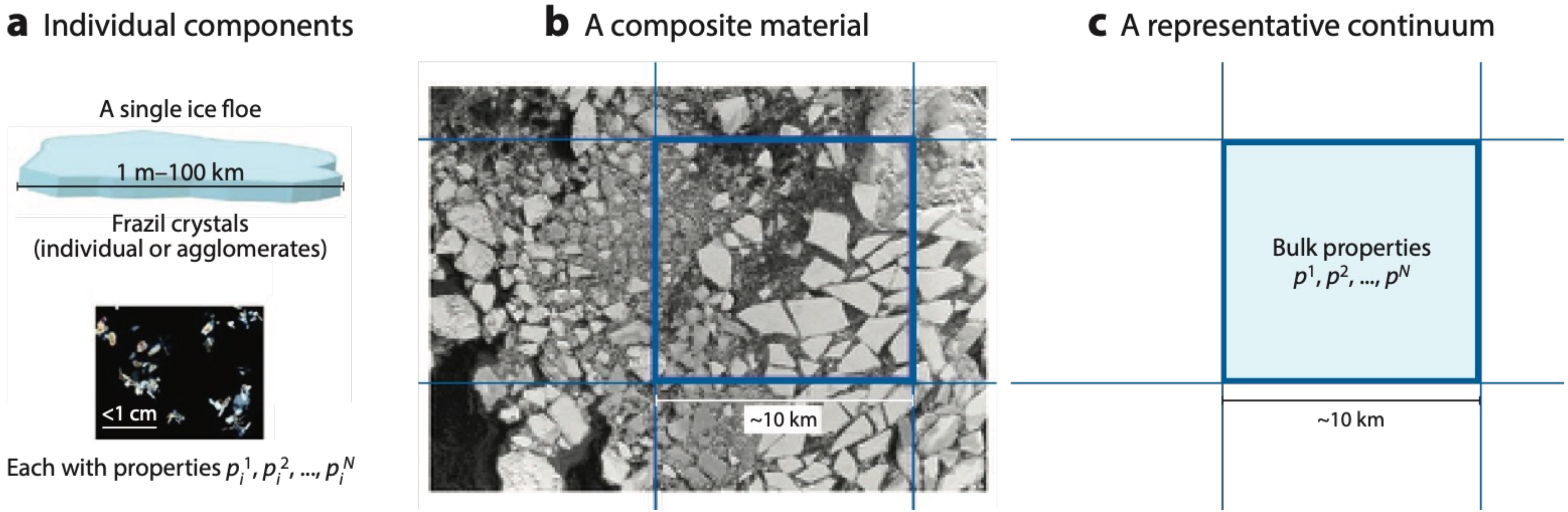


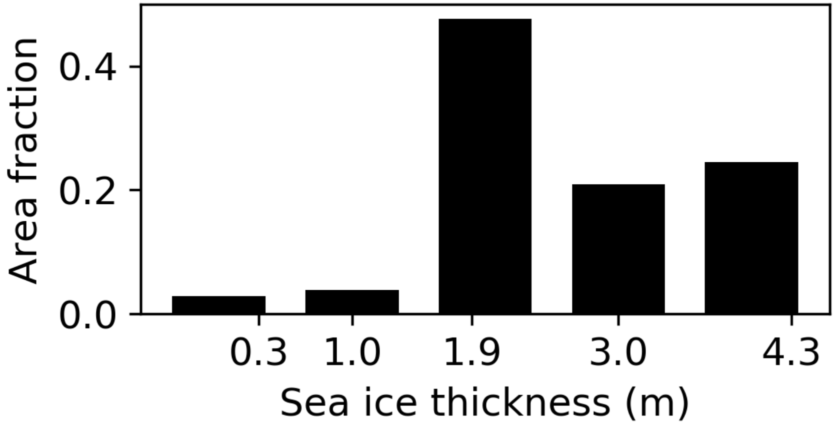
Representing sea ice in climate models



Roach et al. (2024)

The sea ice thickness distribution, g(h)

- Rothrock & Thorndike (1975)



Advection

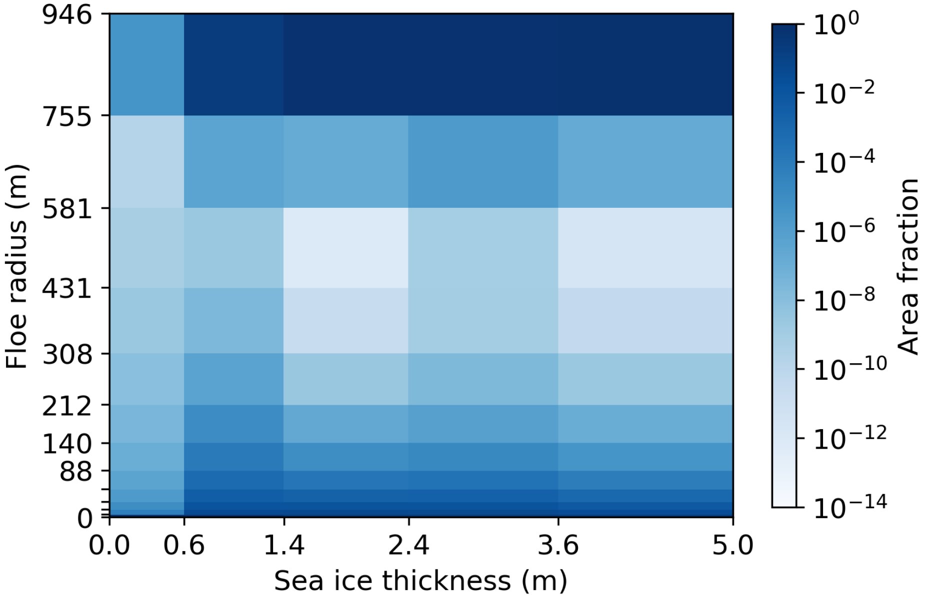
Ridging/rafting

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

Thermodynamics

The sea ice floe size and thickness distribution, f(r,h)

- *f(r,h)* is the fraction of grid surface area covered by ice with thickness between *h* and *h*+d*h* and lateral floe size between *r* and *r*+d*r* (Horvat & Tziperman, 2015)



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

Advection

Thermodynamics

Mechanical interactions

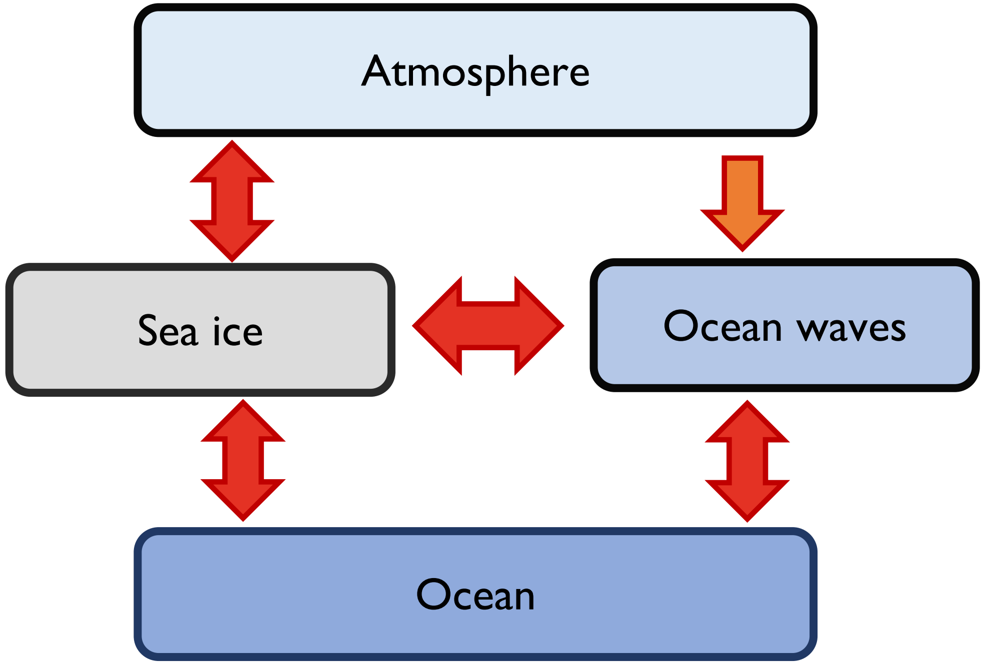
Wave fracture

Implemented by Roach et al. (2018a, 2019) in CICE6/Icepack
- no feedback between FSD and dynamics or mechanical interactions
+ new wave fracture

Variants also by Boutin et al. (2020, 2022), Bateson et al. (2020), and others

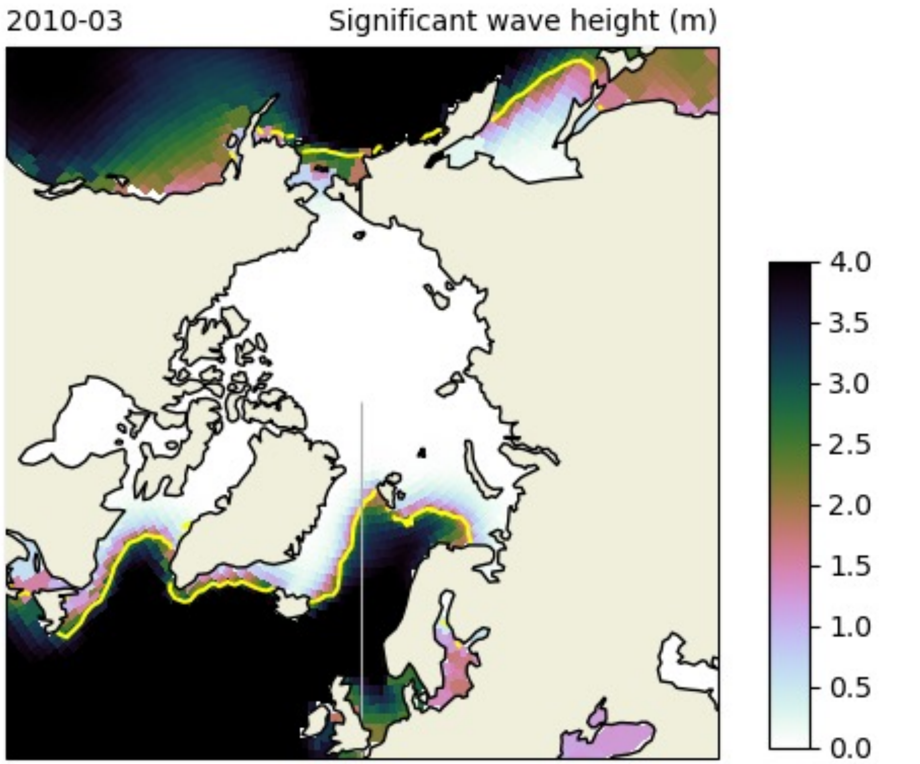
Coupled CESM3 development simulation

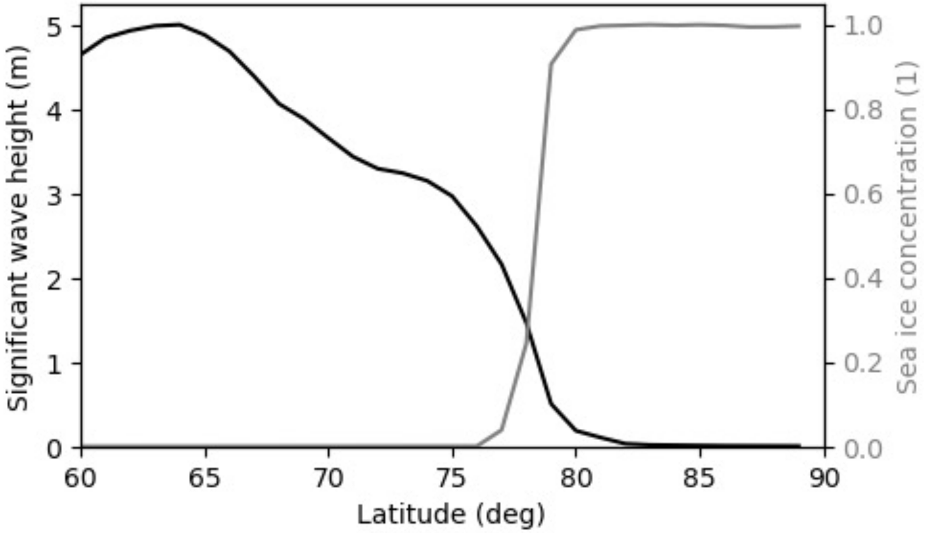
- b.e30_alpha07g.BHISTC_LTso.ne30_t232_wgx3.271



Wave attenuation in sea ice

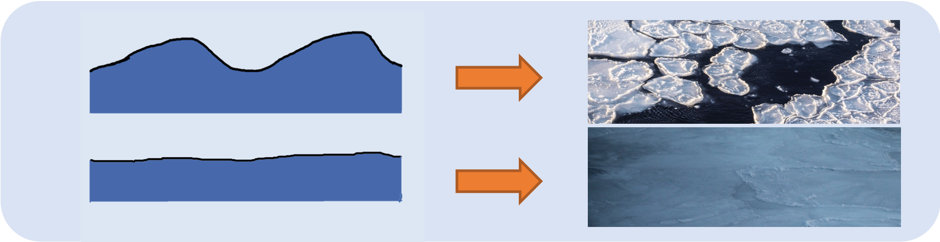
Photo: Lettie Roach, CODA cruise, Beaufort Sea, 2019



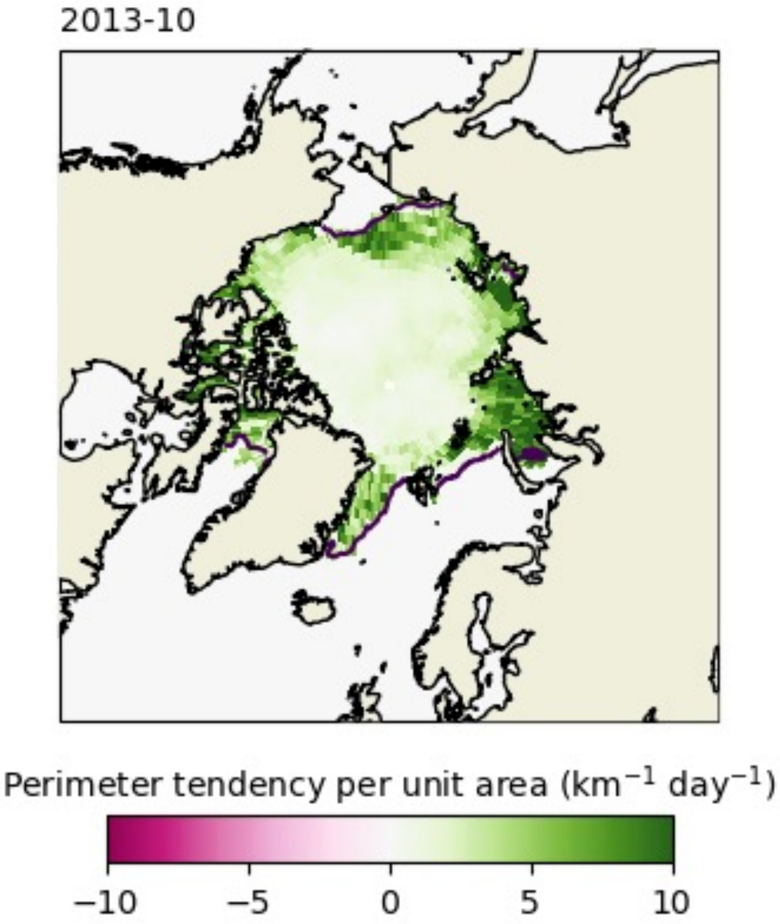


- Considerable uncertainty in wave attenuation (e.g. Cooper et al. 2022)
- We use Meylan et al. (2021) floe-size-dependent attenuation

Wave-dependent new ice growth

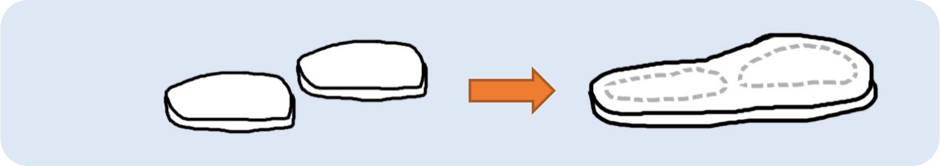


- Tensile failure limit on floe size in a wave field (Shen et al. 2001)
- $$D_{\max} \approx \sqrt{\frac{2C_2\lambda^2}{\pi^3 W_A g \rho_i}},$$
- Calibrated with in situ observations (Roach et al. 2018b)

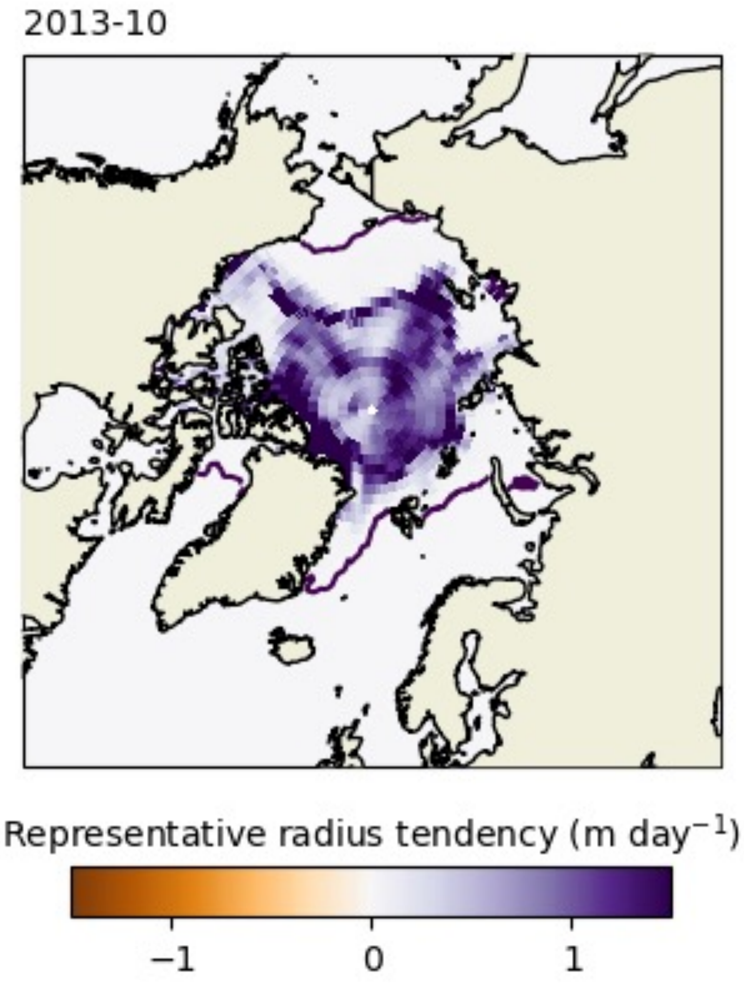


- Very effective in increasing perimeter

Floe welding

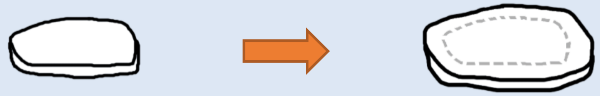


- In freezing conditions, floes freeze together according to geometric probability of overlap - coagulation equation (Roach et al. 2018a)
- Calibrated with in situ observations (Roach et al. 2018b)



- Effective in increasing representative radius

Lateral growth

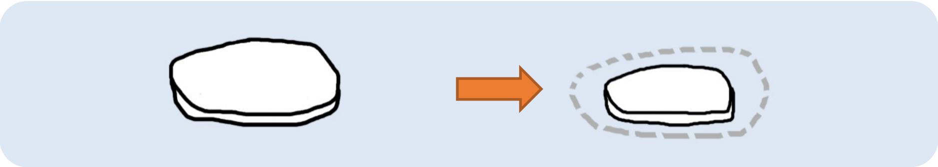


$$\mathcal{L}_T(r,h) = -\nabla_{(r,h)} \cdot (f(r,h)\mathbf{G}) + \frac{2}{r} f(r,h) G_r$$

- Lateral growth rate is the volume of new ice growth in the ‘lead region’ per time

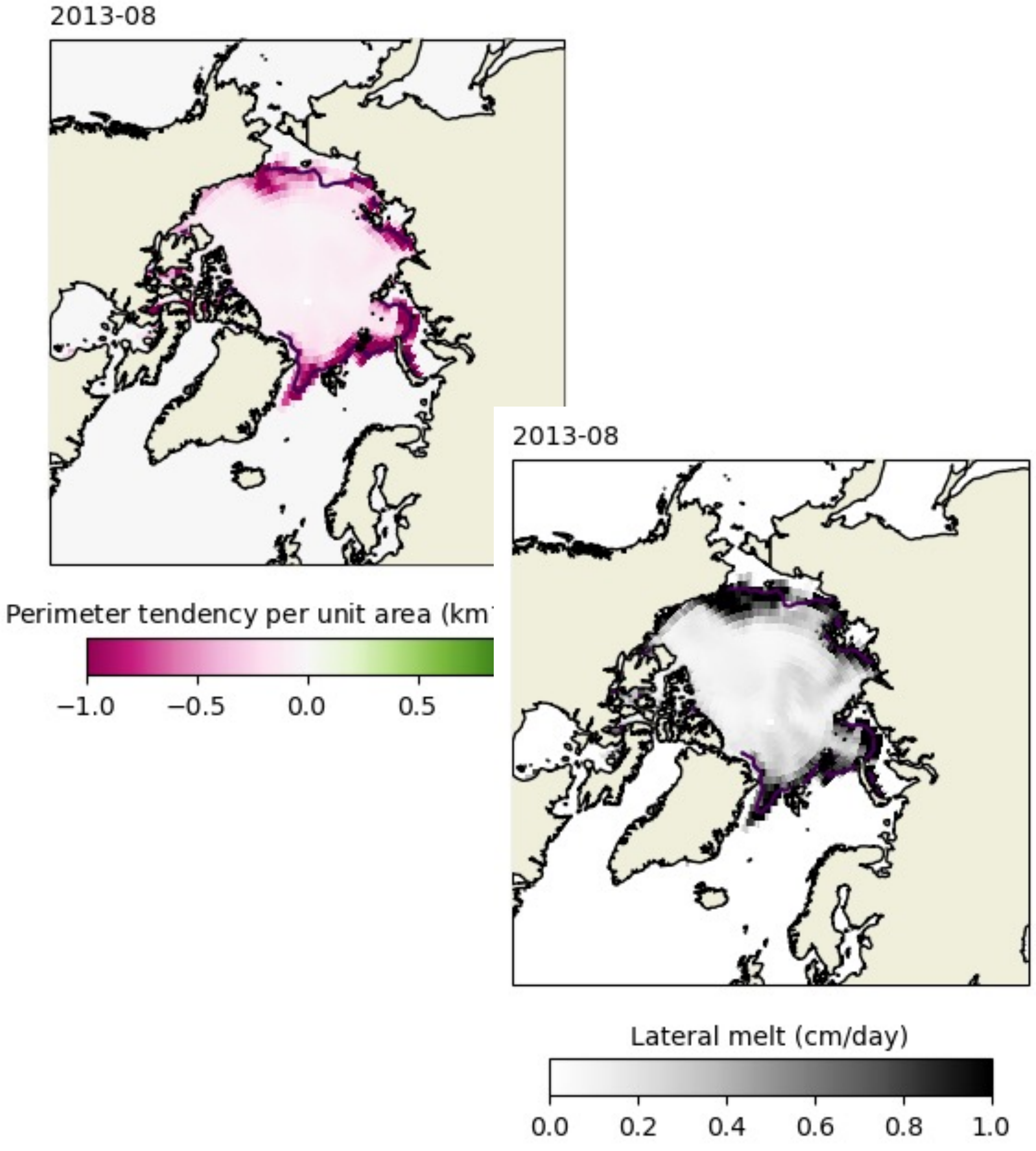
Minimal impact to perimeter, representative radius, concentration

Floe-size-dependent lateral melt

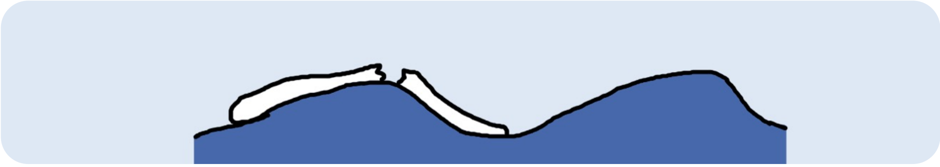


$$\mathcal{L}_T(r,h) = -\nabla_{(r,h)} \cdot (f(r,h)\mathbf{G}) + \frac{2}{r} f(r,h) G_r$$

- Lateral melt rate as standard model
- Impacts ice concentration, thickness distribution



Fracture of sea ice by ocean surface waves



Sea ice is completely rigid

OR

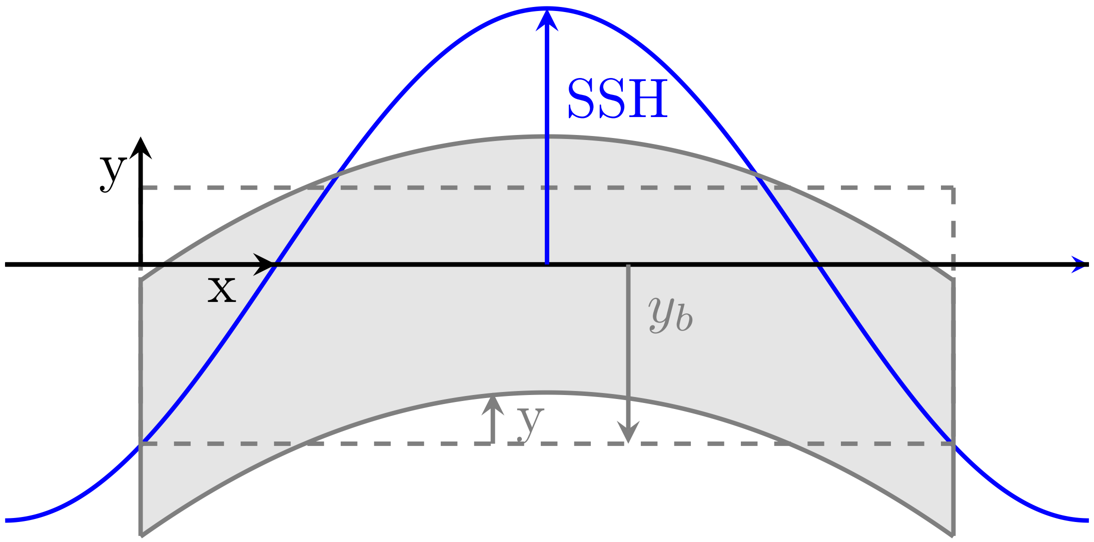
Sea ice is completely flexible

Dumont et al. (2011)

Williams et al. (2013)
Horvat & Tziperman (2015)
Roach et al. (2018a, 2019)

Wave fracture: new approach from thin elastic plate theory

SSH: Sea Surface Height
y: Beam deflection
y_b: Ice draft



Assume hydrostatic equilibrium

$$\frac{d^4y}{dx^4} + \frac{1}{\Lambda^4}y = \frac{1}{\Lambda^4}\sum_{i=1}^{N} A_i \cos(2\pi x/\lambda_i - \phi_i)$$

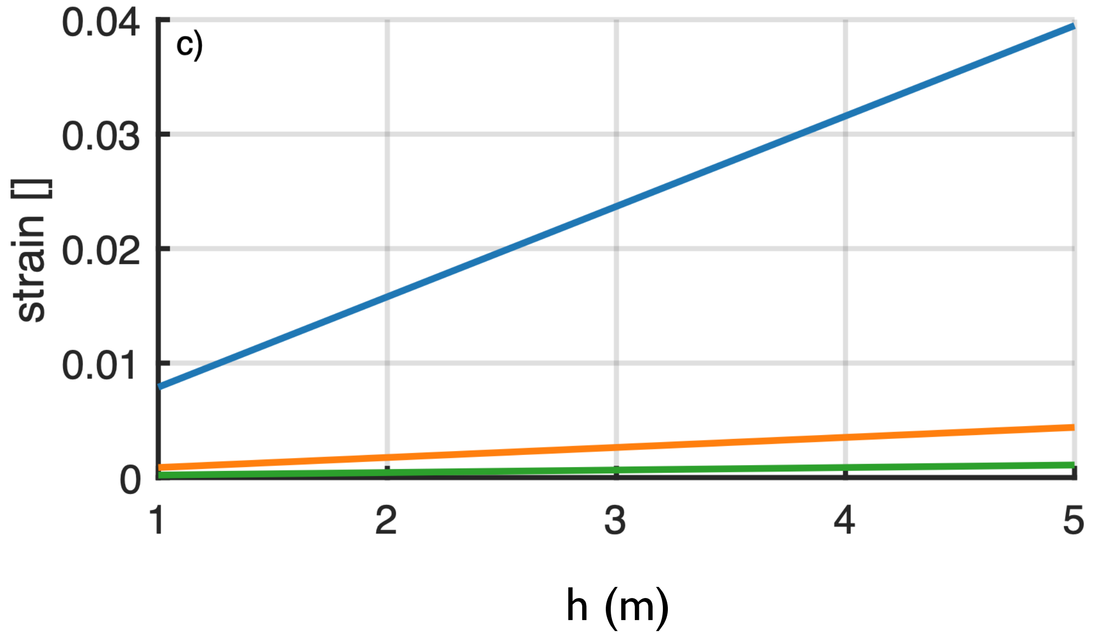
- Fourth-order inhomogeneous ODE that can be solved analytically
- Λ is a characteristic length scale
- Strain $\epsilon = \frac{h}{2}y''(x)$

Tremblay & Roach (2026, submitted)

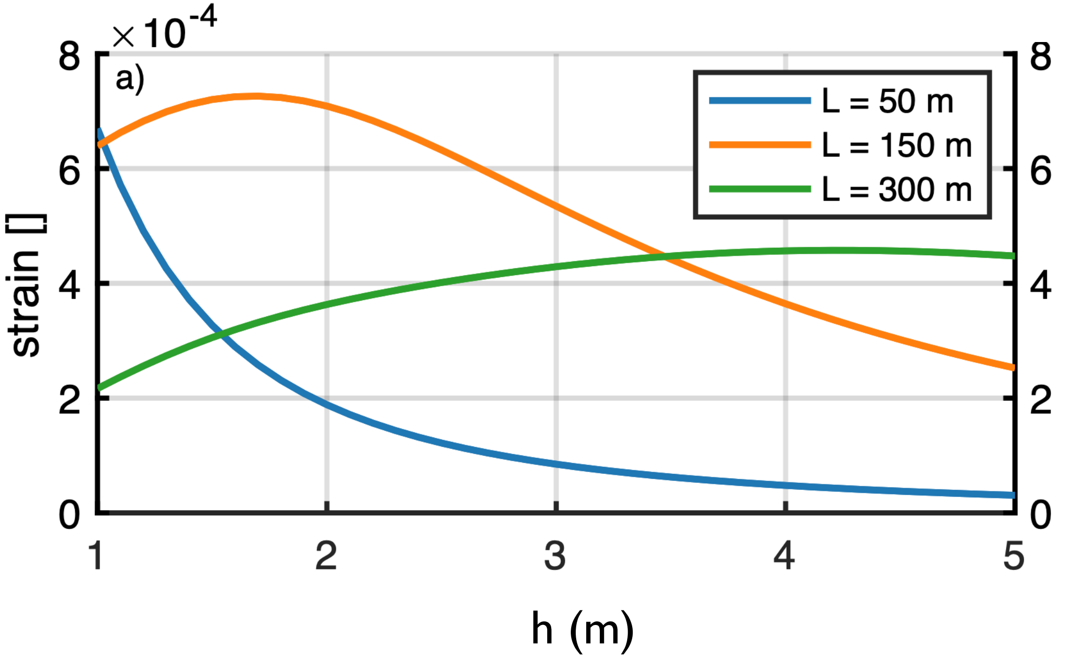
Strain as a function of ice thickness

- Observations suggest a critical strain around 3 x 10^{-5} (Langhorne et al. 1998)
- Force floe with Bretschneider spectrum, 1 m amplitude

Fully-flexible

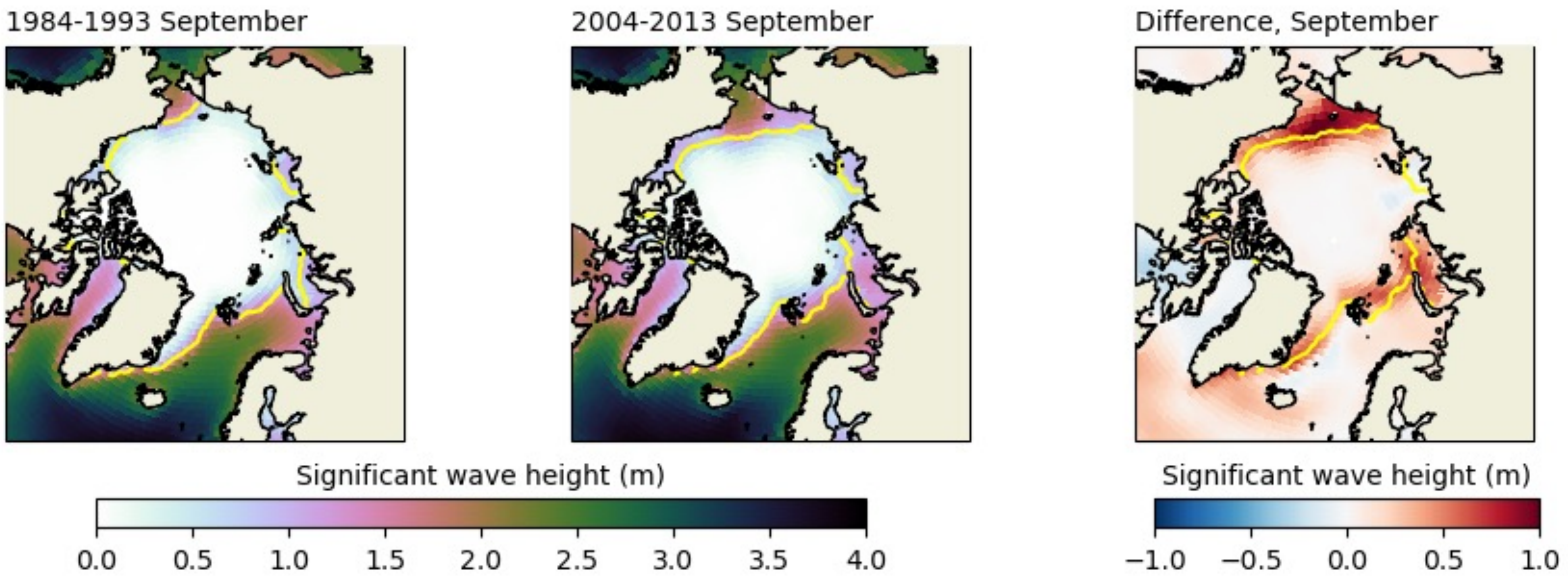


Thin elastic plate



Tremblay & Roach (2026, submitted)

Increasing wave heights in the 'new' Arctic



Open questions

- How do waves and related sea ice processes change in the emerging Arctic and Antarctic?
- How significant are sea ice—wave feedbacks in the coupled model?
- How can we improve process representation?
- How can we compare with limited observations?

Simulation needs

- Some baseline to compare against – no FSD, no wave-ice interactions?
- Constrained simulation to compare with observations – data-atmosphere?
- Wave output / output for CMIP7?

Questions?

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https://lettie-roach.github.io/

Photo: Ben Adkison
PIPERS cruise, Ross Sea, 2017