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Coupled wave-ice interaction modelling in the Antarctic Marginal Ice Zone

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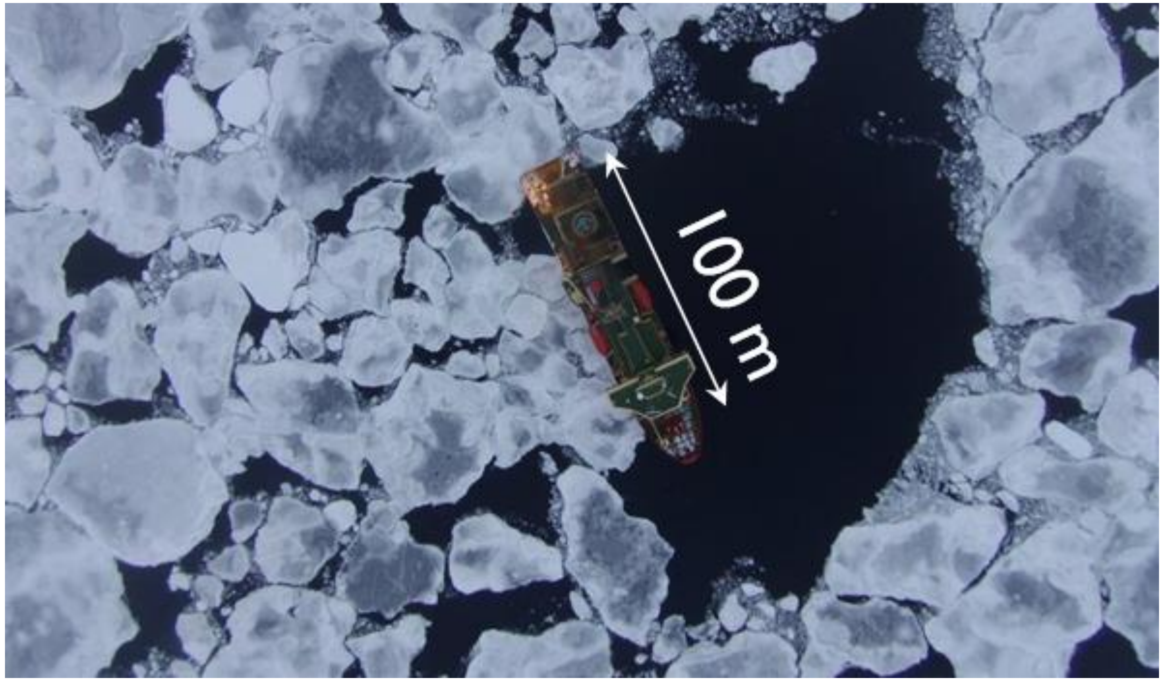
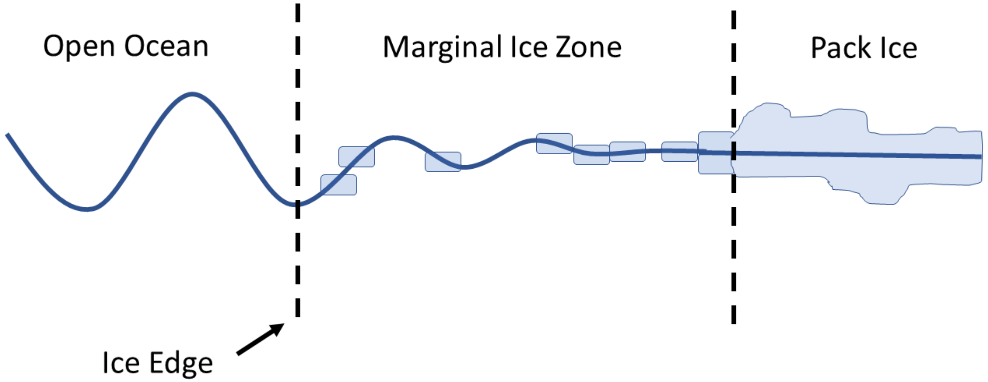
The Marginal Ice Zone

- Most polar navigation needs to transit the Marginal Ice Zone (MIZ) , where sea ice is composed of floes of varying size and thickness
- Waves entering the MIZ are attenuated and scattered by the floes, which can in turn be broken up by wave-induced stresses.
- While several international agencies run operational or research forecast systems capable of providing sea ice information (predominantly for the Arctic), none currently include the effect of wave-ice interaction in their models.





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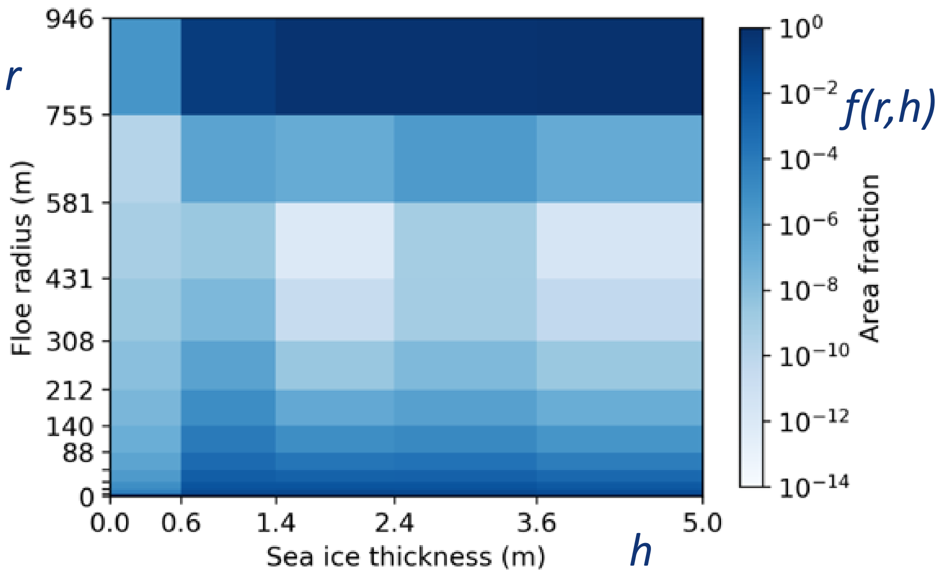
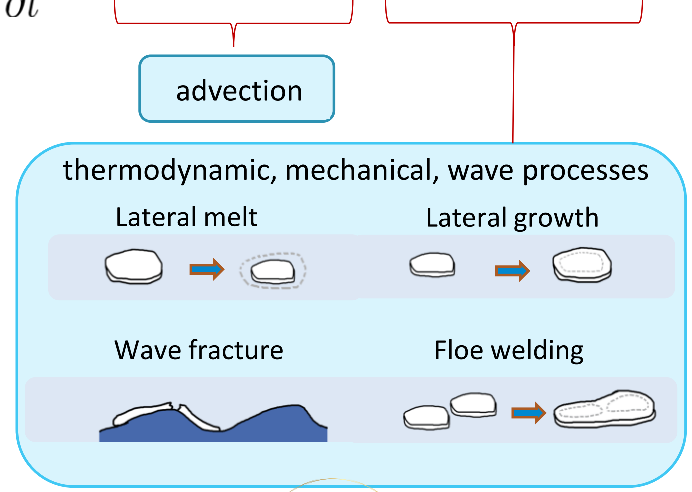
The CICE-FSTD model

- The ice model CICE can now include a representation of ice floes of different (horizontal) sizes in addition to the existing characterisation into different thickness classes, to give a full Floe Size and Thickness Distribution (FSTD)
- This allows the model to represent
  - wave-induced fracturing of ice,
  - mechanical floe interactions (welding, ridging and rafting)
  - new ice formation, lateral freezing and melting

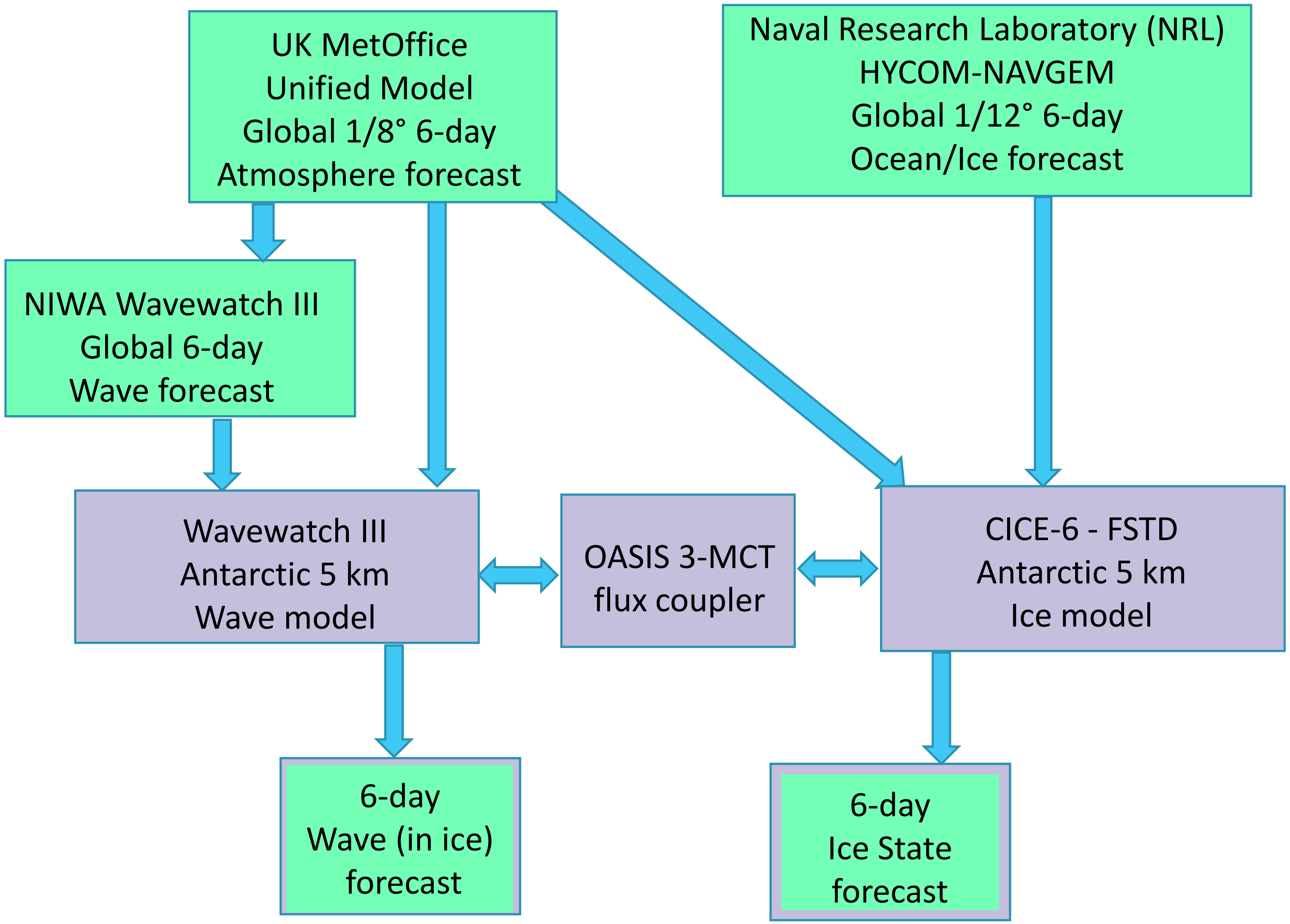
- Horvat, C., Tziperman, E. (2015) A prognostic model of the sea-ice floe size and thickness distribution., The Cryosphere **9**(6): 2119-2134. 10.5194/tc-9-2119-2015
- Roach, L. A., C. Horvat, S. M. Dean and C. M. Bitz (2018). "An Emergent Sea Ice Floe Size Distribution in a Global Coupled Ocean-Sea Ice Model." Journal of Geophysical Research: Oceans **123**(6): 4322-4337.

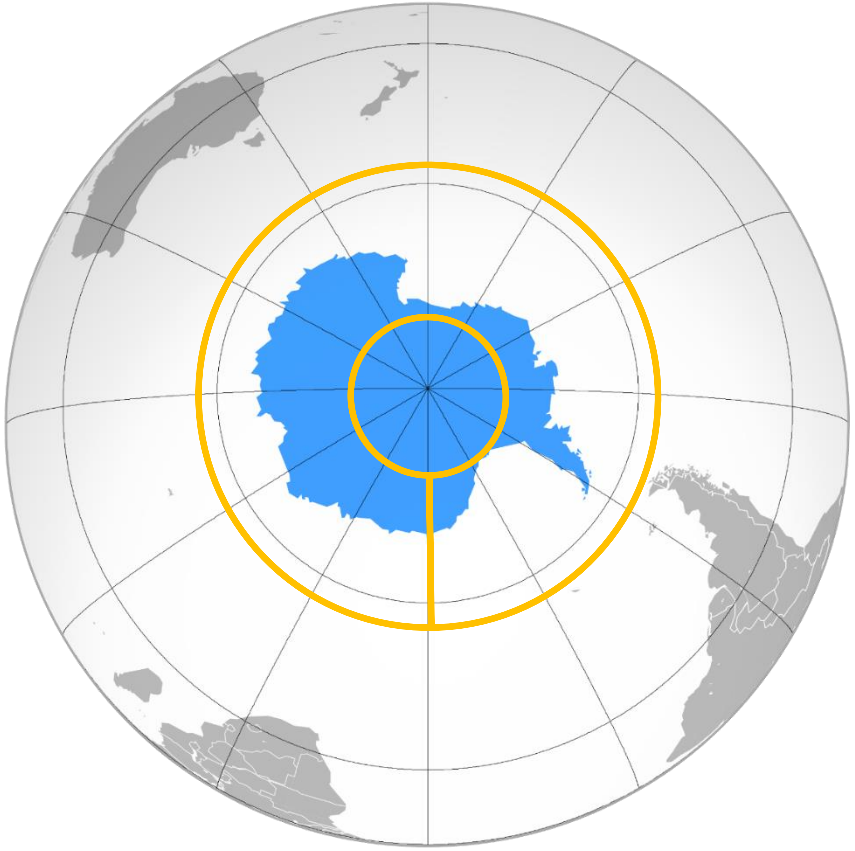


$$\frac{\partial f}{\partial t} = -\nabla \cdot (f(r,h)\mathbf{u}) + \mathcal{L}_T + \mathcal{L}_M + \mathcal{L}_W$$



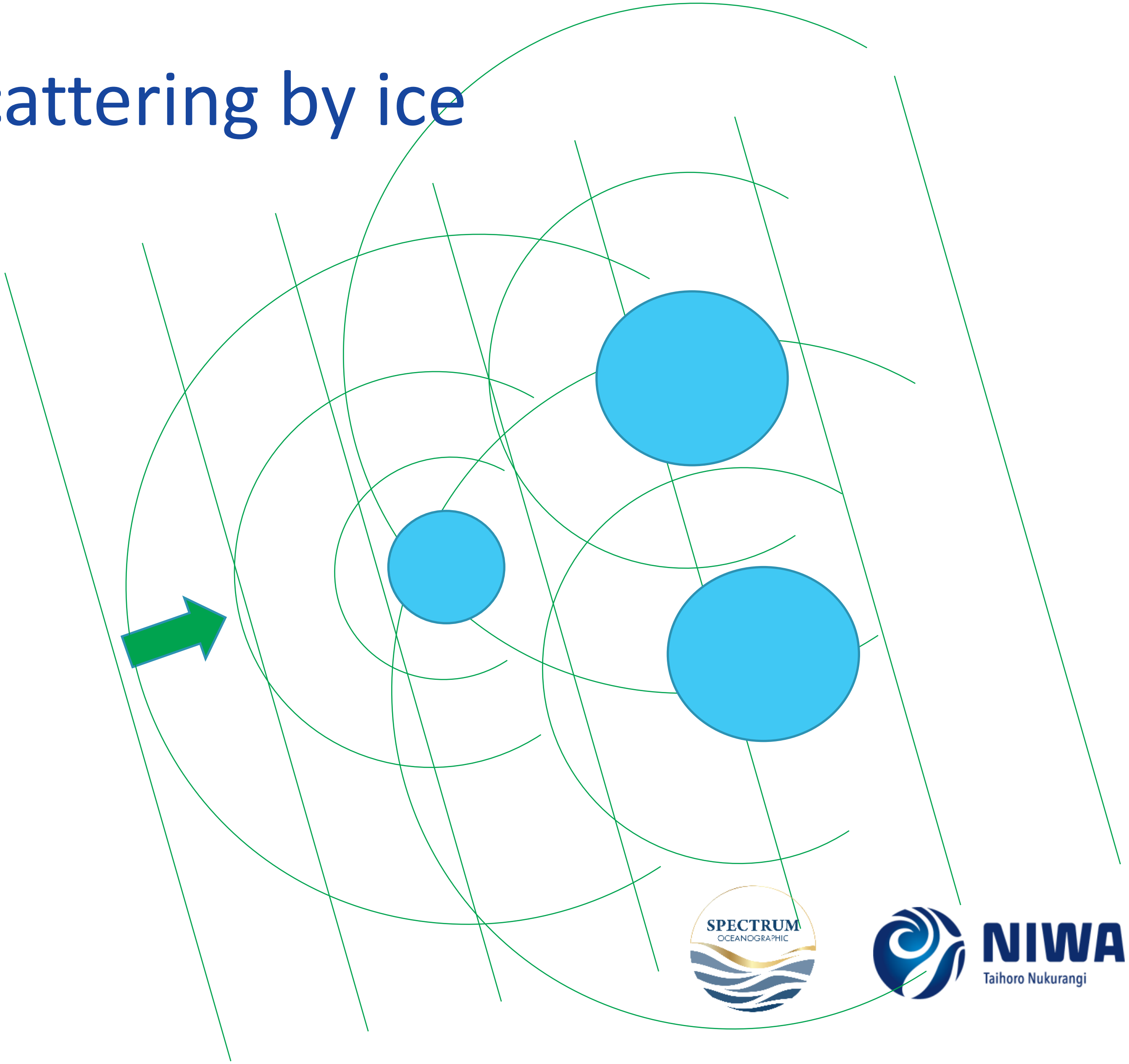
Coupled wave-ice modelling system





Wave attenuation and scattering by ice

- Ice model sends ice concentration, mean ice thickness, mean floe size to wave model
- The Wavewatch III wave model computes attenuation of waves in propagating though ice (energy-dissipating)
- Wavewatch III computes effect of scattering by ice floes (energy-conserving)



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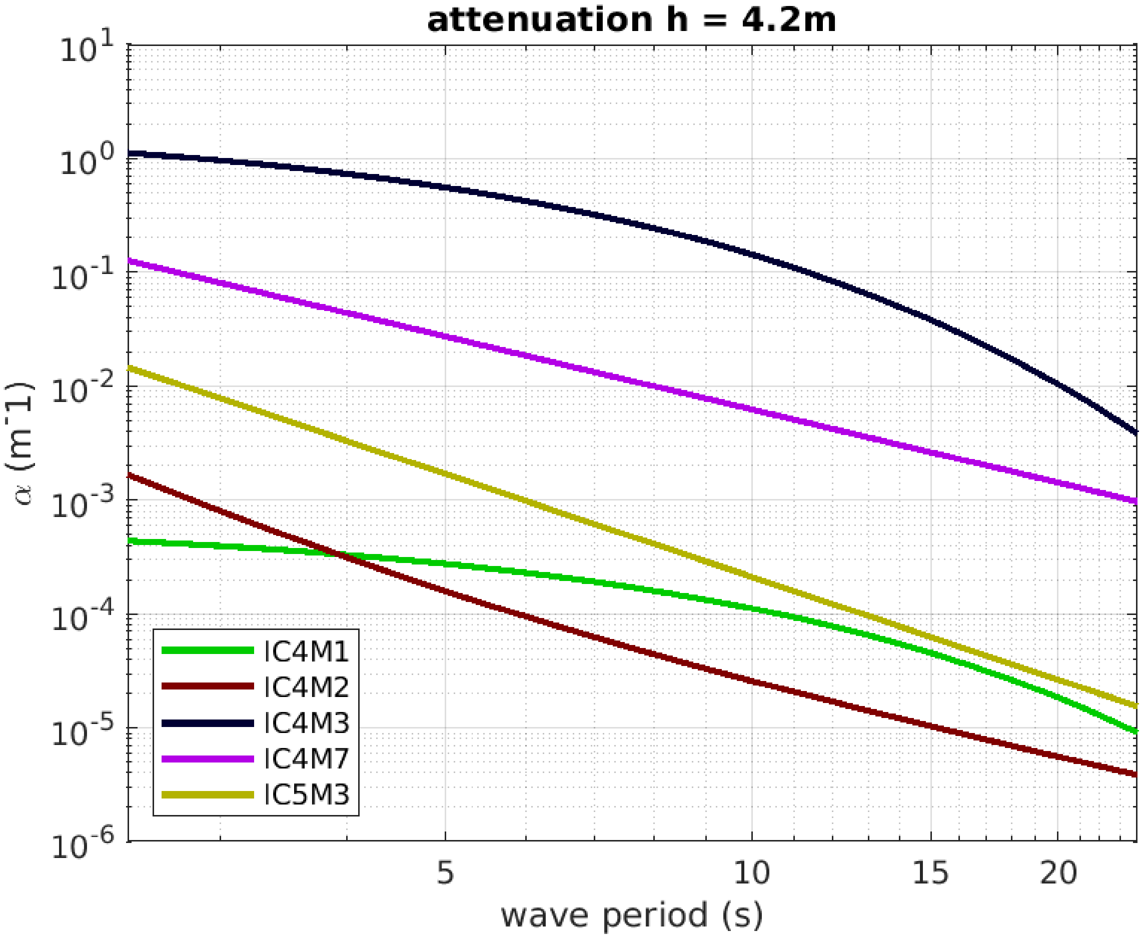
Wave attenuation and scattering in Wavewatch III



Attenuation coefficient:

- IC4M1: Wadhams et al (1988) exponential
- IC4M2: Meylan et al (2014) polynomial fit
- IC4M3: Horvat & Tziperman (2015), based on Kohout & Meylan (2008) scattering model / data
- IC4M7: Doble et al (2015) frazil & pancake ice
- IC5M3: Viscous model with third-order dependence on wave frequency σ (Meylan et al 2018)

$$\alpha(h, \sigma) = \frac{h\eta}{\rho_i g}\sigma^3$$

for ice thickness h, viscosity η, density ρ

Scattering coefficient:

IS2: energy transfer rate $\propto \frac{c_i c_g \alpha_n(\sigma,h)}{D_m}$

using ice concentration c_i, wave group velocity c_g and FSTD weighted floe diameter

$$D_m = 1/\langle D^{-1}\rangle$$

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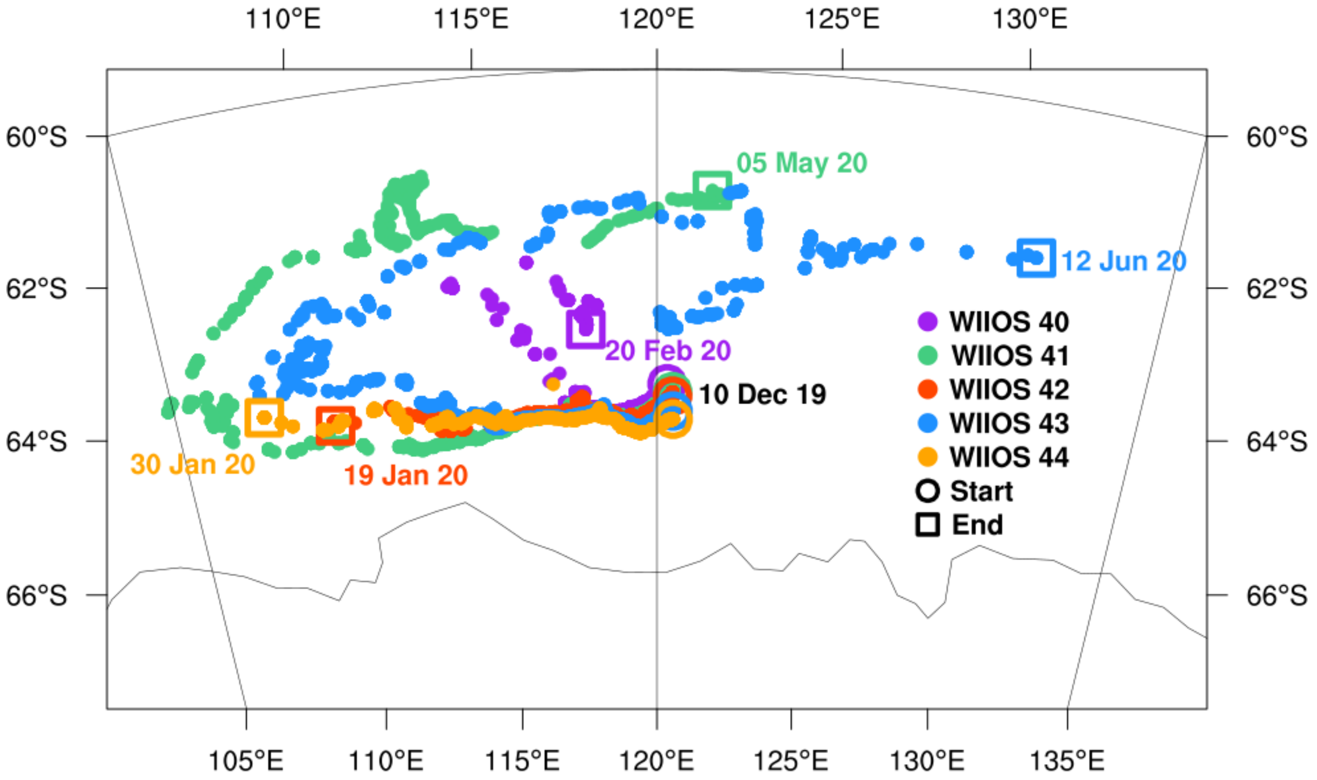
Calibration of wave attenuation

- Coupled wave-ice hindcast starting 2019-03-01 00UT
- Waves In Ice Observing System (WIIOS) buoys deployed in MIZ December 2019 during the 61st Japanese Antarctic Research Expedition (JARE61) (Kohout et al, 2021)
- Compared collocated modelled and measured significant wave height record in the period 10/12/2019 00UT – 13/12/2019 00UT
- $err = \frac{1}{N}\sum_{i=1}^{N}\left[H_i^{(a)} - H_i^{(m)}\right]^2$
- Optimised with effective viscosity parameter η = 56.74 kg m-3 s-1
- Liu et al (2020) estimates:

○ R/V Sikuliaq, Chukchi and Beaufort Seas 2015: η = 14.0 kg m^{-3} s^{-1}

○ SIPEX II Antarctic MIZ (2012): η = 3.0 kg m^{-3} s^{-1}



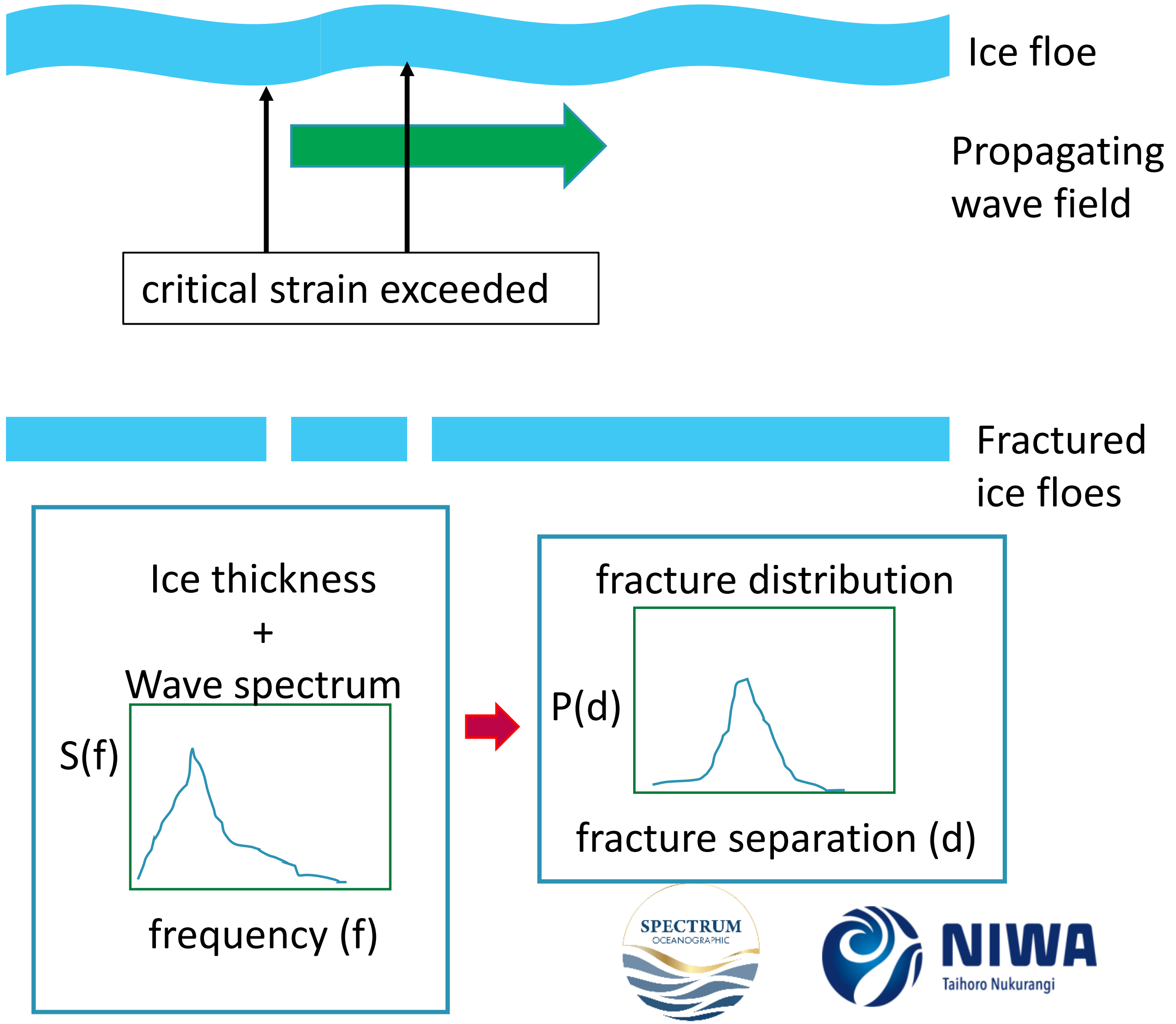
Kohout, A., Williams, G., Wongpan, P. (2021) JARE61 Waves in Ice Observations Mendeley Data. DOI: 10.17632/22hpw2xn3x.1

Liu, Q., Rogers, W.E., Babanin, A., Li, J., Guan, C. (2020) Spectral Modeling of Ice-Induced Wave Decay. *Journal of Physical Oceanography*, 50(6): 1583-1604. 10.1175/jpo-d-19-0187.1

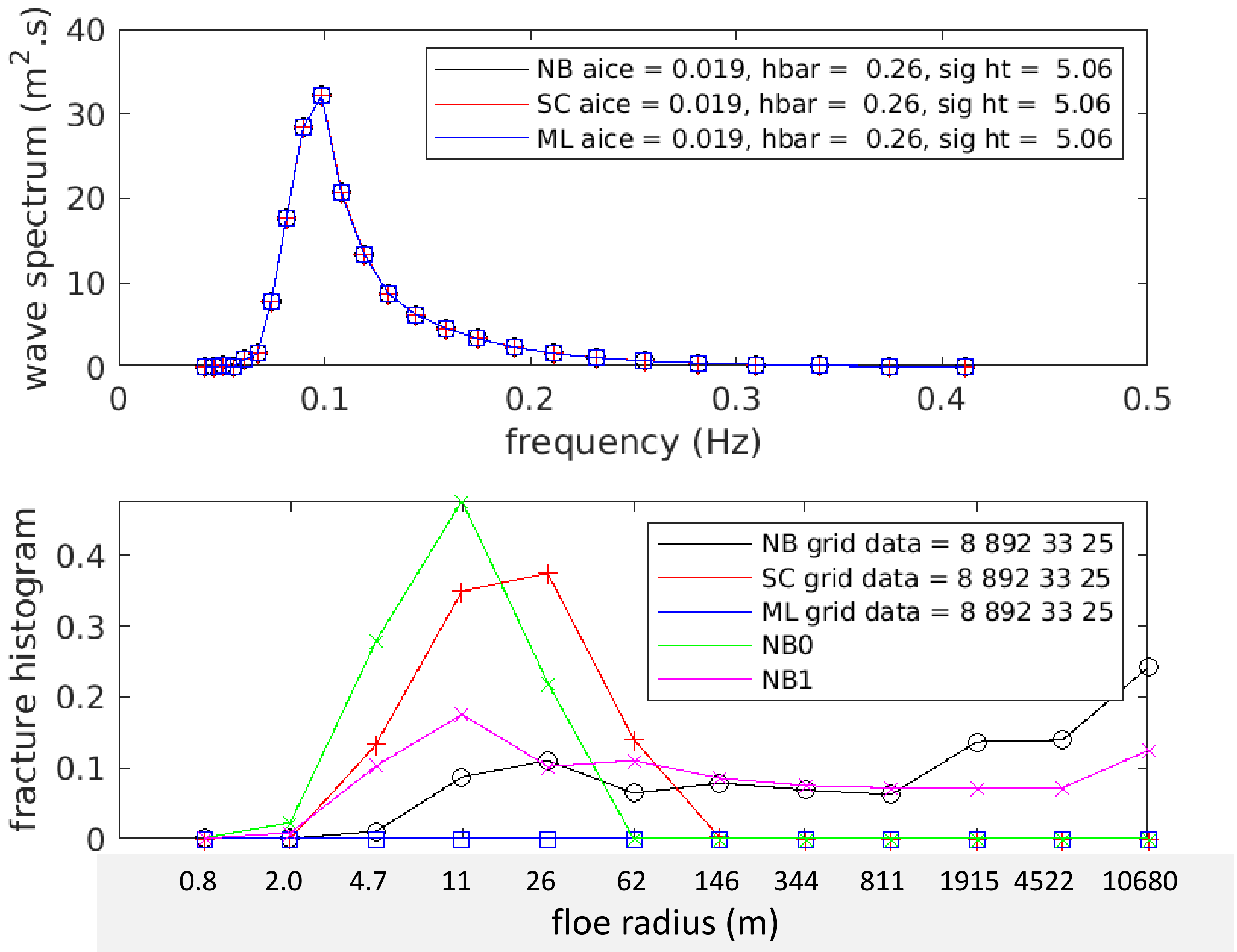
Floe fracture by waves

- Wave model sends 1D wave spectrum E(f) to ice model
- Surface elevation reconstructed from predicted wave spectrum E(f)
- Floes fracture where the resulting strain in ice field exceeds the critical value for a given ice thickness
- Change in floe size & thickness distribution
- Faster alternatives?

1. Neural Network approach after building a suitable training data set (WIFF1.0)*
   - Horvat, C., Roach, L.A. (2021) WIFF1.0: A hybrid machine-learning-based parameterization of Wave-Induced sea-ice Floe Fracture. Geosci. Model Dev. Discuss., 2021: 1-17. 10.5194/gmd-2021-281
2. Narrow band approximation (after Longuet-Higgins)



Comparing wave fracture algorithms



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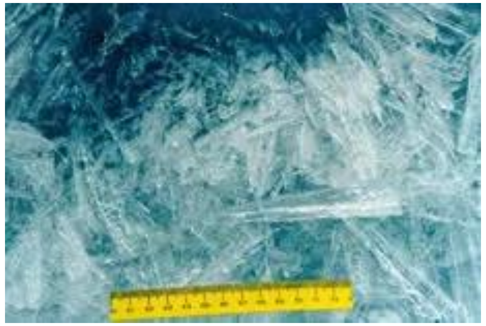
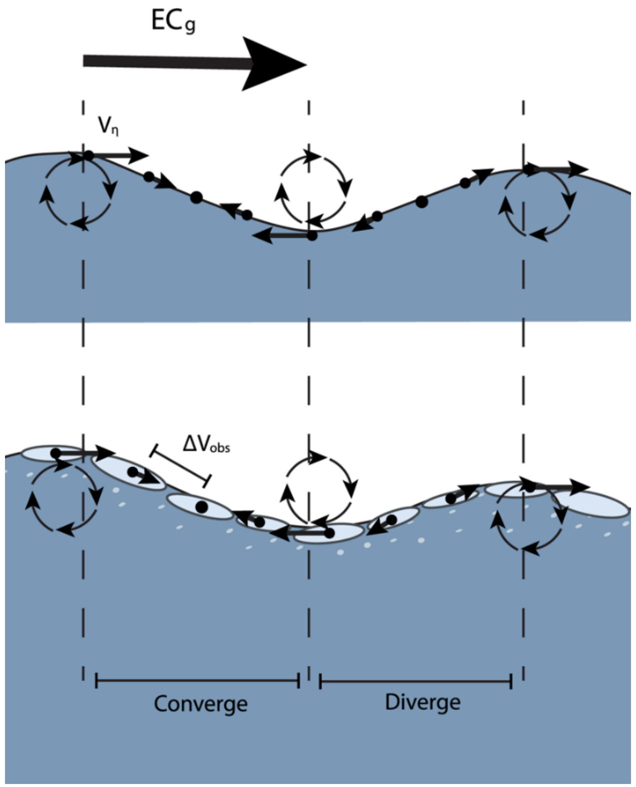
New ice formation

- Initial freezing as suspended crystals (frazil ice)
- In a calm sea, crystals freeze together in large sheets (nilas)
- In the presence of waves, frazil freezes into pancake ice. Shen et al (2001): tensile failure limits maximum diameter to

$$D_{max} = \lambda_p \sqrt{\frac{4C_2}{\pi^3 g \rho_i H_{m0}}}$$

Shen, H.H., Ackley, S.F., Hopkins, M.A. (2001) A conceptual model for pancake-ice formation in a wave field. Annals of Glaciology, 33: 361-367. 10.3189/172756401781818239





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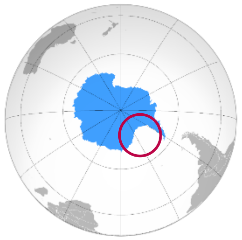
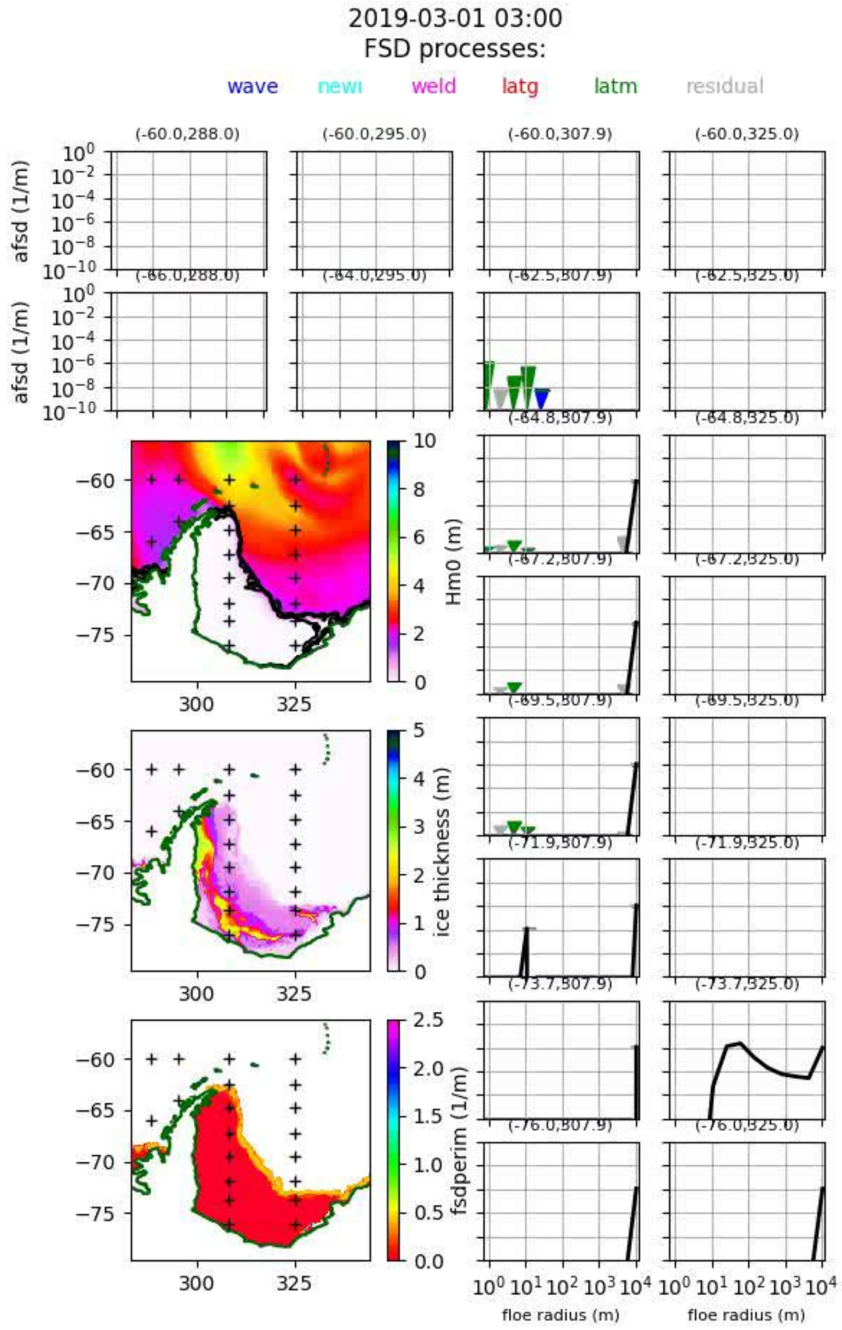
Hindcast outputs



- Weddell Sea
- Start 1 March 2019
- Significant wave height (plus ice concentration contours)
- Mean ice thickness
- Mean perimeter per unit area



- Floe Size Distribution at 20 marked sites
- Accumulated monthly change in FSD due to specific processes (at 6 sites):
  - wave fracture
  - new ice
  - welding
  - lateral growth
  - lateral melt
  - residual (advection)

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Summary

- We have implemented a new coupled wave and ice modelling system suitable for use in the Antarctic Marginal Ice Zone.
- The new model uses a representation of the floe size and thickness distribution
- This allows for the treatment of wave-ice interactions, including wave breaking of floes, and wave attenuation and scattering by floes
- The model is capable of producing a plausible evolution of the Floe Size Distribution
- Validation remains a challenge, particularly of the predicted Floe Size Distribution

Thanks for listening

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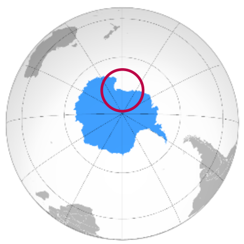
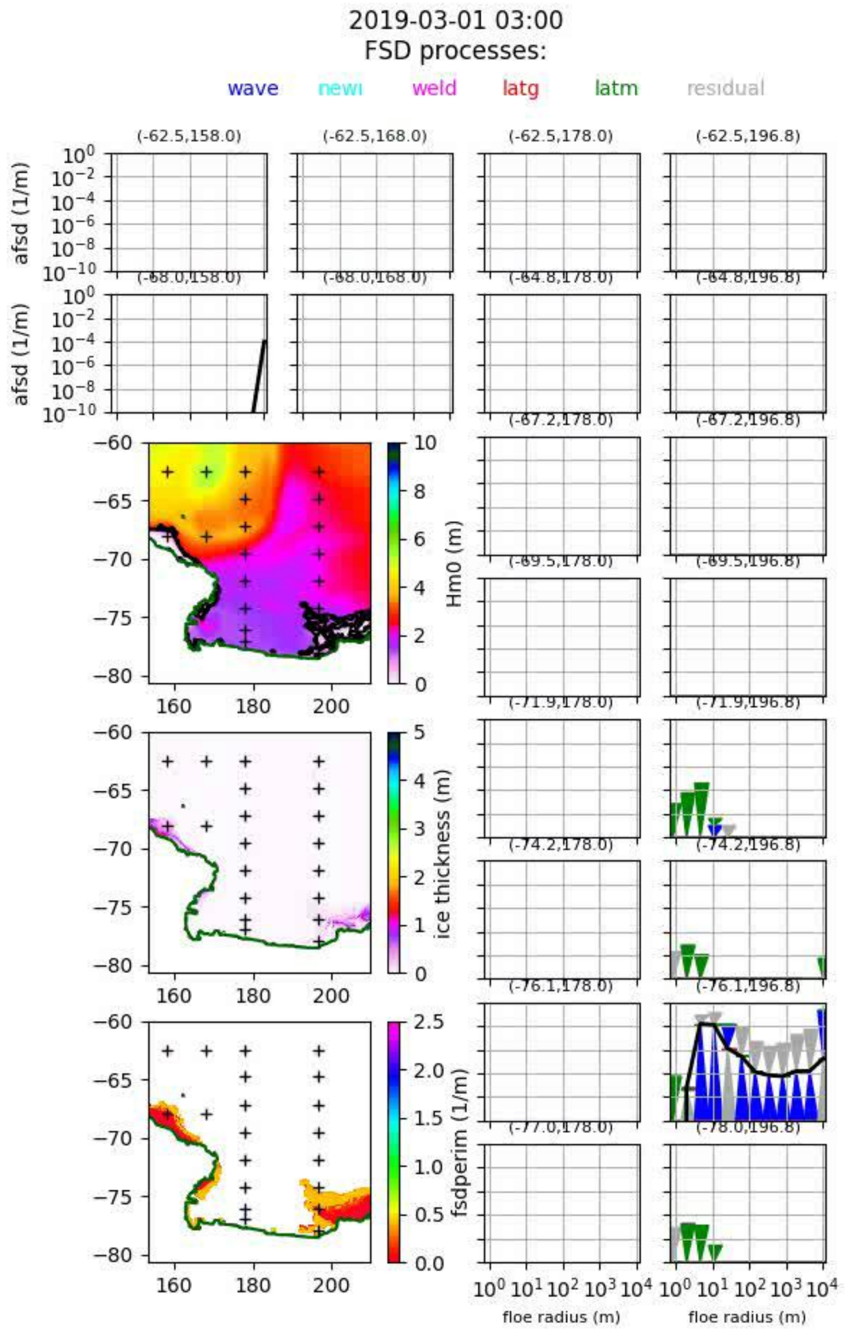
Hindcast outputs



- Ross Sea
- Start 1 March 2019
- Significant wave height (plus ice concentration contours)
- Mean ice thickness
- Mean perimeter per unit area



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