Modelling pancake ice in the Antarctic marginal ice zone

Major review

Noah Day - 8 June 2022

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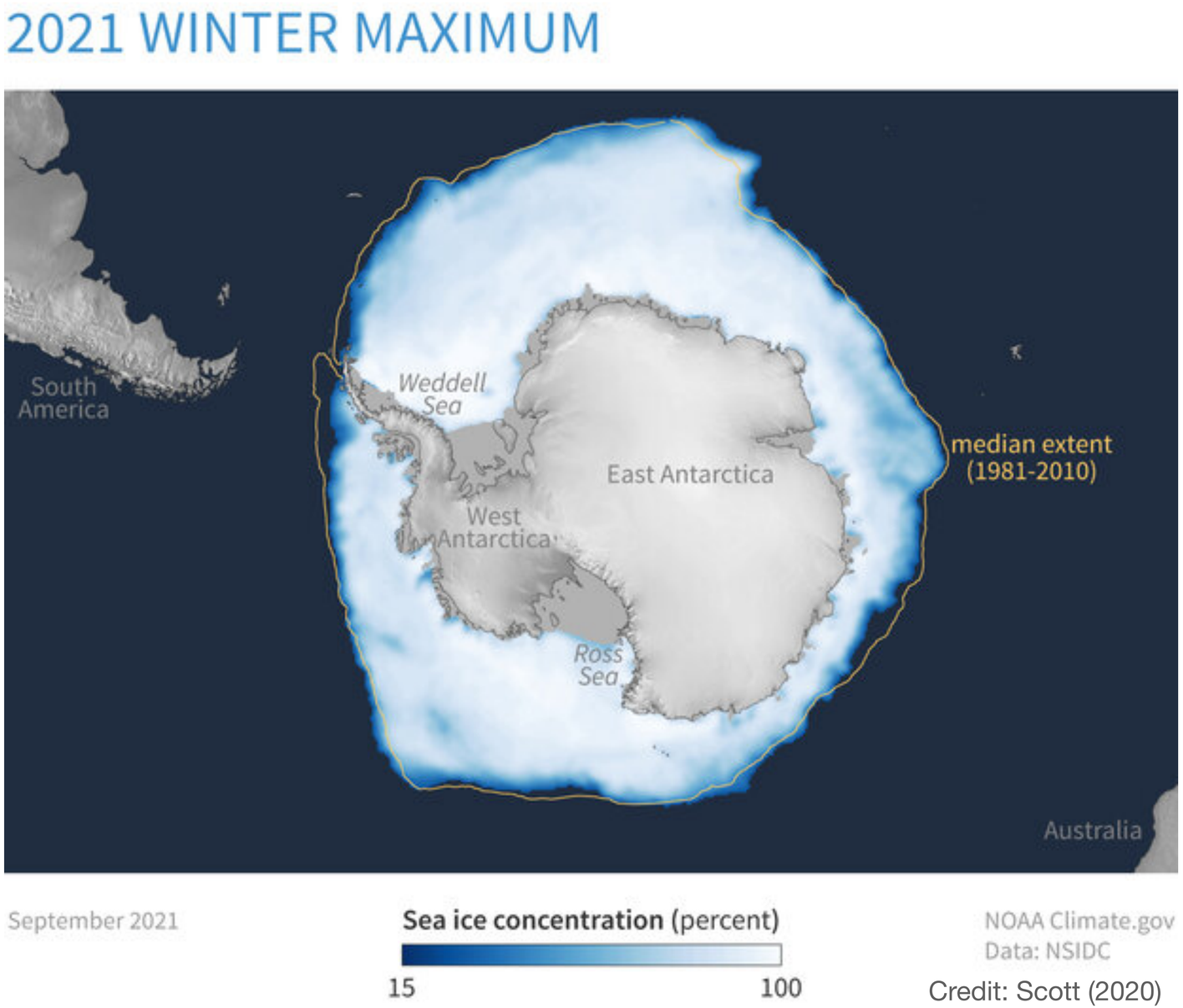
Antarctic sea ice

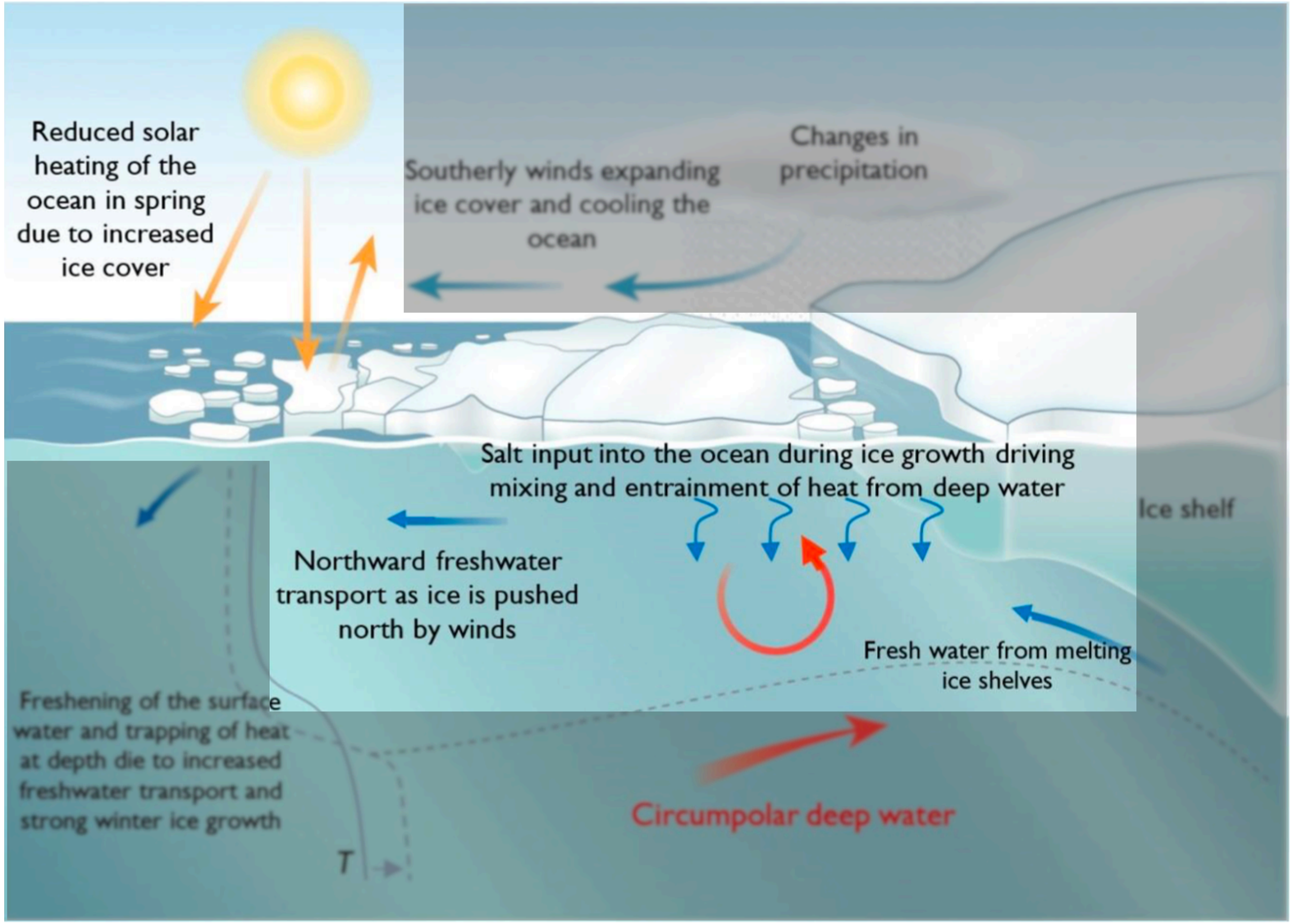
- Antarctica is a land mass surrounded by the Southern Ocean
- The surface of the ocean freezes, producing <u>sea ice</u>
- The areal extent of sea ice increases to approx. the size of Russia each year



Credit: Scott (2020)

Sea ice's role in climate science

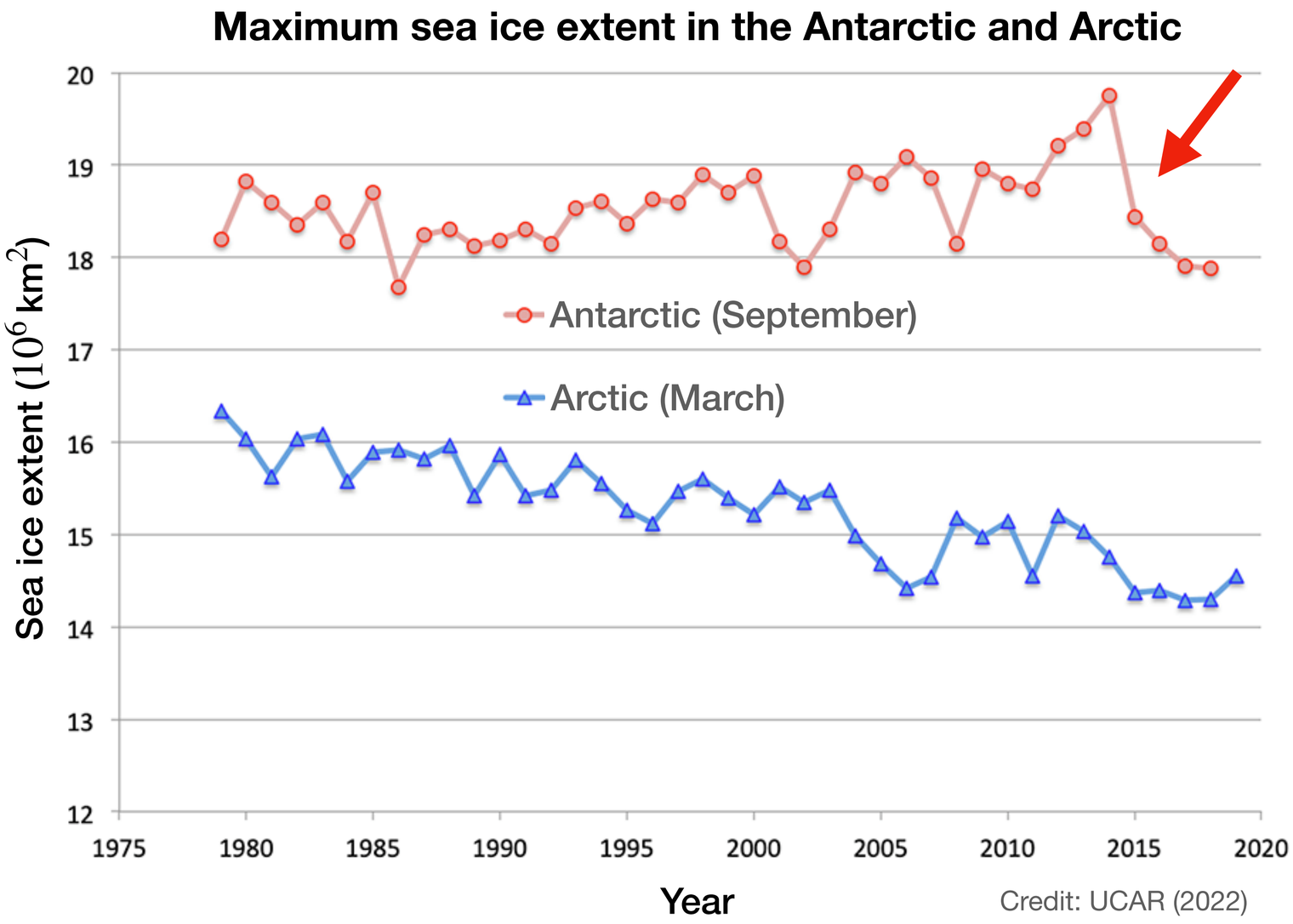
- Sea ice is highly connected to the atmosphere and ocean
- Sea ice reduces the amount of heat the ocean absorbs
- When sea water freezes, some salt is expelled, changing the density of surface water and driving circulation



Credit: Maksym, Ann Rev Mar Sci (2019)

Why look at the Antarctic?

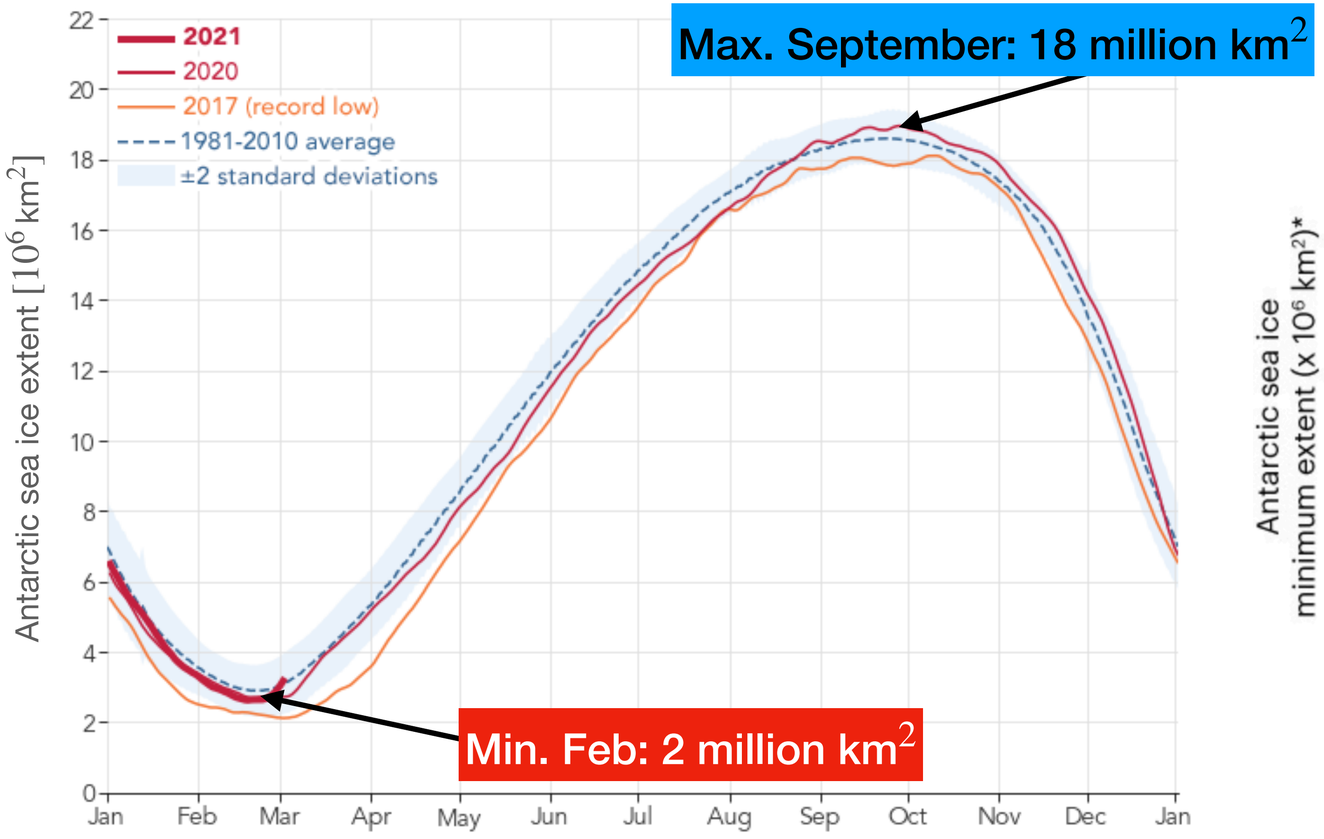
- The Arctic has been consistently declining over the last 40 years
- The majority of research has been focused on the Arctic
- Surprisingly, Antarctic sea ice hasn't shown these trends until a rapid decline from 2014-2017
- Making it very unpredictable



Credit: UCAR (2022)

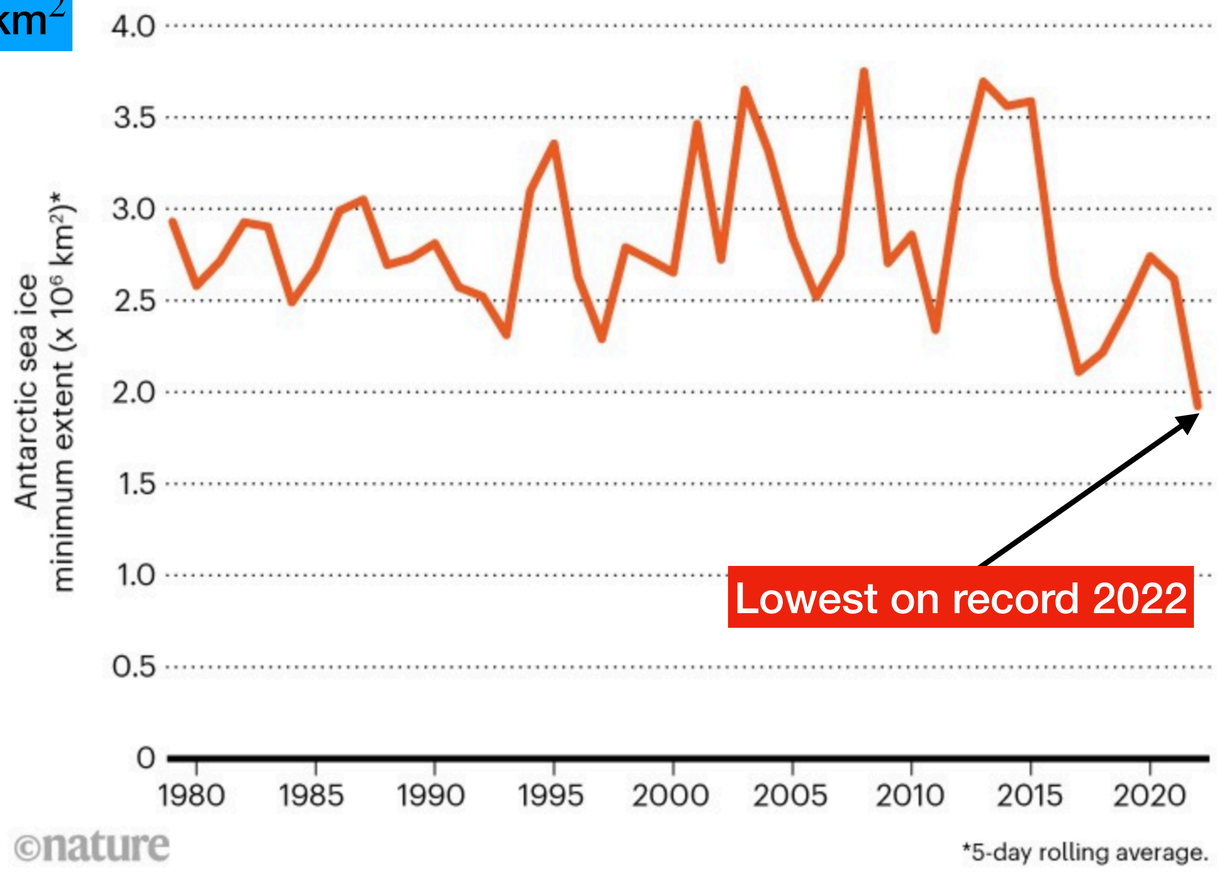
Seasonality and variability of Antarctic sea ice

Seasonality of Antarctic sea ice extent



Antarctic daily sea ice extent (credit: NASA, 2021)

Minimum Antarctic sea ice extent over satellite era

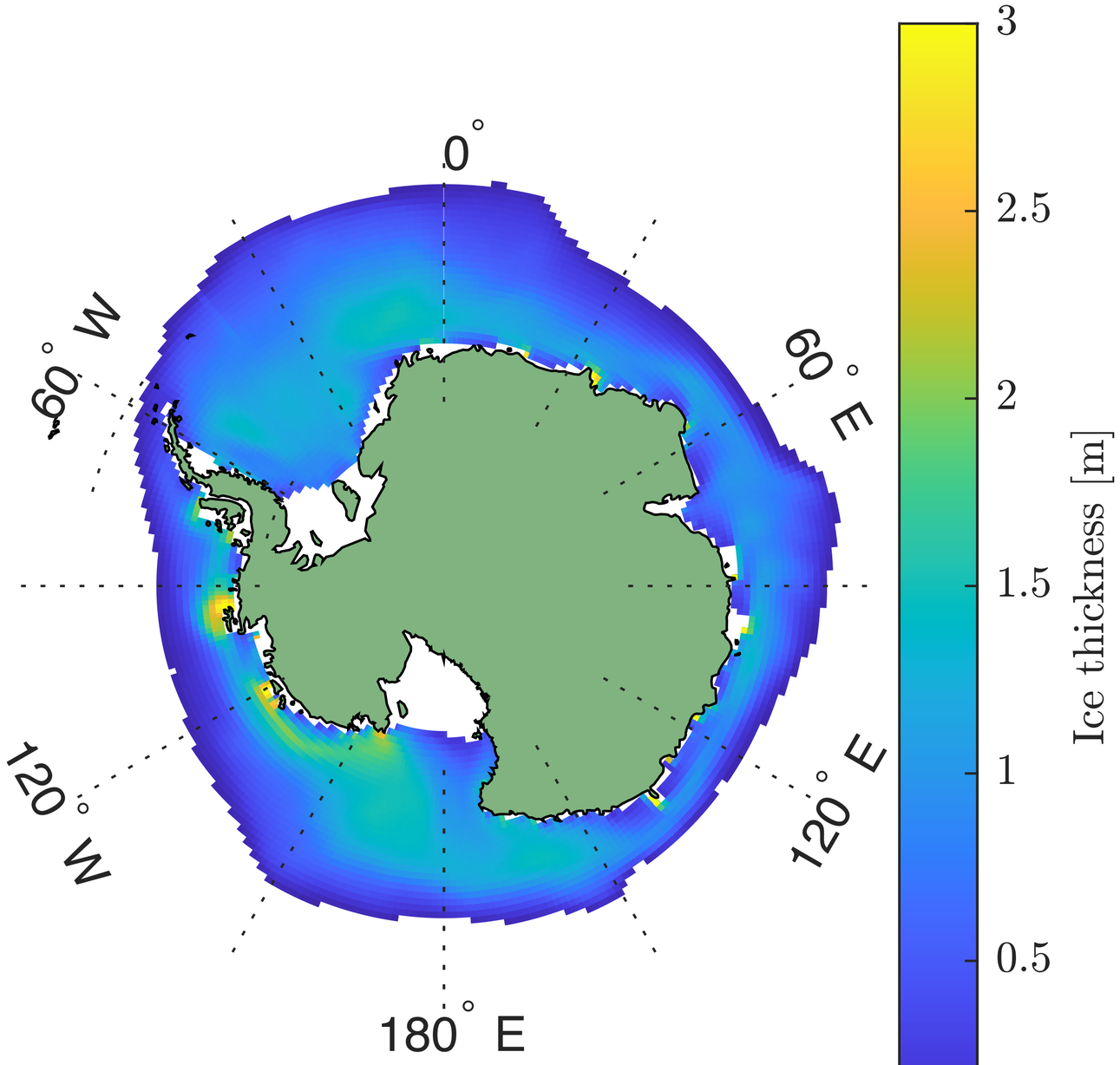


Source: National Snow and Ice Data Center

Credit: Thompson, Nature (2022)

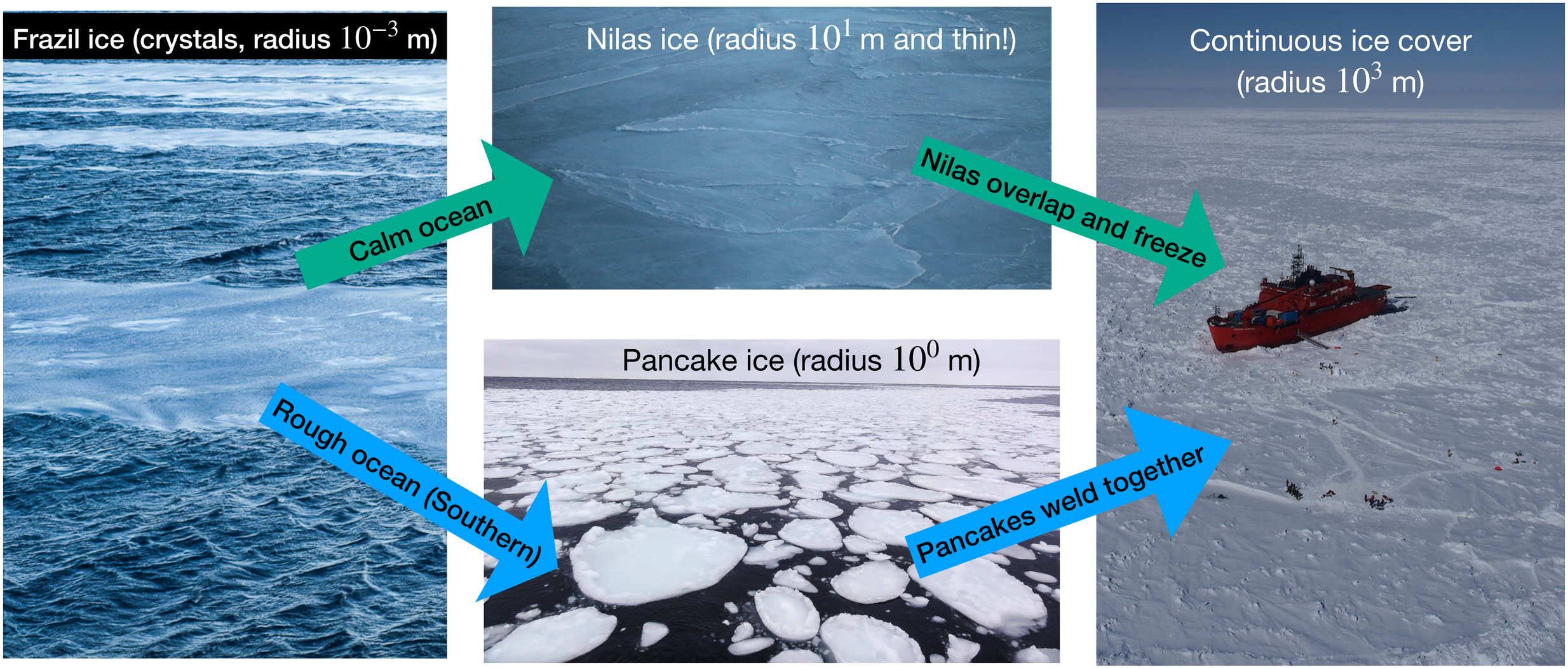
Sea ice volume and thickness

- Areal concentration doesn't measure the volume of sea ice
- The thickness/volume of Antarctic sea ice is very difficult to measure
- For this, we use numerical models



Sea ice thickness from September 2009 generated by a numerical model (CICE).

Winter sea ice (floe) formation



Credit: Lettie Roach on PIPPER cruise.

Credit: Australian Antarctic Division (2012).

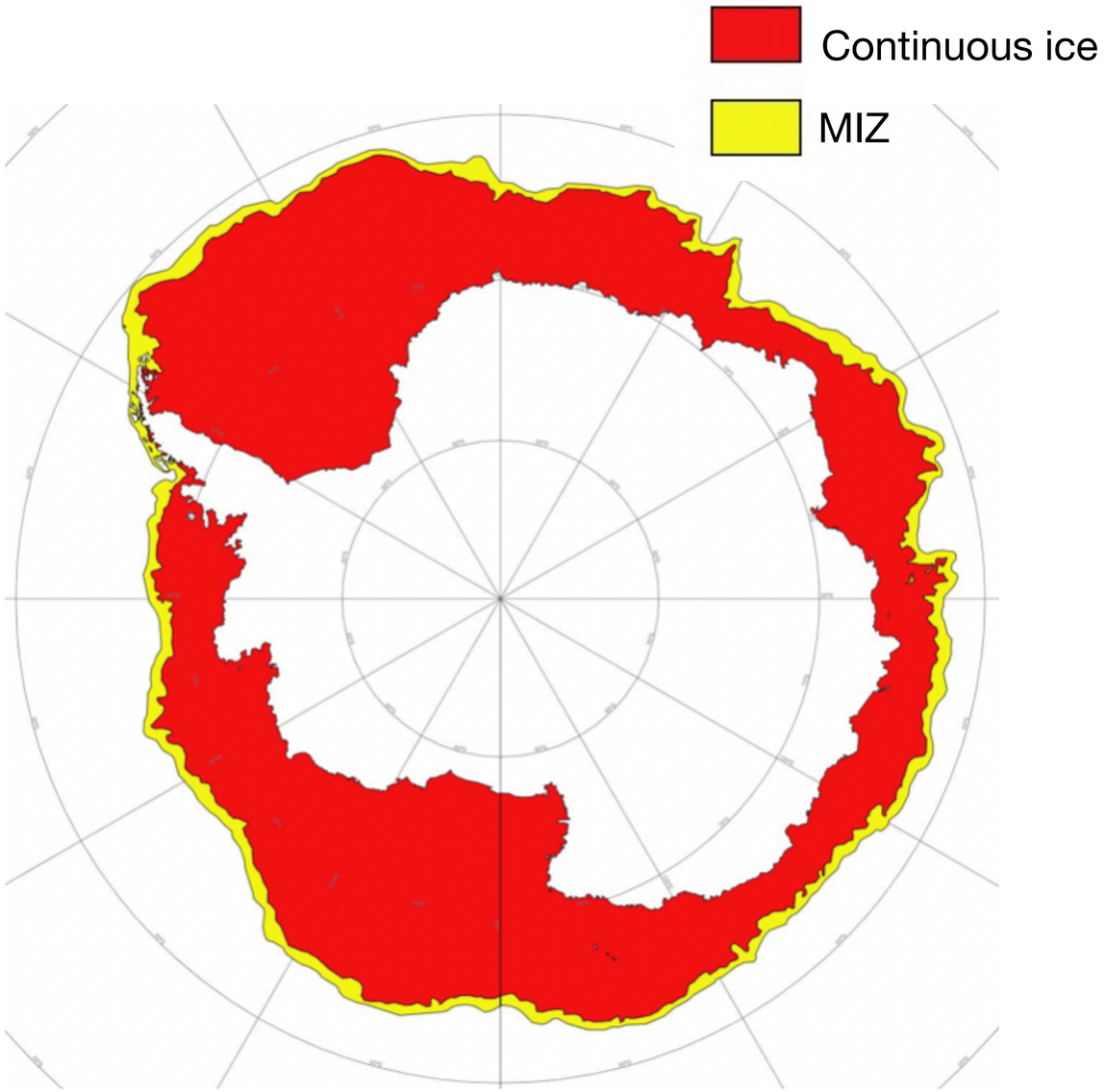
Welding of pancake ice to form large ice floes

- Frazil ice crystals grows on the sea surface in between pancake ice
- An ice bond can form, welding two pancakes together
- This process can create larger floes (chunks of sea ice)
- Ice floes can continue to weld to make continuous ice cover

Ice floes welded together by thin ice in the Antarctic MIZ (credit: Heather Regan).

Antarctic Marginal Ice Zone (MIZ)

- MIZ is generally located in between the ice edge and the inner-continuous ice
- Definitions have been debated!
- Areal concentration definitions are often used due to satellite data
- With a model we can use ice types to define the MIZ



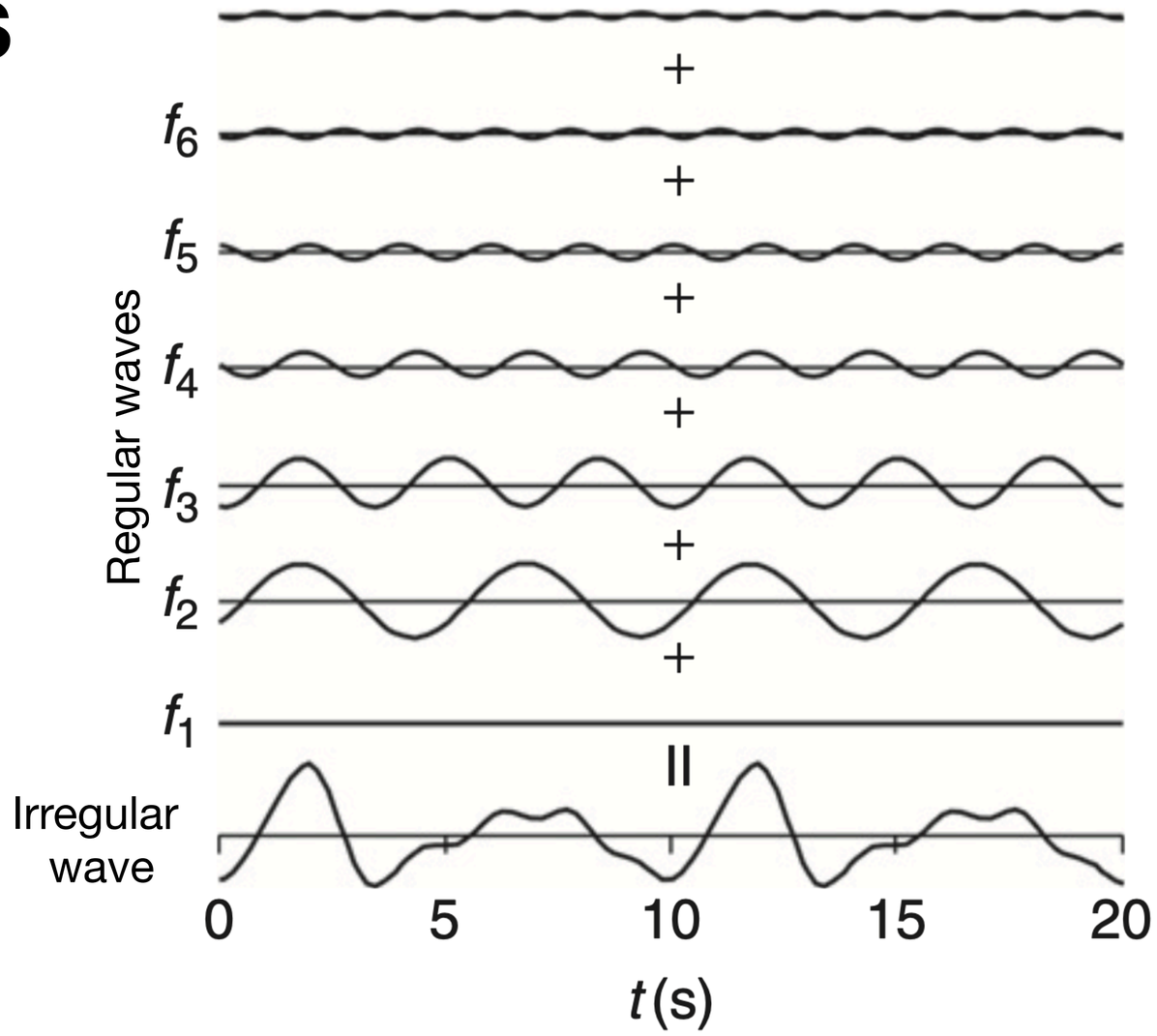
Antarctic marginal ice zone extent in the winter. MIZ is defined between 0.1 and 0.8 sea ice concentration (credit: USNIC, 2022)

Waves in a pancake marginal ice zone

A ship passing through a pancake dominated MIZ (credit: Alessandro Toffoli, 2017).

Waves in open oceans

- Ocean waves are a summation of sinusoidal waves
- Hence, they have a spectrum of frequencies
- We represent the associated wave energy with an energy spectrum, $S(f)$



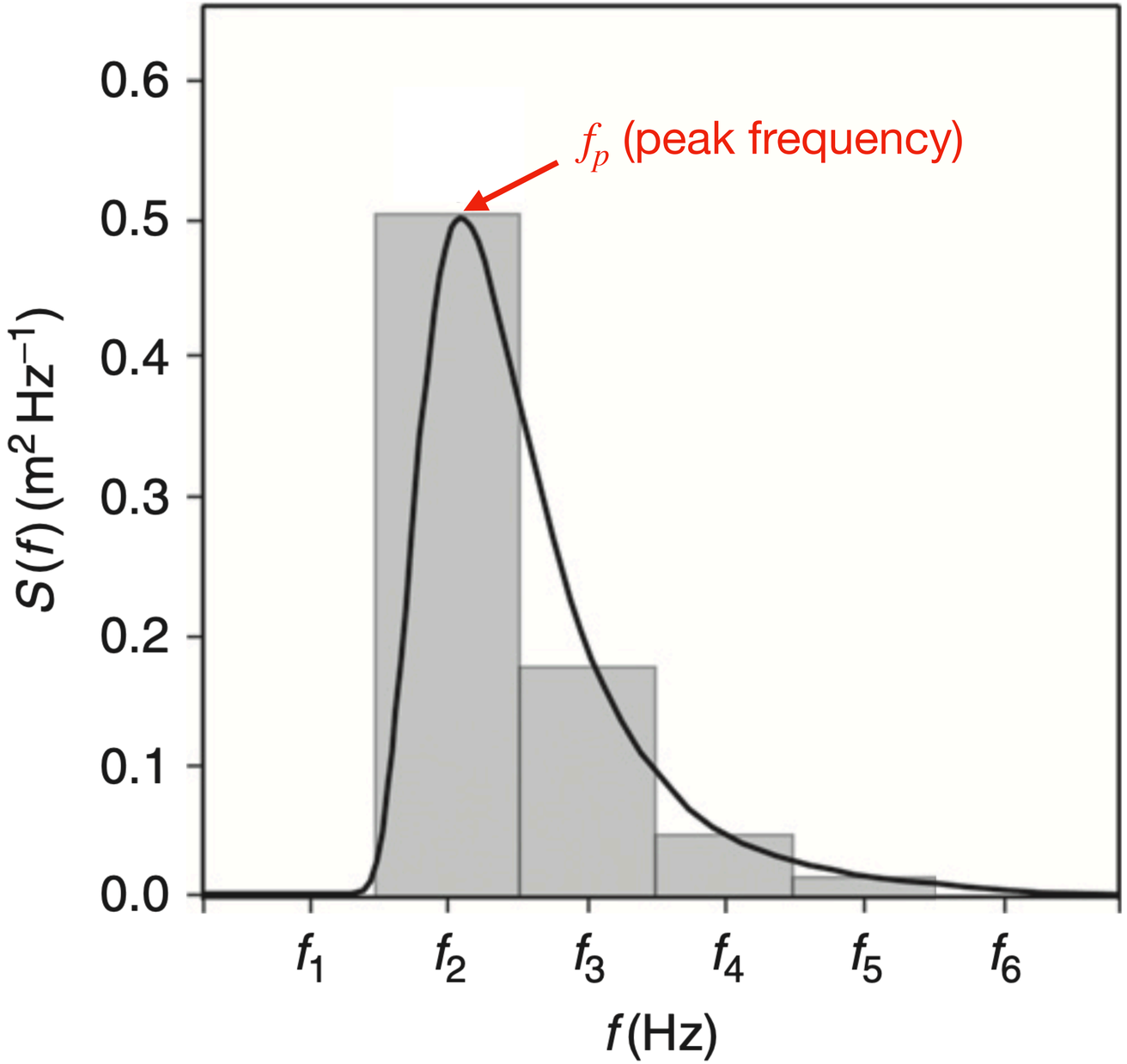
Surface height of an irregular wave (Heller, 2012). f is frequency, t is time.

Wave statistics

- We take significant wave height (m) (which is a proxy for wave energy),

$$H_s = 4\sqrt{\int_0^\infty S(f)df}$$

- Peak period, $T_p = 1/f_p$ (s), is the wave period associated with the greatest energy



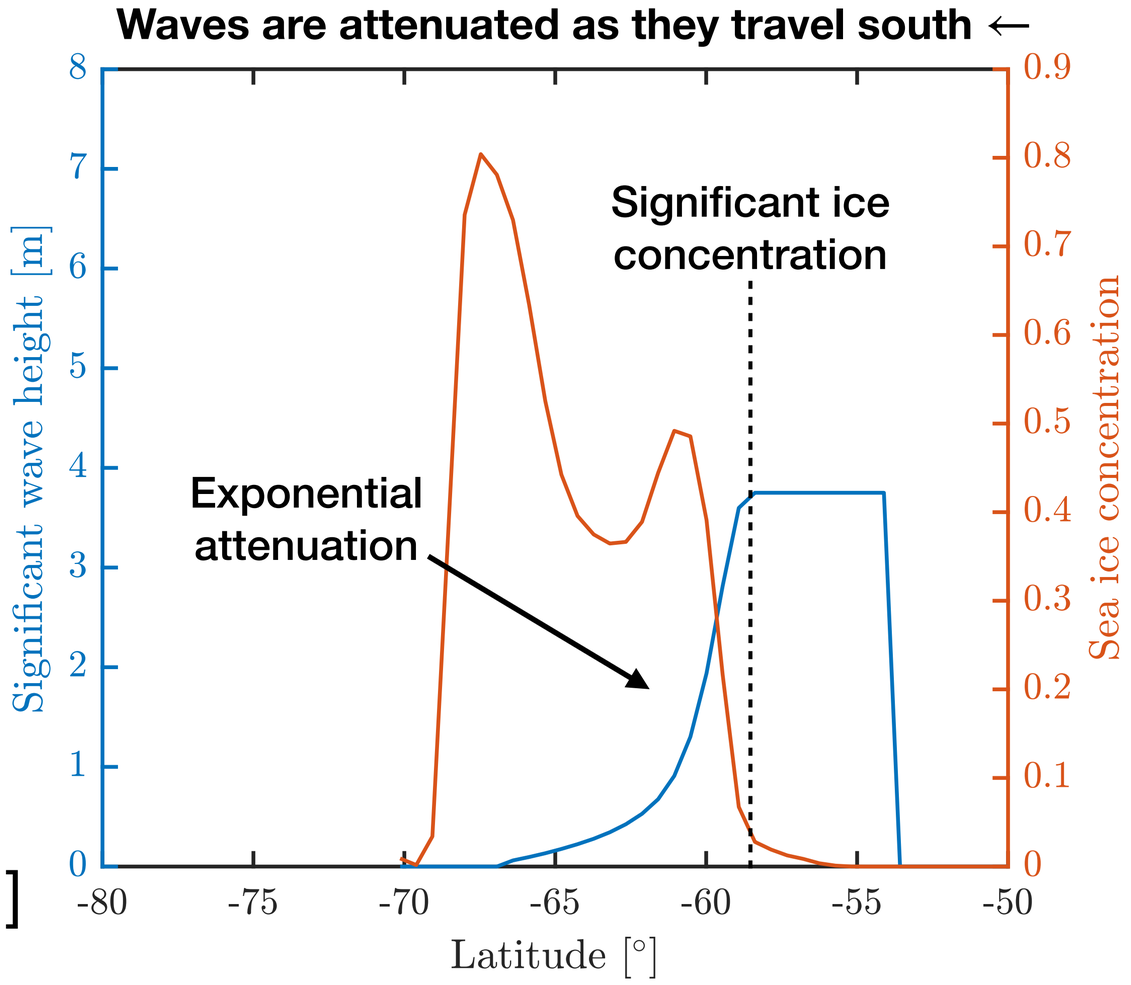
Example of a wave energy spectrum (Heller, 2012).

The impact of ice on ocean waves in the MIZ

- The 1-D energy spectrum of ocean waves, $S(f, x)$, which is x distance in from the ice edge will be exponentially attenuated at rate, $\alpha(T)$

$$S(f, x) = S(f,0)e^{-\alpha(T)x}$$

- $S(f,0)$ is the initial wave energy, f is frequency, T is period, $\alpha(T) = \frac{a}{T^2} + \frac{b}{T^4}$ [1]



Attenuation of waves through ice, along a transect. Significant wave height is a proxy for wave energy.

[1] Meylan et al., Geophys. Res. Lett. (2014).

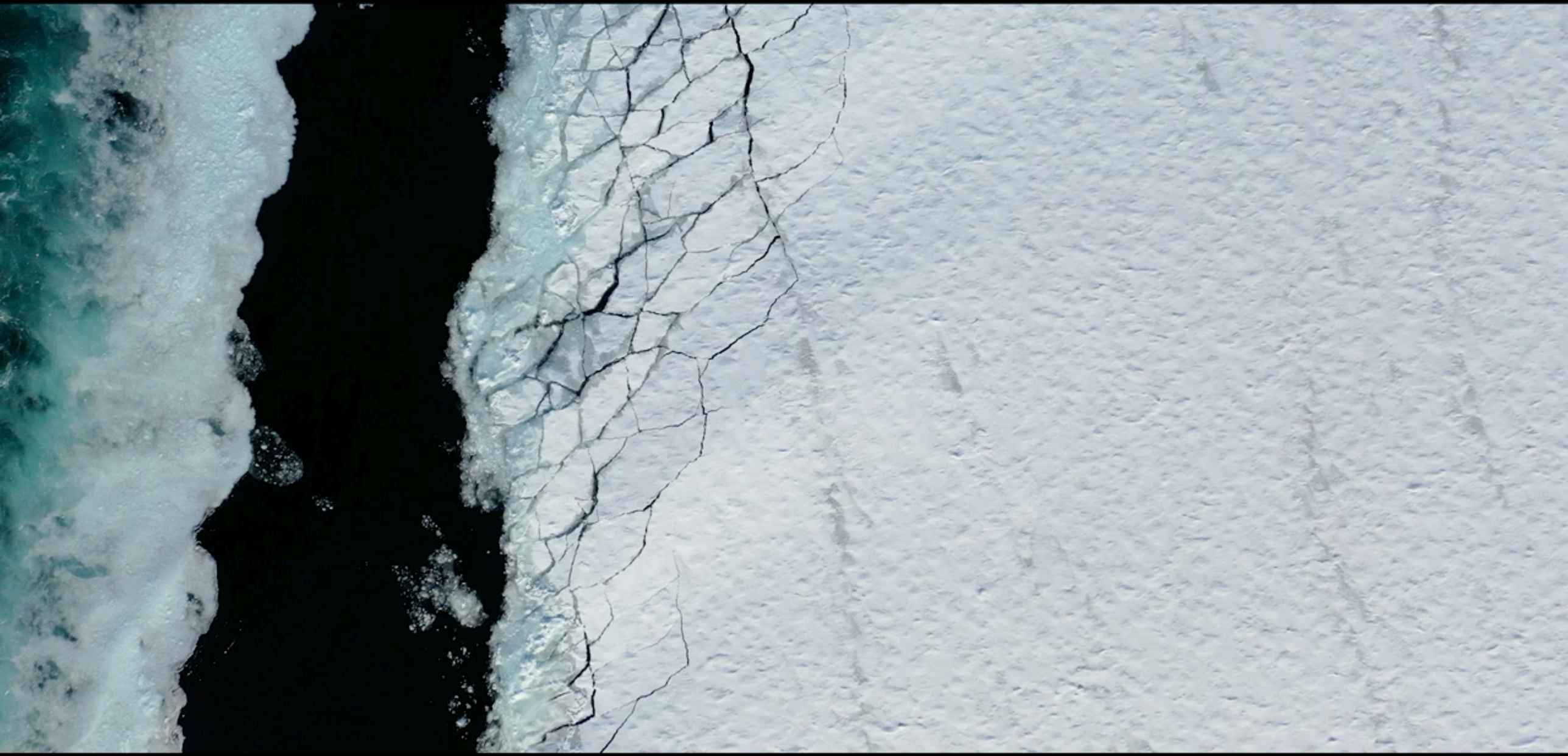
Wave induced break up of floes

- Waves cause sea ice to bend and eventually break
- These waves can pass 100s of km in from the ice edge [2]
- Resulting in the break up of larger floes and continuous ice cover

Example of the MIZ from a spring SCALE cruise. (Credit: Alberto Alberello)

[2] Kohout et al., Nature, (2014).

Continuous ice broken up by waves

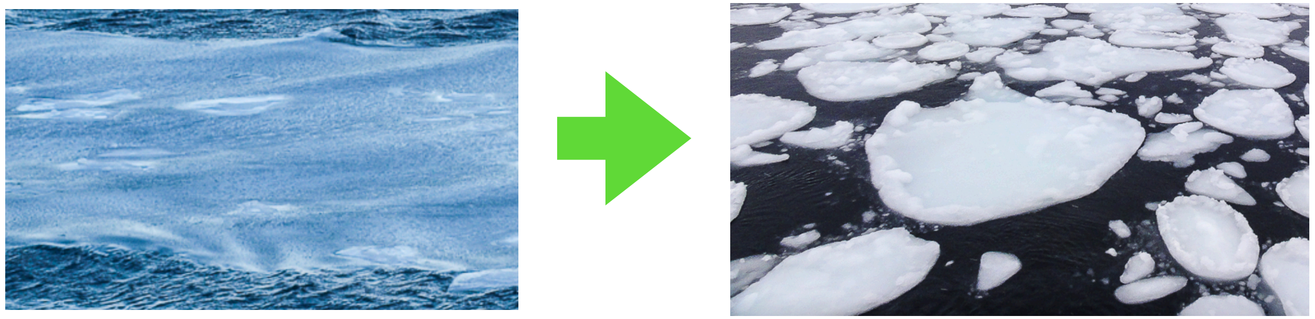


Credit: Elie Dumas-Lefebvre (2022)

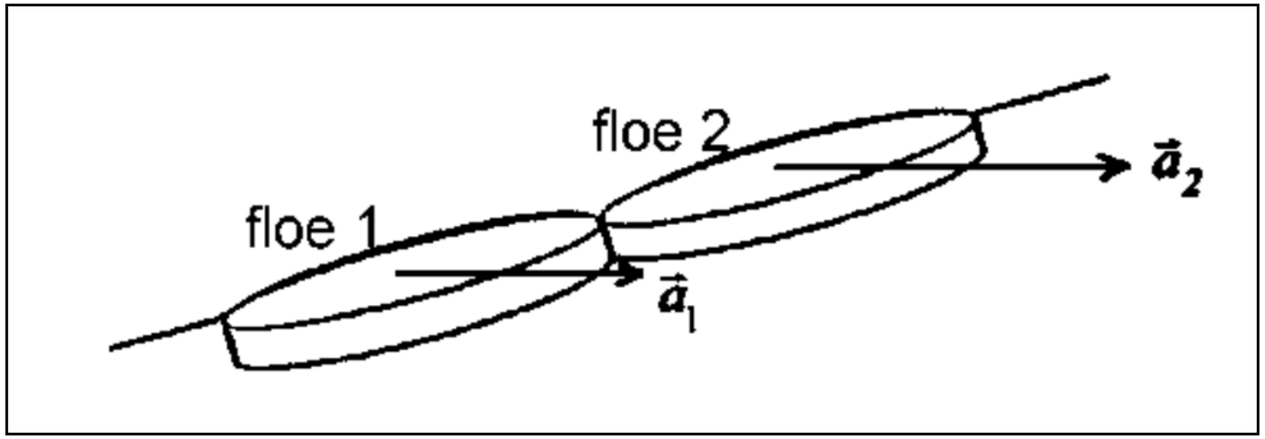
Waves limiting the radius of new ice floes

- Waves limit the size of new ice by bending and stretching ice
- As this phenomena is difficult to measure in situ, theories and lab experiments are used [3, 4]
- A theory suggests that the radius of new floes is determined by the wave field stretching the bonds between two floes [3]

Formation of floes



Credit: Lettie Roach on PIPPER cruise.



Two floes on top of a wave field [3]

[3] Shen et al., Ann. Glaciol., (2001).
[4] Shen et al., JGR, (2004).

CICE: community global sea ice model

- A global numerical model that simulates the growth, melting and movement of sea ice

- The fundamental equation CICE aims to solve is:

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

Change in ice thickness distribution

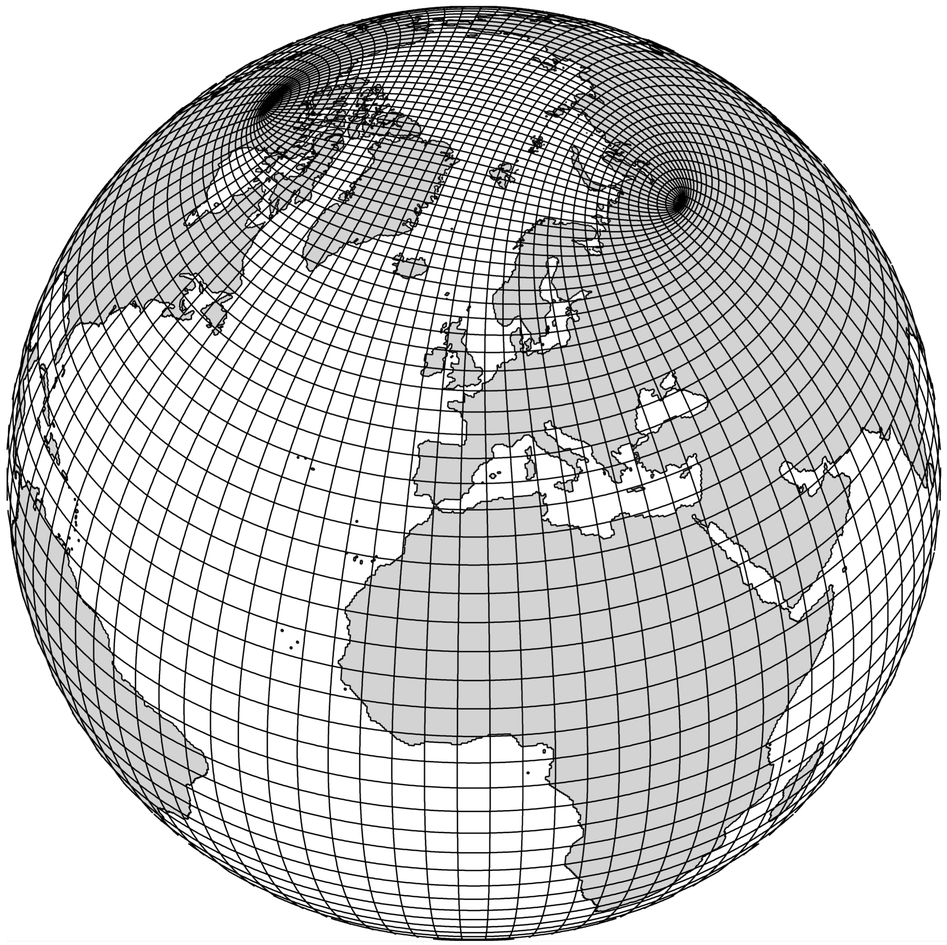
Advection

Thermodynamics

Mechanical redistribution

Sea ice thickness

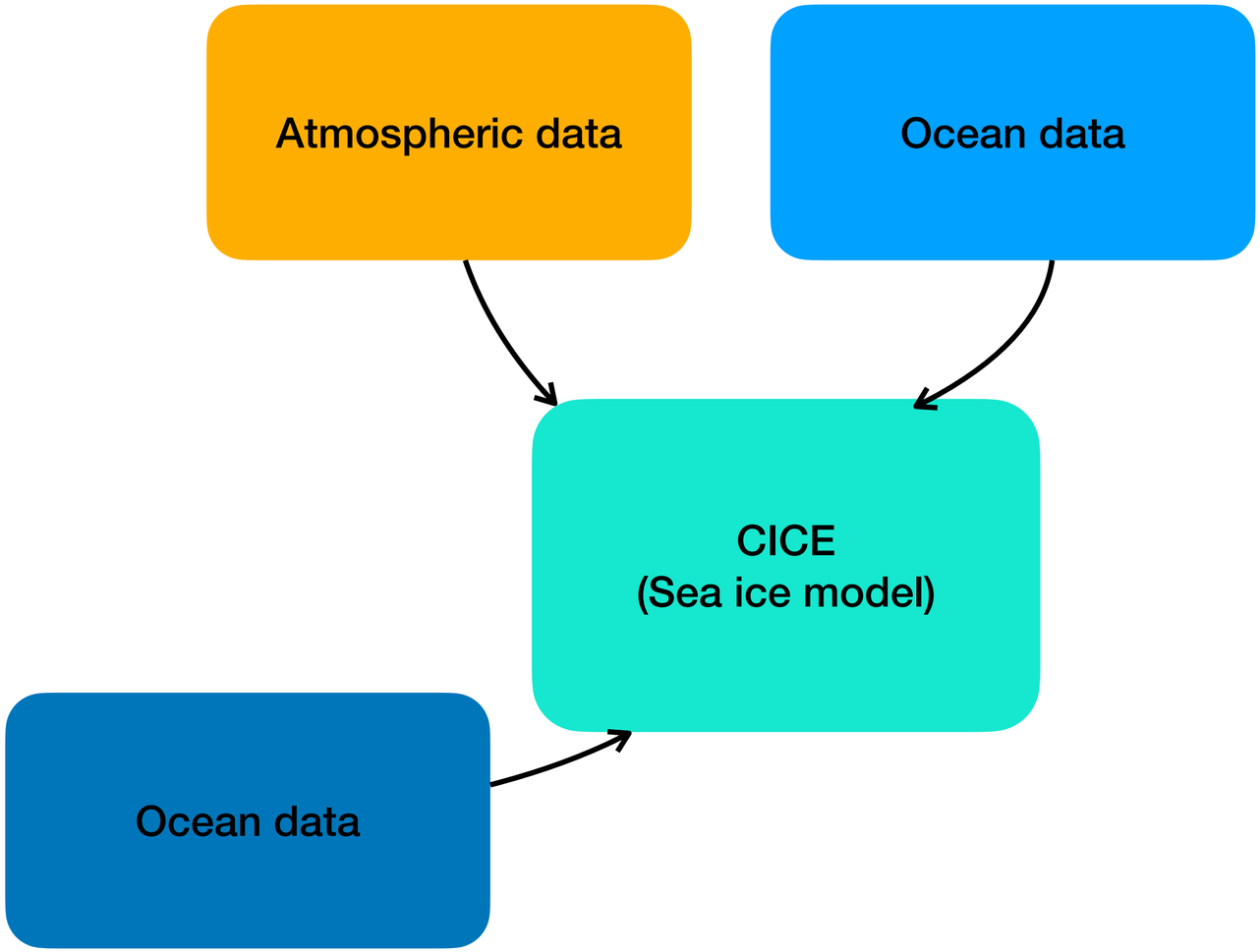
- Where $g(\mathbf{x}, h, t)$ is the ice thickness distribution



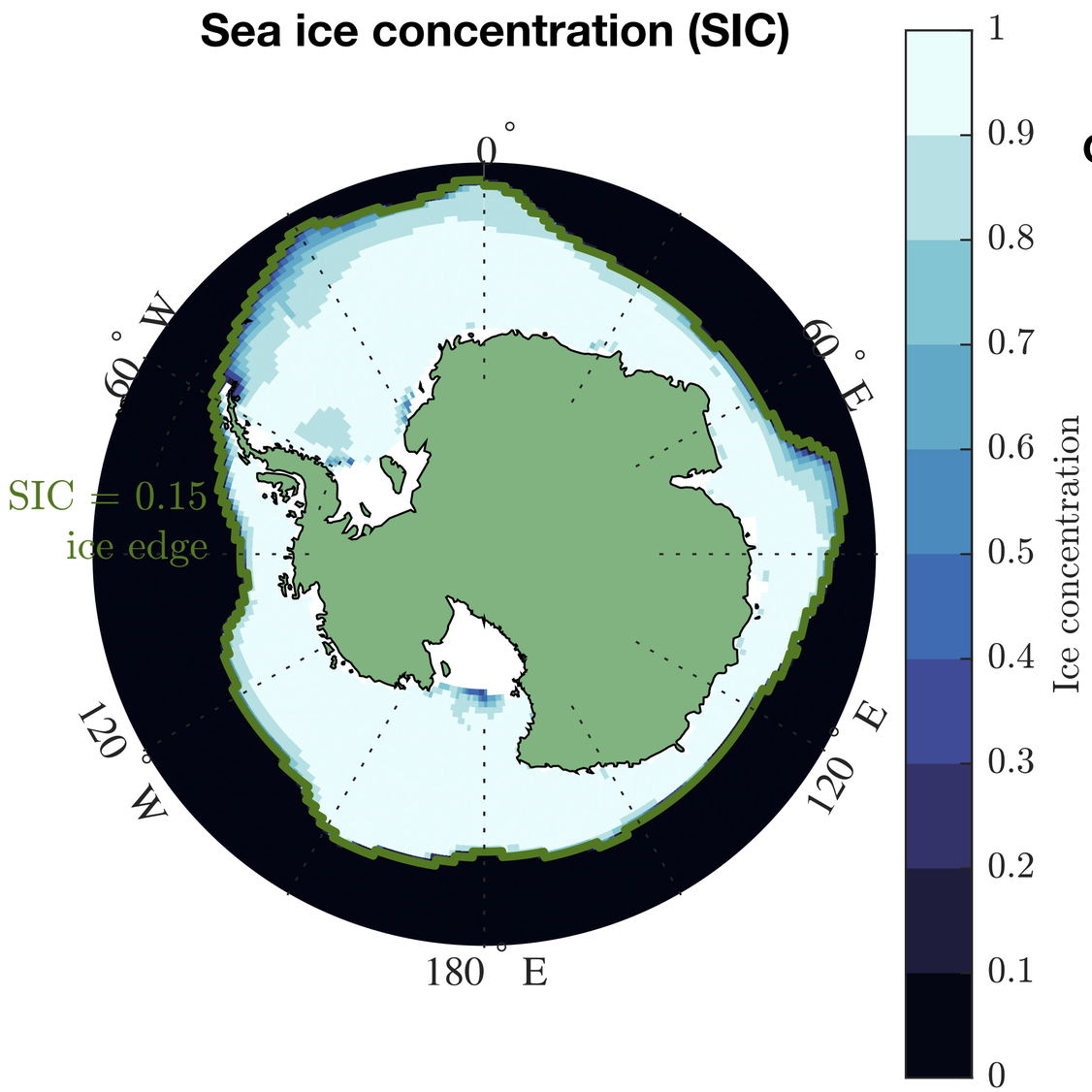
An example of a grid CICE may use (credit: Mats Bentsen).

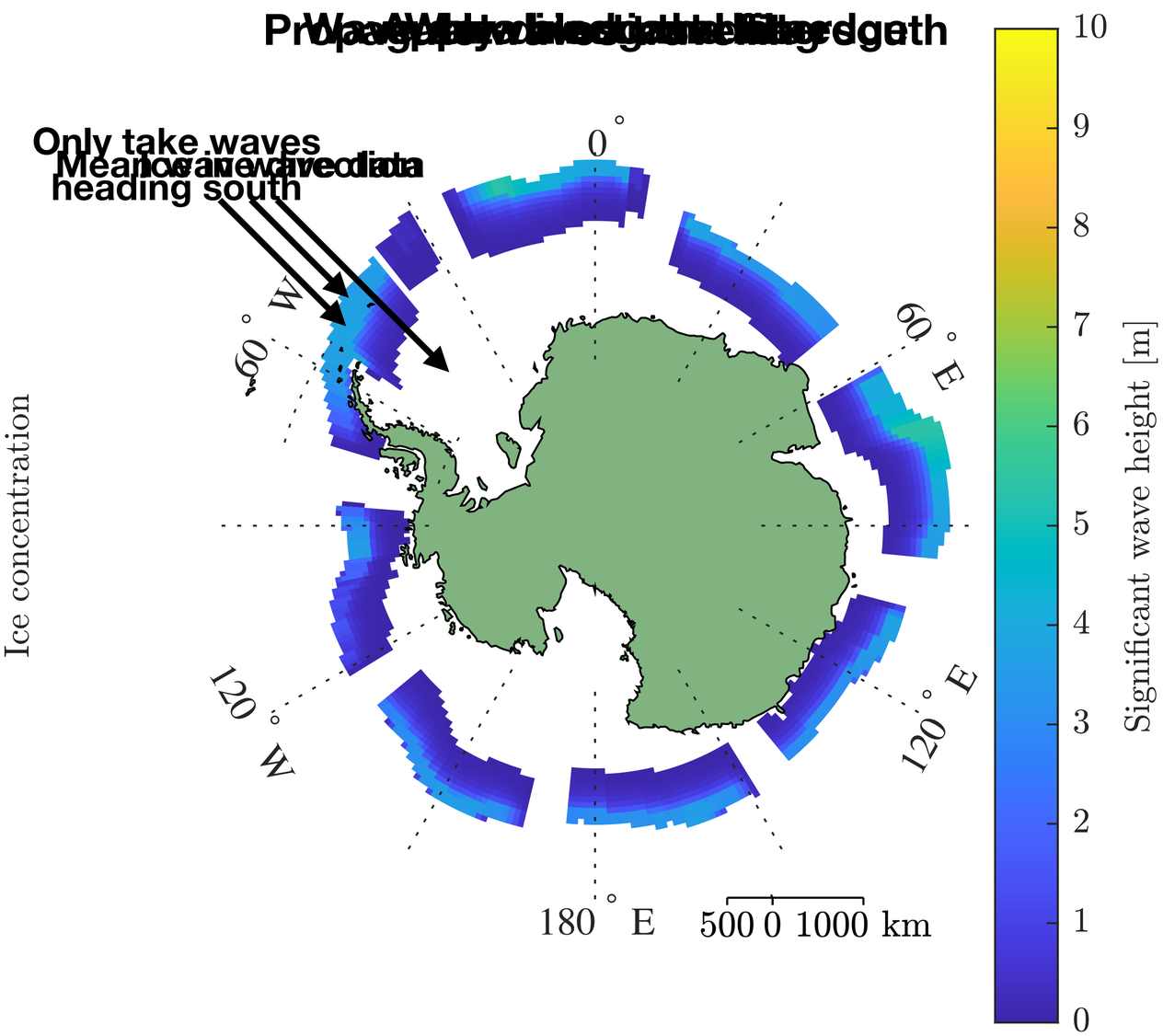
CICE configurations

- Sea ice in the MIZ is impacted by:
  - The atmosphere (winds, air temp, etc)
  - The ocean (currents, surface temperature and salinity)
  - Ocean surface waves



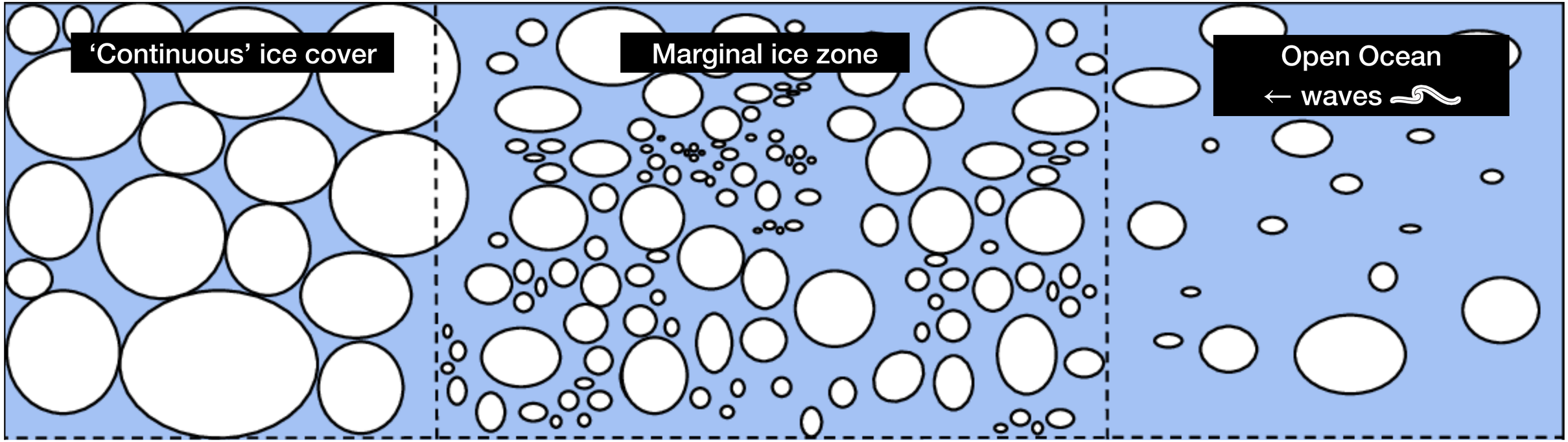
Inputting wave data into CICE





Representing the MIZ in CICE

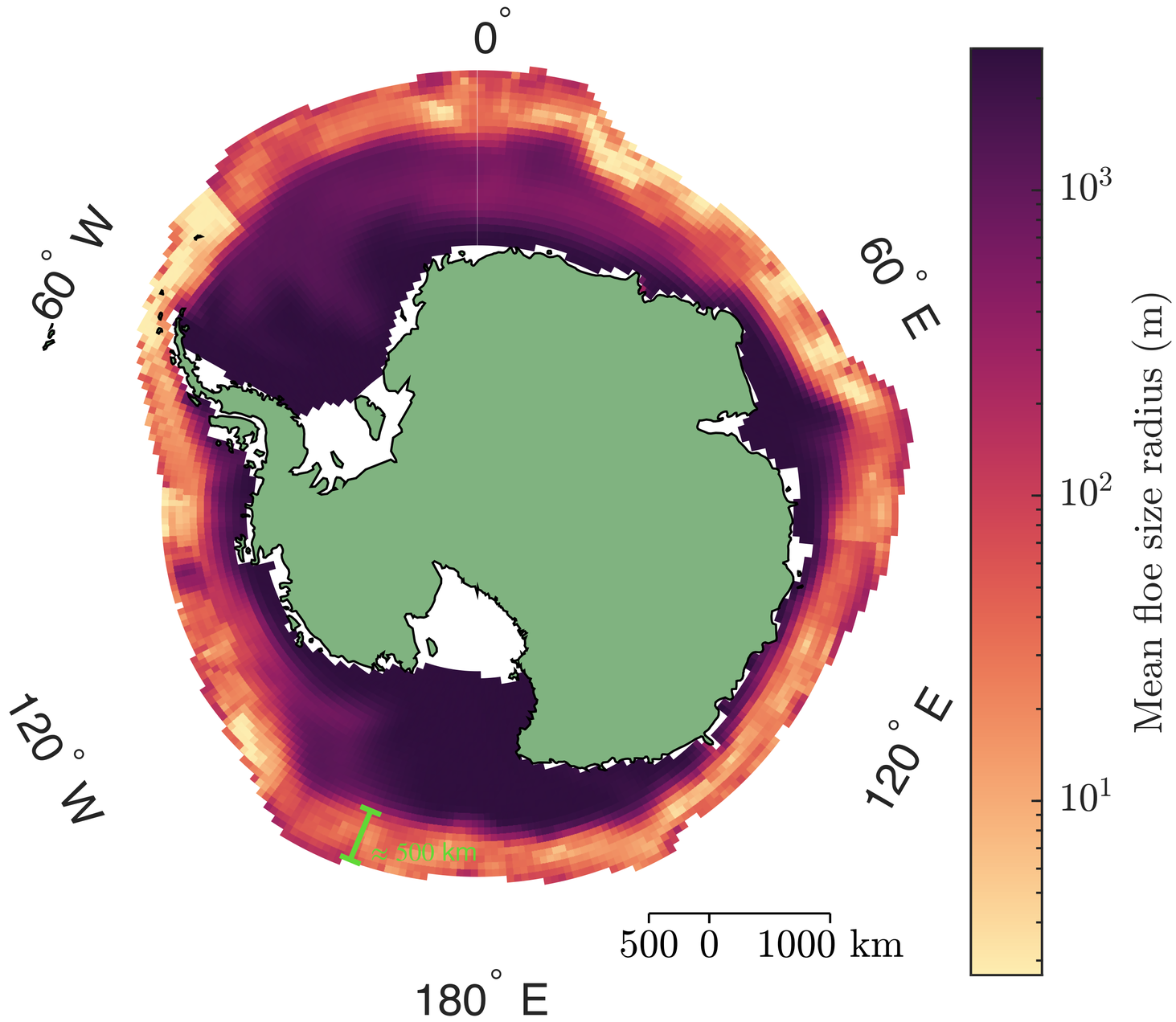
- The MIZ contains pancakes and broken large floes, of various floe sizes
- The latest version of CICE has introduced a floe radius parameter, allowing us to model the MIZ more accurately



Example of how floe sizes change across the ice pack (credit: Horvat and Tziperman, JGR, 2017).

The Antarctic winter MIZ

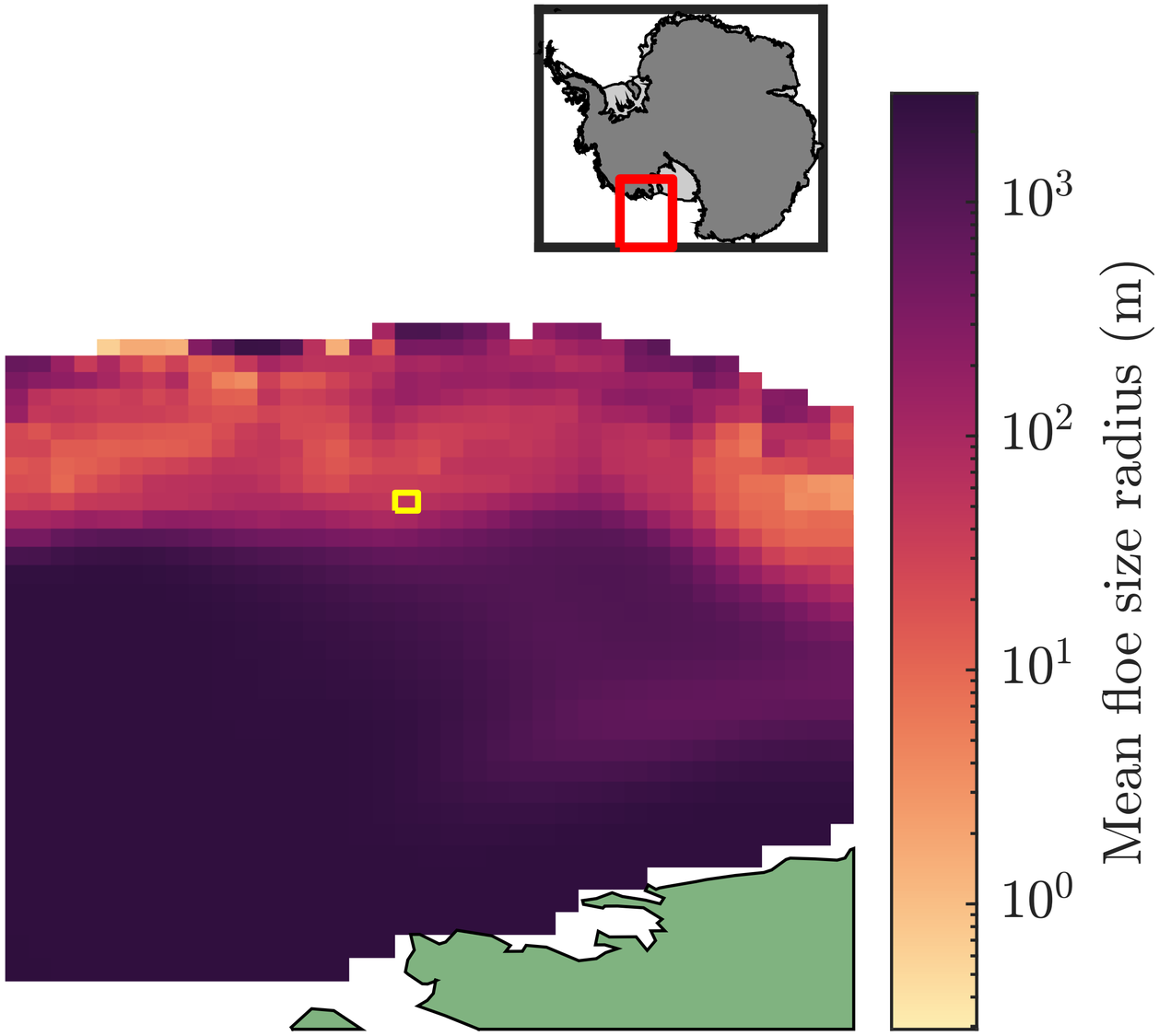
- We can define the marginal ice zone by the radius of these floes
- There's a clear distinction between the marginal ice zone (orange) and continuous ice (purple)



Mean floe size from CICE for September, 2009.

Looking at sub-cell processes

- To simplify the explanation I'm just going to look at how sea ice changes on a cell level
- Each cell on the grid will evolve due to:
    1. Within cell processes (eg. Thermodynamics)
    2. Between cell interactions (eg. Dynamics)



The joint Floe Size and ice Thickness Distribution (FSTD), $f(r,h)$

- We can think of $f(r,h)drdh$ to be the areal concentration of ice in the thickness range $(h, h+dh)$ and floe radius range $(r, r+dr)$

Ice thickness distribution

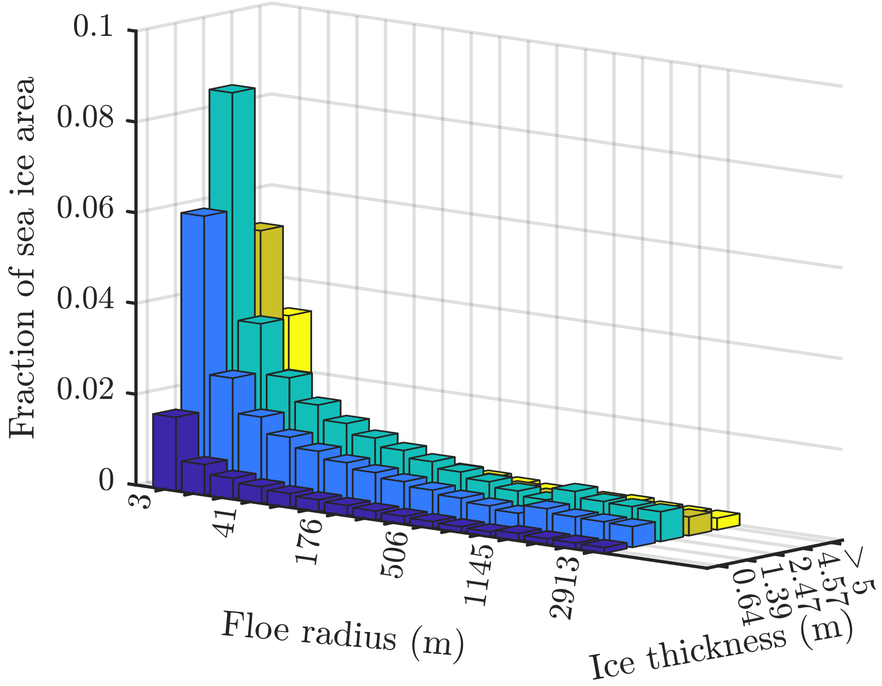
$$g(h) = \int_0^\infty f(r,h)dr$$

Floe size distribution

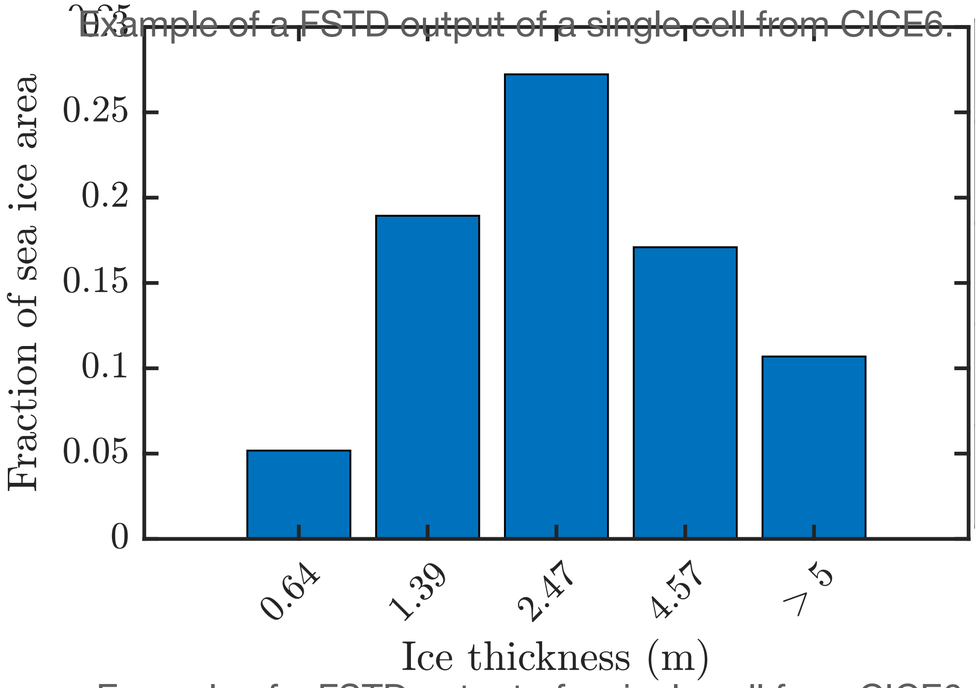
$$F(r) = \int_0^\infty f(r,h)dh$$

Representative radius: $r_a = \dfrac{\int_0^\infty \int_0^\infty rf(r,h)drdh}{\int_0^\infty \int_0^\infty f(r,h)drdh}$

$$\int_0^\infty \int_0^\infty f(r,h)dhdr = \text{areal ice concentration}$$



Example of a FSTD output of a single cell from CICE6.



Example of a FSTD output of a single cell from CICE6.

How does the FSTD evolve?

The governing equation for the changes in joint floe size and thickness distribution over time is:

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

Advection Thermodynamics Mechanical Wave-induced ice break up

- We will focus on the thermodynamics, and then advection

Thermodynamics of the FSTD, $\mathcal{L}_T$

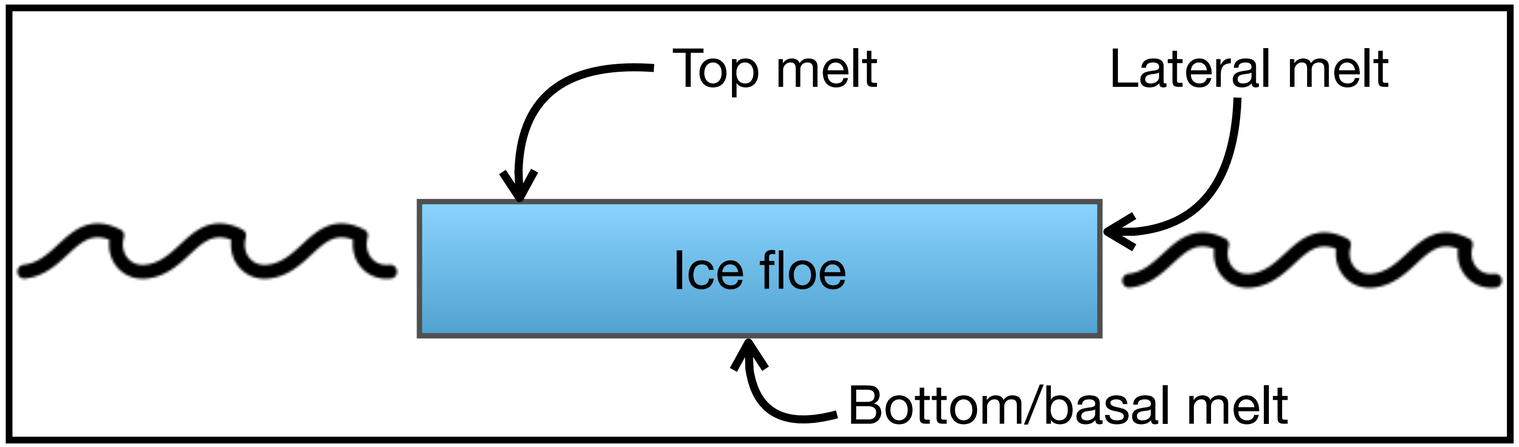
$$\mathcal{L}_T(r,h) = -\nabla_{(r,h)} \cdot (f(r,h)\mathbf{G}) + \frac{2}{r} f(r,h) G_r + \delta\left(r - r_{\min}\right)\delta\left(h - h_{\min}\right)\dot{A}_p + \beta_{\text{weld}}$$

Growth and melt of existing floes through h and r.

New floe production

Welding of floes

where $\mathbf{G} = (G_r, G_h)$

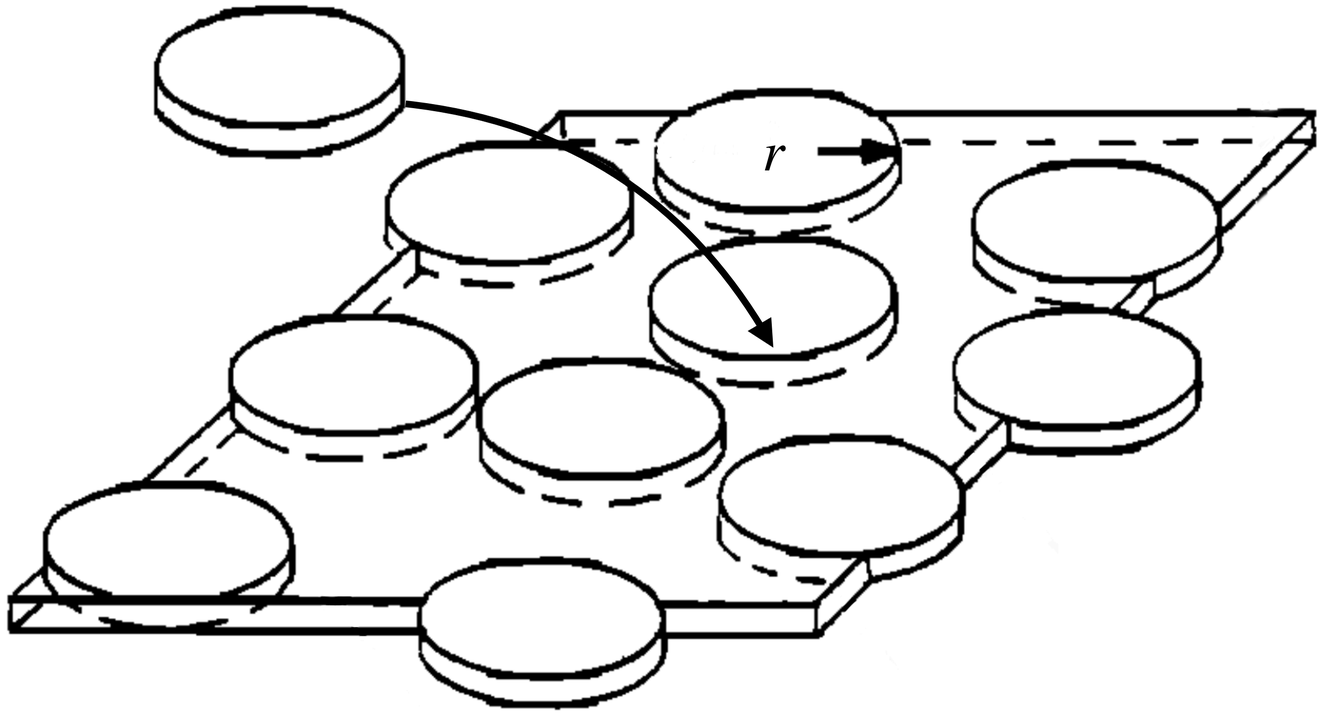


Melt/growth diagram of an ice floe in the ocean.

Floe welding theory

- The rate at which two floes weld together is determined by the probability of those floes overlapping when randomly placed across the cell [5]

[5] Horvat et al., Cryosphere, (2015)



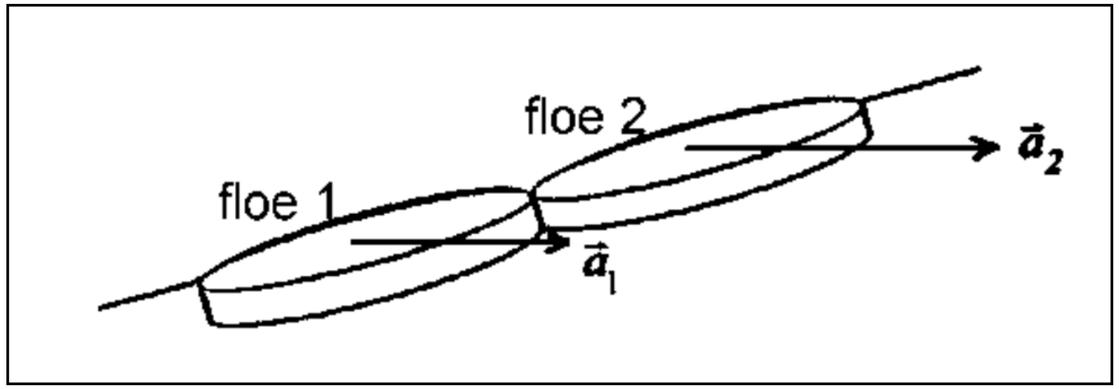
Example of overlapping algorithm (credit: Shen et al., JGR, 1987).

Welding

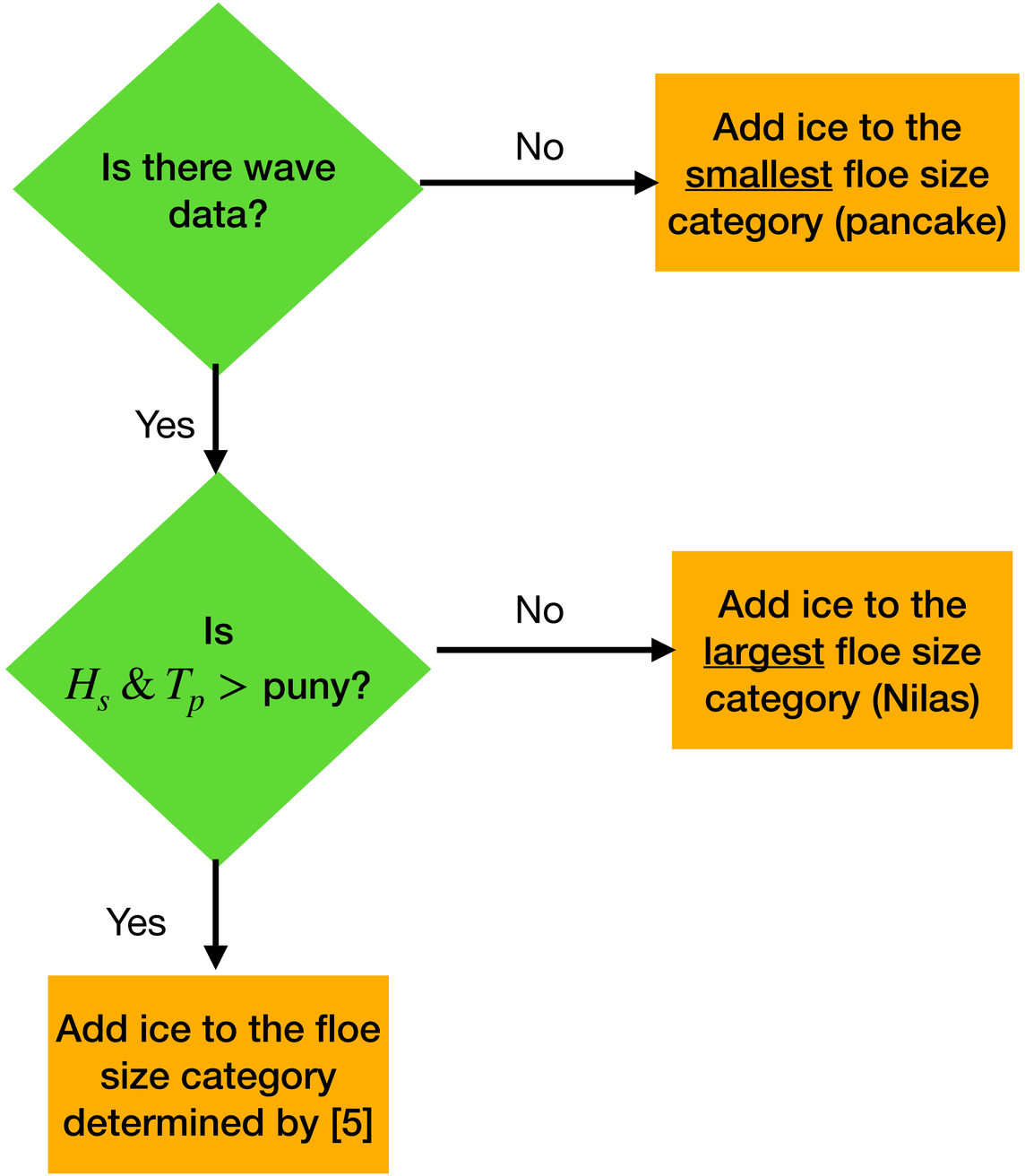
Credit: Nisters and Schröder (2021)

New floe sub-model

- The wave induced tensile failure theory [3] was adopted into CICE to limit the radius of new floes
- In implementation there is a sensitivity to very small amounts of wave energy



Two floes on top of a wave field [3]

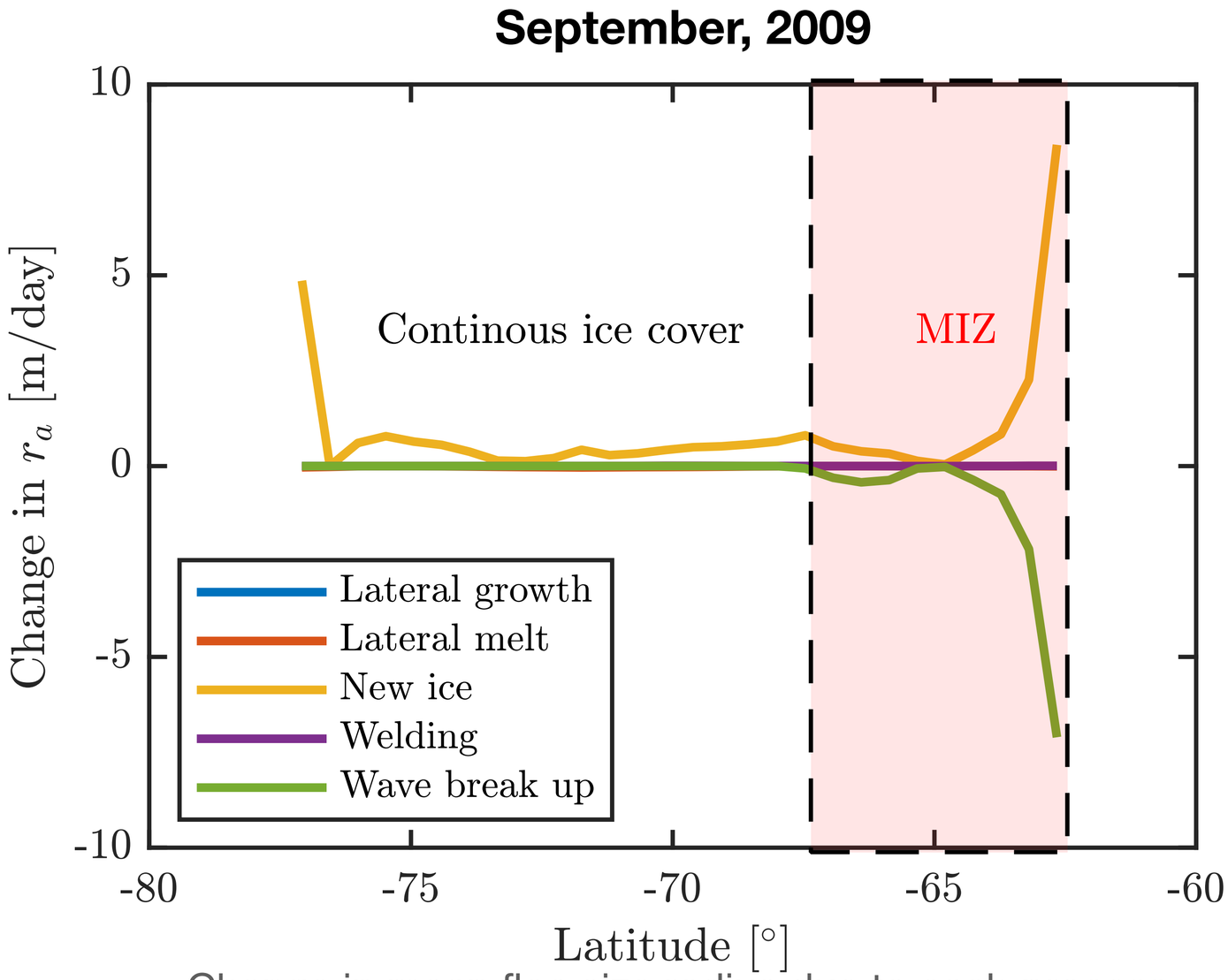


How a new floe's radius is determined within CICE6.

[3] Shen et al., Ann. Glaciol., (2001)

What impacts the size of floes?

- The changes in floe size in the marginal ice zone (MIZ) are dominated by:
  1. New ice production
  2. Wave break up of ice



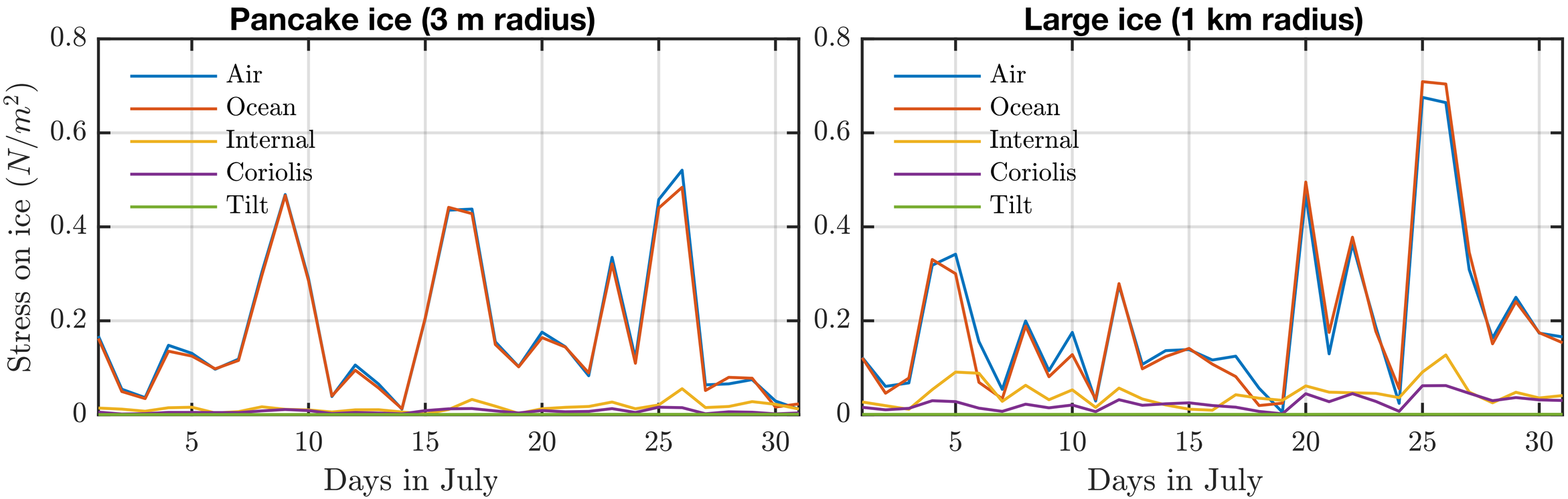
Change in mean floe size radius due to each process.

Advection of sea ice

Momentum equation

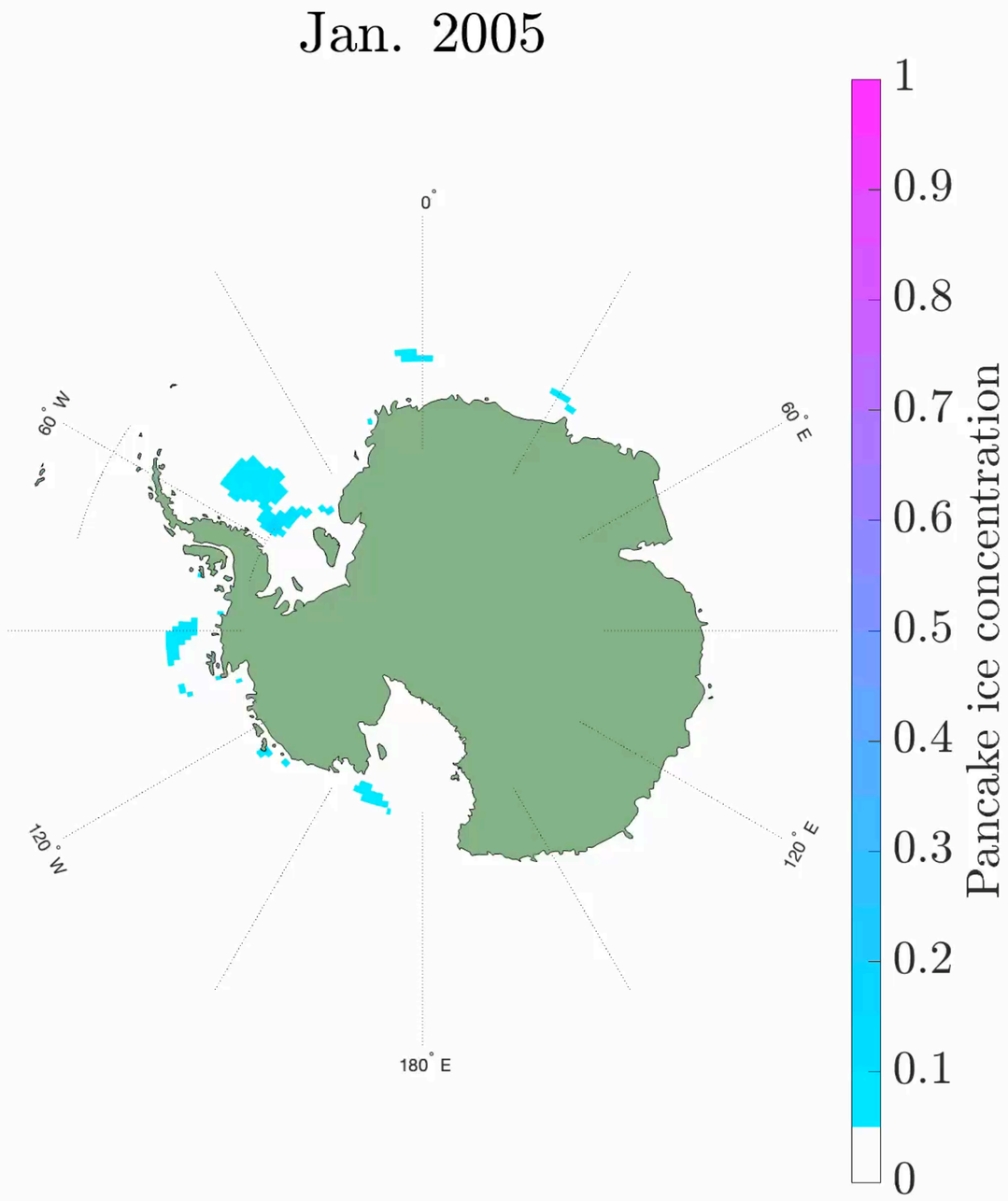
$$m\frac{d\boldsymbol{u}}{dt} = \nabla \cdot \sigma + \boldsymbol{\tau}_a + \boldsymbol{\tau}_w + \tau_b - mf\boldsymbol{k} \times \boldsymbol{u} - m\frac{\partial H_o}{\partial x}$$

Interal ice stress Wind stress Ocean current stress Basal stress Coriolis stress Sea surface tilt



Concentration of pancake ice

- We consider ice in the smallest floe size and thickness category to be pancake ice
- This current definition over-estimates, but we are working on better ones!
- Pancake ice is up to 50% of the sea ice in a winter MIZ

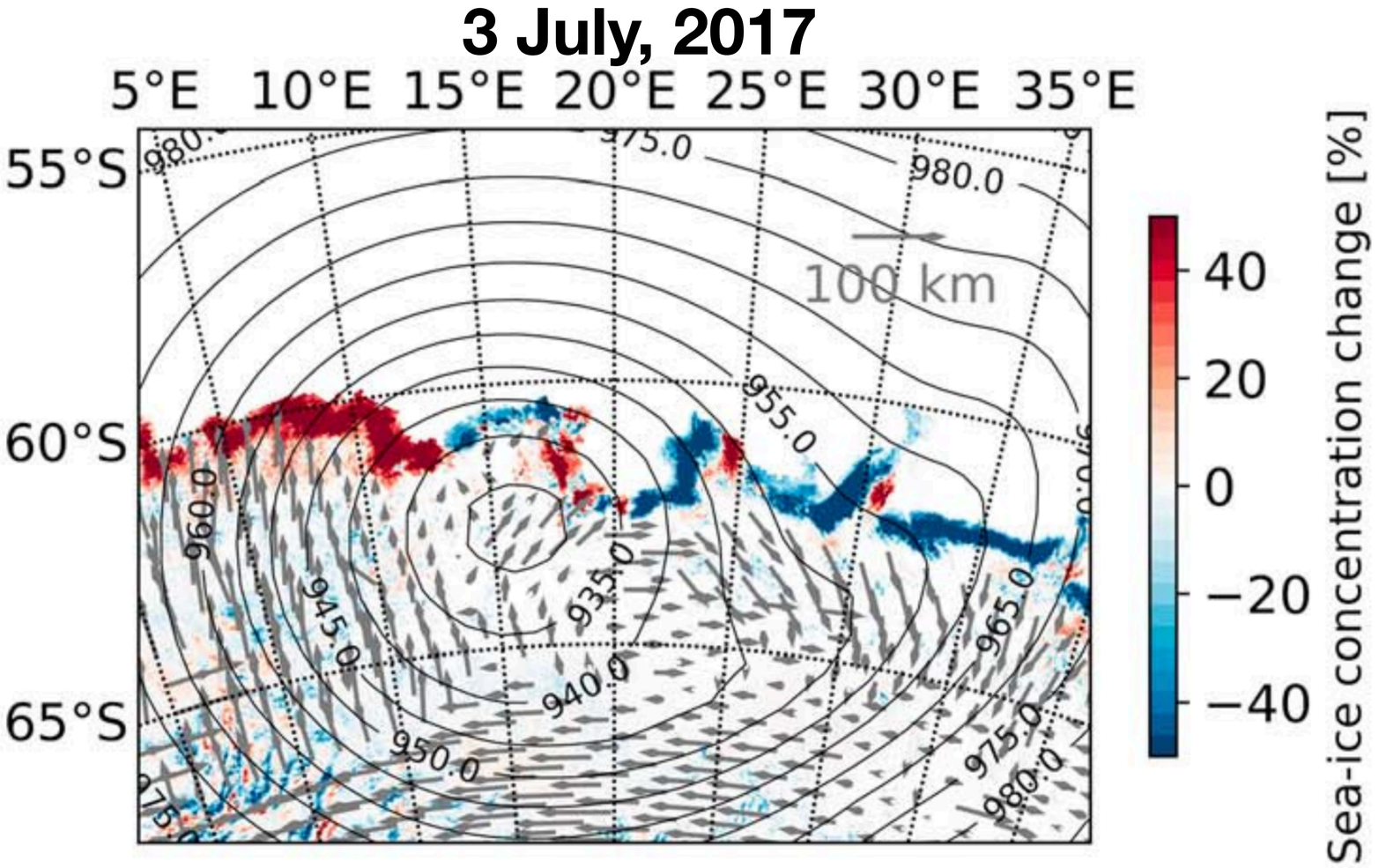


Concentration of pancake ice from 2005-2009.

Future research

Modelling the ice edge during storms

- In 2017 the ice edge was observed to rapidly move over the duration of a cyclone [6]
- We want to model similar behaviour using CICE6
- And run some longer term runs for the seasonality of the ice edge and MIZ



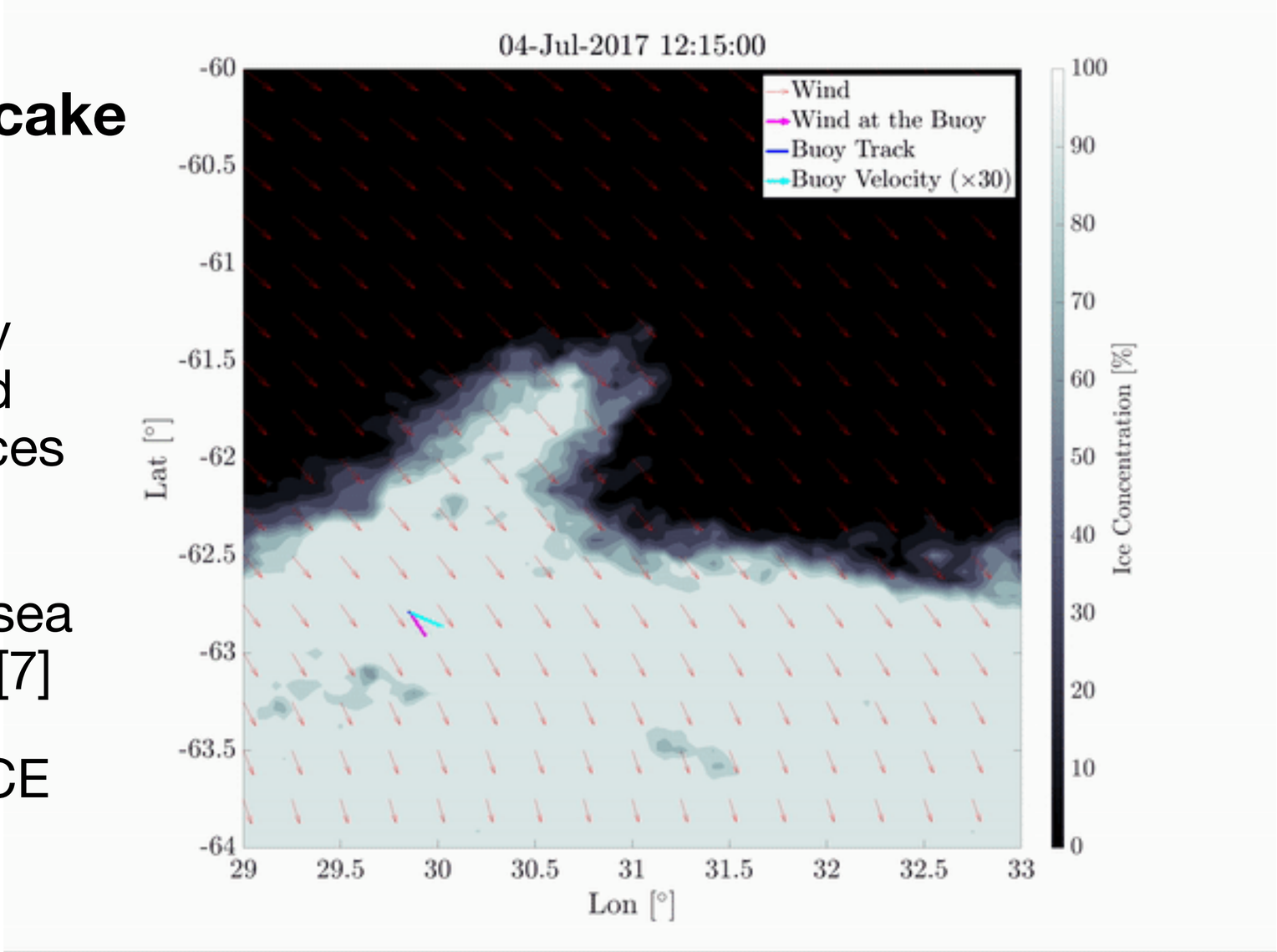
Daily changes in sea ice concentration during an explosive cyclone on the eastern Weddell Sea [6].

[6] Vichi et al., Geophys. Res. Lett, (2019)

Future research

Modelling the drift of pancake floes on a large scale

- It has been recorded that pancake ice becomes highly mobilised during storms and cyclones (where it experiences free-drift)
- The fastest drift speeds for sea ice were recored (0.75 m/s) [7]
- We want to test whether CICE can simulate these observations



The drift of a pancake ice floe during a cyclone in the winter MIZ [7].

[7] Alberello et al., JGR, (2020)