

Analysis of the Antarctic Marginal Ice Zone Based on Unsupervised Classification of Model Data

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Australian Government
Australian Research Council



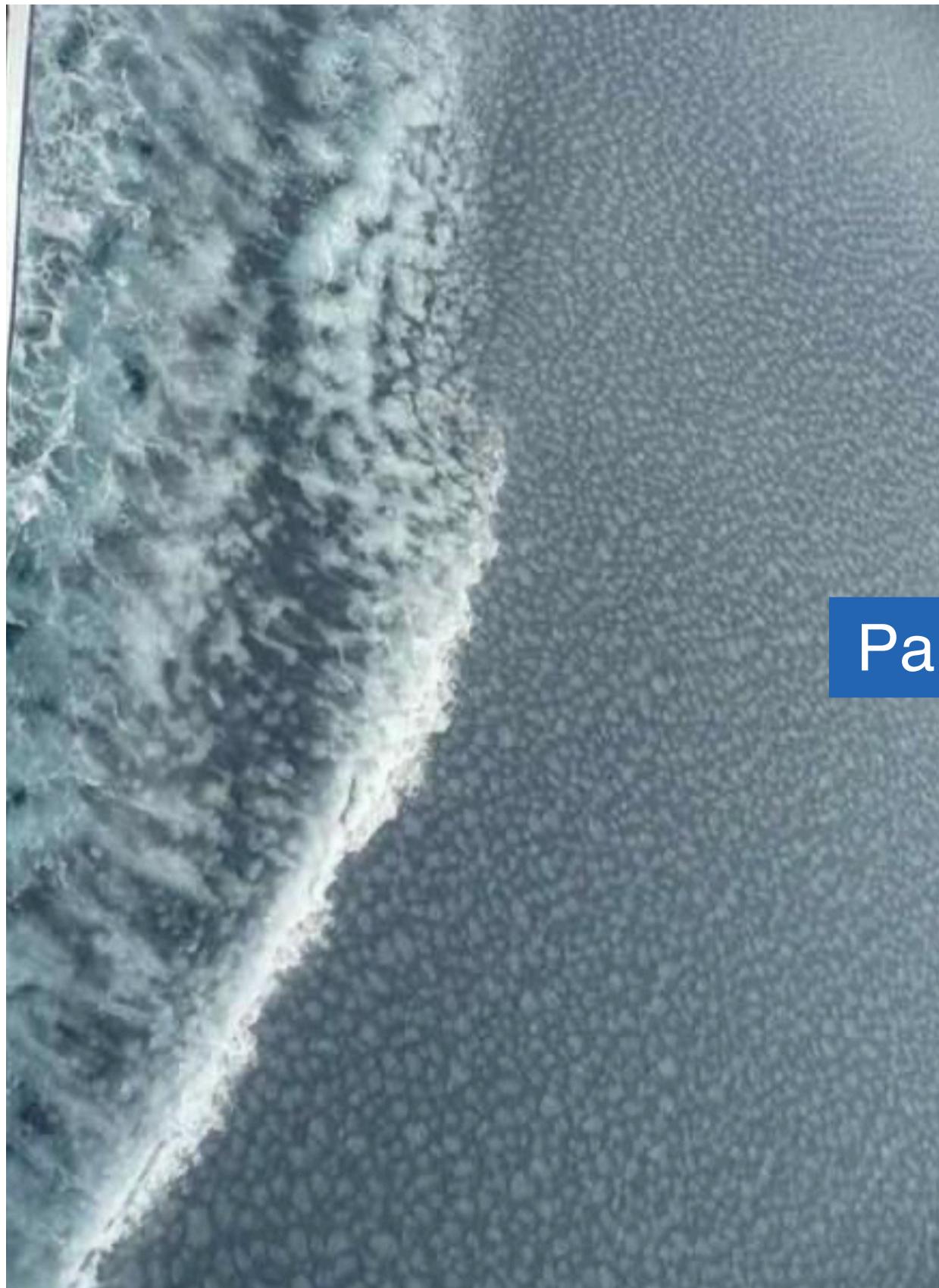
The Antarctic marginal ice zone (MIZ)



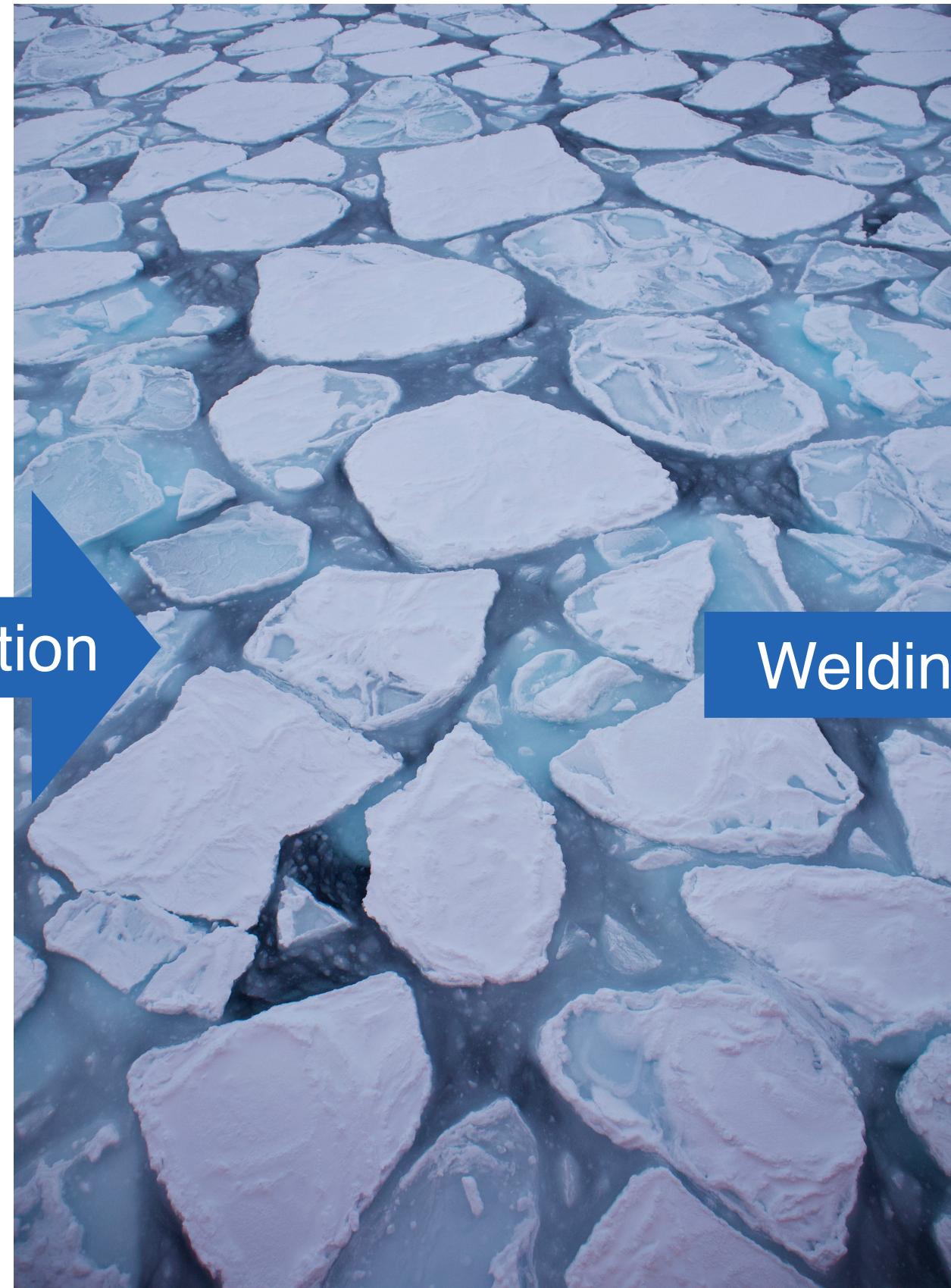
Credit: Alberto Alberello

New ice formation in the MIZ

Frazil and small pancakes



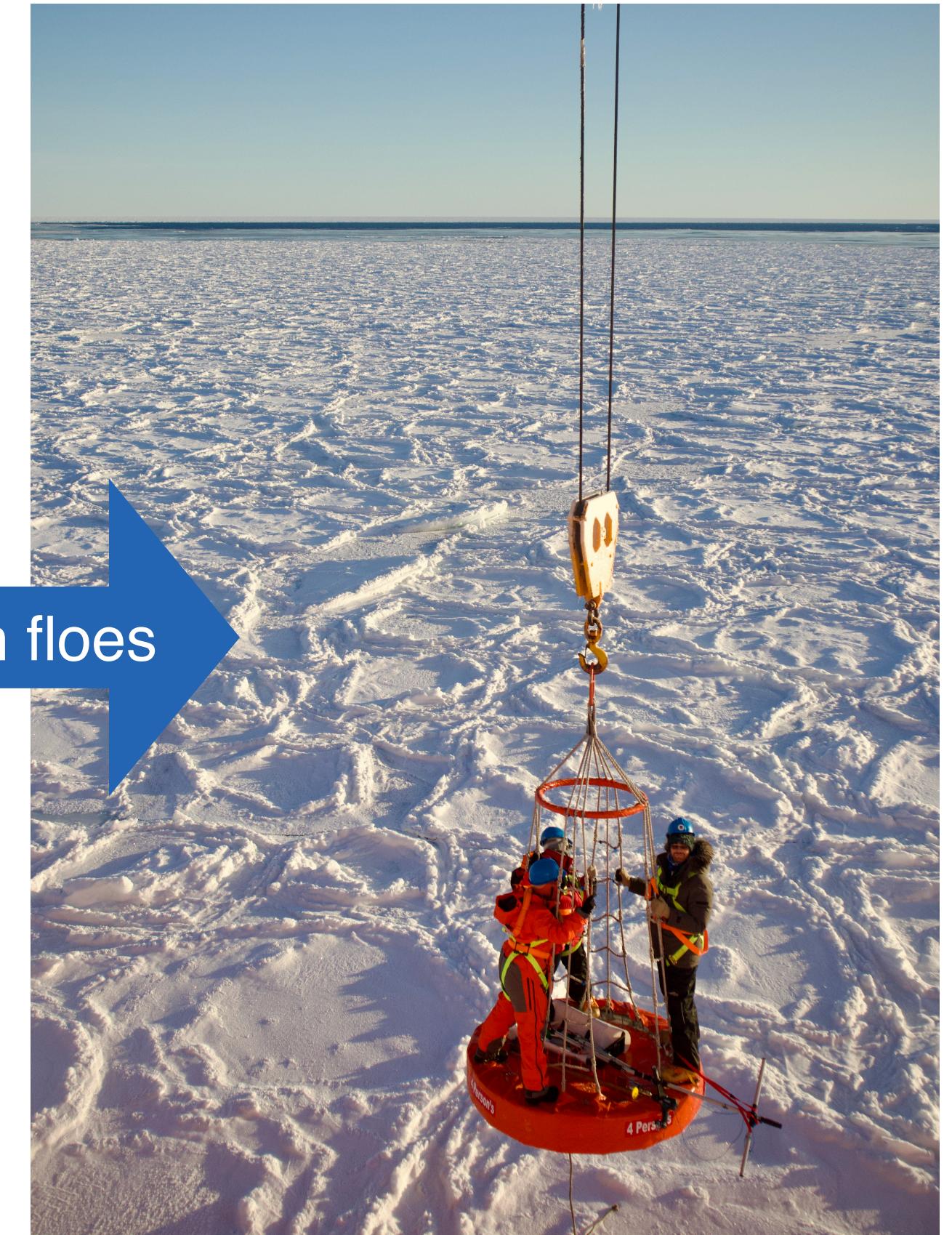
Pancake floes



Pancake formation

Welding between floes

Consolidation of pancakes



Credit: Elizabeth Weir

SCALE 2022 (credit: Kurt Martin/@kurt_artin)

Wave-ice interactions



Image: Dumas-Lefebvre and Dumont, *Cryosphere*, 2023

Wave-ice interactions

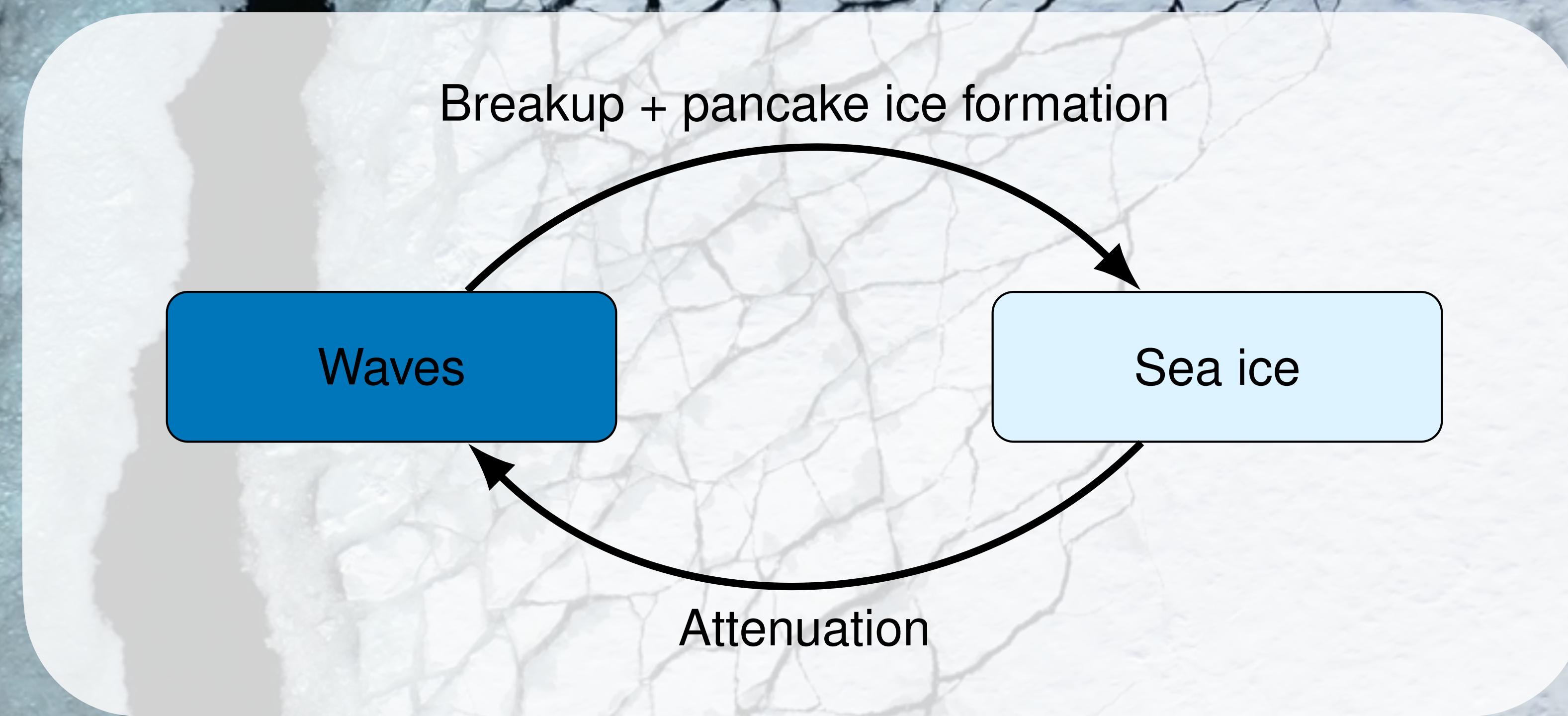


Image: Dumas-Lefebvre and Dumont, *Cryosphere*, 2023

Marginal ice zone processes

- During winter the Antarctic MIZ has been observed to be highly mobile and experience large waves, despite sea ice concentration being near 100%^[1]
- Wave breakup can occur 100s of km from the ice edge^[2]
- Small floes (e.g., broken floes, pancakes) are more prone to melting^[3]
- MIZ studies are hindered by the lack of a pragmatic definition^[4]

- [1] Alberello, JGR: Oceans, 2020
- [2] Kohout et al., Nature, 2014
- [3] Steele, JGR, 1992
- [4] Squire, Phil. Trans., 2022

JGR Oceans
RESEARCH ARTICLE
10.1029/2019JC015418

Drift of Pancake Ice Floes in the Winter Antarctic Marginal Ice Zone During Polar Cyclones

Alberto Alberello¹, Luke Bennett¹, Petra Heil^{2,3}, Clare Eayrs⁴, Marcell Keith MacHutchon⁴, Miguel Onorato^{5,6}, and Alessandro Toffoli⁴

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Abstract High temporal resolution in situ measurements of pancake ice pairs of buoys deployed on floes in the Antarctic marginal ice zone during the over 9 days in which the region was impacted by four polar cyclones. Concentric wave-in-ice activity from the buoys are used to infer that the ice remained undeformed and that the ice remained undeformed under the influence of the cyclone. The mean ice drift follows the wind, but with a strong inertial component, period set to 1 h. Pancake ice drift agrees with the free drift approximation (no internal ice stresses), even though remotely sensed concentration is 100%. The propagation of ocean waves through sea ice is able to transport enough energy to break sea ice hundreds of kilometres from the ice edge. Our results, which are based on concurrent observations at multiple locations, establish that large waves break sea ice much farther from the ice edge than would be predicted by the commonly assumed wave decay. We observe that the wave height increases linearly with distance from the ice edge, and that the significant wave height is greater than three metres, and to be exponential only for small waves. This implies a more prominent role for large ocean waves in sea-ice breakup and retreat than previously thought. We examine the wider relevance of this by comparing observed Antarctic sea-ice edge positions with changes in modelled significant wave heights for the Southern Ocean between 1997 and 2009, and find that the retreat and expansion of the sea-ice edge correlate with mean significant wave height increases and decreases, respectively. This includes capturing the propagation of large storm-generated waves through sea ice has so far not been reported. During our measurement of how waves break sea ice, without improved knowledge of ice breakup we are unable to understand recent changes, or predict future changes, in Arctic and Antarctic sea ice. Here we show that storm-generated ocean waves propagating through Antarctic sea ice are able to transport enough energy to break sea ice hundreds of kilometres from the ice edge. Our results, which are based on concurrent observations at multiple locations, establish that large waves break sea ice much farther from the ice edge than would be predicted by the commonly assumed wave decay. We observe that the wave height increases linearly with distance from the ice edge, and that the significant wave height is greater than three metres, and to be exponential only for small waves. This implies a more prominent role for large ocean waves in sea-ice breakup and retreat than previously thought. We examine the wider relevance of this by comparing observed Antarctic sea-ice edge positions with changes in modelled significant wave heights for the Southern Ocean between 1997 and 2009, and find that the retreat and expansion of the sea-ice edge correlate with mean significant wave height increases and decreases, respectively. This includes capturing the propagation of large storm-generated waves through sea ice has so far not been reported. During our measurement of how waves break sea ice, without improved knowledge of ice breakup we are unable to understand recent changes, or predict future changes, in Arctic and Antarctic sea ice. Five wave sensors were deployed on sea ice between latitudes 60.5° south and 63° south on 23 and 24 September 2012 UTC (Fig. 1). Along the deployment transect, the average ice floe diameter increased steadily from ~2–3 m at the ice edge to 10–20 m approximately 200 km from the ice edge. Beyond this, there was an abrupt increase in floe diameter to hundreds of metres (Extended Data Table 1). Ice was estimated to be 1–2 m thick, and was all first-year ice. The rate at which sea-ice concentration increased with distance from the edge was high relative to the climatological rate for this location (Extended Data Fig. 1). The significant wave heights measured by the sensors include relatively calm conditions and three large-wave events (Extended Data Fig. 2). On 1 October 2012 UTC significant wave heights of 3 m were measured 240 km from the ice edge.

Analysis of wave decay in sea-ice focuses on understanding the evolution of the full wave spectrum propagating through the ice. Linear theory assumes that as a wave propagates through ice, the power at each wave

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A prognosticative synopsis of contemporary marginal ice zone research

Vernon A. Squire

Discussion

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One contribution of 17 to a theme issue 'Theory, modelling and observations of marginal ice zone dynamics: multidisciplinary perspectives and outlooks'.

Subject Areas:
atmospheric science, climatology, meteorology, oceanography

Keywords:
marginal ice zone, waves, floe size distribution, dynamics, modelling, measurements

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1. INTRODUCTION
Ice cover is a jumbled ensemble of floes of shapes floating on the ocean surface. Figure 1 shows a digitized photomosaic obtained during the Joint Experiment (AJIDEK) in the Beaufort Sea (Thorndike, 1984). The volume of ice in a particular floe is given by the distribution function $g(H)$, where H is the fractional cover of ice of thickness h . More commonly, numerical models use for the amount of ice in a given region: h_{mean} (the mean thickness) and A , the areal concentration of ice of thickness threshold h_0 (usually taken as 0.5 m) (Holland, 1979). These parameters are often used to calculate fluxes in the air-ice-ocean system, the top and bottom surfaces of the floes, also occurs at the edges of floes. Steele et al. (2012) discuss how lateral stresses affect flow velocity rates are affected by heat transfer on the lateral faces. This paper describes a numerical simulation for a simple model of the ice states depicted in Figures 2a and 2b, in which cases of uniform floes of a given diameter are approximately the same in both cases, i.e. the thicknesses are also identical. Now ask: what happens in the air-ice-ocean system when two parallel lines (or calipers) that are set against the top and bottom edges of a square, L is the diameter as usually defined; for a square, L is intermediate between the length of a side and the diagonal.

The equations for the ice and ocean models are discussed in section 2, along with the heat, salt, and momentum coupling between the models. The numerical simulations and their results are presented in section 3. Section 4 contains a discussion of the overall results.

2. THEORY
To estimate the partition of fluxes between top, bottom, and lateral ice surface areas, we need to know the relative amount of each type of surface area. The first step is to find a horizontal length scale for a floe that can be related to these surface areas. Following Rothrock and Thorndike (1984), we define the "mean caliper diameter" L as the average over all angles of the distance between two parallel lines (or calipers) that are set against the floe's sidewalls. For a square, L is the diameter as usually defined; for a square, L is intermediate between the length of a side and the diagonal.

The top surface area of each floe will be referred to as "horizontal surface area" (equal to the bottom surface area), in contrast to the "lateral surface area" around the sides of the floe. The concept of mean caliper diameter allows us to use the general result that

$$\rho = \pi L$$

for any convex shape, where ρ is the perimeter. Rothrock and Thorndike found that for Figure 1 the ratio ρ/L had a mean of 3.17 and standard deviation of only 0.04, i.e. floes were highly convex. Note, however, that the smallest floes they digitized from the photomosaic were approximately 1 km in diameter. It is assumed in the paper that the smaller floes found in

LETTER

Storm-induced sea-ice breakup and the implications for ice extent

A. L. Kohout¹, M. J. M. Williams², S. M. Dean³ & M. H. Meylan³

Here we report the measurement of wave attenuation using simultaneous observations across hundreds of kilometers in the Antarctic MIZ, and examine its implications for recent retreat and expansion of Antarctic sea ice. Five wave sensors were deployed on sea ice between latitudes 60.5° south and 63° south on 23 and 24 September 2012 UTC (Fig. 1). Along the deployment transect, the average ice floe diameter increased steadily from ~2–3 m at the ice edge to 10–20 m approximately 200 km from the ice edge. Beyond this, there was an abrupt increase in floe diameter to hundreds of metres (Extended Data Table 1). Ice was estimated to be 1–2 m thick, and was all first-year ice. The rate at which sea-ice concentration increased with distance from the edge was high relative to the climatological rate for this location (Extended Data Fig. 1). The significant wave heights measured by the sensors include relatively calm conditions and three large-wave events (Extended Data Fig. 2). On 1 October 2012 UTC significant wave heights of 3 m were measured 240 km from the ice edge.

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Sea Ice Melting and Floe Geometry in a Simple Ice-Ocean Model

MICHAEL STEELE

Science Center, Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, Seattle

A coupled sea ice-ocean numerical model has been developed that addresses the role of floe geometry during summer melting. The model uses a diagnostic approach for average floe diameter in the ocean and ice concentration in the ocean. The relation between the top, bottom, and lateral (side) surfaces of floes is examined using time-dependent simulations with varying initial average diameter. The different parameterizations for bottom and lateral melting in the model are compared and found to be similar. The results indicate that lateral melting is dominant for floes with diameters less than 0.03 m, given atmospheric thermal forcing typical of the central Arctic summer. This means that the decrease in ice concentration over the summer is a strong function of floe diameter, in keeping with simple geometric arguments. In all cases, about 80% of the net thermal energy enters the ocean through leads going toward melting ice, while the rest warms the ocean.

balances on each ice surface are computed using the observations and models of Makarov and Pavovich (1987) (hereafter "MP87") on the heat budget of summer leads. Figure 1 shows a digitized photomosaic obtained during the Joint Experiment (AJIDEK) in the Beaufort Sea (Thorndike, 1984). The volume of ice in a particular floe is given by the distribution function $g(H)$, where H is the fractional cover of ice of thickness h . More commonly, numerical models use for the amount of ice in a given region: h_{mean} (the mean thickness) and A , the areal concentration of ice of thickness threshold h_0 (usually taken as 0.5 m) (Holland, 1979). These parameters are often used to calculate fluxes in the air-ice-ocean system, the top and bottom surfaces of the floes, also occurs at the edges of floes. Steele et al. (2012) discuss how lateral stresses affect flow velocity rates are affected by heat transfer on the lateral faces. This paper describes a numerical simulation for a simple model of the ice states depicted in Figures 2a and 2b, in which cases of uniform floes of a given diameter are approximately the same in both cases, i.e. the thicknesses are also identical. Now ask: what happens in the air-ice-ocean system when two parallel lines (or calipers) that are set against the top and bottom edges of a square, L is the diameter as usually defined; for a square, L is intermediate between the length of a side and the diagonal.

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6

How can we determine the width of the MIZ?

- ❄️ Sea ice concentrations between 15–80% has been used historically as it is relatively easy to measure, however, MIZ dynamics also occur in near 100% concentrations [5]
- 🌊 Wave heights have been used recently [6, 7], although waves also have a pre-conditioning effect on the ice (i.e., pancake ice formation)
- 🌐 Floe size (radius) could tell us if floes have been affected by waves by either process

[5] Alberello et al., Nature Comms, 2023

[6] Horvat et al., GRL, 2020

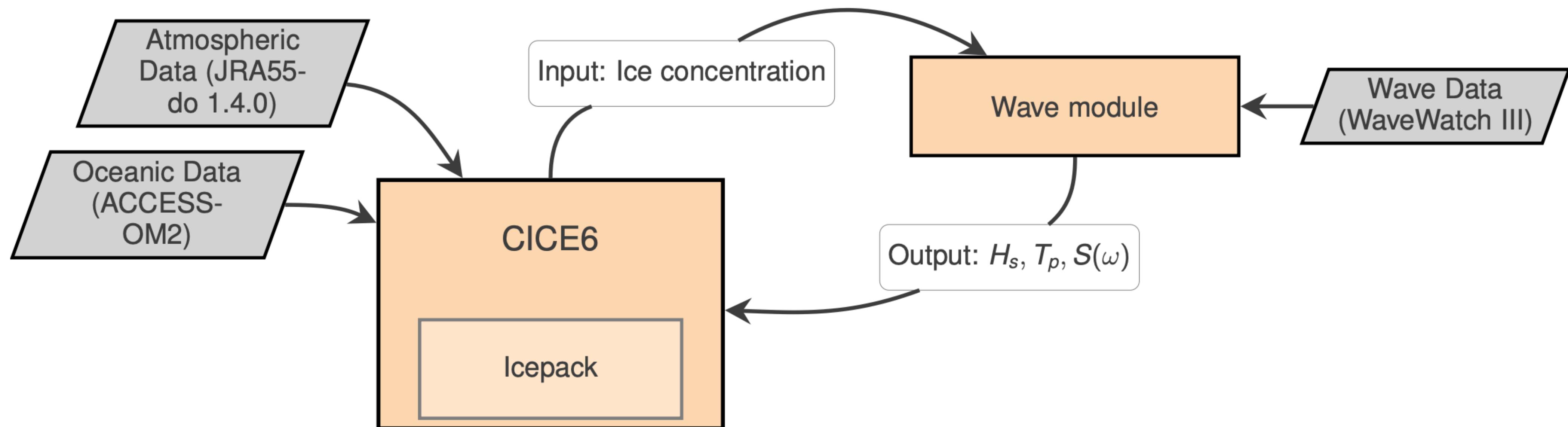
[7] Brouwer et al., Cryosphere, 2022

How can we determine the width of the MIZ?

- What is a marginal ice zone?
 - ─ Sea ice concentration is relatively high in high-latitude oceans
 - ─ Waves are pre-dominated by sea ice
 - ─ Floes are either pre-dominated by sea ice or have a significant fraction of open water
- So, what is the best discriminator for separating the Antarctic marginal ice zone from the inner pack?

Step 1: Collecting sea ice data

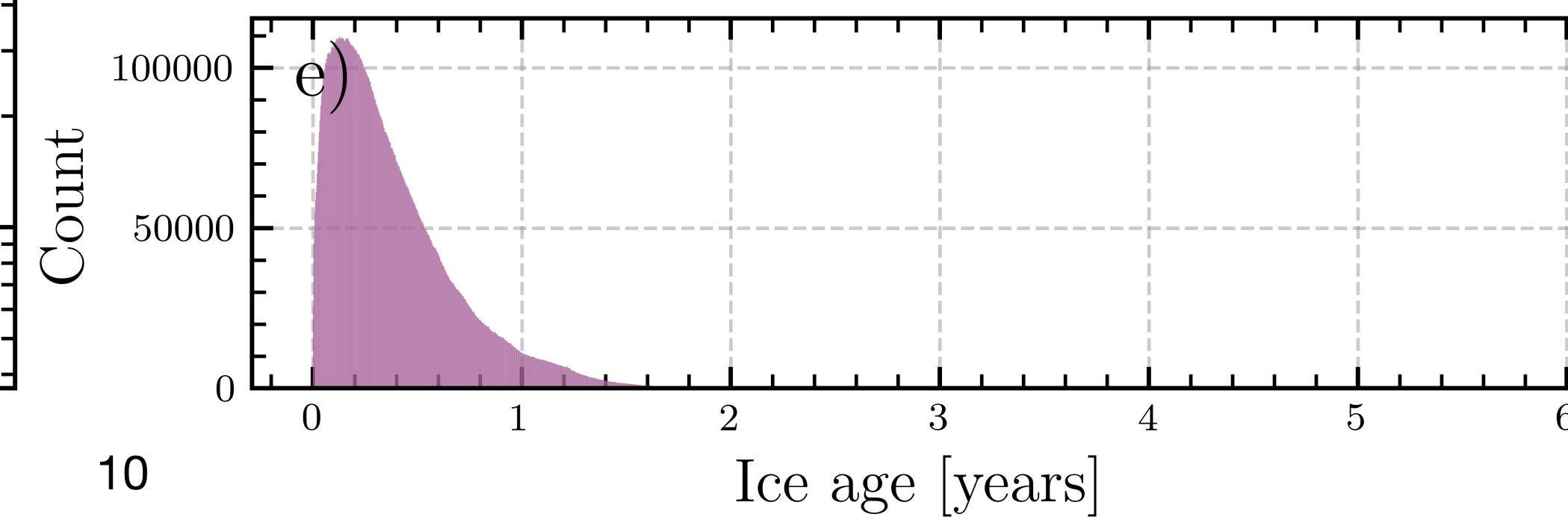
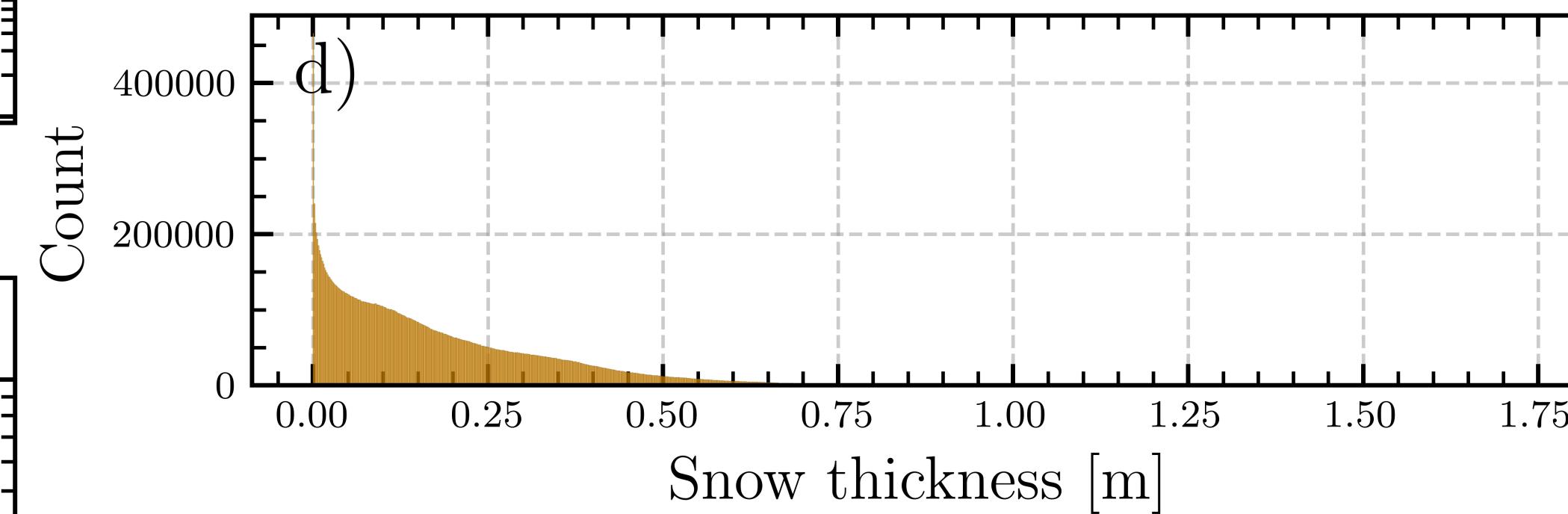
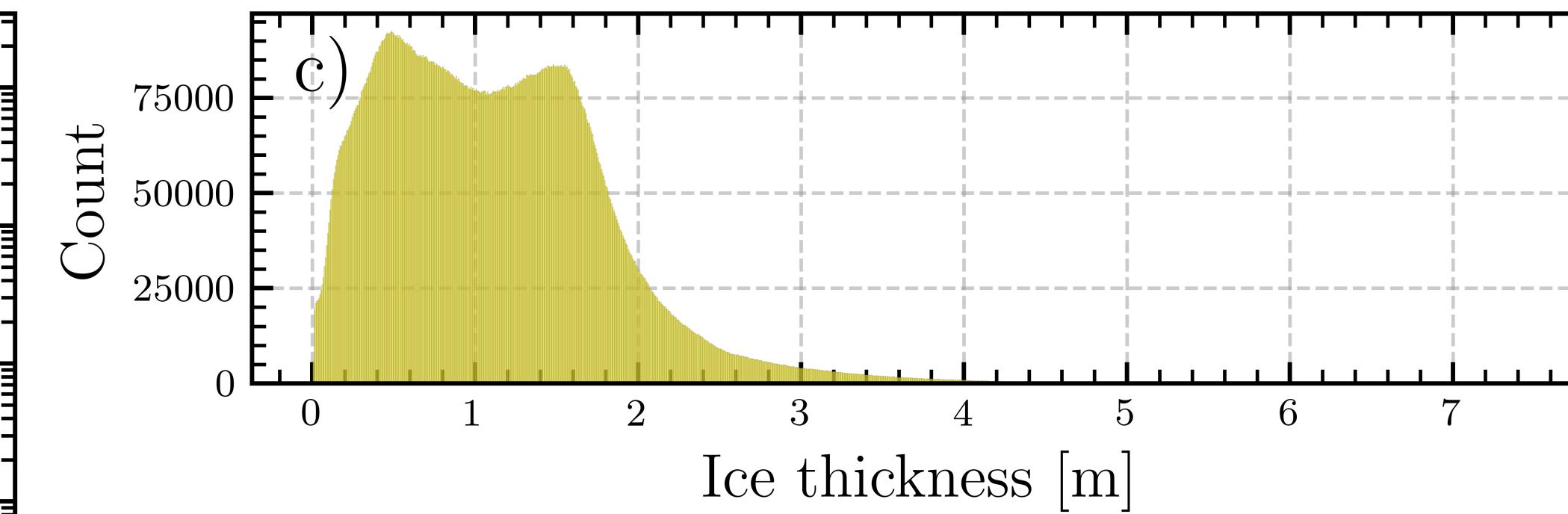
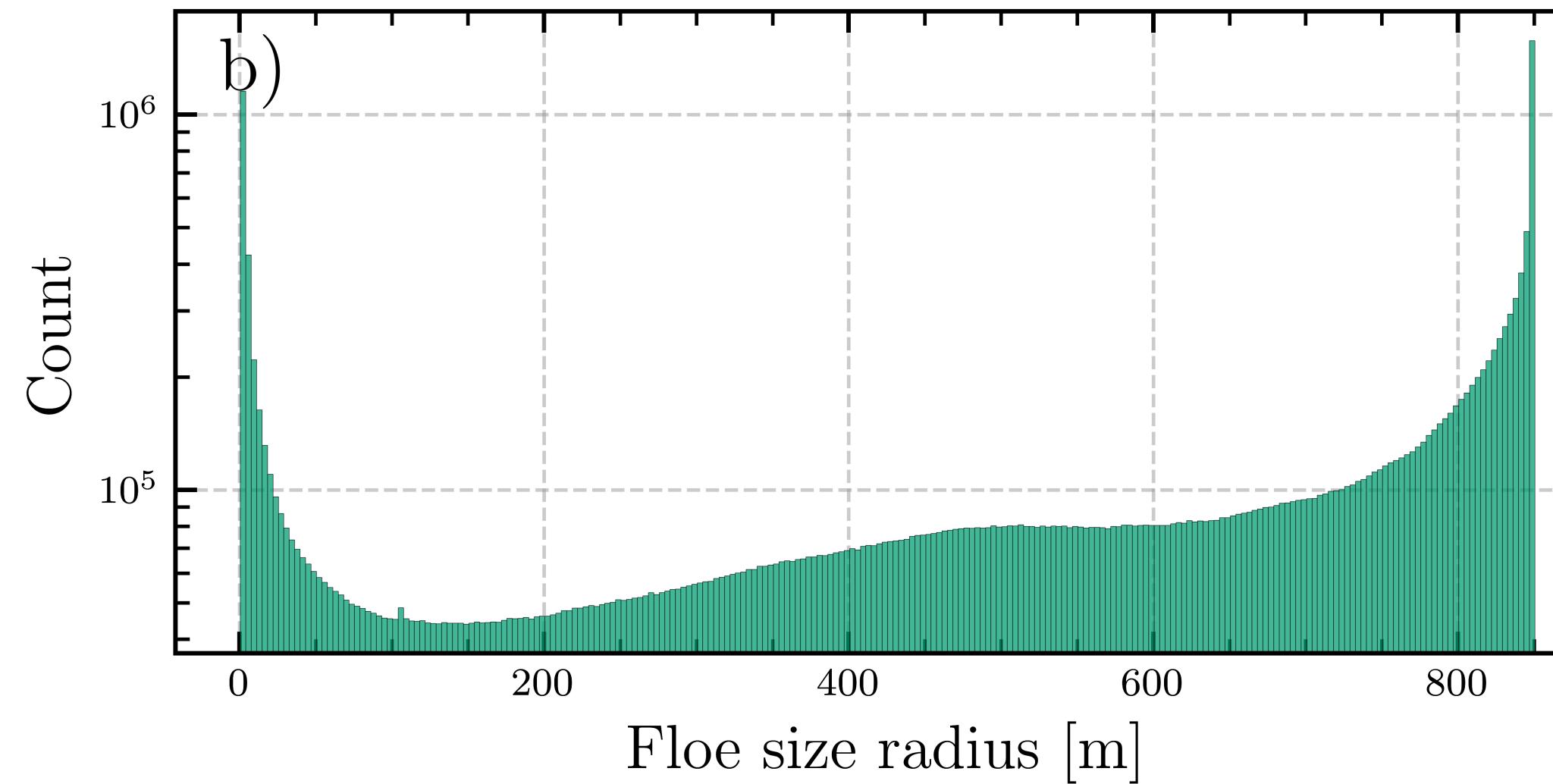
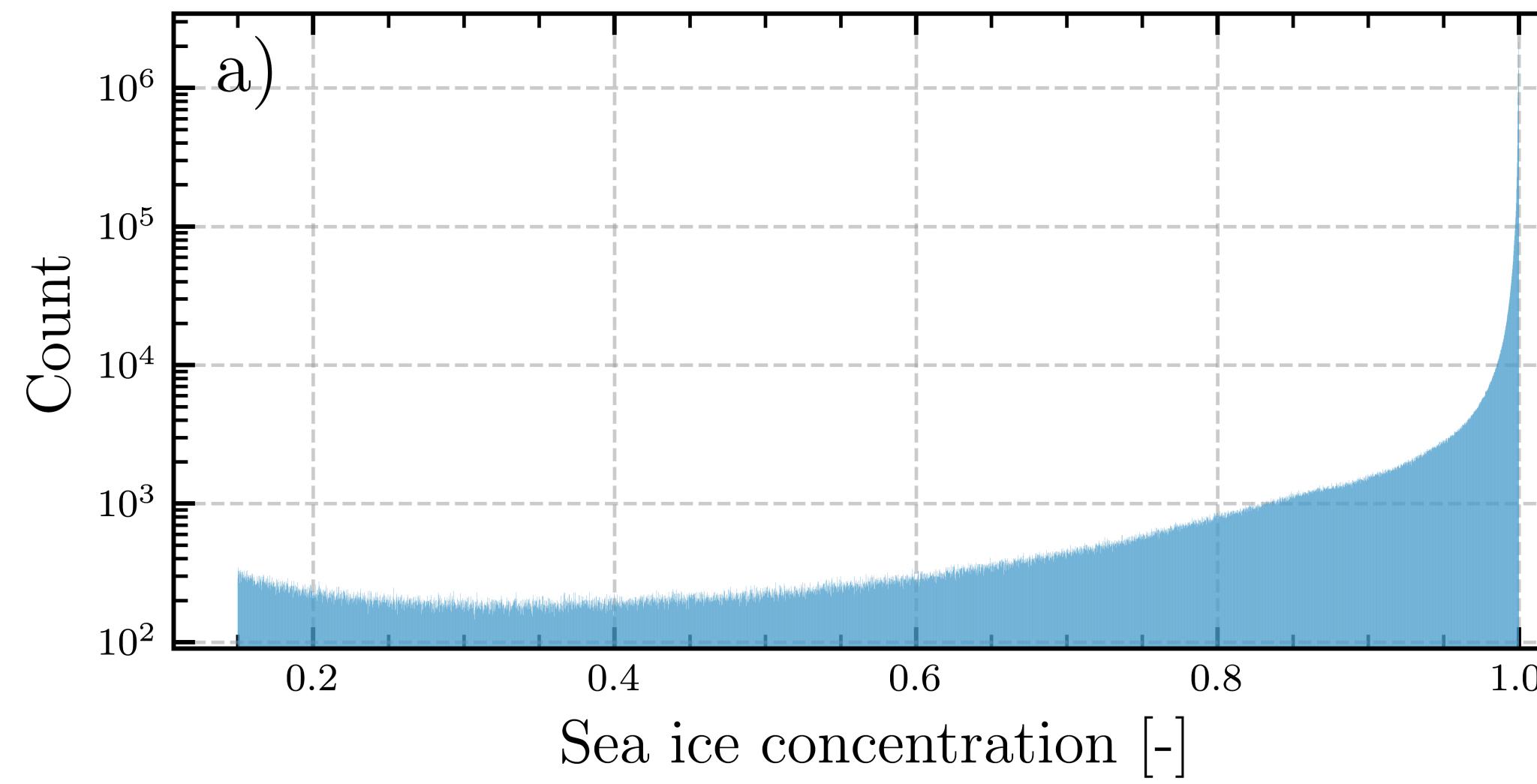
- We analyse standalone CICE6 (a global numerical sea ice model) outputs at 1° horizontal resolution
- CICE6 includes a module that models floe size (FSTD) [8]



Model configuration of standalone CICE6 with a waves-in-ice module (CICE6-WIM).

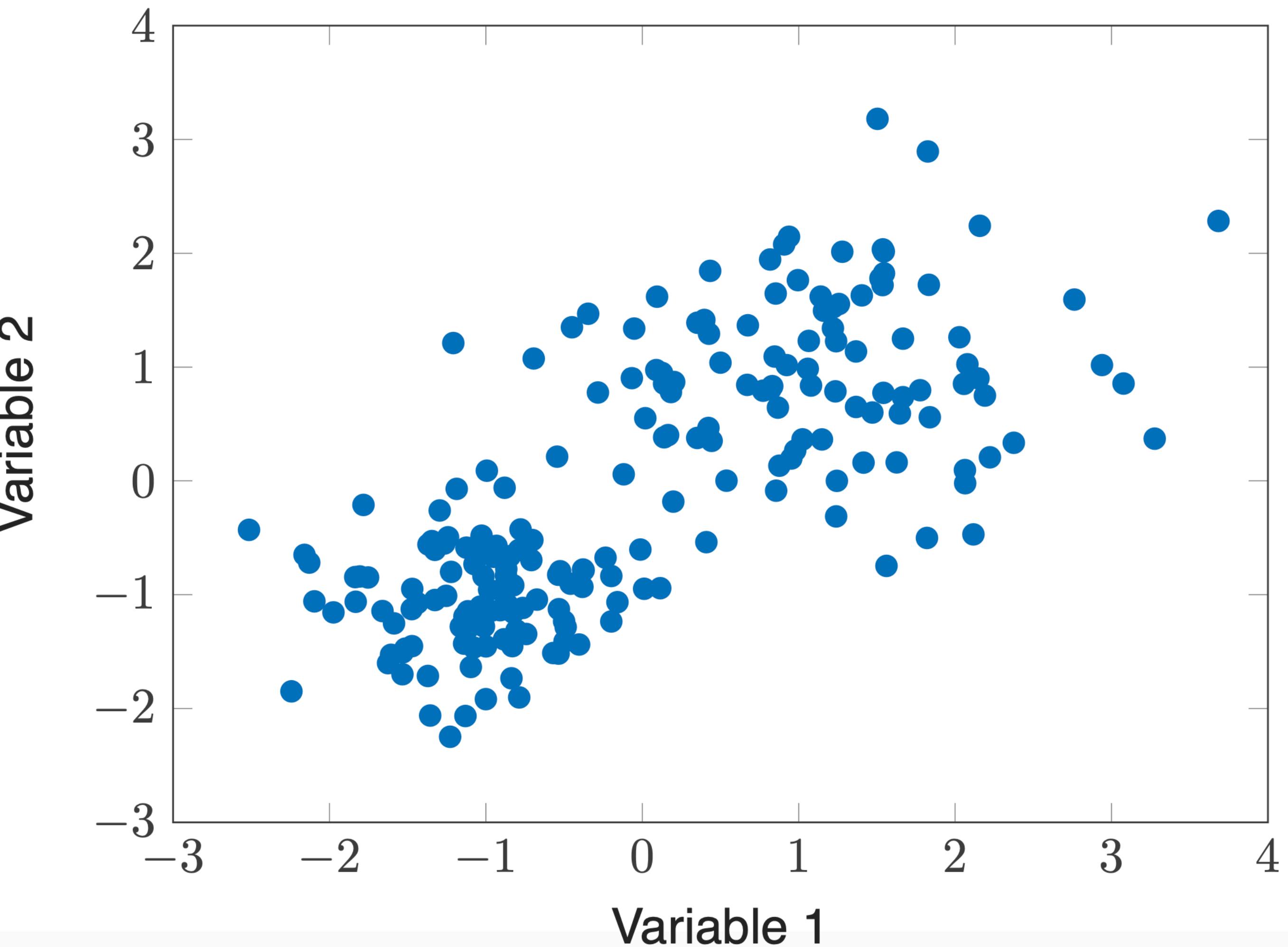
Data overview

Daily model outputs of 5 sea ice properties over 2010–2019

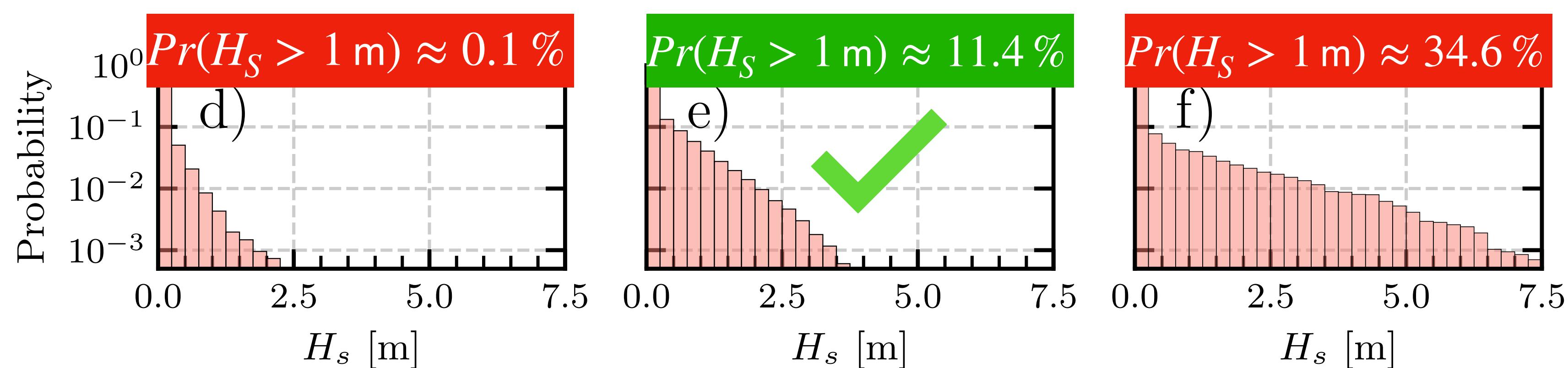
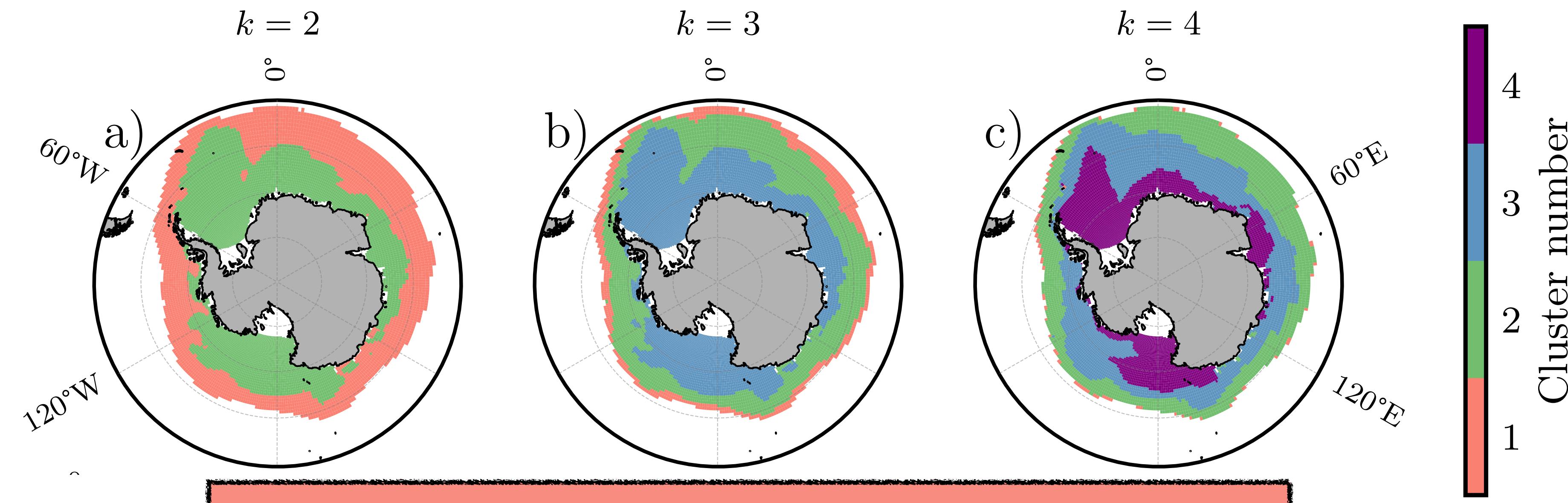


Step 2: Classifying the sea ice data

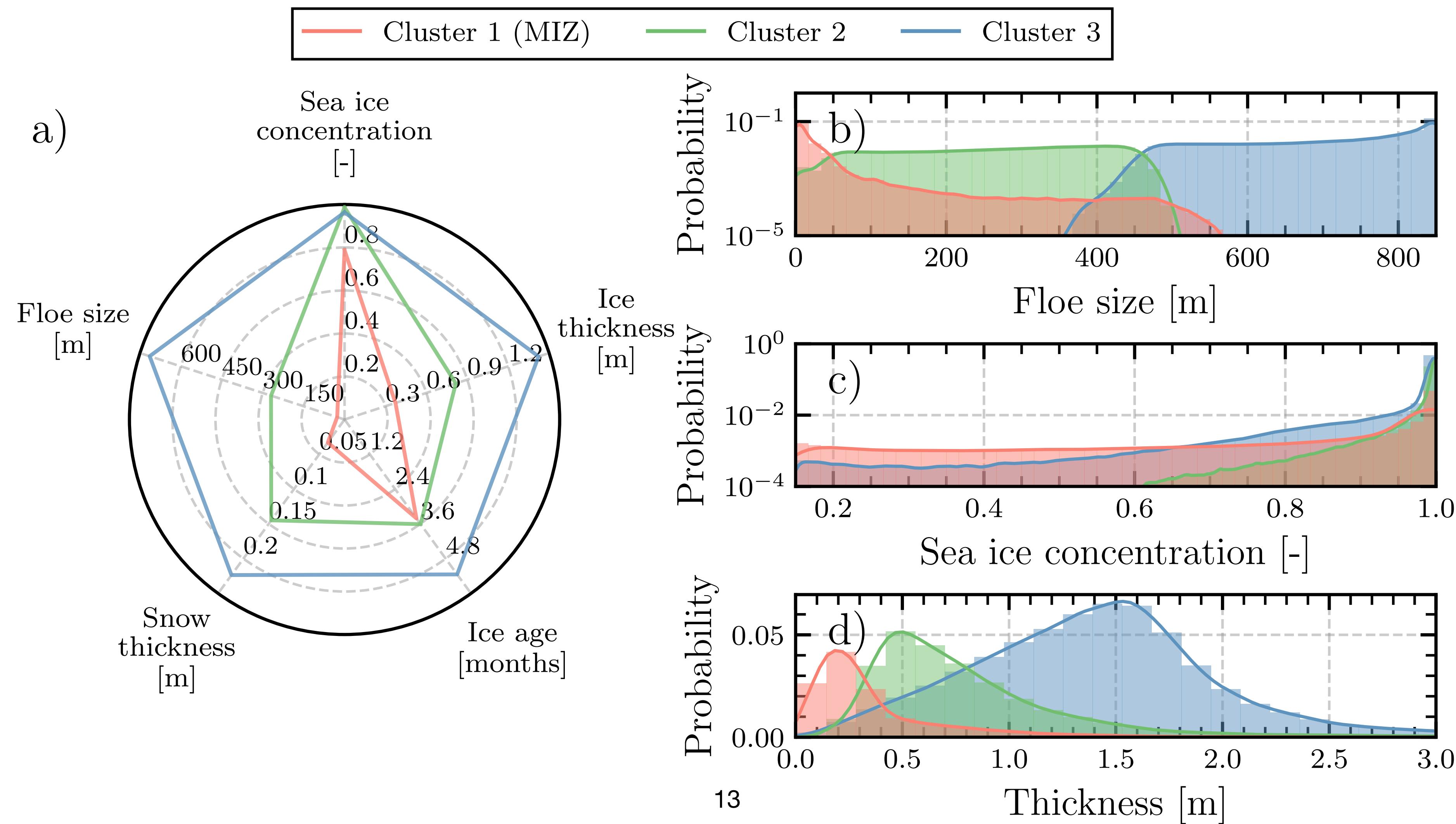
- k -means is an algorithm which clusters similar datapoints into distinct classes
- We cluster on 5 sea ice variables we think are important to differentiate ice regions (SIC, thickness, age, floe size, snow thickness)



How many clusters (k) do we need?



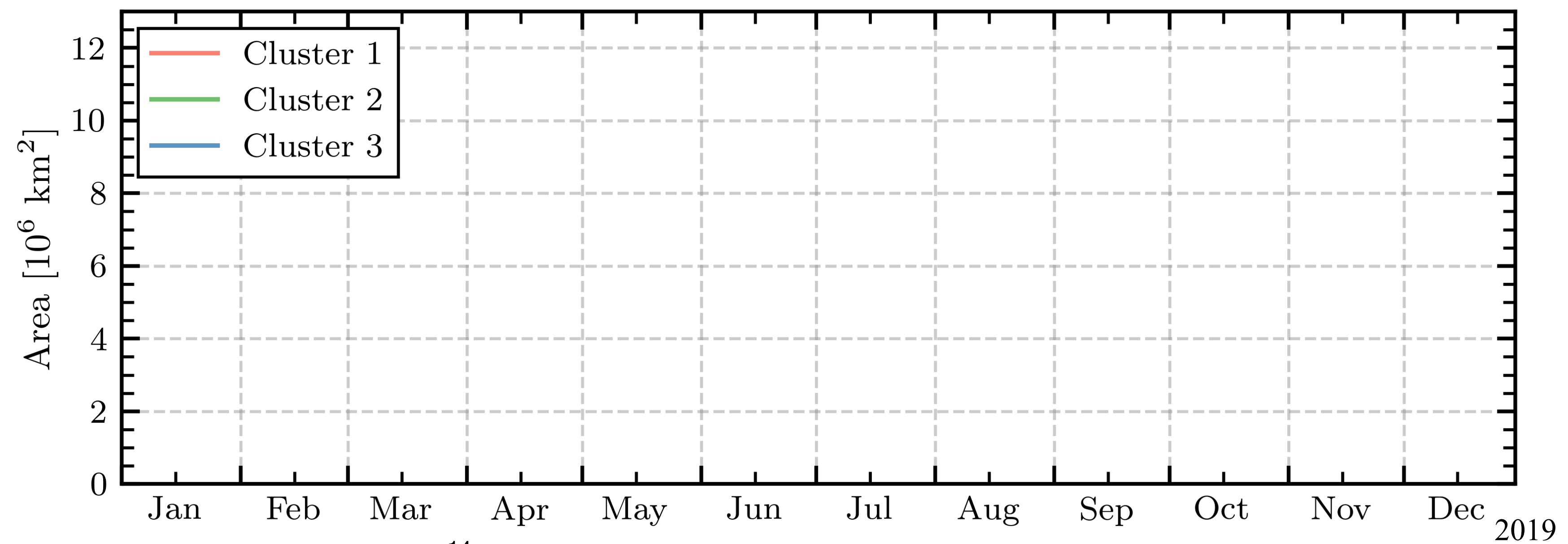
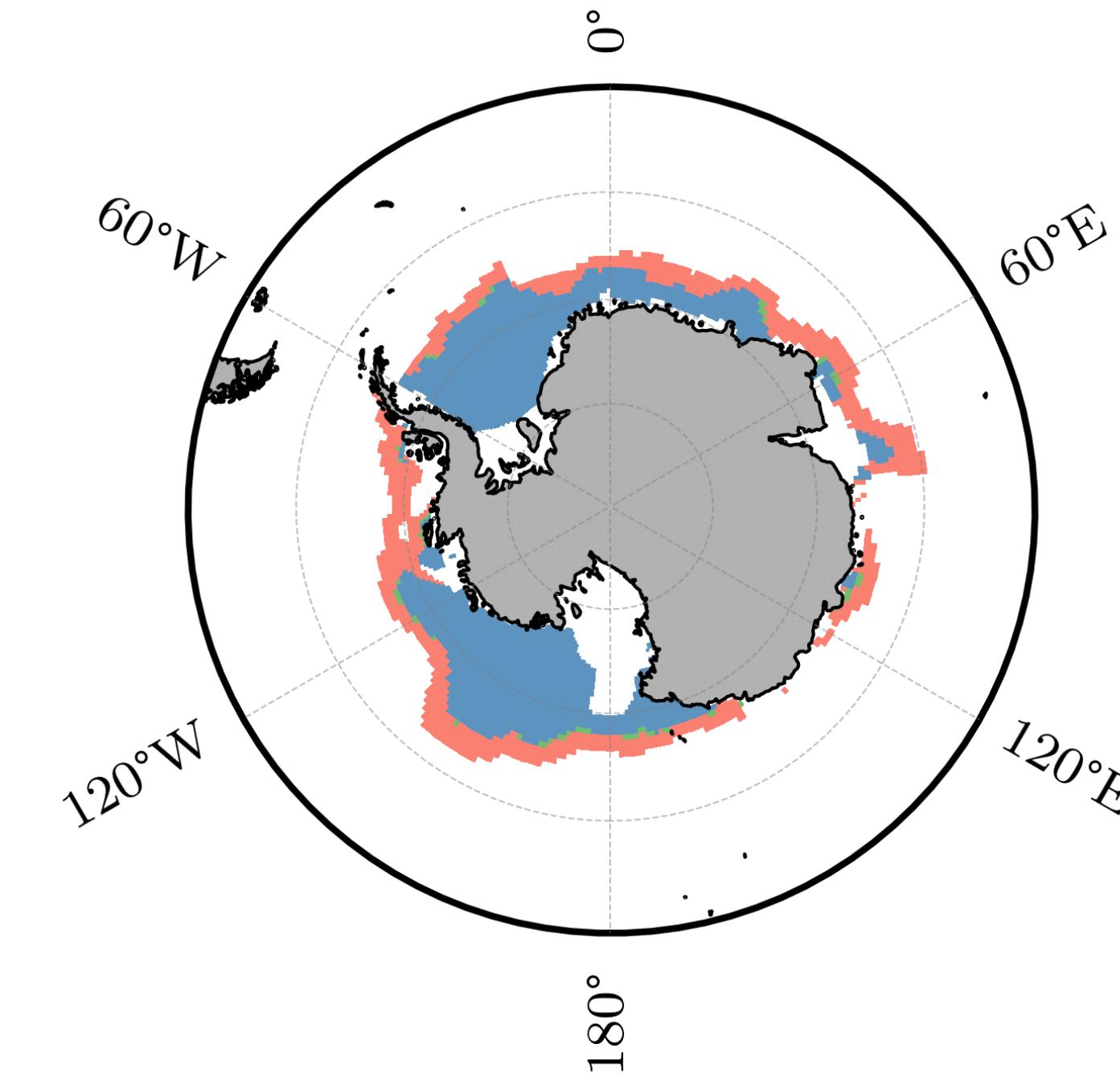
Mean characteristic of the sea ice clusters



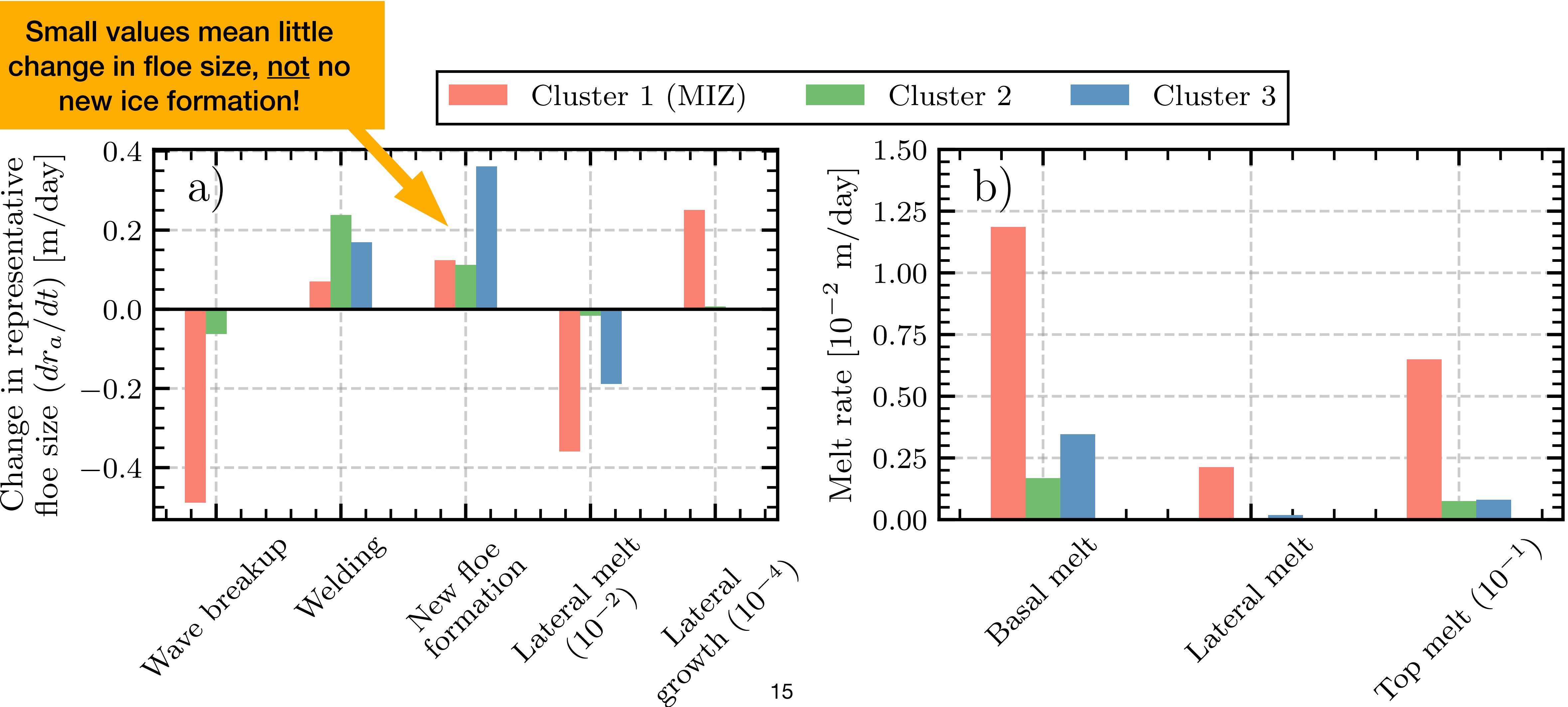
Evolution of the sea ice clusters

- MIZ small, young, thin, unconsolidated floes
- Cluster 2 larger, young, thin consolidated floes
- Cluster 3 largest, oldest, and thickest consolidated floes

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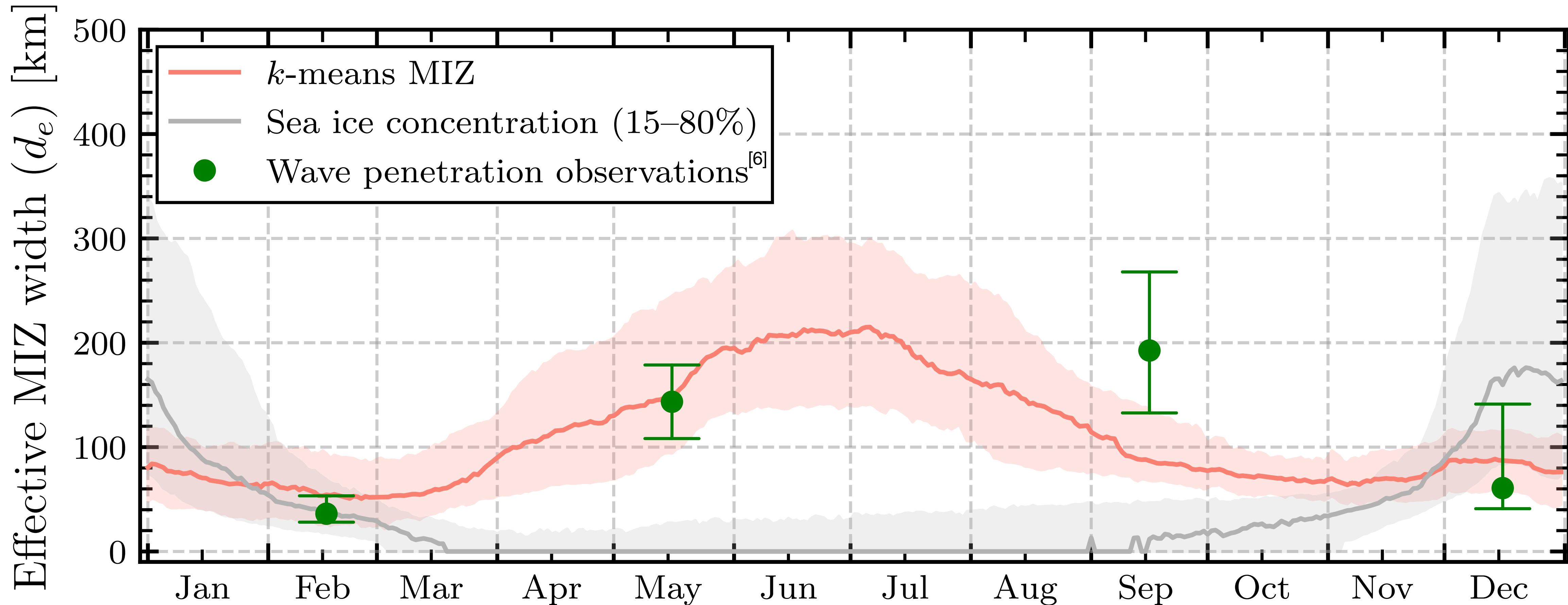


Comparing averaged floe size processes and melt rates



Comparison of MIZ methods

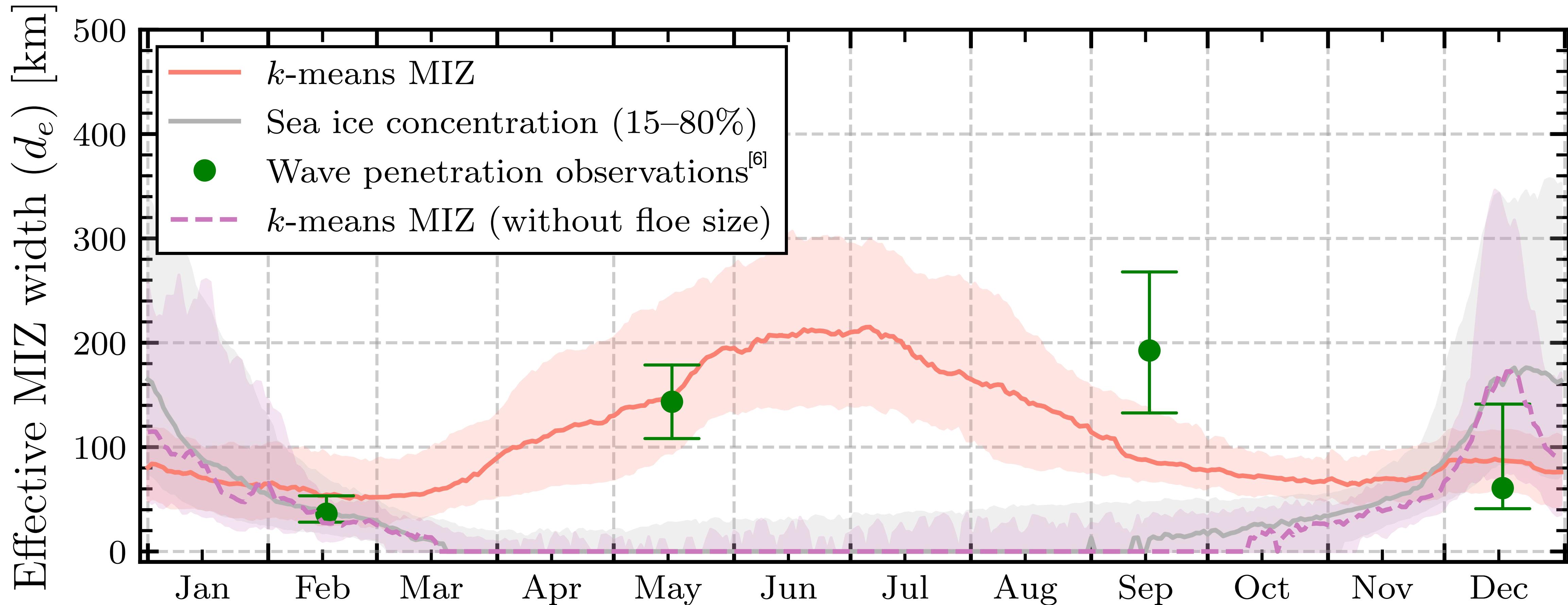
Given $a_i(x)$ is the ice concentration at position x , the effective MIZ width is:

$$d_e = \int_0^d a_i(x)dx .$$


[6] Brouwer et al., *Cryosphere*, 2022

Comparison of MIZ methods

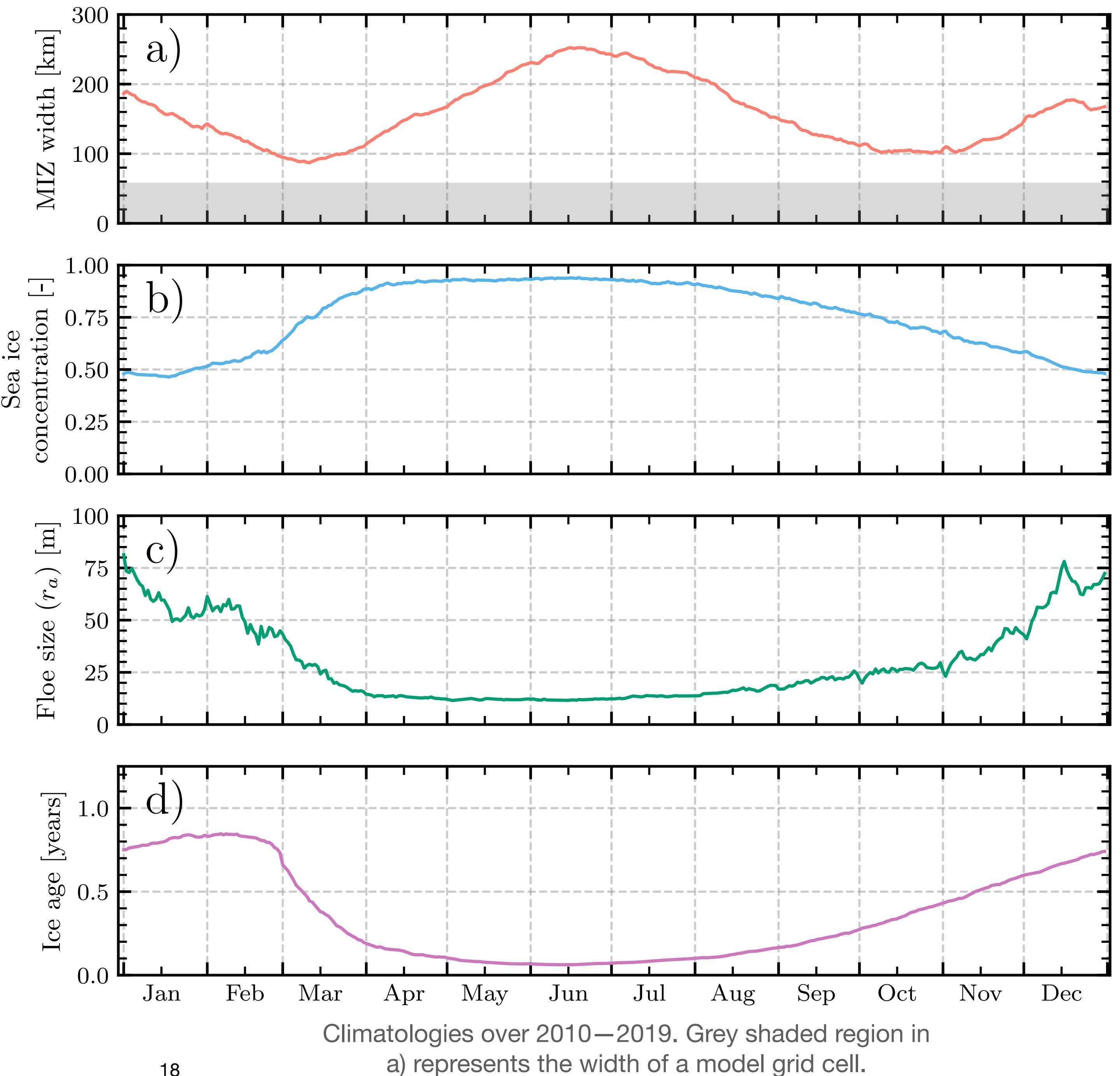
Given $a_i(x)$ is the ice concentration at position x , the effective MIZ width is:

$$d_e = \int_0^d a_i(x)dx .$$


Seasonality of the MIZ properties

❄️ Winter MIZ: high concentrations of small, young floes

☀️ Summer MIZ: low concentrations of larger, older floes

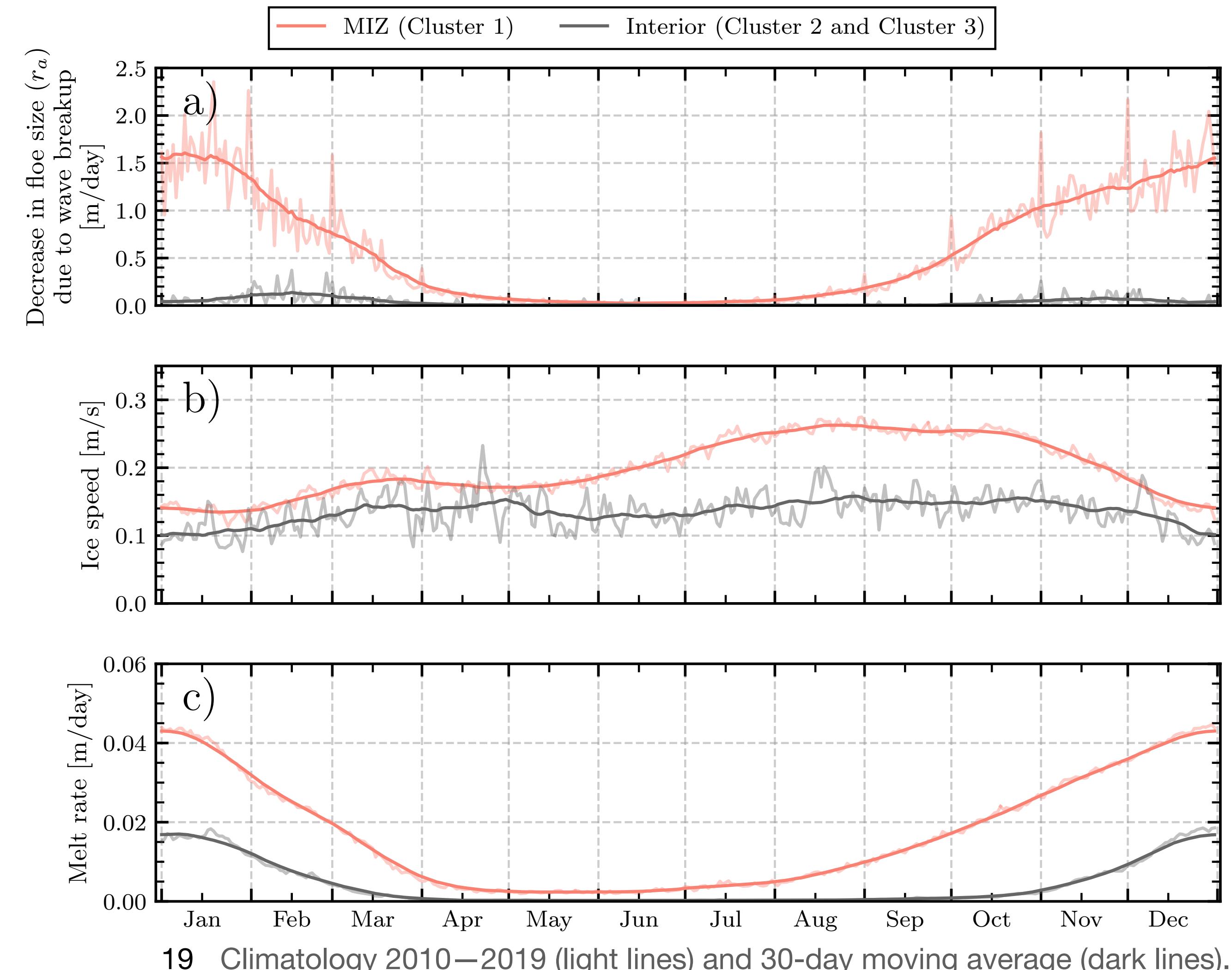


Seasonality of the MIZ processes

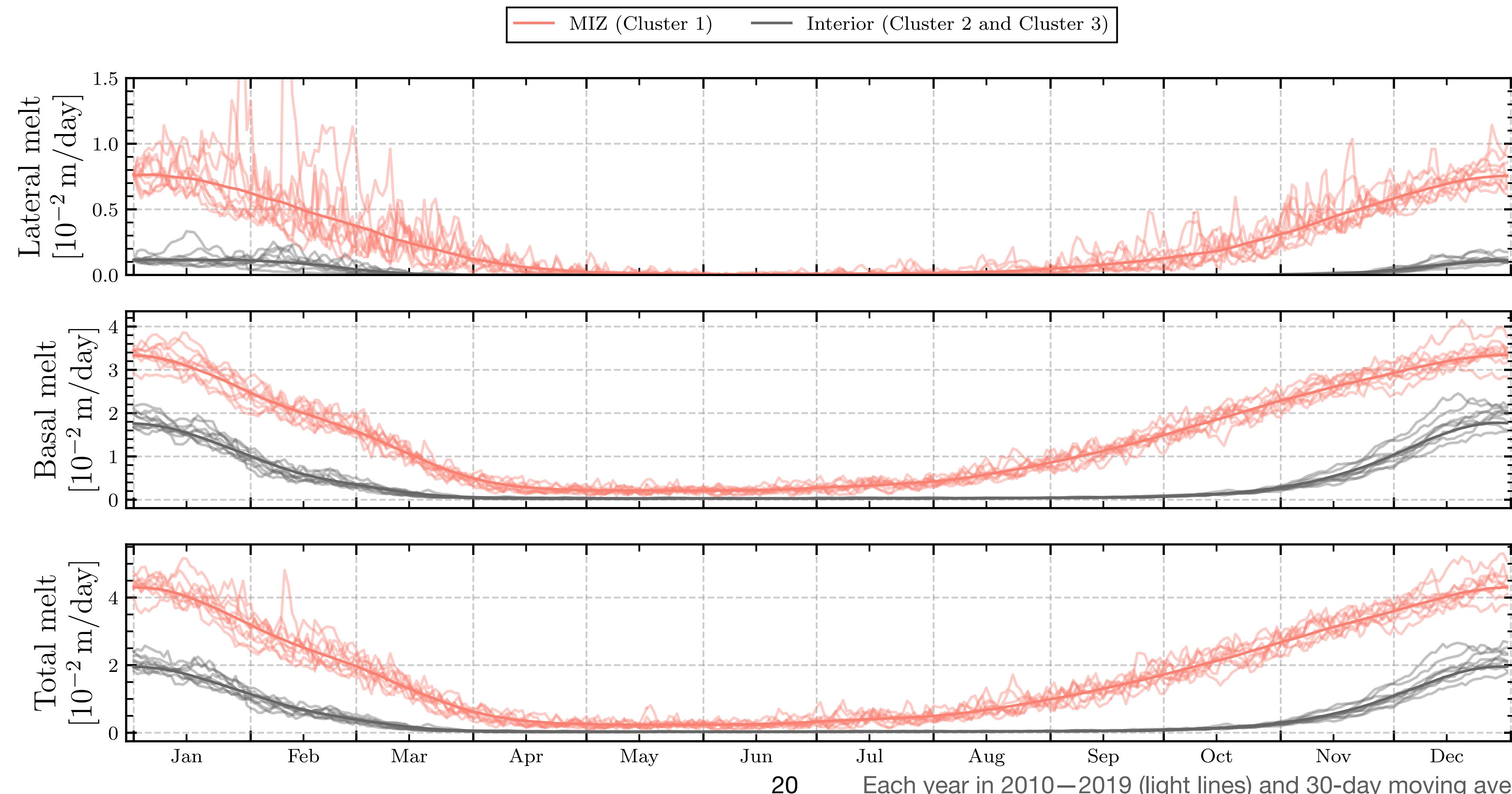
❄️ Winter MIZ: decreased wave-induced breakup

🌱 Spring MIZ: increased drift

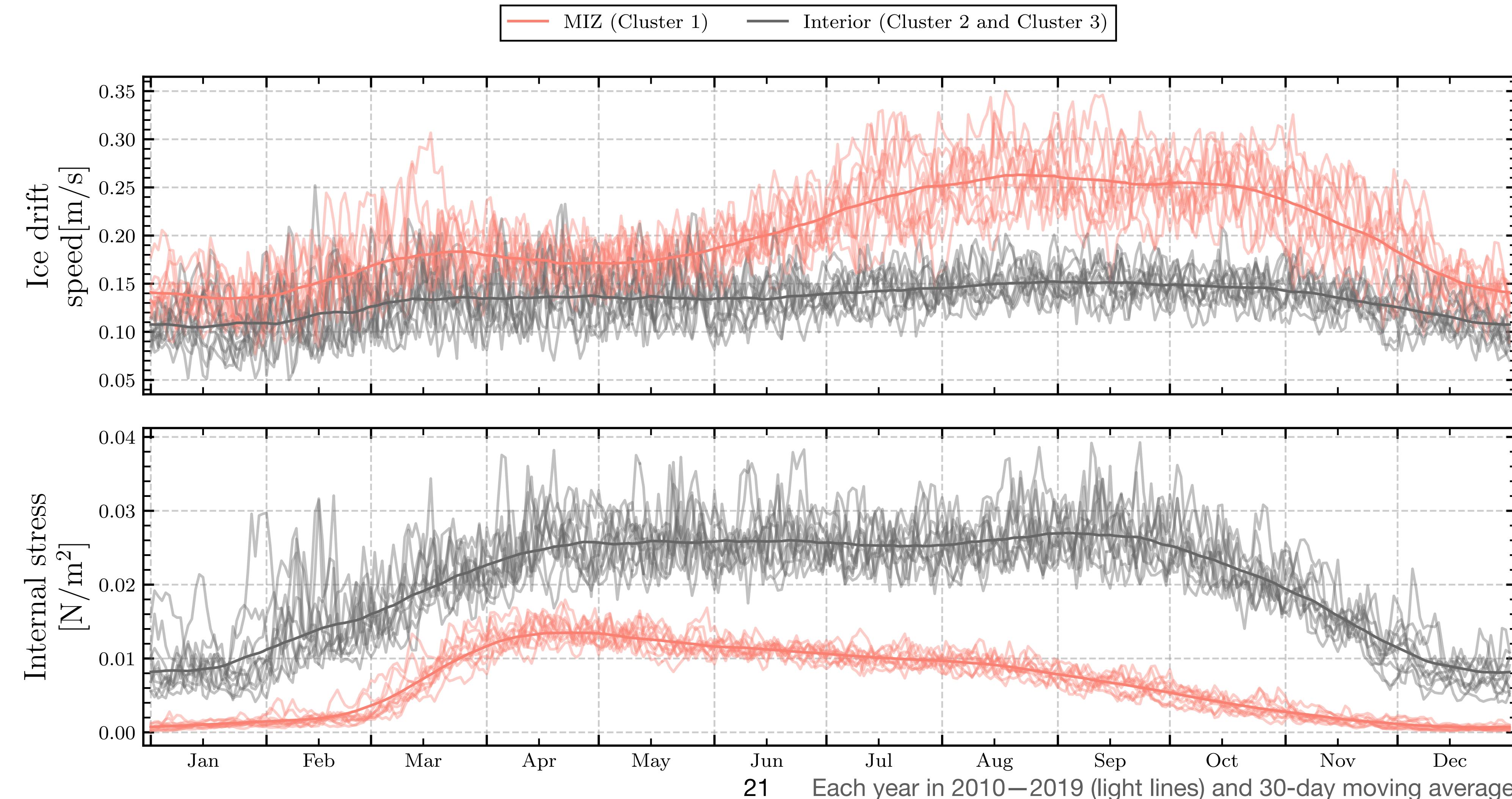
☀️ Summer MIZ: increased wave breakup and melt rates



Seasonality of thermodynamics

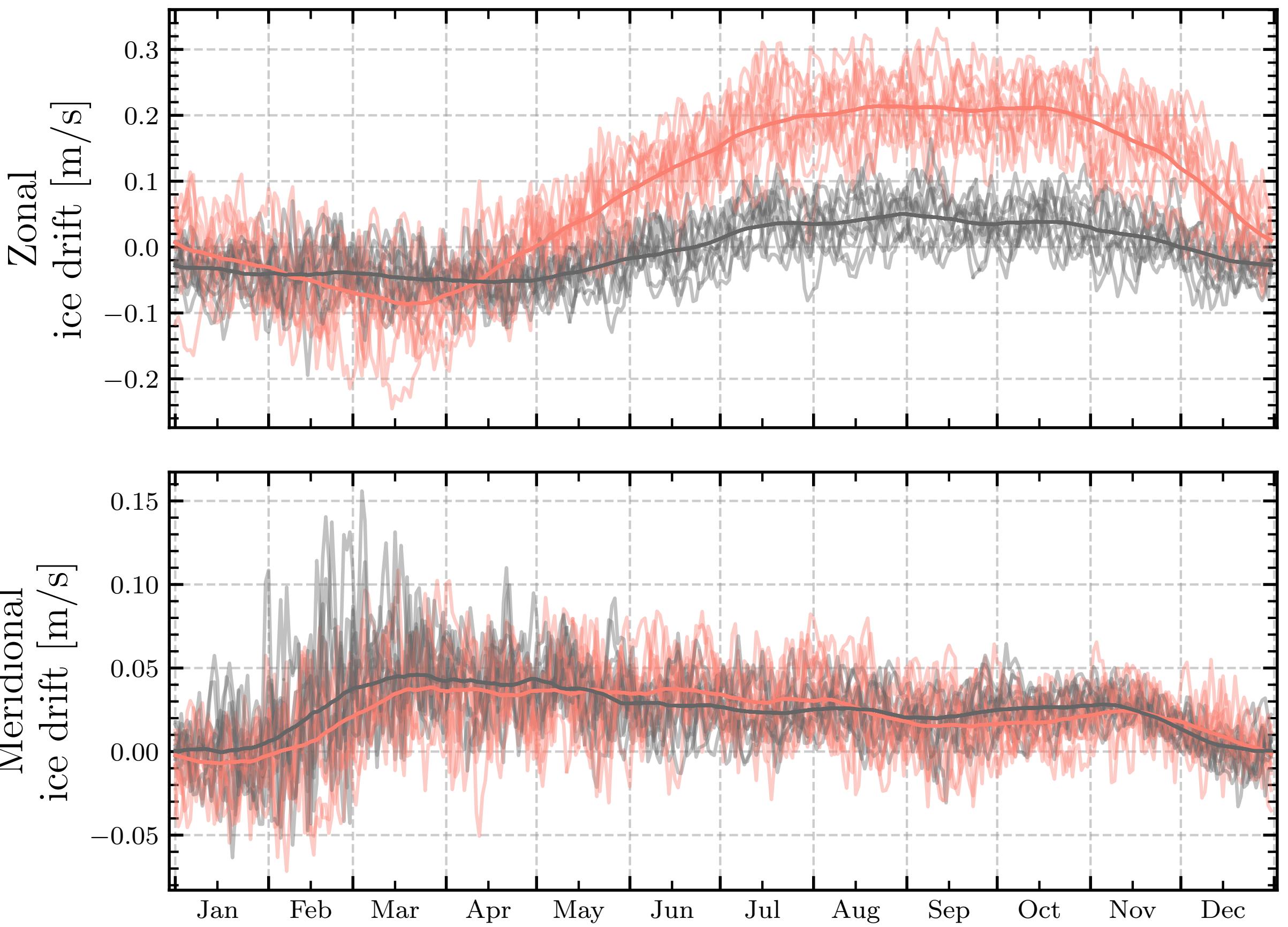


Seasonality of dynamics

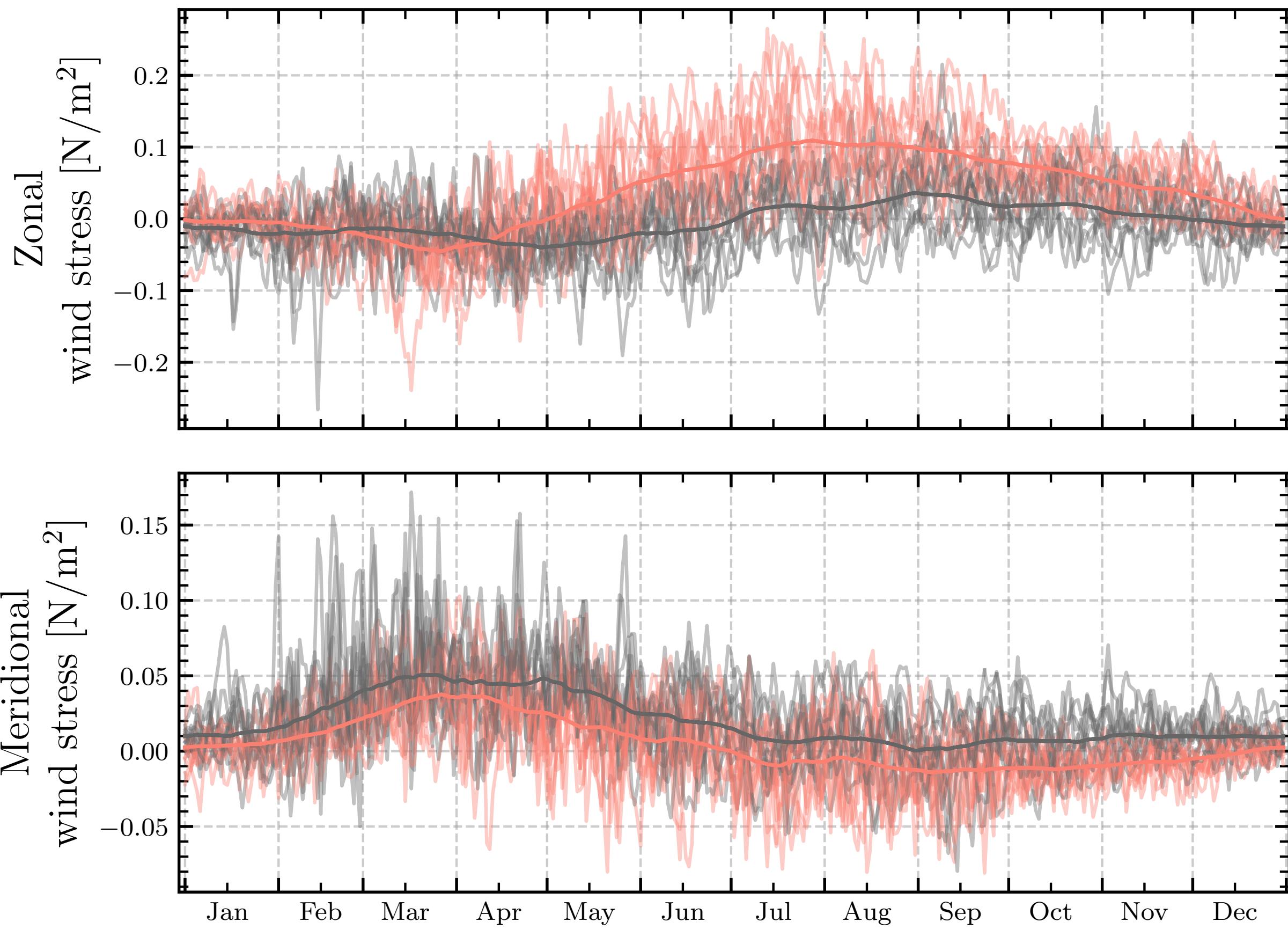


Seasonality of dynamics

Ice drift components



Wind stress components



Summary of study

- An unsupervised algorithm (*k*-means) has quantified the Antarctic wave affected marginal ice zone from simulated sea ice data
- The derived MIZ width agreed with satellite derived waves-in-ice measurements
- The winter MIZ is composed of new pancake floes in high concentrations, the summer MIZ contains larger-broken floes in lower concentrations
- The MIZ undergoes seasonally-dependent physical processes:
 - ❄️ Winter: Pancake ice formation
 - 🌿 Spring: Increased drift
 - ☀️ Summer: Increased wave breakup and melt rates

Check out the pre-print!

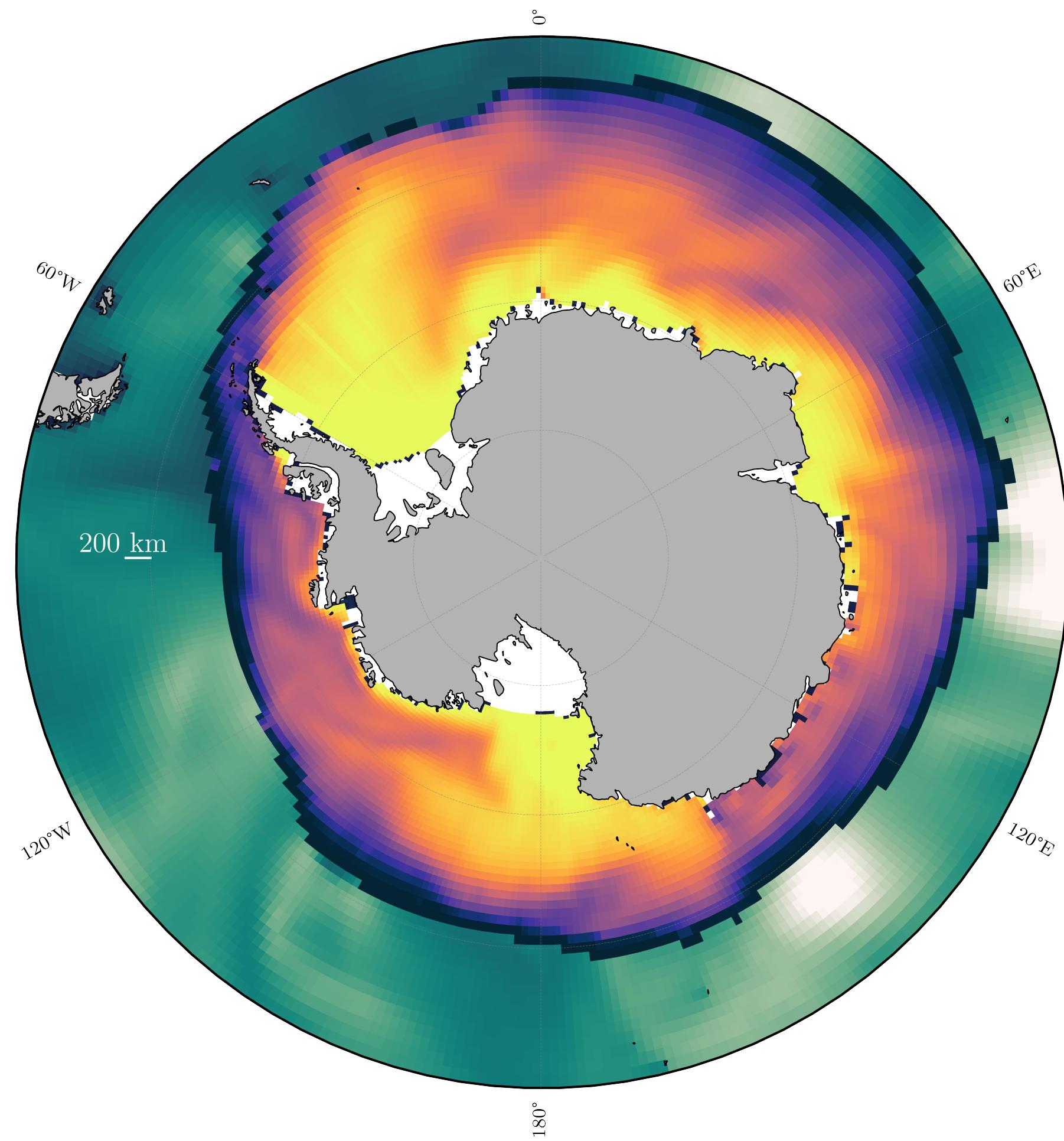


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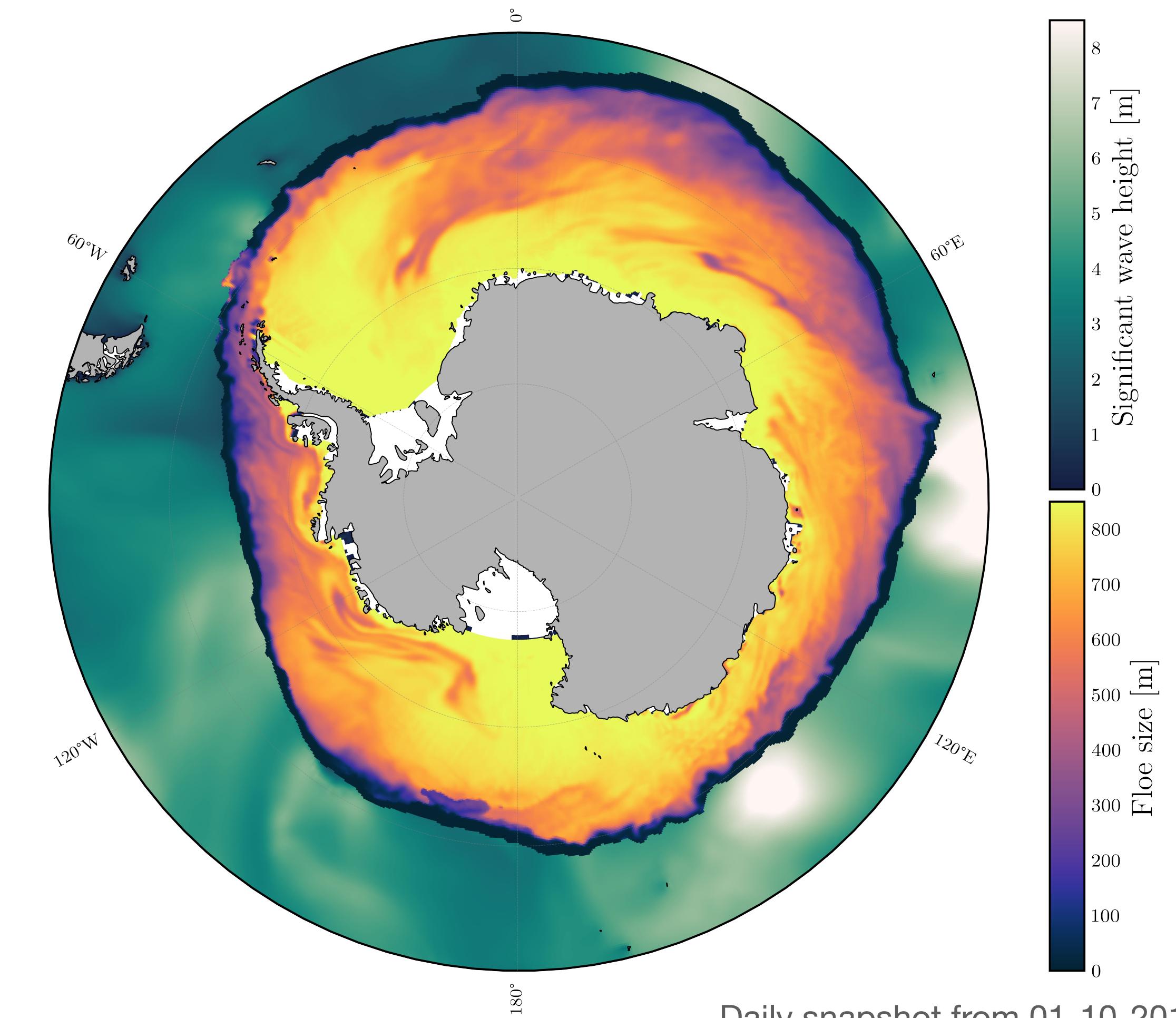
Future work

Higher resolution CICE6-WIM simulations

1° resolution

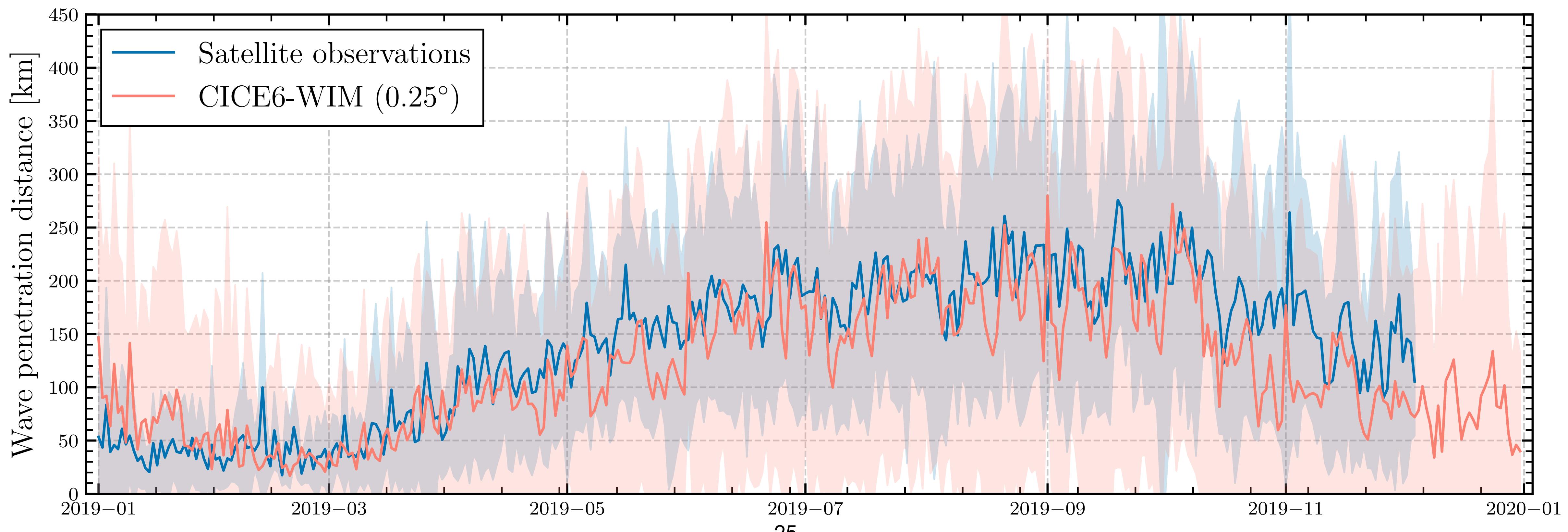


0.25° resolution



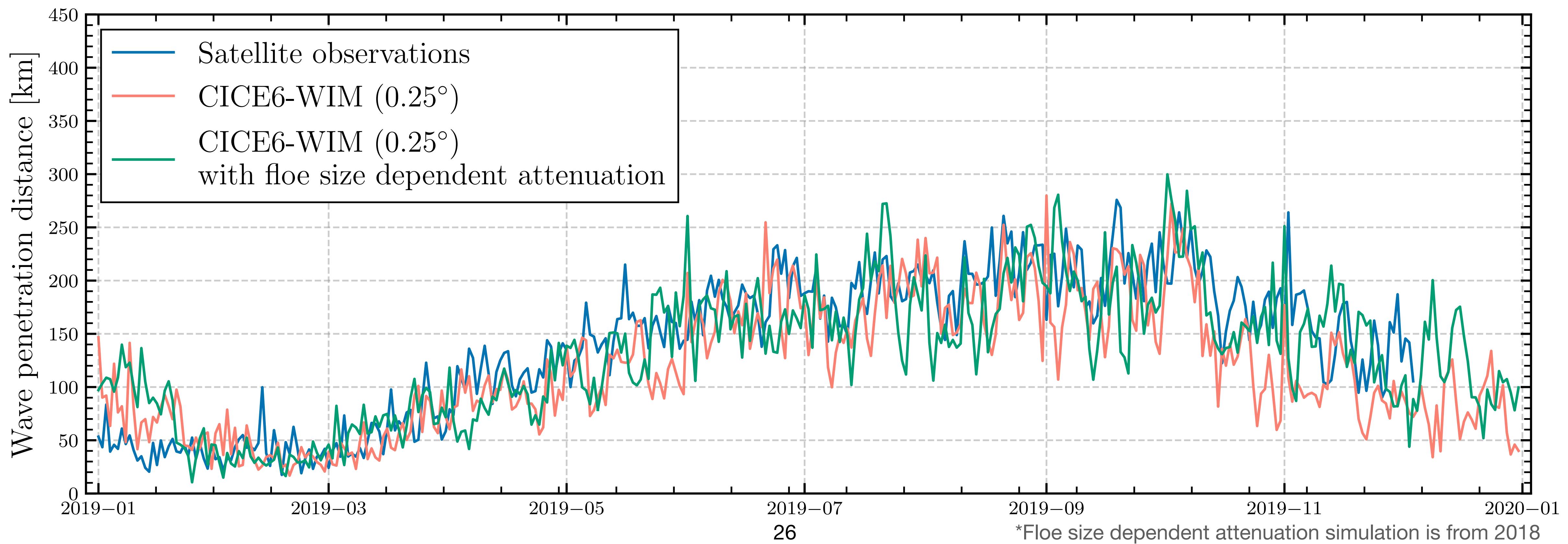
A more thorough comparison with observations

- Alex Fraser et al. have now gathered many more observations of MIZ width estimates (i.e., wave penetration distances) than Brouwer et al. (2022)



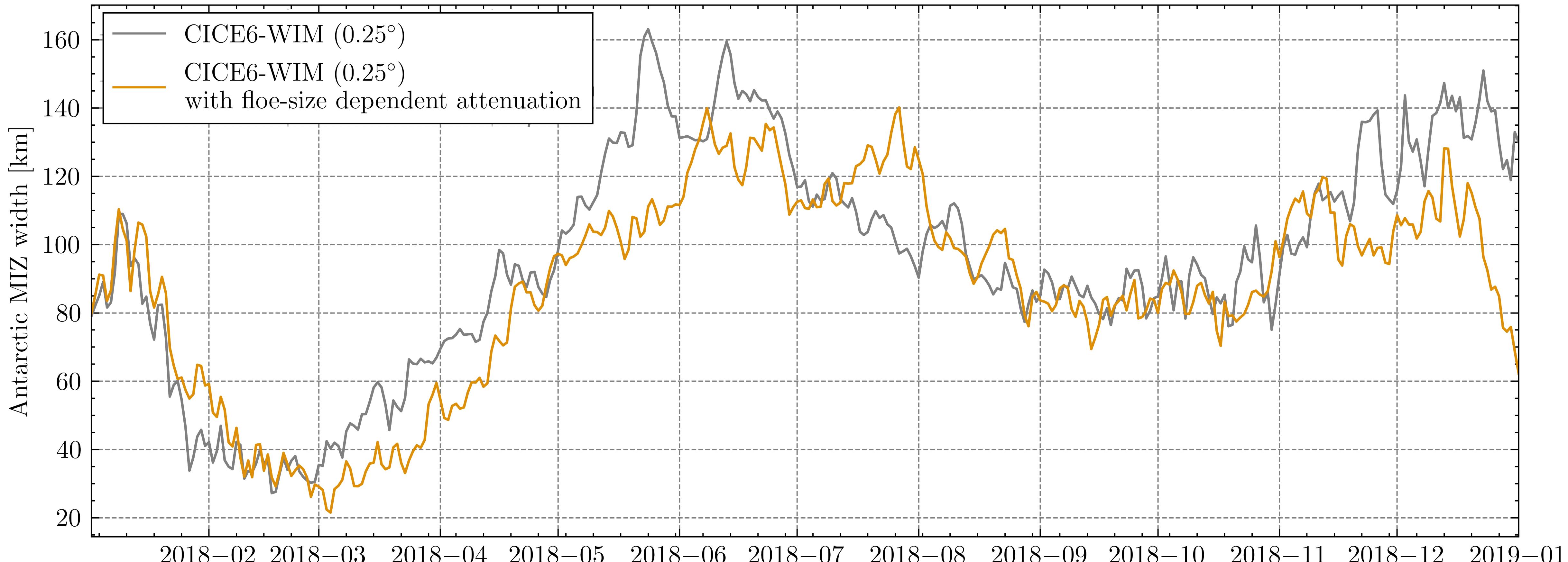
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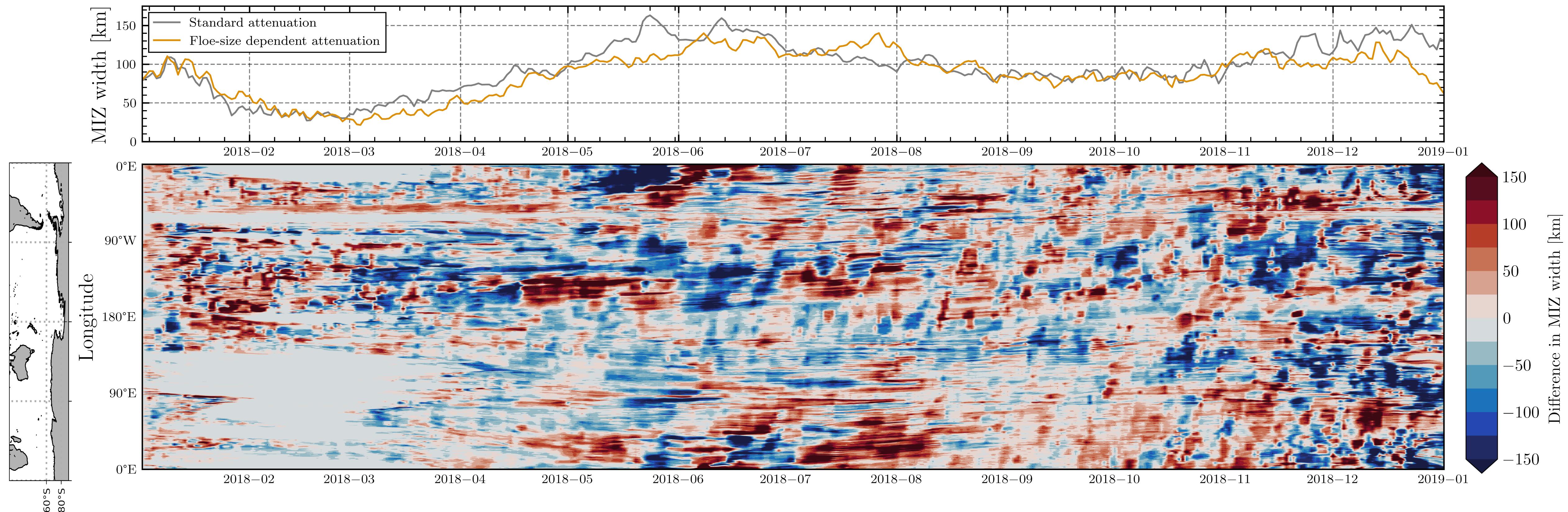
Effect of floe-size dependent attenuation on MIZ widths

- Using a simple floe-size based definition for the MIZ (radius < 20 m)



Effect of floe size dependent attenuation on MIZ widths

- Using a simple floe-size based definition for the MIZ (radius < 20 m)



Our current understanding

- Simple wave-ice attenuation models are producing realistic estimates of circumpolar MIZ width/wave penetration
- However, predicting the width of the MIZ at a particular instance in time or space is still an outstanding problem
- We're looking into what is driving the differences in the MIZ (e.g., the role of polar storms and cyclones) to improve our understanding of the physical processes that create this variability

Thank you!

Contact me at:

noah.day@adelaide.edu.au

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