Detecting Changes in Antarctic Sea Ice Minima

Alexandre Tytgat, François Massonnet, Anna Kirilliouk

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UCLouvain
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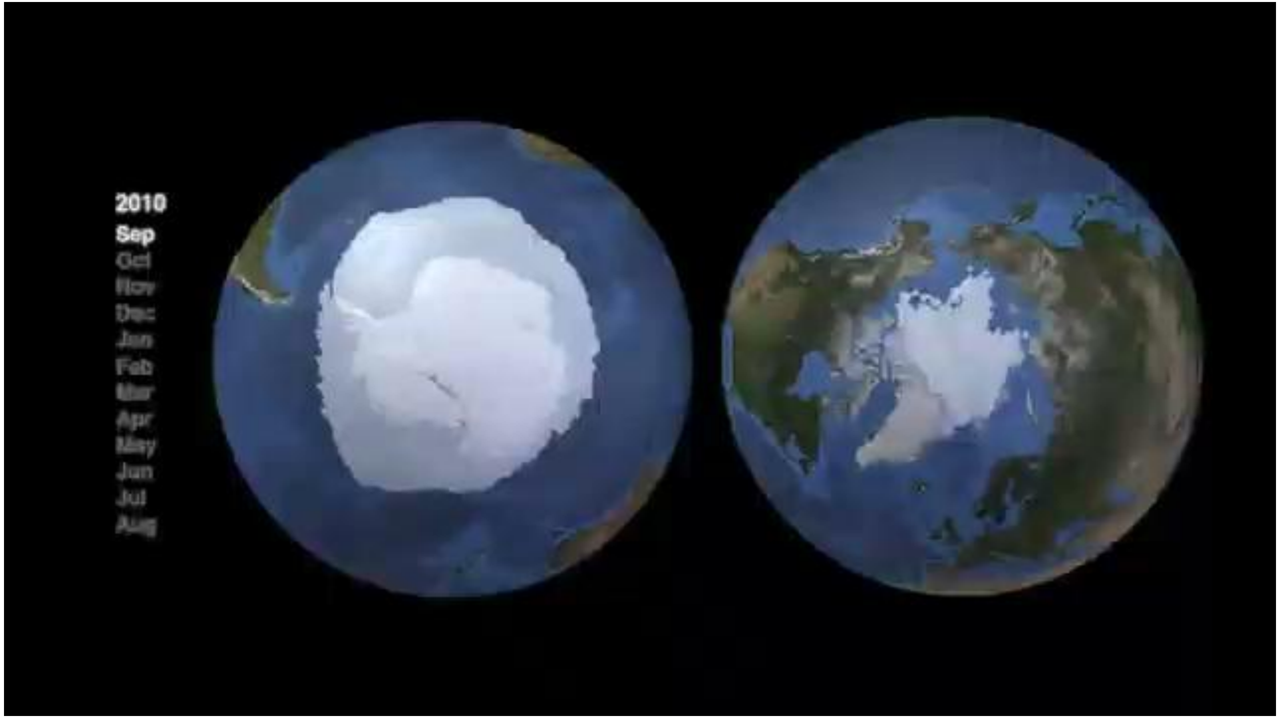
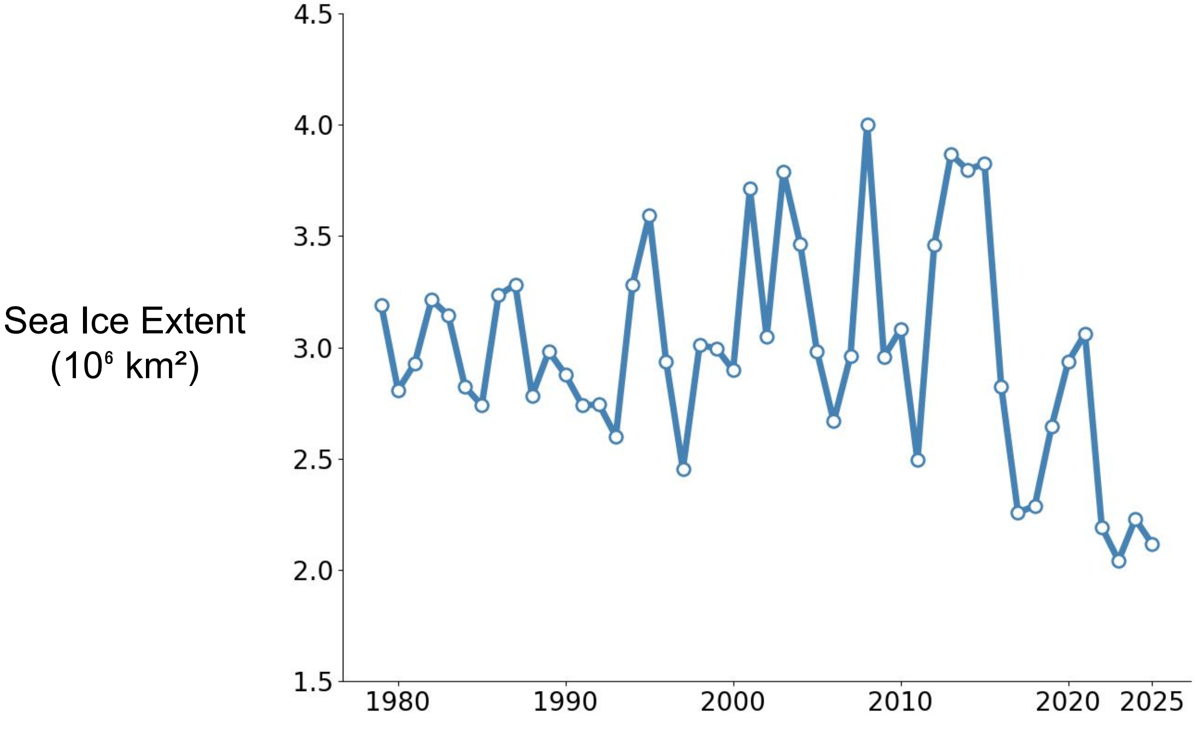
What is sea ice?



NASA/Goddard Space Flight Center Scientific Visualization Studio

Since 2016, Antarctic sea ice has been unusually low



EUMESTAT OSI SAF Global Sea-Ice Concentration CDR

Has the Antarctic sea ice system suddenly changed ?

A twenty-first century structural change in Antarctica's sea ice system

Check for updates

Marilyn N. Raphael[1,2], Thomas J. Maierhofer[3,6], Ryan L. Fogt[4,6], William R. Hobbs[5,6] & Mark S. Handcock[3,6]

Investigating a potential new Antarctic sea ice state during 2021–2023 using an atmosphere-based reconstruction

Nico C. Sartori[1] · Ryan L. Fogt[1]

ARTICLE

Check for updates

https://doi.org/10.1038/s43247-023-00961-9 OPEN

Record low Antarctic sea ice coverage indicates a new sea ice state

Ariaan Purich[1] & Edward W. Doddridge[2]

Review

Emerging evidence of abrupt changes in the Antarctic environment

https://doi.org/10.1038/s41586-025-09349-5
Received: 19 December 2024
Accepted: 1 July 2025
Published online: 20 August 2025
Check for updates

Nerilie J. Abram[1,2,3], Ariaan Purich[4,5], Matthew H. England[6,7], Felicity S. McCormack[4,5], Jan M. Strugnell[8,9], Dana M. Bergstrom[10,11], Tessa R. Vance[12,13,14], Tobias Stål[15,16], Barbara Wienecke[14], Petra Heil[12,14,17], Edward W. Doddridge[12,13], Jean-Baptiste Sallée[18], Thomas J. Williams[13,15], Anya M. Reading[15,16], Andrew Mackintosh[4,5], Ronja Reese[19], Ricarda Winkelmann[20,21,22], Ann Kristin Klose[21,22], Philip W. Boyd[12,13,15], Steven L. Chown[4] & Sharon A. Robinson[10,23]

Antarctic sea ice regime shift associated with decreasing zonal symmetry in the Southern Annular Mode

Serena Schroeter[1], Terence J. O'Kane[1,2], and Paul A. Sandery[1]
[1]Earth Systems, CSIRO Environment, Hobart, Tasmania, Australia
[2]Australian Centre for Excellence in Antarctic Science, Hobart, Tasmania, Australia

Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice

Will Hobbs,[a,b] Paul Spence,[a,c,d,e] Amelie Meyer,[b,d] Serena Schroeter,[f] Alexander D. Fraser,[a] Philip Reid,[a,g] Tian R. Tian,[a,d] Zhaohui Wang,[d,f] Guillaume Liniger,[b,d,h] Edward W. Doddridge,[a] and Philip W. Boyd[a,c]

Has the Antarctic sea ice system suddenly changed ?

Structural change: statistical change in a stochastic process, including changes in mean state, variability or persistence (Raphael et al., 2025).

+ changes in the tail of the distribution

Questions

1. How unusual are the recent records?
2. Is the recent sea ice decline spatially uniform, or does it reflect heterogeneous regional behavior?

1. Introduction
2. Modeling Minima
3. Probabilities of the records
4. Partitioning the Southern Ocean
5. Regional Changes
6. Conclusions

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Modeling block minima

Generalized Extreme-value Distribution (GEV) for minima:

$$G(x) = \begin{cases} 1 - \exp\left\{ -\left[1 - \xi\left(x - \mu\right)/\sigma\right]_+^{-1/\xi} \right\}, & \xi \neq 0, \\ 1 - \exp\left\{ -\exp\left(x - \mu\right)/\sigma \right\}, & \xi = 0, \end{cases}$$

The GEV has three parameters:

Modeling block minima

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The GEV has three parameters:

- μ the location parameter → controls the center
- σ the scale parameter → controls the spread
- ξ the shape parameter → controls the tail and define the support

We consider 5 GEV models

(1) Stationary

$$\mu = \mu_0$$
$$\sigma = \sigma_0$$

(2) Linear location

$$\mu = \mu_0 + \mu_1 t$$
$$\sigma = \sigma_0$$

(3) Linear location & log-scale

$$\mu = \mu_0 + \mu_1 t$$
$$\log(\sigma) = \sigma_0 + \sigma_1 t$$

+2 breakpoint models :

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(1) Stationary

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+2 breakpoint models :

(4) Piecewise linear location

$$\mu = \mu_0 + \mu_1 t + \mu_2 (t - \delta) \mathbf{1}_{\{t \geq \delta\}}$$
$$\sigma = \sigma_0$$

(5) Piecewise linear location & linear log-scale

$$\mu = \mu_0 + \mu_1 t + \mu_2 (t - \delta) \mathbf{1}_{\{t \geq \delta\}}$$
$$\log(\sigma) = \sigma_0 + \sigma_1 t$$

Breakpoint estimated via profile likelihood

Selecting the best model

Bayesian Information Criterion

Likelihood

#parameters

#observations

$$\mathrm{BIC} = \underbrace{-2\ln(\hat{L})}_{\text{Quality of the fit}} + \underbrace{k\ln(n)}_{\text{Complexity}}$$

1. Pick model with the lowest BIC
2. If |ΔBIC|<5 between the best-fitting model and its nested model, perform a likelihood-ratio test at the 5% significance level.

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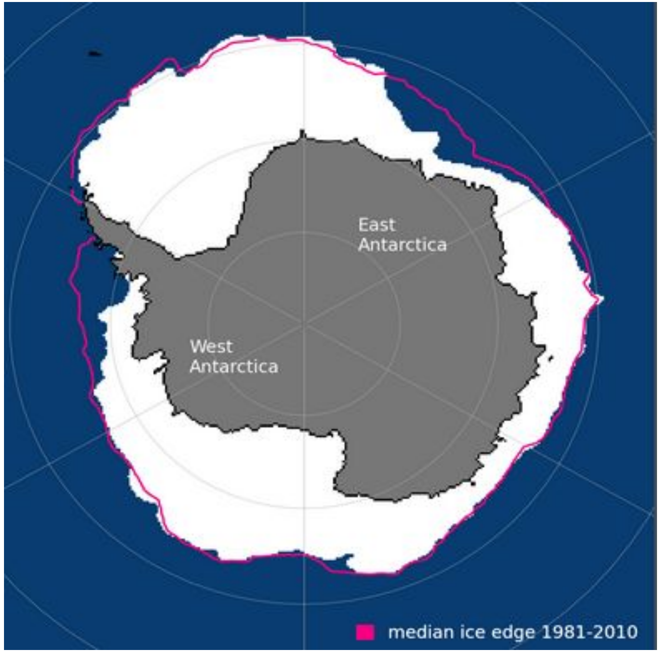
Sea Ice Data

Ocean and Sea Ice Satellite Application Facility (OSI-SAF) data :

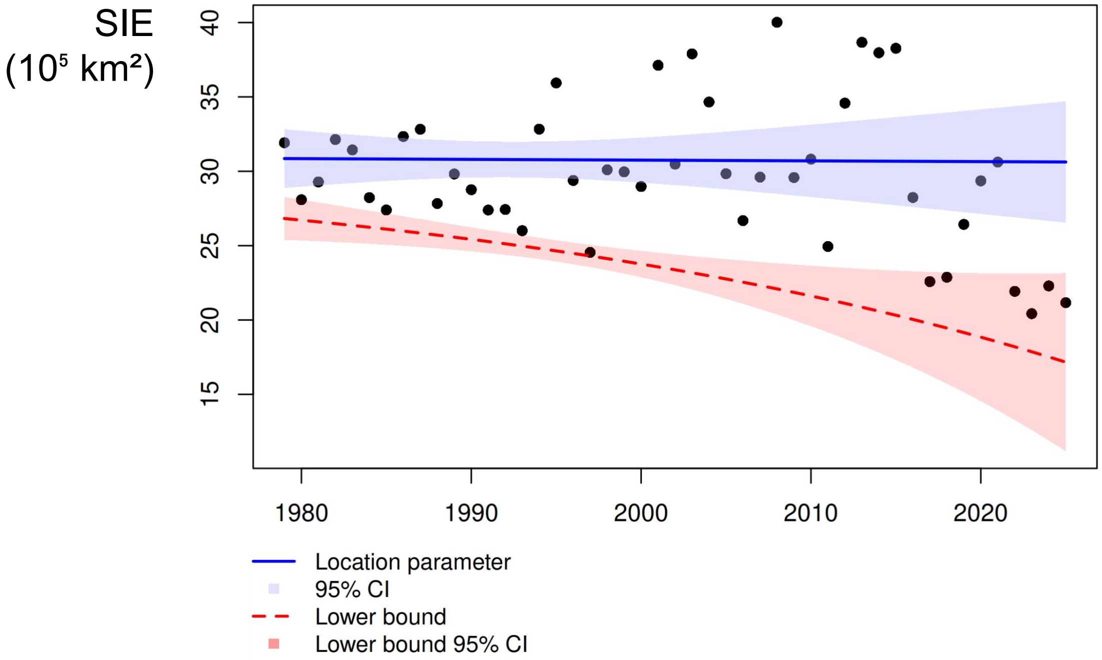
- Grid of 25km spatial resolution
- Sea Ice Concentration (SIC) = % of a cell covered by sea ice
- Period: 1979 - 2025 (daily observations)

Sea Ice Extent (SIE): total area of at least 15% Sea Ice Concentration

$$\mathrm{SIE(cell)} = \begin{cases} 25^2, & \text{if } \mathrm{SIC(cell)} \geq 15\% \\ 0, & \text{otherwise} \end{cases}$$



No abrupt change detected, but the variance of sea ice minima has increased



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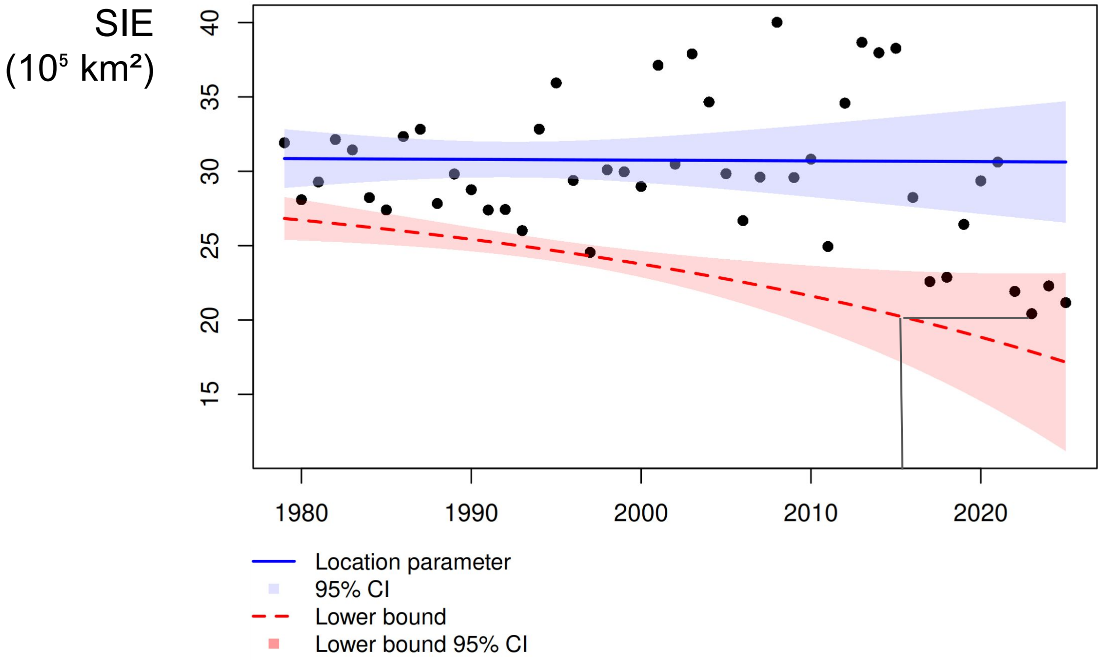
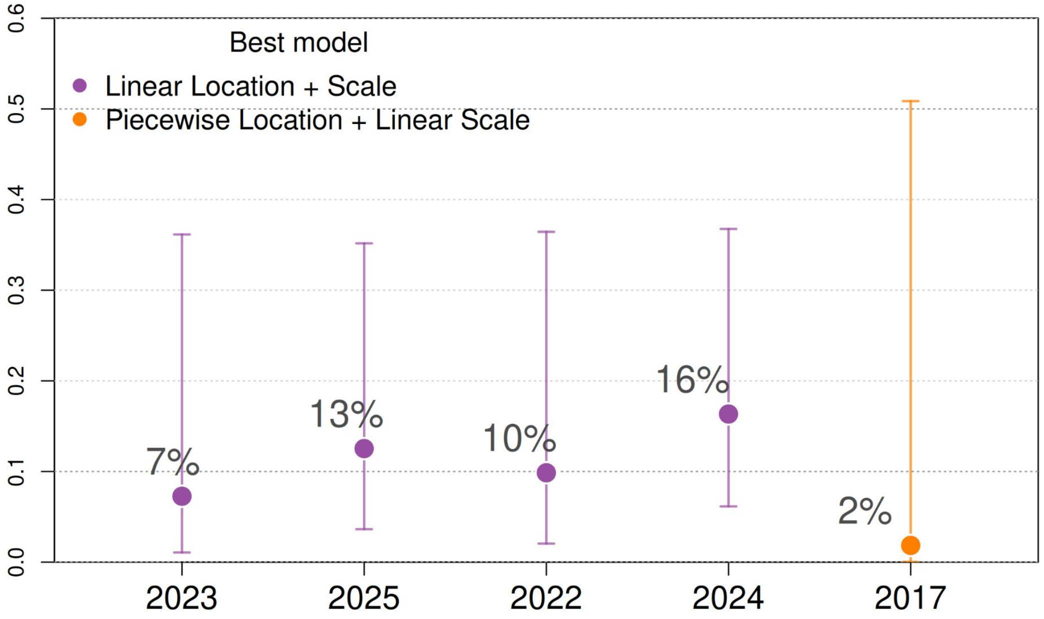


The 2023 event was
impossible before 2015

The recent records are not so unusual given the higher variability

Exceedance probability

P(SIE ≤ record|fit to data ≤ T)



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Discovering the latent spatial structure of sea ice minima

Dynamic agglomerative clustering steps:

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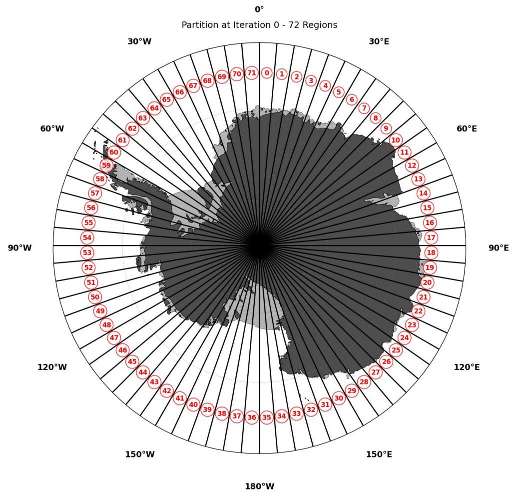

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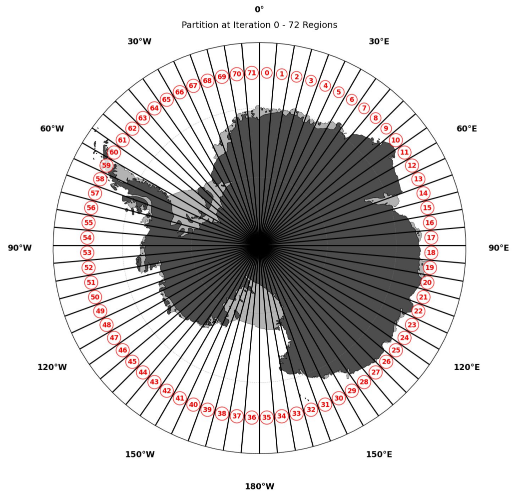

$$D_{k,k'} = \frac{\alpha}{2}\mathbb{E}[\mid F_k(Y_k) - F_{k'}(Y_{k'}) \mid] + (1-\alpha)\omega_{k,k'}$$

F-madogram distance
Measures minima dependence

Angular distance
Penalizes distant regions

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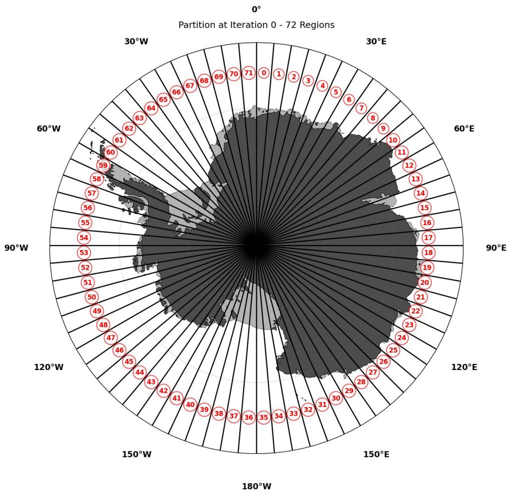

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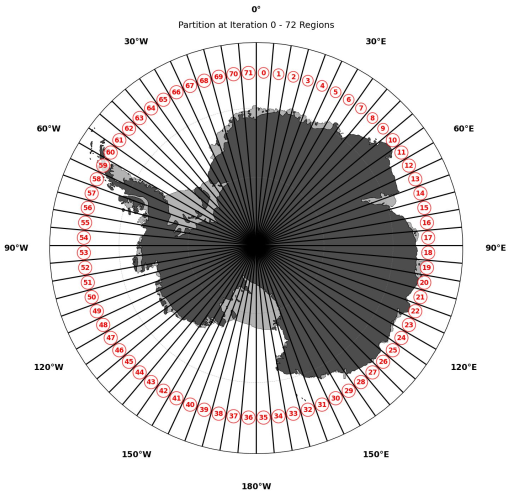

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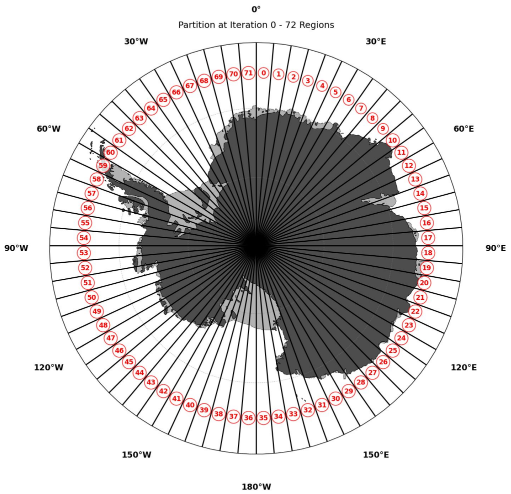

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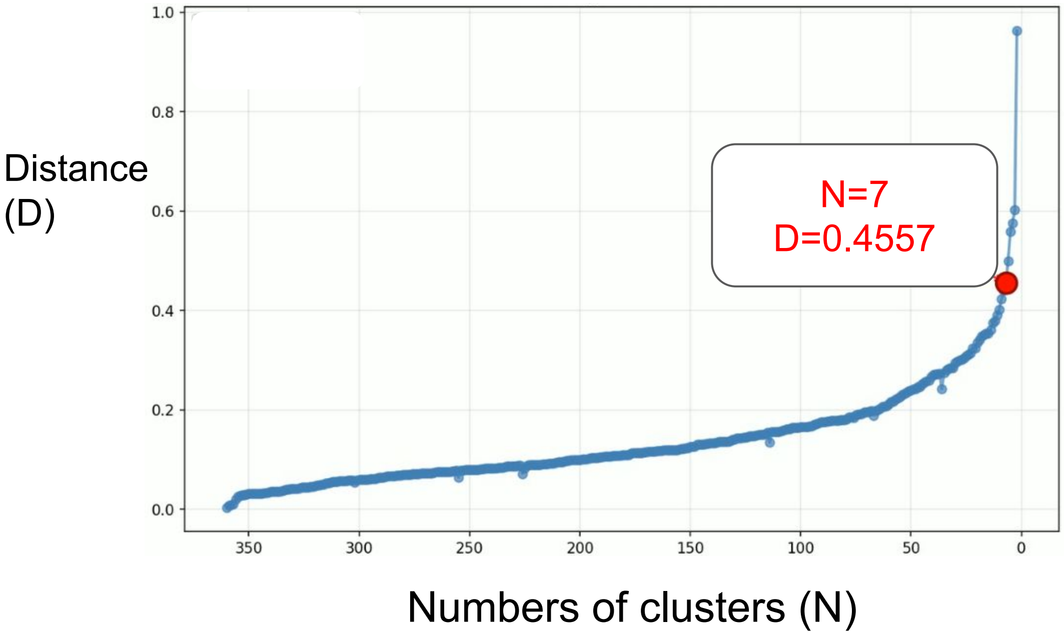
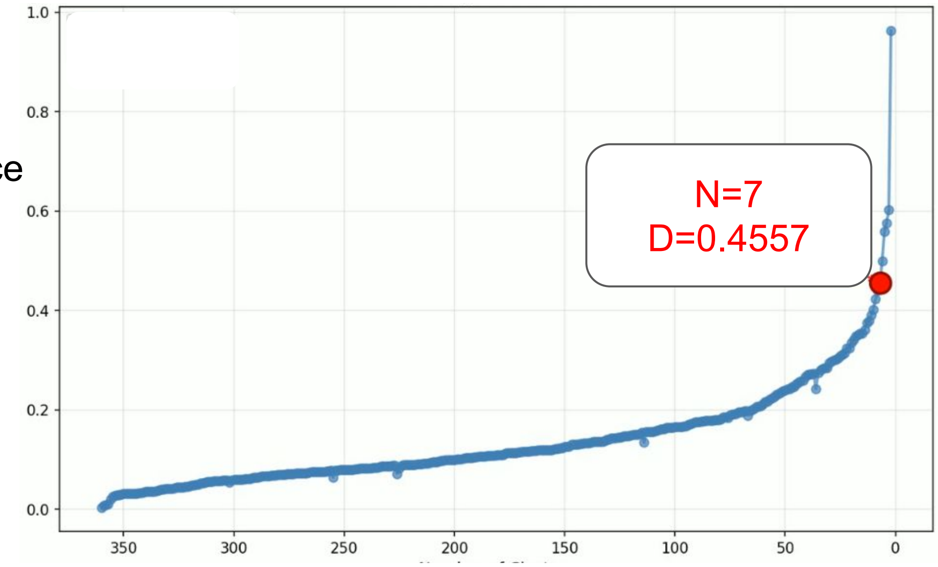
Selecting the size of the partition

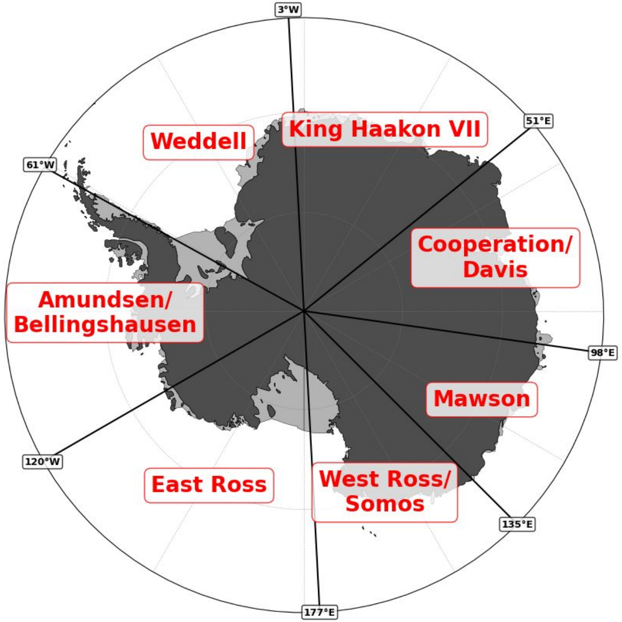


Selecting the size of the partition

Distance (D)



Numbers of clusters (N)



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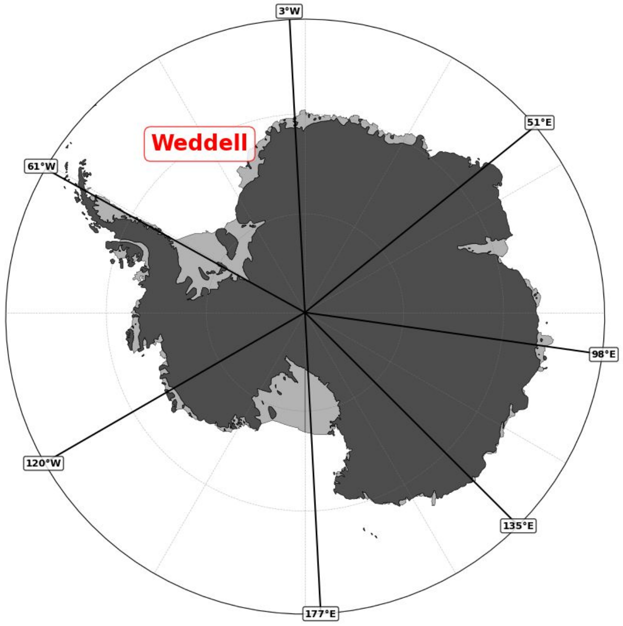
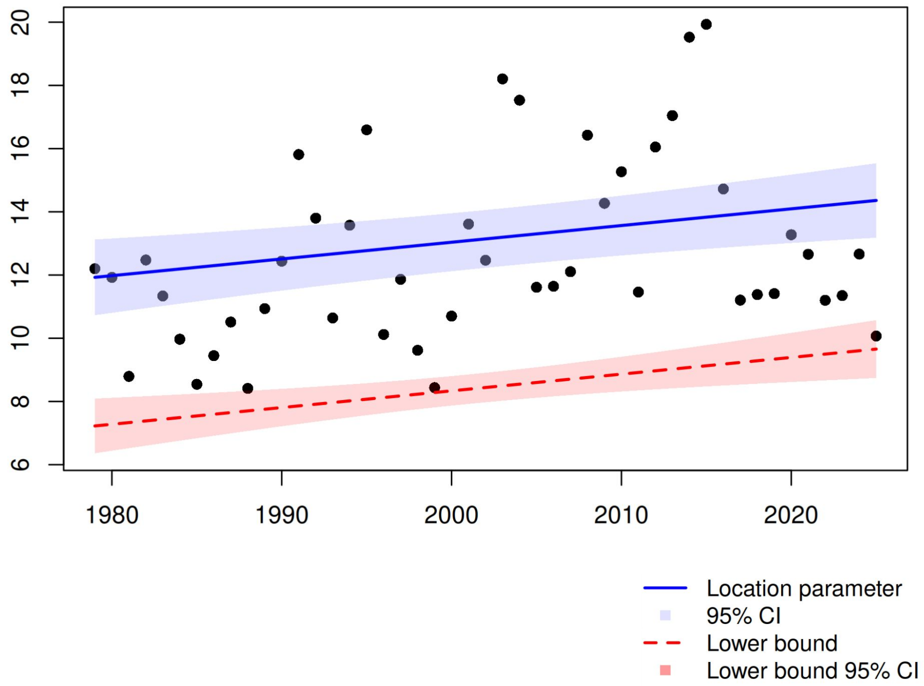
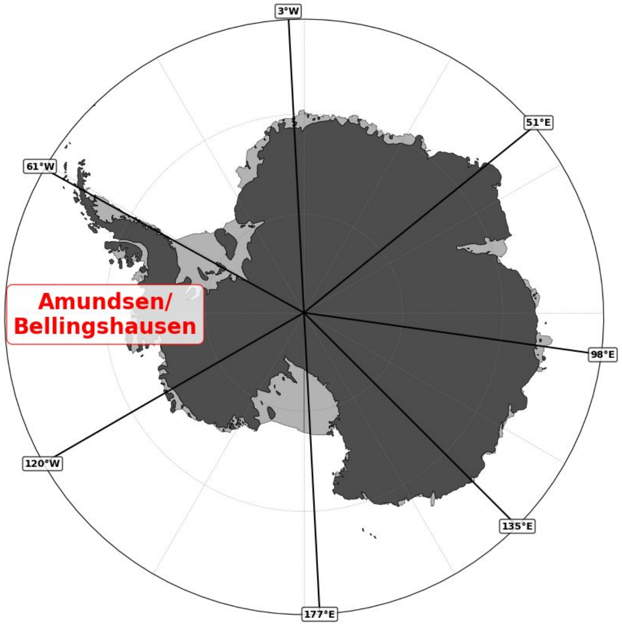
Weddell Sea: modest positive trend in the location



SIE (10^5 km²)



Amundsen/Bellingshausen: stable location and increasing scale since 1991



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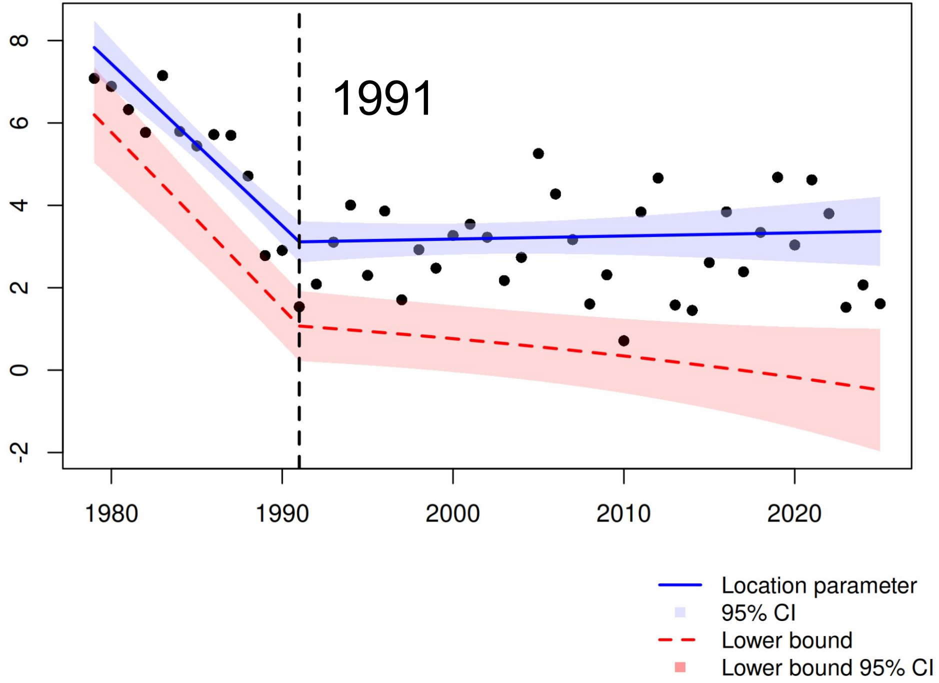
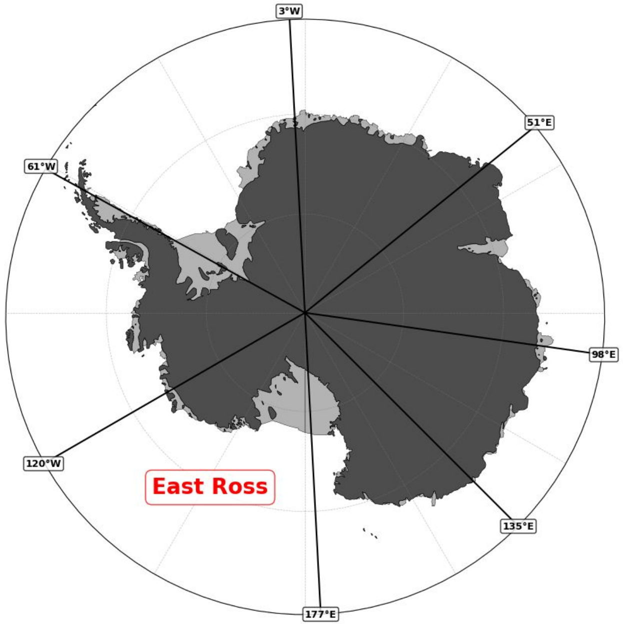
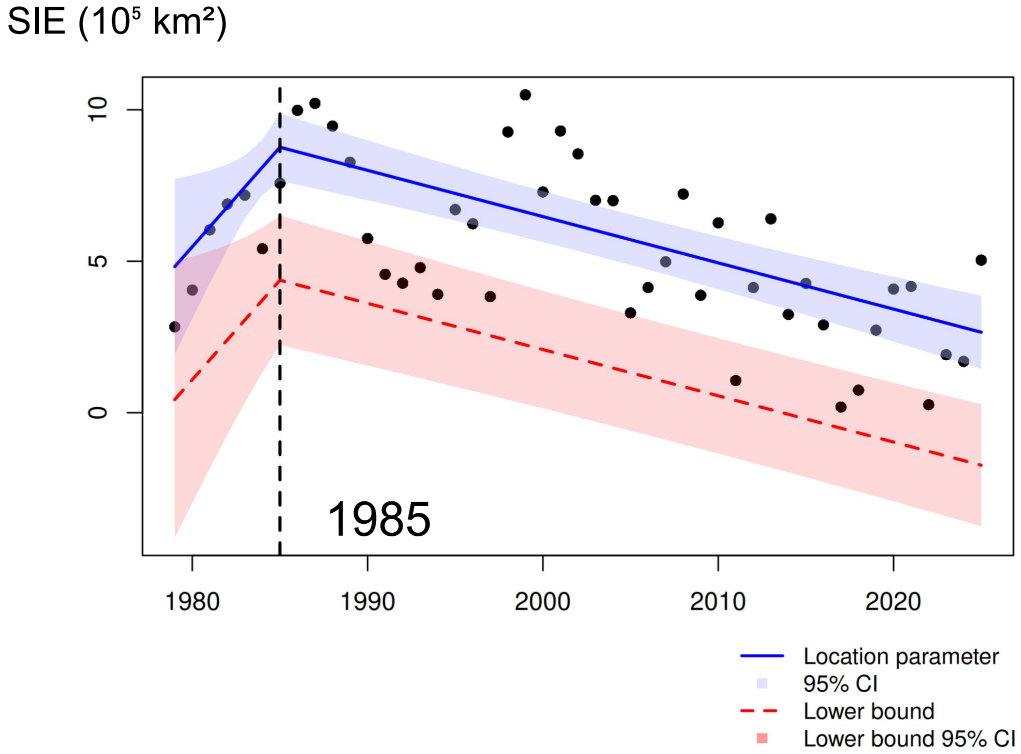
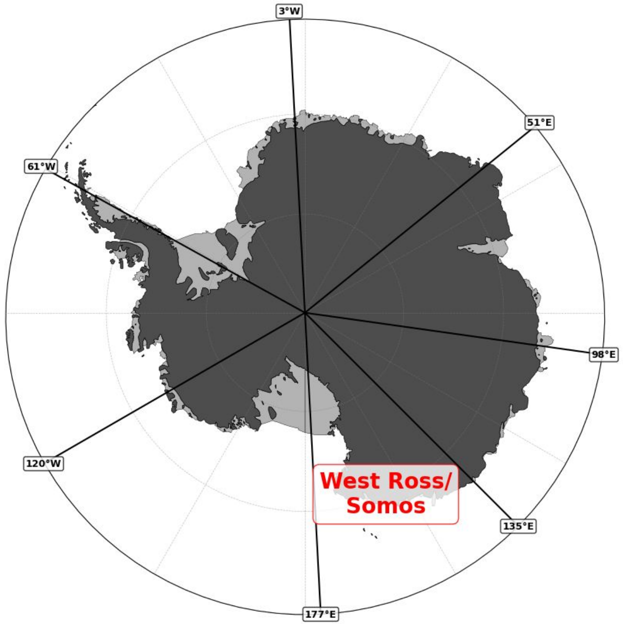


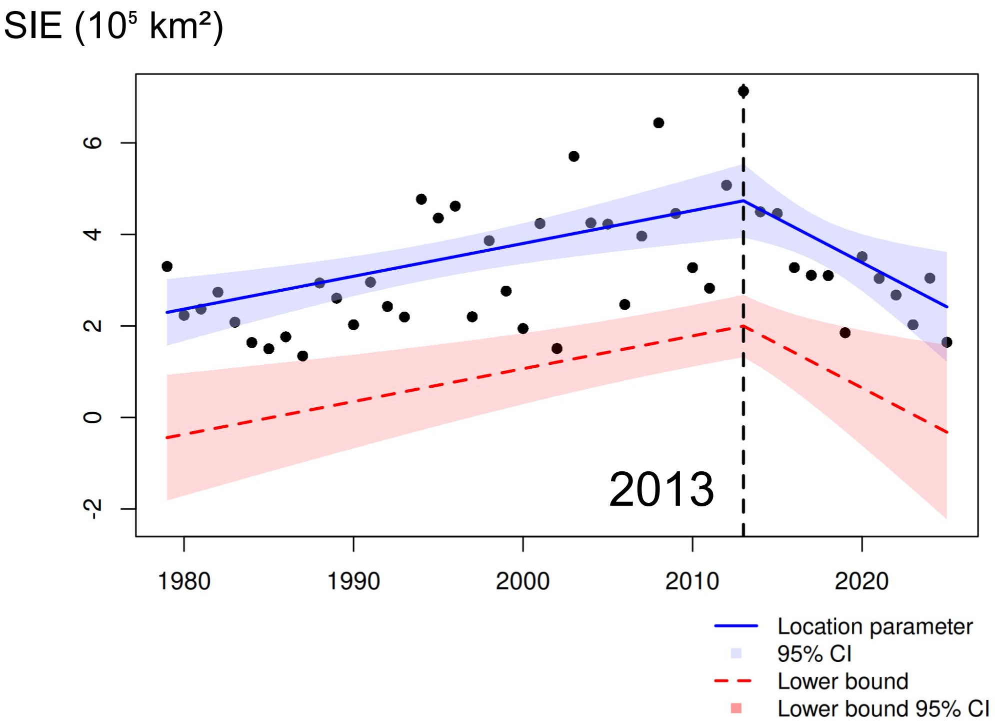
East Ross Sea: persistent decline since 1985



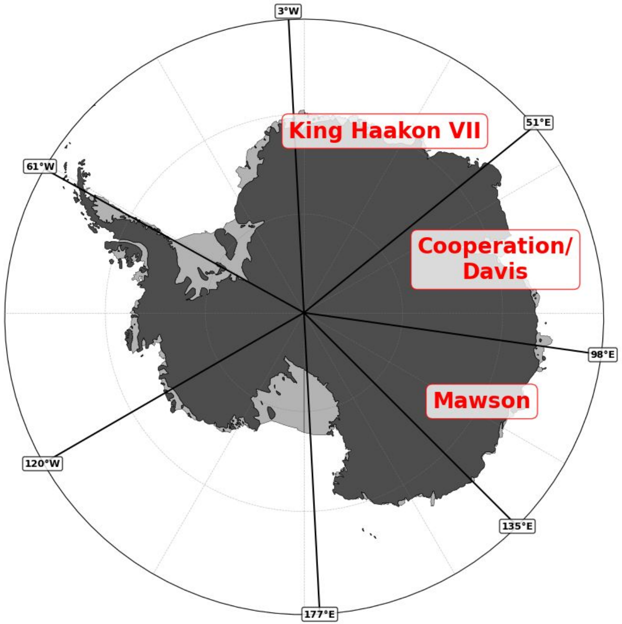


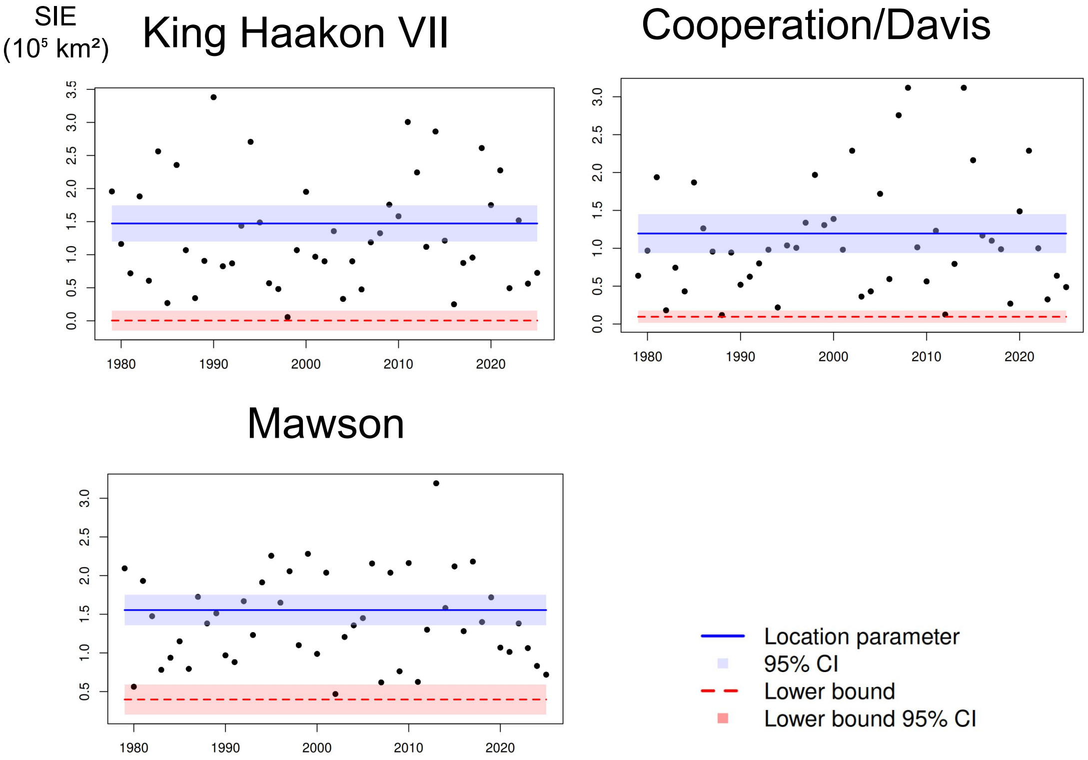
West Ross/Somos Seas: a 2013 breakpoint marks the onset of rapid decline





No changes detected in East Antarctic





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Conclusions

1. No structural break is identified in the circumpolar sea ice minima, but their variance has increased.
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2. The 2023 record had a 7% probability when it happened. The probabilities of most of the other records range from 10-16%.
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Conclusions

1. No structural break is identified in the circumpolar sea ice minima, but their variance has increased.
2. The 2023 record had a 7% probability when it happened. The probabilities of most of the other records range from 10-16%.
3. Regional changes in the summer minima are confined in the West part of the Southern Ocean. They are characterised by opposite trends, with some experiencing increasing variance and sudden change. The most recent sudden change detected is in 2013 in the West Ross/Somos Seas region.

Thank you!

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Block minima and block maxima duality

There is a duality between block minima and block maxima distributions:

$$M_n = \min(X_1, \ldots, X_n) = -\max(-X_1, \ldots, -X_n)$$

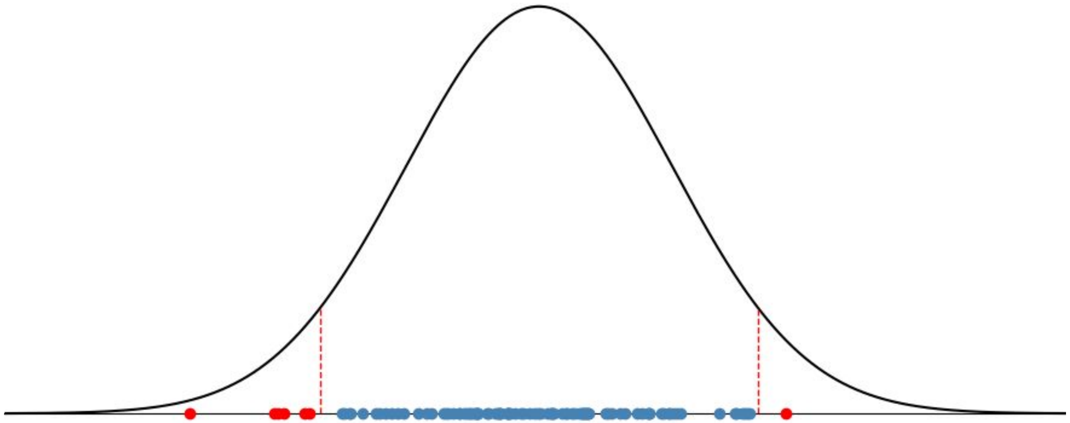
Defining $Y_i := -X_i$

$$P\left[M_n \leq x\right] = 1 - P[\max(Y_1, \ldots, Y_n) \leq -x] \approx 1 - G_Y(-x)$$

where G_Y is a GEV whose parameters are obtained by fitting block maxima of $Y_1, \ldots, Y_n$.

The difficulties with rare events modeling

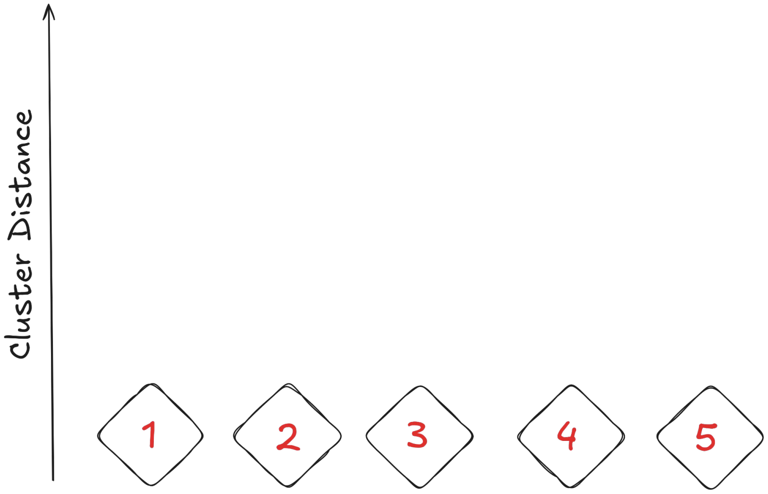
- Standard methods are optimized for the bulk of the data, not the tail
- Tail probabilities are systematically underestimated



Discovering the latent spatial structure of sea ice minima

Dynamic agglomerative clustering steps:

1. Divide the grid into 1° longitudinal regions
2. Compute the pairwise distance between all regions.
3. Merge the two regions with the smallest distance
4. Recompute the annual minima of the newly created region and update the pairwise distance matrix
5. Repeat step 1-4 until only one region remain



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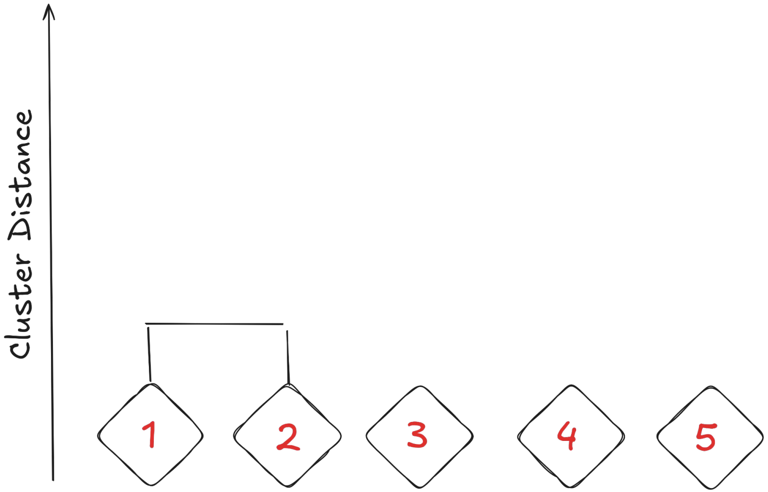

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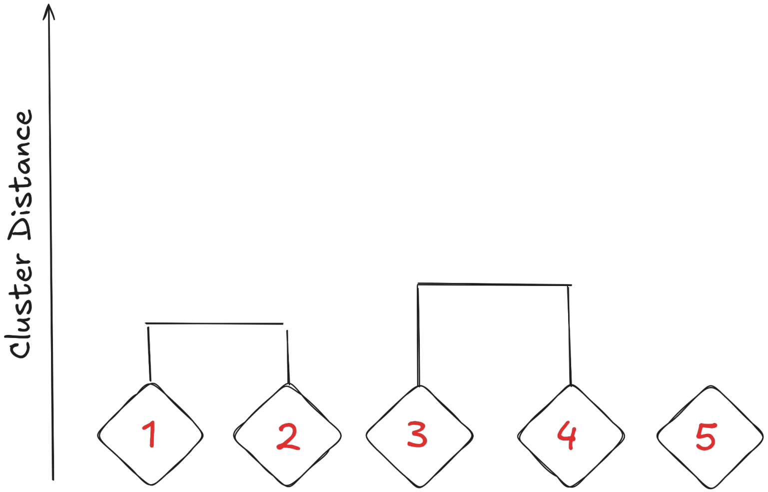

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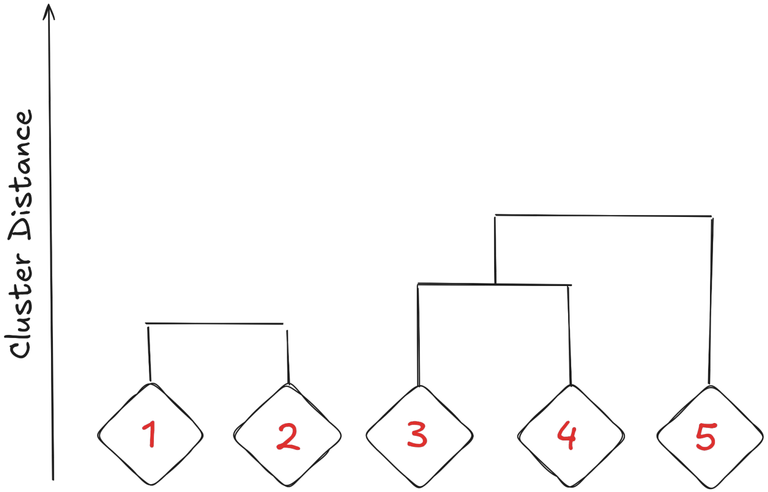
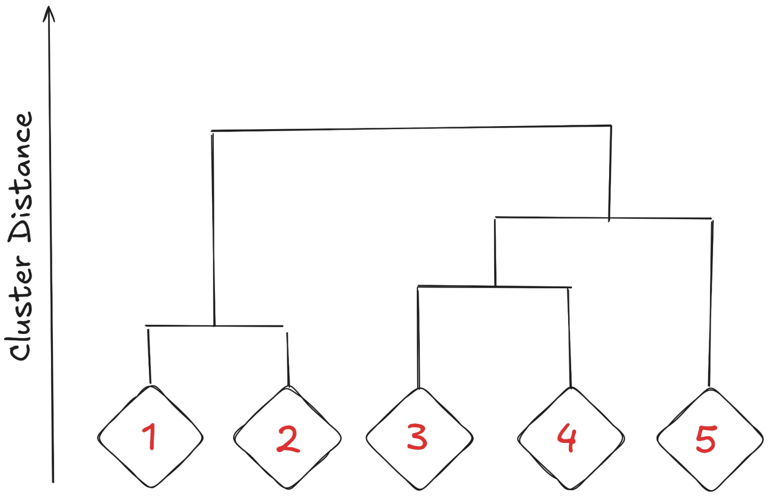


Discovering the latent spatial structure of sea ice minima

Dynamic agglomerative clustering steps:

1. Divide the grid into 1° longitudinal regions
2. Compute the pairwise distance between all regions.
3. Merge the two regions with the smallest distance
4. Recompute the annual minima of the newly created region and update the pairwise distance matrix
5. Repeat step 1-4 until only one region remain



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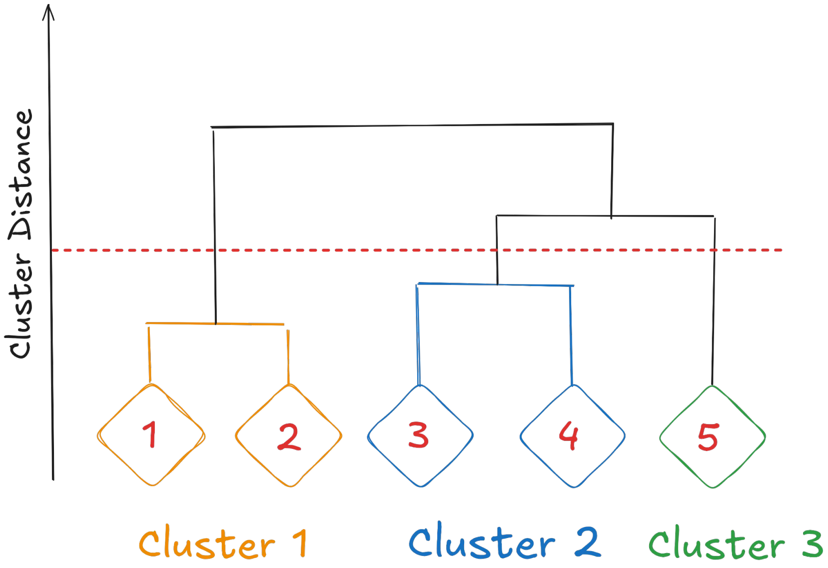
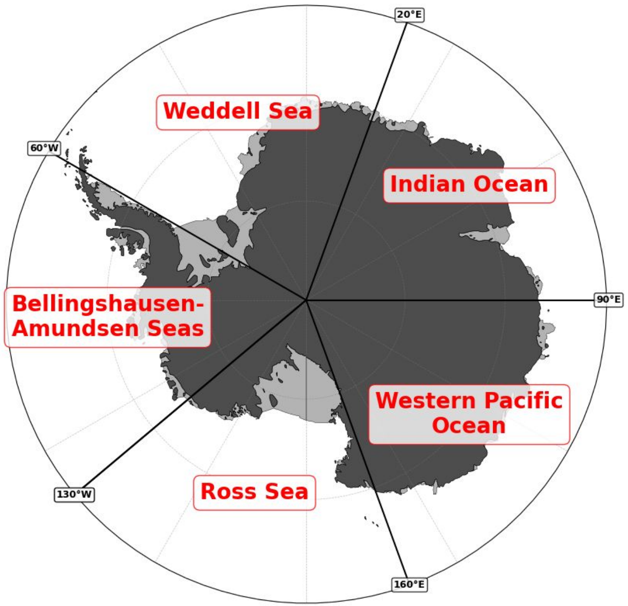
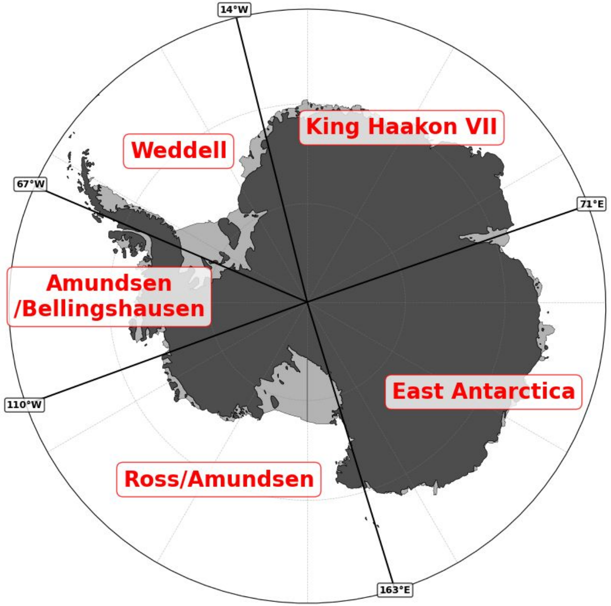


Standard divisions can not capture all the spatial complexity of sea ice



Geographical division

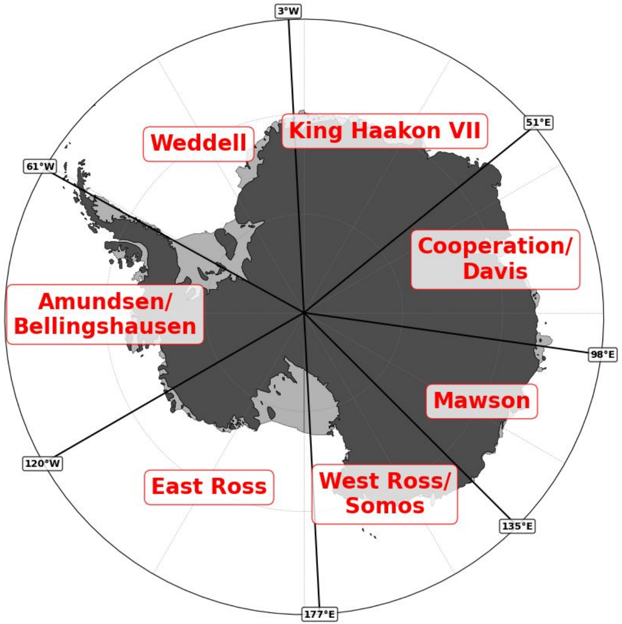
Zwally et al., 1983



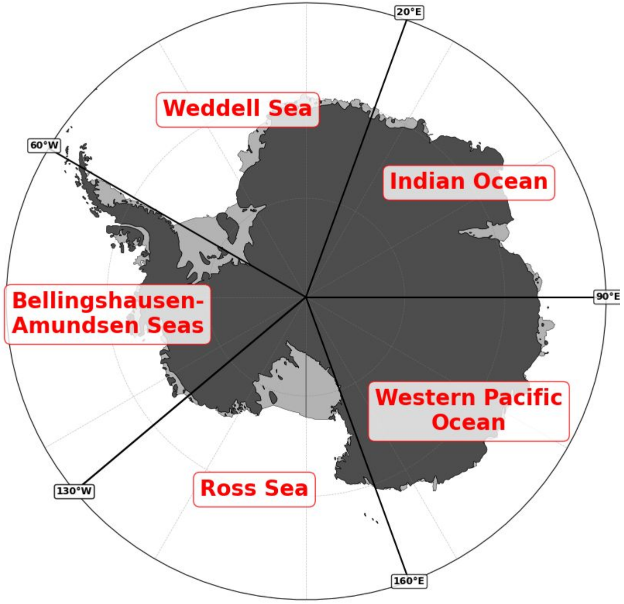
Sea ice seasonal cycle based division

Raphael & Hobbs, 2014

Comparison with standard divisions



Minima based division



Zwally division

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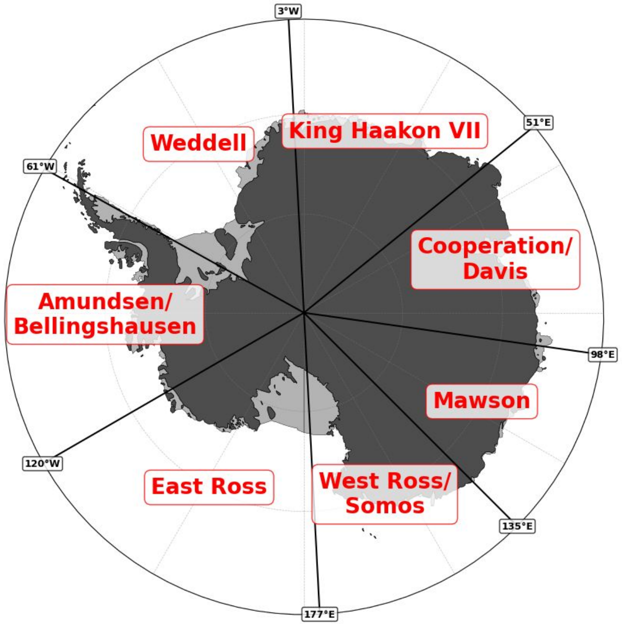

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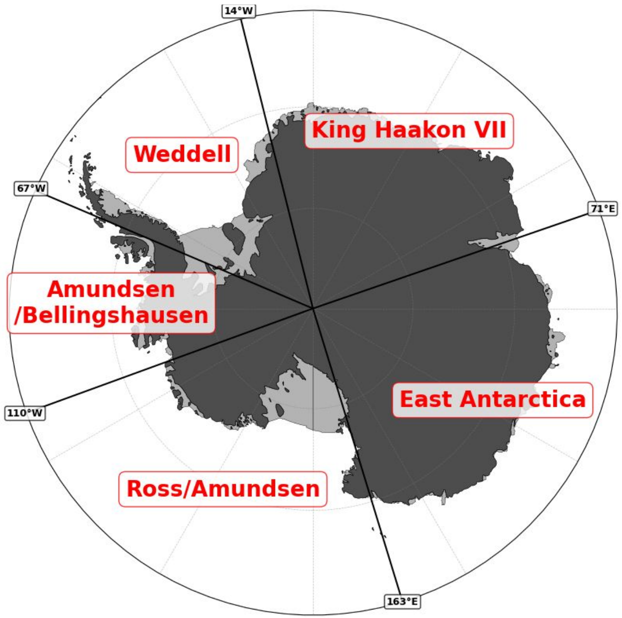
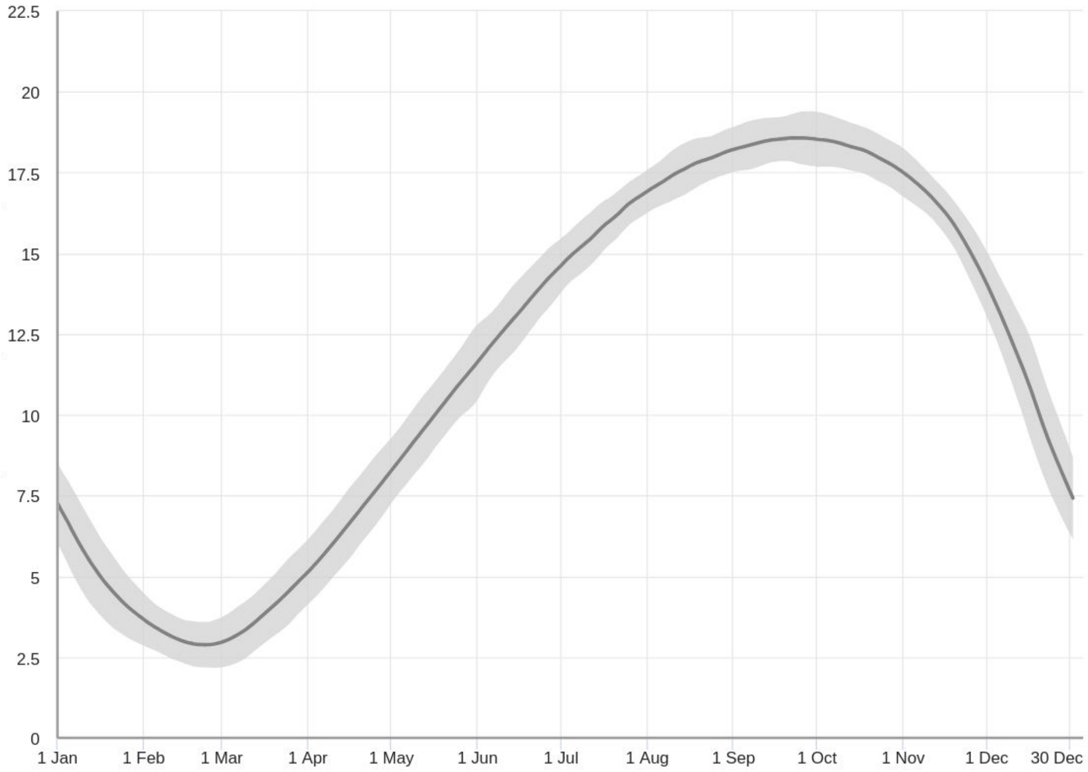


Raphael & Hobbs division

Sea ice seasonal cycle

Sea Ice Extent
(10^6 km²)



National Snow and Ice Data Center, Boulder, CO

Sea ice seasonal cycle

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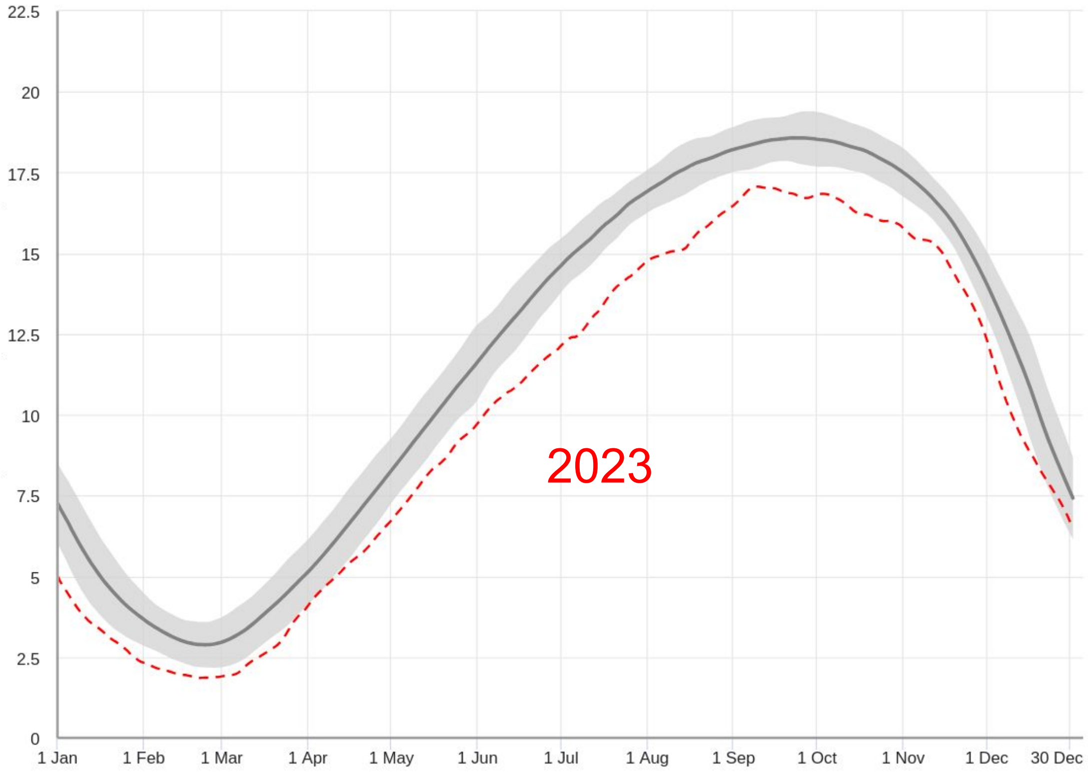
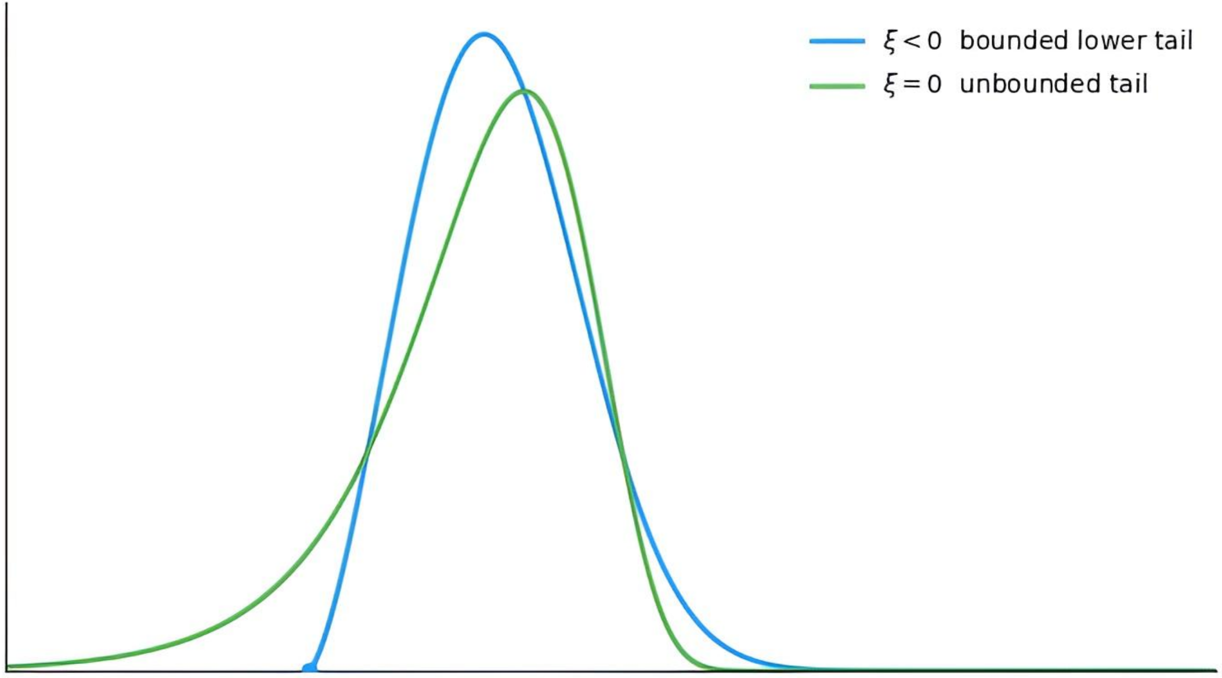


National Snow and Ice Data Center, Boulder, CO

The shape dictates the tail behaviour



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