Drivers of compound extremes in the Southern Ocean

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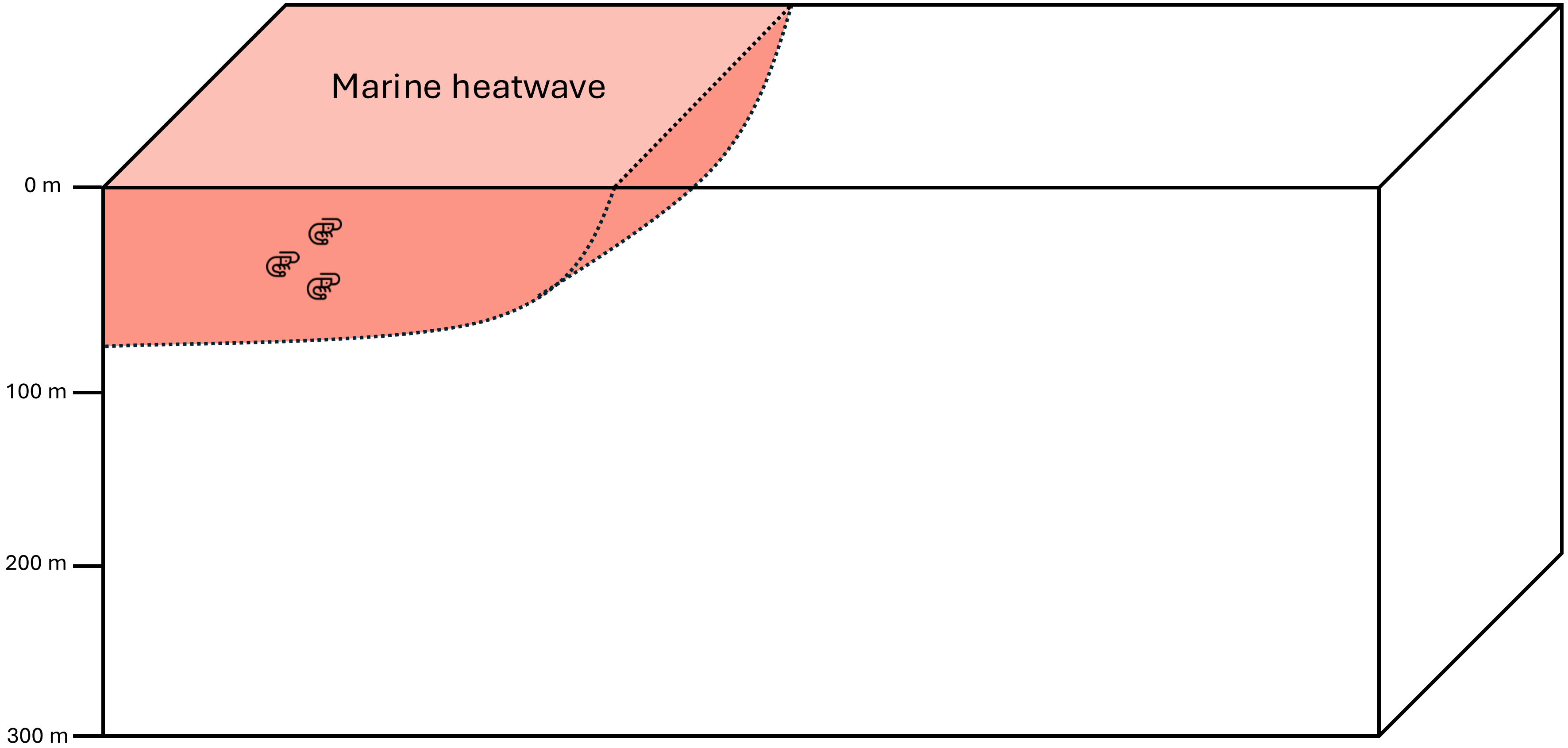
Extremes in the vertical column



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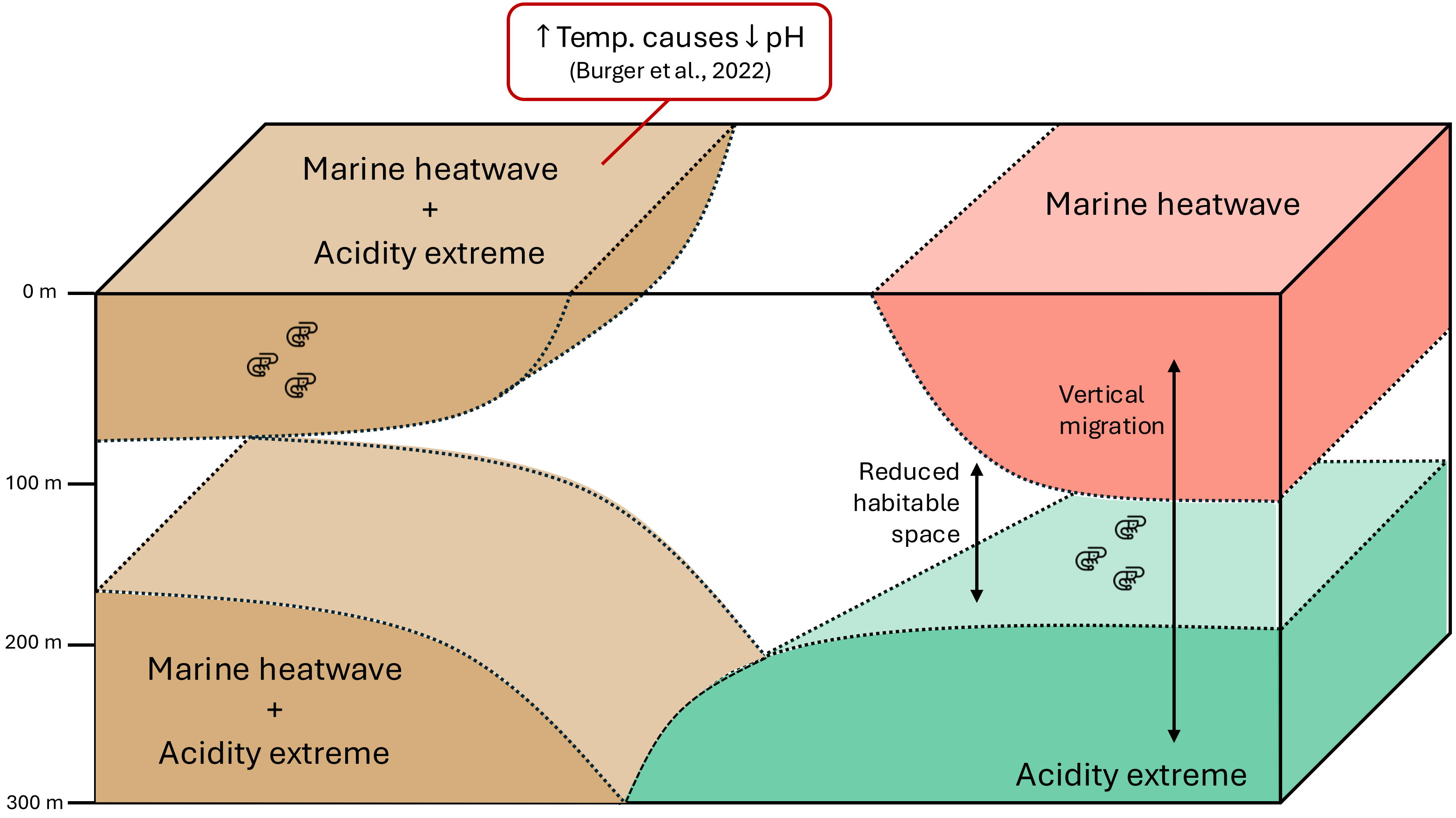


Southern Ocean model hindcast

ROMS-BEC, daily output (1980-2019)

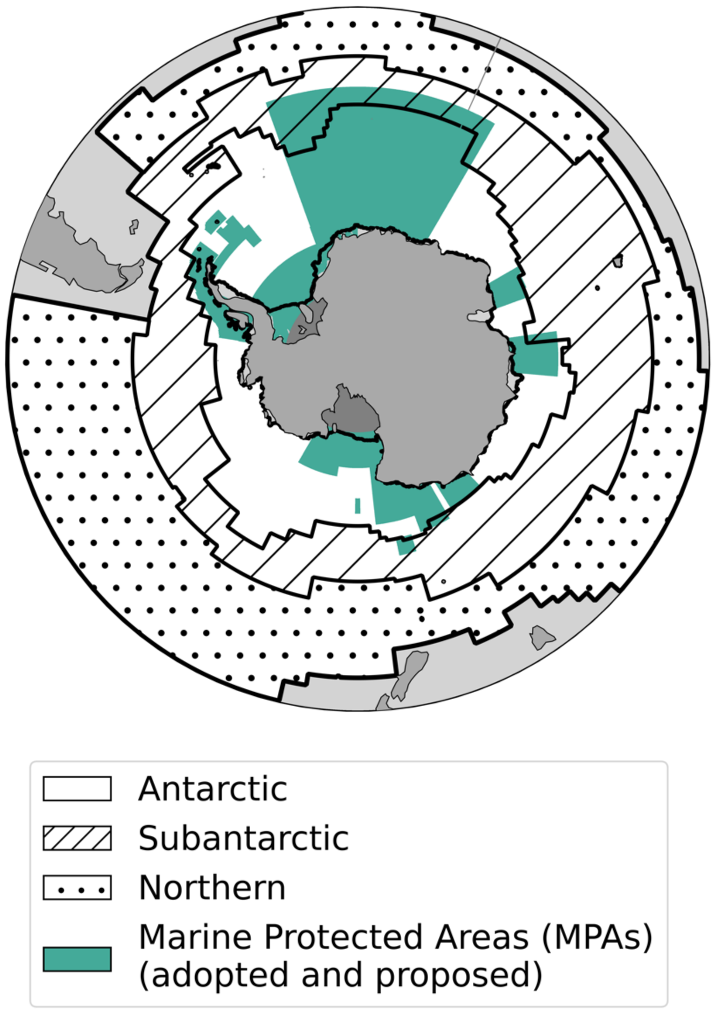
0.25° resolution,
Upper 300m column

Extreme event thresholds

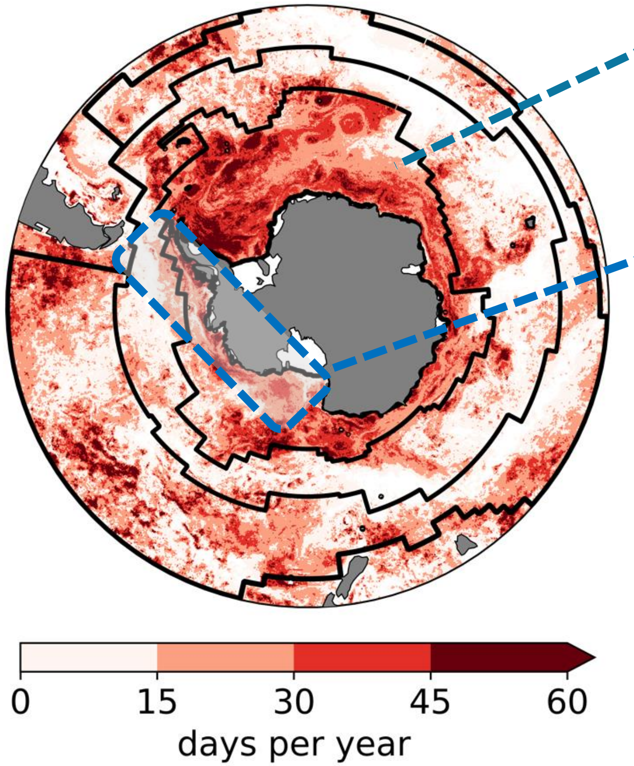
Extreme type	Variable	Percentile threshold
Marine heatwave (MHW)	T	> 95th
Ocean acidity extreme (OAX)	$[H^+]$	> 95th

Compound Extreme	≥ 50m of MHW and OAX extreme

Wong, et al., *AGU Advances* (2024)



Frequent MHW-OAX in the Antarctic zone



High frequency in **Antarctic zone**

Lower frequencies in the **Subantarctic** and **Northern zones**

Highest anomalies in the **Ross and Bellingshausen Seas**

Temperature anomaly $+2.4\ °\mathrm{C}$

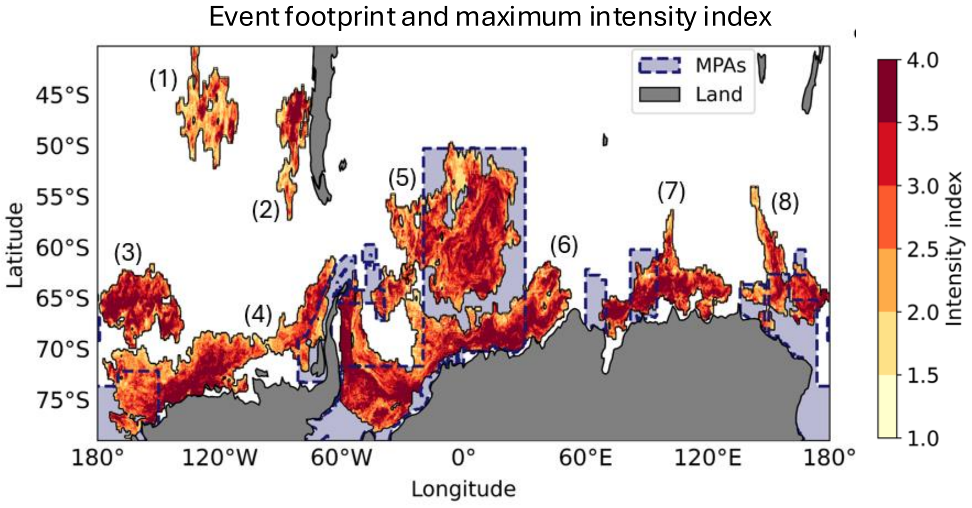
pH anomaly -0.8

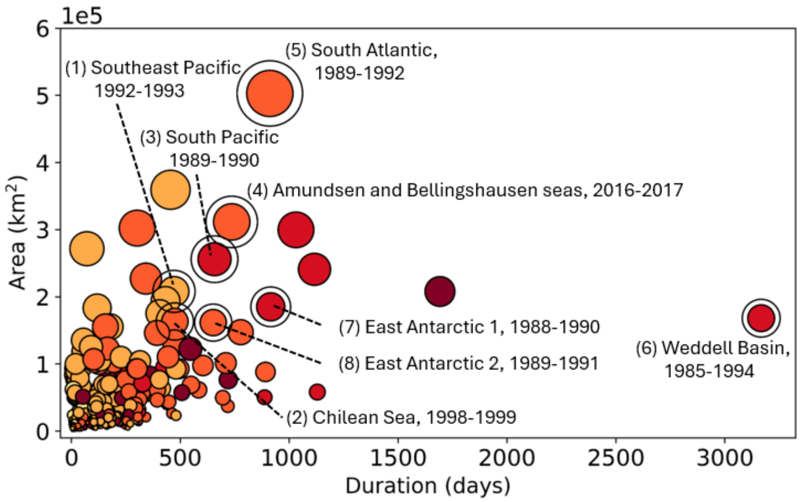
(In 2019, compared to 1980 conditions)

Antarctic krill growth rates decline from $3-4°C$

(Atkinson et al., 2006; Brown et al., 2010)

Largest MHW-OAX in the Southern Ocean



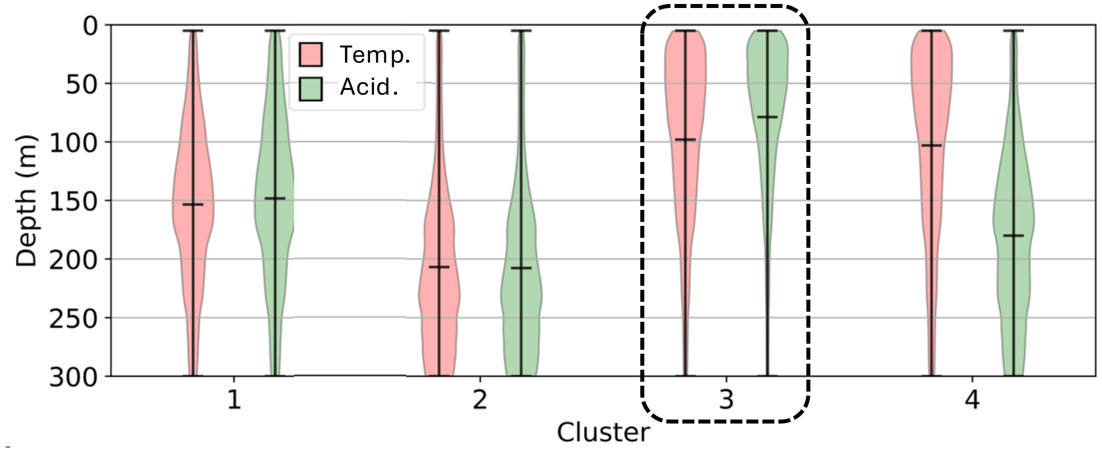


Larger and more intense extremes in the **Antarctic zone**

Extremes occupy the **Antarctic Marine Protected Areas**

Large events are also long (more than 500 days)

Surface compounded MHW and OAX



Cluster 3

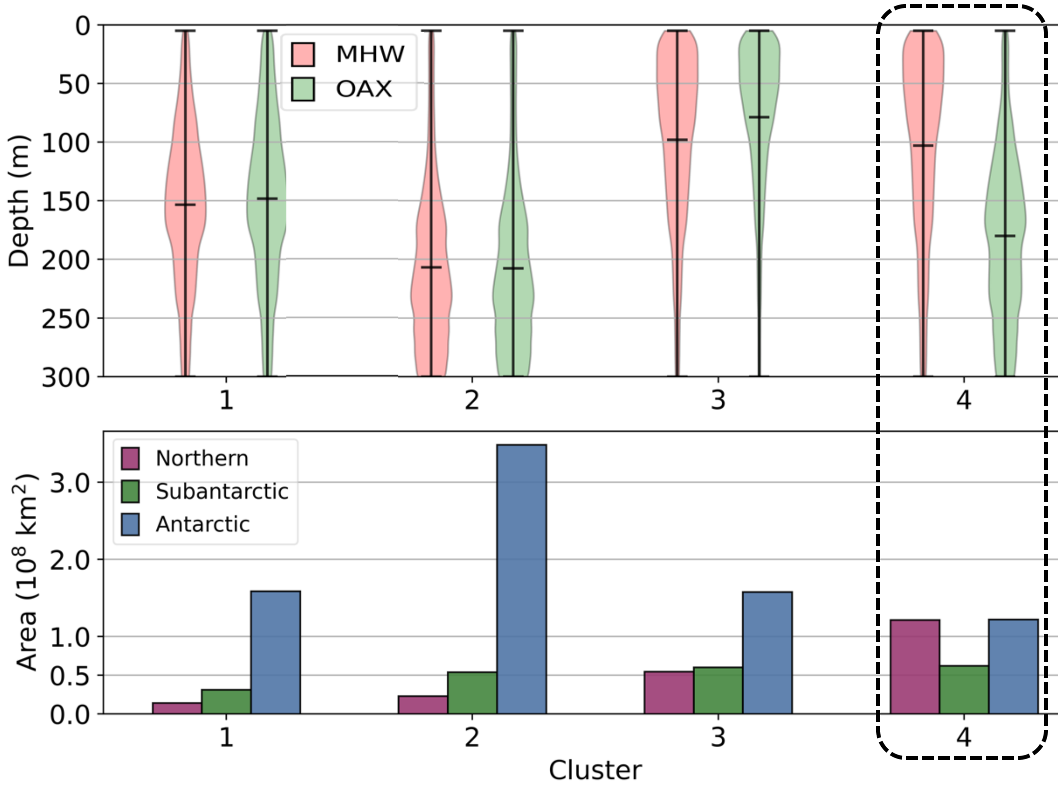
Surface MHW and OAX

↑

Anomalous surface heating → (↑ stratification, ↓ nutrients) → Reduced primary production

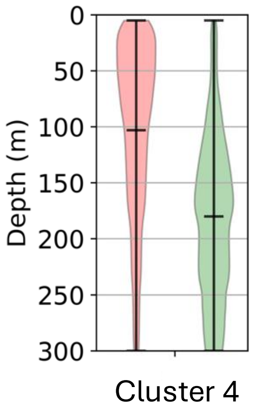
Le Grix et al. (2022); Burger & Frölicher (2023)

Surface MHW and subsurface OAX



Cluster 4
Surface MHW and subsurface OAX
in the **Northern zone**

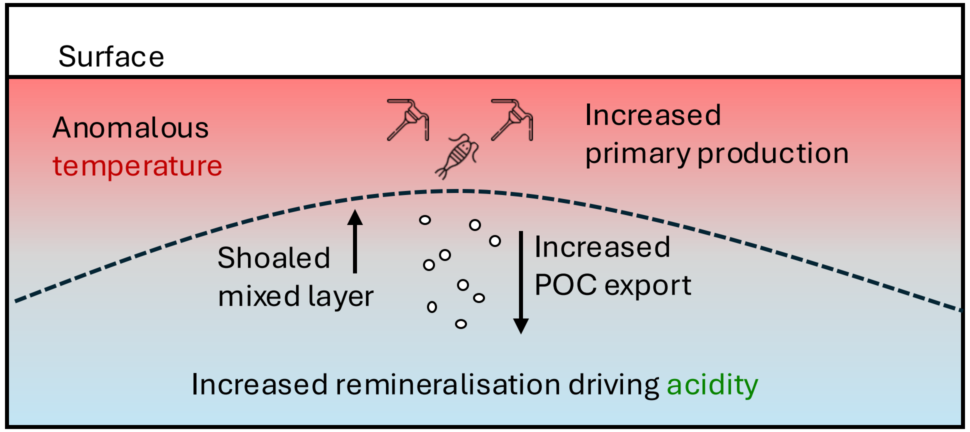
Surface MHW and subsurface OAX



1. Heat gained from the atmosphere (36%) and ocean (64%)
   - *Surface heat flux was <u>not</u> anomalous*
2. Increased primary production
   - *Increased POC export and CO_2 uptake*
3. Remineralisation in the subsurface drives acidity
   - *70% increase in $[H^+]$ driven by ↑ DIC*

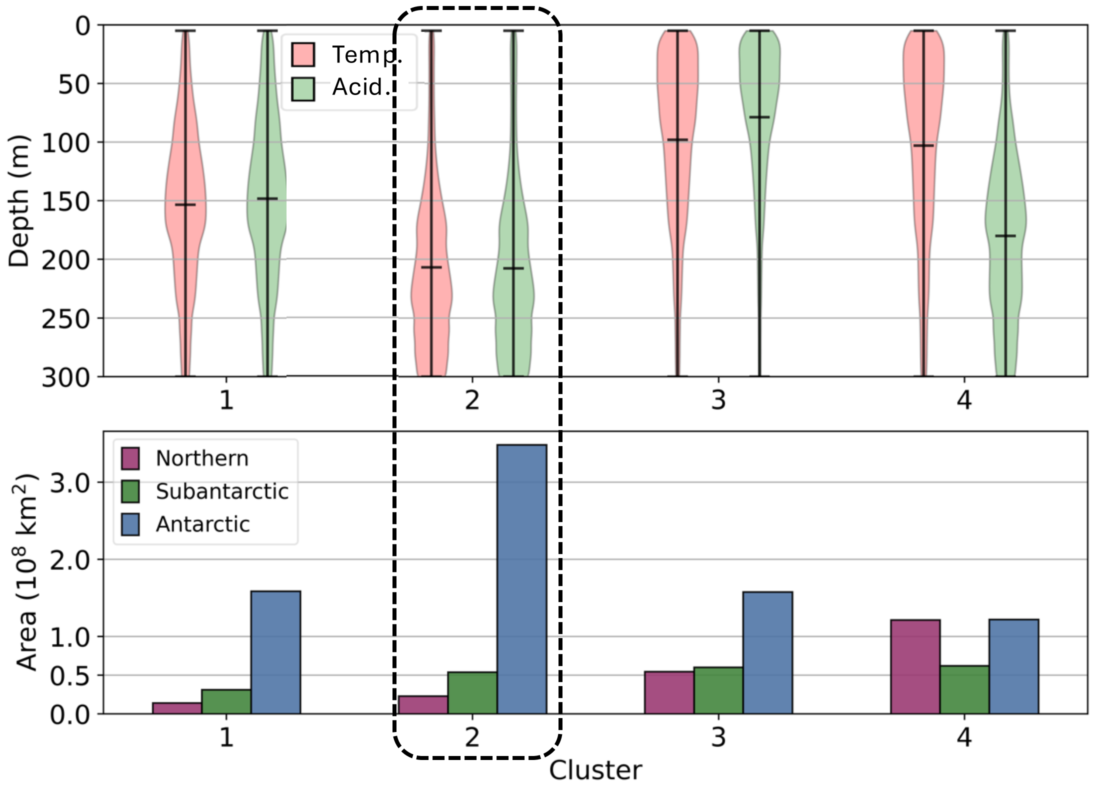
MHW induced at the surface

Temperature-induced productivity at the surface drives subsurface acidity



DIC – Dissolved Inorganic Carbon
POC – Particulate Organic Carbon

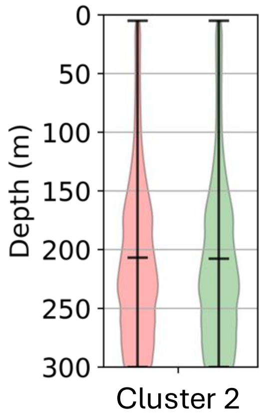
Deep MHW and OAX in the Antarctic zone



Cluster 2

Deep MHW and OAX in the **Antarctic zone**

Deep MHW and OAX in the Antarctic zone



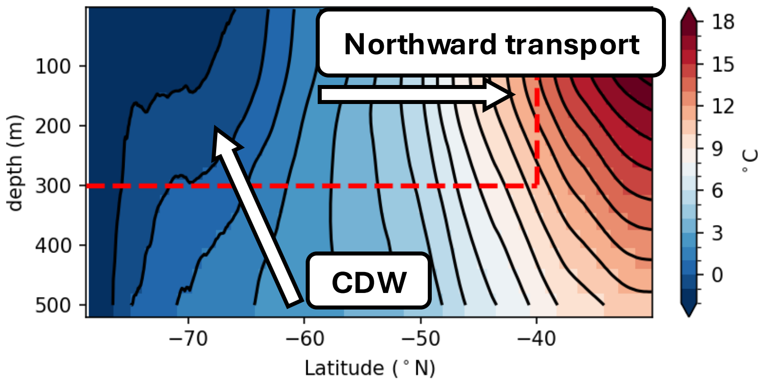
1. Pycnocline depth is anomalously shoaled
2. Increase in $[H^+]$ driven by ↑ DIC and ↑ Temp
   - *Less than 2% ↑DIC and ↑ Temp from surface fluxes*
3. No anomaly in primary production
4. Associated with positive SAM and La Niña
   - *Up to 2.2x increase in extreme area*

Upwelling of warm and acidic Circumpolar Deep Water (CDW)*

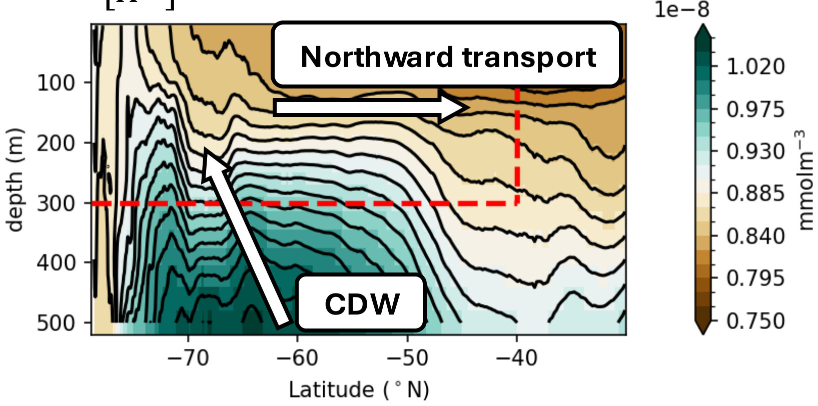
Acidity is not biologically driven

Stronger westerlies drive northward transport†

Temperature



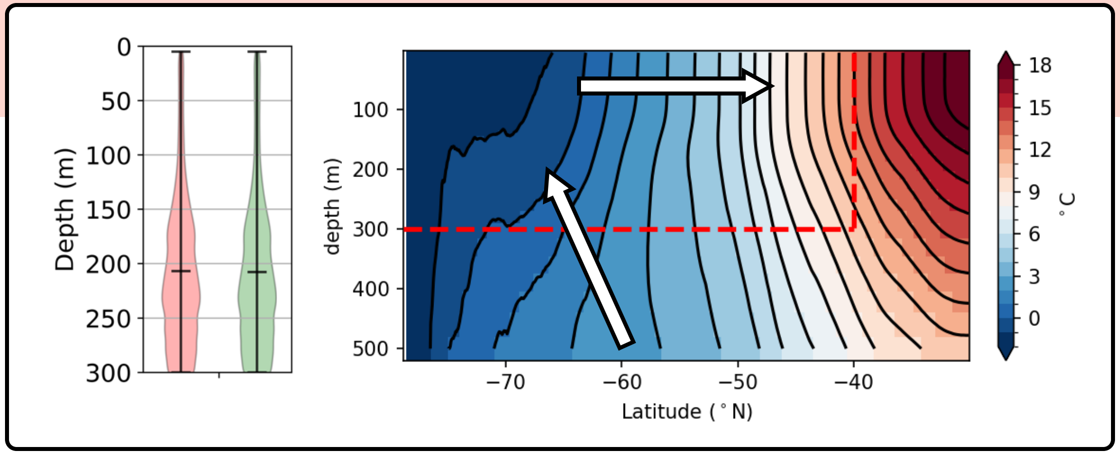
$[H^+]$

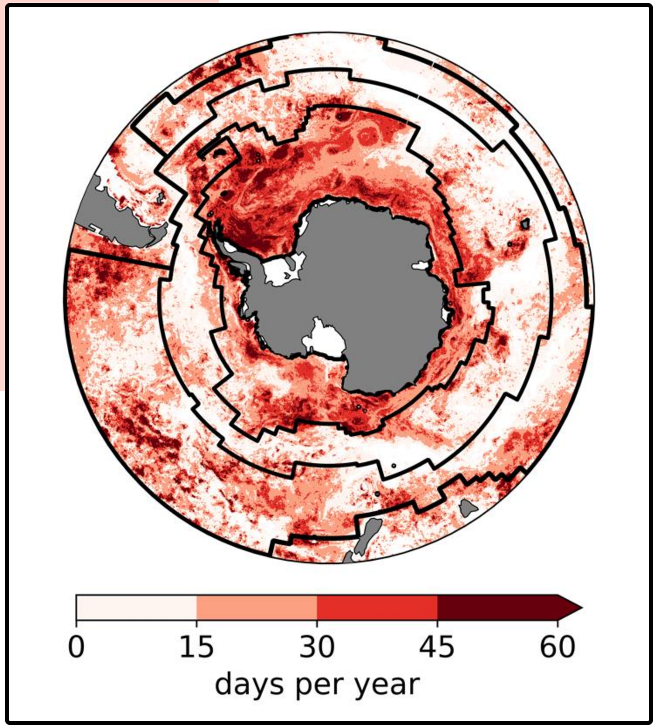


CDW – Circumpolar Deep Water
DIC – Dissolved Inorganic Carbon
SAM – Southern Annular Mode
* Morrison et al. (2015)
† Wang et al. (2023)

Conclusion

- High frequency of MHW + OAX in the Antarctic zone





Conclusion

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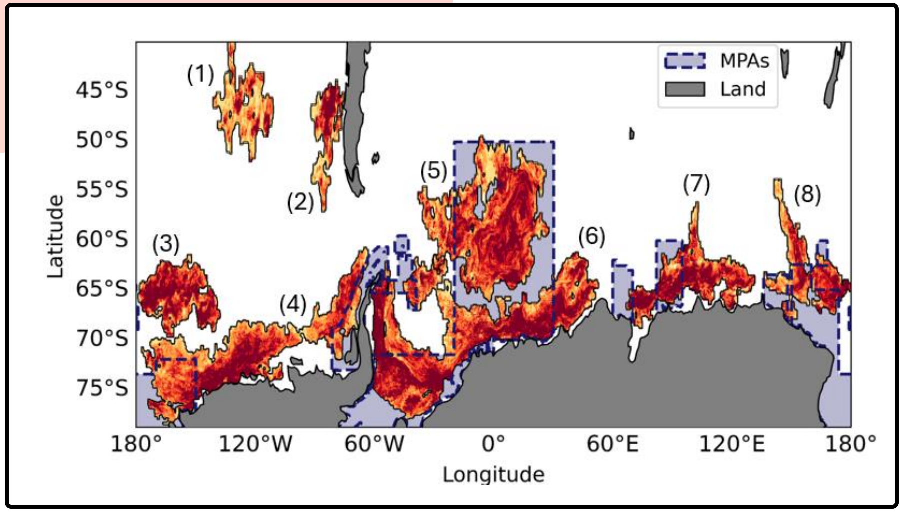
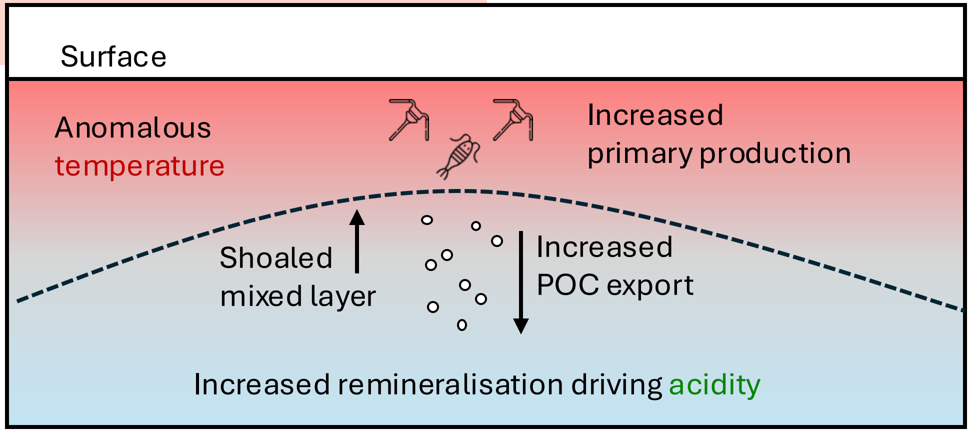
- Largest and longest events in Antarctic MPAs



Conclusion

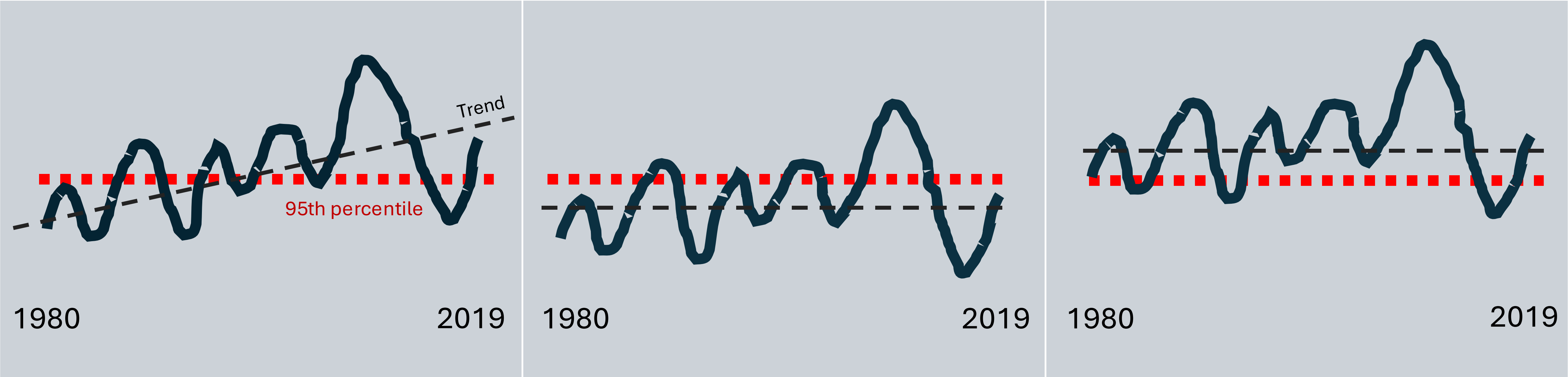
- High frequency of MHW + OAX in the Antarctic Zone
- Largest and longest events in Antarctic MPAs
- Surface MHW drive OAX by modulating primary production



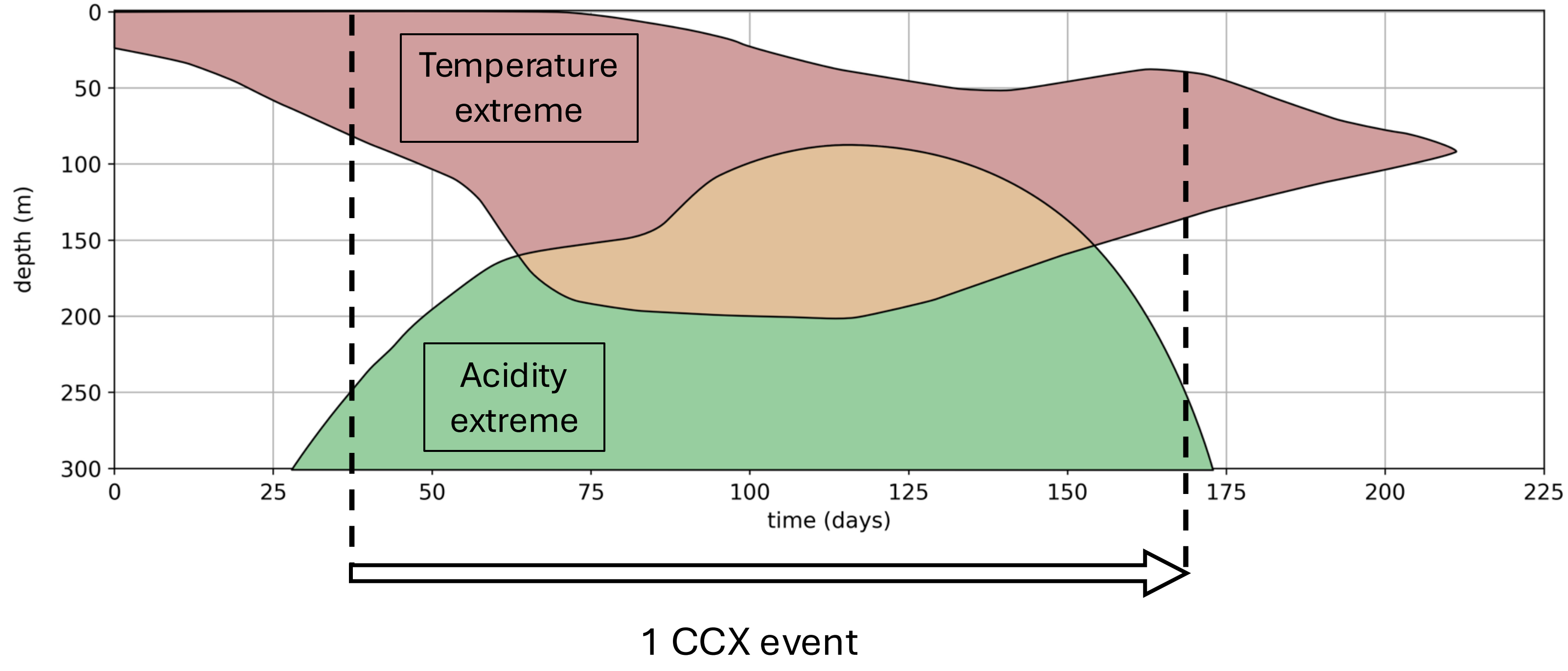
Appendix

Methods: Fixed and moving baselines

Fixed (at 1980)	Detrended backward to 1980 (quadratic)	Detrended forward to 2019 (quadratic)



Methods: Clustering CCX by vertical structure



Sum of no. of days

MHW	OAX
50	0
150	0
100	50
50	70
0	100
0	150

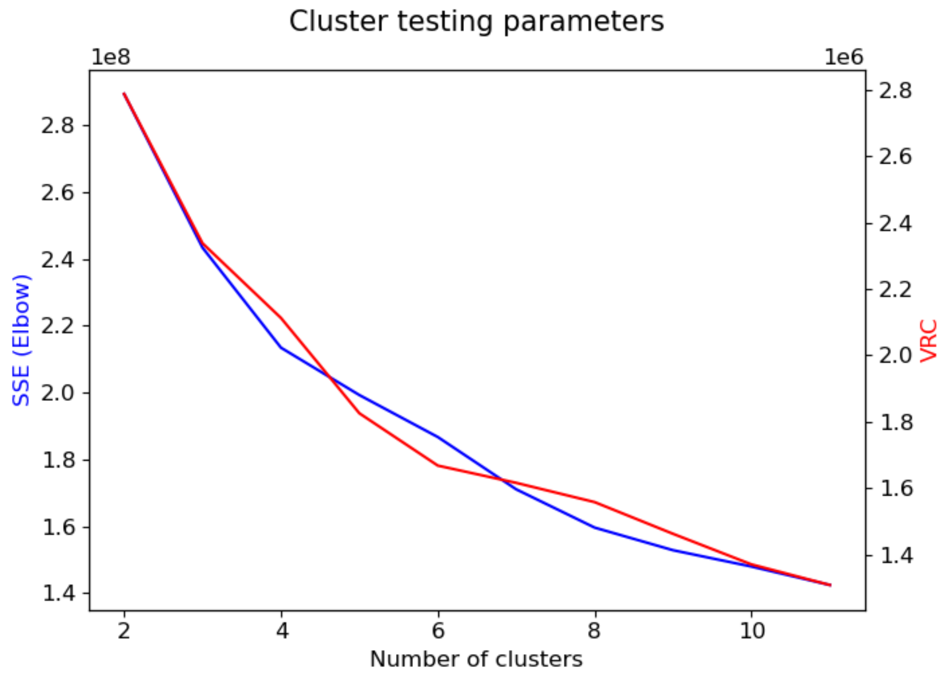
29x2 Depth levels

Normalised by event duration

Principal components analysis (PCA) into 15 features

k-means clustering
($\sim 7 \times 10^6$ events)

Methods: Choosing the number of clusters



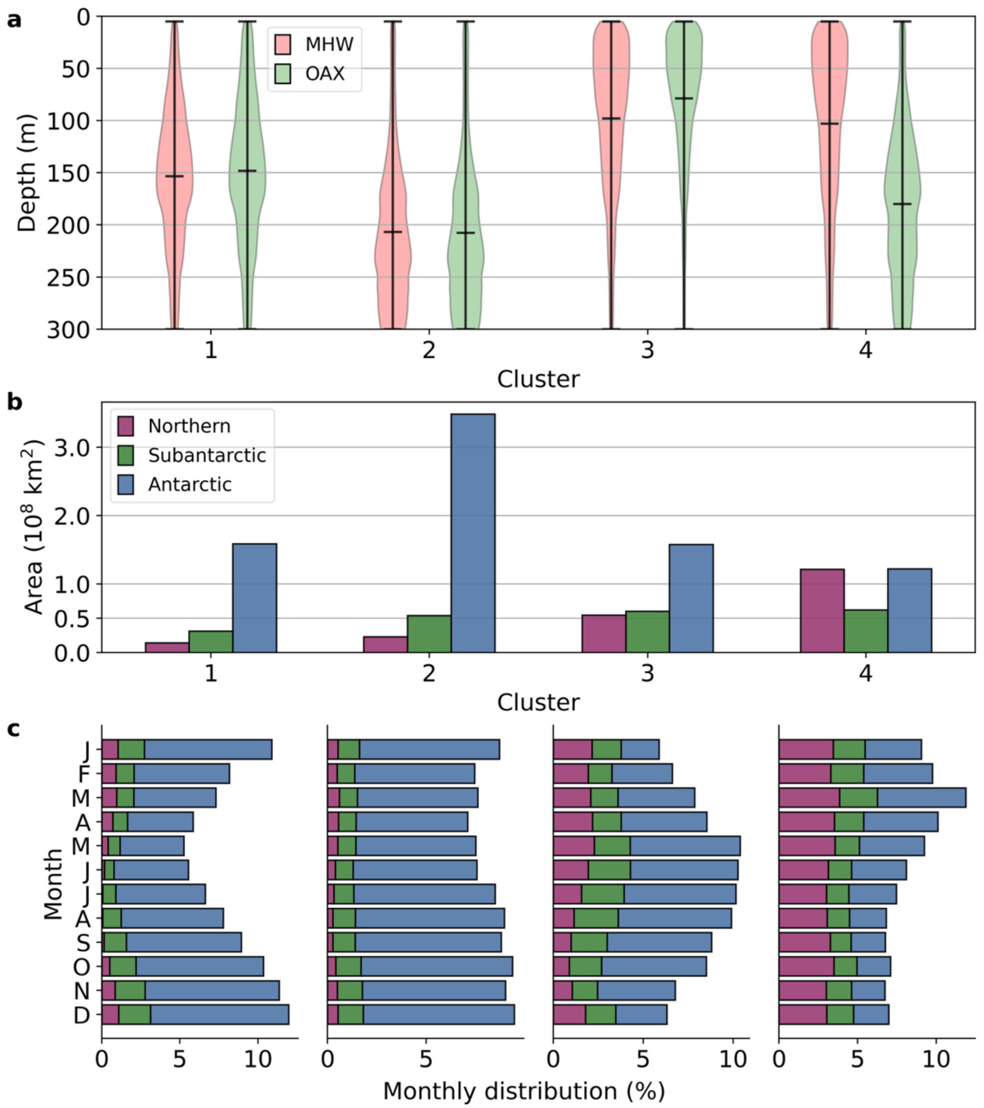
SSE – Sum of Squared Error
VRC – Variance Ratio Criterion

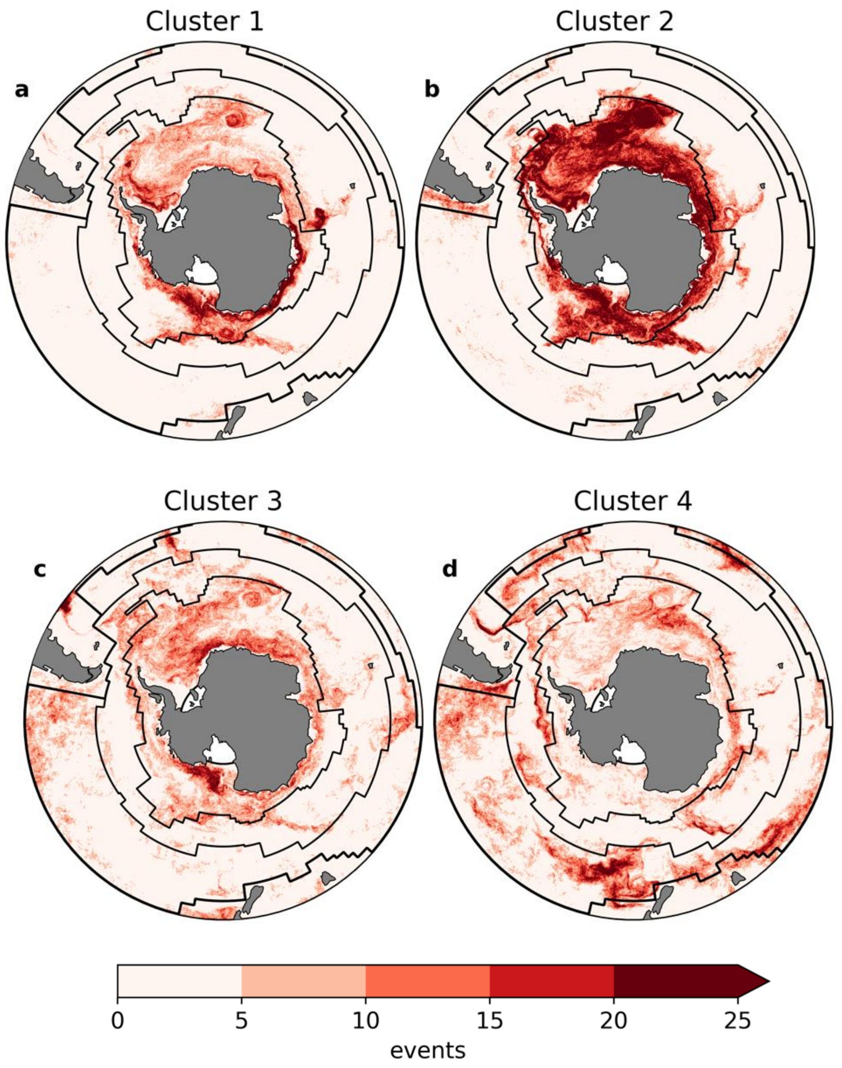
Step 1: Quantitative criteria:
Minimise SSE (blue), while maximising VRC (red)

Step 2: Comparison of cluster characteristics
Are there multiple clusters with similar characteristics?

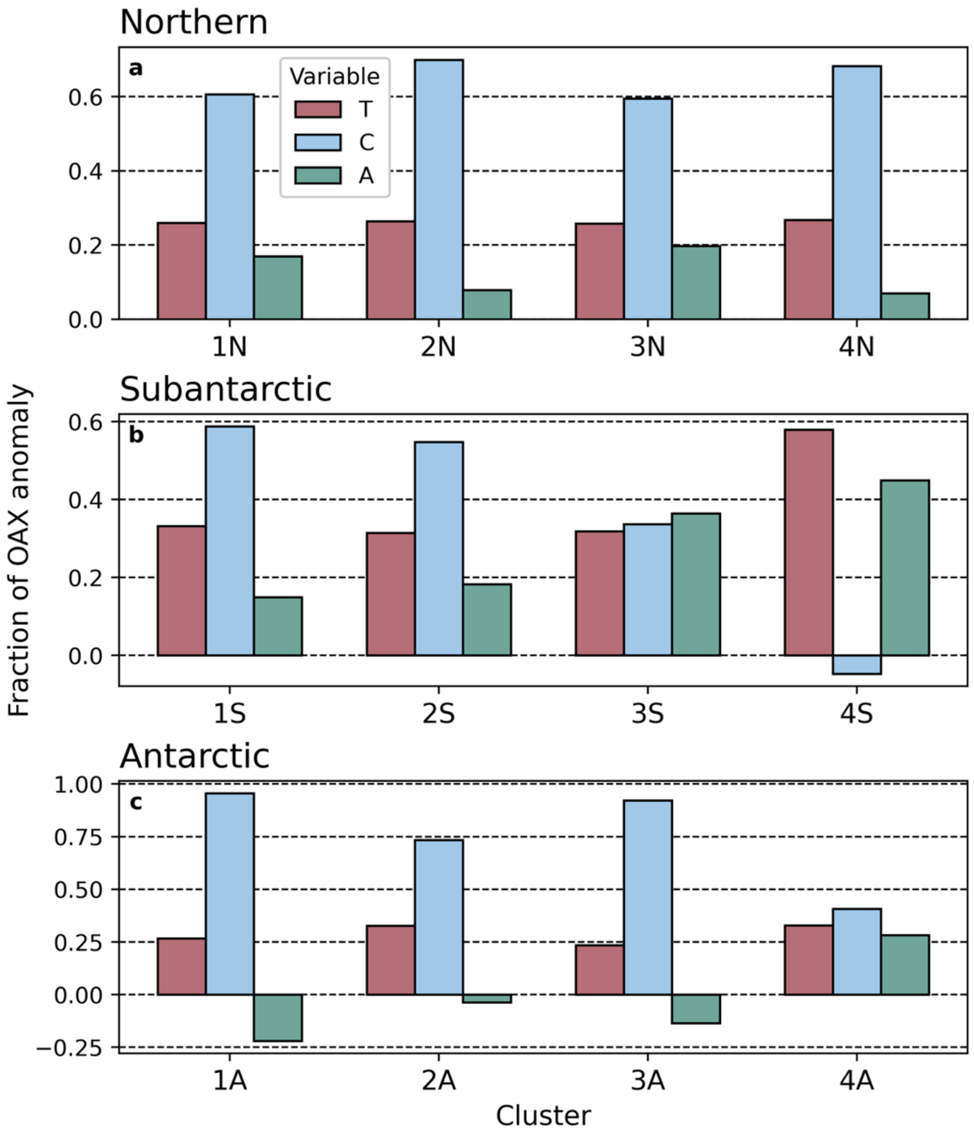
Step 3: Comparison of underlying drivers
Does changing the number of clusters change the conclusions?

Results: Southern Ocean CCX Clusters





Results: Diagnosing drivers of CCX



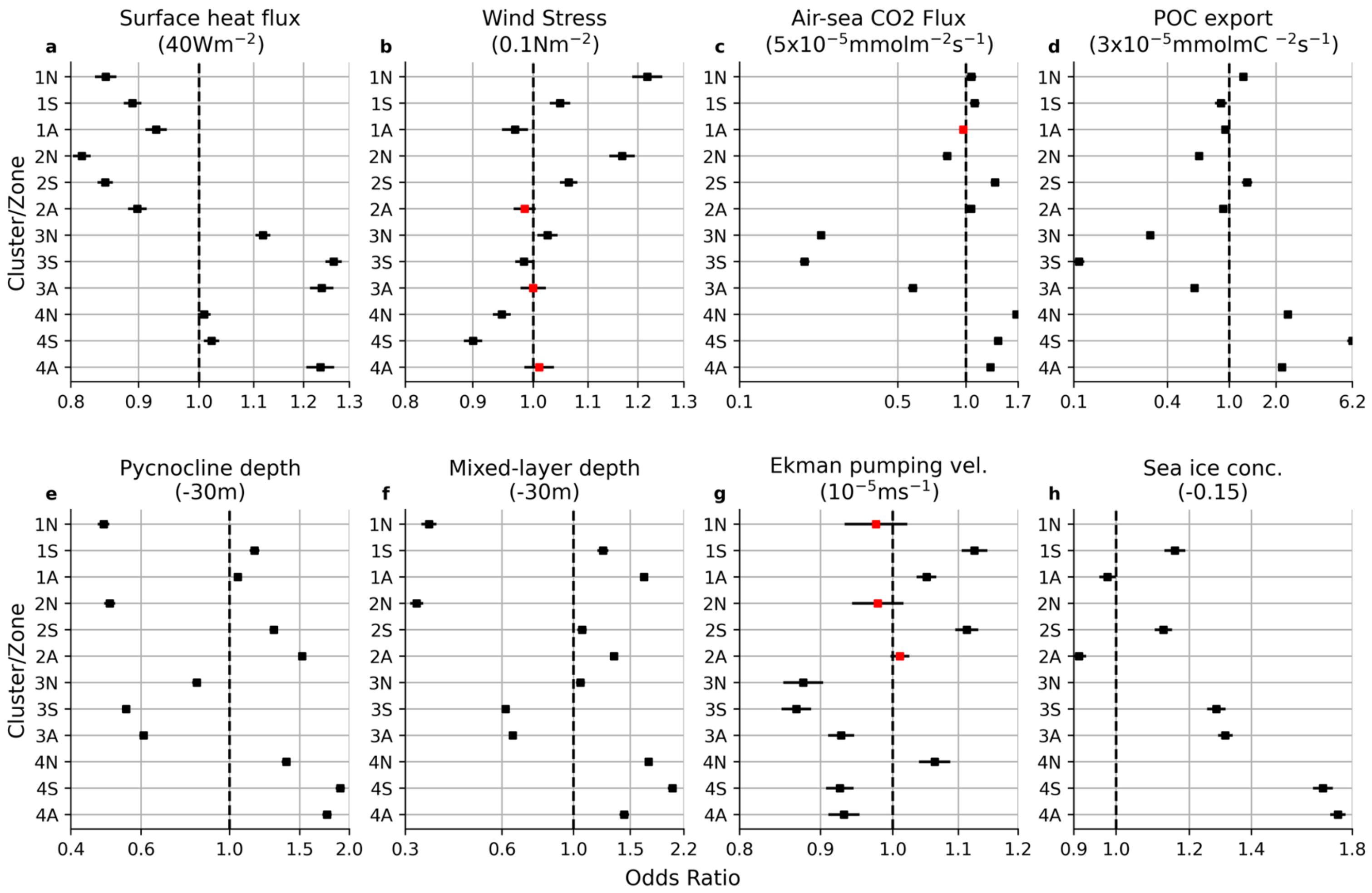
$[H^+]$ anomaly decomposition

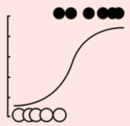
Into temperature, DIC, Alk

Contributions of temperature, DIC, and total Alk to the anomaly in H+ during CCX events

$$\Delta \mathrm{H}^+ = \frac{\partial \mathrm{H}^+}{\partial T}\Delta T + \frac{\partial \mathrm{H}^+}{\partial C}\Delta C + \frac{\partial \mathrm{H}^+}{\partial A}\Delta A + \ldots$$

Results: Diagnosing drivers of CCX





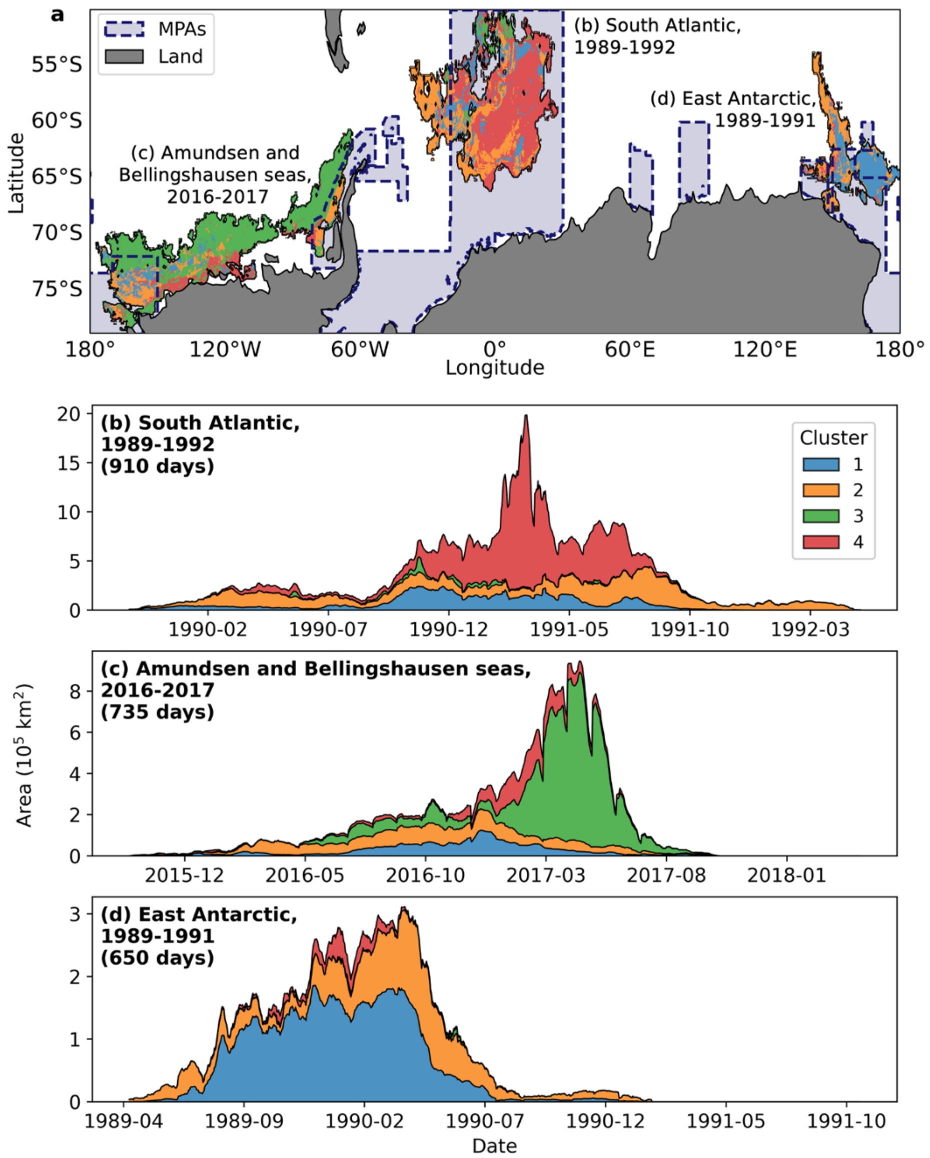
Logistic regression

Of CCX (True) and non-CCX events (False), on anomalies in model and forcing variables

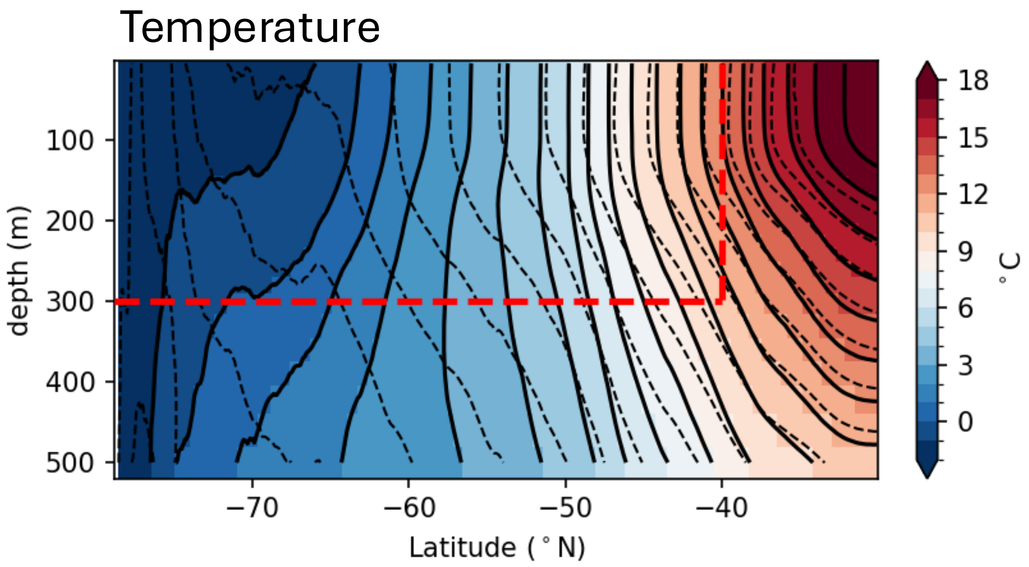
$$\mathrm{logit}(p) = \ln \frac{p}{1-p} = \beta_0 + \beta_1 X$$

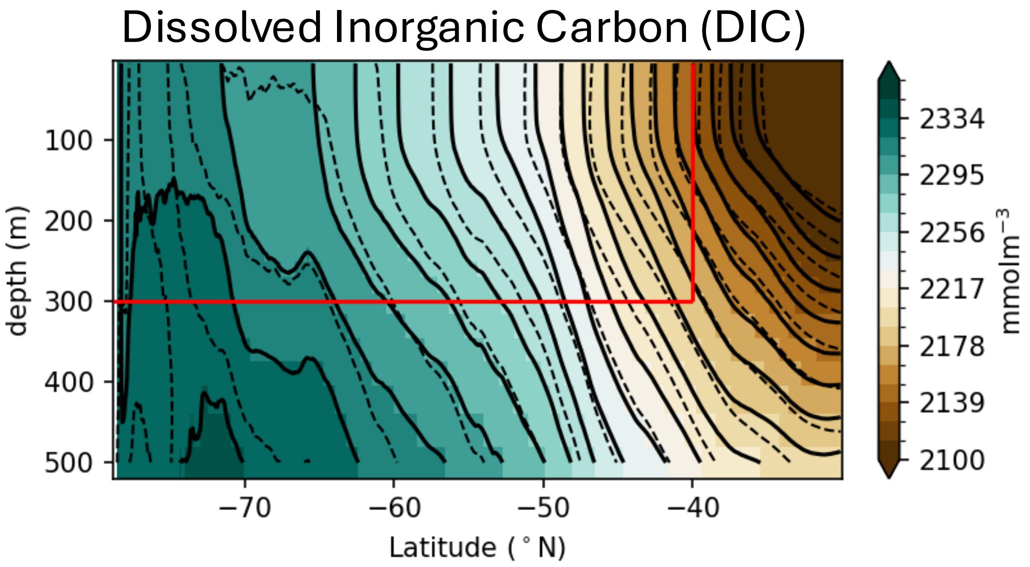
$$\mathrm{OR} = \exp \beta_1$$

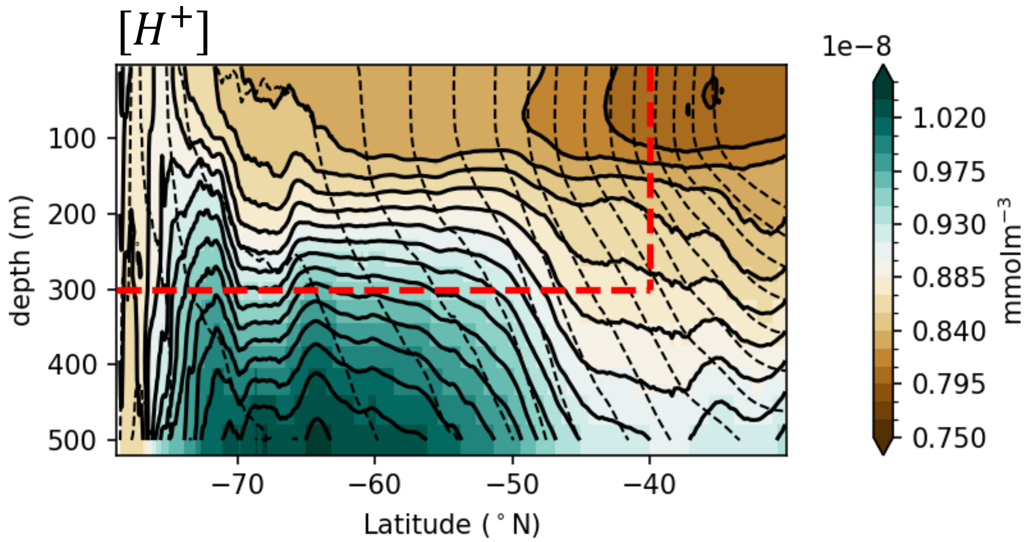
Results: CCX clusters of largest events

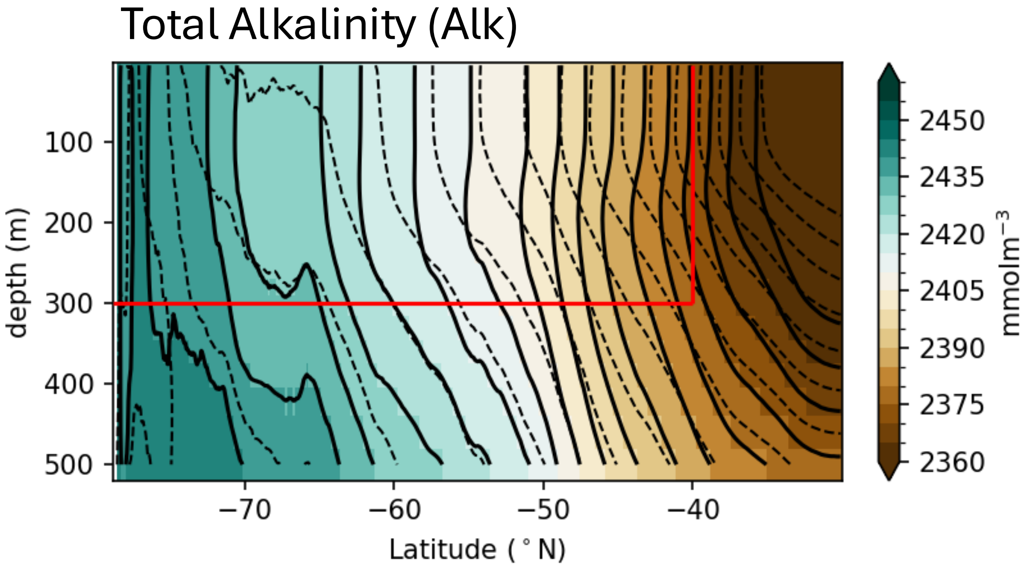


SI: Southern Ocean Mean State









SI: Southern Ocean Overturning