# The Hidden Control Behind Southern Ocean Blooms

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## MOTIVATION

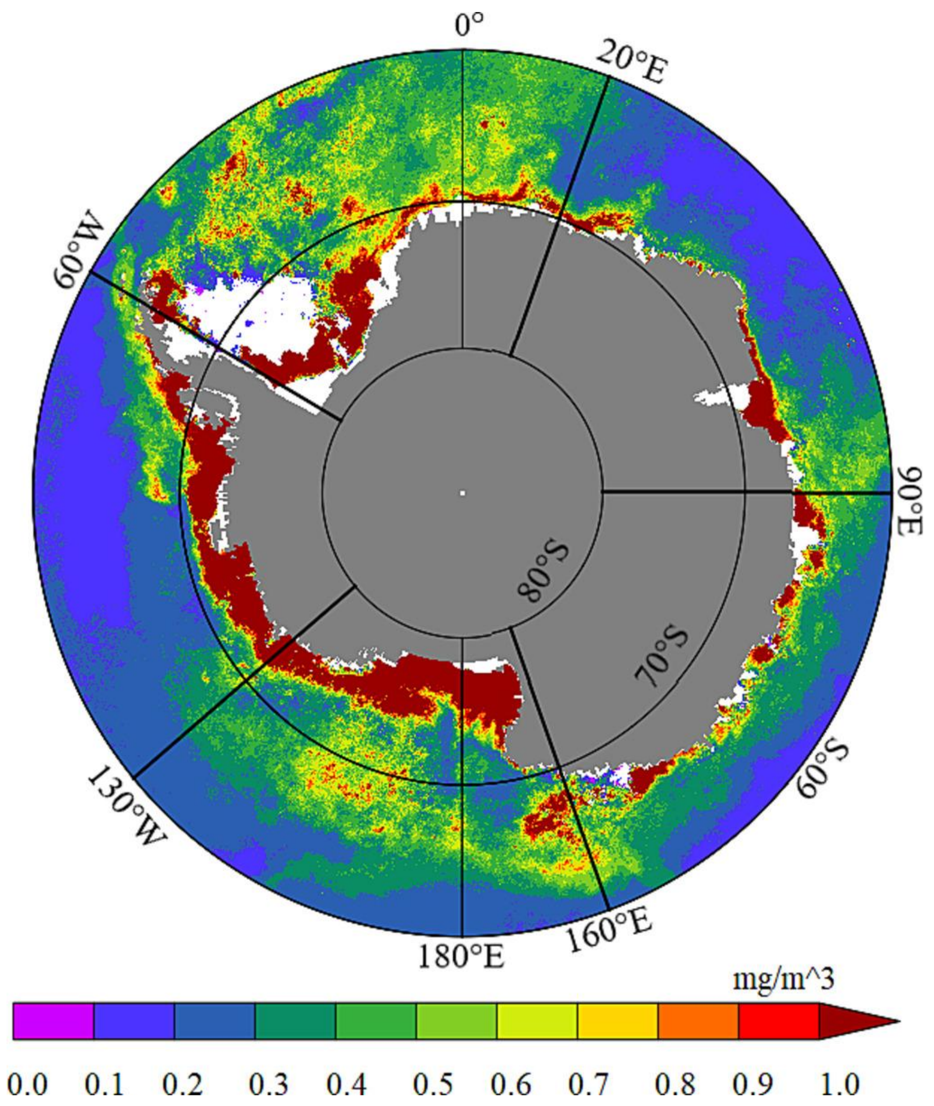


*Fig. 1: Annual climatology of Chl-a in the Southern Ocean (1997–2020) [1]*

**The Southern Ocean (SO)** is the world's largest biological carbon pump, driven by phytoplankton and sea ice, which is the switch that controls it.

**Chlorophyll-a (Chl-a)** is the satellite-observable proxy for phytoplankton biomass.

**Sea ice (SI)** controls light, stratification, and iron supply - key drivers of phytoplankton blooms.

## WHY IT MATTERS

**~50%** of global ocean anthropogenic $CO_2$ absorbed by the SO

**25%** of total global marine primary production from SO phytoplankton

**+40%** projected SO productivity increase by 2100

## SEA ICE CONTROLS THE BLOOM

*How sea ice retreat triggers the phytoplankton spring/summer bloom*

**Sea Ice Present**
High albedo blocks light; brine rejection deepens the mixed layer.

▼

**Ice Retreats**
Light penetrates; meltwater freshens the surface layer.

▼

**Stratification**
Low salinity → shallow stable Mixed Layer Depth (MLD) → Phytoplankton stay in the photic zone.

▼

**Bloom Initiates**
Light + stratification + Iron (Fe) from ice melt → rapid phytoplankton growth.

▼

**Carbon Export**
The biological pump draws $CO_2$ from the atmosphere into the deep ocean.

## SEASONALITY

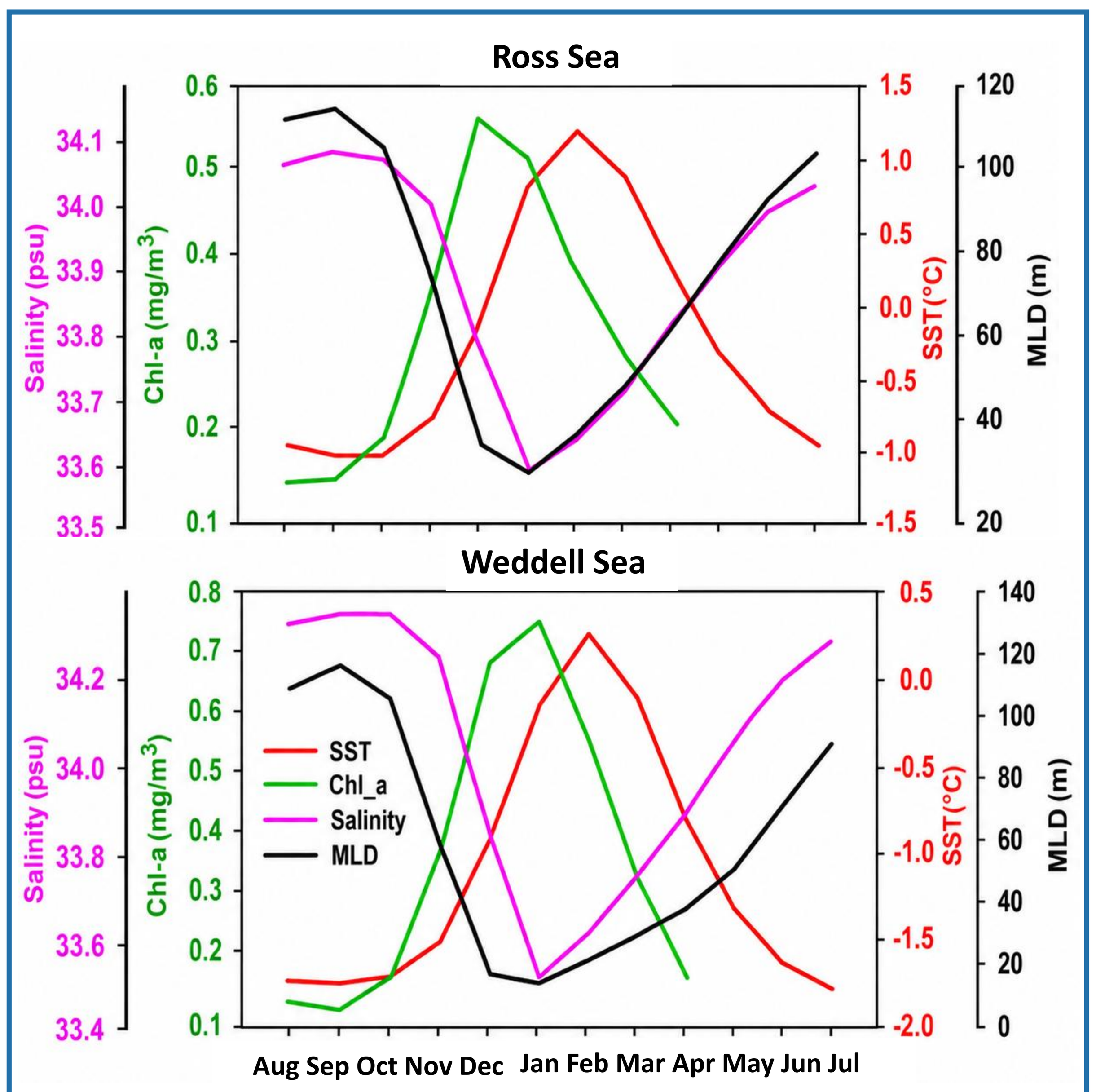


*Fig 2: Monthly climatology time series of Chl-a, Salinity, MLD, and SST [1]*

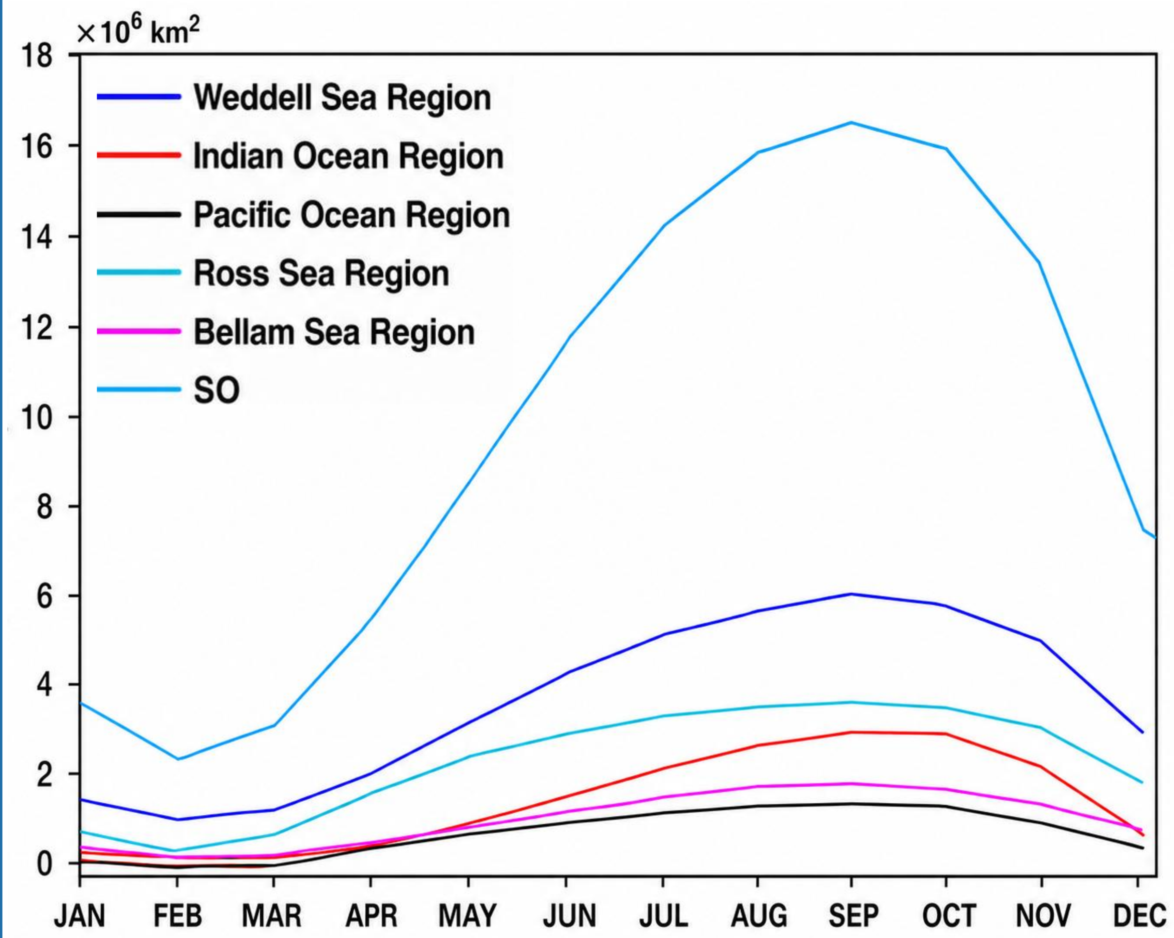


*Fig 3: Monthly climatology of SI extent from 2003 to 2017 [2]*

- SI extent peaks during winter (Sep–Oct)
- Elevated Chl-a follows sea ice retreat.
- Shallow MLD + more light → Chl-a peak (bloom).
- Chl-a and Salinity vary inversely.
- This supports a stratification-driven phytoplankton response.

## A CHANGING SOUTHERN OCEAN

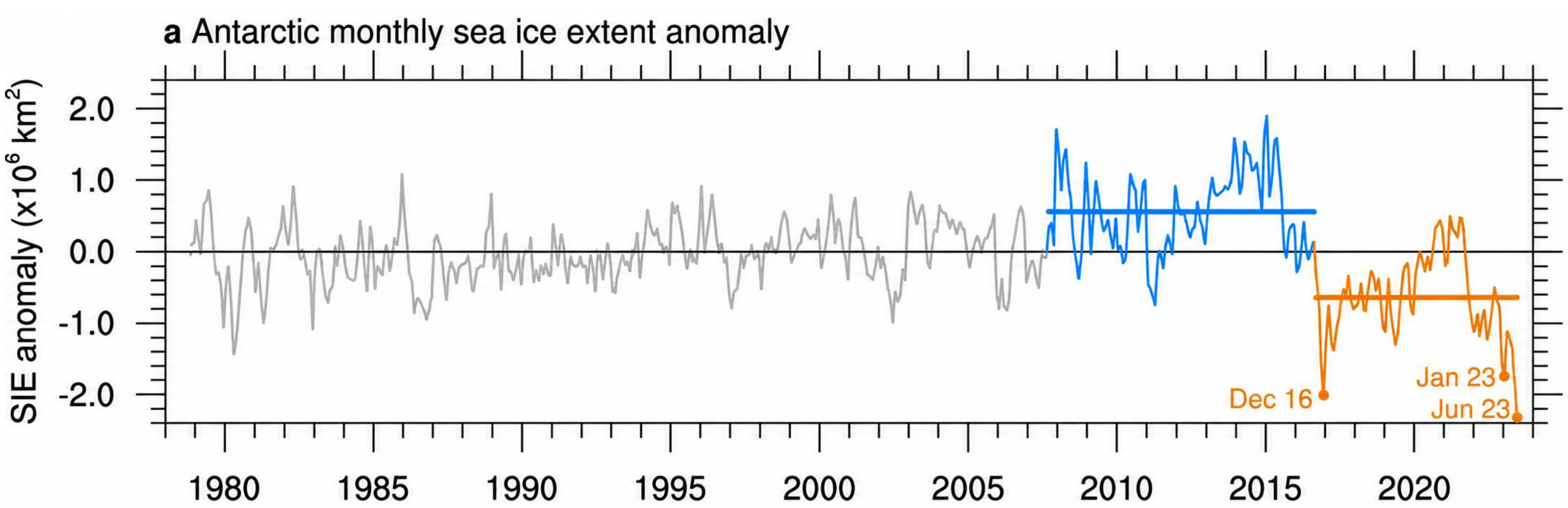


***Fig. 4:** Antarctic monthly sea ice extent (SIE) anomaly time series from NSIDC [4]*

- Antarctic SI extent has declined sharply since 2016, reaching record lows in 2023.
- Evidence suggests this may represent a **state shift** in SO sea ice dynamics, not just normal interannual variability.
- Spring phytoplankton blooms depend on **meltwater-driven stratification**.

- Reduced sea ice leads to:
  - Less melt water → Saltier surface waters
  - Weaker stratification
  - Deeper mixed layers
- In typical low-SIE years, blooms may start earlier, but deeper mixing disrupts phytoplankton growth, resulting in shorter bloom duration and lower biomass.
- The 2023 extreme SI loss produced regionally contrasting responses, with some areas showing earlier, longer blooms and higher biomass, while others remained limited.
- This highlights that phytoplankton responses to SI decline are **region-dependent and not uniform across the SO**.

**The mechanism that drives Southern Ocean blooms is the same mechanism now being dismantled by climate change.**

## CONCLUSIONS

- SI retreat is the primary physical trigger of SO phytoplankton blooms, operating through meltwater stratification, light availability, and Fe supply.
- Bloom–sea ice coupling varies across the SO, with some regions showing stronger responses to sea-ice change than others.
- Antarctic SIE has undergone a dramatic decline since 2016, consistent with a regime shift rather than natural variability.
- The bloom-ice relationship is already shifting. Responses are spatially variable and not yet fully predictable.
- As Antarctic sea ice continues to decline, a key question remains: will future phytoplankton blooms follow historical patterns, or emerge under a new regime?

**References**

[1] Elementa: Science of the Anthropocene Prakash, S. et al. (2025). Phytoplankton dynamics in the Antarctic marginal ice zone: Trends and drivers.
[2] Behera, N., Swain, D. & Sil, S. (2020). Effect of Antarctic sea ice on chlorophyll concentration in the Southern Ocean. Deep-Sea Research II, 178: 104853.
[3] Schlosser, TL, and Strutton, PG. 2025. Phytoplankton blooms in the new Southern Ocean sea-ice regime. Elem Sci Anth, 13: 1. DOI: https://doi.org/10.1525/elementa.2024.00055
[4] Purich, A., Doddridge, E.W. Record low Antarctic sea ice coverage indicates a new sea ice state. Commun Earth Environ 4, 314 (2023). https://doi.org/10.1038/s43247-023-00961-9