# Tracking carbon dioxide in the Southern Ocean


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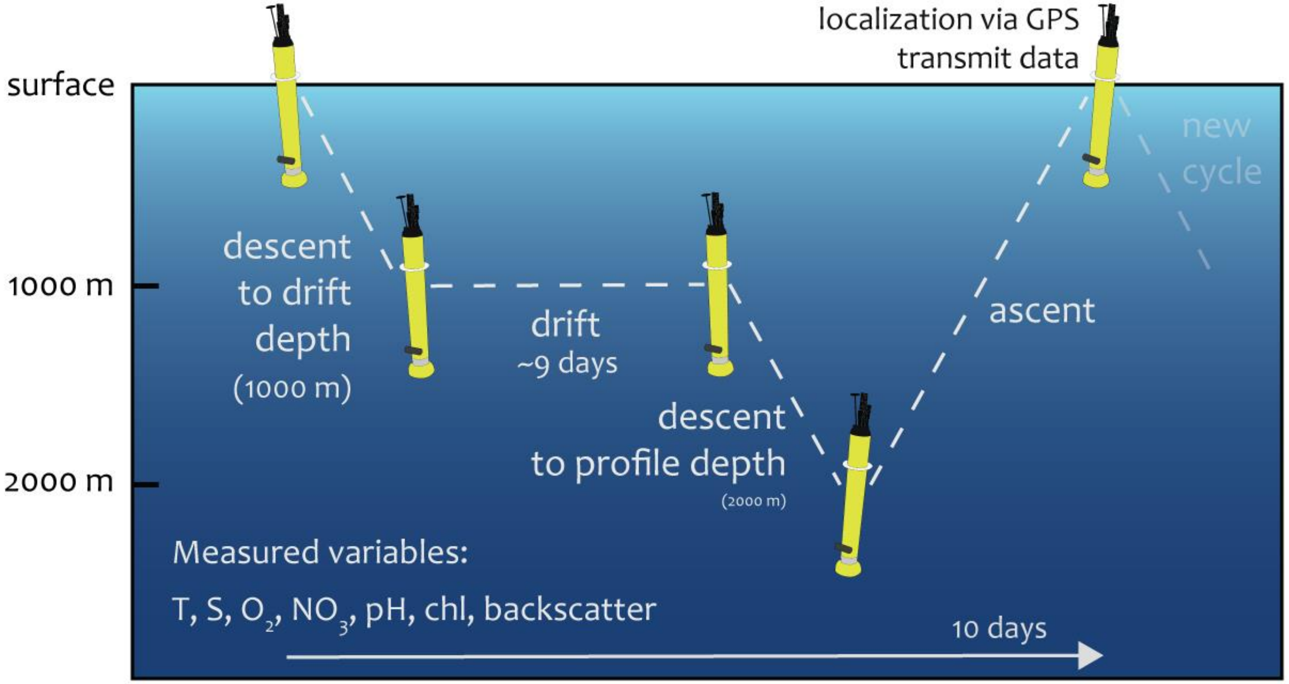
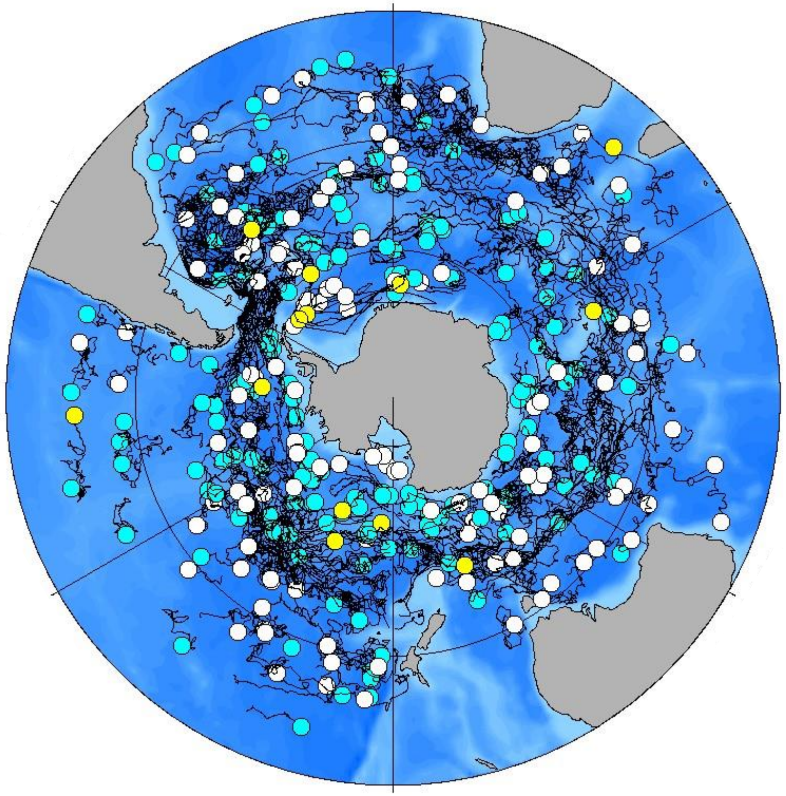
Kat Smith

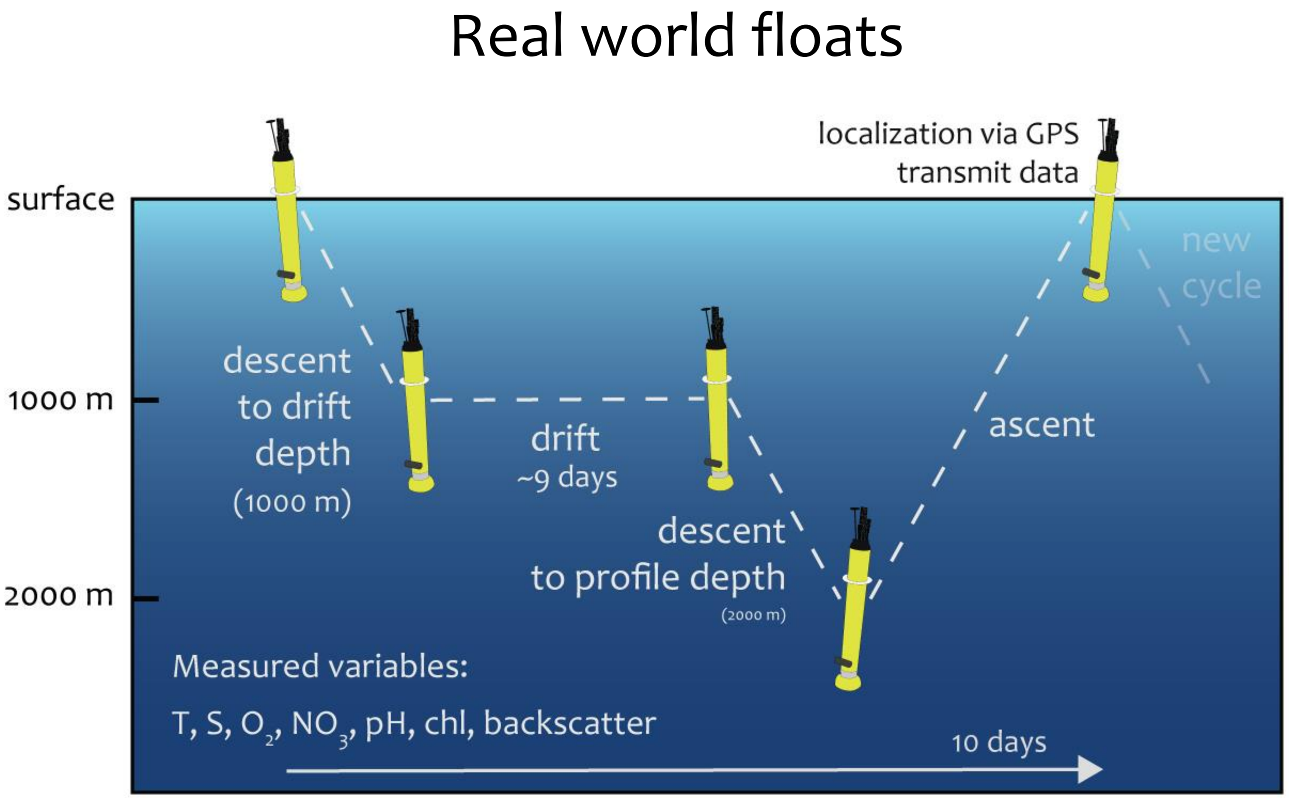

U.S. DEPARTMENT OF ENERGY

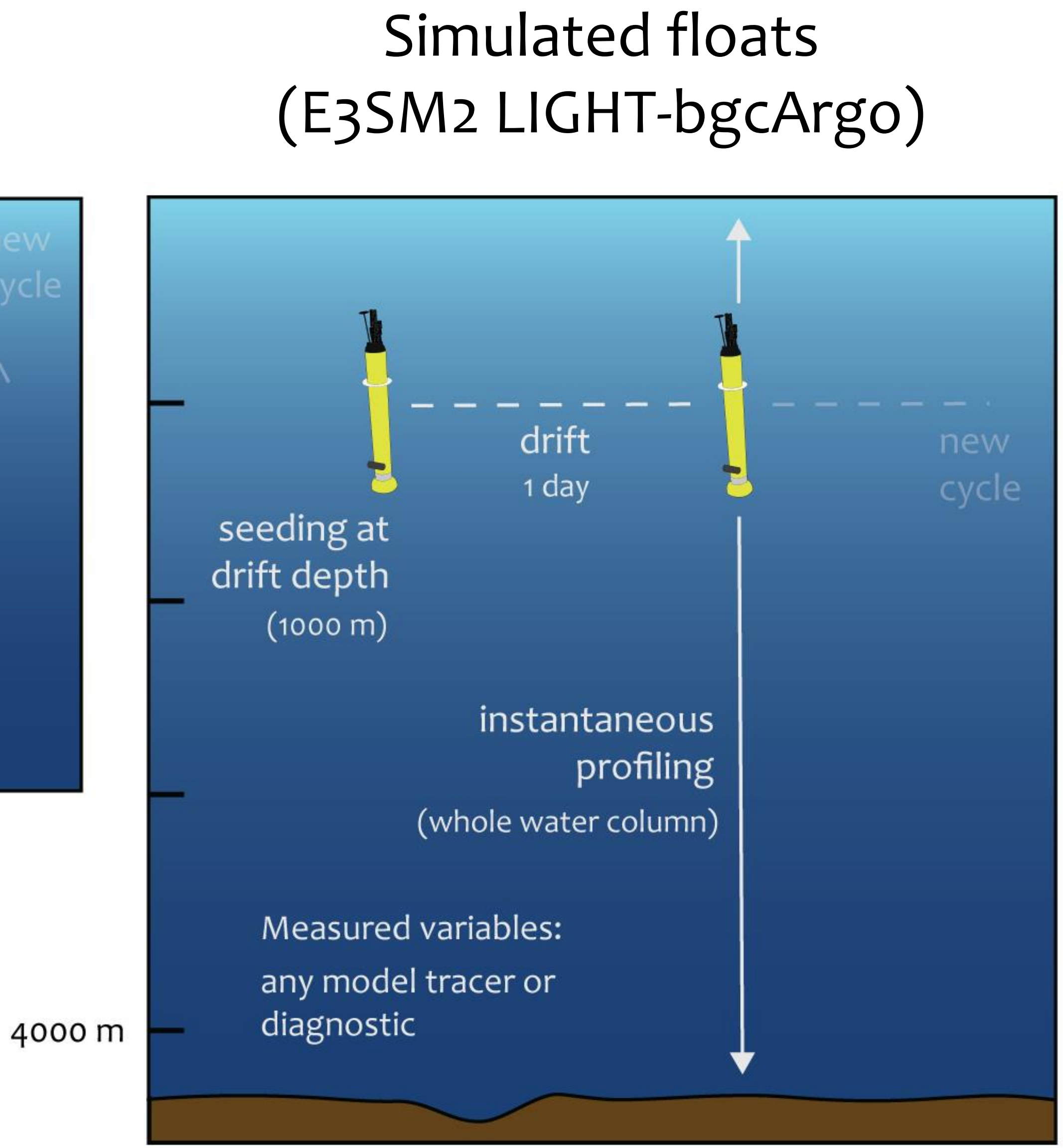
# Biogeochemical-Argo floats



# Simulated Biogeochemical-Argo floats in E3SM

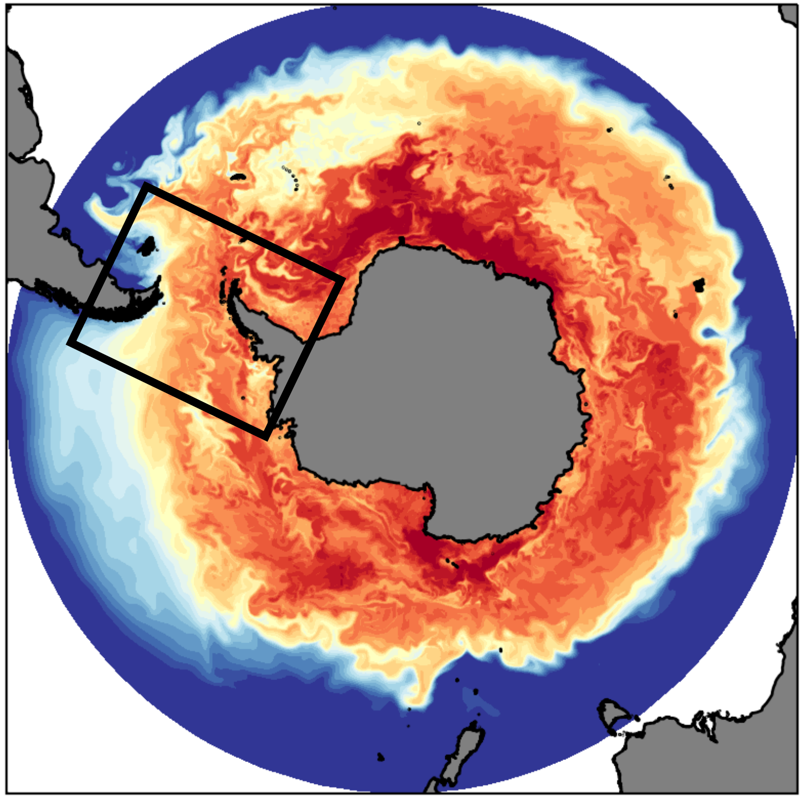


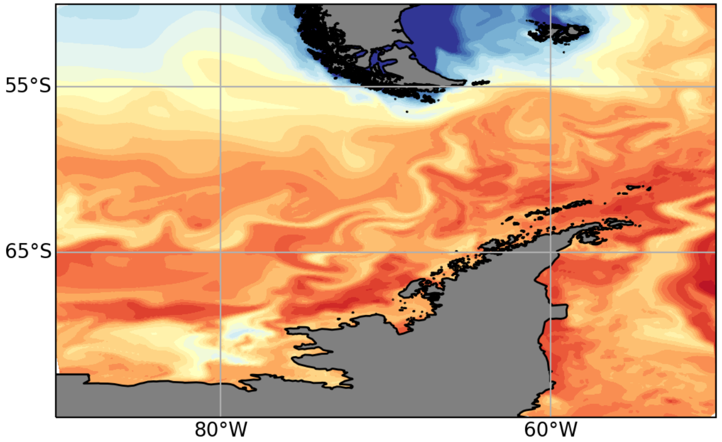




Nissen et al. (in press, GMD)

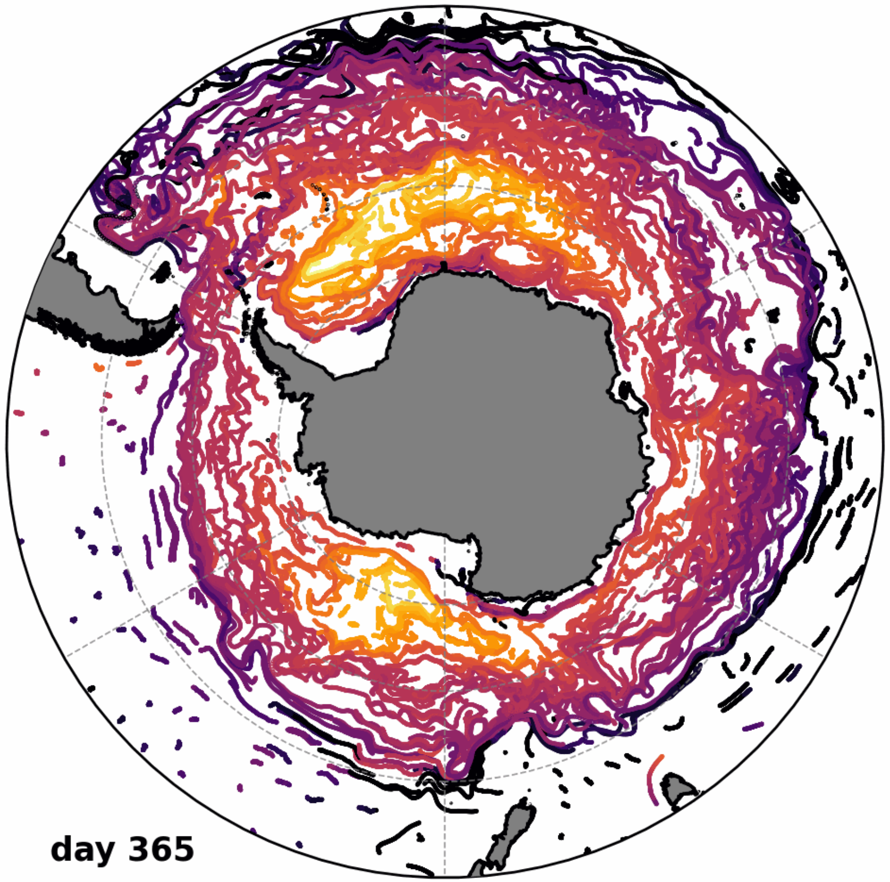
# Simulated floats on the Southern Ocean Regionally Refined Mesh

surface nitrate



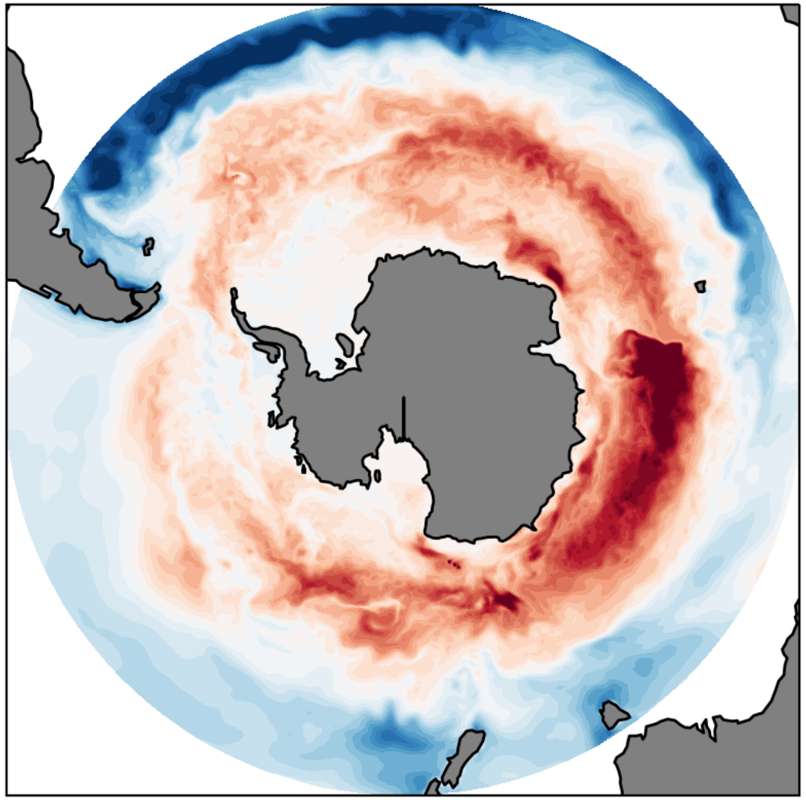



surface dissolved inorganic carbon
(recorded on synthetic floats)



# So. Many. Applications.

Air-sea $CO_2$ flux from floats?



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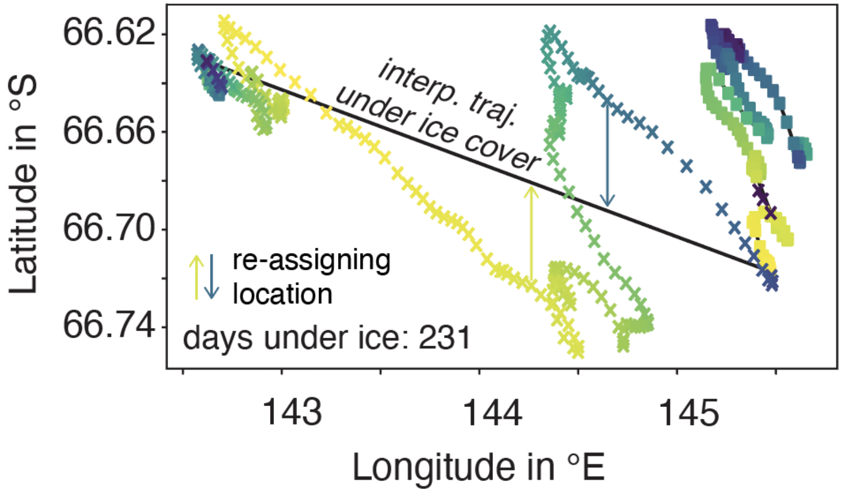
Under the ice: what are floats missing?

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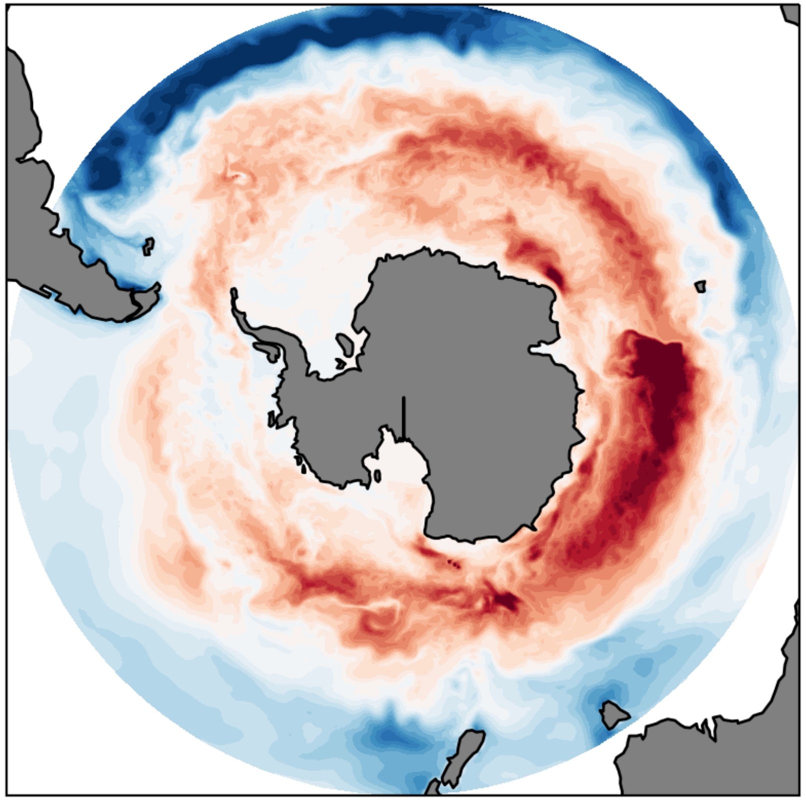

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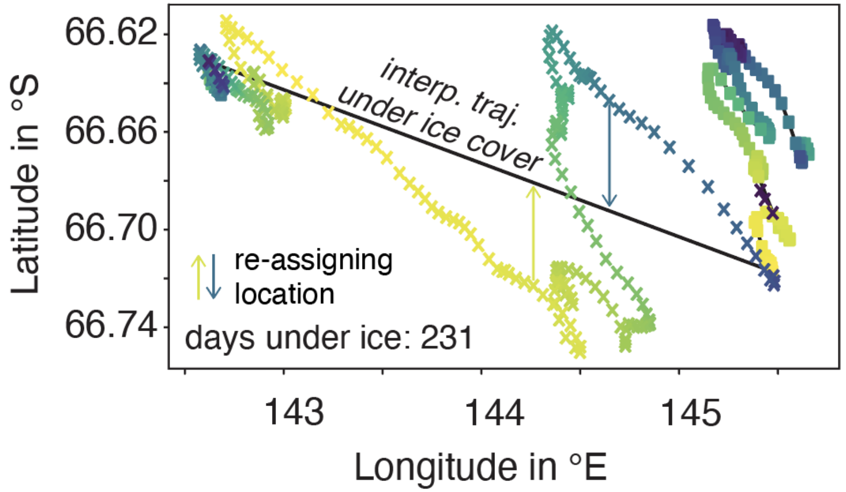


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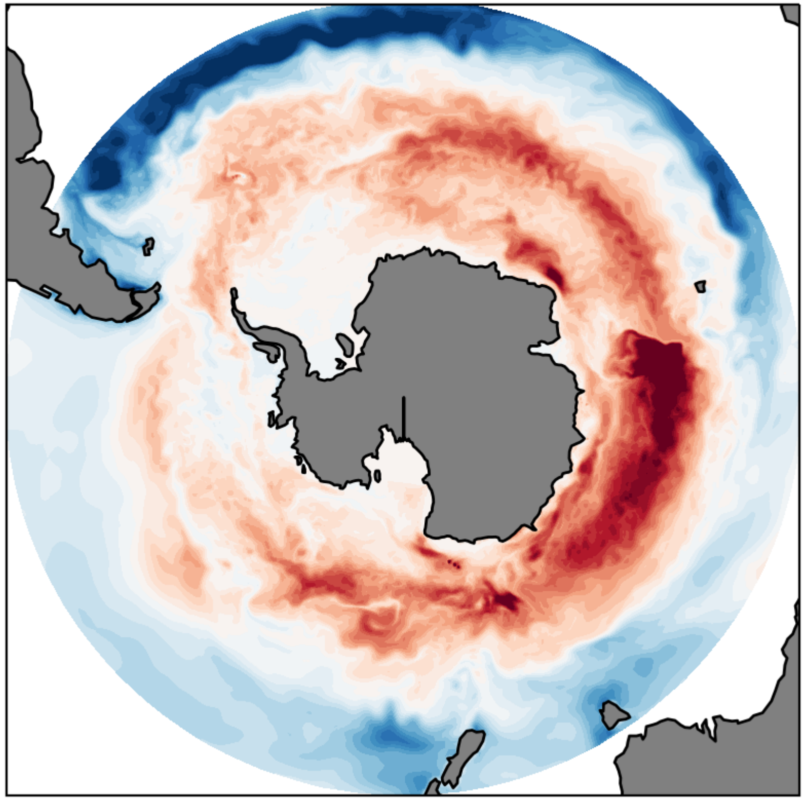
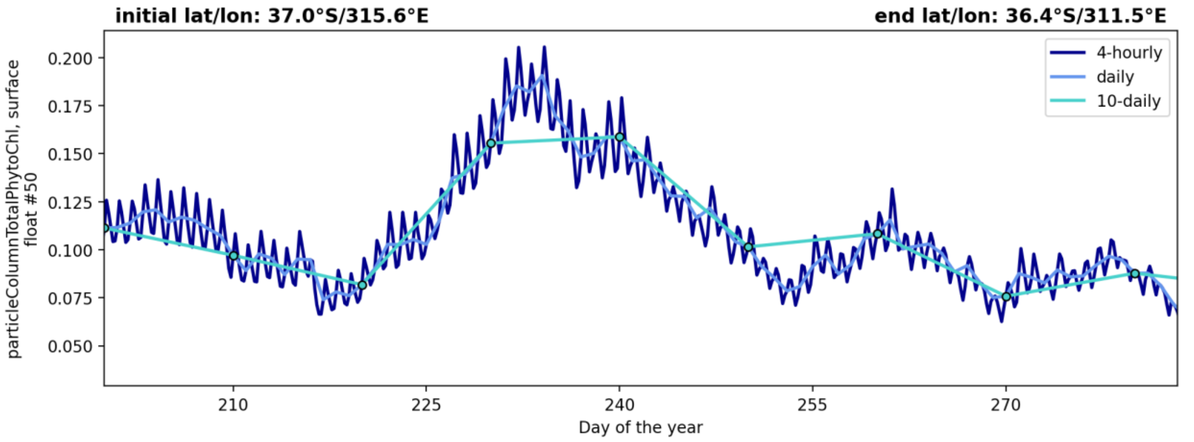
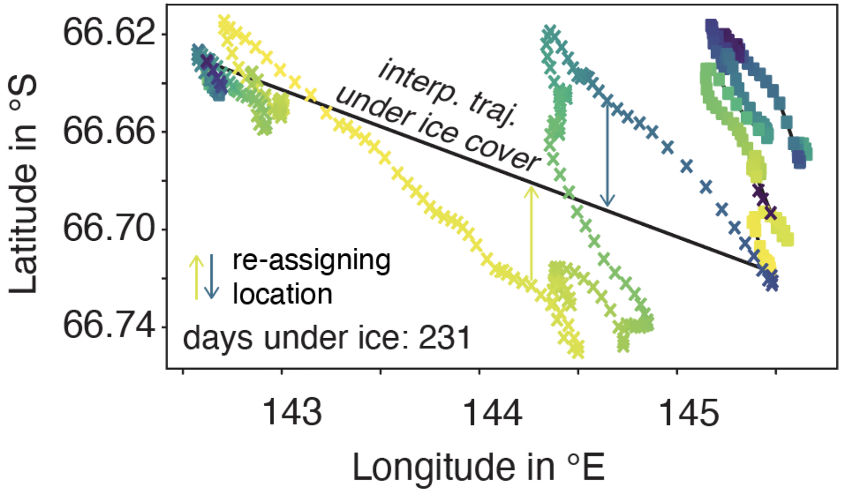


What is the ideal float profiling frequency and timing?

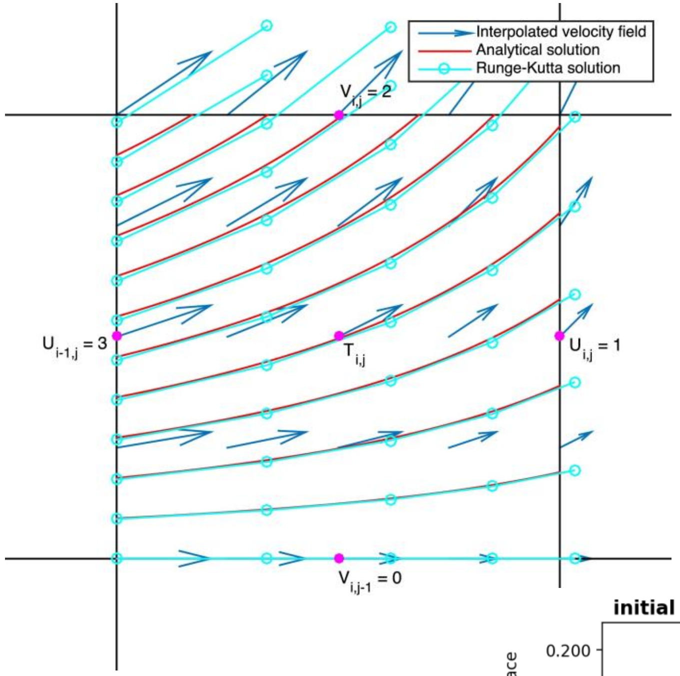


# So. Many. Applications.

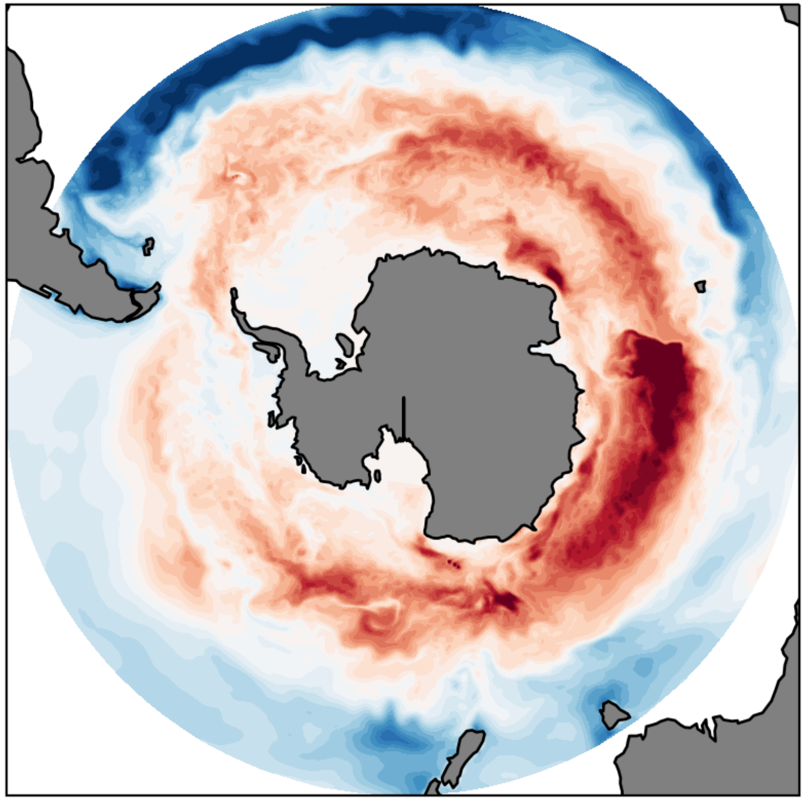
## Under the ice: what are floats missing?



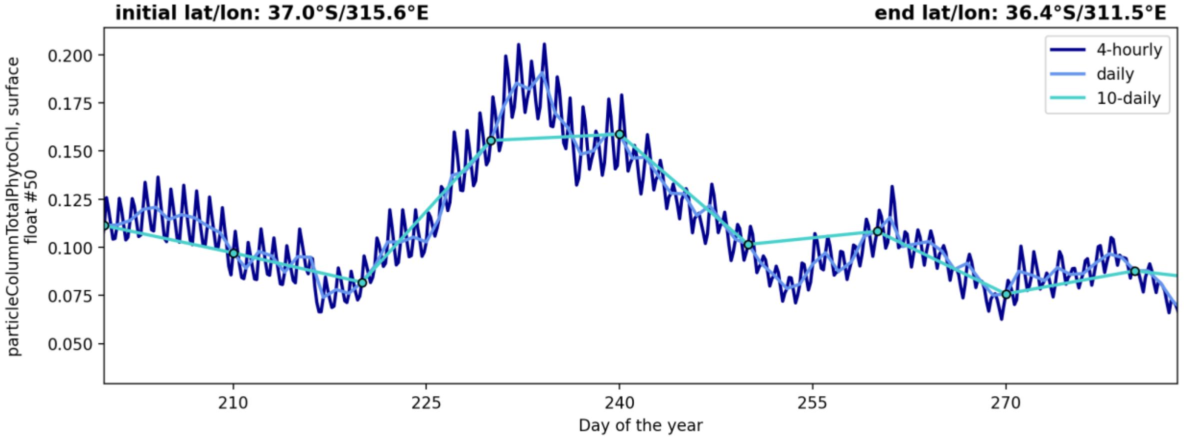

## Online vs. offline sampling: does it matter?



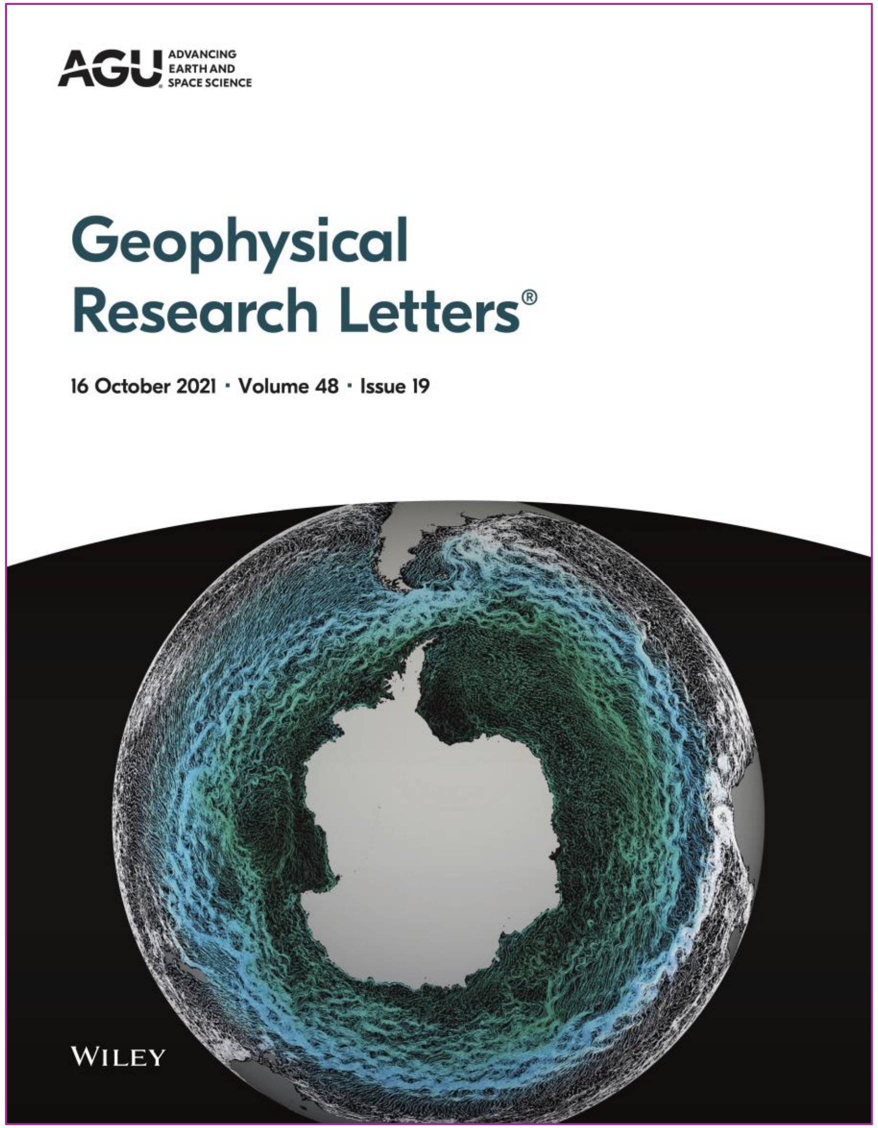

## Air-sea $CO_2$ flux from floats?



## What is the ideal float profiling frequency and timing?



# Want to learn more?




ANNUAL REVIEWS

*Annual Review of Marine Science*

## The Four-Dimensional Carbon Cycle of the Southern Ocean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**Keywords**

Southern Ocean, ocean carbon cycle, overturning circulation, seasonal cycle, zonal asymmetry, mesoscale variability, Southern Hemisphere storms



**Abstract**

The Southern Ocean plays a fundamental role in the global carbon cycle, dominating the oceanic uptake of heat and carbon added by anthropogenic activities and modulating atmospheric carbon concentrations in past, present, and future climates. However, the remote and extreme conditions found there make the Southern Ocean perpetually one of the most difficult places on the planet to observe and to model, resulting in significant and persistent uncertainties in our knowledge of the oceanic carbon cycle there. The flow of carbon in the Southern Ocean is traditionally understood using a zonal mean framework, in which the meridional overturning circulation drives the latitudinal variability observed in both air–sea flux and interior ocean carbon concentration. However, recent advances, based largely on expanded observation and modeling capabilities in the region, reveal the importance of processes acting at smaller scales, including basin-scale zonal asymmetries in mixed-layer depth, mesoscale eddies, and high-frequency atmospheric variability. Assessing the current state of knowledge and remaining gaps emphasizes the need to move beyond the zonal mean picture and embrace a four-dimensional understanding of the carbon cycle in the Southern Ocean.


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RESEARCH ARTICLE

10.1029/2023JC019815


**Key Points:**

- We build a Southern Ocean observation-based mixed layer inorganic carbon budget with circumpolar coverage and a full seasonal cycle
- Biological activity and circulation dominate the seasonal variations in mixed layer dissolved inorganic carbon
- Wind-driven transport from the seasonal ice zone contributes to carbon outgassing in the Antarctic Circumpolar Current

**Supporting Information:**

Supporting Information may be found in the online version of this article.


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**Citation:**

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**Author Contributions:**

**Conceptualization:** Alison R. Gray
**Formal analysis:** Jade Sauvé, Alison R. Gray, Channing J. Prend, Seth M. Bushinsky
**Funding acquisition:** Stephen C. Riser
**Investigation:** Jade Sauvé
**Methodology:** Jade Sauvé, Alison R. Gray
**Software:** Jade Sauvé
**Supervision:** Stephen C. Riser
**Visualization:** Jade Sauvé




## Carbon Outgassing in the Antarctic Circumpolar Current Is Supported by Ekman Transport From the Sea Ice Zone in an Observation-Based Seasonal Mixed-Layer Budget


Jade Sauvé[1], Alison R. Gray[1], Channing J. Prend[1,2], Seth M. Bushinsky[3], and Stephen C. Riser[1]

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**Abstract** Despite its importance for the global cycling of carbon, there are still large gaps in our understanding of the processes driving annual and seasonal carbon fluxes in the high-latitude Southern Ocean. This is due in part to a historical paucity of observations in this remote, turbulent, and seasonally ice-covered region. Here, we use autonomous biogeochemical float data spanning 6 full seasonal cycles and with circumpolar coverage of the Southern Ocean, complemented by atmospheric reanalysis, to construct a monthly climatology of the mixed layer budget of dissolved inorganic carbon (DIC). We investigate the processes that determine the annual mean and seasonal cycle of DIC fluxes in two different zones of the Southern Ocean—the Sea Ice Zone (SIZ) and Antarctic Southern Zone (ASZ). We find that, annually, mixing with carbon-rich waters at the base of the mixed layer supplies DIC which is, in the ASZ, either used for net biological production or outgassed to the atmosphere. In contrast, in the SIZ, where carbon outgassing and the biological pump are weaker, the surplus of DIC is instead advected northward to the ASZ. In other words, carbon outgassing in the southern Antarctic Circumpolar Current (ACC), which has been attributed to remineralized carbon from deep water upwelled in the ACC, is also due to the wind-driven transport of DIC from the SIZ. These results stem from the first observation-based carbon budget of the circumpolar Southern Ocean and thus provide a useful benchmark to evaluate climate models, which have significant biases in this region.

**Plain Language Summary** The ocean surrounding the frozen continent of Antarctica plays an important role in the global cycling of carbon and is important for the climate of our planet. Despite its importance, there are gaps in our knowledge due to the difficulties involved in collecting data from a remote, seasonally ice-covered ocean. In this study, we use year-round data collected by autonomous instruments that can even measure under sea ice. We build a budget of carbon in the surface layer of the ocean, quantifying the different sources and sinks of inorganic carbon. We find that carbon mostly enters the surface layer through mixing with carbon-rich waters below. In the more stormy, northern part of our study area, this carbon is then either consumed by photosynthesis in the ocean or it is transferred to the atmosphere. In the southernmost region, biological activity and gas transfer at the ocean-atmosphere interface is hindered by the presence of sea ice and the surplus of carbon is instead transferred north by wind-driven circulation. Our results show that year-round measurements of carbon are necessary to understand carbon cycling in the region and we provide a useful product to compare to global simulations of the Earth system.


### 1. Introduction

The Southern Ocean plays a significant role in the global carbon cycle. Around 40% of oceanic uptake of anthropogenic carbon dioxide ($CO_2$) occurs in the waters south of 35°S (DeVries, 2014). Ekman divergence driven by strong westerly winds leads to a combination of upwelling and downwelling of natural and anthropogenic carbon, respectively. Consequently, the Southern Ocean is a strong $CO_2$ sink between 35 and 55°S, although the picture is not as clear at higher latitudes (Gruber et al., 2019). Historically, observations from this remote region have been strongly biased towards summer and limited spatially, particularly in the seasonally ice-covered areas. Data from autonomous biogeochemical floats deployed by the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project showed a stronger wintertime outgassing of carbon dioxide at high latitudes than expected, leading to a low Southern Ocean annual mean carbon uptake (Bushinsky et al., 2019;




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## Using synthetic float capabilities in E3SMv2 to assess spatio-temporal variability in ocean physics and biogeochemistry


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[3]School of Oceanography, University of Washington, Seattle, WA, USA

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## Going with the flow: Evaluating modeled Southern Ocean biogeochemistry using Argo float observations


*Alison R. Gray[1], *Nicole S. Lovenduski[2], Yohei Takano[3], Raffaele Bernardello[4], Kristen Falcinelli[2], Takamitsu Ito[5], Keith Lindsay[6], Mathew Maltrud[3], Cara Nissen[1], Jade Sauvé[2], Katherine M. Smith[3], and Katsuya Toyama[7]

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The end!

# Simulated floats on the Southern Ocean Regionally Refined Mesh