Uncharted pathways of the Southern Ocean's sink of carbon dioxide

The ocean plays a buffering role in the climate system and slows down climate change by absorbing huge amounts of heat and carbon dioxide. Since the industrial revolution, the ocean has taken up, respectively, 90 per cent and 30 per cent of the excess heat and carbon dioxide (CO_2) introduced into the Earth system due to human activities.

Adobe Stock © alonesdj

Among all the ocean basins, the remote Southern Ocean stands out for its impact on the pace of climate change by being responsible for 43 per cent and 75 per cent, respectively, of the excess carbon and heat uptake by the ocean. This disproportionately important contribution, relative to the size of the Southern Ocean, is driven by the unique large-scale circulation patterns in this region–where old, deep water masses upwell to the surface and interact with the atmosphere before sinking back to the deep ocean. Unfortunately, recent evidence suggests that the Southern Ocean's sinks of heat and carbon are threatened by ongoing changes in wind patterns and ocean circulation caused by global warming. However, the response of the carbon sink to these perturbations is still very uncertain due to our limited understanding of the processes responsible for CO_2 sequestration, which negatively impacts our confidence in climate projections for the coming decades.

The Marie Skłodowska-Curie Action "Southern Ocean Carbon Uptake" (SO-CUP) addressed this critical problem by improving our mechanistic understanding of the Southern Ocean carbon sink. Specifically, the project focused on a group of water masses, the Sub-Antarctic Mode Waters (SAMW), responsible for most of the CO_2 uptake in the Southern Ocean. The carbon concentration in these water masses is determined during winter, when they are exposed to the atmosphere in a series of strong surface mixing hotspots in the Indian and Pacific Oceans, along the northern flank of the Antarctic Circumpolar Current (ACC), a large current system encircling the globe at 50–60ºS (Figure 1A). The scarcity of observations in this remote region has historically limited our understating of the processes controlling SAMW carbon drawdown. This observational gap has been progressively relieved in recent years with the advent of autonomous technologies for ocean observation. Since 2014, the US SOCCOM programme has deployed hundreds of autonomous profiling floats equipped with biogeochemical sensors into the Southern Ocean, allowing unprecedented scrutiny of the Southern Ocean's carbon cycle. SO-CUP's main goal was to leverage the ongoing expansion of in situ observations to identify and quantify the processes governing the drawdown of atmospheric CO_2 by SAMW.

SO-CUP relied on a twofold strategy, combining the analysis of observational data from the SOCCOM floats with the output of an ocean physical and biogeochemical 3-dimensional computer model of the Southern Ocean (B-SOSE), fed with float data. The analysis of these new datasets revealed a hidden wealth of water pathways and processes influencing SAMW formation, transforming our view of the Southern Ocean circulation and carbon sink. In the traditional view (outlined in a previous article in the PRJ, vol. 9, pages 94–96, 2021), SAMW ultimately originate from the deep (>2000 m) Circumpolar Deep Waters (CDW) sourced in the North Atlantic centuries ago. CDW upwell to the ocean surface around Antarctica and travel northward across the Antarctic Circumpolar Current due to wind-induced flows before sinking back to the ocean interior as the shallower (<1000 m) SAMW. During their transit at the Southern Ocean's surface, CDW would take up carbon from the air to equilibrate with the present-day atmosphere, which has much higher CO_2 compared to the time when CDW were last in contact with it, before the industrial revolution. The analysis performed during SO-CUP showed that this is only part of the story, that SAMW formation pathways are multiple, and so are the competing processes determining the associated CO_2 uptake.

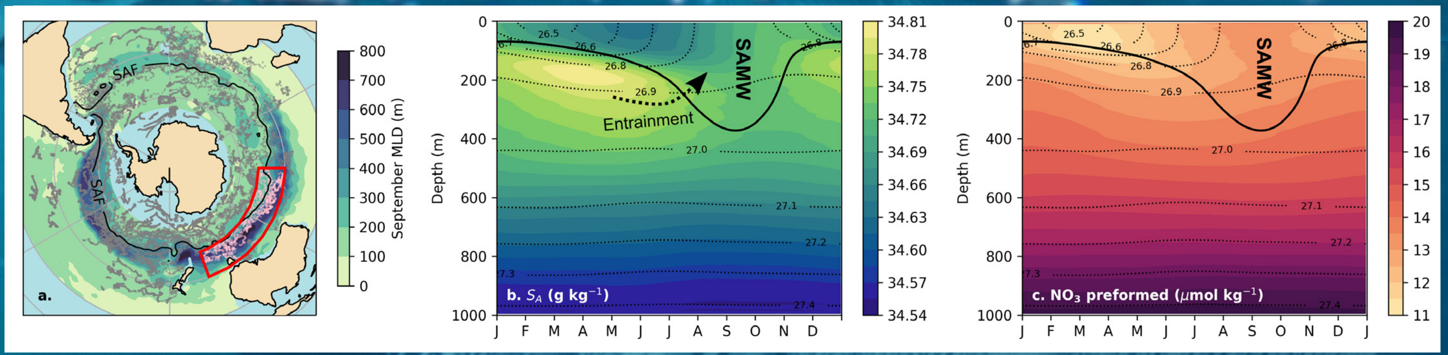

Figure 1: (A) Map of the Southern Ocean showing the locations of the SOCCOM float profiles (dots), the mean depth of the surface mixed-layer (colour shading) and the position of the sub-Antarctic front (SAF, black line), which follows the main pathway of the Antarctic Circumpolar Current; seasonal cycles of salinity (S_A, B) and nitrate concentration (NO_3, C) as a function of month (x axis) and depth (y axis) in the SAMW formation area of the Indian Ocean (red box and pink dots in panel a). The black think line in B,C represents the depth of the surface well-mixed layer. Adapted from Fernández Castro et al., 2022. The dashed line in panel b) depicts the entrainment of high-salinity, low-nutrient subtropical waters into the winter surface mixed layer, thus contributing to SAMW.

Surprises from float observations

SO-CUP opened a window into this complexity with the analysis of the seasonal cycles of salt and nitrate concentrations, derived from float data in the areas of SAMW formation (Figure 1B,C). The black line indicates the depth of the well-mixed surface layer (due to wind-driven mixing and cooling). The well-mixed layer is deeper during winter (~400 m), and SAMW acquire their properties there before leaving the ocean surface in spring and travelling away from the formation region. The seasonal variations in salinity revealed a surprising feature: the build-up of high salt concentrations between 200 and 400 m depth during the summer months. This subsurface pattern is opposed to that in the surface layer, where salinity decreases during summer due to the northward advection of Antarctic waters, ultimately originating from CDW and becoming fresher due to ice melt. The high-salinity imprint of the subsurface waters suggests a subtropical origin (subtropical waters are salty due to evaporation) north of the SAMW formation region. The subtropical signature is confirmed by a decrease in nitrate concentration during summer (subtropical waters have low nutrient concentrations). The subsurface subtropical waters are entrained into the well-mixed layer as it gets deeper between July and October, contributing to the SAMW volume and property budgets (Figure 1B,C).

The SOCCOM float data thus revealed that SAMW do not originate exclusively

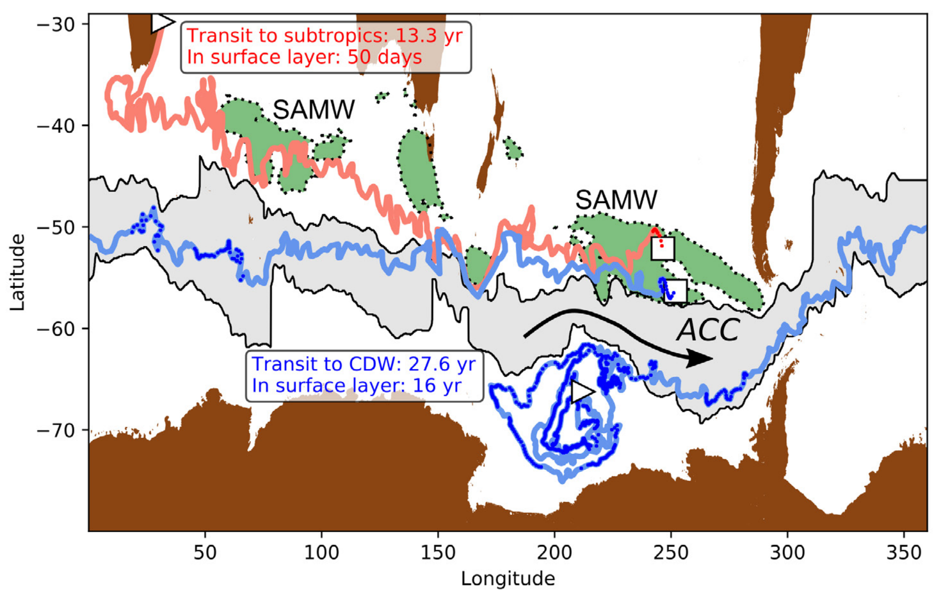

Figure 2: Example of two particle trajectories in B-SOSE: the red line represents the trajectory of a particle of subtropical origin (in this case, entering the model domain via the Agulhas Current, the Western Boundary Current along East Africa), and the blue line, a particle originating from upwelling of CDW to the south of the Antarctic Circumpolar Current (in this case, in the Ross gyre). The starting and end points (at the SAMW formation region) of the particle trajectories are represented by triangles and squares, respectively. The green patches represent the areas of SAMW formation, and the grey patch is the pathway of the Antarctic Circumpolar Current. Darker dots along the particle trajectories indicate times when the particles are within the surface mixed layer. The examples illustrate the shorter transit times and lesser exposure to the atmosphere in the subtropical pathway, compared to the Antarctic pathway.

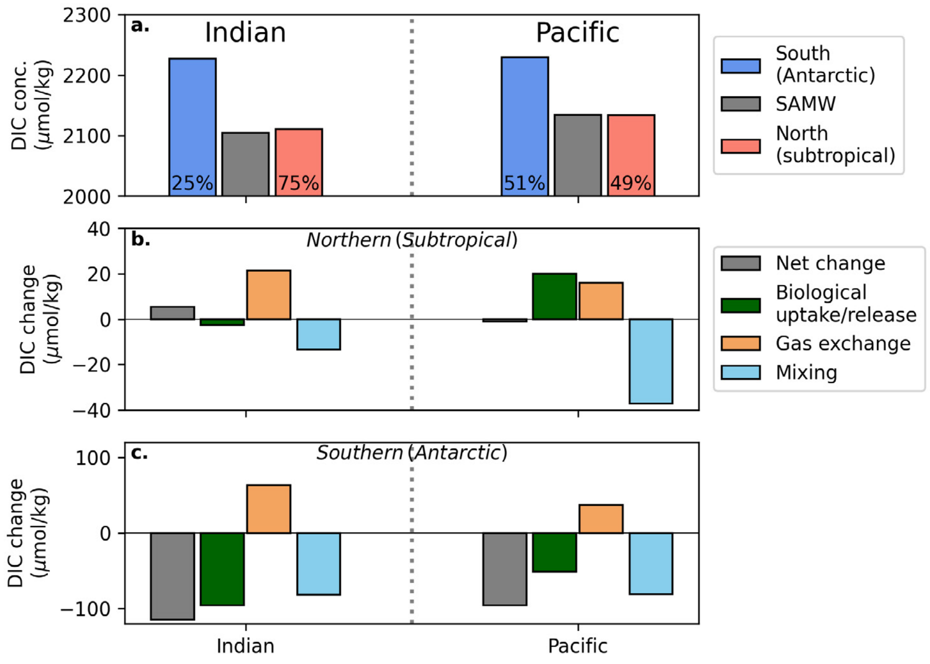

Figure 3: (A) Mean carbon (dissolved inorganic carbon) concentration in SAMW (grey bars), and in the source waters to the north (subtropical, red bars) and south (Antarctic, blue bars) of the Antarctic Circumpolar Current; net carbon concentration changes (grey bars) between source waters and SAMW, and contribution from biological uptake/release (green bars), air-sea gas exchange (yellow bars), and ocean mixing processes (cyan bars), for the northern (B) and southern sources (C) Relative number (%) of particles per source are given in panel (A).

from CDW but have an important contribution from subtropical sources (Fernández Castro *et al.*, 2022). Important questions arise from this finding:

- What is the quantitative contribution of the subtropical sources to SAMW volume and properties?
- Where do the subtropical waters come from, and what pathways do they follow to reach the SAMW formation regions?
- Different varieties of SAMW are formed across the Indian and Pacific Ocean: are the subtropical contributions and pathways different among varieties?
- What is the contribution of the different pathways to carbon drawdown by SAMW?

Answers from an ocean model

To answer these questions, we analysed the B-SOSE 3-dimensional model using a so-called Lagrangian approach. This approach consists of releasing a large number of virtual particles in the model and following them as they are carried by ocean currents. In order to identify the sources of SAMW and quantify carbon fluxes along trajectories, particles were released in the SAMW formation regions and tracked backwards in time for 25 years (see examples in Figure 2).

The particle trajectories confirmed the importance of the subtropical contribution to SAMW, showing that 75 per cent and 49 per cent of the particles reaching the SAMW formation region in the Indian and Pacific Ocean, respectively, originate in the subtropics (Figure 3A). Subtropical particles enter the Southern Ocean with the Western Boundary Currents flowing southward along South America, Africa, and Australia (Figure 2). Then, they join the eastward flow of the Antarctic Circumpolar Current to reach the SAMW formation regions. The transit times from the Western Boundary Currents are short in the Indian Ocean (less than three years) and longer in the Pacific Ocean (five to ten years).

The connection of SAMW with the subtropics is generally much quicker than with the CDW upwelled to the south of the Antarctic Circumpolar Current, which takes about 15 years on average. Waters from the southern pathway also spend more time in the surface layer (~5 years, as opposed to 1.5 years for subtropical waters), allowing for stronger interaction with the atmosphere.

Therefore, the different characteristics and history of the northern and southern SAMW source waters determine their contribution to CO_2 sequestration. Subtropical source waters have similar carbon concentrations to SAMW (~2100 micromolar), both ~5 per cent lower than in Antarctic waters (2200 micromolar, Figure 3A). This pattern is due to the different physical properties of the source waters: CDW is colder than subtropical waters, and cold waters can hold more dissolved CO_2 than warm waters. Although subtropical waters experience little changes in carbon concentration and Antarctic waters experience a net significant decrease to become SAMW, particles following both pathways behave as net sinks of CO_2 from the atmosphere (positive yellow bars in Figure 3B, C). This net uptake is allowed by the action of other biological and physical processes, which tend to decrease carbon concentration. This decrease is mainly driven by ocean mixing processes (cyan bars) for the subtropical pathway and by a combination of mixing processes within the ocean and biological carbon uptake by microscopic algae for the Antarctic pathway (green bars) (Figure 3C). Therefore, in spite of the net decrease in carbon concentration from CDW to SAMW imposed by physical changes, southern-sourced waters behave as a strong net sink of CO_2 from the atmosphere due to biological processes.

Implications

The SO-CUP findings represent an important step forward in our understanding of the role of SAMW in the Southern Ocean carbon sink. Contrary to the standing theoretical framework—where the CDW is the primary source of SAMW—our results underline the contribution of subtropical waters to SAMW volume and carbon budgets. They also emphasise the key role of biological processes in driving a net drawdown of CO_2 from the atmosphere, specifically along the pathways of the southern sources of SAMW, which was hitherto considered a physically-mediated process. Based on the classical theoretical framework, previous attempts to understand the decadal changes in the Southern Ocean carbon sink and to predict its long-term evolution focused on changes in CDW upwelling caused by perturbations of large-scale wind patterns due to climate change. The SO-CUP results indicate an urgent need to broaden this focus to consider changes in the subtropical gyre circulation and exchange with the Antarctic Circumpolar Current, as well as in the productivity of the Southern Ocean algal communities.

References

Fernández Castro, B., Mazloff,M., Williams, R.G., Naveira Garabato, A.C. (2022) ‘Subtropical contribution to Sub-Antarctic Mode Waters’, *Geophysical Research Letters*, 49(11), e2021GL097560, doi:10.1029/2021GL097560.

PROJECT NAME

Southern Ocean Carbon Uptake (SO-CUP)

PROJECT SUMMARY

The Southern Ocean sequesters vast amounts of carbon and heat from the atmosphere, thereby mitigating climate warming. This exchange occurs mainly during winter when intense mixing brings large volumes of deep water into contact with the atmosphere. SO-CUP investigates the magnitude and drivers of carbon uptake with novel wintertime observations made available recently with the deployment of autonomous profiling floats.

PROJECT PARTNERS

University of Southampton (UK)
Scripps Institution of Oceanography (US)

PROJECT LEAD PROFILE

Bieito Fernández Castro is an interdisciplinary oceanographer. His main research interest is to understand how the different scales of variability of ocean dynamics—from small-scale mixing to large-scale circulation—influence the plankton communities and the ocean's biogeochemical cycles.

PROJECT CONTACTS

Bieito Fernández Castro
Ocean and Earth Science
National Oceanography Centre
University of Southampton
Waterfront Campus
European Way
Southampton SO14 3ZH

☎ +44 2380 593040
✉ b.fernandez-castro@soton.ac.uk
🌐 www.southampton.ac.uk/oes/about/staff/bfc1g20.page
🌐 www.researchgate.net/profile/Bieito_Fernandez-Castro

FUNDING

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Individual Fellowship (MGA MSCA-IF) grant agreement No. 834330.