The changing Southern Ocean carbon sink

Physical drivers of the Southern Ocean carbon sink in a changing climate

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In Short

- We analyze the response of the Southern Ocean carbon uptake to anthropogenic climate change in the next decades using a high-resolution ocean model.
- We disentangle the relative role of different physical drivers (winds, temperature, Antarctic freshwater discharge).
- We quantify the effect of explicitly resolving mesoscale eddies.

Background and aims: The Southern Ocean, currently the largest oceanic sink of anthropogenic carbon, will play an important role in modulating the pace of climate change in the 21st century. There is intense debate regarding the response of the Southern Ocean carbon sink to projected changes in Southern Hemisphere winds and temperatures. The past decades saw the Southern Ocean rapidly evolving in terms of wind speed, ocean circulation, hydrography and carbon uptake [**??**], [**??**]. A compelling question is how future changes in Southern Ocean circulation and hydrography will impact the Southern Ocean carbon uptake. An aspect that adds considerable uncertainty to future projections is that Earth System Models typically do not explicitly resolve ocean mesoscale eddies, which modulates the way in which the Southern Ocean circulation and its CO_2 uptake respond to climate change. In this project we aim to assess and disentangle the role of different physical drivers, including ocean mesoscale eddies, for the present and future Southern Ocean carbon sink.

Modeling approach: We use a hierarchy of global ocean biogeochemistry model configurations based on the ocean sea-ice model NEMO-LIM2 [**??**] and including the biogeochemical model MOPS [**??**]. The configurations have horizontal resolutions of 1/2°, 1/4° and 1/10° in the Southern Ocean (hereafter ORION10-MOPS). The model configurations will be used to perform a set of perturbation experiments to evaluate the role of different physical drivers on the Southern Ocean carbon sink in the next decades (2015-2064). To extend the forced ocean-only simulations into the future, the methodology of ocean dynamical downscaling of a bias-corrected future scenario projection will be applied to the ocean-only models. The method consists of adding to an atmospheric reanalysis product [**??**] an anomaly obtained by removing a recent period from a future period of a climate model simulation [**??**].

Report for the period 1.11.2021 to 31.12.22

In the project period from 1.11.2021 to 31.12.22, the work focused on investigating physical drivers of the Southern Ocean carbon uptake in present climate. The following topics were analyzed: (1) the time-varying properties of the mesoscale eddy field, (2) the role of mesoscale eddies for the Southern Ocean carbon uptake, and (3) the impact of wind stress and buoyancy forcing for the variability and trends of the Southern Ocean carbon uptake. The experiments performed within this project also contributed to the intercomparison project RECCAP-2 (https://reccap2-ocean.github.io/) where the proponent is one of the lead authors in its Southern Ocean chapter. They also contributed to the Master Thesis of Mariana Pacheco [**??**], and to the ongoing PhD thesis of Sweety Mohanty (https://www.mardata.de/2nd-cohorts/neural-networks-reveal-evolving-patterns-of-ocean-carbon-uptake), both supervised by the proponent. In the following, some detail will be given on topics (1) and (2).

Role of eddies for the Southern Ocean carbon uptake The Southern Ocean features a rich mesoscale eddy field, which modulates the way in which the Southern Ocean circulation and its CO_2 uptake respond to climate change. Ocean biogeochemical models often lack the resolution to explicitly resolve mesoscale eddies and include eddy parameterizations to mimic their effects on the larger scales. Here, a suite of global ocean biogeochemistry configurations at increasing horizontal resolution is used to assess how the representation of mesoscale eddies affects the Southern Ocean CO_2 uptake. The configurations are based on the NEMO-MOPS and FESOM-REcoM ocean biogeochemistry models and include non-eddying resolutions of 1° (FESOM-LR) and 0.5° including (ORCA05) and excluding an eddy parameterization (ORCA05noGM), eddy-present 0.25° (ORCA025, FESOM-HR) and eddy-rich 0.1° (ORION10) configurations. As shown in Fig. 1, we find that eddy-present and eddy-rich models exhibit a higher total and anthropogenic carbon uptake than the models where mesoscale eddies are parameterized. This is associated with steeper isopycnals across the ACC, which translates into higher surface density at high latitudes and deeper ventilation of mode and intermediate

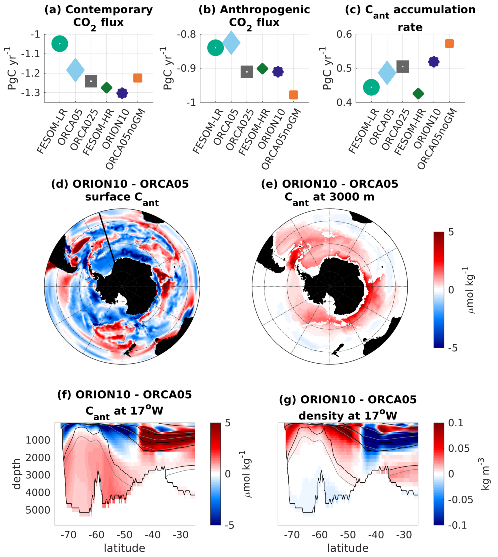

__Figure 1:__ The role of model resolution for the Southern Ocean carbon uptake. (a-c) Integrals over the Southern Ocean and between 2000-2018 of (a) contemporary air-sea CO_2 fluxes, (b) anthropogenic air-sea CO_2 fluxes and (c) anthropogenic carbon (C_{ant})accumulation rates over the whole water column. (d-e) ORION10 minus ORCA05 differences in (d) surface and (e) 3000 m depth C_{ant}, (f-g) ORION10 minus ORCA05 sections at 17°W of (f) C_{ant} and (g) potential density, where contours show isopycnal slopes in ORCA05 (grey) and ORION10 (black)

waters. As a result, more anthropogenic carbon is stored in both Antarctic Bottom Water and mode and intermediate waters in the eddy-present and eddy-rich models with respect to the eddy-parameterized models.

Changing properties of the Southern Ocean mesoscale eddy field The Southern Ocean features a rich mesoscale eddy field, which modulates the way in which the Southern Ocean circulation and its CO_2 uptake respond to climate change. The mesoscale eddy field is thought to respond to changes in climate, especially to changes in wind stress, but little is known about how the statistical properties of the eddy field vary in time. Here the eddy statistics in the Southern Ocean were analyzed using an eddy detection and tracking algorithm based on the Okubo Weiss parameter. The temporal evolution of the eddy statistics is driven to a large extent by the sustained strengthening of the Southern Hemisphere westerly winds, with a gradual shift towards smaller and more energetic eddies since the 1970s. Part of this study formed the basis of the Master thesis of Mariana Pacheco [**??**].

In the period 1.4.2023 - 31.03.2024, the objectives will be three: 1) **Improve and update the biogeochemical model MOPS:** a new set of parameters and a simple scheme to simulate iron limitation will be included. 2) **Test an extended version of the ORION10 high-resolution model**: the new configuration (ORION10X) will extend until the Antarctic coast. 3) **Physical drivers of the future Southern Ocean carbon uptake:** the improved ocean biogeochemistry model (ORION10X-MOPS) will be used to simulate the present and future Southern Ocean carbon uptake.

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More Information

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