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Decadal trends in the Southern Ocean carbon sink in MPI-ESM Large Ensemble

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Recent observations suggest pronounced decadal variations in the Southern Ocean carbon sink. However, due to the sparse spatial and temporal coverage, it is challenging to discern the dynamics of internally varying processes. Earth-system-models, while being a useful tool to analyze processes that contribute to variability, do not always capture this variability. By analyzing a historical large ensemble of 100 simulations based on Max Planck Institute's Earth System Model (MPI-ESM) with slightly perturbed initial conditions but identical forcing, we assess modeled internal variability of the Southern Ocean carbon sink and address the following three research questions:

1) How large is the modeled internal variability in the Southern Ocean carbon sink?
2) Do we find similar trends to those observed in the 1990s and 2000s in this large ensemble?
3) Which processes drive decadal internal variability in this large ensemble?

We quantify the decadal internal variability of the Southern Ocean carbon sink south of 35°S with ±0.18 PgC (1σ ensemble standard deviation).

We identify decadal trends in the Southern Ocean carbon sink similar to those observed in observations. Decadal internal variability is driven primarily by the strength of the westerly winds which triggers responses in the thermal pump, upper-ocean overturning circulation and biology.

Sea-surface temperature decreases south of 50°S, which facilitates deeper mixing and leads to a negative thermal CO_2 flux contribution, but the non-thermal response overwhelms:
Intensified westerly winds in the Southern Ocean strengthen the upper-ocean overturning circulation. The corresponding upwelling south of 50°S, the northward Ekman transport and the downwelling at 30-50°S is enhanced. The strengthened upwelling to the south of 50°S brings more carbon-rich waters from the deep ocean to the surface, and hence increase surface dissolved inorganic carbon which weakens the carbon sink.
Intensifying winds mix the water column deeper than usual. Thereby standing stock of phytoplankton is mixed deeper into the ocean. Light limitations at depth reduce the phytoplankton growth rate resulting in a decrease of total primary production and hence the carbon sink. The increased upwelling nutrient supply does not strengthen primary production because nutrients are already abundant in the surface waters.

MPI-ESM Large Ensemble captures multi-year positive and negative trends as suggested by observations. We find two wind-driven regimes: Both responses towards intensified winds - biology and upper-ocean overturning circulation - weaken the carbon sink at the latitudes with the largest internal variability (50-60°S) and for the overall Southern Ocean south of 35°S. The same mechanisms apply vice versa for decreasing wind strengths leading to an increase in the carbon sink.