**The role of internal variability for decadal carbon uptake anomalies in the Southern Ocean**

**or**

**Reproducing decadal Southern Ocean carbon sink trends in large ensemble simulations**

Aaron Spring1, Hongmei Li1, Tatiana Ilyina1

1 Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany.

Corresponding author: Aaron Spring ([aaron.spring@mpimet.mpg.de)](mailto:email@address.edu))

Key Points:

* Large internal variability of the Southern Ocean carbon uptake.
* Large ensemble simulations are required to reproduce the internal variability of Southern Ocean carbon uptake.
* Southern Ocean carbon sink is sensitive to atmospheric wind forcing on upwelling and on primary production

Abstract

The Southern Ocean is a major sink for anthropogenic CO2 emissions and hence it plays an essential role in modulating global carbon cycle and climate change. Previous studies based on observations show pronounced decadal variations of carbon uptake in the Southern Ocean in recent decades and this variability is largely driven by internal climate variability. However, due to limited ensemble size of simulations, the variability of this important ocean sink is still poorly assessed by the state-of-the-art earth system models (ESMs). To assess the internal variability of carbon sink in the Southern Ocean, we use a large ensemble of 100 member simulations based on the Max Planck Institute-ESM (MPI-ESM). Here we use model simulations from 1980-2015 to compare with available observation-based dataset. We found several ensemble members showing decadal decreasing trends in the carbon sink, which are similar to the trend shown in observations. This result suggests that MPI-ESM large ensemble simulations are able to reproduce decadal variation of carbon sink in the Southern Ocean. Moreover, the decreasing trends of Southern Ocean carbon sink in MPI-ESM are mainly contributed by region between 50-60°S. To understand the internal variability of the air-sea carbon fluxes in the Southern Ocean, we further investigate the variability of underlying processes, such as physical climate variability and ocean biological processes. Our results indicate two main drivers for the decadal decreasing trend of carbon sink: i) Intensified winds enhance upwelling of old carbon-rich waters, this leads to increase of the ocean surface pCO2; ii) Primary production is reduced in area from 50-60°S, probably induced by reduced euphotic water column stability; therefore the biological drawdown of ocean surface pCO2 is weakened accordingly and hence the ocean is in favor of carbon outgassing.

1 Introduction

The oceans are major carbon sink by taking up about 25-30% of the anthropogenic carbon emissions from the atmosphere [*C. Le Quéré et al.*, 2016].

The Southern Ocean connects to all major ocean basins and therefore has an important role for the global water mass distribution. As a formation site of Antarctic Intermediate Waters, it serves as an entry into the deeper waters. It is also a large contributor of 40% for the global oceanic carbon sink [Sabine 2004].

LeQuere 2007 reported decline of SOCS because of SAM increase, Lovenduski modelled that. Wang and Moore model variability of primary production and air sea co2flux in southern Ocean.

Due to sparse and fairly recent observational sample the use of different approaches, observation-based estimates of the Southern Ocean carbon sink have a large spread [*Rödenbeck et al.*, 2015]. [*Landschützer et al.*, 2015] . They also reveal that the evolution of the Southern Ocean carbon sink shows large variability [*Landschützer et al.*, 2015] .

Multi-model intercomparison exercises, such as Coupled Model Intercomparison Project Phase 5 (CMIP5) indicate that evolution of the Southern Ocean carbon uptake is quite robustly projected in the models [Ilyina, 2016]. However, observation-based estimates suggest a weakening of the Southern Ocean carbon sink in the 1990s against the forced signal of climate change [*Landschützer et al.*, 2015] .

By using a large ensemble simulation based on the Max Planck Institute Earth System Model (MPI-ESM), we investigate the variability of the oceanic carbon uptake and try to answer the following questions: How large is the internal variability of the Southern Ocean carbon sink? Are large ensembles able to reproduce decreasing decadal trends of the Southern Ocean carbon sink? And if so, what are the main drivers for variability?

2 Methods

2.1 Model description

[Hongmei’s] The MPI-ESM version 1.1 with a low-resolution configuration (MPI-ESM-LR) is used for the large ensemble simulations [Giorgetta 2013]. The ocean component is MPI Ocean Model (MPIOM) has a horizontal resolution of 1.5° on average and 40 vertical levels [*Jungclaus et al.*, 2013]. The Hamburg Ocean Carbon Cycle Model (HAMOCC) [*Ilyina et al.*, 2013] represents the ocean biogeochemistry component of MPI-ESM. ~~Changes~~ ~~[~~*~~Ilyina et al.~~*~~, 2013]~~

Atmospheric pCO2 uses prescribed and well mixed values. The carbon cycle is not coupled (so called diagnostic), so effects of changes in the terrestrial or oceanic carbon sink are not reflected in pCO2\_atm.

An ensemble of 100-member CMIP5 historical simulations and RCP4.5 scenario simulations are integrated for the periods from 1850-2005, and 2006-2100, respectively. Ensemble members differ through starting from different year of the pre-industrial control simulation, so ocean and atmosphere have different initial conditions in each run. This set of large ensemble simulations advanced our understanding of internal variability in atmosphere [*Stevens*, 2015] and ocean physical fields.

2.2 Data

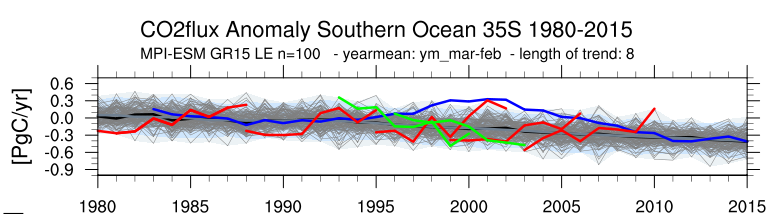
For comparison with model simulations, we use the ETH-SOMFFN data and its uncertainty [Landschützer et al., 2014; Landschützer et al., 2015].

3 Results I: Historical evolution of the Southern Ocean carbon sink

We focus our analysis on the recent three decades (eg. 1980-2015) when more ocean surfacce observation are available. Fig. 1 shows the carbon sink south of 35° south of the MPI-ESM 100-member simulations in the context of ETH-SOMFFN data. The ocean carbon uptake in the Southern Ocean decreases in the 1990s, and it reinvigorates in the recent decade [*Landschützer et al.*, 2015]. The model simulation spread in the Southern Ocean are the same magnitude as the uncertainty of ETH-SOMFFN data. The MPI-ESM median follows the expected atmospheric forcing of rising pCO2\_atm. As assumed in other ensemble studies [Thompson et al., 2015], the annular Southern Ocean carbon sink follows a normal distribution. (SI Fig. Gaussian left). The 1σ-spread of the 100-members (~0.15±0.03 PgC yr-1) is constant over this period. ETH-SOMFFN data ranges within 2σ ensemble spread.

As an entry point of our analysis, we try to find trends similar to the anomalous outgassing trends of ETH-SOMFFN data from the 1990s. To get a large sample size, we take running interval boundaries. Because of the overestimated seasonal cycle of primary production in HAMOCC [Nevison et al. 2016], we compute trends of the annual Southern Ocean Carbon trend. The amount of trends and the corresponding significance vary depending on the choosen length of trends (SI Fig.1 Trend Heatmap). A monotonous trend of ten years only appears once in 2600 available intervals. Most continuous trends only sustain for shorter than a decade. To ensure a certain amount of monotonous trends and a similar trendlength to a decade, we take 8-year trends in this analysis. For a meaningful analysis of the impact of biology, we separate the years in March to February, to ensure that a complete primary production bloom is captured in each year. Furthermore, the members used in this study are required to be monotonous similar to ETH-SOMFFN data.

Applying those requirements, we find three candidates of decreasing decadal trend. They appear independent of the timestamp in the simulation, although increasing atmospheric pCO2 forcing would favor earlier decades. These candidates are mostly in the 2σ ensemble spread.



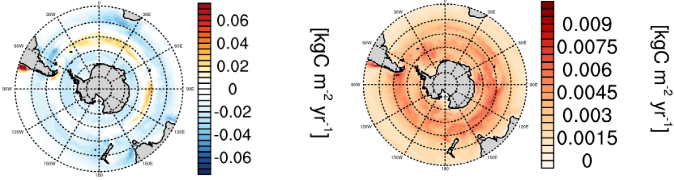
Drawing 1: Evolution of the Southern Ocean carbon sink anomaly south of 35°S. Grey lines show the 100 ensemble members, the black line the ensemble median, the gray shading is the range of the ensemble, the blue shading is the 2σ ensemble spread, the red lines are decreasing sink trend candidates, the green line increasing sink trend candidates, the blue line is ETH-SOMFFN observation-based estimates

4 Results II: Spatial distribution of Southern Ocean carbon sink trend

4.1 Increased upwelling

The Southern ocean shows zonal structures in variables related to the carbon sink.

The large member ensemble median is defined as the ‘forced’ signal, and the differences of single members with the ensemble mean as standard deviation equals internal variability, respectively [Deser et al., 2014; Ting et al., 2009]. The ‘forced’ signals in the Southern Ocean show dominant increasing trend (Fig.2 left). Also in spatial distribution, the carbon sink in each grid point follows a normal distribution (Fig. SI Gaussian right). The standard deviation (Fig. 2 right) shows differences in magnitude of internal variability in a zonal pattern. The largest internal variability appears in 50-60°S south of the polar front, where outgassing occurs. Internal variability seems to drop north of 45°S, showing the large internal variability of the Southern Ocean compared to other basins.

  
Drawing 2: Southern Ocean carbon sink (20-year mean): ensemble median (left) as forced signal and ensemble standard deviation (right) as internal variability

Exemplarily for all decrease carbon sink trend candidates, we show the candidate of most extreme case of anomalous outgassing. The region of 50-60°S has the strongest decreasing trend in co2flux.

As shown in previous studies [*Landschützer et al.*, 2015; *Corinne Le Quéré et al.*, 2009][, the variations of oceanic carbon uptake are related to the background thermal and dynamic changes.](#_ENREF_7)

Insight to the drivers is gained by separating ΔpCO2 in a component driven by changes in sea surface temperature (the thermal trend; Fig. SI xb) and one driven by changes in DIC and/or alkalinity (the non-thermal trend: Fig. SI xc) [Takahashi et al. 2002; p1612].

Fig. SI xc shows that the non-thermal trend is dominating like in [*Landschützer et al.*, 2015].

Previous studies state that intensified wind lead to increased upwelling, which then impacts the surface DIC/pCO2 to rise and thereby weaken the carbon uptake. Our candidates also show this pattern: Intensified winds (Fig. 2) are reflected in increased trend in SAM (Fig. SI) which leads to intensified upwelling (Fig. 2).