The impact of biology ~~to~~ on decadal decreasing trends of carbon sink in the Southern Ocean

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Key points:

- Large ensebmle simulations are able to reproduce decadal decreasing trends in the Southern Ocean carbon sink
- Internal variability of the Southern Ocean carbon uptake links to primary production
- Southern Ocean carbon sink is sensitive to stability of the water column which is needed for primary production blooms

Internal note: I will reduce the amount figures later. Especially in cases were two years and a trend is shown, I would show the trend only.

Abstract

The Southern Ocean is a major sink for anthropogenic CO_2 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 focus on the impact of biology on decadal decreasing trends of carbon sink: Primary production is reduced in area from 50-60°S due to a reduced euphotic water column stability; therefore the biological drawdown of ocean surface pCO_2 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 [Le Quéré et al., 2016]. The Southern Ocean connects all major ocean basins and therefore has an important role for the global water mass distribution. It is also a large contributor of 40% for the global anthropogenic oceanic carbon sink [Sabine et al., 2004].

The evolution of the Southern Ocean carbon sink shows large variability [Landschützer et al., 2015]. ~~However,~~ observation-based estimates suggest ~~a weakening of~~ the Southern Ocean carbon sink in the 1990s ~~against the forced signal of atmospheric pCO$_2$ increase~~ [Landschützer et al., 2015, Le Quéré et al., 2007]. Due to sparse and fairly recent observational samples and diverse ~~mechanism of calculation,~~ observation-based estimates of the Southern Ocean carbon sink have a large spread [Le Quéré et al., 2007, Rödenbeck et al., 2013, Landschützer et al., 2015].

The decreasing trend is explained by intensified winds ~~that cause~~ enhanced upwelling of carbon-rich waters [Le Quéré et al., 2007]. This causality was also confirmed by model results associated with positive states in the Southern Annular Mode (SAM) indicating intensified winds [Lovenduski et al., 2007]. The influence of SAM on the carbon sink on decadal timescales has been demonstrated in ocean-only simulation with historical NCEP forcing [Lovenduski et al., 2008]. In all those studies, biology was found to be not changing significantly, and thus not included in an explanation for a decadal trend.

However, model studies suggest that changes in circulation also affect the biological pump [Sarmiento et al., 1998]. As ~~deducted~~ from observations ~~on short-term timescales,~~ intensified winds in the context of increasing Southern Annular Mode change the Southern Ocean circulation and ~~hence biology due to~~ enhance~~d~~ nutrient supply [Lovenduski and

Gruber, 2005]. The role of biology on decadal trends in ~~an unforced~~ coupled model remains unadressed.

Model simulations are a useful complementary method to study variations, their driving processes and the consequences for biogeochemical cycles. 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 [?]. ~~Internal variability, like decadal trends, can be studied in large ensemble simulations, such as the separation of trends from internal variability in the ocean carbon sink~~ [McKinley et al., 2016].

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. We 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? How does variability in physical processes influence biology and hence the carbon sink?

2 Methods

2.1 Model description

The MPI-ESM version 1.1 with a low-resolution configuration (MPI-ESM-LR) is used for the large ensemble simulations [Giorgetta et al., 2013]. The atmosphere component ECHAM6.3 is on a T63 grid, corresponding to 1.9° at the equator (better would be values of high latitudes), with 47 vertical layers up to 0.01 hPa [Stevens et al., 2013]. The ocean component 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. Atmospheric pCO_2 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 $pCO_{2,atm}$ and hence terrestrial and oceanic carbon sink can not interact.

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.

2.2 Data

For comparison of CO_2flux with model simulations, we use the SOM-FFN data [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 surface observation are available. On multi-decadal timescales, the carbon sink south of 35° south of the MPI-ESM 100-member simulations as well as SOM-FFN data follow the atmospheric increase of pCO_2 (Fig. 1). However, observations follow a decreasing carbon sink trend in the 1990s. The model simulation spreads in the Southern Ocean are of comparable magnitude as the uncertainty of SOM-FFN data. Previous studies assume gaussian statistics for large ensemble simulations [Thompson et al., 2015]. We found the annular Southern Ocean carbon sink follows a normal distribution (Fig. SI 11). The 1σ-spread of the 100-members (0.15 ± 0.03 PgC yr^{-1}) is constant over this period. SOM-FFN data ranges within the 2σ ensemble spread.

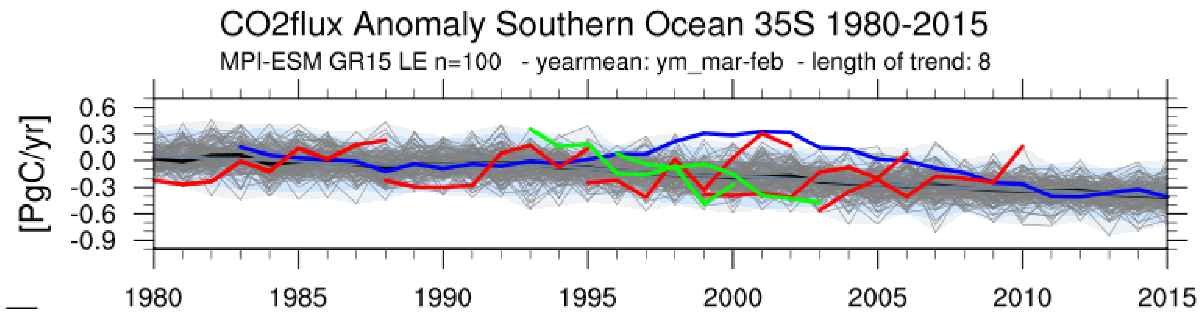

Figure 1: Evolution of the Southern Ocean carbon sink anomaly south of 35S. Grey lines show the 100 ensemble members, the black line the ensemble mean, the gray shading is the range of the ensemble, the blue shading is the 2σ ensemble spread, the red lines are decreasing sink trend candidates, the blue line is the SOM-FFN observation-based estimate

As an entry point of our analysis, we try to find trends similar to the anomalous outgassing trends of SOM-FFN data from the 1990s. To get a large sample size, we take running interval boundaries over the whole observational record of 1980-2015. Because of the strong seasonality in the high latitudes, we compute trends of the annual Southern Ocean carbon sink trend. The distribution of trends and the corresponding significance vary depending on the choosen length of trends (Fig. SI **??**). A greatly monotonous trend of ten years only rarely occurs in 2600 available intervals. Most continuous trends only sustain for shorter than a decade. To ensure a certain amount of monotonous trends and still 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 SOM-FFN data in the 1990s.

Applying those requirements, we find someamounttobechanged ensemble members with a decreasing decadal trend. They appear independent of the timestamp in the

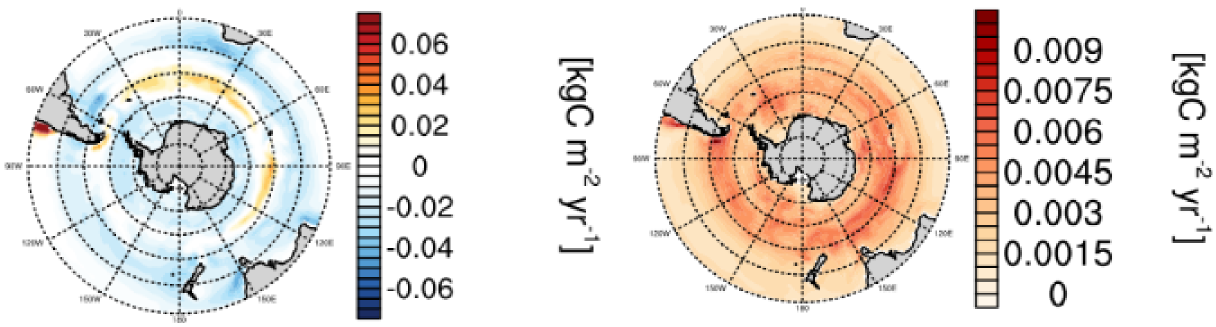

Figure 2: Southern Ocean carbon sink: ensemble mean (left) as forced signal and ensemble standard deviation (right) as internal variability [SHOULD I INCLUDE THE SAME FOR INTPP???]

simulation, although increasing atmospheric pCO_2 forcing would favor earlier decades. These candidates are mostly in the 2σ ensemble spread.

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

The Southern Ocean shows zonal structures in variables related to the carbon sink. The large ensemble mean is defined as the forced signal and the standard deviation as internal variability, respectively [Deser et al., 2012]. The forced signal shows a dominant increasing trend in the Southern Ocean (Fig. 2 left). Also in spatial distribution, the carbon sink in each grid point follows a normal distribution (Fig. 11). 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. Internal variability seems to drop north of 45°S, showing the large internal variability of the Southern Ocean compared to other basins.

Exemplarily for all decadal decreasing carbon sink trend members, we show the candidate of most extreme case of anomalous outgassing. The region of 50-60°S has the strongest decreasing trend in CO_2flux.

As shown in previous studies [Le Quéré et al., 2007], the variations of oceanic carbon uptake are related to the background thermal and dynamic changes. Insight to the drivers is gained by separating the pCO_2 seasonal amplitude in the thermal component driven by changes in sea surface temperature (Fig. SI 12) and the non-thermal component driven by changes in DIC and/or alkalinity (Fig. SI 12) [Takahashi, 2002]. The non-thermal trend dominates the seasonal amplitude and decreases drastically in 50-60°S, giving a first indication to a decline in primary production.

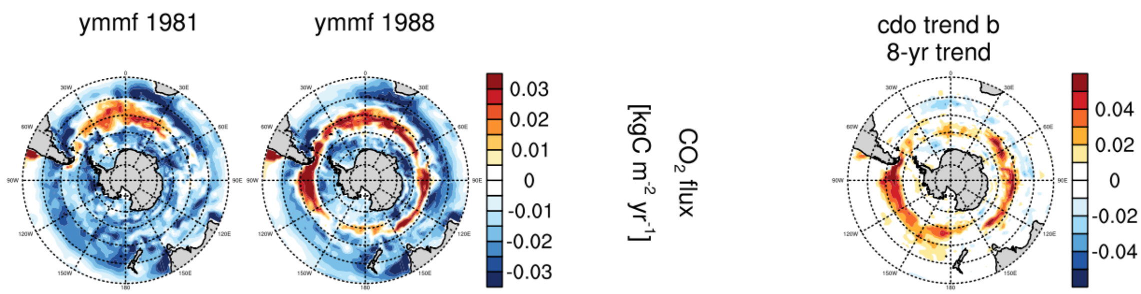

Figure 3: CO_2flux in the first and last year of the trend period; trend over 8 years

Primary production and CO_2flux show opposing trend patterns as plankton growth takes up large amounts of surface DIC and hence lowers pCO_2. Temperature, nutrients and light availability can directly effect the phytoplankton growth rate. There are no significant trends in limiting factors found in the surface layers south of 40°S. The Southern

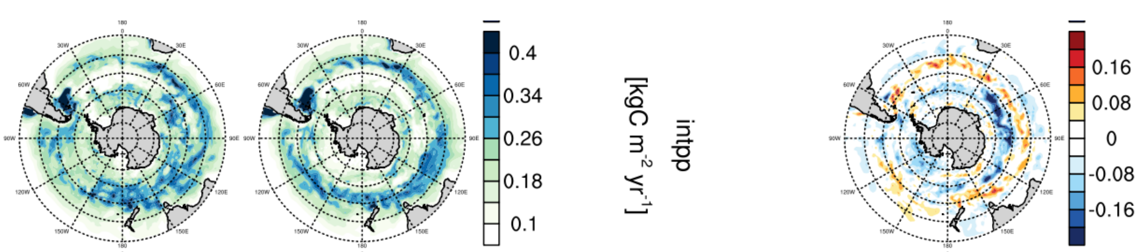

Figure 4: Vertically integrated primary production in the first and last year of the trend period; trend over 8 years

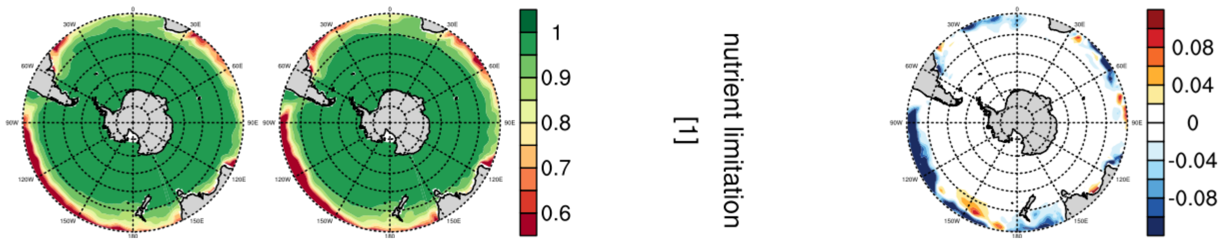

Figure 5: Nutrient limitation for primary production in the first and last year of the trend period; trend over 8 years

Ocean as an upwelling area has plenty of supply of nutrients from below in our model. Even in the austral summer months, the nutrient limitation function stays close to 1, which mean not limiting at all. Nutrient concentrations in surface nitrate, phosphate or iron also follow the opposite path of primary production: They have an increasing trend where less primary production took place, consequently primary production declined over the trend period. Contrary, in region of increased primary production, nutrient concentrations decreased (Fig. 13). Therefore we conclude that in our model the Southern Ocean is not nutrient depleted. Hence the probable increase of upwelling deep ocean nutrients effects the primary production only little.

However, the mixed depth layer increased in 50-60°S. Mixing can bring phytoplankton to deeper depths where the are exposed to less light which inhibits growth. Sverdrup [Sverdrup, 1953] introduced his concept of critical depth based turbulent mixing as a requirement for plankton blooms [Franks, 2014]. We use his theory not in an overall manner discussing theoretical requirements of the water column for plankton bloom dynamics, but rather the straight-forward effect of mixing plankton to deeper layers. Sverdrup based this theory on turbulent mixing. However, here we use a hydrologically defined mixed layer depth based on a density criterion which serves as a first approach to wind-induced mixing strength. The direct effect of wind on the water column is decribed by the vertical

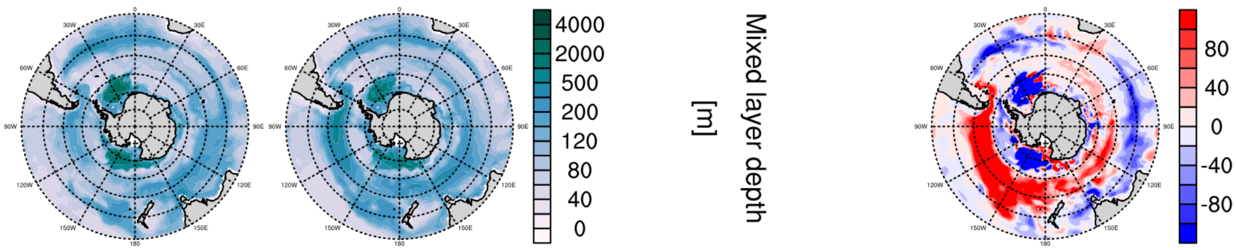

Figure 6: Mixed depth layer in the first and last year of the trend period; trend over 8 years

diffusivity due to wind. The spatial coexistence/correlation justifies to use of mixed layer depth as an inidicator for turbulent wind mixing.

Deeper winter mixing also effects the plankton bloom as it shortens the available time of a stratified water column required for primary production. The water columns of the Southern Ocean are deeperly mixed in the winter seasons. In spring, solar radiation restratifies the water column. The more mixing happened in winter and during restratification spring, the longer plankton cannot bloom. So wind-mixing has a two-fold implication on primary production and the carbon sink: It shortens the timeframe for primary production and it deepens a fraction of the standing stock. In 50-60°S deeper winter mixing inhibits plankton growth in early spring (Fig. 7). Also throughout the growth season, the mixed depth layer increases by 10m which drags standing stock down to depths with less light. This effect is not seen at 40-50°S because winds decrease slightly here. There is even a slight increase in primary production that may be attributed to a more stratified water column, because additionally to less wind stress, sea-surface temperature experiences a warming trend here.

Previous studies state that intensified wind lead to increased upwelling, which then impacts the surface pCO_2 to rise and thereby weaken the carbon uptake. We also see this pattern of intensified winds (Fig. 8) in a positive trend in SAM (Fig. 9).

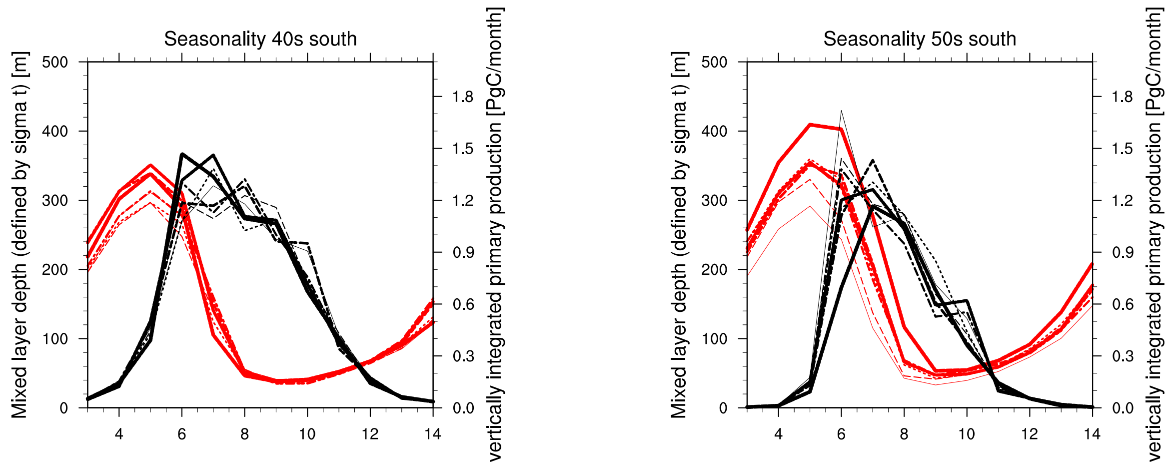

Figure 7: Seasonality of vertically integrated primary production and mixed depth layer

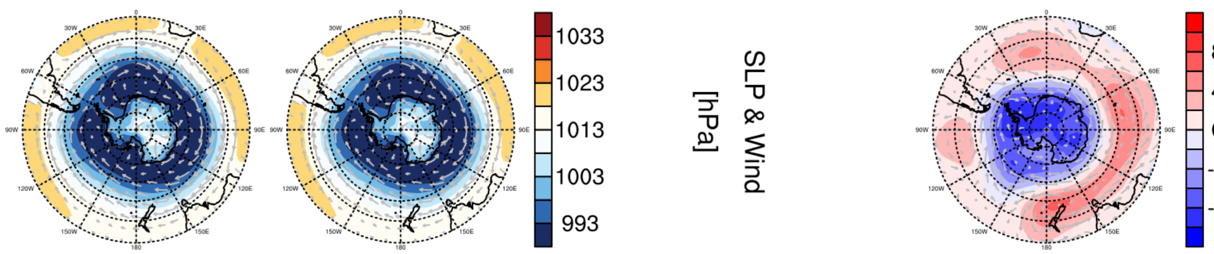

Figure 8: Sea-level pressure and wind fields in the first and last year of the trend period; trend over 8 years

Increased upwelling brings cold water from the deep ocean. This cools the surface layer. This cold sea-surface temperature anomaly reduces stratification, so wind stress is more effective in mixing the water column.

We reason that intensified winds cause increased turbulent mixing of the water column (Fig. 10). Deeper mixing occurs in 50-60°S whereas 40-50°S experiences less winds which stabilizes the water column.

The strong trend in MLD could also be a sign of increase outgassing due to more

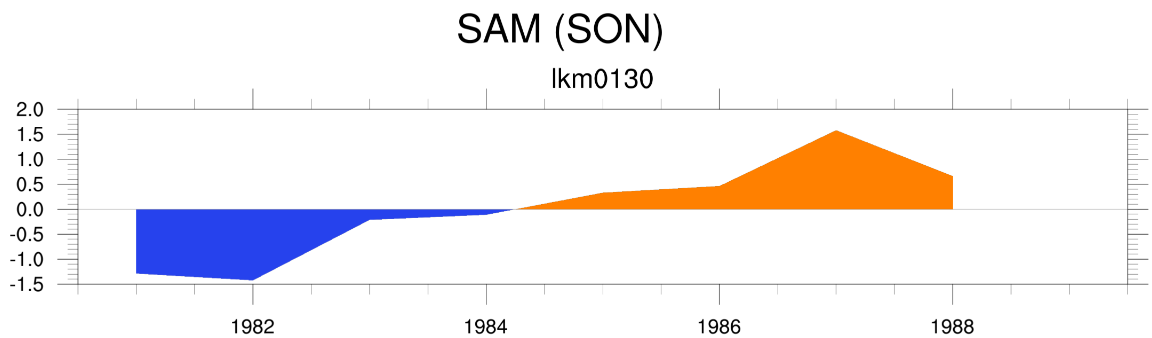

Figure 9: SAM timeseries for September, October and November

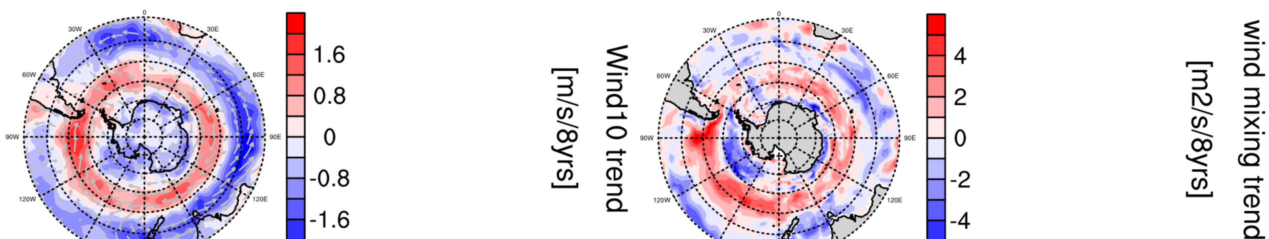

Figure 10: Trends in Wind and Vertical diffusivity due to wind

mixing. Mixing brings surface water incl. phytoplankton to deeper layers. This comes in exchange for carbon-rich deep water. We were not able to attribute weights on the two follow-up effects on upwelling in the sense of impact on the carbon sink. [Maybe later]

5 Discussion

Lovenduski and Gruber 2005: how is model different, how are results different

1. our MLD responds differently than Lovenduski2005 Fig.2 schematic illustration
2. increase in SAM increase in chlorophyll south of PF/45S because of iron supply from below (we have phy-decrease)
3. increase in SAM reduction in chlorophyll north of PF/45S because of increased ZMLD (we have a slight phy-increase)
4. BUT we dont have iron limitation in SO, so this study can be used as a direct physical effect of stronger winds on primary production excluding nutrient supply changes

Limitations of HAMOCC vs obs/other models:

1. too early and enhanced Southern Ocean seasonal cycle [Nevison et al., 2016]
2. location of polar jets in ECHAM [I remember this from a group meeting, but didnt check so far]
3. basically no nutrient limitation in SO? - other models and observations disagree
4. other observation studies use sparse (mostly cruises up to 2010s) for pCO2 or proxy (satelite chl-a)

5. MPIOM performance on circulation patterns and water masses (Yohei mentioned Anne M. could know this) in SO

6. only one phytoplankton type in HAMOCC? - more variety of plankton species might be able to adapt to depth? or is this too unrealistic for a global model such as HAMOCC?

6 Summary and conclusions

MPI-ESM large ensemble simulations produces internal variability of the Southern Ocean carbon sink including decreasing decadal carbon sink trends over the past decades, which were seen in observations. Decreasing carbon sink trends are accompanied by intensified winds as in previous studies [Le Quéré et al., 2007, Lovenduski et al., 2008]. The changes in circulation show a different response to biology as in a previous study [Lovenduski and Gruber, 2005]. ~~This is explained by~~ different responses in water column stability and the different impact of changes in nutrient supply. The increasing winds not only enhance upwelling of carbon-rich waters, but also decrease water column stability which inhibits primary production. An overall decrease in primary production decreases the Southern Ocean carbon sink.

Acknowledgements

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Supplementary information

Normal distributions of the southern ocean carbon sink

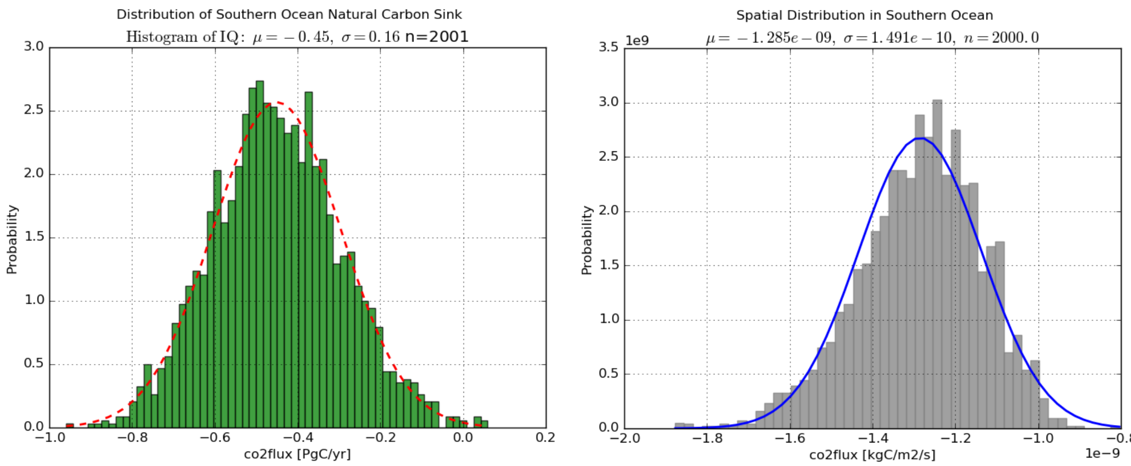

Figure 11: Southern Ocean carbon sink fieldsum 35-90S

Delta pCO_2-separation

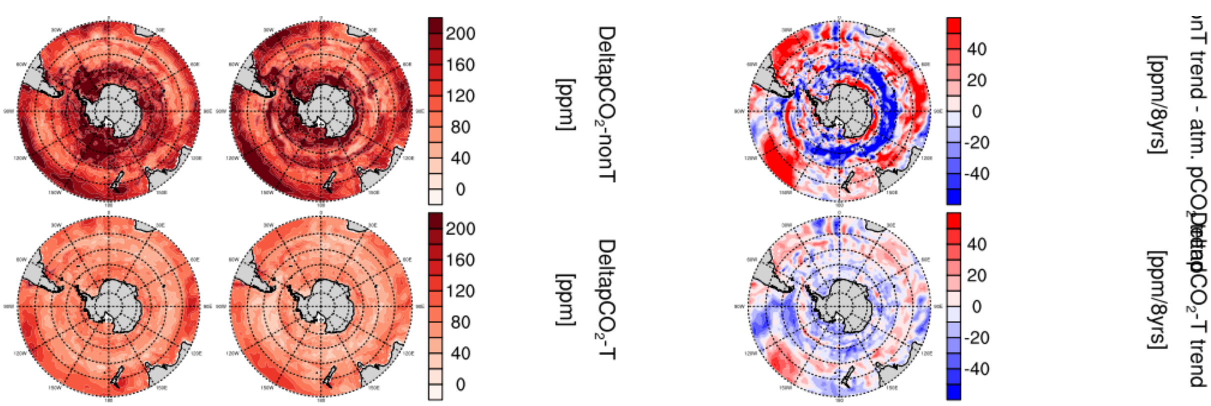

Figure 12: Delta pCO_2-separation [Takahashi, 2002]

Misc

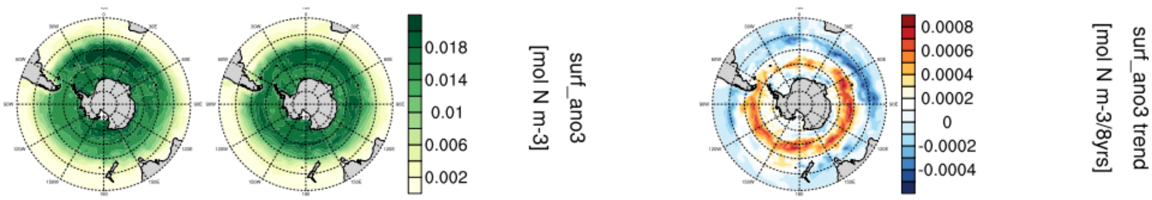

Figure 13: Nutrient

Selection criteria for decadal trend members

1. positive CO2flux trend: value PgC/yr
2. monotony Mann-Kendall
3. significance student t-Test