Decadal variations
of the Southern Ocean carbon sink
in 100 historical MPI-ESM ensemble simulations

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ABSTRACT

Recent observations suggest pronounced decadal variations in the Southern Ocean carbon sink. However, due to the sparse spatial and temporal coverage of observations, it is challenging to discern the dynamics of internally varying processes. Earth system models (ESMs), while being a useful tool to analyze processes that contribute to variability, rarely capture this variability in a small ensemble size. By analyzing a large ensemble of 100 historical simulations based on Max Planck Institute's ESM (MPI-ESM) starting from different initial conditions but using identical forcing, I assess modeled decadal internal variability.

The modeled decadal internal variability of the Southern Ocean carbon sink south of 35°S is quantified to be $\sim \pm 0.19$ PgC/yr/decade in the historical period. This amounts to $\sim 20\%$ of the mean state of carbon sink at ~ -1.15 PgC/yr and dominates over the forced signal of ~ -0.14 PgC/yr/decade. MPI-ESM Large Ensemble captures decadal variations of similar magnitude as suggested by observations. The largest variability is found at 50-60°S, where CO_2 flux follows two wind-driven regimes: Stronger winds enhance the upper-ocean overturning circulation and the corresponding upwelling of deep waters weakens the carbon sink. For weakening winds, the upper-ocean circulation slows down and hence strengthens the carbon sink.

ZUSAMMENFASSUNG

Neue Beobachtungsdaten zeigen dekadische Schwankungen in der Kohlenstoffsenke im Südlichen Ozean auf. Die spärliche räumliche und temporäre Beobachtungsdatendichte macht das Unterscheiden der Dynamik der variablen Prozesse herausfordernd. Erdsystemmodelle, die ein nützliches Hilfsmittel zum Analysieren von variablen Prozessen sind, erfassen selten diese internen Schwankungen. Durch das Analysieren eines Ensembles mit 100 historischen Simulationen basierend auf dem Max-Planck-Institut ESM (MPI-ESM) mit leicht veränderten Anfangsbedingungen untersuche ich modellierte interne Variabilität.

Die modellierte dekadische interne Variabilität der Kohlenstoffsenke im Südlichen Ozean südlich von 35°S beträgt $\sim \pm 0.19$ PgC/Jahr/-Dekade. Dies macht $\sim$ 20% der durchschnittlichen Kohlenstoffaufnahme von ~ -1.15 PgC/Jahr aus und dominiert über das erzwungene Klimawandelsignal von ~ -0.14 PgC/Jahr/Dekade. Die 100 MPI-ESM Simulationen erfassen dekadische Trends von ähnlicher Stärke im Vergleich mit Beobachtungsdaten. In der Region mit der höchsten Variabilität bei 50-60°S ergeben sich zwei wind-getriebene Regime: Stärkere Winde stimulieren die obere Umwelzzirkulation, was das Aufsteigen von Tiefenwasser verstärkt. Das darauf folgene Ausgasen reduziert die Kohlenstoffsenke. Schwächere Wind reduzieren die Umwelzzirkulation und stärken somit die Kohlenstoffsenke.

CONTENTS

1 INTRODUCTION

The increasing atmospheric concentrations of carbon dioxide (CO_2) drive anthropogenic climate change, which alters the Earth's climate system at a soaring rate [Crutzen, 2002]. While roughly half of the anthropogenic CO_2 emissions remain in the atmosphere, the carbon reservoirs in oceans and on land modulate the global carbon cycle and hence the climate [Le Quéré et al., 2016]. The oceans currently take up about 25-30% of the anthropogenic carbon emissions [Sabine et al., 2004]. As a key region, the Southern Ocean is estimated to contribute about 50% to the global ocean carbon sink [Takahashi et al., 2012]. The large uptake ability of the Southern Ocean arises from the unique position of the Southern Ocean in the global overturning circulation [Talley, 2013]. Deep waters, which have not been exposed to the atmosphere of higher CO_2, take up additional anthropogenic CO_2 and sink back into the ocean as intermediate waters [Morrison et al., 2015]. Additionally, pronounced primary production in the Southern Ocean sequesters carbon into the deep ocean [Falkowski et al., 1998]. Moreover, high solubility of Southern Ocean due to low sea-surface temperature permits the waters to hold higher oceanic pCO_2 concentrations than in the tropical oceans [Heinze et al., 2015].

The extreme conditions of the Southern Ocean result in sparse spatial and temporal coverage of observations, so even various observation-based CO_2 flux products yield large uncertainties [Rödenbeck et al., 2015]. Also modeling results have a large spread [Wang et al., 2016], but claim the Southern Ocean as a constraint to reduce model uncertainties in future projections [Kessler and Tjiputra, 2016]. Recent observations suggest pronounced decadal variations in the Southern Ocean carbon sink [Rödenbeck et al., 2013; Landschützer et al., 2015]. Understanding internal variability is important to recognize whether the climate changes due to external forcing or natural fluctuations of the earth system [Murphy et al., 2004]. Contrasting the expected increasing Southern Ocean carbon sink due to the increasing atmospheric forcing, Landschützer et al. [2015] even reported a decadal declining trend in ocean uptake. Due to the sparse spatial and temporal coverage of measurement data, it is challenging to discern the dynamics of internally varying processes, which demands for the evaluation with models. Models, numerical representations of the climate system based on physical, biological and chemical principles, are a useful tool to analyze processes that contribute to variability.

By forcing an ocean model with atmospheric reanalysis data, Lovenduski et al. [2007, 2008] demonstrated that increased upwelling due to stronger and southward shifted westerly winds in the Southern hemisphere cause a decline in the Southern Ocean carbon sink.

Yet, Earth System Models (ESMs), containing a freely evolving coupled atmospheric and ocean component, have challenges in capturing the decadal variations in sea-air CO_2 flux as suggest by observations [Wang et al., 2016]. Advances in computing power now enable simulating a larger number of model realizations, which increases the likelihood of capturing pronounced decadal trends. Using a large ensemble of simulations with perturbed initial conditions but identical forcing and model allows to separate trends into an ensemble mean trend, the forced signal, and the residual, the internal variability [McKinley et al., 2016, 2017].

By using a large ensemble of 100 simulations based on the MPI-ESM (hereafter MPI-ESM LE), I investigate the decadal internal variability of oceanic carbon uptake to answer the following research questions:

- What is the modeled internal variability of the Southern Ocean carbon sink?
- What are the sources of this internal variability?
- What are the contributions of different processes to multi-year trends in sea-air CO_2 flux in the Southern Ocean?

My thesis revisits the dominant processes leading to strong trends in the Southern Ocean carbon sink in the ocean biogeochemical model HAMburg Ocean Carbon Cycle Model (HAMOCC) of MPI-ESM [similar to Lovenduski et al., 2007; 2008].

This revisit is particularly interesting as other large ensembles of perturbed initial conditions ESM simulations do not capture strong decadal variations in the Southern Ocean carbon sink; whereas MPI-ESM LE does [private communication N. Lovenduski (NCAR) and S. Schlunegger (GFDL)].

Working on my research questions builds the outline for this thesis:

I describe the large ensemble of MPI-ESM simulations in ch. 2 and evaluate the model in the key features related to the Southern Ocean carbon sink variability in ch. 3. I qualitatively described the response of individual processes related to changes in Southern Hemisphere winds in ch. 4. In ch. 5, I quantitatively assess the individual responses of different processes on oceanic pCO_2. Finally, I draw my main conclusions and evaluate how relatable perturbed initial conditions large ensembles are for internal variability in observations and give an outlook on possible future research ch. 6.

6 SUMMARY, CONCLUSIONS AND OUTLOOK

To assess decadal internal variability of the Southern Ocean sea-air CO_2 flux , I analyze the large ensemble of 100 Max Planck Institute-Earth System Model simulations (MPI-ESM LE) in the historical period from 1980 to 2004, for which the observational sea-air CO_2 flux product Self-Organizing Map-Feed-Forward Network (SOM-FFN) is available. I summarize this thesis by revisiting the research questions posed in the introduction.

What is the modeled internal variability of the Southern Ocean carbon sink?

I estimate the modeled decadal internal variability to $\sigma_{DIV} =\sim \pm 0.19$ PgC/yr/decade (fig. 3.2, A1a). Compared to the 1980-2004 mean sea-air CO_2 flux south of 35°S of ~ -1.15 PgC/yr, decadal internal variability σ_{DIV} amounts to $\sim 20\%$. In addition, internal variability dominates over the forced signal of ~ -0.14 PgC/yr/decade and hence are crucial in evaluating changes in the Southern Ocean carbon sink.

The area at 50-60°S hold the largest decadal variability (fig. 3.1b) and dominates the overall Southern Ocean CO_2 flux trend (ch. 4). MPI-ESM LE contains decadal trends of sea-air CO_2 flux of the same magnitude but less monotonic behavior as suggested by observations [Landschützer et al., 2015] (fig. A2). The same monotonic behavior as observations is found in 8 year trends of $\sim +0.5$ PgC/yr/8yrs and ~ -0.6 PgC/yr/8yrs (fig. 3.2). The underlying source and responses in the carbon sink are analogous on decadal and multi-year timescale.

What are the sources of this internal variability?

I investigate the sources of internal variability as the origins which trigger internally varying responses of CO_2 flux from thermal, physical and biological processes. The major source is the variability in strength and position of westerly winds. I find two distinct wind-driven regimes in the area of at 50-60°S with the largest internal variability of sea-air CO_2 flux (fig. 4.1):

On the one hand, stronger and southward shifting westerly winds associated with a positive trend in the Southern Annular Mode (SAM) reduce the Southern Ocean carbon sink. On the other hand, weakening and northward shifted westerly winds leads to an increase in the

Southern Ocean carbon sink.

What are the contributions of different processes to multi-year trends in sea-air CO_2 flux in the Southern Ocean?

The increasing atmospheric $pCO_{2,atm}$ drives the sea-air CO_2 flux trends towards a more CO_2 uptake state, whereas the oceanic $pCO_{2,ocean}$ is susceptible to internally varying processes:

For intensifying and southward shifting westerly winds, Sea-Surface Temperature (SST) cooling drives $pCO_{2,ocean}$ decrease (sec. 4.2.1). Cooling and deeper wind-mixing reduce primary production, which increases $pCO_{2,ocean}$ (sec. 4.2.3). Theses responses are dominated by a process that cannot be accounted for directly and is likely the increased upper-ocean overturning circulation, which enhances outgassing of deep waters and overall weakens the Southern Ocean carbon sink (summarizing fig. 5.2).

Vice versa, for weaker and northward-shifting westerly winds the trends in the different processes reverse. Decreasing upwelling and increased primary production result in an additional increase in the climate-change driven increasing Southern Ocean carbon sink (summarizing fig. 5.3).

What do we learn from this large ensemble simulation about the Southern Ocean carbon sink?

While MPI-ESM LE aims to capture model spread due to internal variability and not reproduce CO_2 flux trends suggested by observations in the first place, I find that perturbed initial conditions large ensemble simulations are capable of capturing decadal internal variations similar to observations; even though other ensembles such as from GFDL or NCAR do not and this only applies for the most extreme decadal trends in MPI-ESM LE.

Forcing MPI-ESM with a historical CO_2 emissions instead of prescribed $pCO_{2,atm}$ increases internal variability of the global carbon sink by 25% [Ilyina et al., 2013]. Therefore, in an emission-driven ESM configuration with interactive carbon cycle the internal variability of the Southern Ocean carbon sink could be an even higher σ_{DIV}.

The strong trends discussed in this thesis originate in strong changes of the position and strength of Southern hemisphere westerly winds and effect of those on ocean circulation. However, the parametrized eddies in MPI-ESM LE might allow deeper mixing to sustain on longer time-scales than the seasonal timescale at which the eddies would counteract those trends [Thompson et al., 2011]. The impact of eddies on the carbon cycle in high-resolution simulations, especially in the Southern Ocean, is under current research [Ito et al., 2010; Dufour et al., 2013; Gnanadesikan et al., 2015; Meredith, 2016]. Only a variable definition of isopyncal thickness diffusion could parametrize the expected eddy response from high-resolution simulations [Gent and Danabasoglu, 2011]. Lovenduski et al., 2013 reproduces these increasing eddy fluxes and the response to the carbon cycle, but the general challenge of differing ocean circulation patterns remains and makes a comparison between a high-resolution resolved eddies and low-resolution parametrized eddies impossible [Bryan et al., 2014]. Among with improved circulation patterns, high-resolution perturbed initial conditions ensemble simulations give a more realistic representation of internal variability.

This thesis suggests that even though decadal variations are captured, decadal trends as in Landschützer et al., 2015 are rare and raise the question whether biogeochemical processes are missing or implemented in overestimated robustness. From an observational perspective, the historically under-sampled Southern Ocean now got equipped with ARGO floats, including 200 floats with biogeochemical sensors. For the first time, this permits accurate in-situ measurements during austral winter months and even under ice [Williams et al., 2017]. This allows the possibility to adjust biogeochemical models to primary production in meltponds or under thinning sea-ice. Most models lack this potentially additional variable contribution to the oceanic carbon sink [Long, 2015; Horvat et al., 2017].

The Southern Ocean water-column is very susceptible to density changes to the water-column. Modeling this area where different water masses converge faces long-standing challenges with stability. Open-ocean convection appears in models although not observed for decades [de Lavergne et al., 2014; Stössel et al., 2015] and sea-ice is underestimated in MPI-ESM [Jungclaus et al., 2013; Notz et al., 2013]. Additional freshwater input from icebergs stratifies the high-latitude Southern Ocean and thereby hinders open-ocean convection and too deep winter mixing [Sallée et al., 2013a; Stössel et al., 2015]. A higher-resolution atmosphere introduces counter gyres in the Weddell and Ross Sea, which push the sea-ice edge to more realistic and northern extent [Stössel et al., 2015]. Introducing these developments to MPI-ESM benefits the biogeochemical representation in HAMOCC.

The history of large ensemble simulations with perturbed initial conditions is fairly recent. The attempt to study internal variability with MPI-ESM LE gives first insights into internal variability from many realizations of simulations. Understanding internal varying processes in our climate system might become increasingly important in the case of global CO_2 emission reductions, when the CO_2 reduction efforts are tracked by measurements and evaluated by scientists and politicians [Hawkins and Sutton, 2009; McKinley et al., 2016; Lovenduski et al., 2016; Marotzke et al., 2017]. A further interesting project would be the comparison of different perturbed initial conditions large ensembles based on different models, i. e. comparing CESM LE, GFDL LE and MPI-ESM LE.