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

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1. Preamble

Recent observations suggest pronounced decadal variations in the Southern Ocean (SO) carbon sink [Landschützer et al. 2015]. 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, don't always capture this variability. By analyzing the Max Planck Institute's Earth System Model Large Ensemble (**MPI-ESM LE**) based on 100 historical simulations, we address the question: *What are the drivers of internal variability of the SO carbon sink?* We specifically focus on the positive trends (i.e. weakening of the carbon sink), because those are unforeseen given the ongoing increase in atmospheric CO_2 concentrations.

2. Methods

- MPI-ESM1.1 forced by prescribed atmospheric CO_2 concentrations
- Ocean biogeochemical model represented by HAMOCC [Ilyina et al. 2013]
- perturbed initial conditions ensemble initiated from 100 different starting years from pre-industrial control run
- historical forcing from 1850 to 2005
- Comparison to observation-based estimate SOM-FFN [Landschützer et al. 2015]
- Decadal internal variability σ as standard deviation of decadal anomalies

$$\sigma=\sqrt{\frac{1}{N\,M}\sum_{n=ens}^{N}\sum_{m=yr}^{M}\left(X_{m,n}-\overline{X_{m,n}}\right)^2} \qquad X_{m,n}=x_{endyear,n}-x_{startyear,n}$$

3. Internal Variability of the SO carbon sink

- Largest internal variability in outgassing area
- Modeled decadal internal variability σ = 0.22 PgC
- We find distinguishable positive and negative multi-year air-sea CO_2 flux trends
- Decadal internal variability in MPI-ESM LE is comparable to SOM-FFN

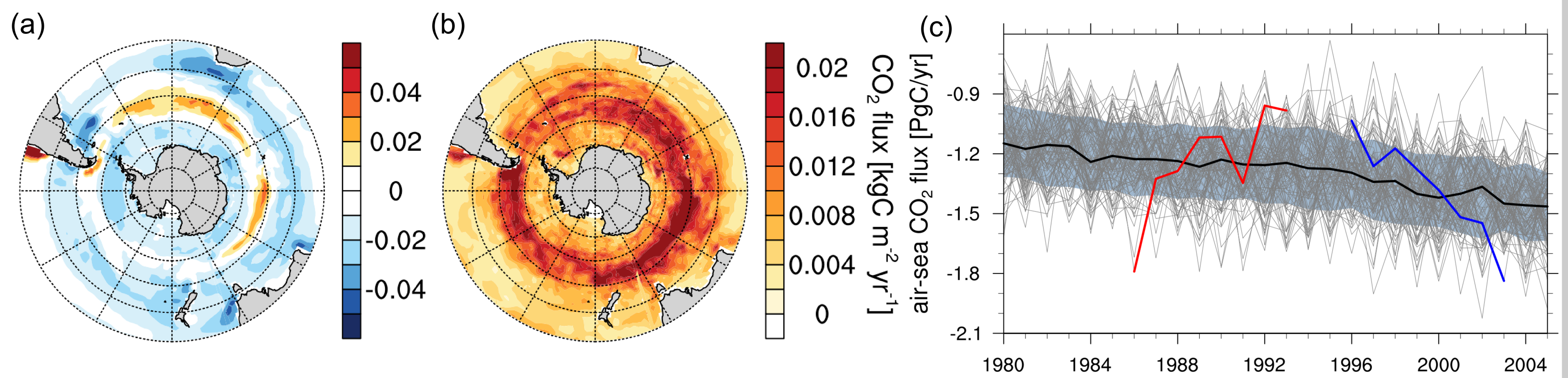


Figure 1: Air-sea CO_2 flux in the Southern Ocean carbon sink and its variability:
(a) Climatology (1980-2005) in MPI-ESM ensemble mean,
(b) Decadal internal variability σ as decadal anomaly standard deviation,
(c) Temporal evolution of the Southern Ocean south of 35°S from 1980 to 2005. Gray lines are from 100 ensemble members. The red line is the most extreme positive 8-year trend. The blue line is the most extreme negative trend. The gray shading shows the decadal internal variability σ.
Negative values mean oceanic carbon uptake

4. Winds drive CO_2 flux variability

Relationship between CO_2 flux & SAM suggests two regimes in SO carbon sink:

- Stronger winds lead to a weakening of the carbon sink (outgassing anomalies)
- Weaker winds lead to a stronger carbon sink (ingassing anomalies)

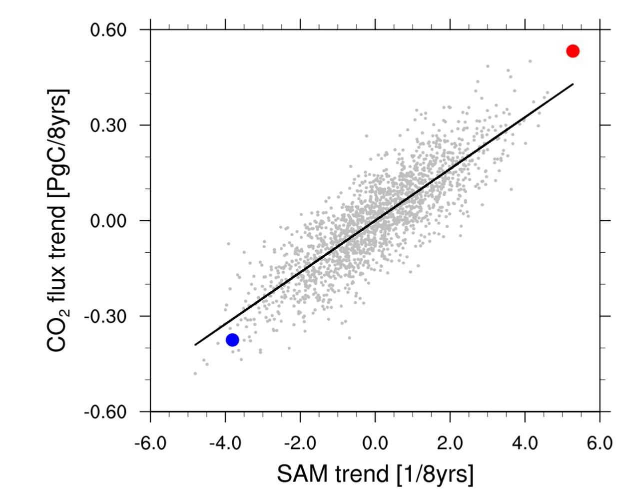
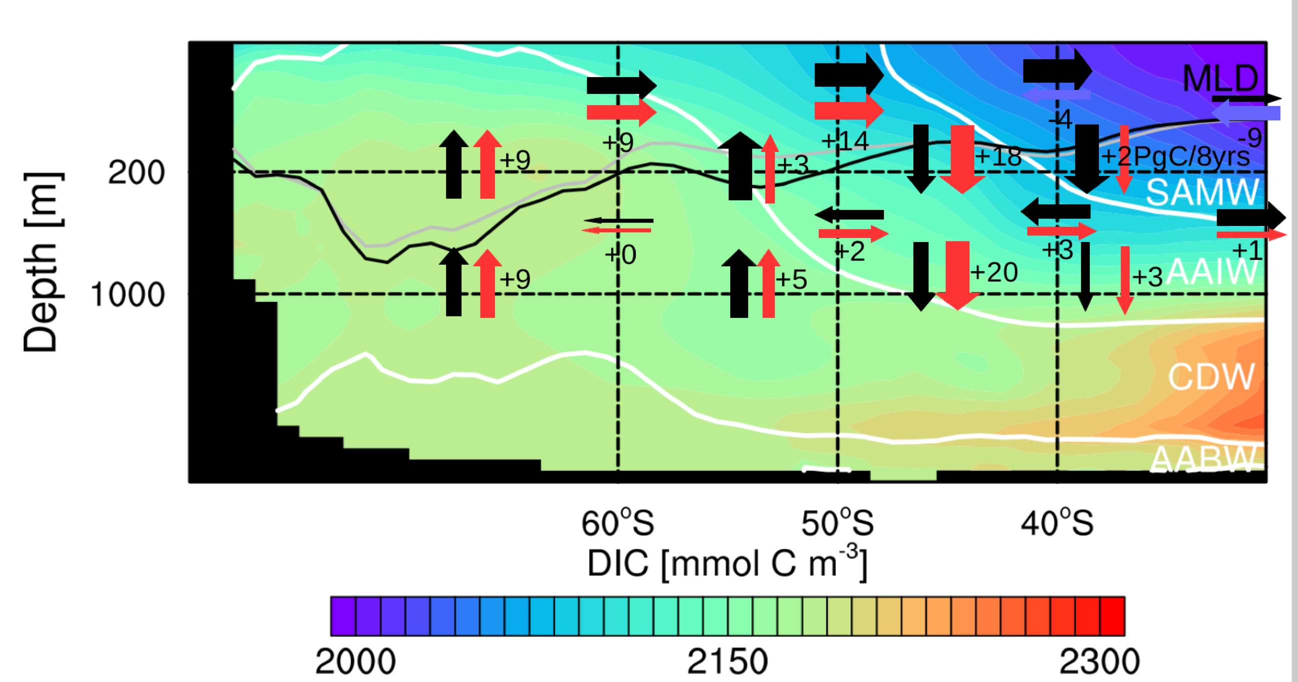


Figure 2: Trends in the SAM index and CO_2 flux at 50-60°S. The gray dots are individual 8-year trends. The red/blue dot is the most positive/negative 8-year CO_2 flux trend, respectively.

5. Response of circulation to stronger winds

- Intensified upper-ocean overturning circulation (similar to inverse modeling results from DeVries et al. [2017])
- Increased upwelling of carbon-rich deep waters, increased Ekman northward transport and increased Ekman subduction

Figure 3: Linear trends in upper-ocean overturning circulation of the most positive CO_2 flux trend in the zonally averaged transect in the Southern Ocean for enhanced westerly winds. Black arrows indicate mean advection of carbon. Red arrows show intensification in carbon advection. Blue arrows show decline. The numbers show the trend over 8 years. The gray line is the mixed-layer depth in the beginning and the black line at the end of the period. White lines are isopycnals separating Southern Ocean water masses.



6. Response of biology to stronger winds

- Summer trends in CO_2 flux and primary production of opposite direction
- Trends in primary production not driven by changes in nutrient availability
- Deeper mixing due to enhanced winds inhibits primary production

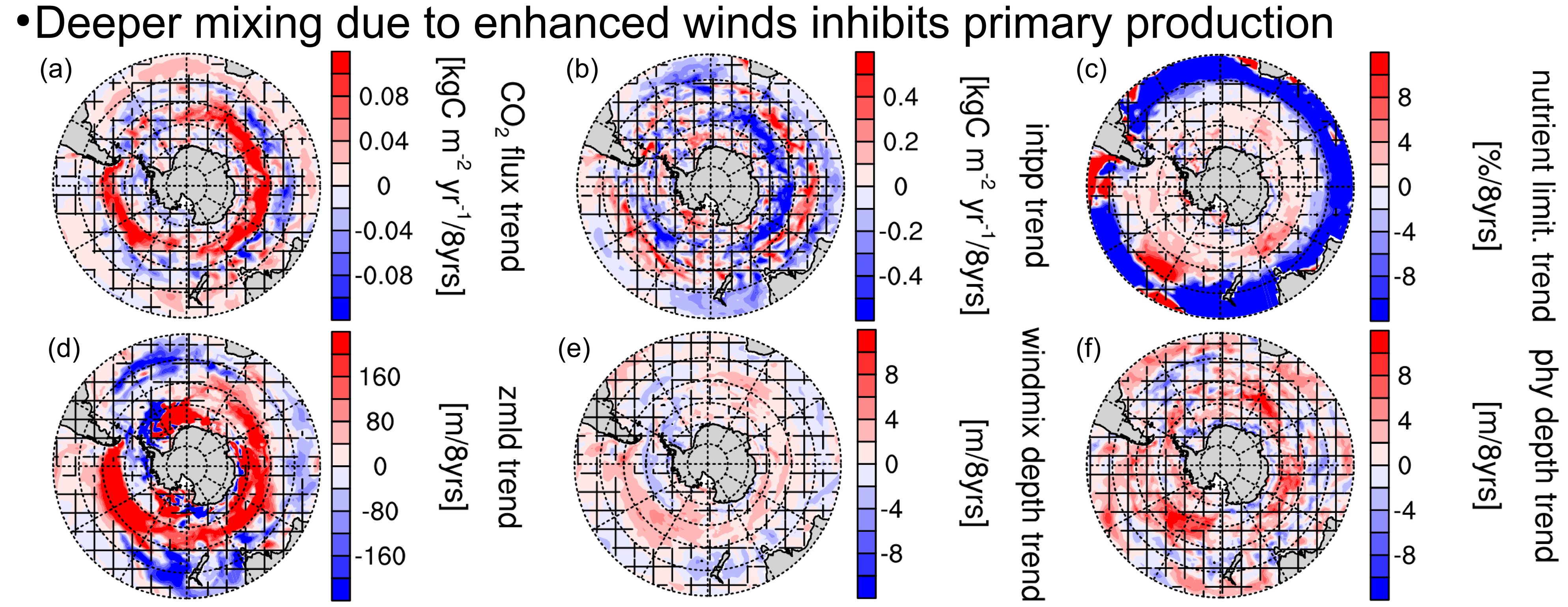


Figure 4: Linear trends in austral summer of the most positive CO_2 flux trend: (a) CO_2 flux, (b) integrated primary production, (c) nutrient limitation, (d) mixed-layer depth, (e) average depth of vertical diffusivity due to wind and (f) average phytoplankton depth; hatched area indicate where the linear trends are outside the 5% significance level

7. Summary

MPI-ESM Large Ensemble captures multi-year positive and negative trends as suggested by observations (Fig 1c).
We find two wind-driven regimes of the SO carbon sink (Fig. 2): Enhanced winds increase upwelling (Fig. 3) and decrease primary production (Fig. 4). This weakens the carbon sink and vice versa for weaker winds.
The decadal internal variability is largest at 50-60°S (Fig. 1b).

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References:
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- DeVries et al., 2017, Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning, Nature, 542, 215-218
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