# Decadal trends in the Southern Ocean carbon sink in the MPI-ESM grand ensemble

**Aaron Spring[1], Hongmei Li[1], Tatiana Ilyina[1]**

[1]Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany, aaron.spring@mpimet.mpg.de

## 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 a historical Large Ensemble of 100 simulations based on the Max Planck Institute's Earth System Model (MPI-ESM), we address the question what are the drivers of internal variability of the Southern Ocean carbon sink? We specifically focus on the negative 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 $pCO_2$ concentrations
- Ocean biogeochemical model represented by HAMOCC [Ilyina et al. 2013]
- 100 perturbed initial conditions ensemble initiated with 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

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

## 3. Internal Variability of the SO carbon sink

- Largest internal variability in outgassing area
- Modeled decadal internal variability σ = ±0.2 PgC
- Identification of positive and negative multi-year $CO_2$ flux trends of similar magnitude of those in SOM-FFN
- Compromise between trend length and signal strength: 8-year trends
- MPI-ESM Large Ensemble 2σ ~ SOM-FFN decadal variations

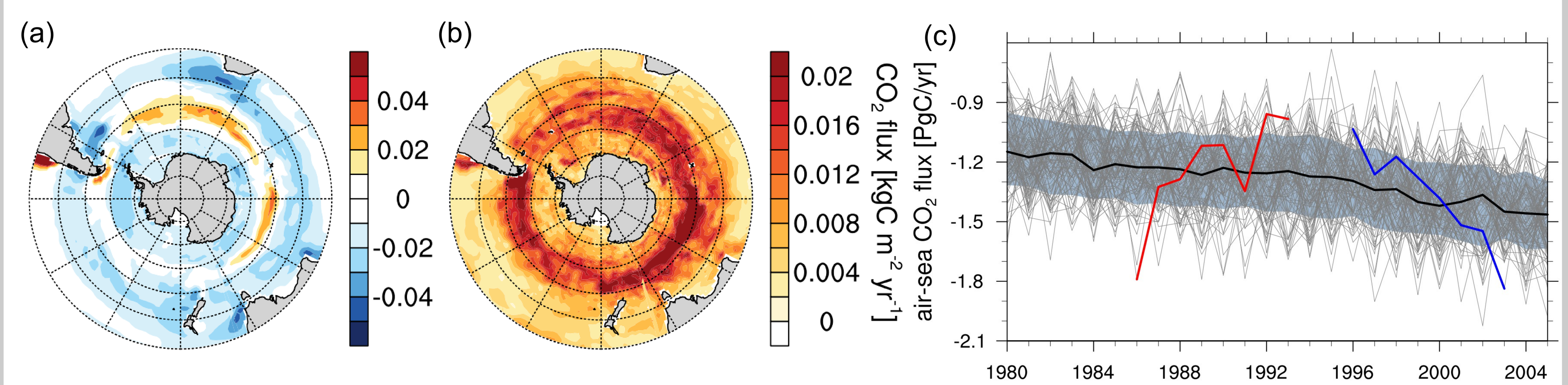


Figure 1: Air-sea $CO_2$ flux in the Southern Ocean carbon sink and its variability; negative values indicate oceanic carbon uptake: (a) $CO_2$ flux climatology 1980-2005 in MPI-ESM ensemble mean, (b) decadal internal variability σ as decadal anomaly standard deviation, (c) temporal evolution of the Southern Ocean air-sea $CO_2$ flux 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 $CO_2$ flux trend, the blue line is the most extreme negative $CO_2$ flux trend, the gray shading shows the decadal internal variability σ

## 4. Winds drive $CO_2$ flux variability

Relationship between $CO_2$ & 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)

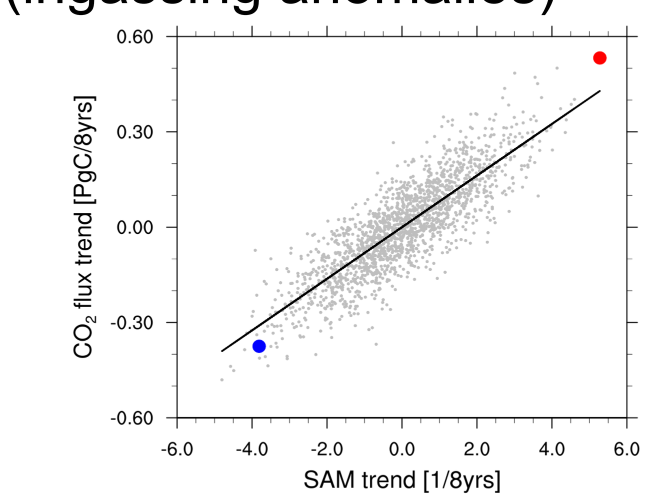
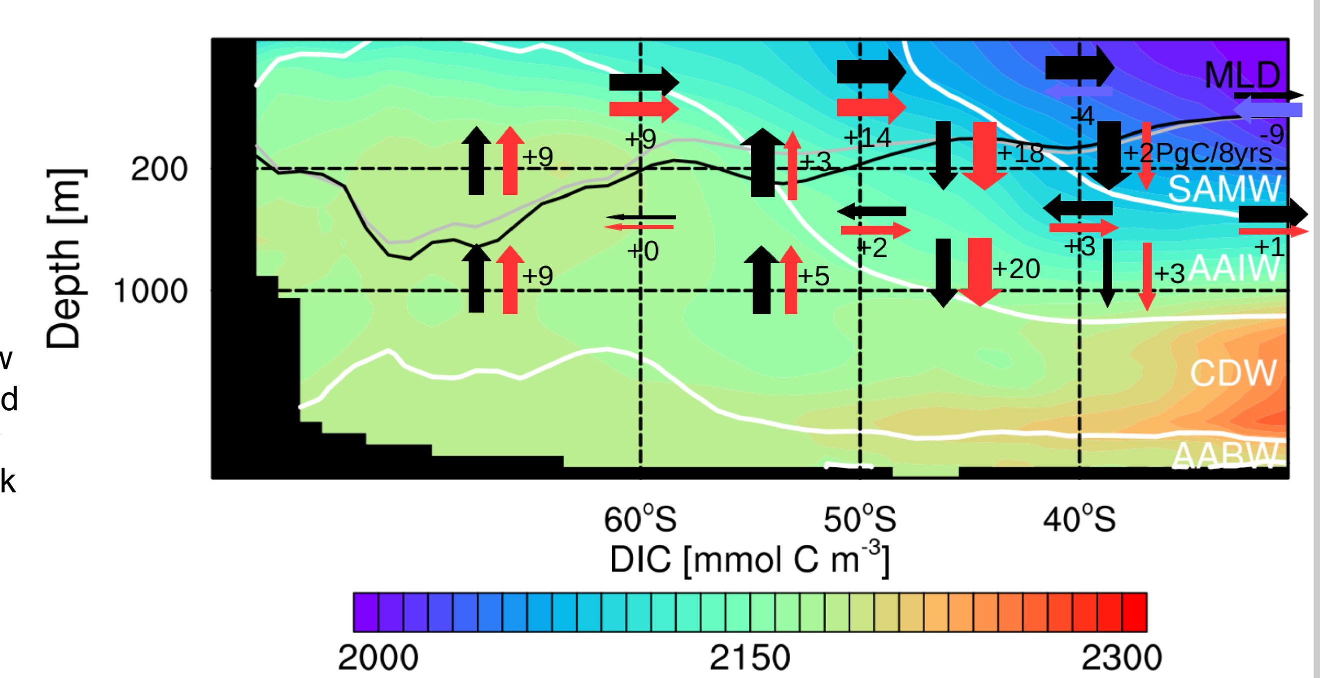


Figure 2: Trends in the SAM index and $CO_2$ flux links the carbon sink at 50-60°S to westerly winds; red/blue dot is the most positive/negative 8-year $CO_2$ flux trend

## 5. Response of circulation to stronger winds

- Intensified upper-ocean overturning circulation (similar to [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 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, gray line, 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
- Nutrient availability does not decrease
- Deeper mixing due to enhanced winds inhibits primary production

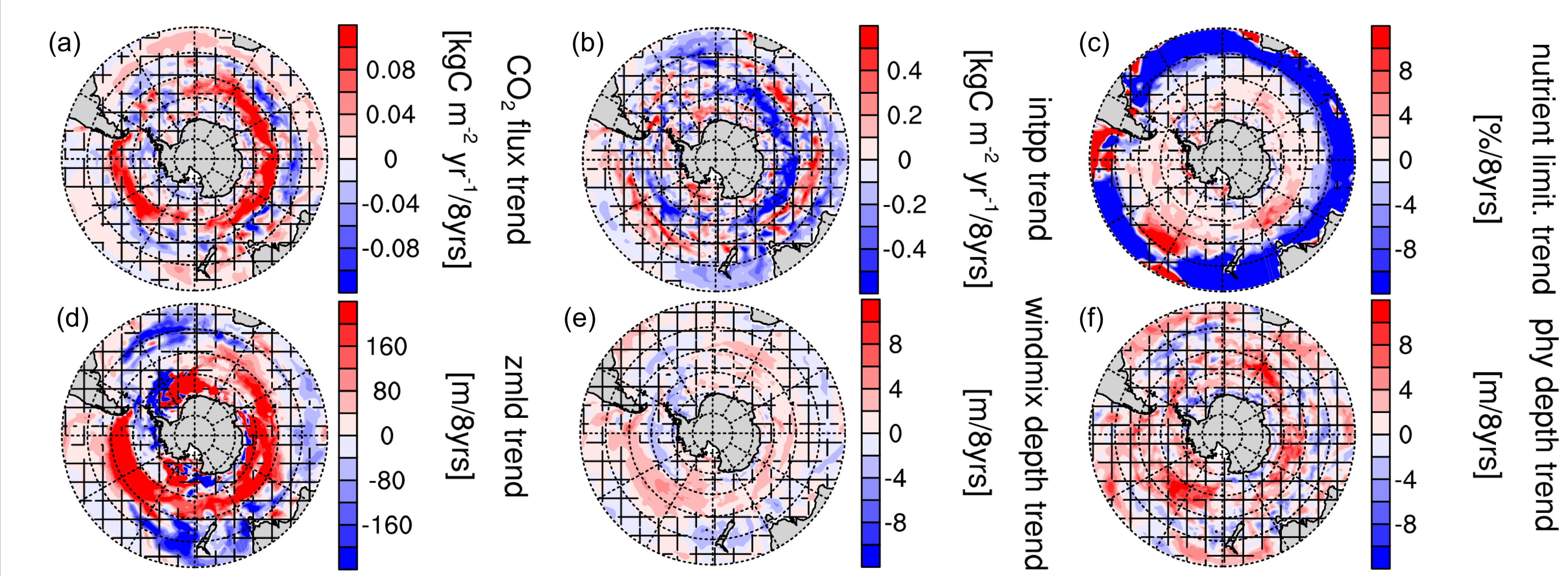



Figure 4: Linear trends in austral summer of the most positive $CO_2$ flux trend: (a) $CO_2$ flux, (b) integrated primary production, (c) nutrient limitation, (d) mixed-layer depth, (e) average depth of vertical diffusivity due to wind and (f) average phytoplankton depth

## 7. Summary

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

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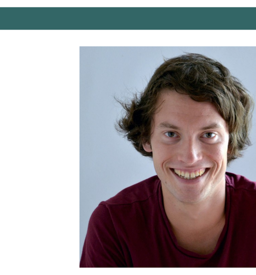

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**References:**
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- DeVries et al., 2017, Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning, Nature, 542, 215-218
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