~~MPI-ESM Large Ensemble simulations reproduce decadal carbon trends in the Southern Ocean~~

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1. Preamble

Observations-~~based estimates report large~~ decadal variations in the Southern Ocean (SO) carbon sink [LeQuéré et al. 2007, Landschützer et al. 2015]. ~~Sparse observational data lack the ability to show the dynamics of internally varying processes, which demands for the evaluation with models.~~

~~Forced ocean models reproduce this variability. However, coupled earth system models poorly capture climate variability.~~ By analyzing a historical ~~large~~ ensemble of 100 simulations based on Max Planck Institute's Earth System Model (MPI-ESM), we assess modeled internal variability of the Southern Ocean carbon sink. ~~Here we analyze what drives internal variability and focus on negative carbon sink trends unforeseen just from atmospheric forcing alone.~~

2. Methods

- MPI-ESM1.1 ~~with a non-interactive carbon cycle~~
- Ocean biogeochemical model represented by HAMOCC [Ilyina et al. 2013]
- 100 ensemble members with different starting years from pre-industrial control run
- historical forcing from 1850 to 2005 extended under the RCP4.5 scenario to 2100
- Comparison to observation-based estimate SOM-FFN [Landschützer et al. 2015]
- Decadal internal variability: $X_{m,n} = x_{endyear,n} - x_{startyear,n}$

$$\sigma_{D.I.V.} = \sqrt{\frac{1}{N\,M} \sum_{n=ens}^{N} \sum_{m=yr}^{M} \left(X_{m,n} - \bar{X}_{m,n}\right)^2}$$

- Analysis of linear trends of ~~various quantities~~ impacting the carbon cycle

3. Internal Variability of the SO carbon sink

- Largest internal variability in outgassing ~~region~~
- Decadal internal variability: $\sigma = \pm 0.2$ PgC
- Detection of positive and negative decadal carbon sink trends similar to those in the 1990s and 2000s in SOM-FFN
- Compromise between trend length and signal strength: 8-yr trends
- SOM-FFN data range within MPI-ESM large ensemble range

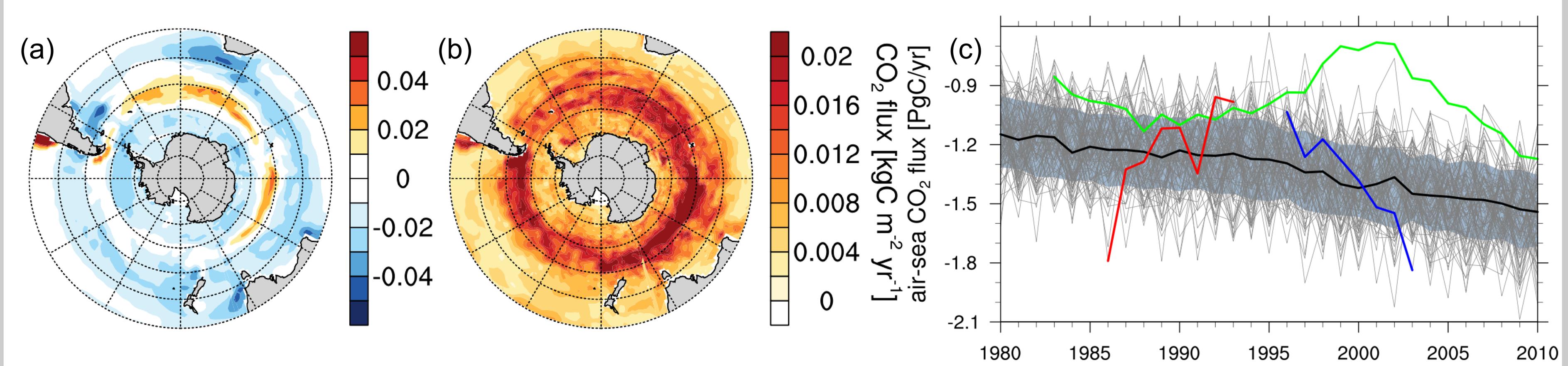


Figure 1: ~~The Southern Ocean carbon sink~~ and its variability; negative ~~CO_2 flux~~ values indicate oceanic carbon uptake: (a) CO_2 flux climatology in MPI-ESM, (b) internal variability in CO_2 flux, (c) evolution of the Southern Ocean ~~carbon sink~~ south of 35°S, green line from SOM-FFN [Landschützer et al. 2015], red line is a negative carbon sink trend, blue line is a positive carbon sink trend, gray shading shows the 1σ internal variability

4. Winds drive CO_2 flux variability

- Stronger winds lead to CO_2 outgassing anomalies
- Weaker winds lead to CO_2 uptake anomalies

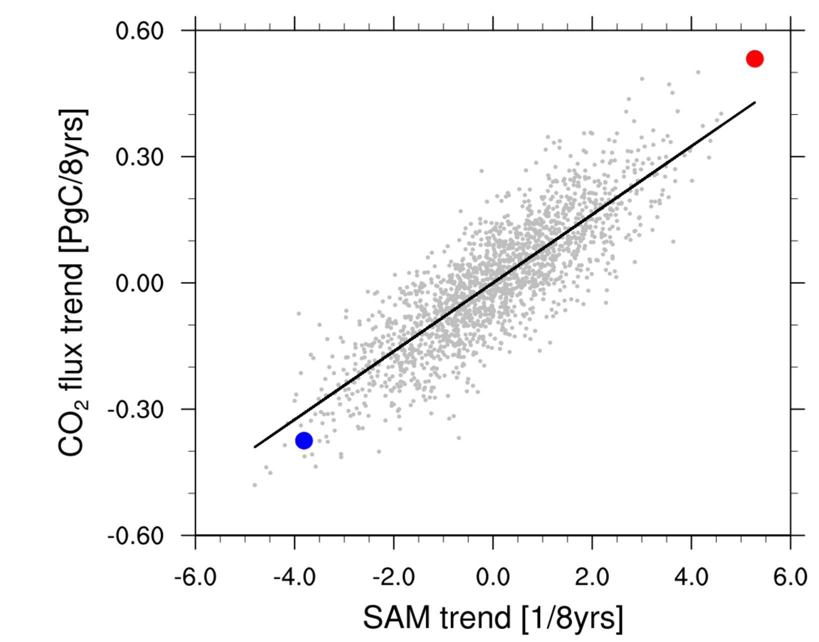
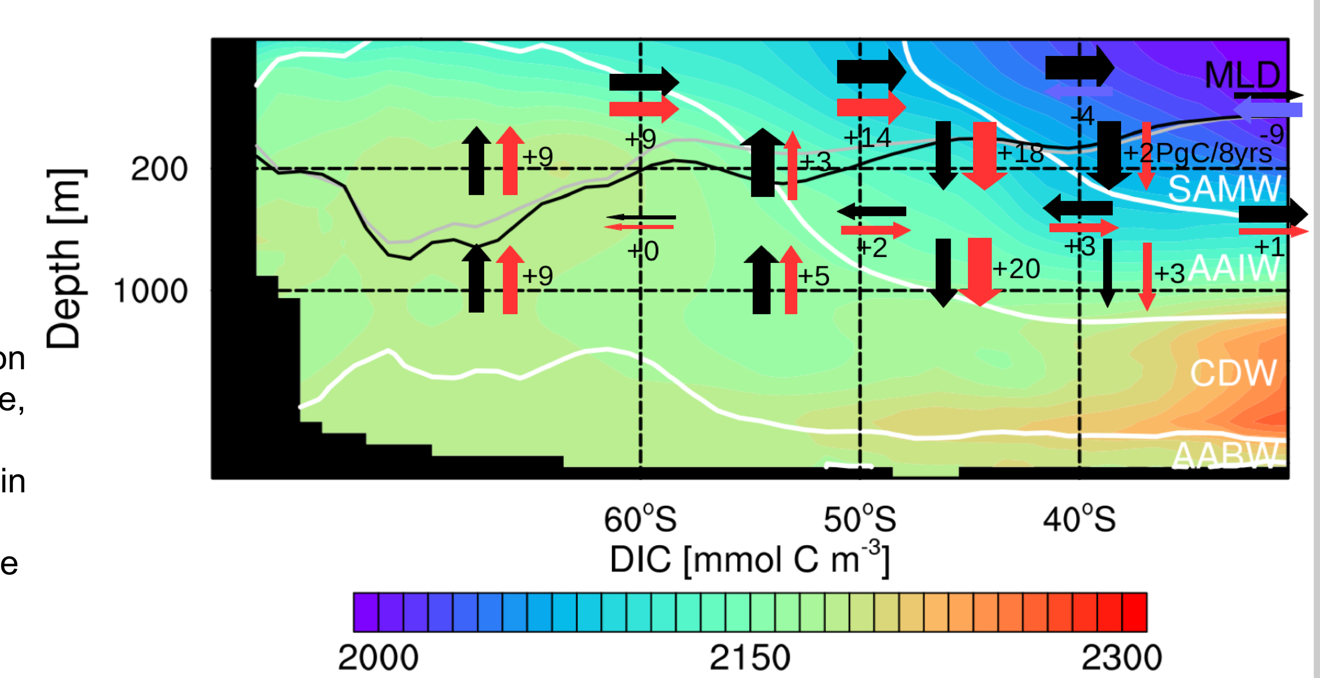


Figure 2: Relation of trends in the SAM index and CO_2 flux links the carbon sink at 50-60°S to westerly winds.

5. Response of circulation to stronger winds

- Intensified upper-ocean overturning circulation
- Increased upwelling of carbon-rich deep waters, increased Ekman northward transport and increased Ekman subduction
- Similar upper-ocean overturning circulation trends as in [DeVries et al. 2017]

Figure 3: Trends in upper-ocean overturning circulation in the zonal Southern Ocean show how increasing westerly winds intensify the overturning which weakens the carbon sink. 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

- Opposing summer trends in CO_2 flux and primary production
- No change in nutrient limitation
- Deeper mixing due to winds inhibits primary production

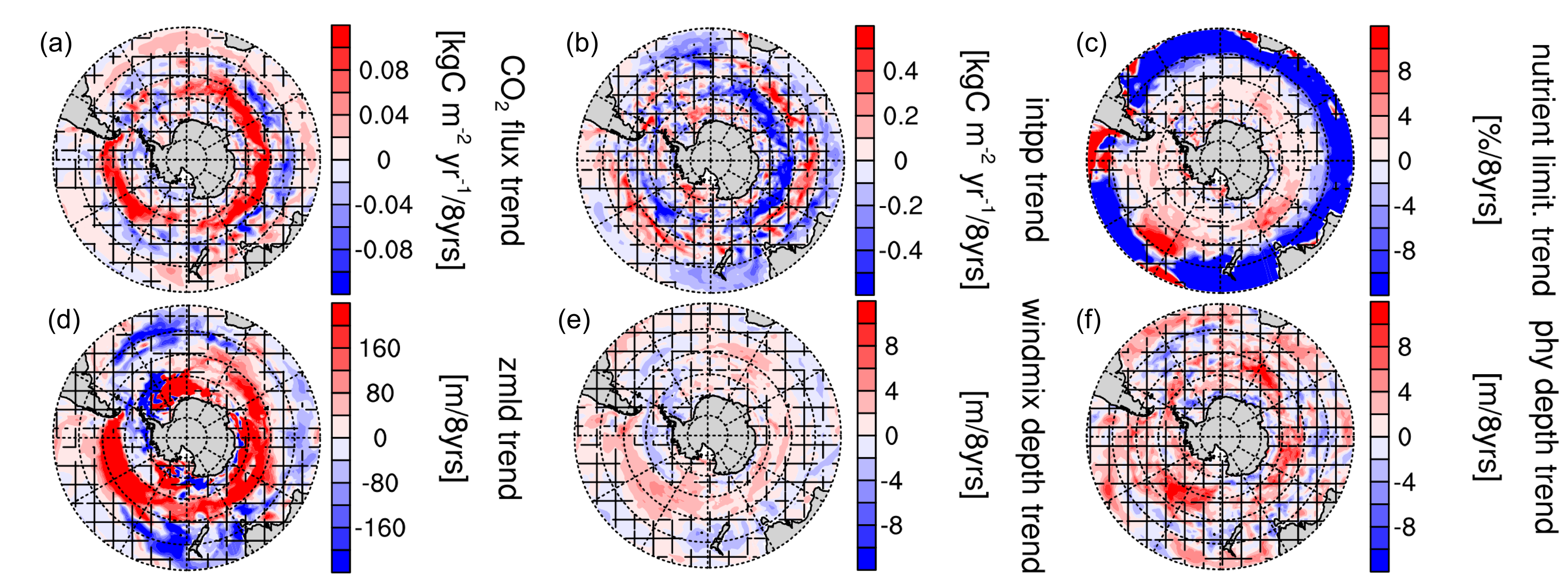


Figure 4: Trends in austral summer in Southern Ocean: (a) CO_2 flux, (b) vertically integrated primary production, (c) nutrient limitation, (d) mixed-layer depth, (e) vertical diffusivity due to wind and (f) phytoplankton depth

7. Conclusions

- Latitudes of largest variability: 50-60°S (Fig. 1b)
- Decadal carbon sink trends similar to 1990s and 2000s reproducible in coupled ESM (Fig. 1c)
- Southern Ocean carbon sink variability driven by westerly winds (Fig. 2)
- Stronger winds decrease primary production (Fig. 3), increase upwelling (Fig. 4) and vice versa for weaker winds (Fig. 2)

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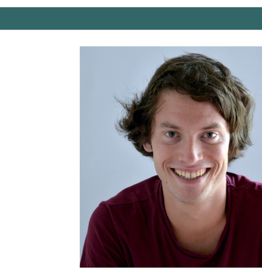

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