Decadal variations in the Southern Ocean carbon sink in MPI-ESM 100 Ensemble simulations

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Recent observations ~~[Landschützer et al., 2015]~~ suggest pronounced decadal variations in the Southern Ocean carbon sink.

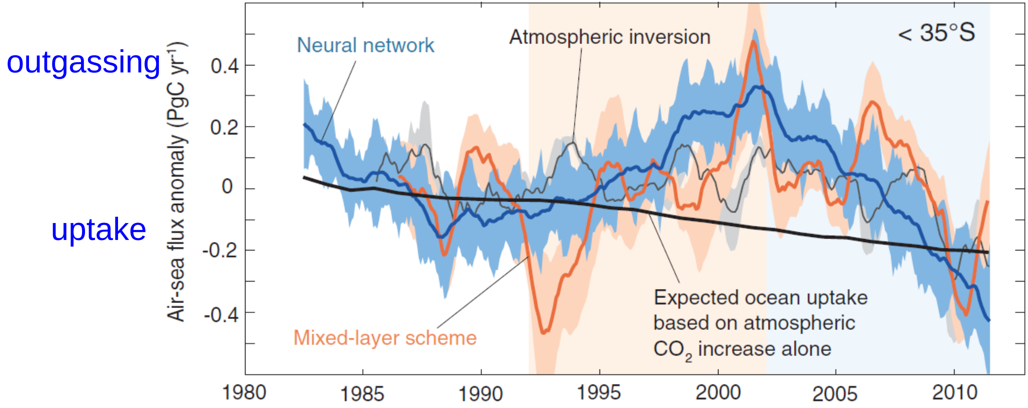

Figure: Evolution of the Southern Ocean carbon sink anomaly south of 35°S. Negative CO_2 flux values indicate anomalous ocean uptake with respect to the 1980s mean. From Landschützer et al. [2015]

However, due to the sparse spatial and temporal coverage, it is challenging to discern the dynamics of internally varying processes.

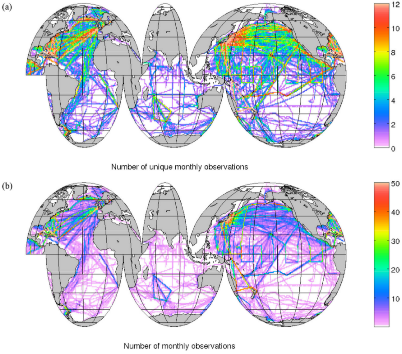

Figure: The number of (a) months of the year and (b) total months with surface water pCO_2 from 1970 to 2011 in SOCATv2 [Bakker et al., 2014]

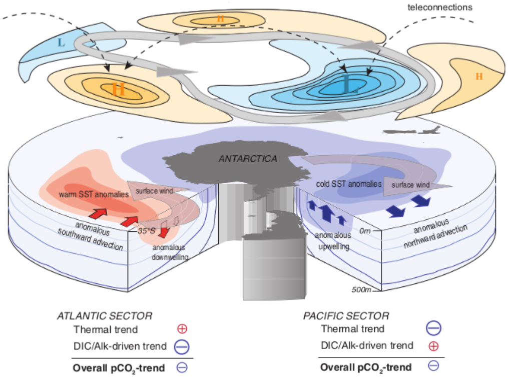

Figure: Schematic of the processes governing the changes in ΔpCO_2 trends in the Southern Ocean since 2001 [Landschützer et al., 2015]

~~Earth-system-models~~, while being a useful tool to analyze processes that contribute to variability, do not always capture this variability.

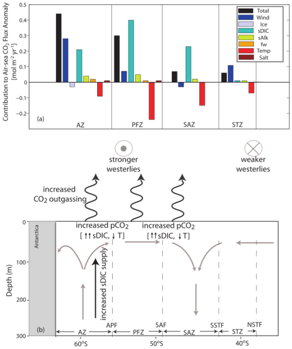

Figure: Contribution to air-sea CO_2 flux anomaly and schematic illustration of the upper ocean response to a positive phase of the SAM [Lovenduski et al., 2007]

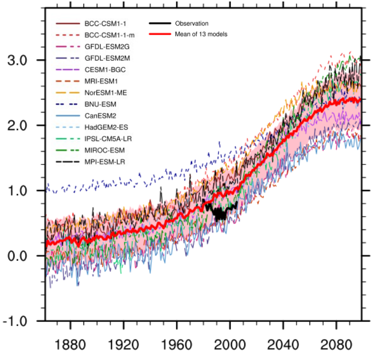

Figure: Historical and projected total air-sea CO_2 fluxes simulated by 13 CMIP5 models in the Southern Ocean [Wang et al., 2016]

By analyzing a large ensemble of 100 historical simulations based on Max Planck Institutes Earth System Model (MPI-ESM) with ~~slightly~~ different initial conditions but identical forcing, we assess modeled internal variability of the Southern Ocean carbon sink.

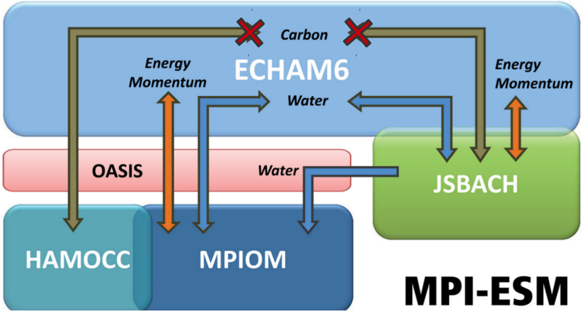

Figure: Schematic view of MPI-ESM1.1 with prescribed atmospheric pCO_2

Scientific questions

1. How large is the modeled decadal internal variability in the Southern Ocean carbon sink?
2. Do we find similar trends to those observed in the 1990s and 2000s in this large ensemble?
3. Which processes drive decadal internal variability in this large ensemble?

What is internal variability?

$$\text{signal} = \underbrace{\text{forced signal}}_{\text{ensemble mean}} + \underbrace{\text{internal variability}}_{\text{residual}}$$

$$CO_2\text{flux} = k_w \cdot \underbrace{(pCO_{2,\text{ocean}} - pCO_{2,\text{atm}})}_{\Delta pCO_2}$$

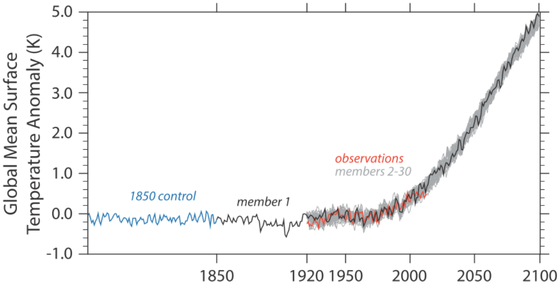

Figure: Global surface temperature anomaly [Kay et al., 2015]

I define decadal internal variability σ_{DIV} as the standard deviation of differences of the annual mean state after a decade over all N ensemble members and $\cancel{N}$ decades.

$$\sigma_{DIV}(X) = \sqrt{\frac{1}{MN} \sum_{n=\text{ens}}^{N} \sum_{m=\text{yr}}^{M} (\chi_{m,n} - \bar{\chi}_{m,n})^2} \qquad \chi_{m,n} = X_{\text{decade}_{\text{end}},n} - X_{\text{decade}_{\text{start}},n}$$

The modeled internal decadal variability σ_{DIV} is ± 0.18 PgC/yr.

anomalous?

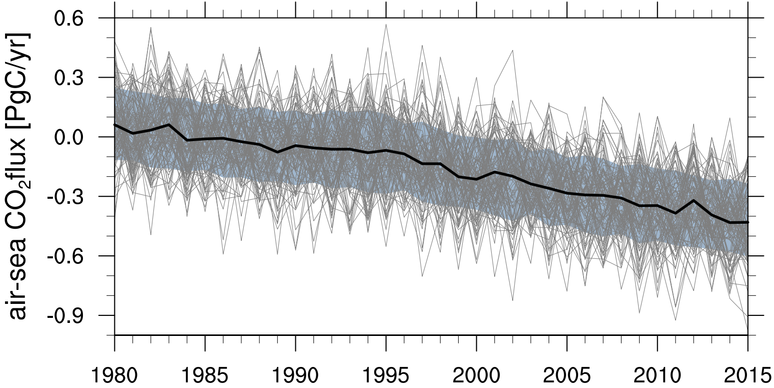

Figure: Temporal evolution of the Southern Ocean air-sea CO_2 flux south of 35°S. Grey lines show the 100 ensemble members, the black line the ensemble mean, the blue shading is the ensemble decadal internal variability σ_{DIV}; negative values indicate anomalous carbon uptake.

We find positive and negative decadal CO_2 flux trends similar to observations in the 1990s and 2000s.

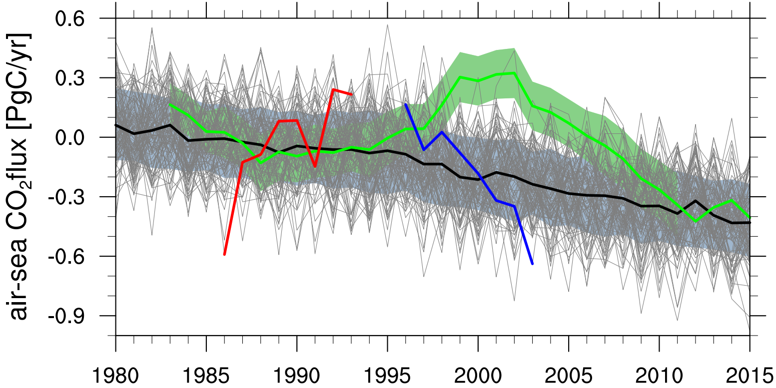

Figure: Temporal evolution of the Southern Ocean air-sea CO_2 flux south of 35°S. The red line shows a positive CO_2 flux trend, the blue line shows a negative CO_2 flux trend, the green line represents the SOM-FFN observation-based estimate [Landschützer et al., 2015].

The decadal internal variability σ_{DIV} is largest at 50-60°S.

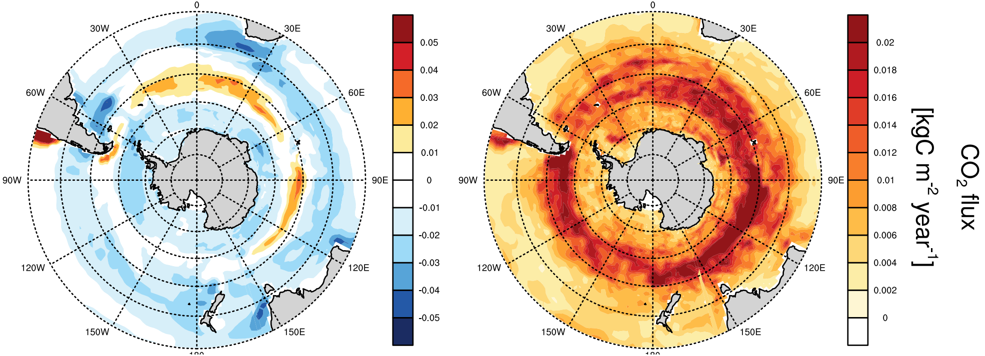

Figure: Spatial distribution of the climatology and decadal internal variability σ_{DIV} from 1980-2004 of the Southern Ocean air-sea CO_2 flux: MPI-ESM LE ensemble mean as forced signal and ensemble decadal standard deviation as decadal internal variability σ_{DIV}; negative values indicate ocean uptake.

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We find westerly winds as the main driver of internal variability.

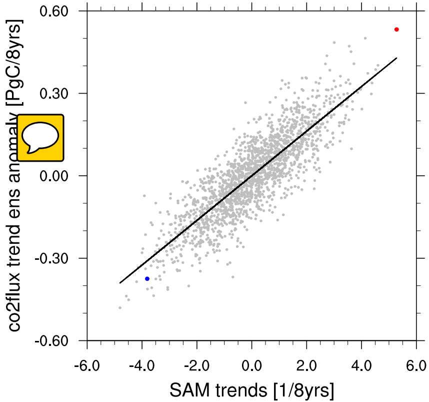

Figure: Linear trends in the Southern Annular Mode (SAM) as indicator of wind strength ~~vs.~~ CO_2 flux at 50-60°S; each data point represents 8-year trends of a single realization normalized for the ensemble mean trend between 1980 and 2005; the blue dot is the most negative monotonic CO_2 flux trend; the red dot is positive monotonic CO_2 flux trend.

Southern Ocean Review

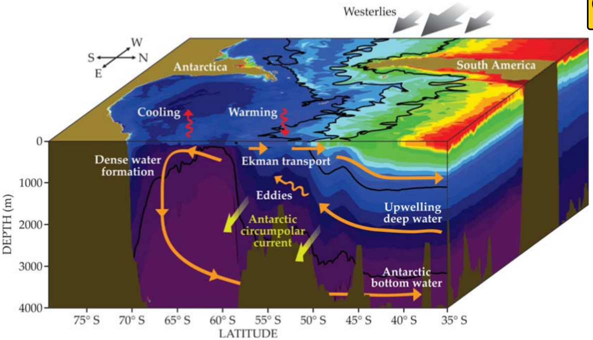

Figure: Dynamics of the Southern Ocean [Morrison et al., 2015]

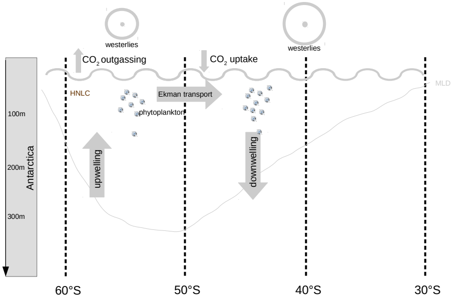

Figure: Schematic illustration of the Southern Ocean under the context of increasing westerly winds

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Enhanced and southward shifted westerly winds induce positive CO_2 flux trends. What's the response in thermal pCO_2, biology and ocean circulation?

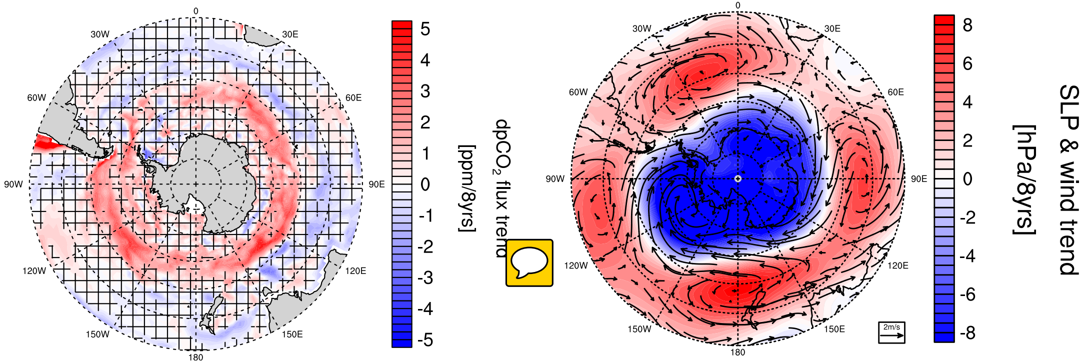

Figure: Linear trends in ΔpCO_2 (left) and sea-level pressure & winds (right) for the case of the most positive monotonic 8-year CO_2 flux trend; hatched areas indicate where ~~trends were below 5%~~

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The non-thermal trend dominates over the thermal.

[Takahashi, 2002]:
$$pCO_{2,\text{thermal}} = \overline{pCO_2} \cdot \exp\left[0.0423^\circ C^{-1}\left(T - \overline{T}\right)\right]$$
$$pCO_{2,\text{non-thermal}} = pCO_2 \cdot \exp\left[0.0423^\circ C^{-1}\left(\overline{T} - T\right)\right]$$

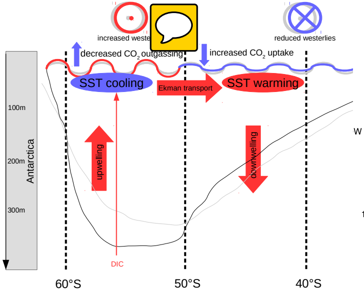

Figure: Schematic illustration of the Southern Ocean for increasing westerly winds

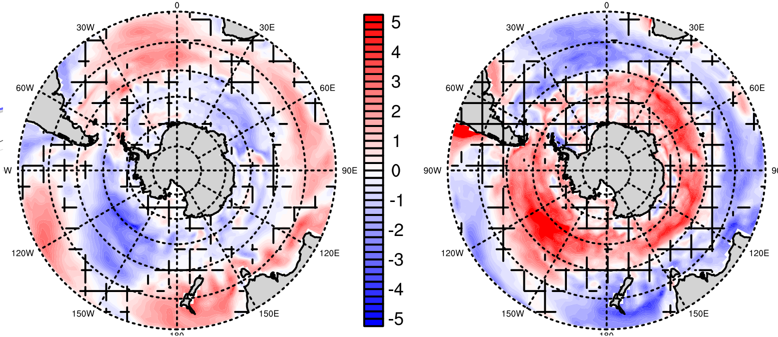

Figure: Linear trends in $pCO_{2,\text{thermal}}$ (left) and $\Delta pCO_{2,\text{non-thermal}}$ (right) for the case of the most positive monotonic 8-year CO_2 flux trend; hatched areas indicate where trends ~~were below 5%~~

Upper-ocean overturning circulation is enhanced.

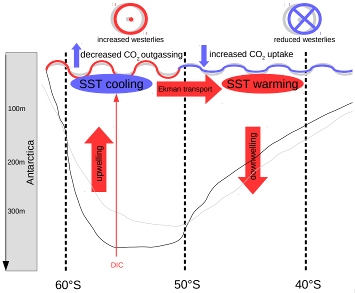

Figure: Schematic illustration of the Southern Ocean for increasing westerly winds

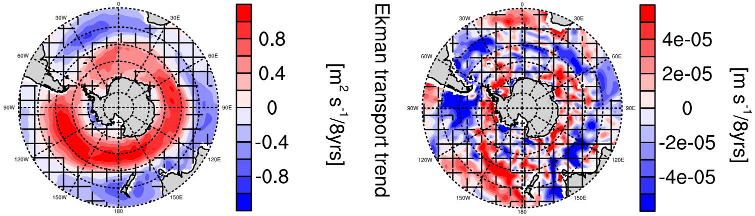

Figure: Linear trends in Ekman transport, Ekman pumping and, zonally averaged upper-ocean overturning circulation in the case of the most positive 8-year CO_2 flux trend

Upper-ocean overturning circulation is enhanced and drives outgassing.

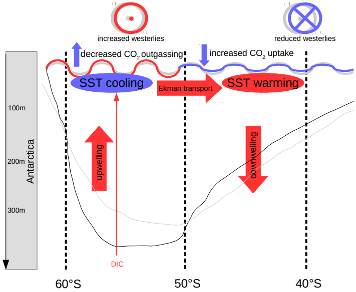

Figure: Schematic illustration of the Southern Ocean for increasing westerly winds

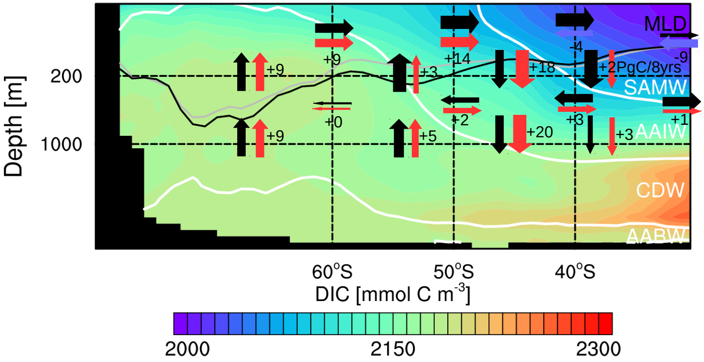

Figure: Zonally averaged upper-ocean overturning circulation in the case of the most positive 8-year CO_2 flux trend; similar [DeVries et al., 2017]

Primary production trends oppose trends in CO_2 flux, but not caused by changes in nutrients.

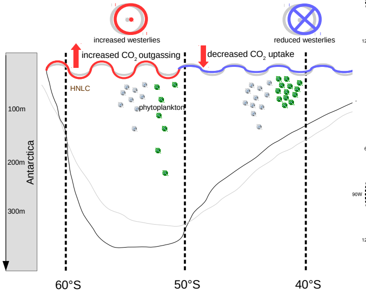

Figure: Schematic illustration of the Southern Ocean for increasing westerly winds

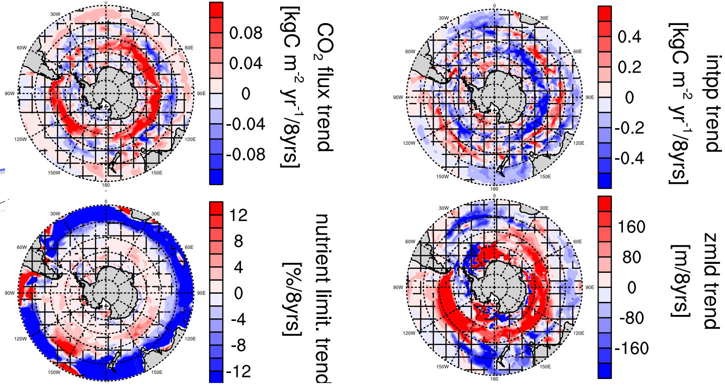

Figure: Southern Ocean austral summer trends over 8 years: CO_2flux (top left), vertically integrated primary production (top right), surface nutrient limitation (bottom left) and mixed layer depth (bottom right); hatched areas indicate where trends were below 95% significance

Light & temperature limitation causes the decline in primary production at 50-60°S. Phytoplankton gets mixed deeper into the ocean.

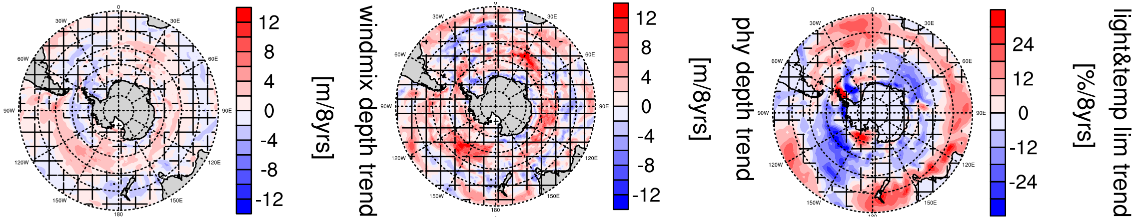

Figure: Trends in of average depth of vertical diffusivity due to wind (left), phytoplankton average depth (middle) and surface light & temperature limitation factor; hatched areas indicate where trends were below 95% significance

Previous studies show increasing primary production for increasing winds. Increased upwelling brings more nutrients, but this has no effect on biology in HAMOCC. However, biology signal much smaller than circulation.

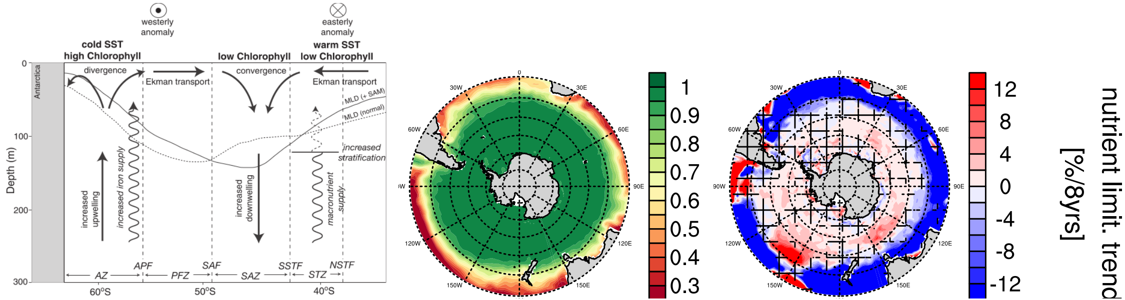

Figure: (left) Schematic view of the upper ocean response to a positive SAM phase [Lovenduski and Gruber, 2005]; (right) surface nutrient limitation function summer mean and trend

related papers: [Lovenduski et al., 2008] [Wang and Moore, 2012] [Hauck et al., 2013]

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Summary

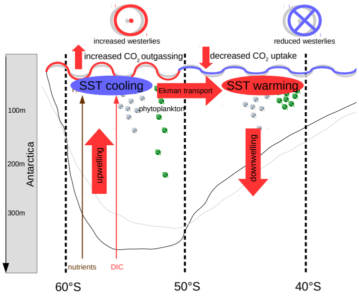


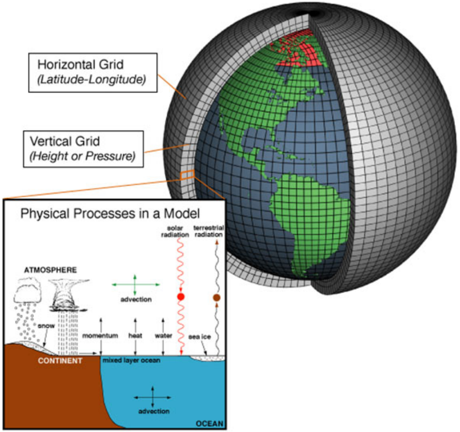
Figure: Schematic illustration of the Southern Ocean for increasing westerly winds

- MPI-ESM Large Ensemble captures multi-year positive and negative trends as suggested by observations
- The decadal internal variability is largest at 50-60°S
- Trends reverse for decreasing winds
- We find two wind-driven regimes of the Southern Ocean carbon sink: Enhanced winds...
  - increase thermal CO_2 uptake
  - increase upwelling
  - decrease primary production

Overall, this weakens the carbon sink and vice versa strengthens for weaker winds.

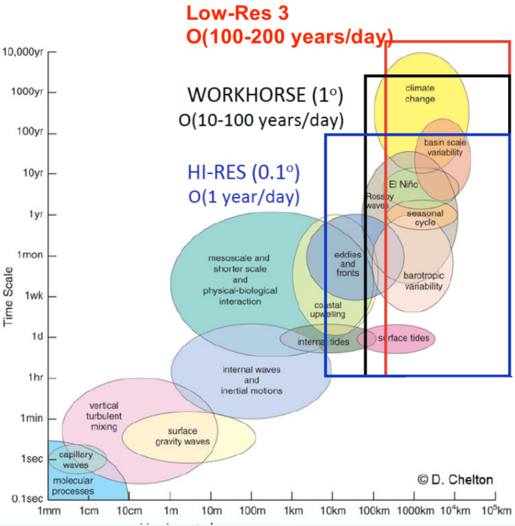
Appendix

Earth-system-modeling

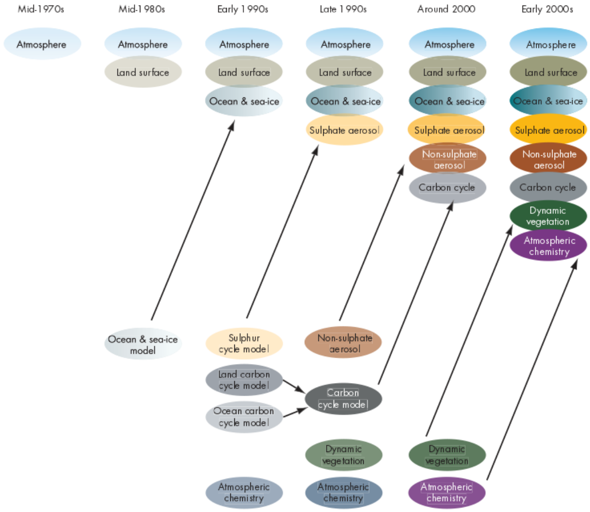


HAMOCC Visualisation:
https://www.dkrz.de/about/media/galerie/Vis/esm/hamocc

Earth-system-model scales



Earth-system-model processes



CO_2 flux Southern Ocean Trendmap

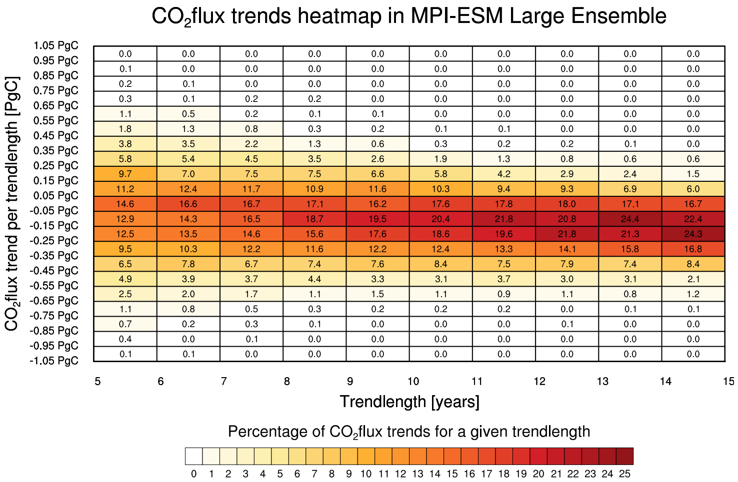


Figure: Southern Ocean carbon sink trends per trendlength

Model Evaluation - CO_2 flux

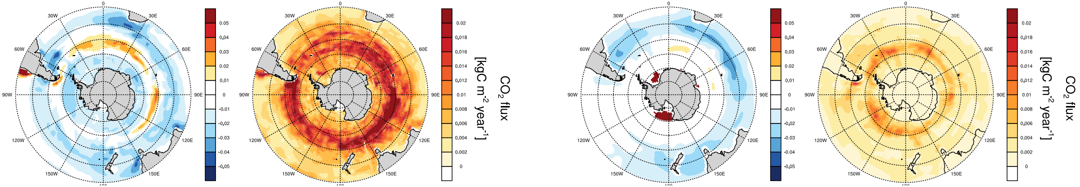


Figure: Spatial distribution of the climatology (a,c) and decadal internal variability σ_{DIV} (b,d) from 1980-2004 of the Southern Ocean air-sea CO_2 flux: MPI-ESM LE ensemble mean as forced signal (a), ensemble decadal standard deviation as decadal internal variability σ_{DIV} (b), SOM-FFN climatology 1982-2004 (c), SOM-FFN decadal variability σ_{DIV} (d); negative values indicate ocean uptake.

Model Evaluation - Winds

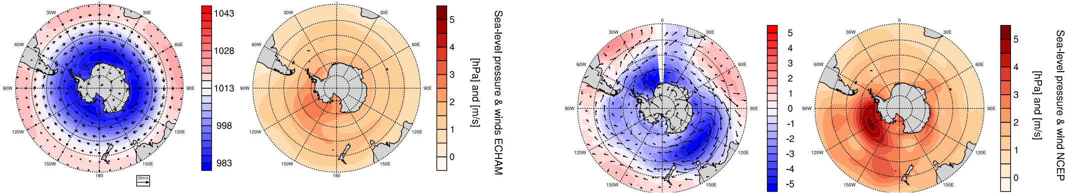


Figure: Spatial distribution of the Southern Ocean sea-level pressure and winds: ensemble mean climatology from 1980 to 2004 (a) as forced signal and ensemble decadal standard deviation (b) as decadal internal variability σ_{DIV}; and the difference between MPI-ESM and reanalysis data from NCEP climatology (c), and decadal internal variability σ_{DIV} from NCEP climatology (d).

Model Evaluation - Nutrients

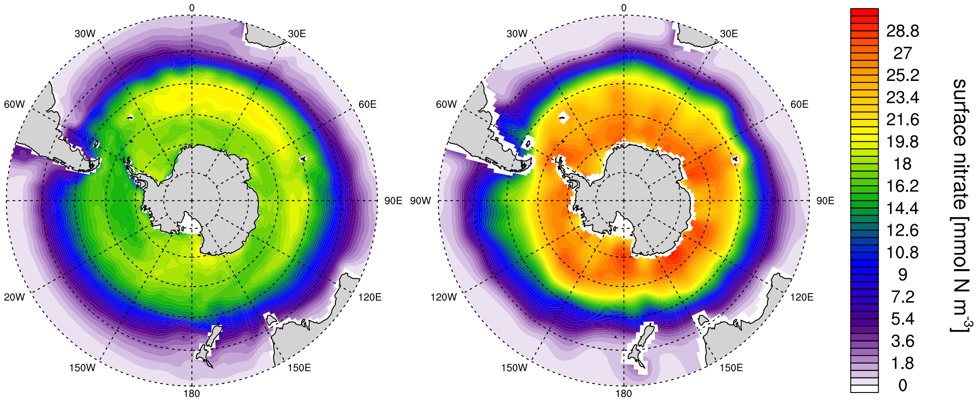


Figure: Spatial distribution of the climatology of surface nitrate (left) compared with WOA data [Garcia et al., 2013] (right)

Model Evaluation - SST

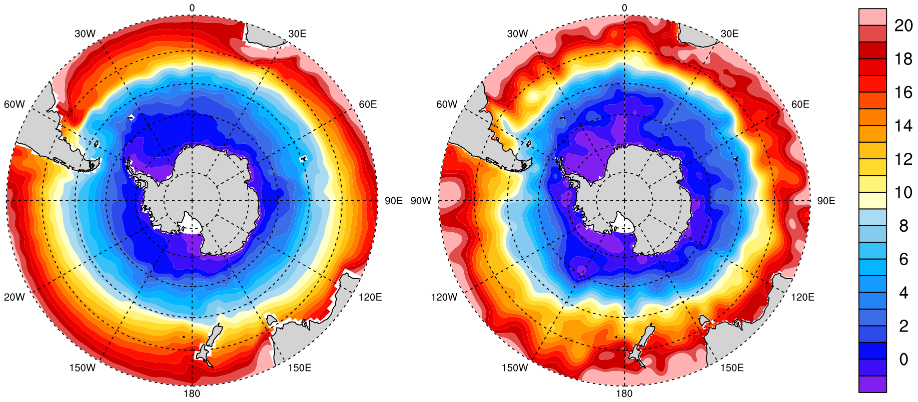


Figure: Spatial distribution of the ensemble mean climatology (1980-2004) of the sea-surface temperature (SST) (left) compared with xyz

References I

D. C. E. Bakker, B. Pfeil, K. Smith, S. Hankin, A. Olsen, S. R. Alin, C. Cosca, S. Harasawa, A. Kozyr, Y. Nojiri, K. M. O'Brien, U. Schuster, M. Telszewski, B. Tilbrook, C. Wada, J. Akl, L. Barbero, N. R. Bates, J. Boutin, Y. Bozec, W.-J. Cai, R. D. Castle, F. P. Chavez, L. Chen, M. Chierici, K. Currie, H. J. W. de Baar, W. Evans, R. A. Feely, A. Fransson, Z. Gao, B. Hales, N. J. Hardman-Mountford, M. Hoppema, W.-J. Huang, C. W. Hunt, B. Huss, T. Ichikawa, T. Johannessen, E. M. Jones, S. D. Jones, S. Jutterstrm, V. Kitidis, A. Krtzinger, P. Landschtzer, S. K. Lauvset, N. Lefèvre, A. B. Manke, J. T. Mathis, L. Merlivat, N. Metzl, A. Murata, T. Newberger, A. M. Omar, T. Ono, G.-H. Park, K. Paterson, D. Pierrot, A. F. Ríos, C. L. Sabine, S. Saito, J. Salisbury, V. V. S. S. Sarma, R. Schlitzer, R. Sieger, I. Skjelvan, T. Steinhoff, K. F. Sullivan, H. Sun, A. J. Sutton, T. Suzuki, C. Sweeney, T. Takahashi, J. Tjiputra, N. Tsurushima, S. M. A. C. van Heuven, D. Vandemark, P. Vlahos, D. W. R. Wallace, R. Wanninkhof, and A. J. Watson. An update to the surface ocean CO_2 atlas (SOCAT version 2). *Earth*

References II

System Science Data, 6(1):69–90, mar 2014. doi: 10.5194/essd-6-69-2014. URL https://doi.org/10.5194%2Fessd-6-69-2014.

T. DeVries, M. Holzer, and F. Primeau. Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature*, 542(7640):215–218, feb 2017. doi: 10.1038/nature21068. URL https://doi.org/10.1038%2Fnature21068.

H. E. Garcia, R. A. Locarnini, T. P. Boyer, J. I. Antonov, O. Baranova, M. Zweng, J. Reagan, and D. Johnson. *World Ocean Atlas 2013, Volume 4: Dissolved Inorganic Nutrients (phosphate, nitrate, silicate)*, volume 76 of *25*. NOAA Atlas NESDIS, 2013. URL https://www.nodc.noaa.gov/OC5/woa13/pubwoa13.html.

J. Hauck, C. Völker, T. Wang, M. Hoppema, M. Losch, and D. A. Wolf-Gladrow. Seasonally different carbon flux changes in the southern ocean in response to the southern annular mode. *Global Biogeochemical Cycles*, 27(4):1236–1245, dec 2013. doi: 10.1002/2013gb004600. URL http://dx.doi.org/10.1002/2013GB004600.

References III

J. E. Kay, C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J. M. Arblaster, S. C. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J.-F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein. The community earth system model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.*, 96(8):1333–1349, aug 2015. doi: 10.1175/bams-d-13-00255.1. URL http://dx.doi.org/10.1175/BAMS-D-13-00255.1.

P. Landschützer, N. Gruber, F. A. Haumann, C. Rödenbeck, D. C. E. Bakker, S. van Heuven, M. Hoppema, N. Metzl, C. Sweeney, T. Takahashi, B. Tilbrook, and R. Wanninkhof. The reinvigoration of the southern ocean carbon sink. *Science*, 349 (6253):1221–1224, 2015. ISSN 0036-8075. doi: 10.1126/science.aab2620. URL http://science.sciencemag.org/content/349/6253/1221.

References IV

N. S. Lovenduski and N. Gruber. Impact of the southern annular mode on southern ocean circulation and biology. *Geophys. Res. Lett.*, 32(L11603), 2005. doi: 10.1029/2005GL022727. URL http://onlinelibrary.wiley.com/doi/10.1029/2005GL022727/pdf.

N. S. Lovenduski, N. Gruber, S. C. Doney, and I. D. Lima. Enhanced co2 outgassing in the southern ocean from a positive phase of the southern annular mode. *Global Biogeochemical Cycles*, 21(2), 2007. ISSN 1944-9224. doi: 10.1029/2006GB002900. URL http://dx.doi.org/10.1029/2006GB002900. GB2026.

N. S. Lovenduski, N. Gruber, and S. C. Doney. Toward a mechanistic understanding of the decadal trends in the southern ocean carbon sink. *Global Biogeochem. Cycles*, 22, 2008. doi: 10.1029/2007GB003139.

A. Morrison, T. Frlicher, and J. Sarmiento. Upwelling in the southern ocean. *Physics Today*, 2015. doi: 10.1063/PT.3.2654. URL http://dx.doi.org/10.1063/PT.3.2654.

References V

T. Takahashi. Global seaair co and ux based on climatological surface ocean and pco and seasonal biological and temperature effects. *Deep-Sea Research II*, 2002.

L. Wang, J. Huang, Y. Luo, and Z. Zhao. Narrowing the spread in CMIP5 model projections of air-sea CO2 fluxes. *Scientific Reports*, 6:37548, nov 2016. doi: 10.1038/srep37548. URL https://doi.org/10.1038%2Fsrep37548.

S. Wang and J. K. Moore. Variability of primary production and air-sea CO2 flux in the Southern Ocean. *Global Biogeochemical Cycles*, 26(1):n/an/a, 2012. ISSN 1944-9224. doi: 10.1029/2010GB003981. URL http://dx.doi.org/10.1029/2010GB003981. GB1008.