Variability and trends in the Southern Ocean carbon fluxes

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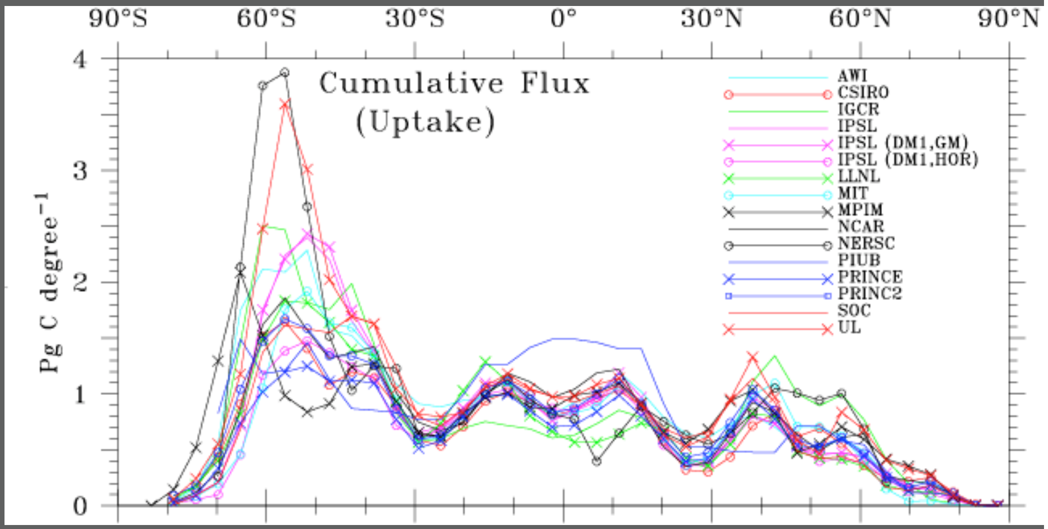
Outline

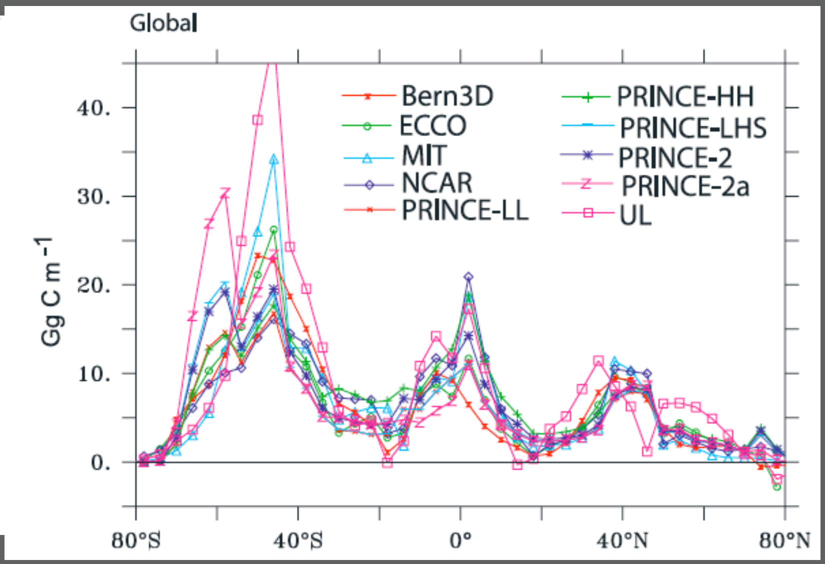
- Introduction / Motivation
  - Extratropical Southern Hemisphere (South of 30S)
  - Mean, large-scale pattern of CO_2 fluxes
- Variability and trends
  - Trends (>decadal)
  - Atmospheric and oceanic variability
- The future
  - Southern Ocean winds and stratification

Why focus on the Southern Ocean?

Forward model: OCMIP-2
Orr et al. (2002)



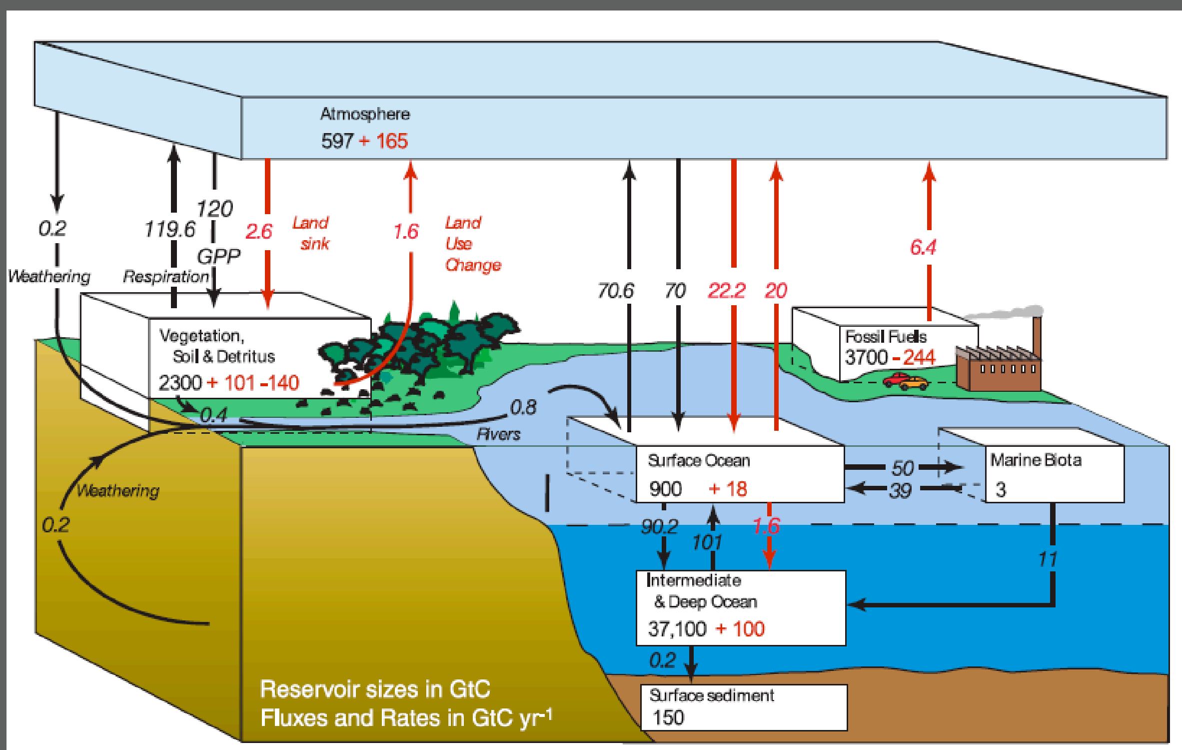
Inverse model:
Mikaloff-Fletcher et al. (2006)



- Highlights the importance of the Southern Ocean
- Disagreement comes from differences in modeled ocean transport

Natural and anthro CO_2 fluxes

- Preindustrial pCO2 = 280 ppm
- Atmospheric pCO_2 has increased by ~ 100 ppm
- ~ 25% of CO_2 in the air comes from fossil fuel
- Variability of natural CO_2 can play crucial role



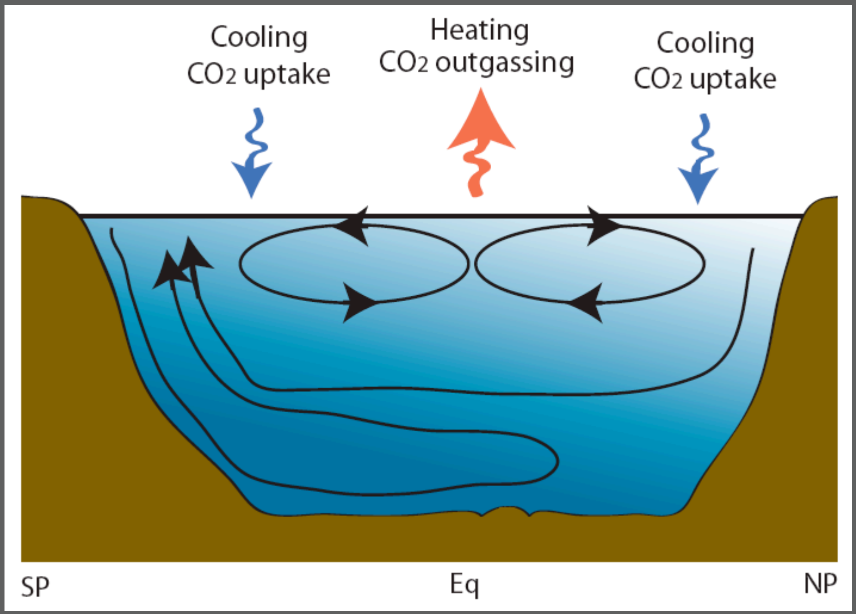
Air-sea CO_2 flux

$$\frac{\text{Anthro}}{\text{Natural}} \approx 0.25$$

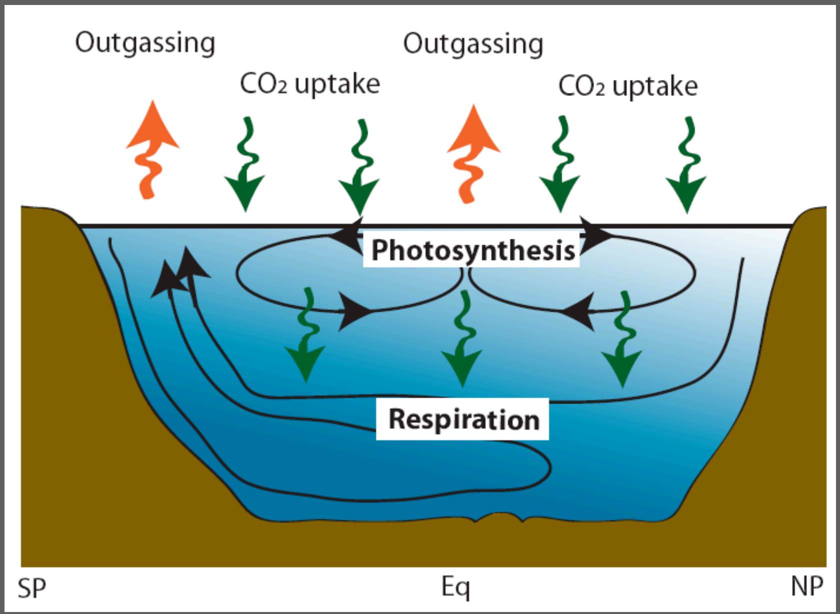
N. Gruber

Thermally and biologically driven carbon fluxes

Thermal flux

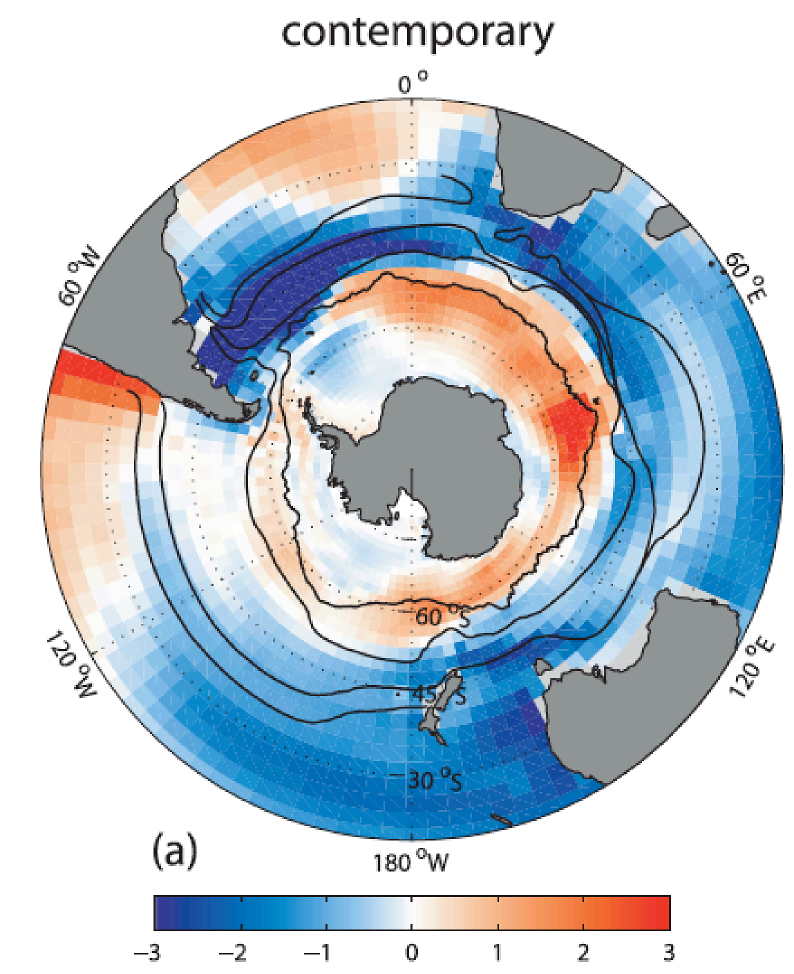


Biological flux



- Patterns of uptake and outgassing for natural CO_2
- CO_2 uptake: cooling and net biological carbon sink
- CO_2 outgassing: heating and upwelling of regenerated DIC

Mean CO_2 fluxes

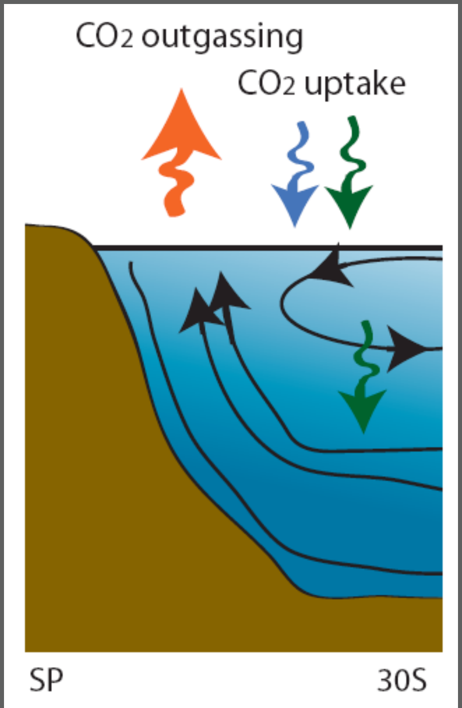


into ocean
out of ocean
(mol m^{-2} yr^{-1})

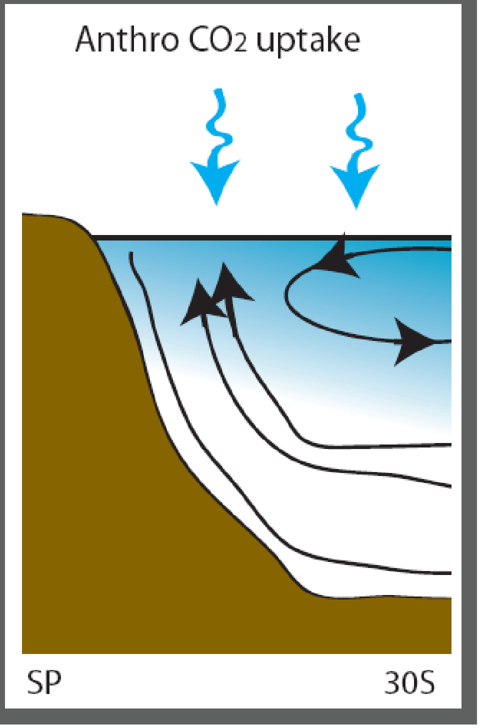
Lovenduski et al. (2007)

- Extratropical SH is a region of net CO_2 uptake
- Is the SH carbon flux changing? How?

Natural

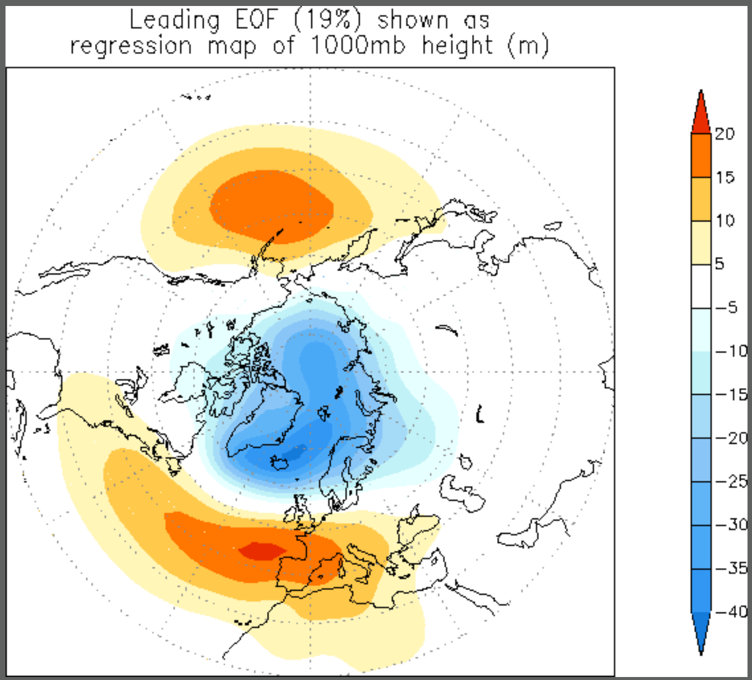


Anthro



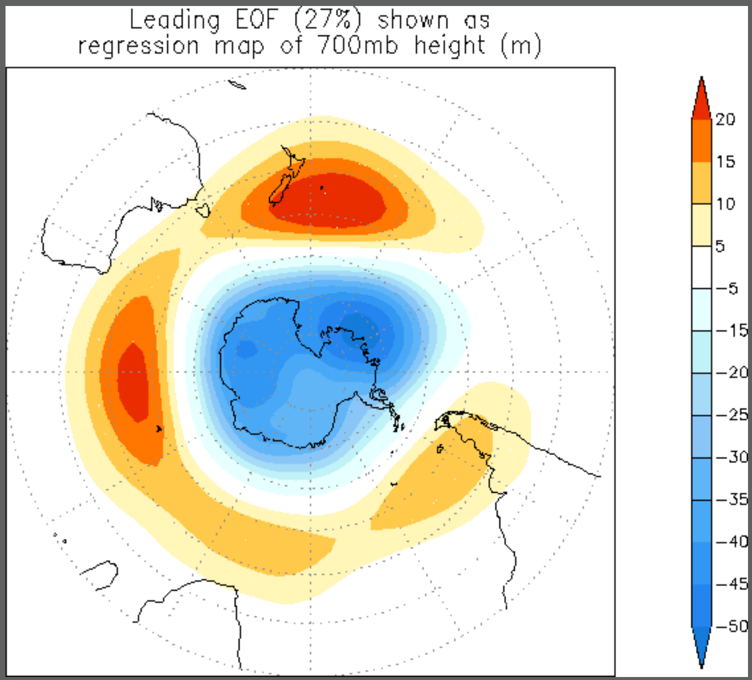
Extratropical atmospheric variability

NAM



SAM

From NWS CPC

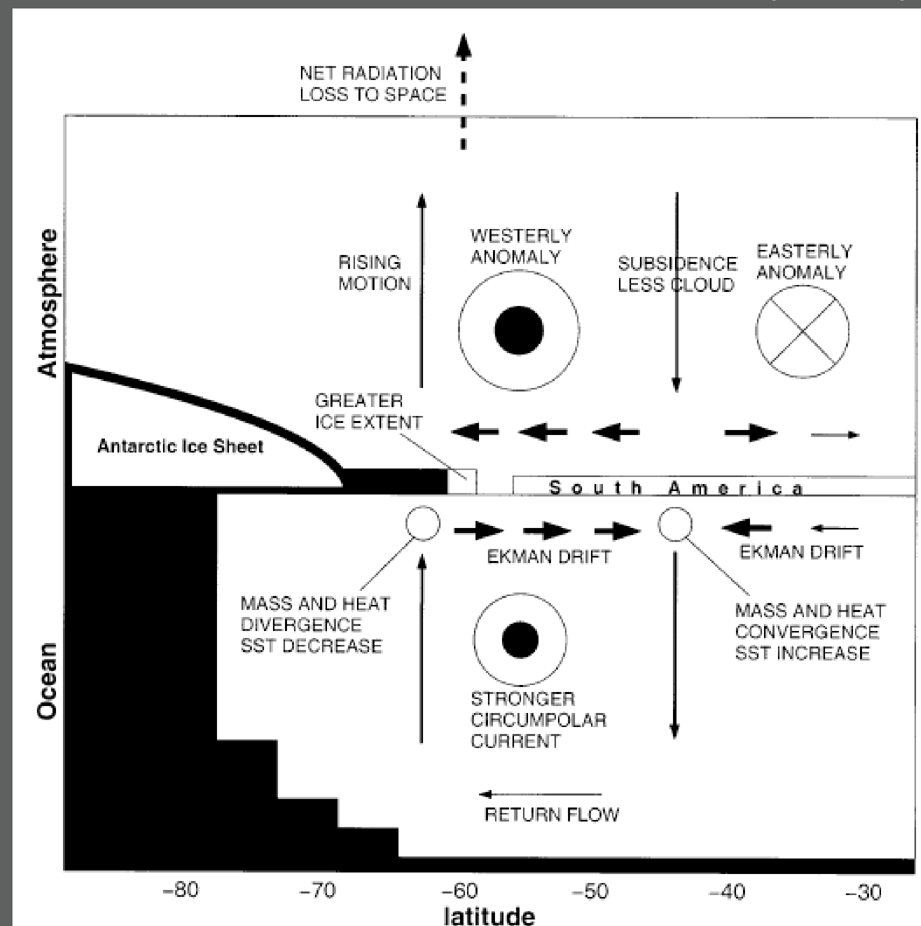


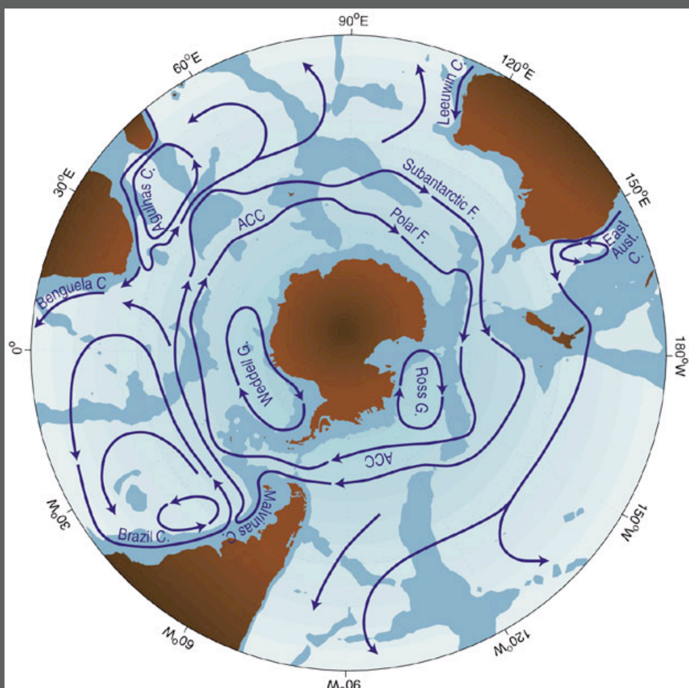
- Month-to-month variability of atmospheric pressure
- Contraction and expansion of polar vortex
- Shift of westerly wind belt

SAM impacts on SH circulation

- During positive phase of SAM, stronger wind over ACC increases zonal transport and upwelling in the Antarctic region

Hall and Visbeck (2002)



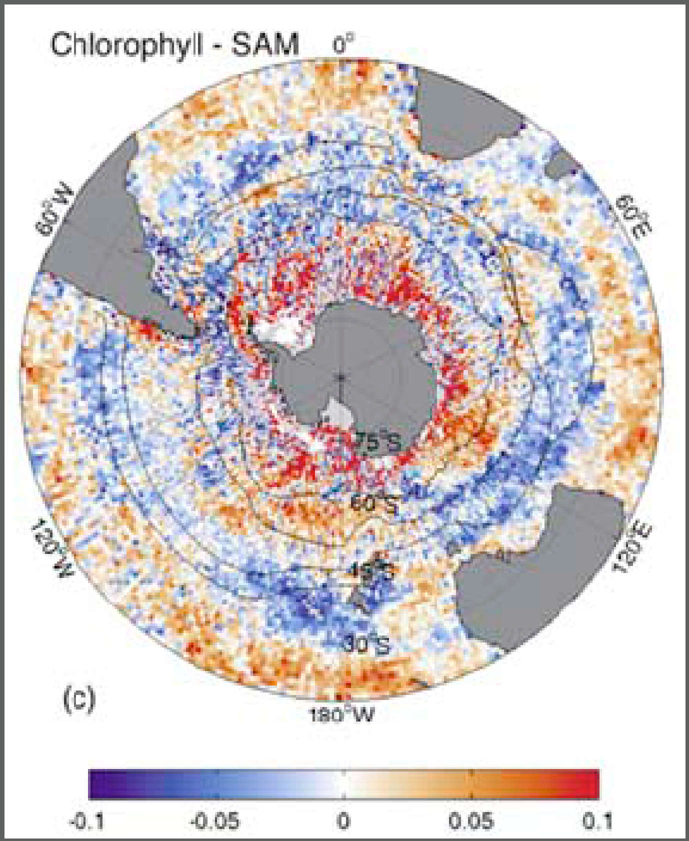


Rintoul et al. (2000)

Observed biological response

- Chlorophyll responds to SAM (Lovenduski and Gruber 2005)
- Antarctic region
  - Chl increases with SAM index
- Subantarctic region
  - Chl decreases with SAM index
- Mechanisms?
- Impact on carbon fluxes?

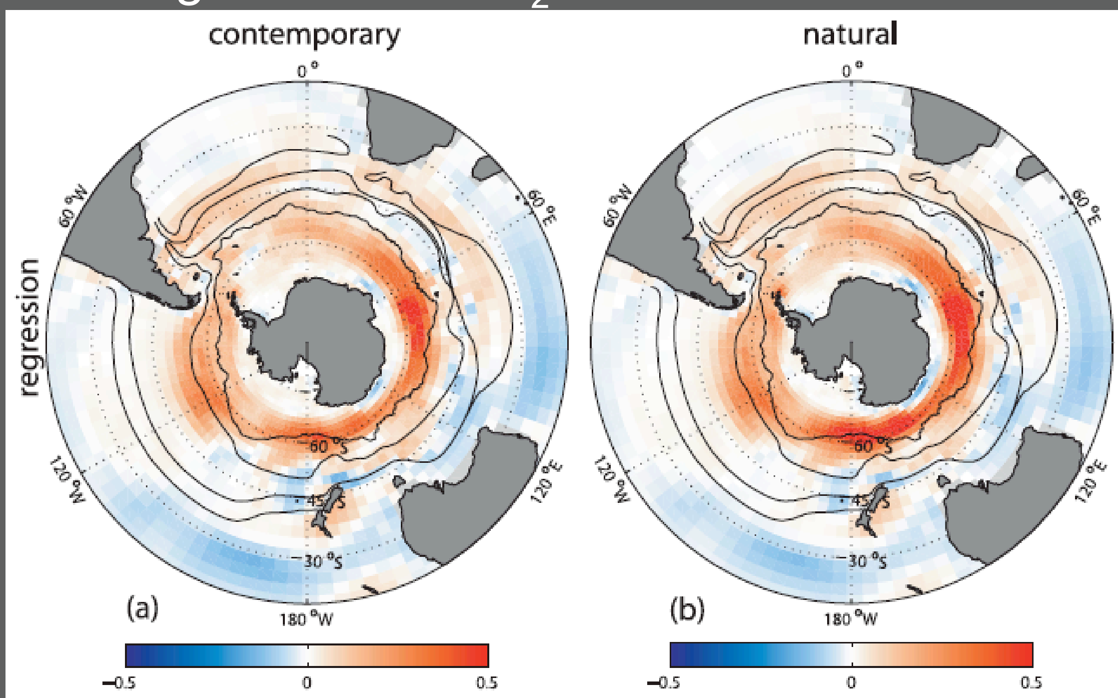
Regression of SeaWIFS chlorophyll anomaly onto SAM index (1997-2004)

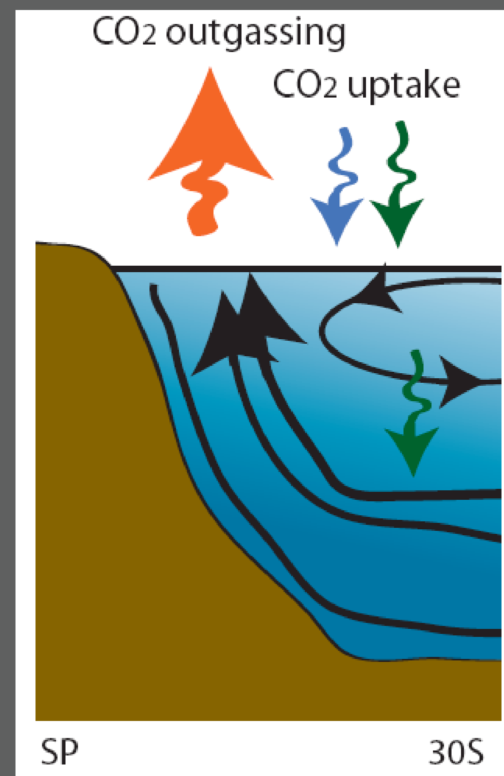


Variability of SH carbon fluxes

- Positive-phase of SAM leads to anomalous outgassing
  - Atmospheric CO_2 budget: Butler et al. (2007)
  - GCM simulation: Lovenduski et al. (2007)
- Driven by increased wind-driven upwelling of deep waters enriched in DIC

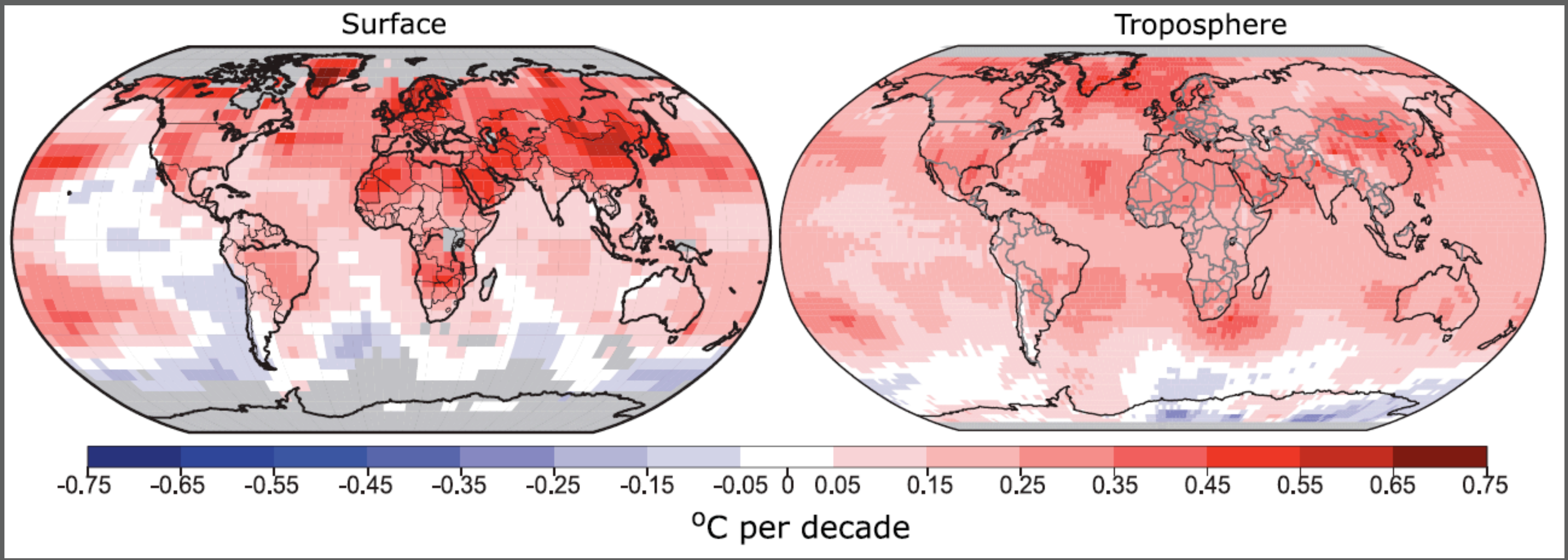
Regression of CO_2 flux onto SAM index





Multi-decadal trends

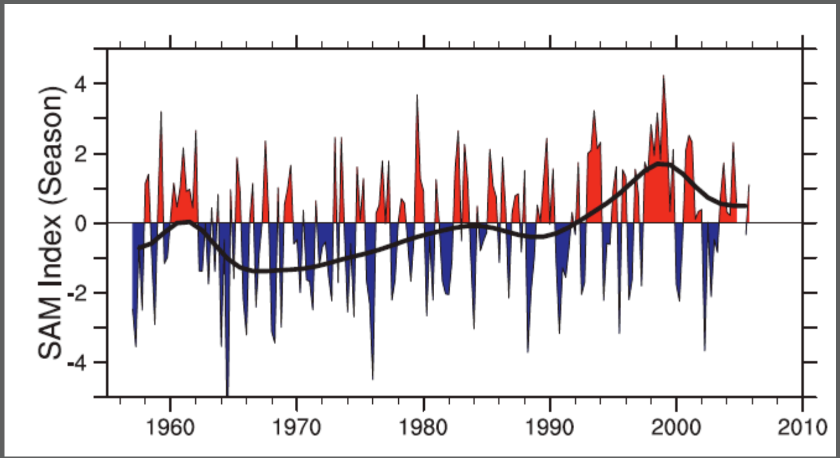
Observed temperature trend : IPCC (2007) chap 3



- Linear trend (1979-2005) based on satellite observation
- Relatively small temperature change in the SH
  - Large heat capacity of the Southern Ocean

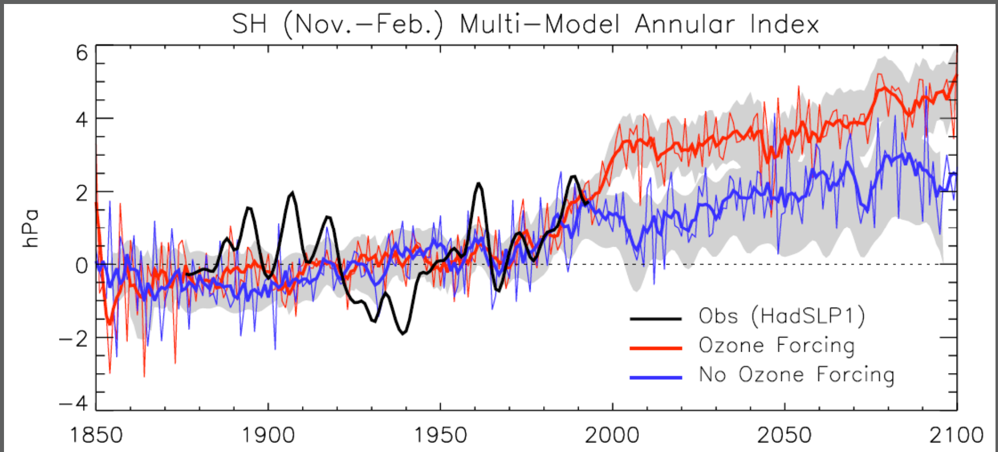
Observed and modeled SAM trends

Observation



G. Marshall (2003)

IPCC models

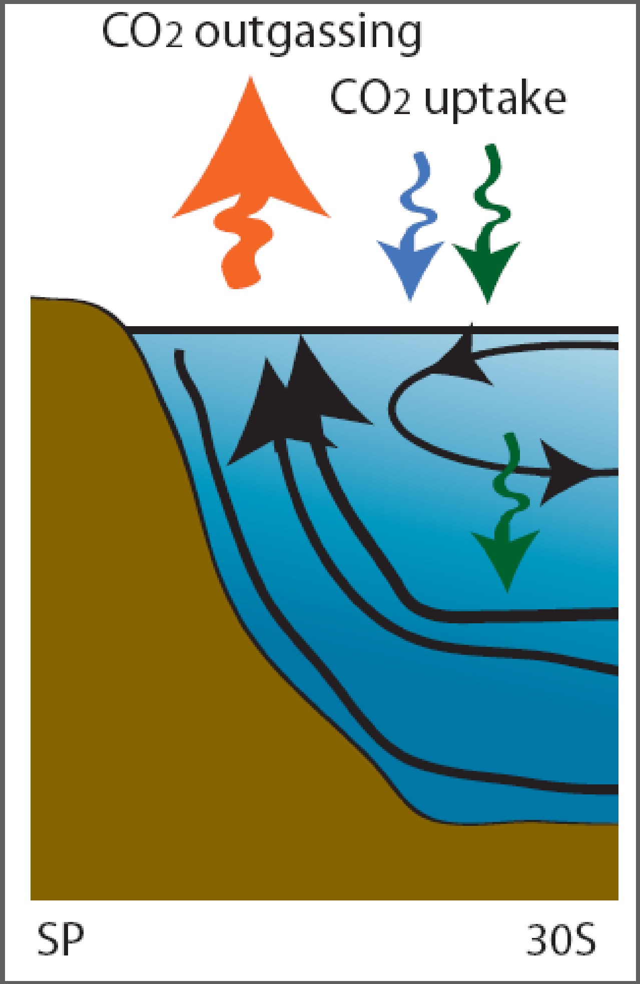


R. Miller (2006)

- Positive trend in SAM
- All of the IPCC models predict positive trend
- Driven by ozone depletion and global warming
- Stronger westerly wind over ACC

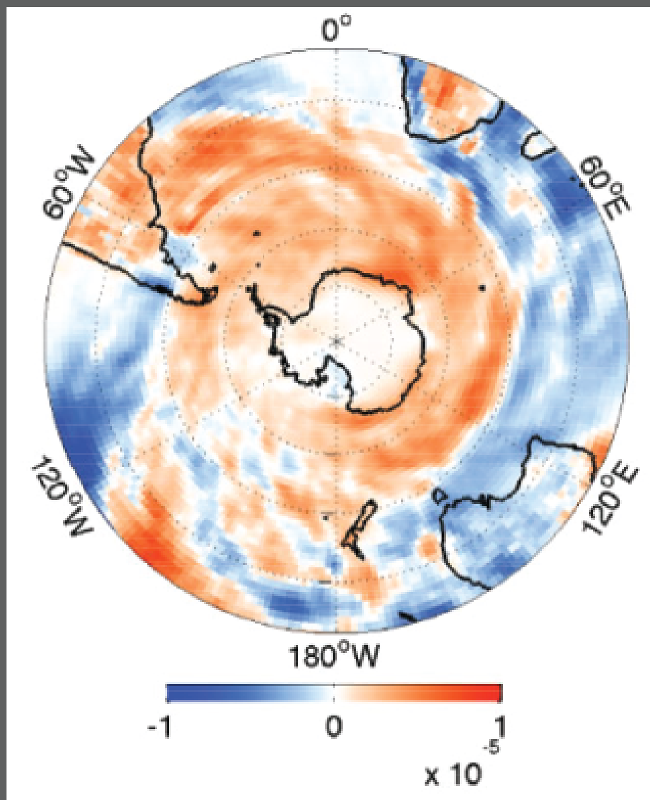
Carbon flux trends driven by SAM

- Positive trend in SAM leads to increased upwelling of deep waters enriched in DIC
  - Outgassing of natural CO_2
- Atmospheric inversion (1981-2004) (Le Quéré et al. 2007)
- Carbon uptake in the Southern Ocean may decline over time…



The future: the effect of Southern Ocean stratification

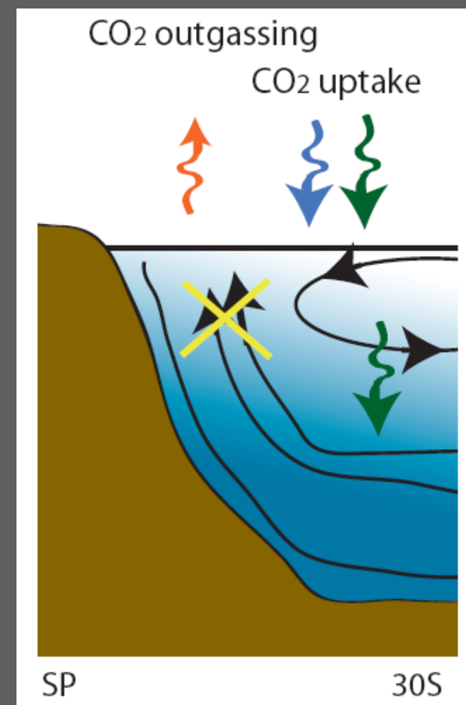
Precipitation change (2095-2005)



NCAR CCSM SRES A1B scenario

- Increased precipitation under global warming
- Potential melting of Antarctic ice sheet
- SST warming

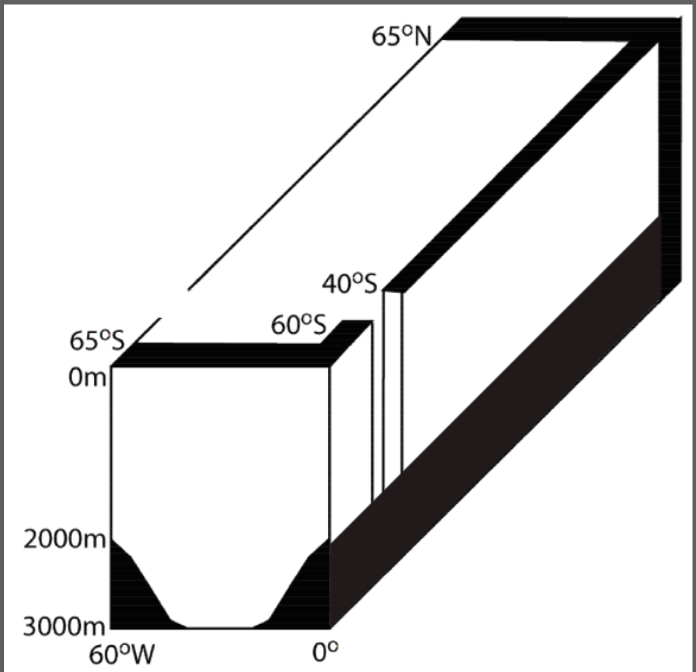
Can stratification counteract wind stress changes?

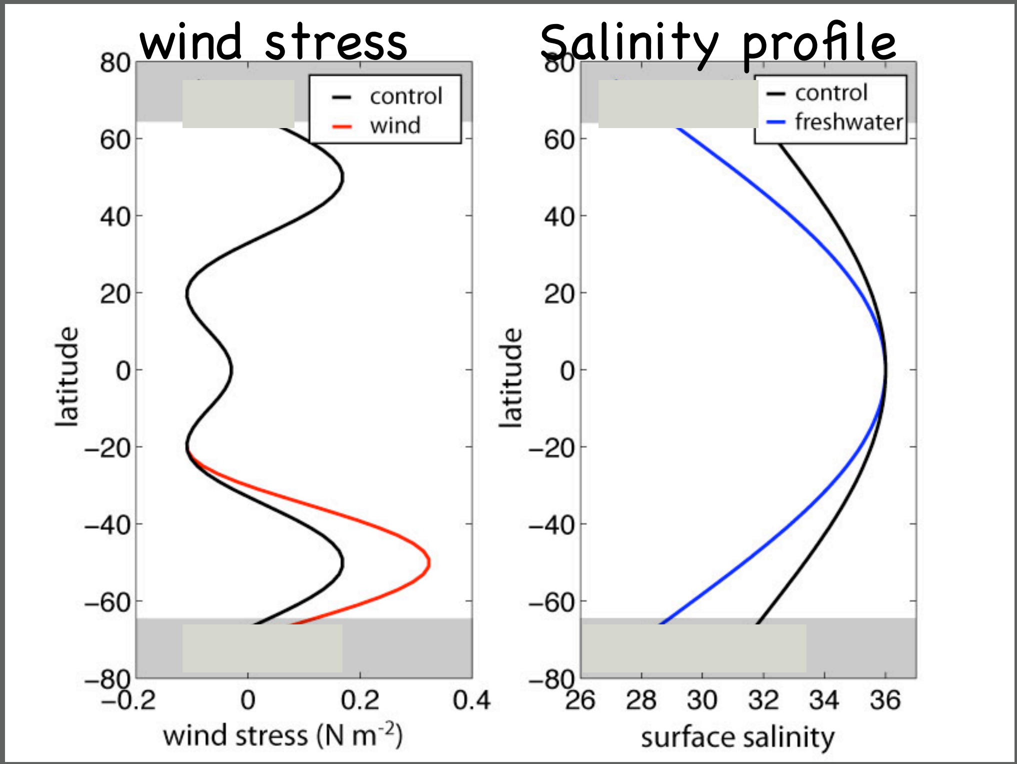


Attribution experiments

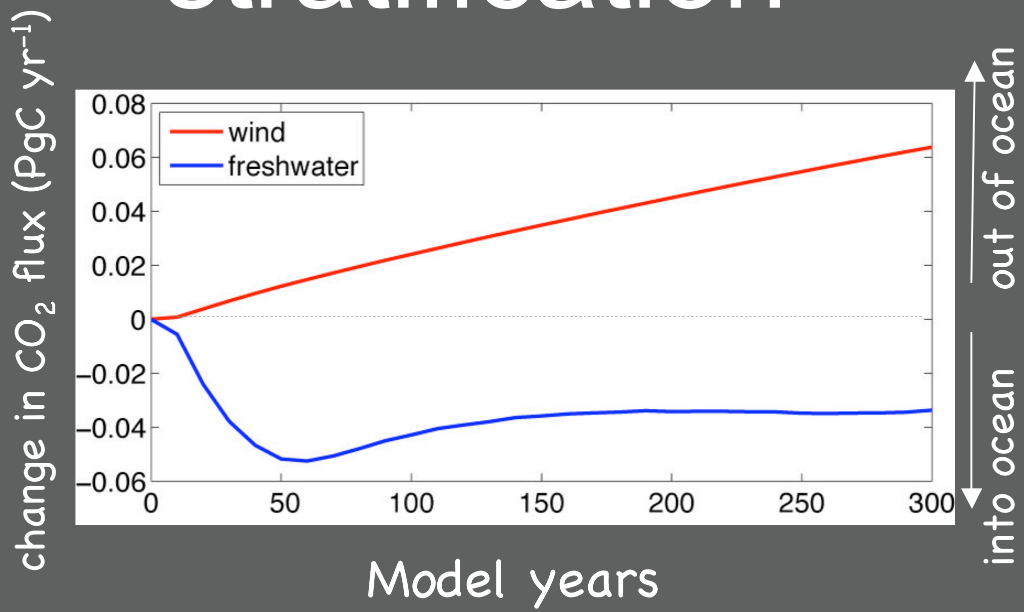
- Idealized ocean GCM with OCMIP-like biogeochemistry
- Sensitivity experiments
  - Impose linear trend in wind and surface salinity
  - With / without anthropogenic CO_2, biological response, etc

N. Lovenduski





Competing effects of wind and stratification



- Opposite response to wind and freshwater fluxes
- Linear response to wind change
- Non-linear response to freshwater change
  - Due to circulation changes and biological response

Oceanic variability

- Explicitly resolved eddies impact on MOC structure and its sensitivity to the surface winds

Hallberg and Gnanadesikan (2006)

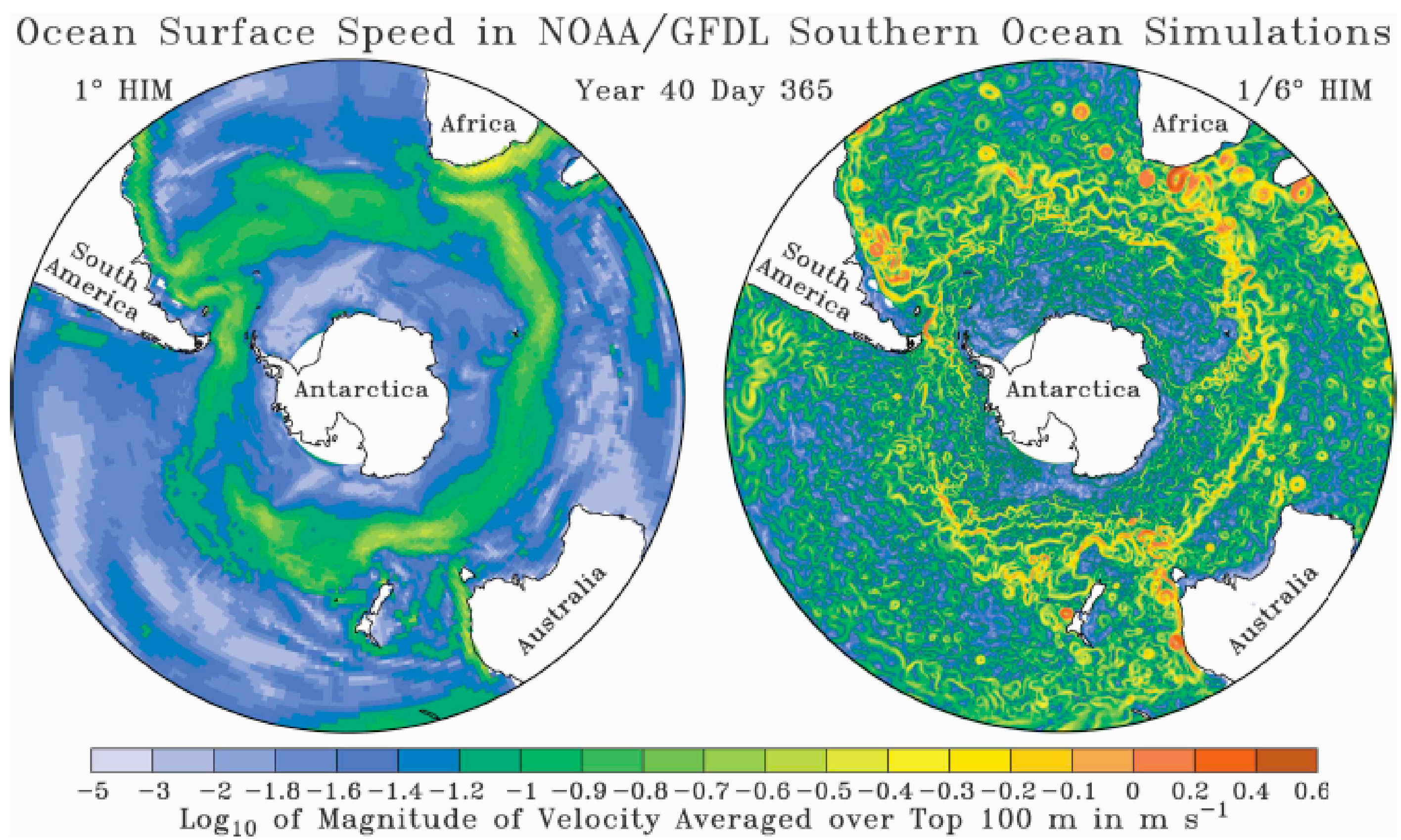
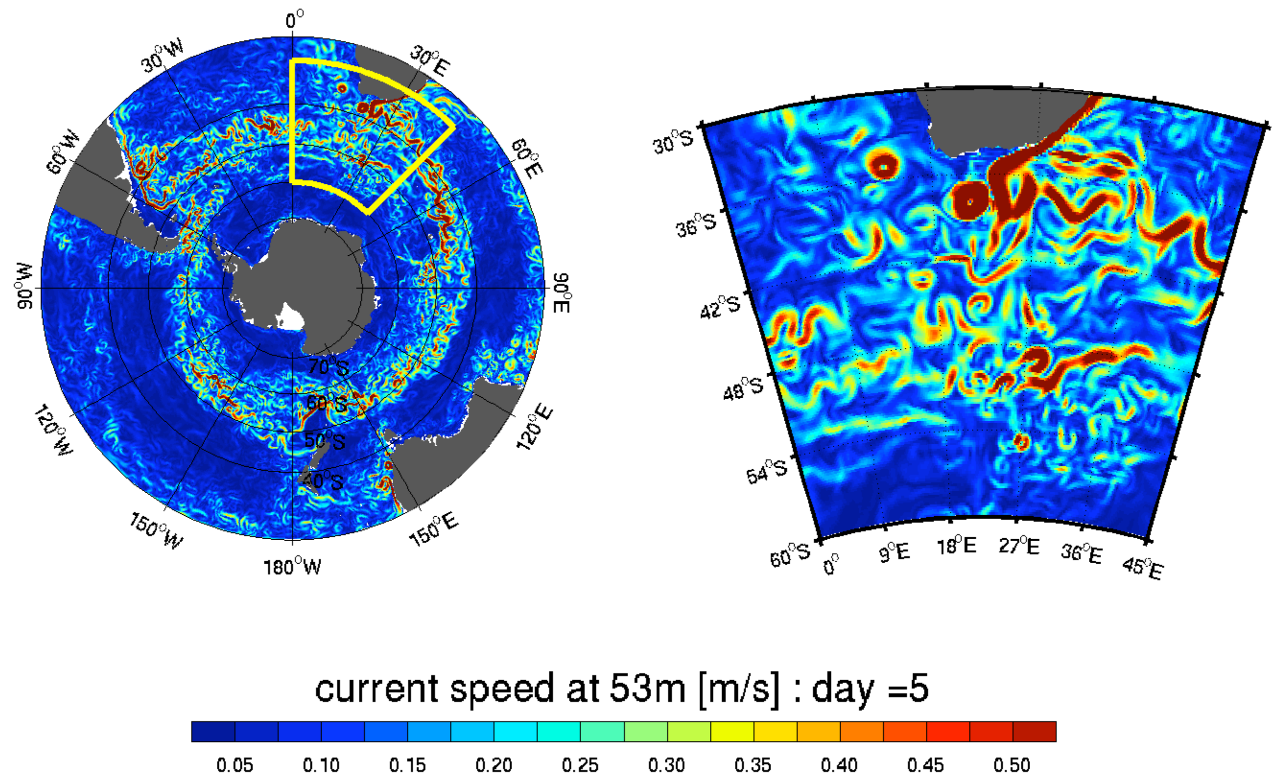


FIG. 6. Instantaneous surface speed in 1° and ⅙° models after 40 yr. Note that the large-scale structure of the 1° model is quite similar to the ⅙° model (the currents have similar locations and have similar horizontal extents). The main difference is in the presence of intense jets and eddies in the ⅙° model.

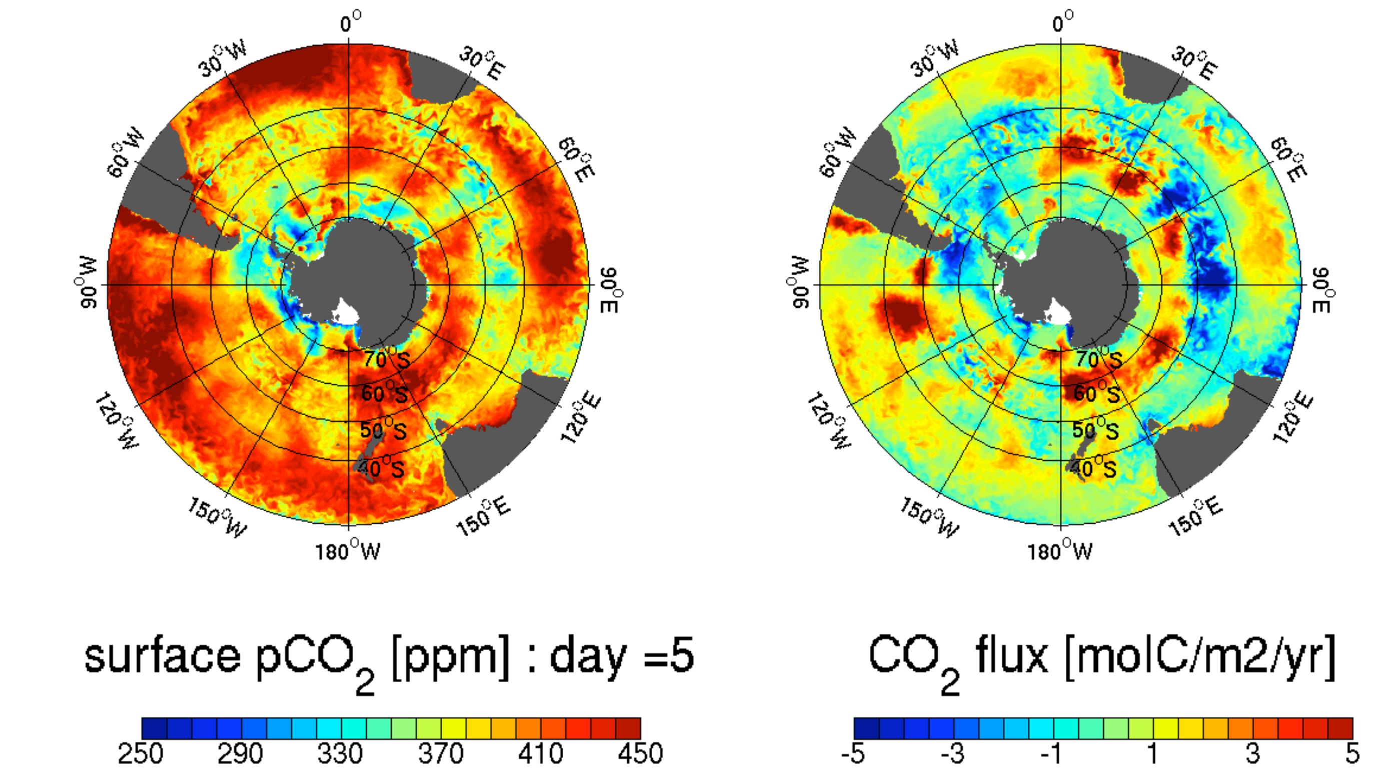
Toward realistic Southern Ocean carbon cycle simulation

- *Southern Ocean State Estimate (Mazloff, Heimbach and Wunsch, MIT)*
- *OCMIP / ecosystem model (Dutkiewicz et al. 2005)*
- *Executed on columbia supercomputer (NASA)*



Simulated carbon fluxes

- OCMIP contemporary simulation
- Significant mesoscale variability (~ mean fluxes)



Challenges for future modeling

- Model evaluation and improvements
  - Process-level improvements
  - Testing models against observational metric
- Statistical analysis
  - Determine modes of carbon flux variability
- Attribution experiments
  - Hierarchical modeling
  - Repeat calculations taking out one process at a time
  - Simple models help to interpret complex simulations