Ocean carbon uptake

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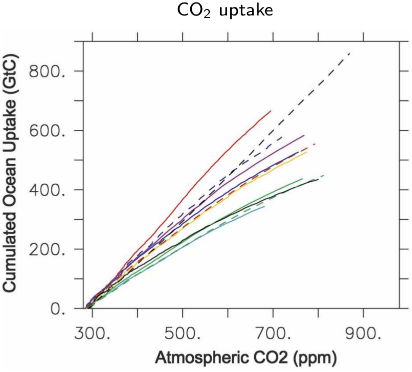
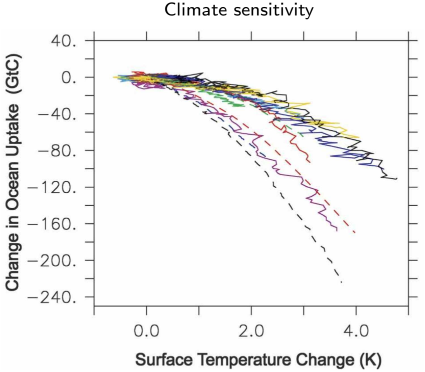
Substantial model uncertainty regarding future carbon uptake

Coupled Climate-Carbon Cycle Model Intercomparison Project (C[4]MIP)





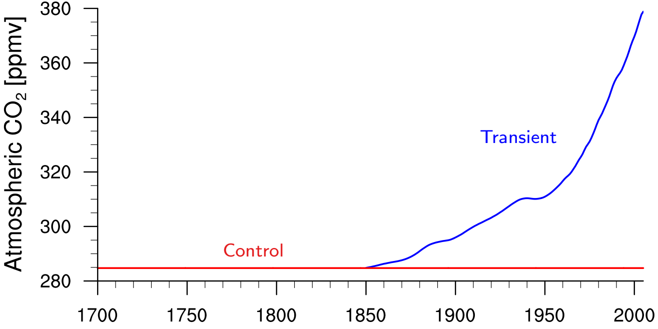
- Ocean carbon sink reduces airborne fraction, mitigating CO_2-induced warming;
- Climate warming will reduce the ocean sink, but projected climate sensitivity varies widely;
- Use observations to validate model performance.

Friedlingstein et al. 2006

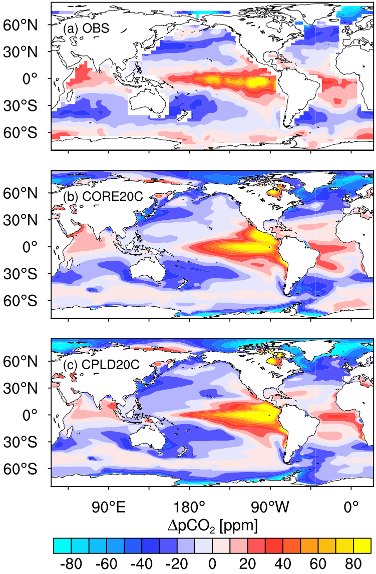
Two 20^{th}-Century experiments: ocean-ice & coupled

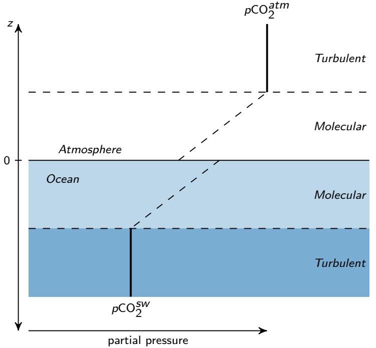
1. **CORE20C**: CORE-forced hindcast (60 year repeating cycle)
   - Ocean model forced with atmospheric observations and reanalyses

2. **CPLD20C**: fully-coupled 20^{th} Century integration



Sea-air pCO_2 difference drives gas exchange





Obs: Takahashi et al. 2009

negative := ocean uptake

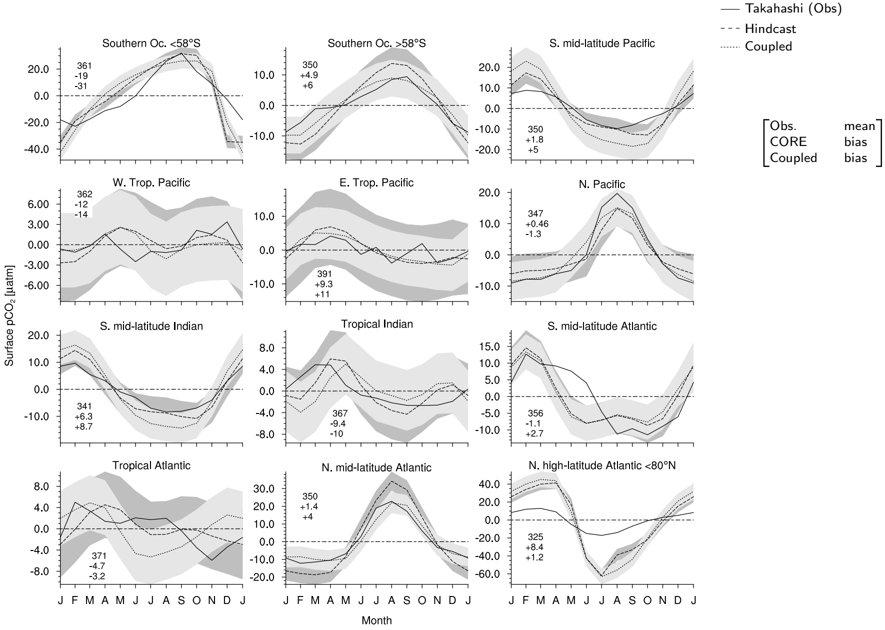
Air-sea exchange:

$$J_{co_2} = (1 - A_{ice})k\alpha\left(pCO_2^{sw} - pCO_2^{atm}\right)$$
$$= (1 - A_{ice})k\alpha\Delta pCO_2$$

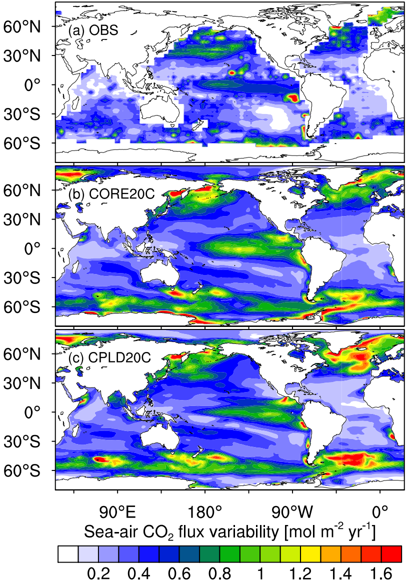
where
k = piston velocity (empirical), and
α = solubility, $f(T, S)$

Sarmiento & Gruber 2006

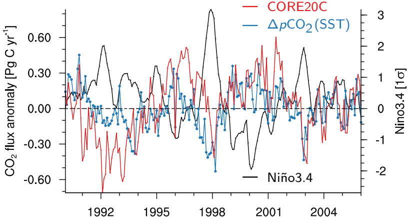
Seasonal pCO_2^{sw}-cycle is well simulated



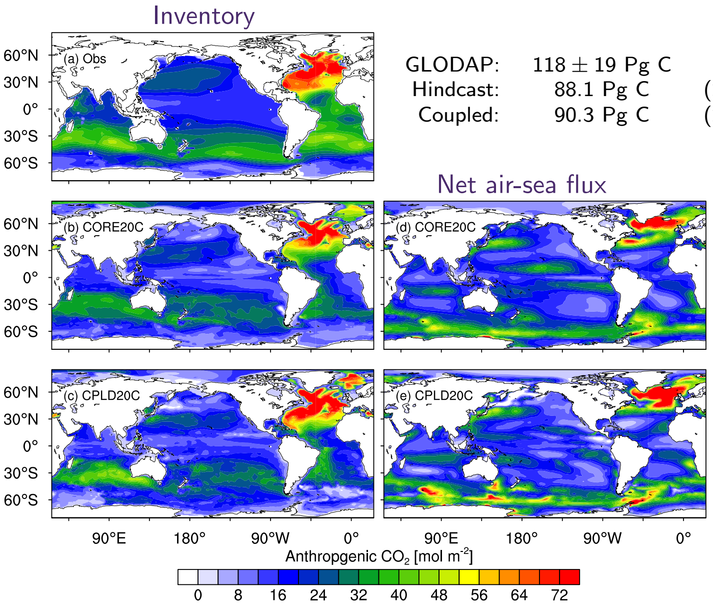
Interannual variability in sea-air CO_2 flux



Monthly sea-air flux anomalies

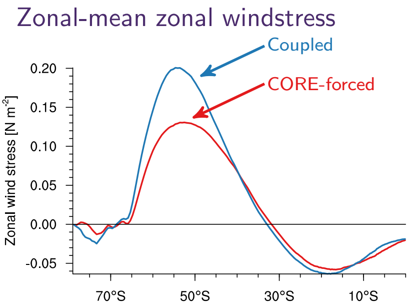


Anthropogenic CO_2



GLODAP:	118 ± 19 Pg C	($\pm$16%)
Hindcast:	88.1 Pg C	(25% low)
Coupled:	90.3 Pg C	(23% low)

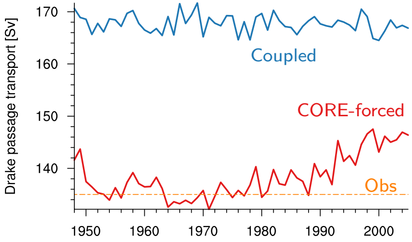
One ocean model, different atmospheric forcing



- Coupled model winds:
  - max wind stress ∼50% greater;
  - shifted poleward.

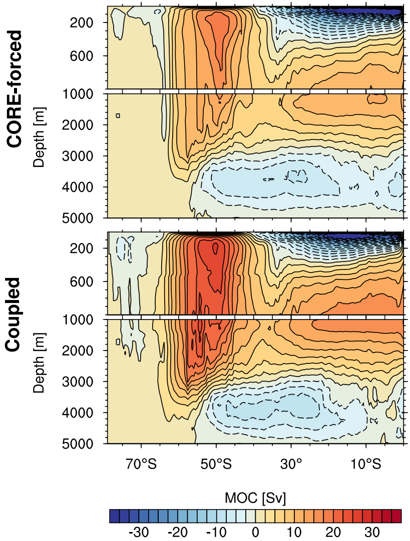
Antarctic circumpolar current

Drake Passage transport



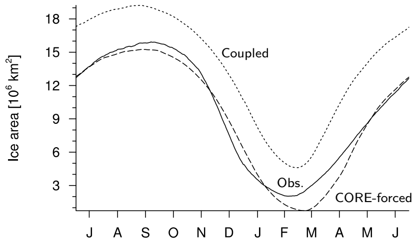
- Stronger winds in coupled model drive accelerated ACC flow, stronger overturning.

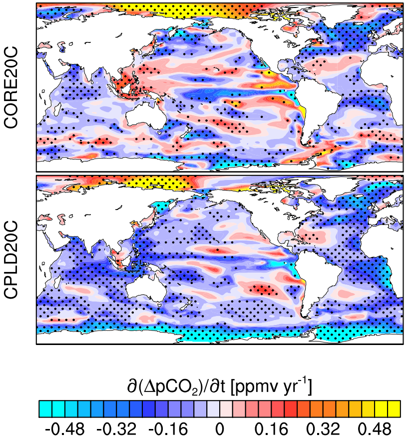
Meridional overturning circulation



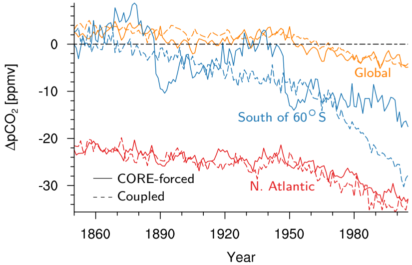
Polar Southern Ocean falls behind

Sea ice coverage





Sea-air $\Delta p CO_2$

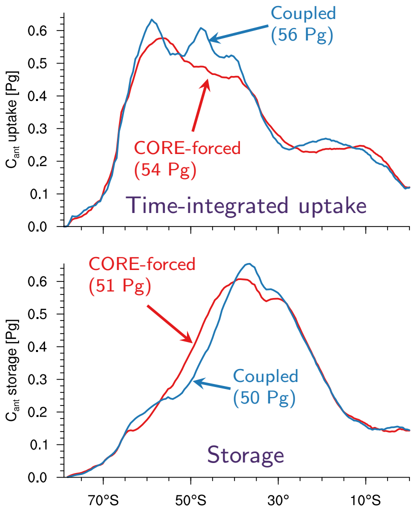


Carbon budget (below 60°S) [Pg C]

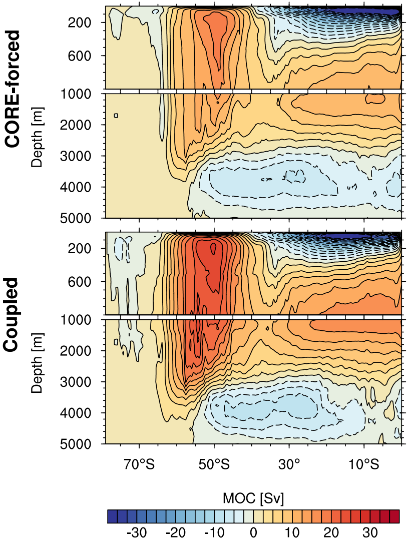
	ΔDIC	Phy	Bio	Gas	Virt
CORE	+0.61	+23.5	−22.7	+6.8	−7.1
CPLD	+0.25	+18.9	−18.5	+8.4	−8.5

Southern Ocean anthropogenic CO_2

Zonal integral of C_{ant}

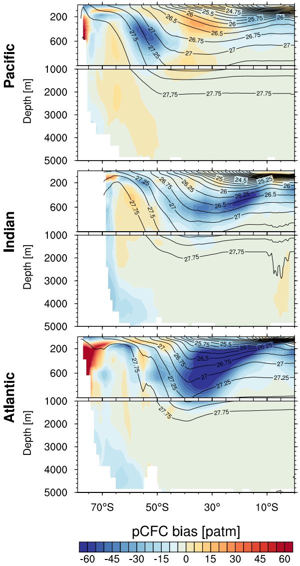


Meridional overturning circulation

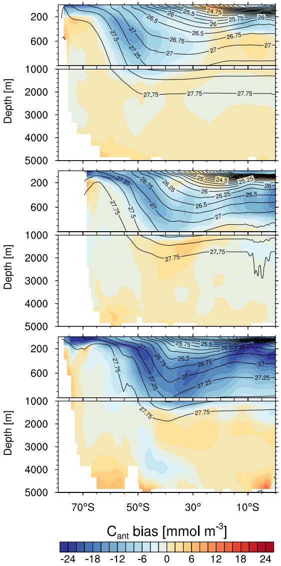


Strong deficiencies in mode and intermediate waters

pCFC-11

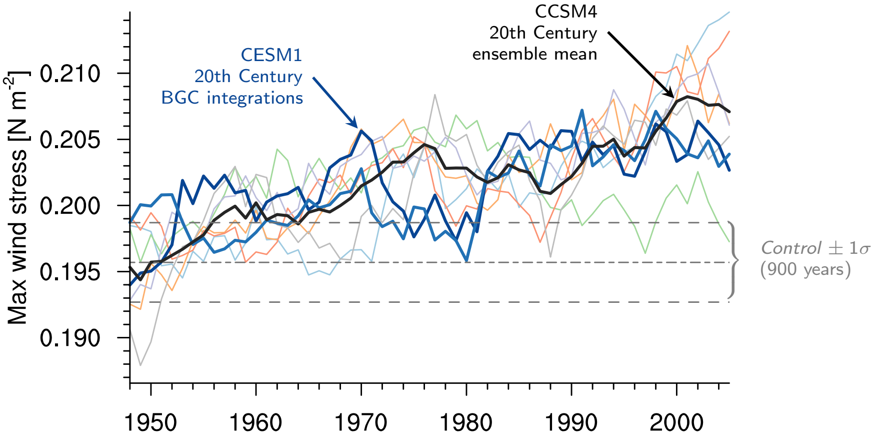


Anthropogenic CO_2



Trends in Southern Hemisphere winds

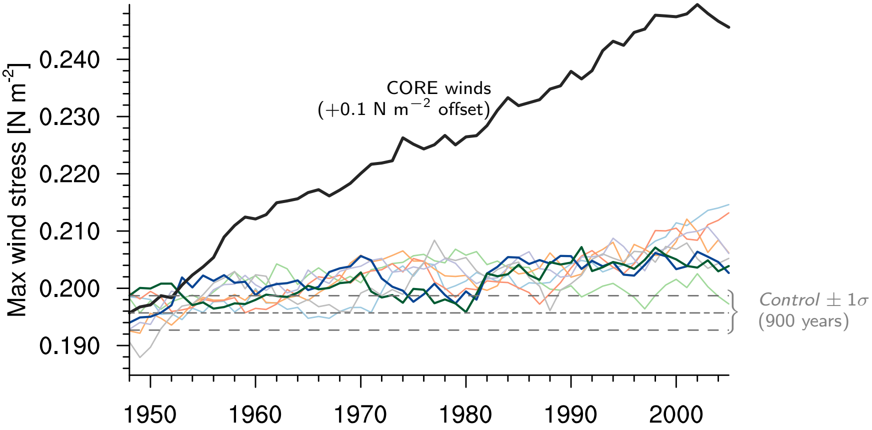
Maximum zonal-mean zonal windstress



11-year running mean

Trends in Southern Hemisphere winds

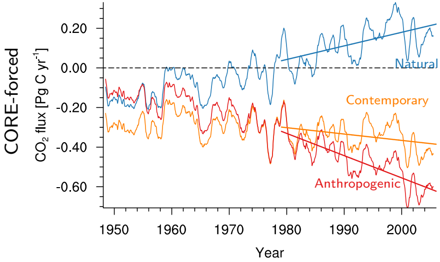
Maximum zonal-mean zonal wind



11-year running mean

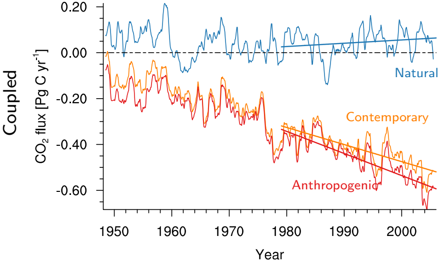
Trends in Southern Ocean CO_2 fluxes

Spatially-integrated fluxes (south of 45°S)



Trends (Pg yr^{-2})

	CORE[1]	Coupled	CCSM3[2]
Modern:	−0.003	−0.007	−0.004
Natural:	+0.007	+0.001	+0.005
Anthro:	−0.011	−0.010	+0.009



1 Includes 0.004 Pg yr^{-2} global drift correction.

2 *Lovenduski et al. 2008*

Mechanisms governing variability in air-sea CO_2 flux

Monthly anomalies

$$Y' = Y - \overline{Y}_{mon}$$

Taylor series approximation

$$Y' \approx \sum_i \frac{\partial Y}{\partial X} X_i' + \mathcal{O}(X_i'^2, X_i' X_j')$$

Application to carbon system variables

$$J'_{co_2} \approx (k\alpha)' \overline{\Delta p\mathrm{CO}_2} + \overline{(k\alpha)} \Delta p\mathrm{CO}_2' + \left((k\alpha)' \Delta p\mathrm{CO}_2' - \overline{(k\alpha)' \Delta p\mathrm{CO}_2'} \right)$$

$$p\mathrm{CO}_2' \approx \frac{\partial p\mathrm{CO}_2}{\partial T} T' + \frac{\partial p\mathrm{CO}_2}{\partial S_{FW}} S' + \frac{\partial p\mathrm{CO}_2}{\partial DIC} sDIC' + \frac{\partial p\mathrm{CO}_2}{\partial Alk} sAlk'$$

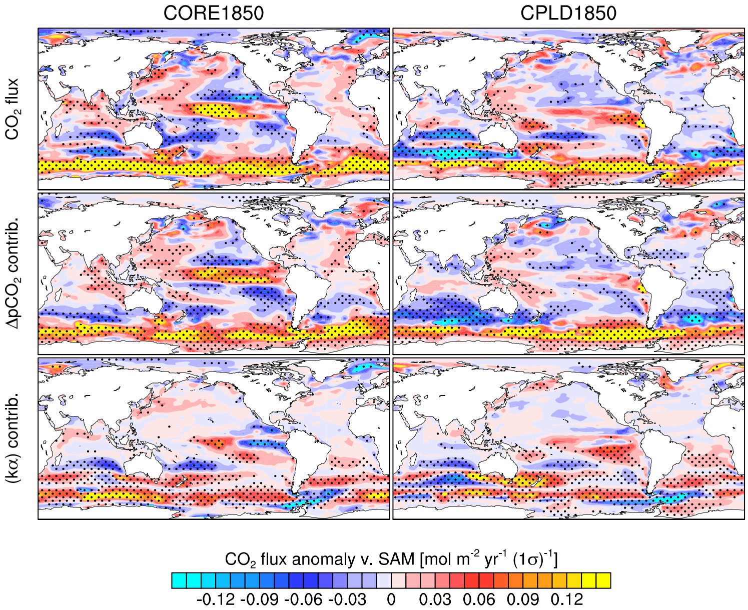
$$\int_0^{100} \left(\frac{\partial \mathrm{DIC}}{dt} \right)' dz = J'_{co_2} + J'_{virtual} + J'_{bio} + J'_{phy}$$

Climate variability control

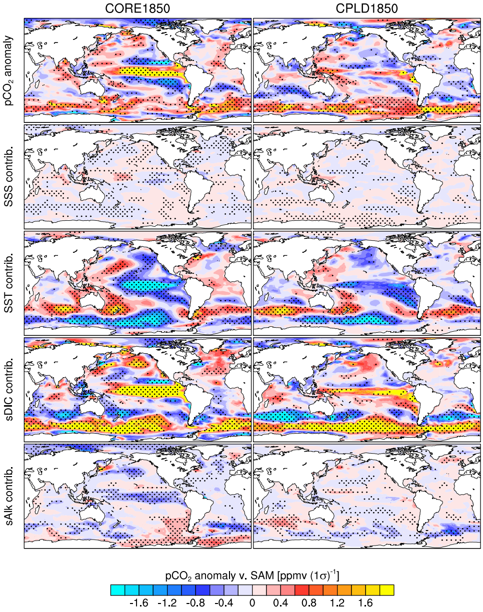
Regress Taylor-series components ($\frac{\partial Y}{\partial X} X_i'$) on climate indices ($\Psi$):

$$\frac{\partial Y}{\partial X} X_i' = \beta \Psi$$

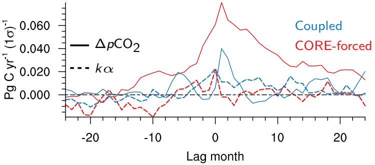
Sea-air CO_2 flux response to SAM



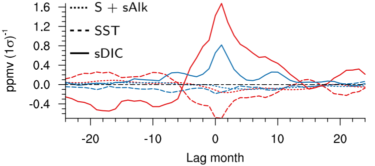
pCO_2^{sw} response to SAM



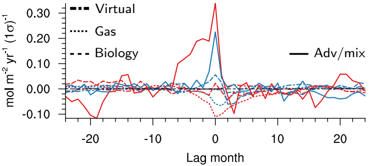
Sea-air flux anomaly



pCO_2^{sw} anomaly



DIC inventory anomaly



Summary

- CESM has a credible representation of ocean carbon cycle dynamics; despite some local biases, the model captures the overall mean state, seasonal cycle, and variability in carbon-related variables reasonably well.

- Anthropogenic CO_2 uptake remains weak; the Southern Ocean is a prime culprit. The representation of physical processes controlling ventilation and subduction is likely the primary problem; biases at the sea surface may also play a role—but are likely secondary to ventilation.