Ocean carbon sink dynamics in CESM1

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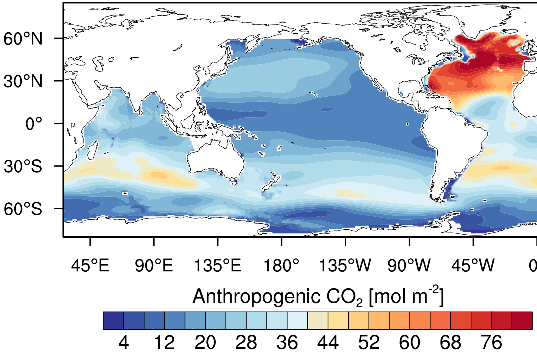
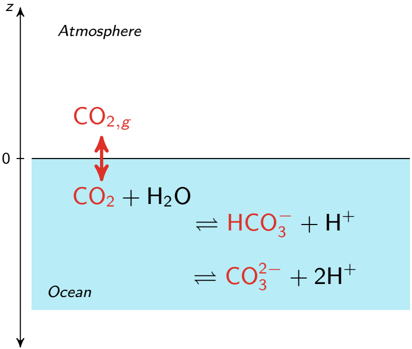
The ocean carbon sink



Sabine et al. 2004

- The ocean has absorbed ~50% of fossil fuel CO_2 to date.
- What is the fidelity of CESM1's ocean carbon cycle representation?
- What are the dominant mechanisms generating variability in the ocean carbon sink?

Ocean carbon system



Dissolved inorganic carbon

$$DIC = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

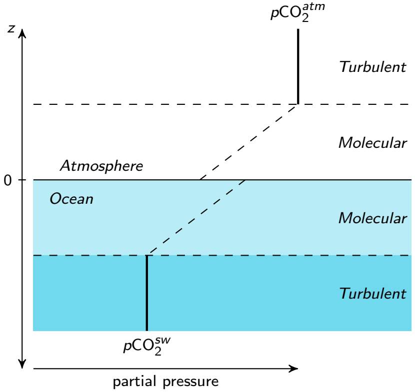
pCO_2^{sw}

$$pCO_2 = \frac{[CO_2]}{K_0(T, S)}$$

Alkalinity

$$Alk = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] + [B(OH)_4^-] + \text{minor bases}$$

Gas exchange depends on surface boundary condition



Sarmiento & Gruber 2006

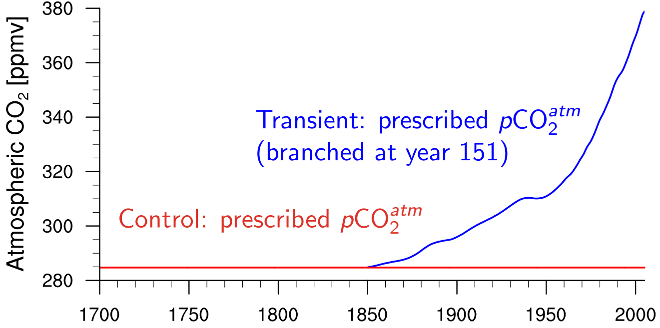
Air-sea exchange:

$$J_{ex} = (1 - A_{ice}) k \gamma \left(pCO_2^{atm} - pCO_2^{sw} \right)$$

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

Numerical experiments

Fully coupled run (BDRD)*:

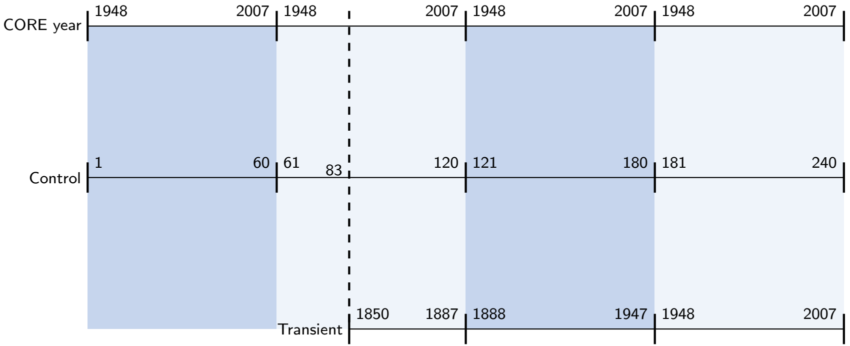


*Notation:
b[cdp]r[cdp] = b[BGC CO_2 option]r[radiative CO_2 option]

[cdp]: CO_2^{atm} options
c = constant, [1850 value]
d = diagnostic (specified), [1850 value, historical record, RCP trajectory]
p = prognostic, [zero emissions, historical emissions, RCP emissions]

Hindcast ocean-ice spin-up and forcing

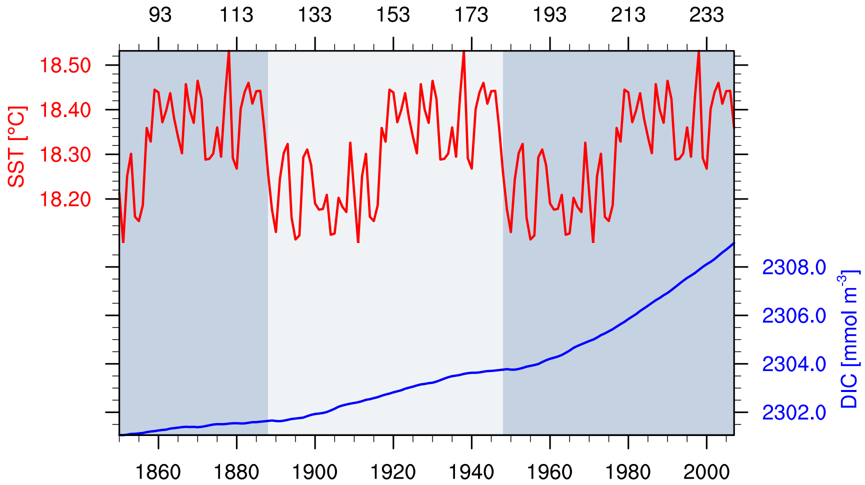
60 year repeating CORE forcing



Physical fields & dynamical tracers reinitialized at each cycle.

Hindcast ocean-ice spin-up and forcing

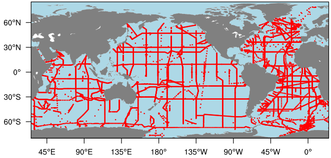
Global mean fields in hindcast transient



Validation datasets

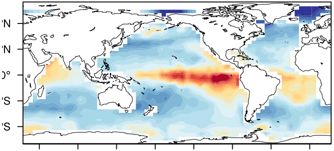
3D fields

- GLobal Ocean Analysis Project (GLODAP)

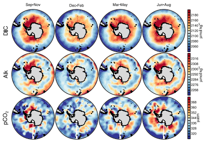


Surface

- Takahashi et al. [2009] pCO_2

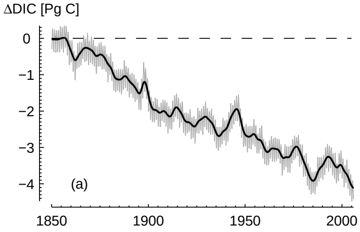


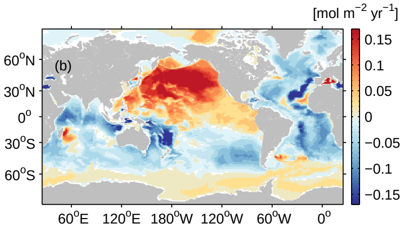
- McNeil et al. [2007] Southern Oc. C

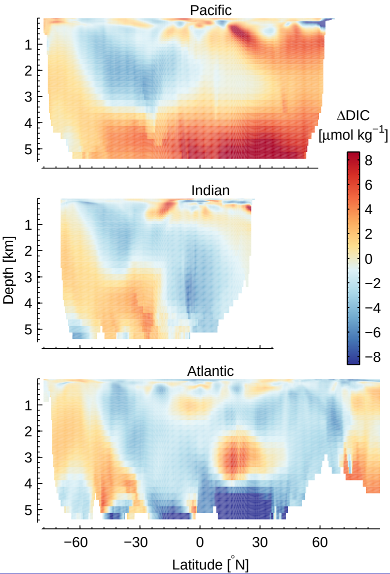


Accounting for model drift

Change in DIC inventories in 1850-bdrd

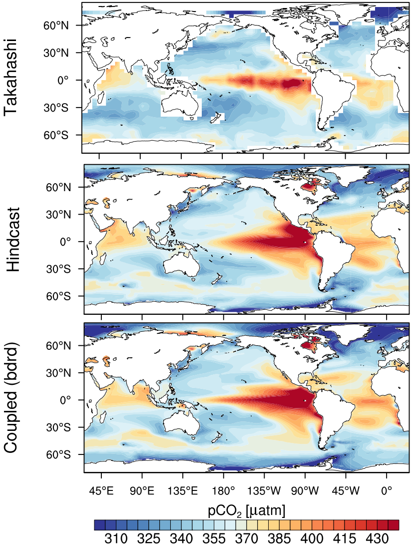






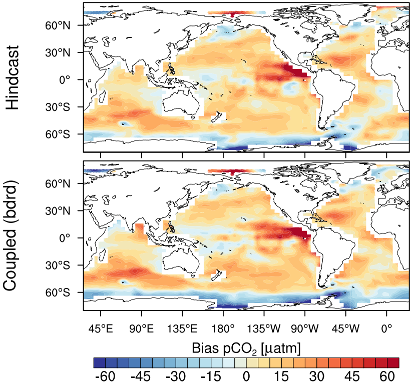
pCO_2^{sw} spatial structure about right, positively biased

Annual mean

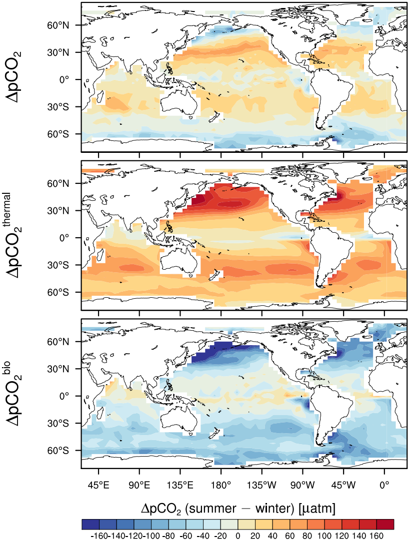


Biases

	Δ(mean)	RMS error
Hindcast:	1.4%	17.0 μatm
Coupled:	0.9%	18.8 μatm



Takahashi



Seasonal variability in pCO_2^{sw}

Magnitude comparable to spatial variability in annual mean.

Mechanisms:

- → ΔSST
- → ΔDIC, ΔAlk (biology)

Thermal effect computed using:

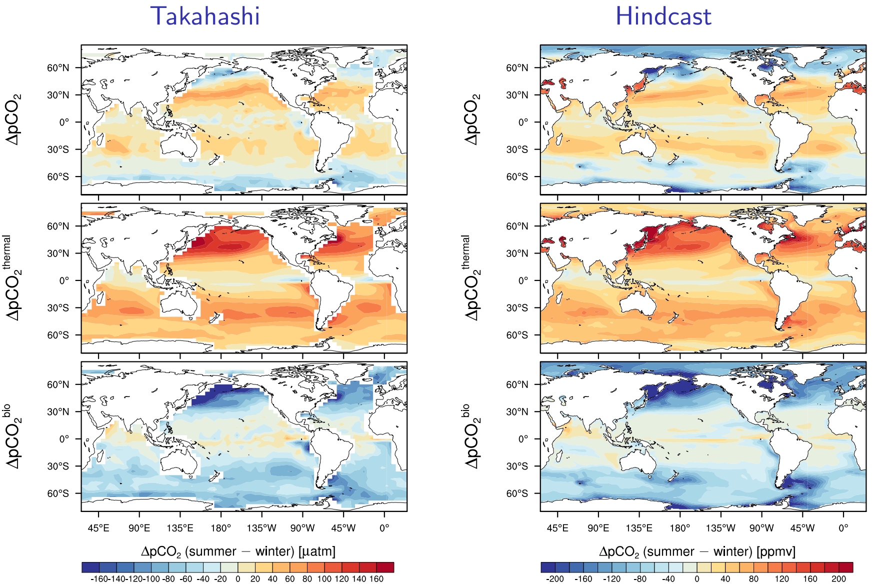
$$\Delta pCO_2^{sum} = pCO_2^{win} \exp[0.0433(T^{sum} - T^{win}) - 4.35 \times 10^{-5}((T^{sum})^2 - (T^{win})^2)]$$

Biological component computed as residual.

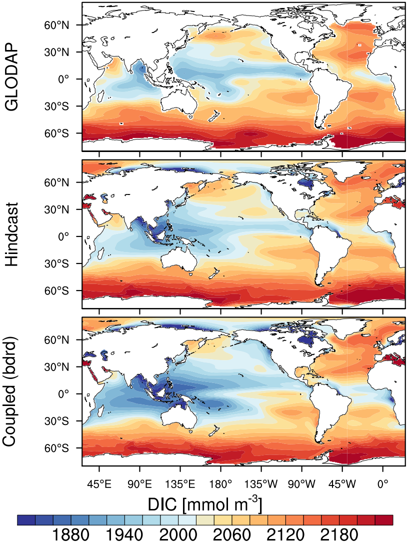
Summer = JFM (south) and JAS (north)

Winer = JAS (south) and JFM (north)

Seasonal Variability in pCO_2^{sw}: thermal & biological effects

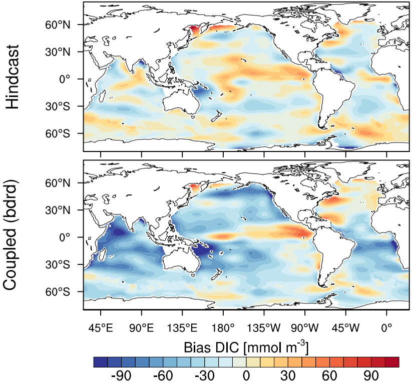


Dissolved inorganic carbon

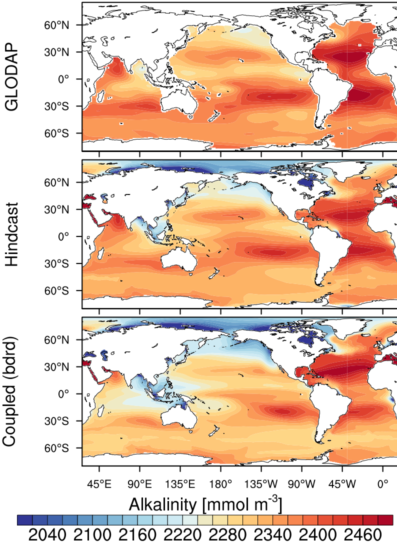


Biases

	Δ(mean)	RMS error
Hindcast:	–0.6%	22.9 mmol m^{-3}
Coupled:	–1.9%	43.0 mmol m^{-3}

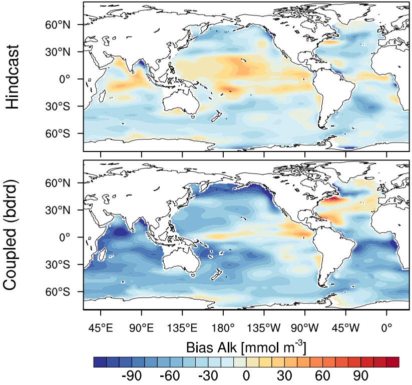


Alkalinity



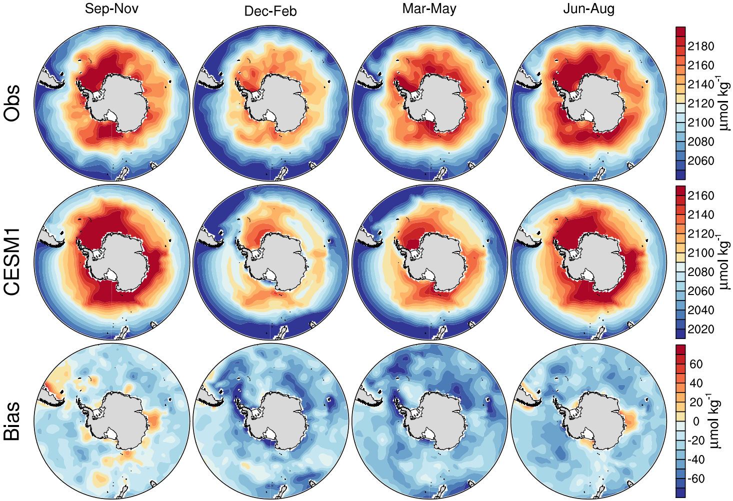
Biases

	Δ(mean)	RMS error
Hindcast:	–1.4%	28.1 mmol m^{-3}
Coupled:	–2.8%	55.0 mmol m^{-3}



DIC is largely underestimated by CESM1

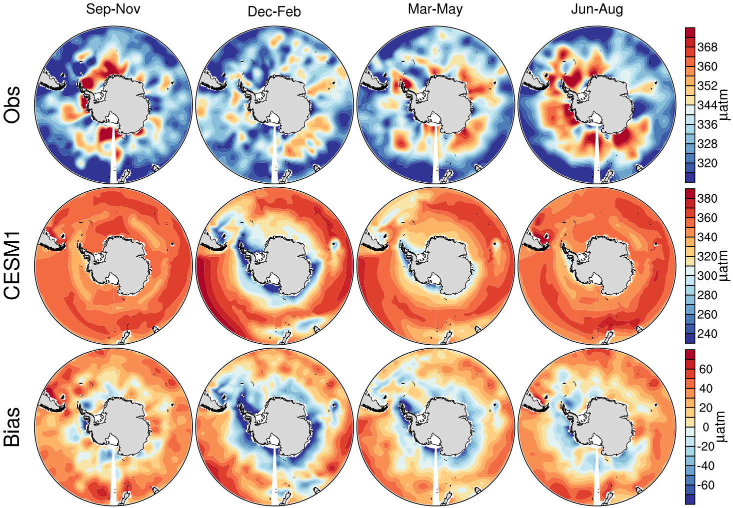
Dissolved inorganic carbon



Coupled, bDrD, years 1990–2000

. . . but $p\mathrm{CO}_2$ is overestimated, except near the continent

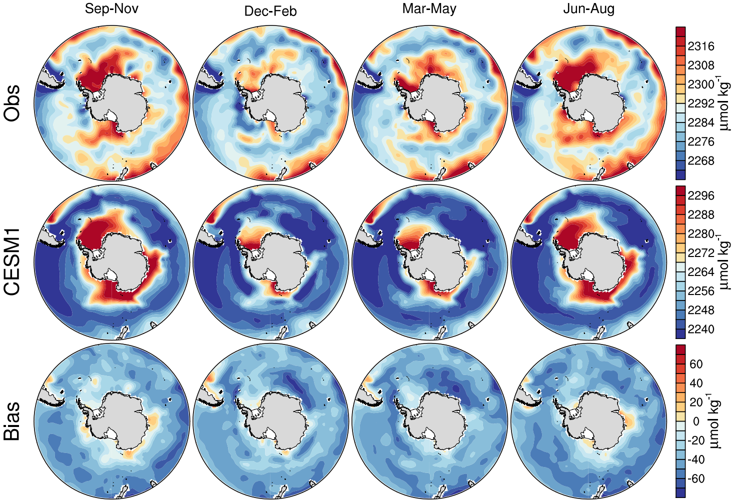
$p\mathrm{CO}_2$



Coupled, bDrD, years 1990–2000

Does alkalinity underestimation cause pCO_2 biases?

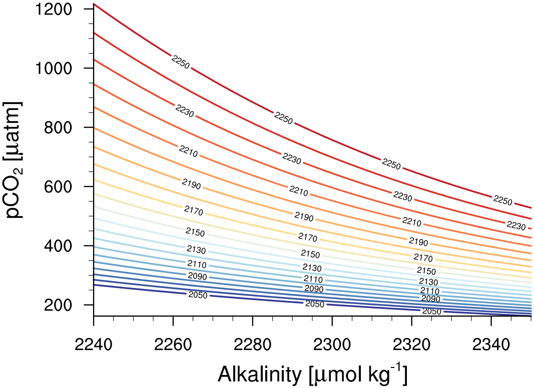
Alkalinity



Coupled, bDrD, years 1990–2000

DIC:Alk ratio controls pCO_2^{sw}

pCO_2 v. Alk, at DIC

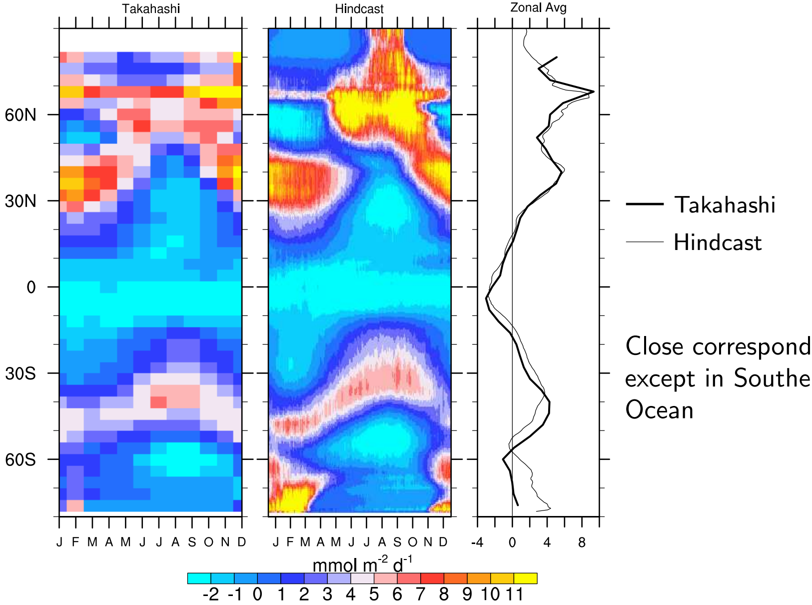


At
DIC $= 2150\ \mu$mol kg^{-1} and
Alk $= 2280\ \mu$mol kg^{-1}

$$\frac{\partial pCO_2}{\partial \mathrm{DIC}} \approx +2.8\ \mu\mathrm{atm}$$

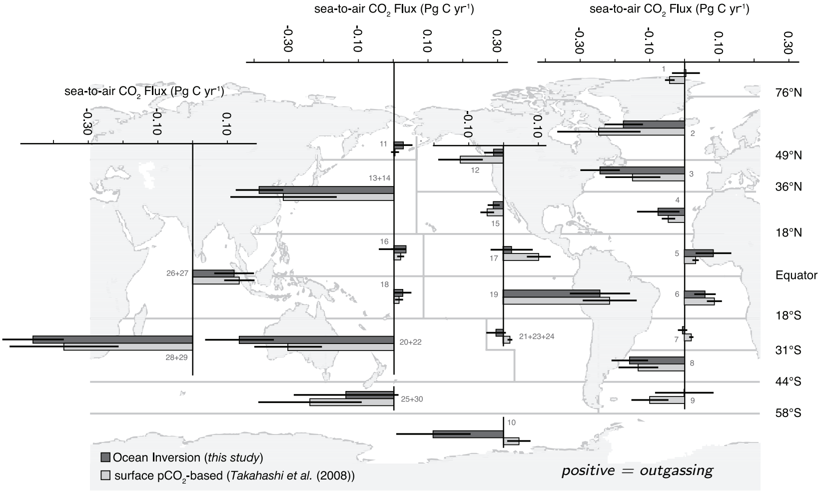
$$\frac{\partial pCO_2}{\partial \mathrm{Alk}} \approx -2.6\ \mu\mathrm{atm}$$

Zonal distributions of CO_2 flux



Close correspondence, except in Southern Ocean

Zonal distributions of CO_2 flux

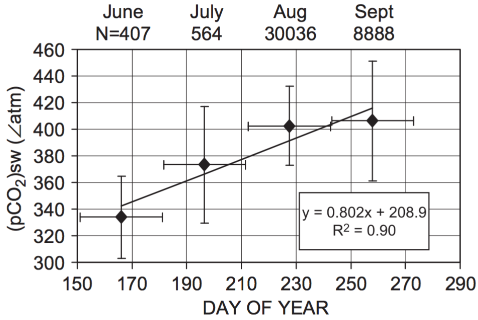


- Different flux estimates show largest discrepancies in Southern Oc.

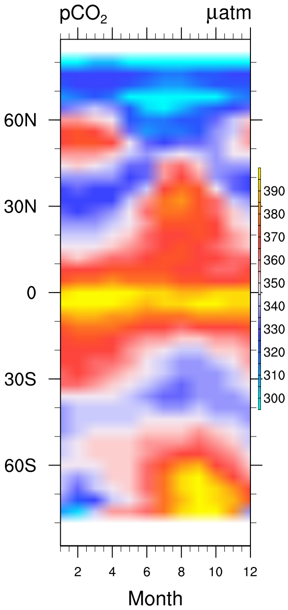
Gruber et al. 2009

Zonal distributions of CO_2 flux

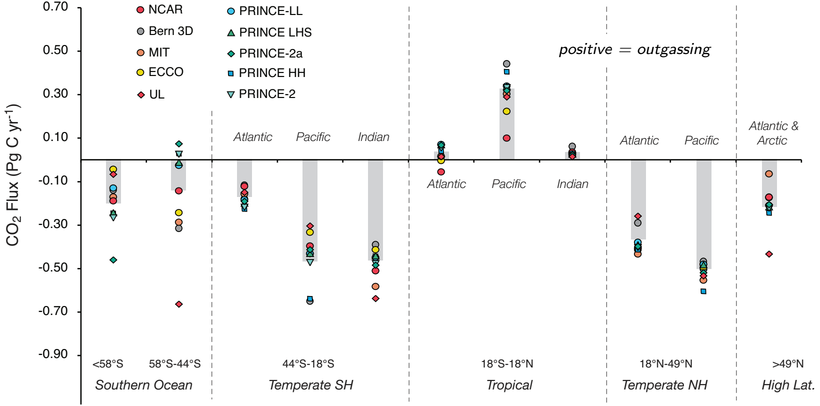
pCO_2 accumulation under ice



Takahashi et al. 2009



Zonal distributions of CO_2 flux

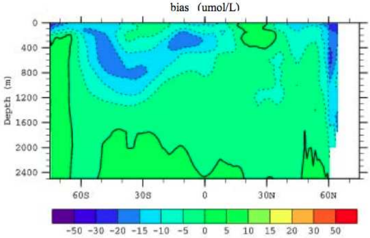


- Models show large range of variability in Southern Oc. fluxes; a component of this is related model physics and variation in intermediate, deep, and bottom water formation.

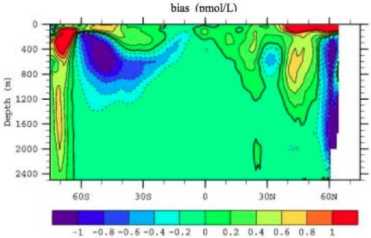
Gruber et al. 2009

Anthropogenic CO_2 and CFC uptake biases, CCSM3

Anthropogenic CO_2



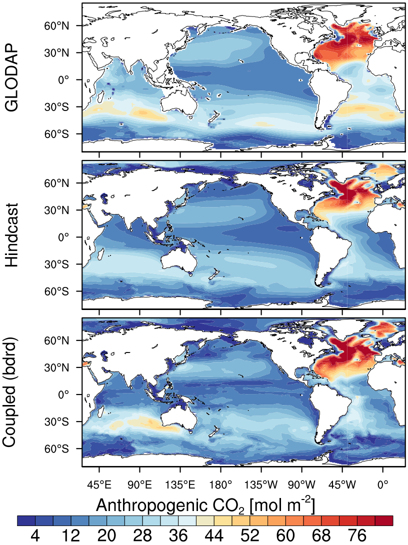
CFC-11



- Overall structure similar to observations; but
- Low biases in the Southern Ocean: Weak Antarctic intermediate and mode water formation?
- CFC pattern indicates too strong ventilation along Antarctic margin; N. Atlantic deep convection too far south—and/or SST biases.

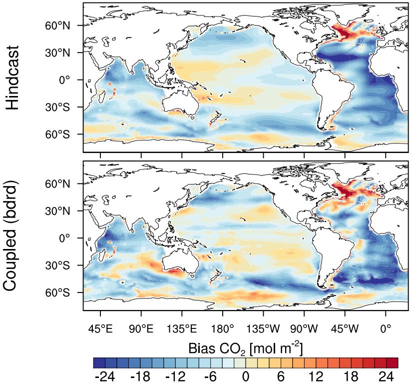
Thornton et al. 2009

CESM1 anthropogenic CO_2 inventories



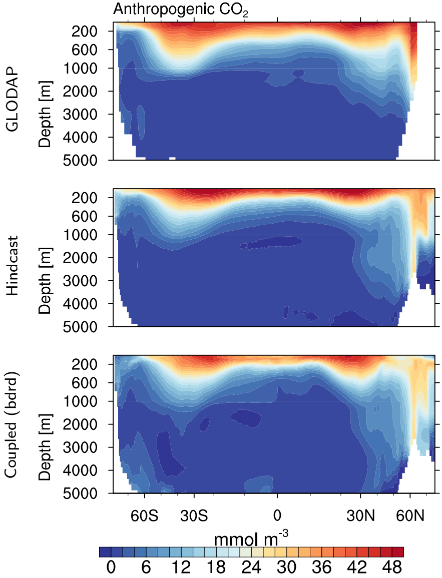
Inventories

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



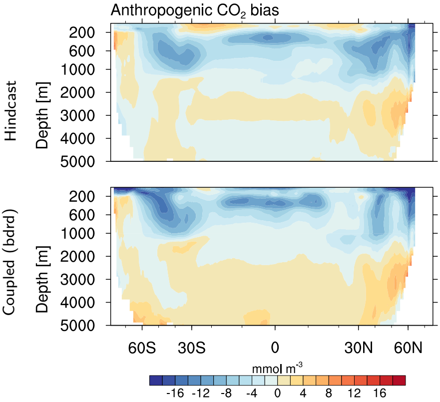
$(1 \text{ Pg} = 10^{15}\text{g})$

CO_2 uptake too weak in both forced and coupled runs

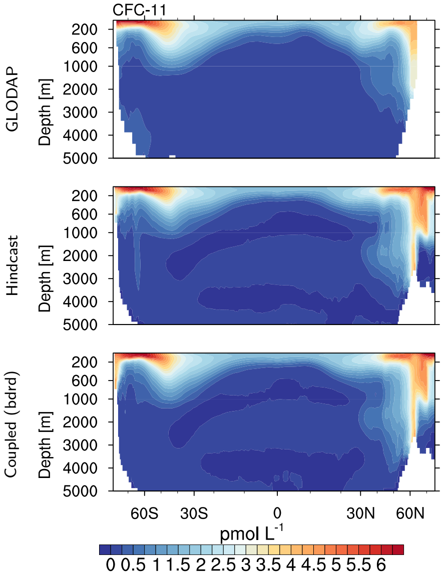


Biases

	Δ(mean)	RMS error
Hindcast:	–12.9%	5.4 mmol m^{-3}
Coupled:	–23.3%	7.8 mmol m^{-3}

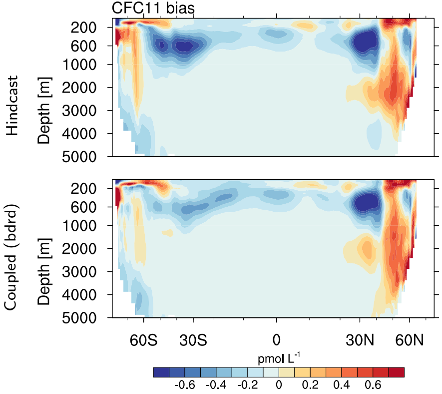


CFC-11 uptake in forced and coupled runs



Inventories*

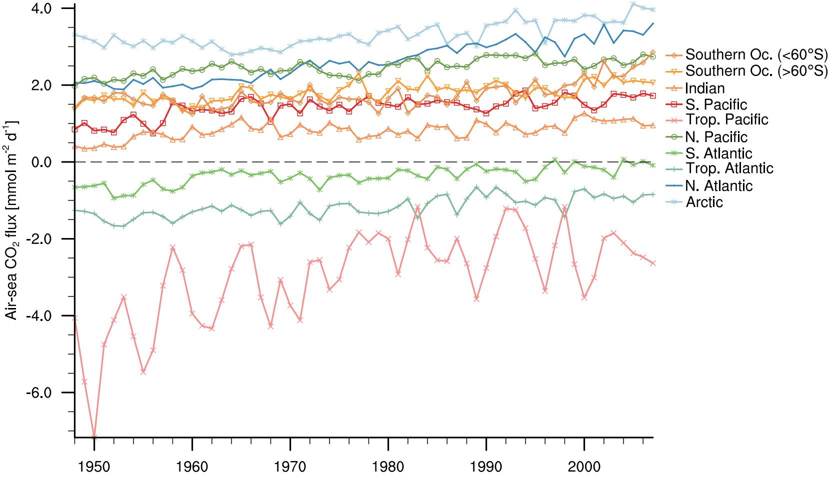
GLODAP:	5.44×10^8 mol	(±15%)
Hindcast:	4.90×10^8 mol	(10% low)
Coupled:	5.14×10^8 mol	(5% low)



*Inventories exclude Arctic

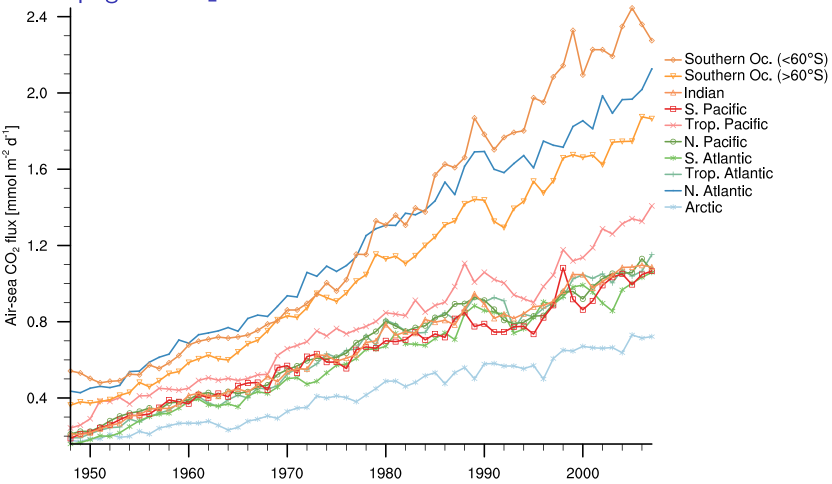
Regional trends in air-sea CO_2 flux

Contemporary CO_2

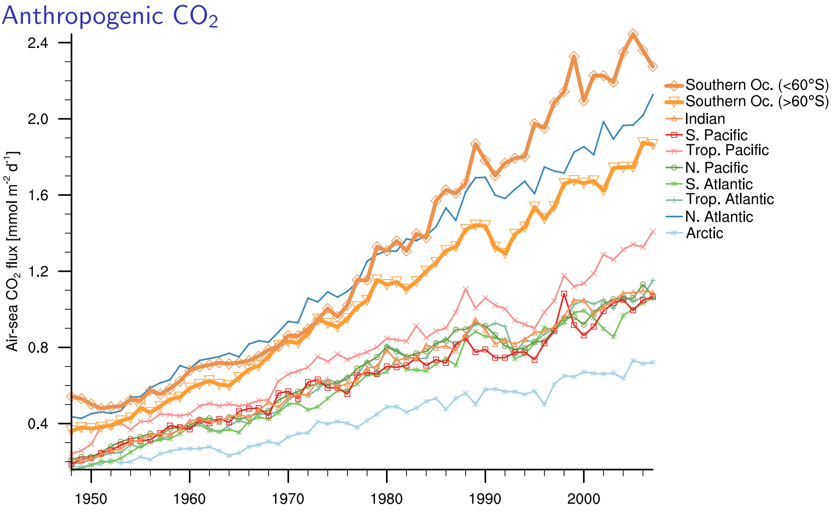


Regional trends in air-sea CO_2 flux

Anthropogenic CO_2



Regional trends in air-sea CO_2 flux



Summary

- Getting carbon uptake right requires accurate representation of both
  1. surface processes affecting air-sea exchange; and
  2. physical subduction and transport.
- Spatial and temporal variability in pCO_2^{sw} compares favorably with observations; model pCO_2^{sw} is too high compared to observations, alkalinity cycling may play a role.
- Anthropogenic CO_2 uptake is improved relative to CCSM3; although weak uptake persists and the structure of biases is similar:
  high latitude regions remain problematic.
- Dramatic 20th century changes in regional sink performance are not evident in the model.