Ocean CO_2 Uptake: Predictions from an Ocean Circulation Inverse Model (OCIM)

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Global Carbon Budget

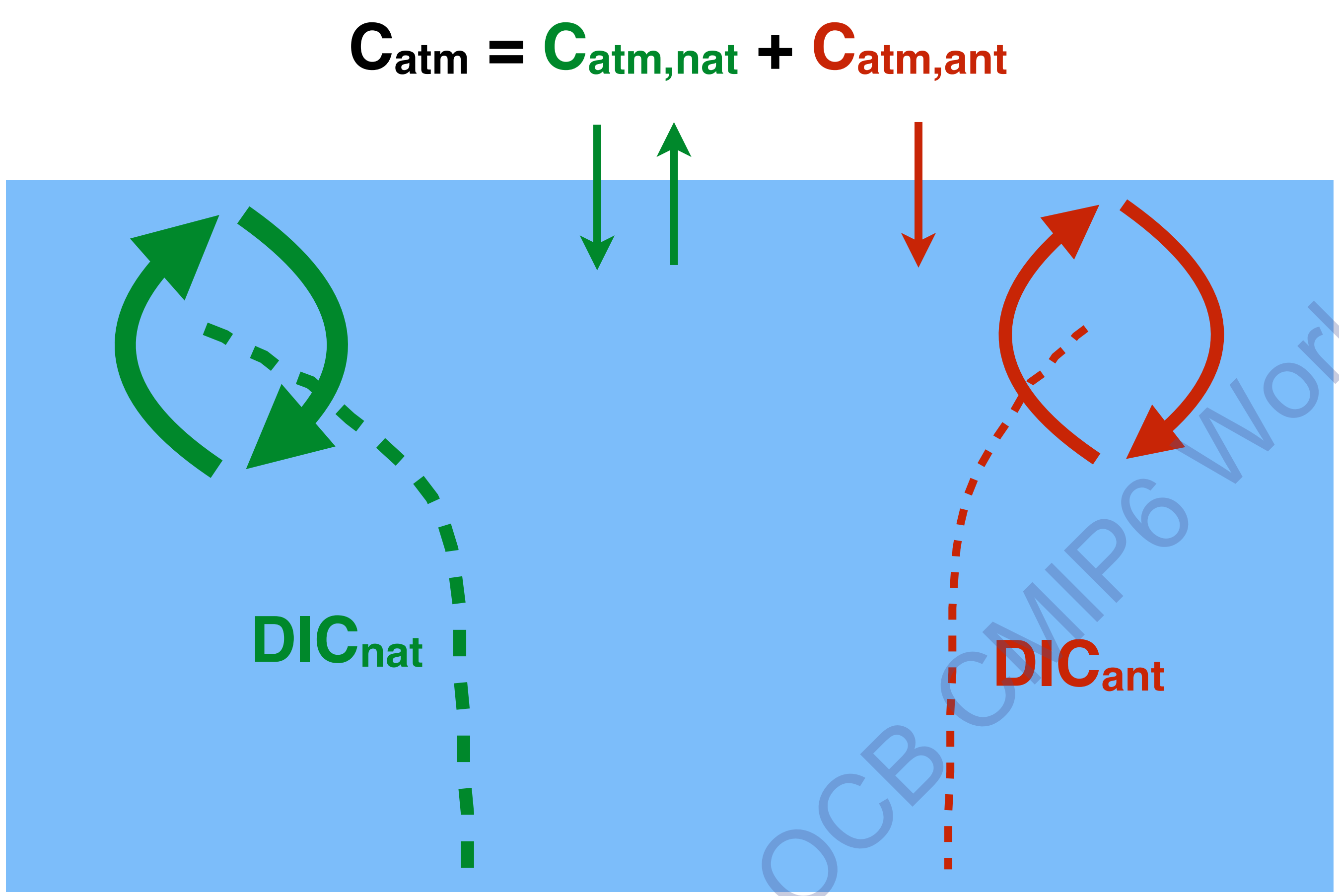
$$\overset{\checkmark}{C_{emissions}(t)} = \overset{\checkmark}{C_{atmosphere}(t)} + \overset{?}{C_{ocean}(t)} + \overset{?}{C_{land}(t)}$$

3 sinks for anthropogenic CO_2 emissions:
(i) Atmosphere - Can be measured over time (global network of stations), well mixed
(ii) Ocean - Few measurements over time, not well mixed
(iii) Land - Very difficult to detect, highly heterogeneous

Problem: 1 equation, 2 unknowns

Solution: Estimate either the land or ocean sink by indirect methods

Estimating the Ocean Anthropogenic CO_2 Sink with Ocean Inverse Models



Ocean inverse models take advantage of two facts:

1. ***Anthropogenic*** CO_2 in the ocean can be treated as a transient conservative tracer (assuming no effect on biology), and
2. The atmospheric boundary condition is known.

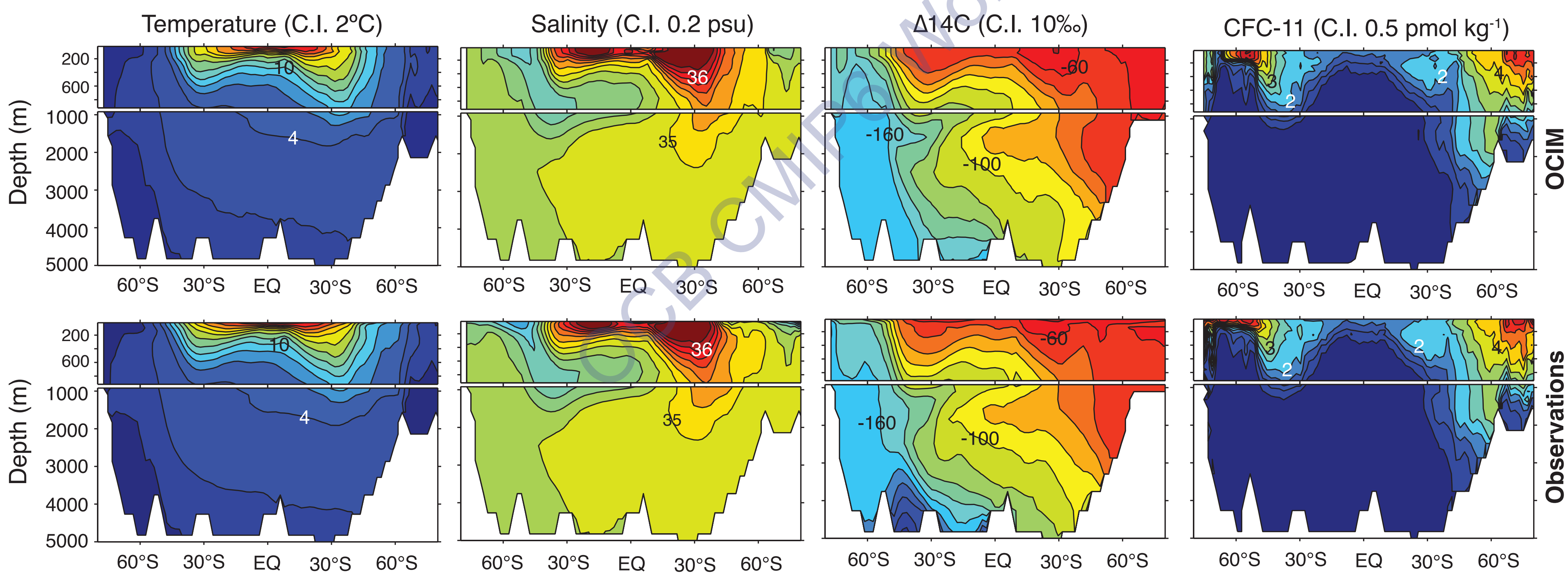
If we have a good estimate of ocean circulation/ventilation rates (very important) and air-sea gas exchange (not as important), we can estimate the anthropogenic CO_2 uptake.

Examples: Mikaloff-Fletcher et al. (2006), Gruber et al. (2006), Khatiwala et al. (2009,2013), DeVries (2014)

Ocean Circulation Inverse Model (OCIM)

The OCIM is a data-assimilated model of the climatological mean ocean circulation (state estimate):

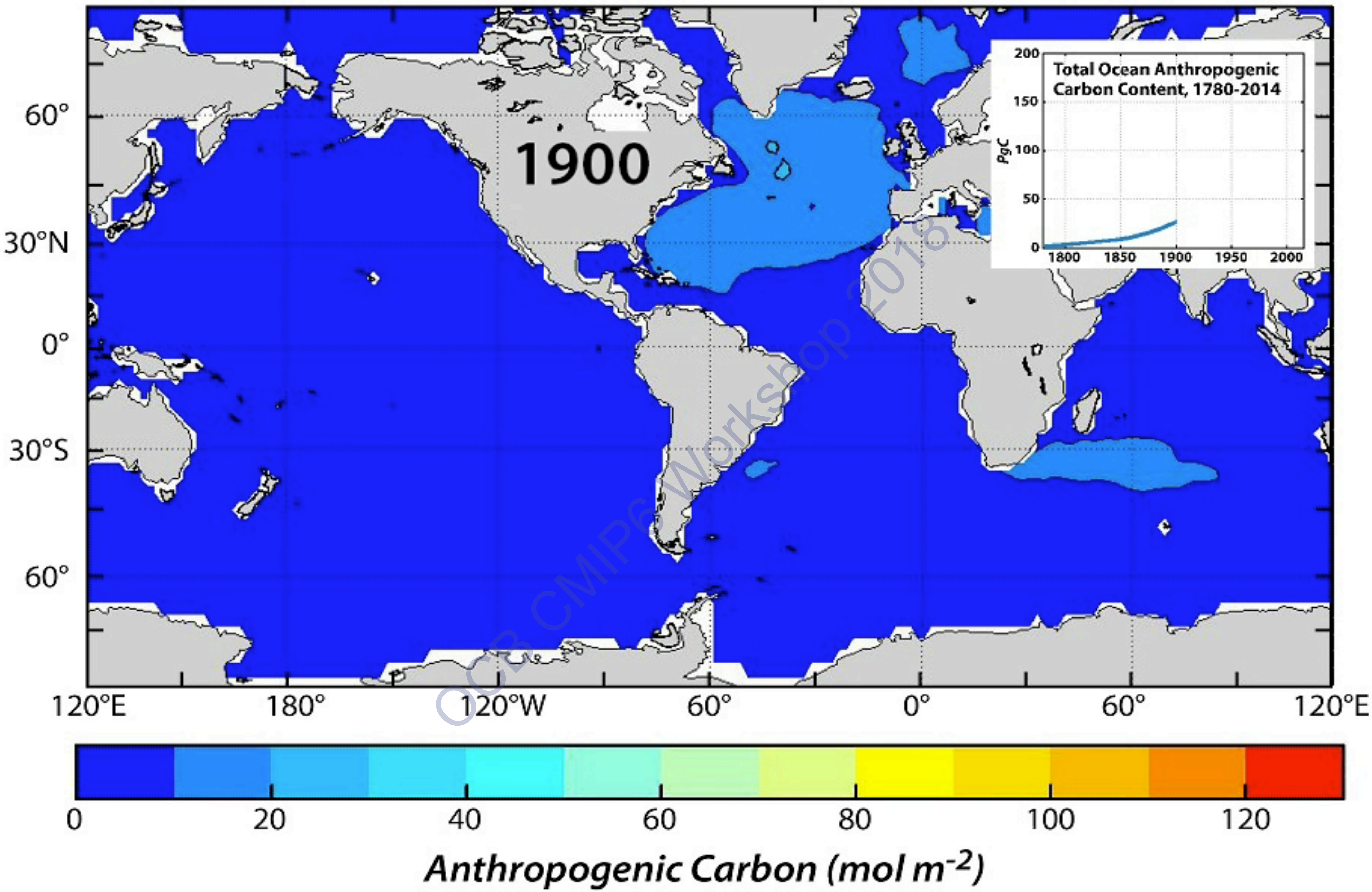
- Resolution is 2° in the horizontal with 24 vertical levels
- Linearized dynamics
- Imposed sub-gridscale diffusivities (Redi + vertical w/ enhanced diffusivity in surface mixed layer)
- Momentum balance is adjusted to achieve maximal consistency with 4 physical circulation tracers (T, S, $\Delta^{14}C$, CFC-11) and 3 surface fields (air-sea heat and salt fluxes, and sea-surface height).



Atlantic Ocean averaged OCIM (top) and observed (bottom)

OCIM has a realistic distribution of water masses and ventilation times. Should be good to use for anthropogenic CO_2.

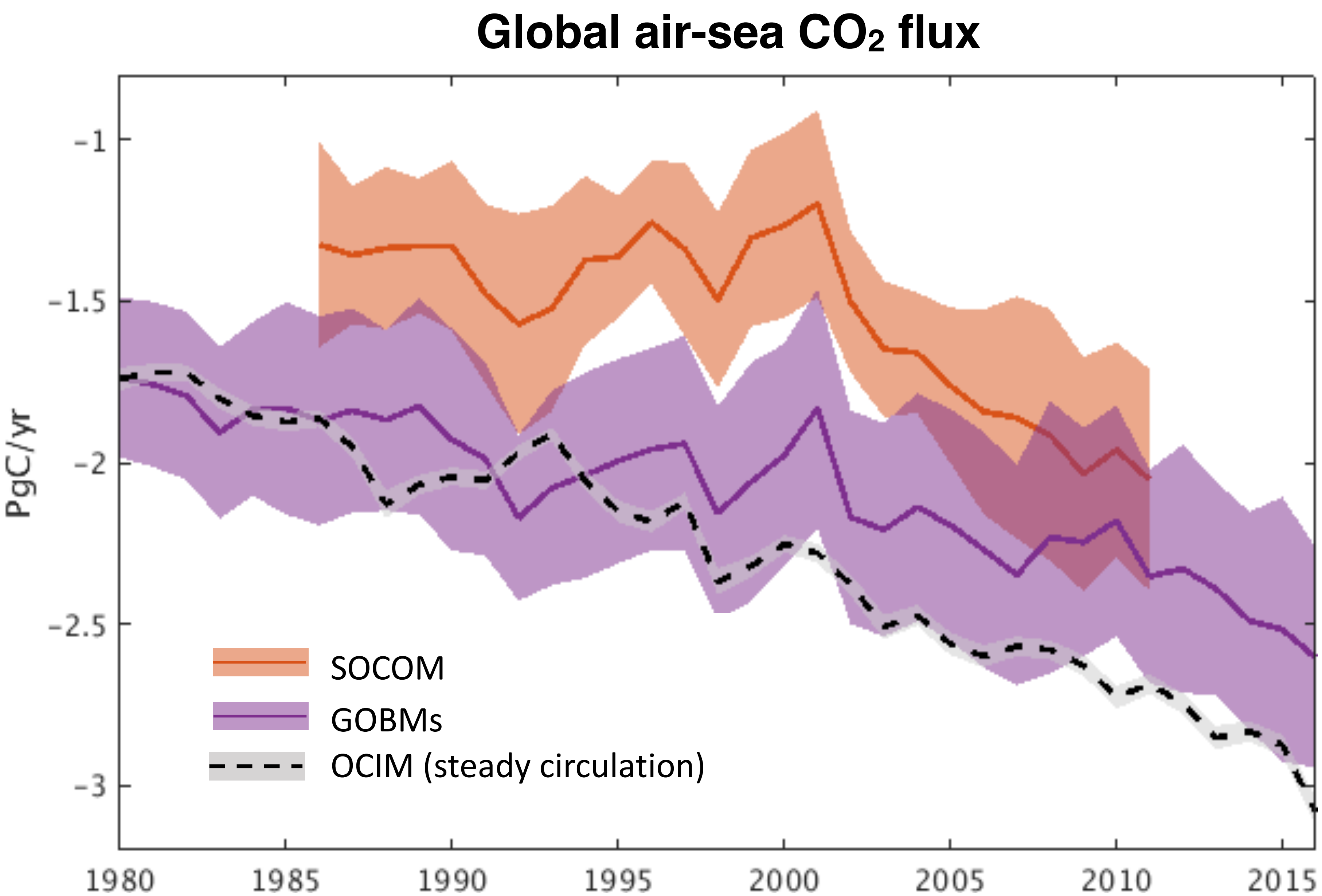
Anthropogenic Carbon Distribution in the Ocean



Devries (2014), *Global Biogeochemical Cycles*

Khatiwala, DeVries, McKinley et al. (2015)

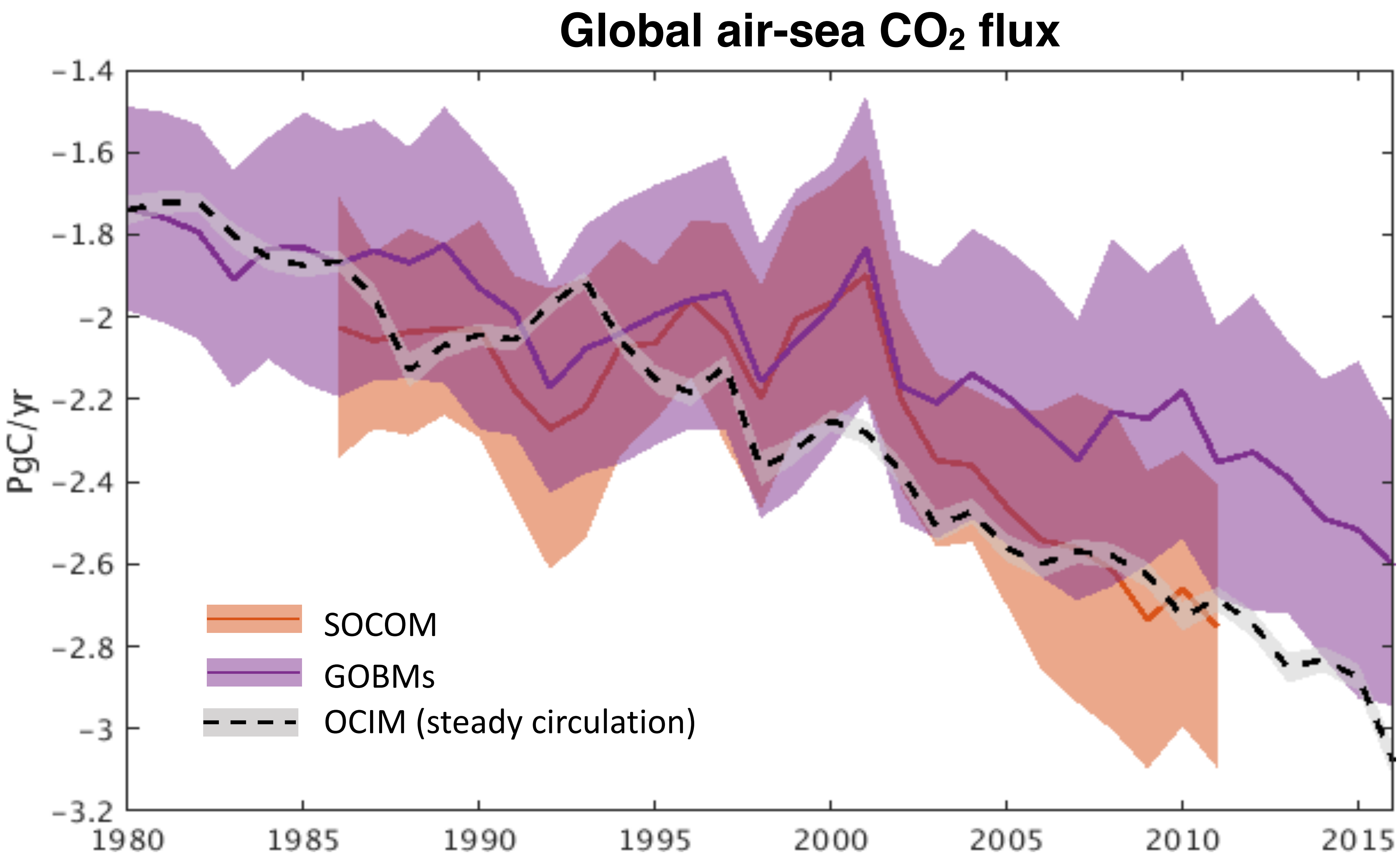
OCIM: Comparison to other methods



OCIM (black dashed) compared to Global Ocean Biogeochemistry Models (GOBMs, purple), and Surface Ocean pCO2 Mapping (SOCOM, red) products.

OCIM and GOBMs roughly agree but SOCOM flux much higher. Need to correct for riverine CO_2 degassing (not resolved in OCIM or GOBMs).

Variability of the Oceanic CO_2 Sink



Subtracting **0.7 PgC/yr** efflux of riverine CO_2 from the SOCOM models brings them in line with OCIM. Similar to Resplandy et al. (2018) 0.78 PgC/yr.

The OCIM does not capture as much variability in the oceanic CO_2 uptake as the SOCOM or GOBMs because OCIM assumes constant circulation and biology.

We re-assimilated the OCIM using decadal "chunks" of tracer data to see if we could capture some of this variability (due to decadal variability in the ocean circulation).

OCIM with decadally-varying circulation

- OCIM fit to ocean tracer data (T, S, CFC-11, CFC-12, $\Delta^{14}C$) from three different time periods: pre-1990 (~**1980s**), 1990-1999 (**1990s**), and 2000-2012 (**2000s**).
- Mean circulation (steady-state) derived for each period.
- Prognostic C cycle model (OCMIP-2) coupled to OCIM and run from 1765-2014 under observed atmospheric CO_2 concentrations.
- Circulation held steady prior to 1990, then abrupt switches applied at 1990 and 2000.
- Biological C cycling held constant (no change in biological pump).
- Change in "natural" CO_2 and "anthropogenic" CO_2 inventories separately diagnosed.
- Goal: Estimate effect of decadal variability in ocean circulation on oceanic CO_2 sink.
- Caveats: Steady-state circulation within each time period ignores interannual variability. Biological changes ignored.

LETTER

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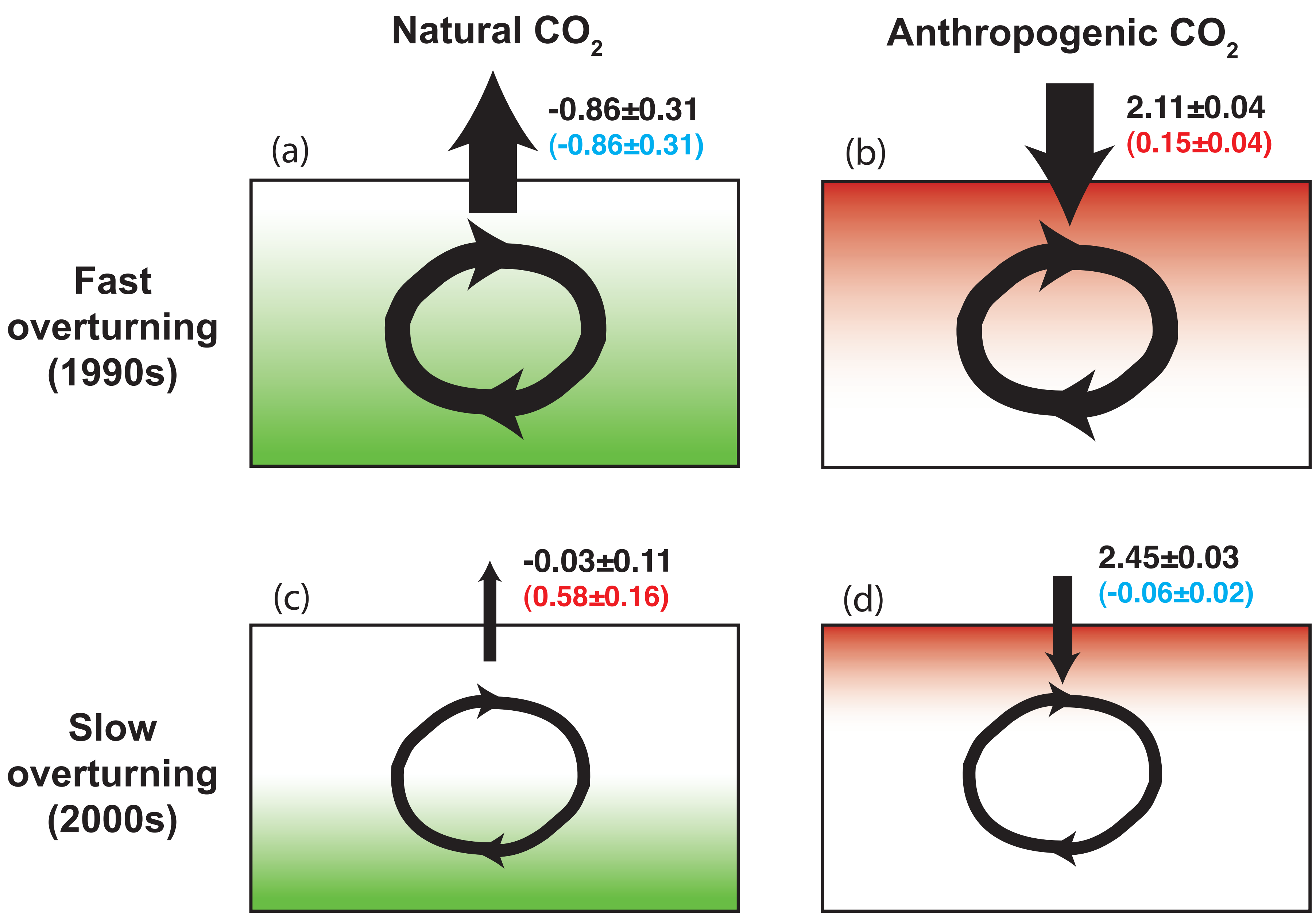
Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning

Tim DeVries[1,2], Mark Holzer[3,4] & Francois Primeau[5]

OCIM: Decadally-variable circulation



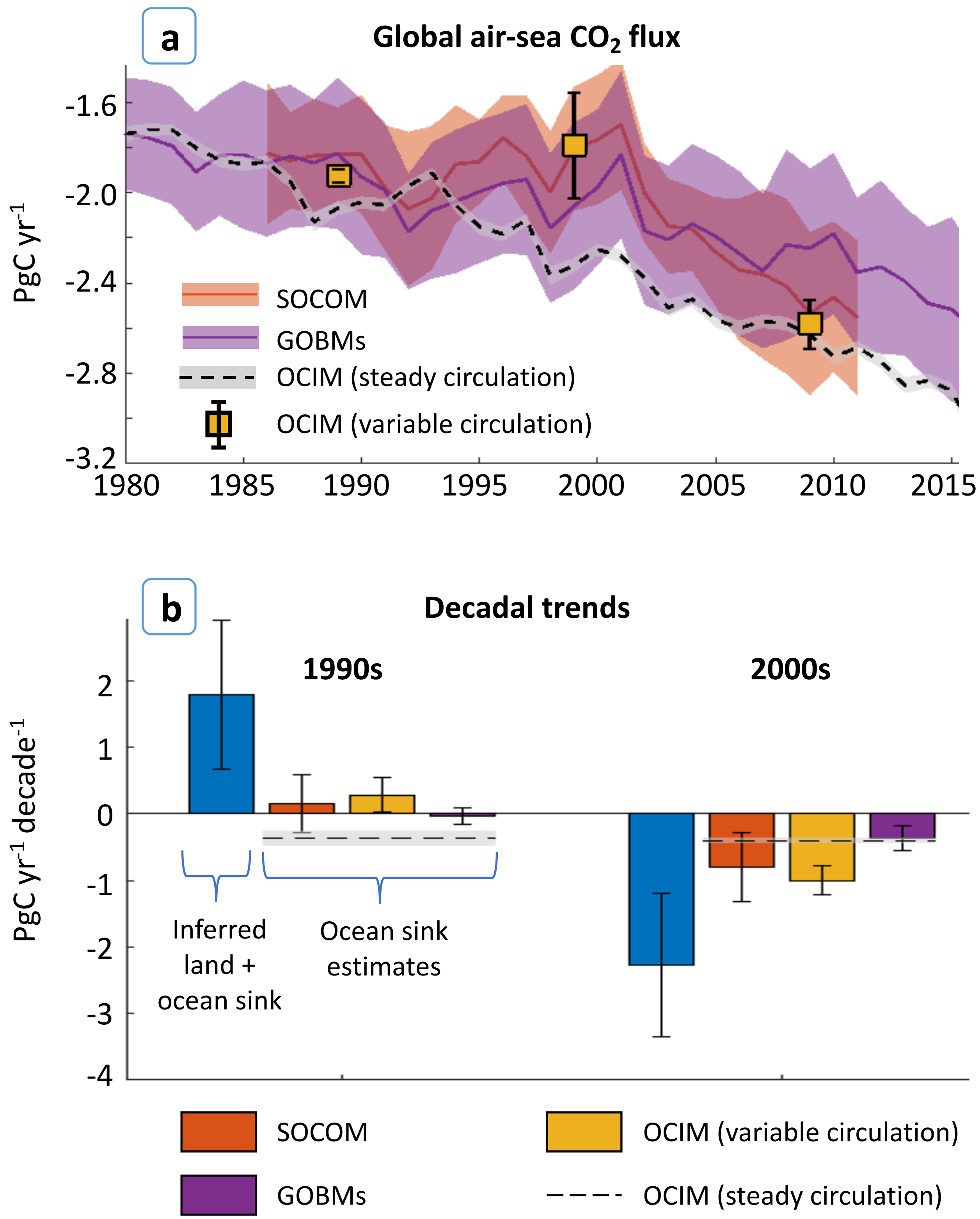
1990s

Increased overturning increases outgassing of C_{nat} in upwelling regions. Increase in C_{ant} uptake not enough to counteract C_{nat}. **Ocean CO_2 sink weakens.**

2000s

Reduced overturning decreases outgassing of C_{nat} in upwelling regions. Decrease in C_{ant} uptake not enough to counteract increase in C_{nat}. **Ocean CO_2 sink strengthens.**

Decadal variability of ocean CO_2 sink

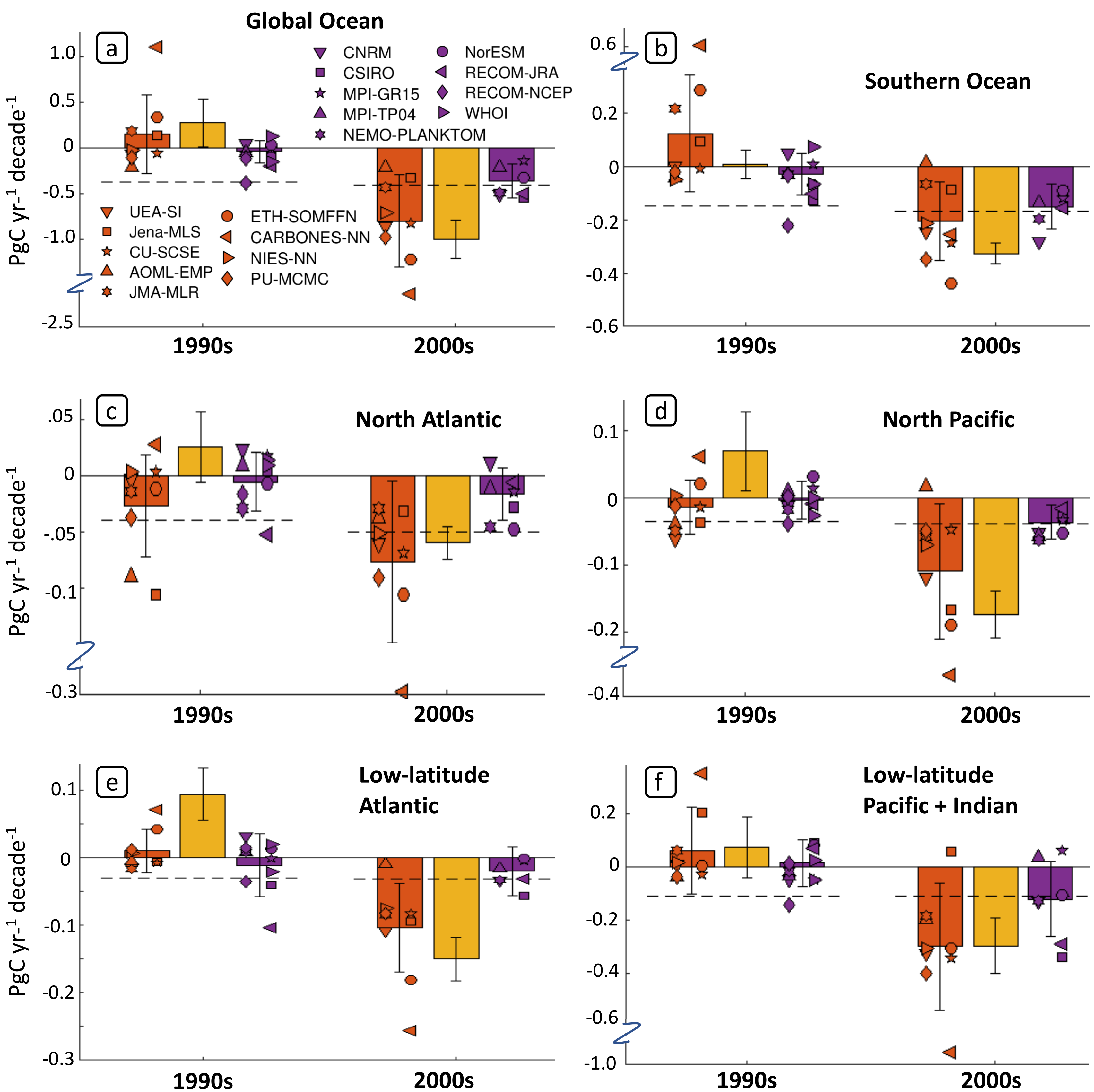


The OCIM with decadally-variable circulation matches well with the pattern of variability from the SOCOM (pCO_2 flux mapping) products.

Suggests observed decadal trends in ocean CO_2 uptake due to changes in ocean circulation.

About 5-40% of the observed decadal variability in the total land+ocean CO_2 sinks could be due to the ocean.

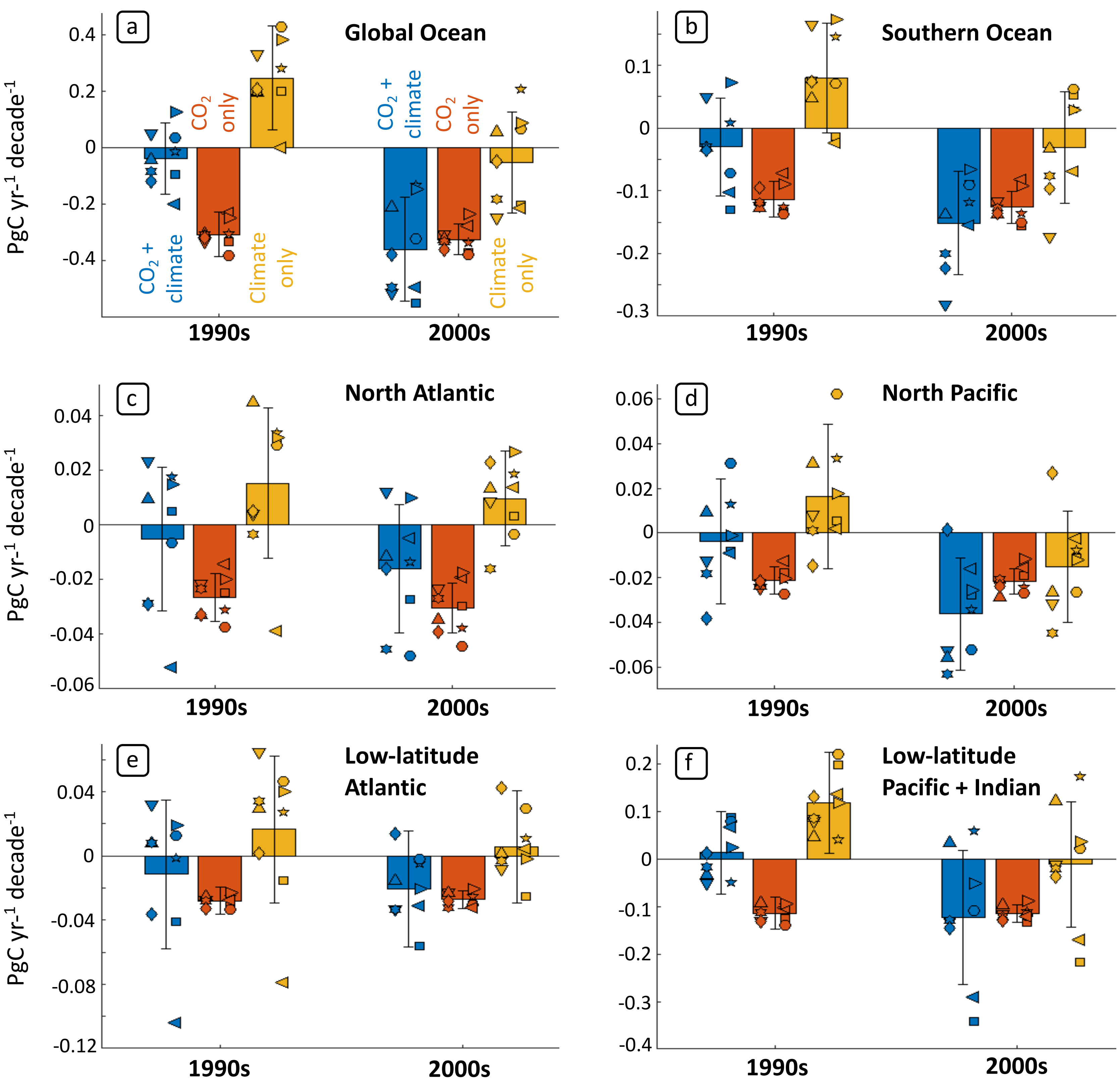
Regional decadal variability of ocean CO_2 sink



1990s: OCIM and SOCOM agree on a global weakening trend, but OCIM has more of the trend due to low latitudes than SOCOM. GOBMs show little trend.

2000s: OCIM and SOCOM agree on both global and regional strengthening trends. GOBMs show same general pattern but a bit weaker.

Climate-driven decadal variability of ocean CO_2 sink in GOBMs

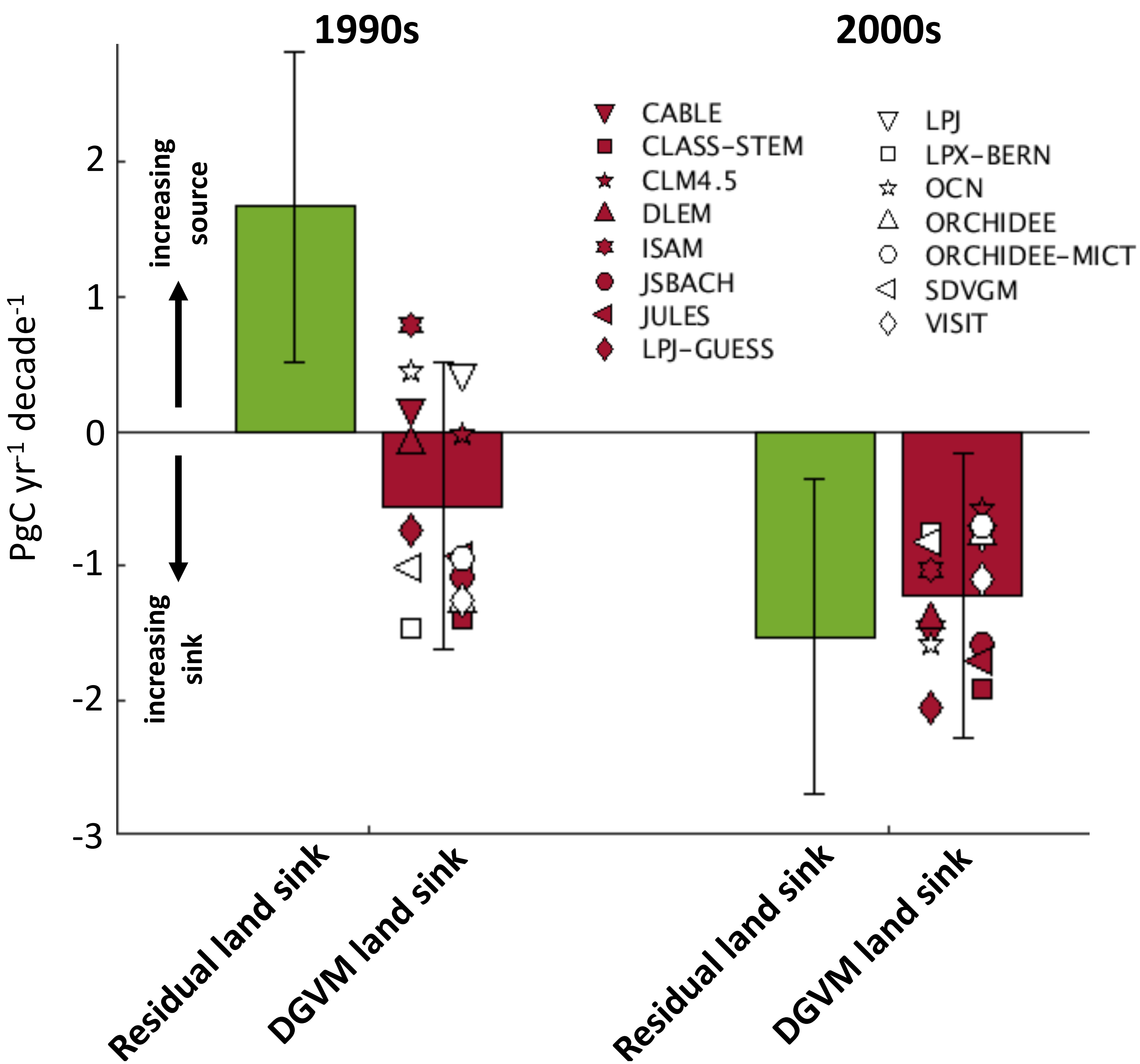


We ran a constant-climate and variable-climate simulation with 9 different GOBMs. The difference between the two runs is attributed to climate variability.

Climate variability drove a weakening CO_2 sink in the 1990s in 8/9 models. It drove a strengthening CO_2 sink in the 2000s in 5/9 models.

In almost all regions of the ocean, climate variability enhanced the uptake of CO_2 in the 2000s as compared to the 1990s.

Implications for the terrestrial sink



1990s: Terrestrial sink was weakening. Only 4/14 DGVMs agree. (Problem with LUC estimates??)

2000s: Terrestrial sink was strengthening. All the DGVMs agree.

DGVM = Dynamic global vegetation model

Conclusions

- An Ocean Circulation Inverse Model that assimilates ocean tracer data produces accurate estimates of ocean CO_2 uptake. Results are available at CDIAC or (updated) from myself.
- Decadal-mean circulations that assimilate decadal-mean tracer data closely match estimates of decadal variability from pCO_2 mapping methods.
- Three independent methods (OCIM, ocean biogeochemical models, and pCO_2 flux mapping products) agree on the magnitude of the mean ocean CO_2 sink, and on the sign of its decadal trends in the 1990s and 2000s.
- Climate variability drives these trends, probably by the effect of global winds on ocean circulation.
- We have a pretty good handle on the ocean CO_2 sink and it can be used to further constrain the terrestrial CO_2 sink.

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