"Substantially larger atmosphere-ocean CO2 fluxes from surface observations" -- an update on near-surface temperature effects

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We gratefully acknowledge all those who have contributed data to SOCAT!

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Questions concerning calculation of ocean – atmosphere CO2 flux from surface data

1. Biases and corrections due to near-surface temperature effects
2. The precision with which global-scale fluxes can be constructed from interpolated surface data.

ARTICLE

https://doi.org/10.1038/s41467-020-18203-3

Watson et al, Nat. Comms (2020).

Revised estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory

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- Important to take into account near-surface (temperature gradients and biases when calculating air-sea flux from surface data (e.g. SOCAT) using bulk formula.
- When this is done, global estimates of atmosphere-to-ocean flux are substantially increased – we suggested by ~0.8-0.9 PgC yr^{-1}. This brings surface fluxes into close agreement with estimates of the rate of increase in the ocean carbon inventory.
- Bottom line: we probably overestimated the correction somewhat, it may be closer to 0.6 PgC yr^{-1}, -- still important however!

Two sources of gradients and biases that affect air-sea CO_2 flux

1. Bias between measured “inlet” and true mixed layer temperatures. (warm ships’ engine rooms?)
2. The cool skin of the surface ocean

1) SOCAT "inlet" T differs from satellite-derived remote sensing product for subskin* temperature (at ~20cm depth).

- The difference ΔT can be positive or negative, but inlet temperatures are higher by ~0.2-0.3°C on average than co-located satellite temperature estimates of subskin T.
- Why?
  - Probably on average a small increase in T with depth this close to the surface.
  - Most likely affected by warm bias in "Engine-room Inlet" temperatures, warmed by ship's infrastructure – a well known effect observed in studies of surface temperature observations.
- Dissolved CO_2 needs to be adjusted to take this into account when calculating air-sea fluxes.

*For discussion and definition see GHRSST group page: https://www.ghrsst.org/ghrsst-data-services/products/

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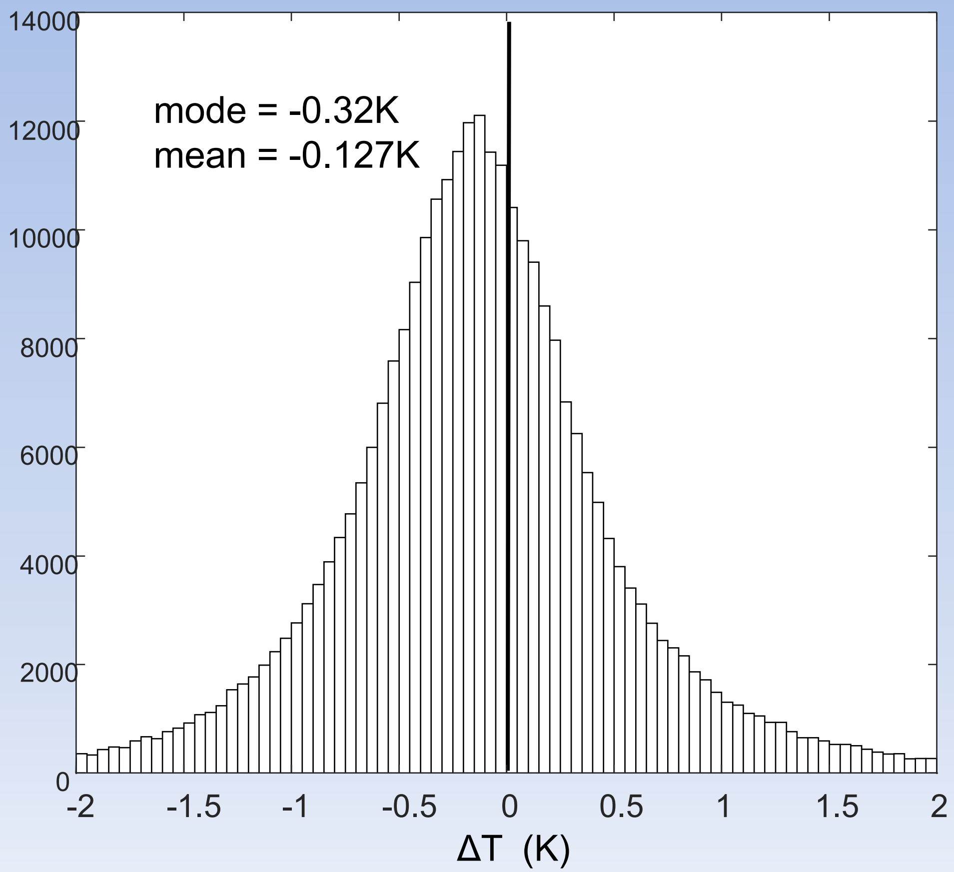
- We used OISST product from NOAA (Reynolds et al, 2007).
- Huang et al (2021)* identify a cold bias in the OISST data set compared to global Argo data
  - Regionally variable
  - -0.14 K in the global average.
- Dong et al (2022) suggest small net warm bias in SOCAT data using surface buoy data (*i*Quam)
  - ~0.02 K globally
  - "Update on the temperature correction of global air-sea CO2 flux estimates": Dong, Y, et al:https://doi.org/10.1002/essoar.10510573.1
- Still open, but it looks as if the Watson et al value for this component is too high.

* "Improvements of the daily optimally interpolated sea surface temperature (DOISST) version 2.1", Huang, B. et al, J. Clim. (2021). DOI: 10.1175/JCLI-D-20-0166.1

Histogram of OISST subskin temperature – SOCAT inlet temperature (SOCAT v2019)



From Holding et al product, constructed using OISST monthly average SSTs co-located with SOCAT data, then "cruise-weighted" average taken

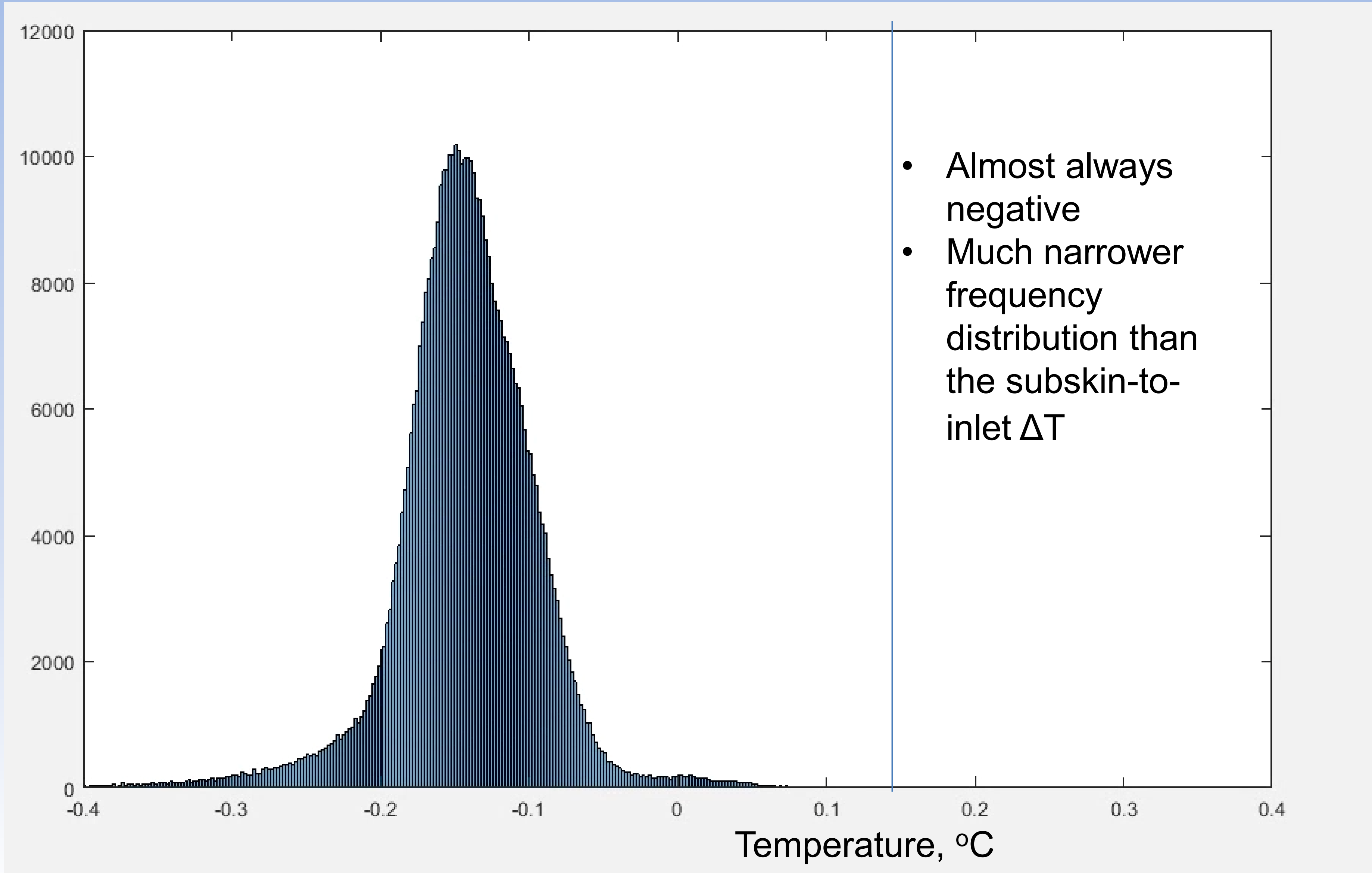
- Skewed distribution with mean heavily influenced by the tails.
- Most SOCAT measurements are biased warm, but a few large cold biases reduce the mean warm bias.

Two sources of gradients and biases that affect air-sea CO_2 flux

2) There is a cool "skin" at the surface.

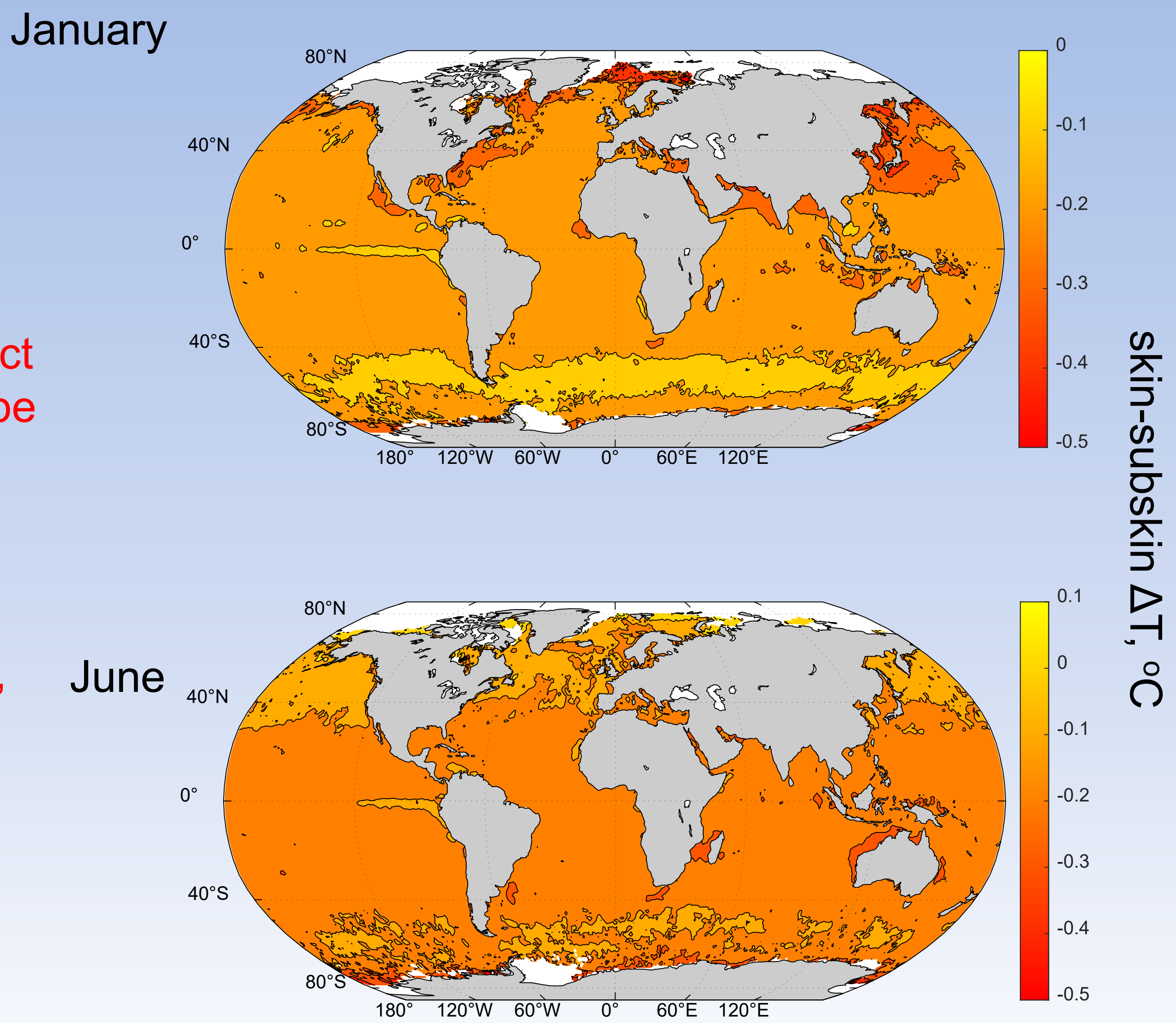
- Increase in solubility results in higher concentration of dissolved CO_2 in equilibrium with atmospheric CO_2.

Histogram of climatological surface-subskin temperature, 2003-2011. (ESA CCI SST product)



ESA CCI SST product: Merchant, C.J. et al., *Nat Sci Data* 6, 223, 2019.

Climatological skin temperature deviation, 2003-2011: from ESA CCI SST.



1 x 1 degree, monthly climatology

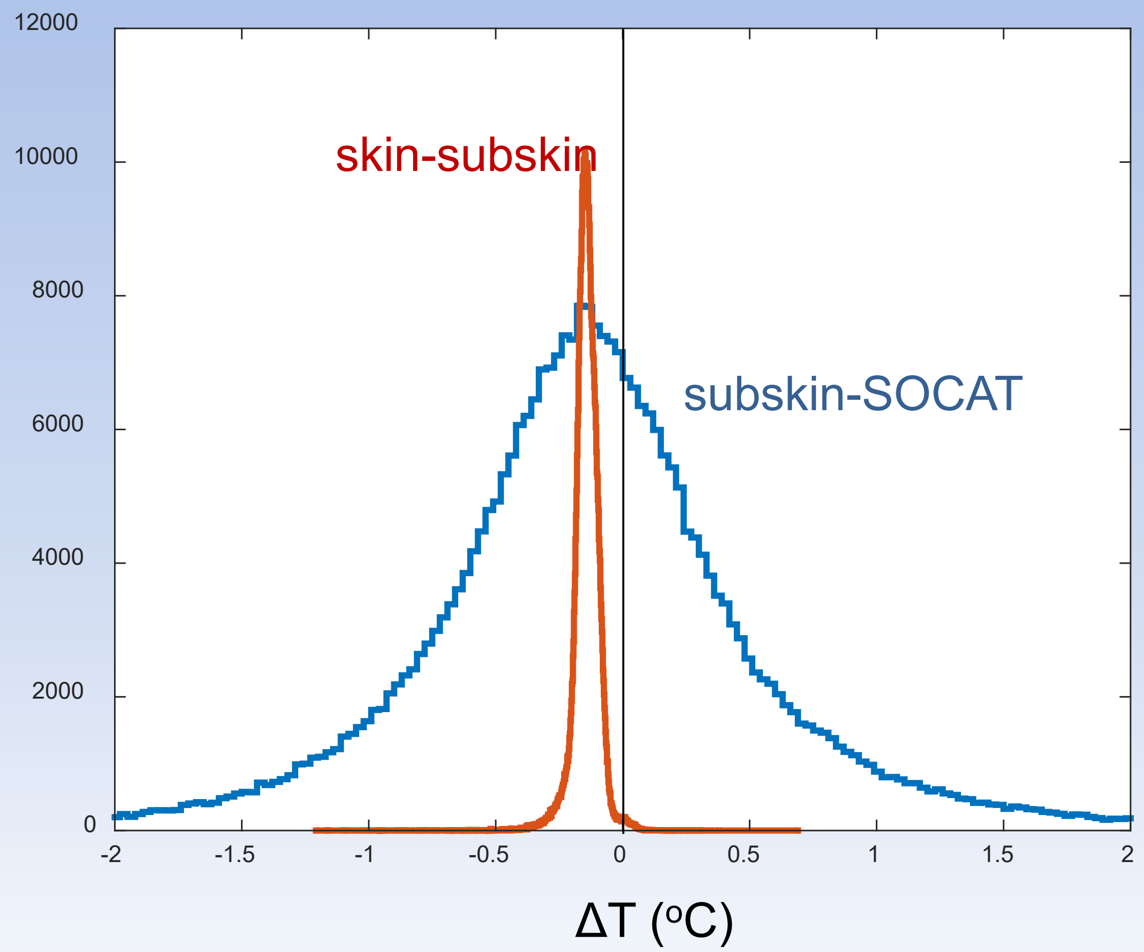
Deviation is largest in the winter hemisphere, and in warm currents (Gulf Stream, Kuroshio).

*Should skin temperature effect on CO_2 budget be included in models?

See poster by Andrea Rochner, tonight

ESA CCI SST product: Merchant, C.J. et al., *Nat Sci Data* 6, 223, 2019.

Comparison of frequency distributions of near-surface temperature differences

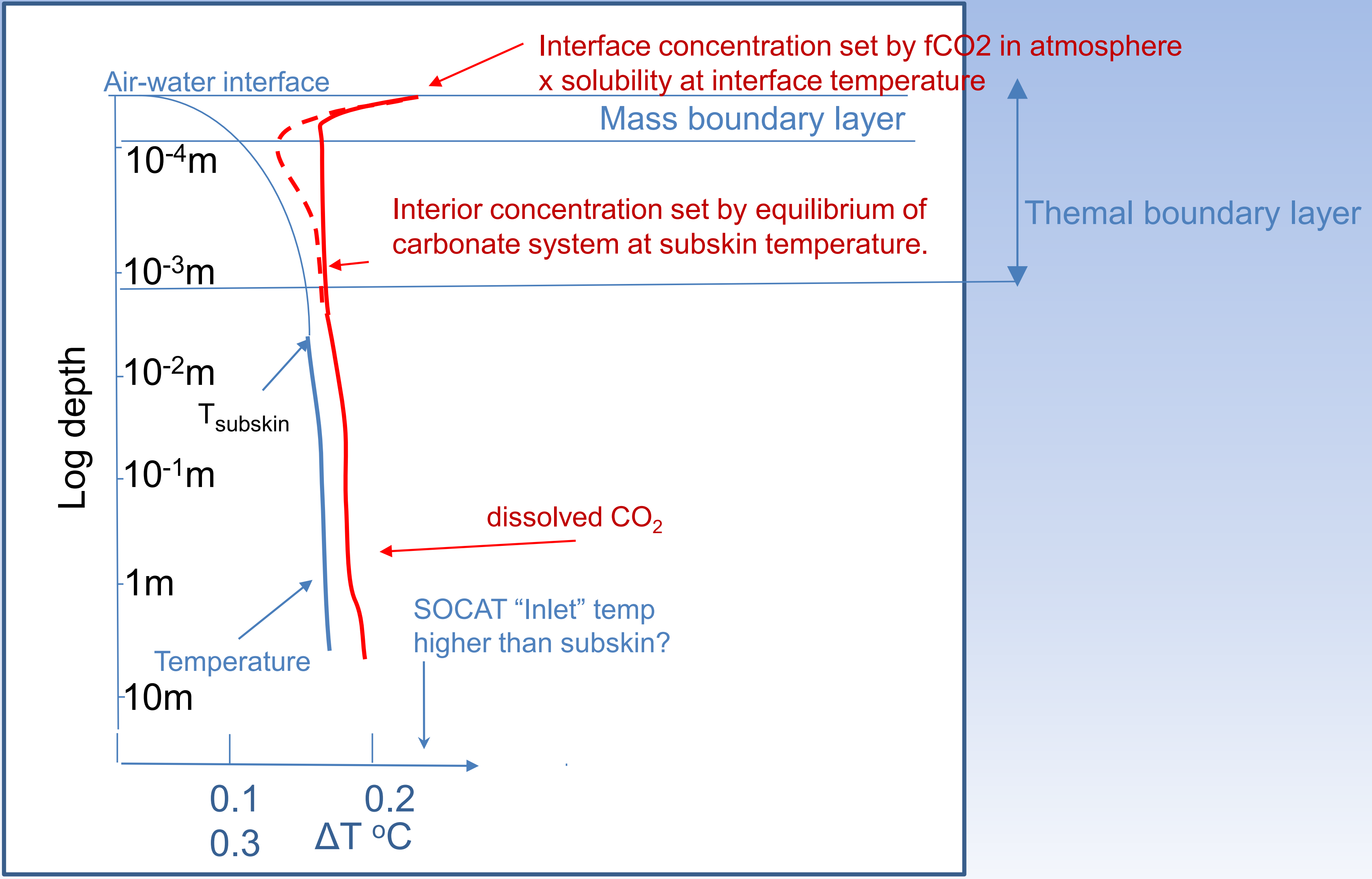


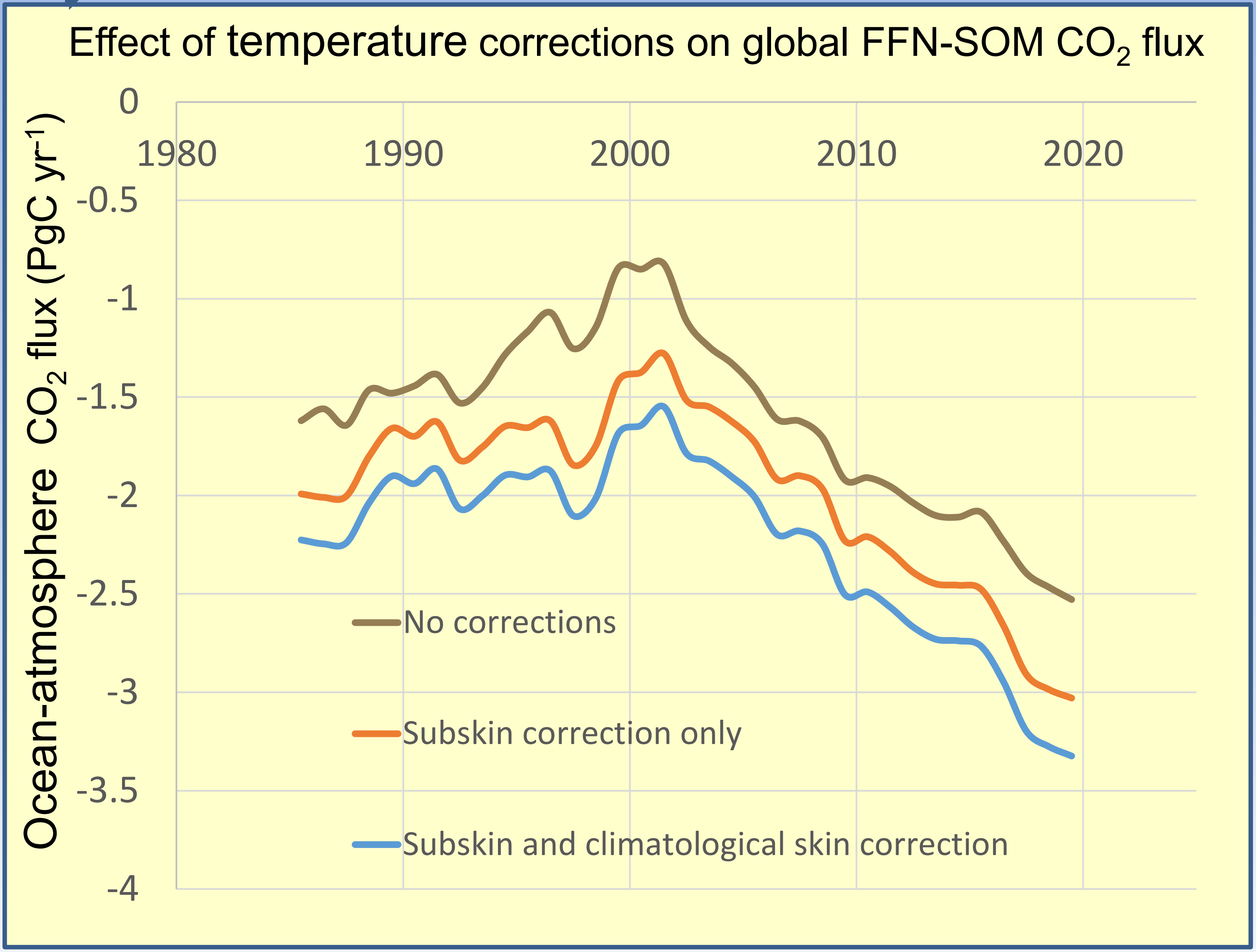
Temperature and dissolved CO_2 in the top layer of the ocean

This cartoon shows typical temperature (blue) and dissolved CO_2 (red) in the top 10m.

Note the log depth scale!

For detailed discussion see Woolf, D. K. et al, J. Geophys. Res Oceans, **121** pp. 1229–1248 (2016)





References:

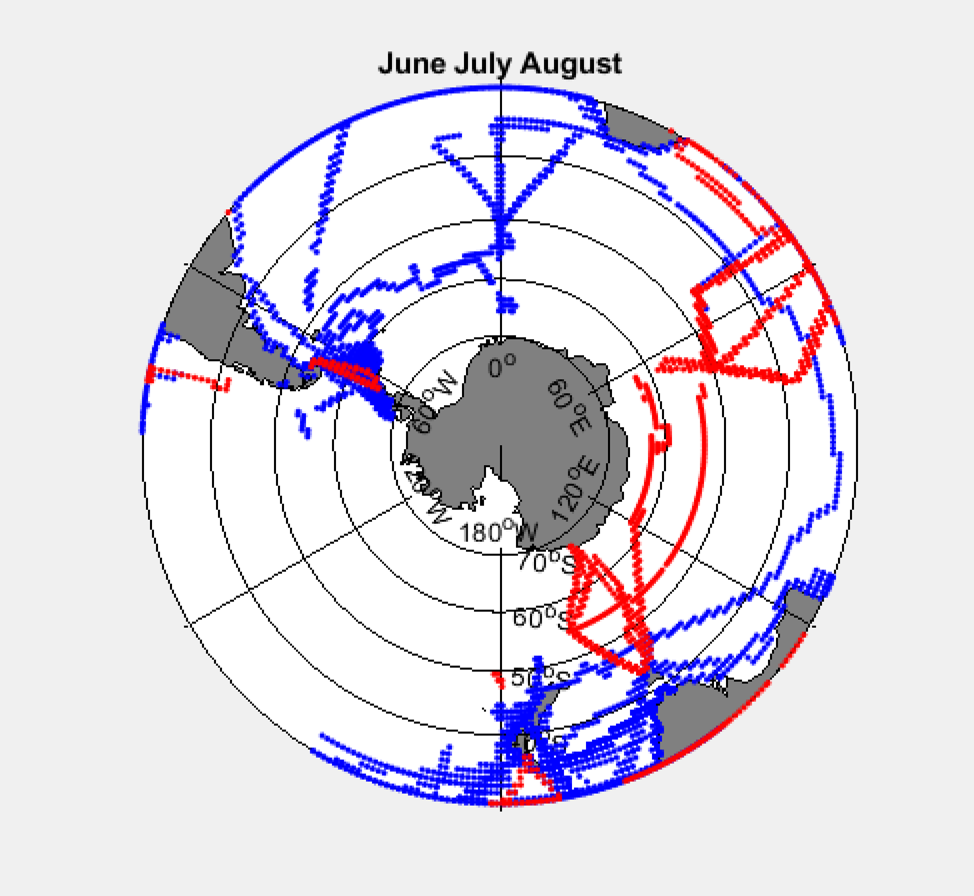
Watson, A. J. et al, Nat Comm **11**, art no. 4422 (2020) doi.org/10.1038/s41467-020-18203-3

Woolf, D. K. et al, JGR **121** 1229 (2016) doi.org/10.1002/2015JC011427

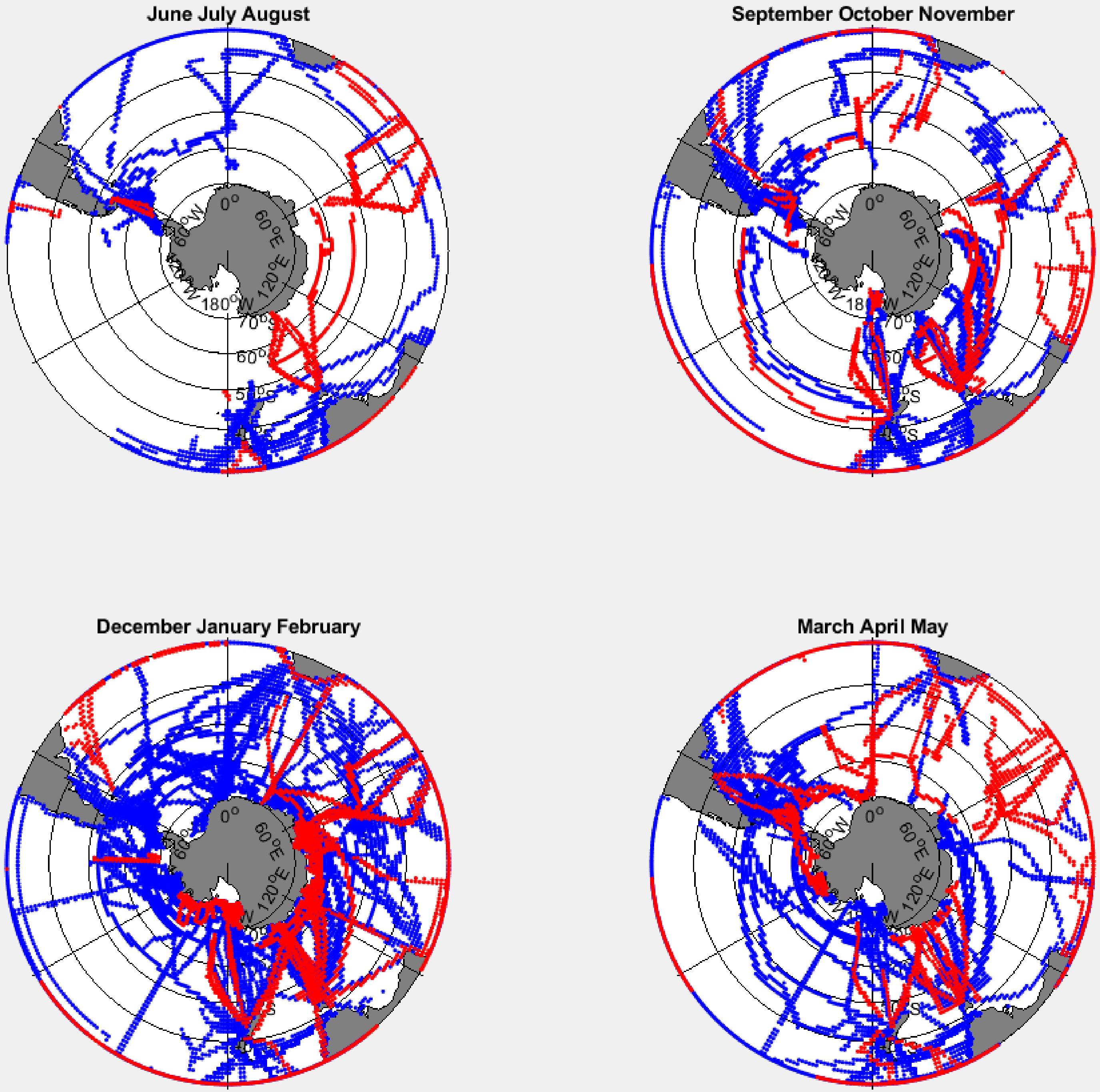
Quantifying uncertainties in ocean-atmosphere fluxes due to the imperfect coverage of surface data

Quantifying uncertainties in ocean-atmosphere fluxes due to the imperfect coverage of surface data

SOCAT Coverage in the Southern Ocean of winter-time data



Red – data in SOCAT 1992-2000
Blue – data in SOCAT 2000-2018


June July August
September October November
December January February
March April May

What is the ocean sink and its uncertainty as calculated by SOCAT coverage?

Start from SOCAT gridded data,

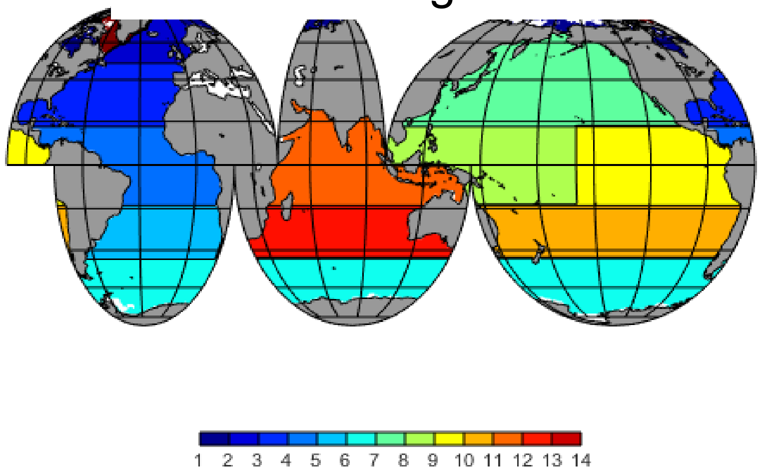
- Gap-fill by three methods.
- Apply to oceans divided up in each of three ways, so 9 estimates in total.

Gap filling methods

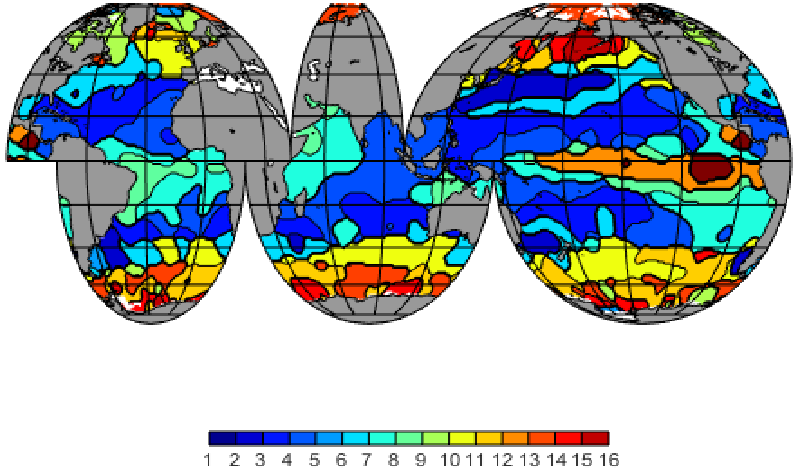
- Method 1: Fit seasonal cycle and linear time trend of fCO_2 to all monthly mean of data, apply fitted values over whole region.
- Method 2: Multiple linear regressions of fCO_2 on SST, SSS, Mixed layer depth, XCO_{2atm}.
- Method 3: Landschützer feed-forward neural net.

Divide the Ocean up in three different ways

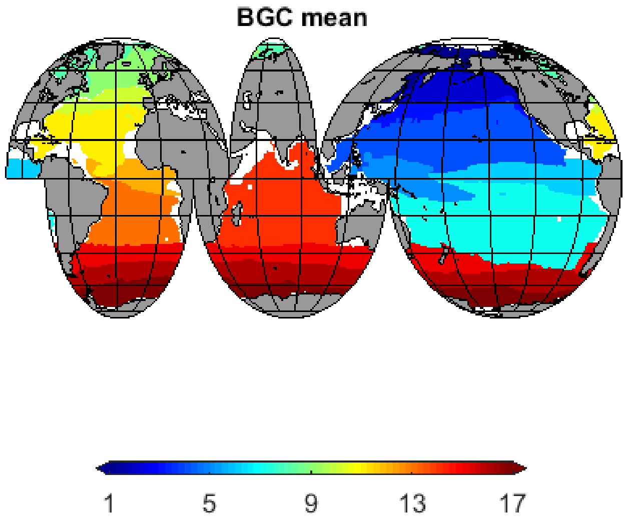
“Transcom” regions



SOM-”Takahashi” biomes (December)

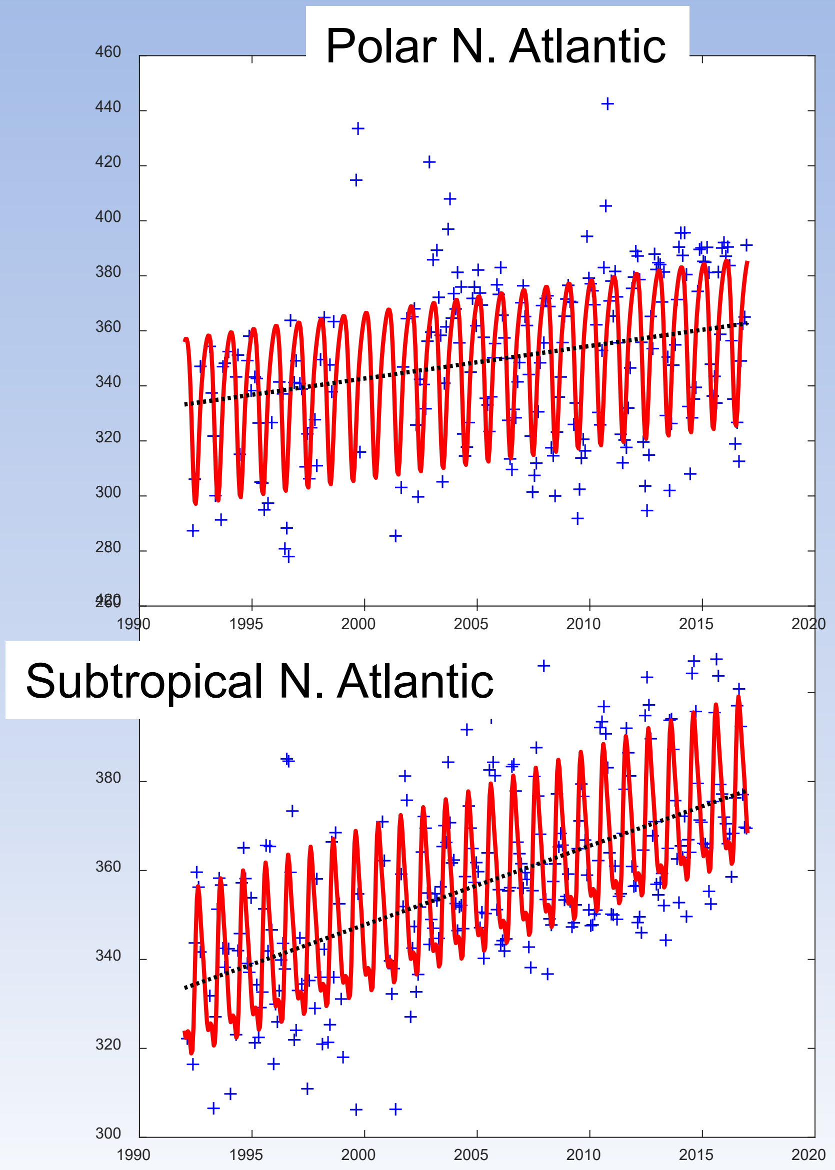


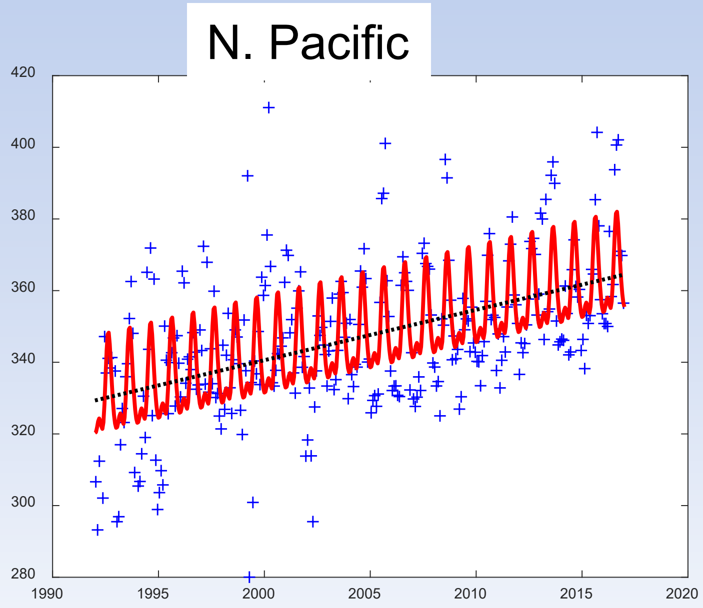
Fay and Mckinley (2012) biomes

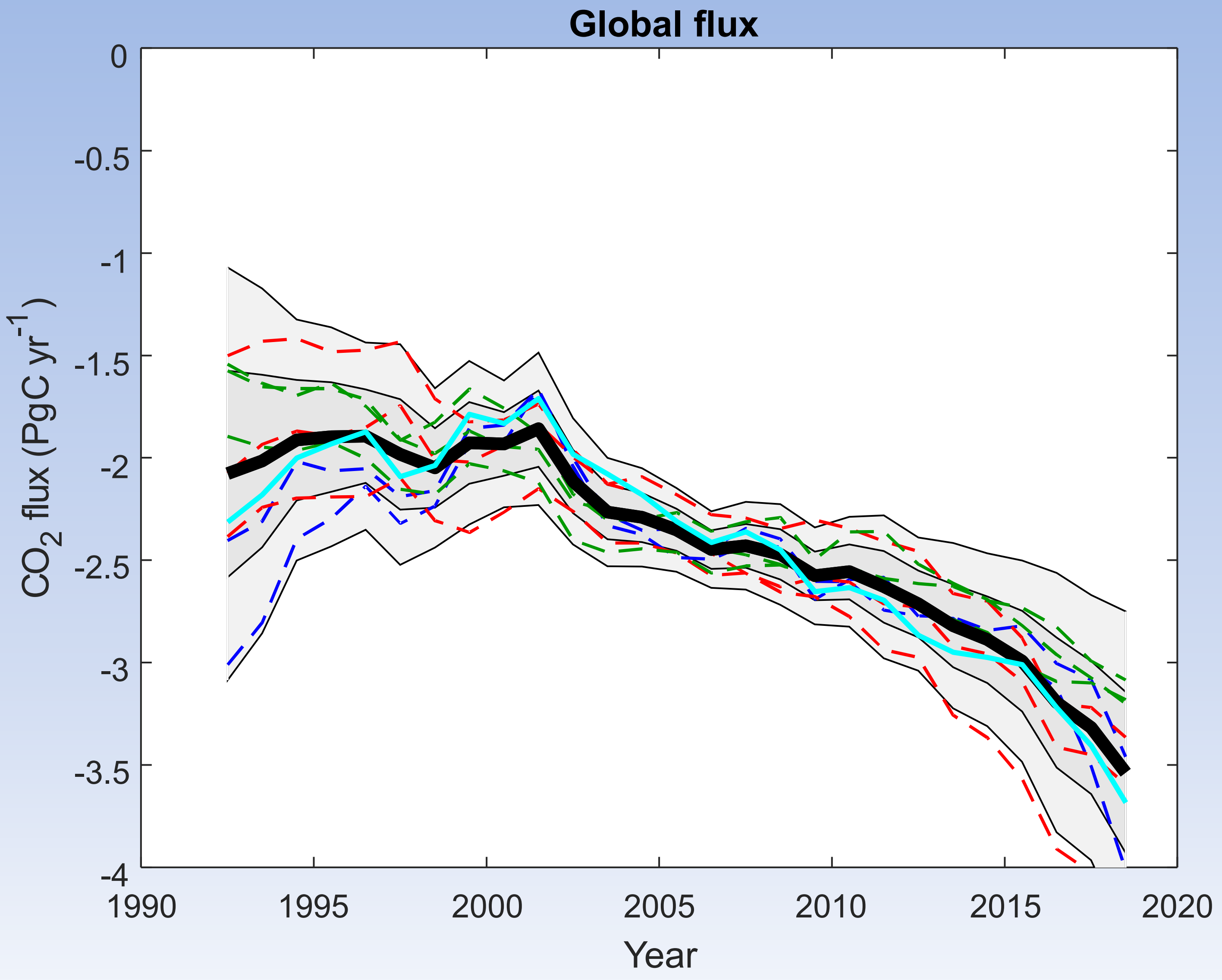


Method 1:

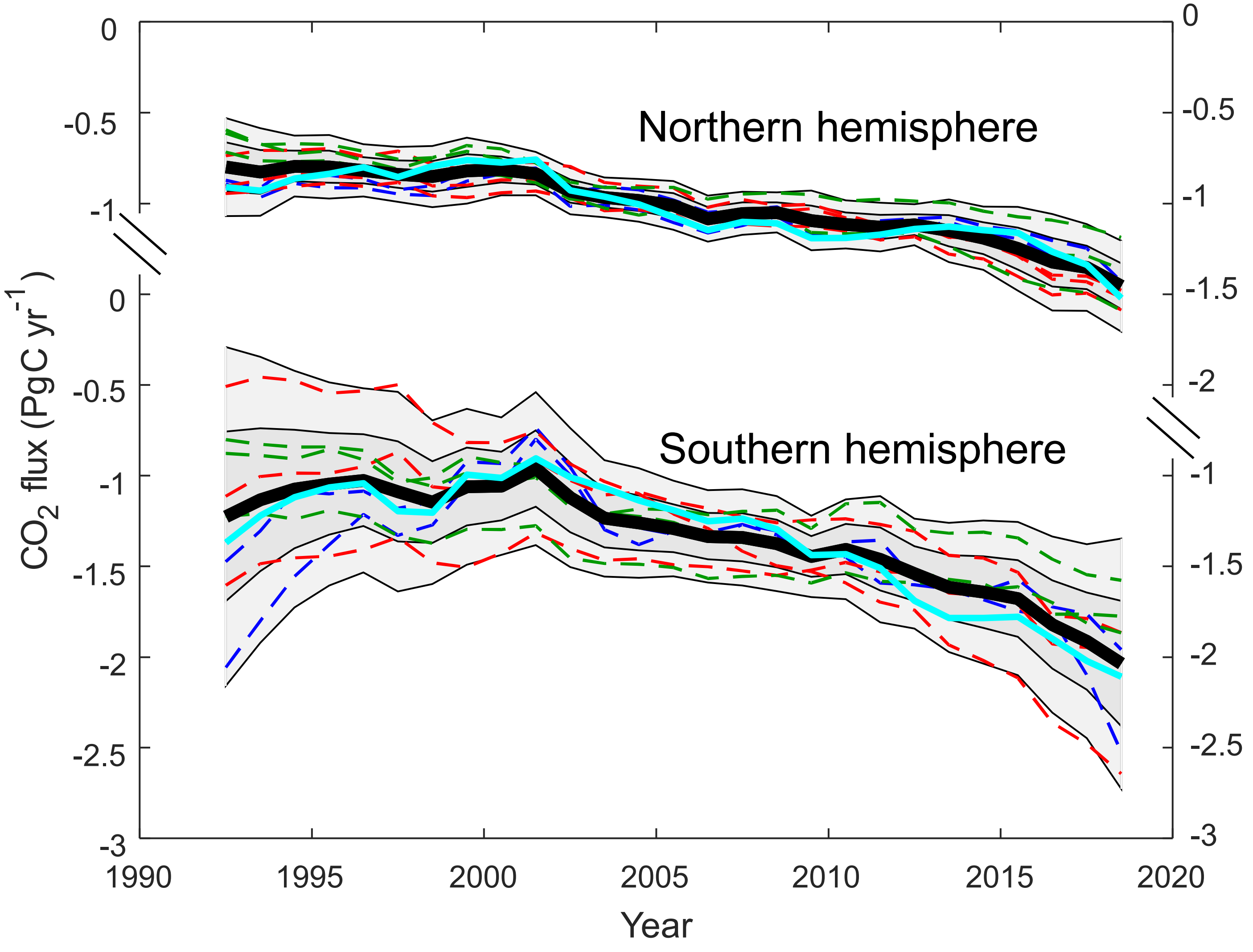
- deliberately simplistic!
- generally poor fits!





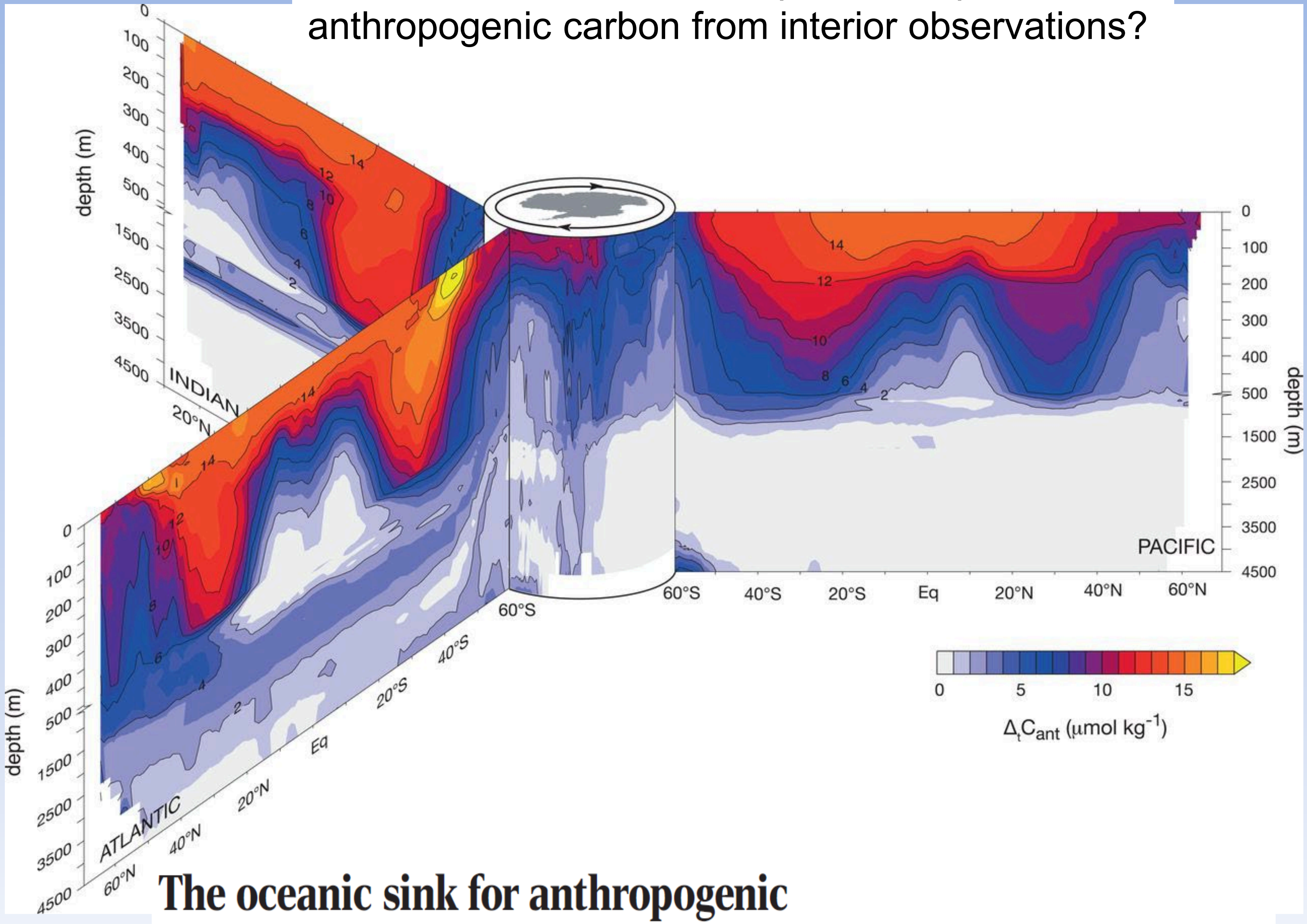


Global flux
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
CO2 flux (PgC yr-1)
1990
1995
2000
2005
2010
2015
2020
Year



Northern hemisphere
Southern hemisphere
CO2 flux (PgC yr-1)
Year
0
-0.5
-1
0
-0.5
-1
-1.5
-2
-2.5
-3
0
-0.5
-1
-1.5
-2
-1
-1.5
-2
-2.5
-3
1990
1995
2000
2005
2010
2015
2020

How does our estimate of uptake compare with anthropogenic carbon from interior observations?



The oceanic sink for anthropogenic CO_2 from 1994 to 2007

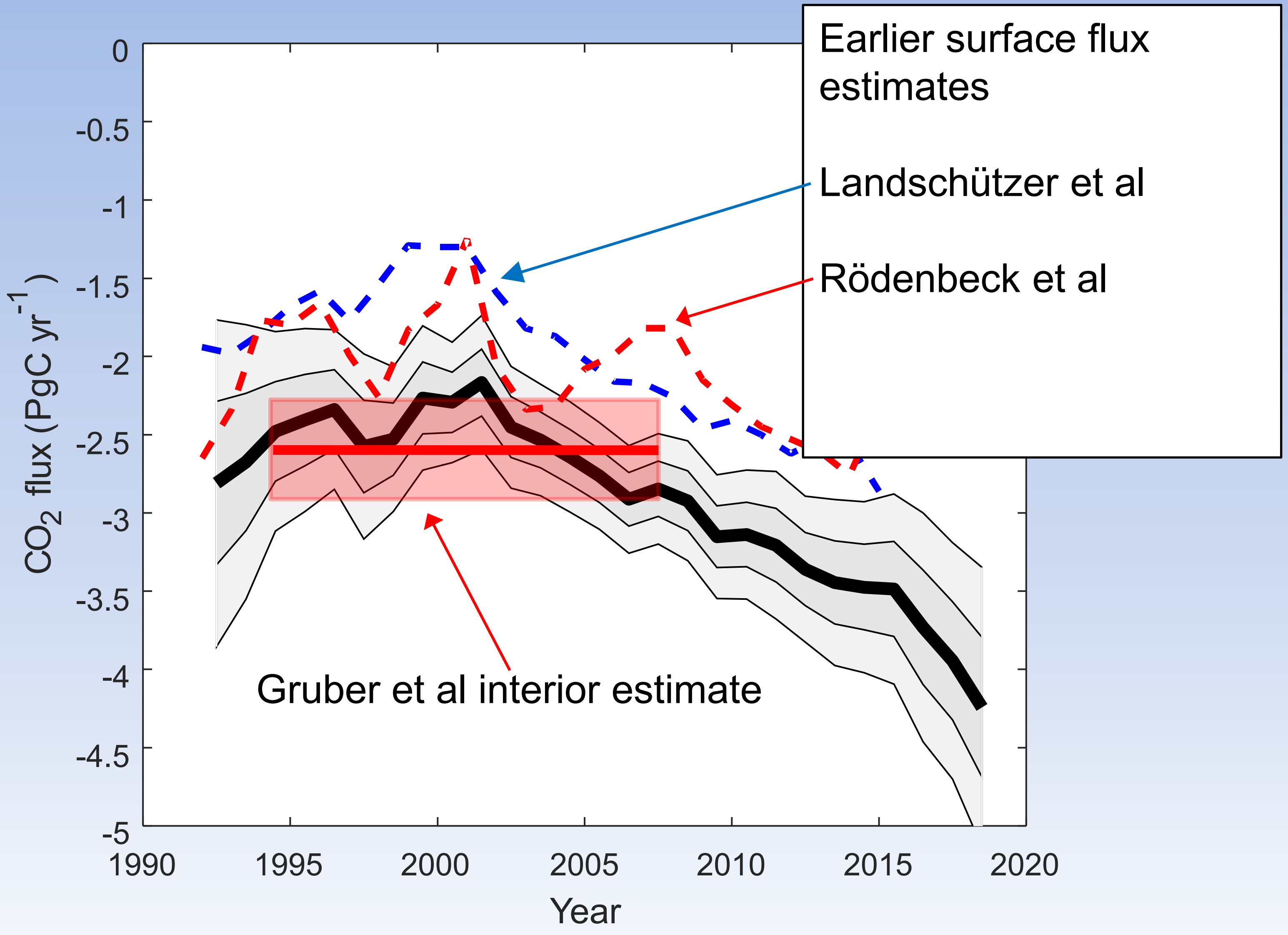
Gruber et al, Science, 2019)

Estimates of ocean uptake compared to interior inventory of anthropogenic carbon

Cumulative CO_2 uptake through surface (–ve is into ocean) July 1994- June 2007 (PgC, ± 2σ)					
	Atlantic	Pacific	Indian	Other basins	global
north	--5.68±0.97	-6.60±0.90	+1.16±0.43	-1.56±0.8	-12.7±1.6
south	-3.22±0.91	-3.43±4.6	-7.41±0.96	-	-14.1±4.6
basin	-8.91±1.50	-10.04±4.3	-6.25±1.20	-	-26.8±3.4
Gruber et al[15] estimates of inventory increase 1994-2007 (PgC)					
north	6.0±0.4	5.2±0.6	0.8±0.4	1.5±0.6	13.5±1.0
south	5.9±1.2	8.0±1.2	6.3±3.4	-	20.1±3.8
basin	11.9±1.3	13.2±1.3	7.1±3.4	-	33.7±4.0

- The difference is the pre-industrial “riverine” flux (plus estimate for the Arctic)
- 33.7-26.8 = 6.9 PgC in 13 years → 0.53 PgC yr^{-1}
- Consistent with previous estimates of 0.45 (riverine) and 0.12 (arctic) →0.57 PgC yr^{-1}
- Not consistent with the additional “natural non-steady-state” flux hypothesised by Gruber et al.

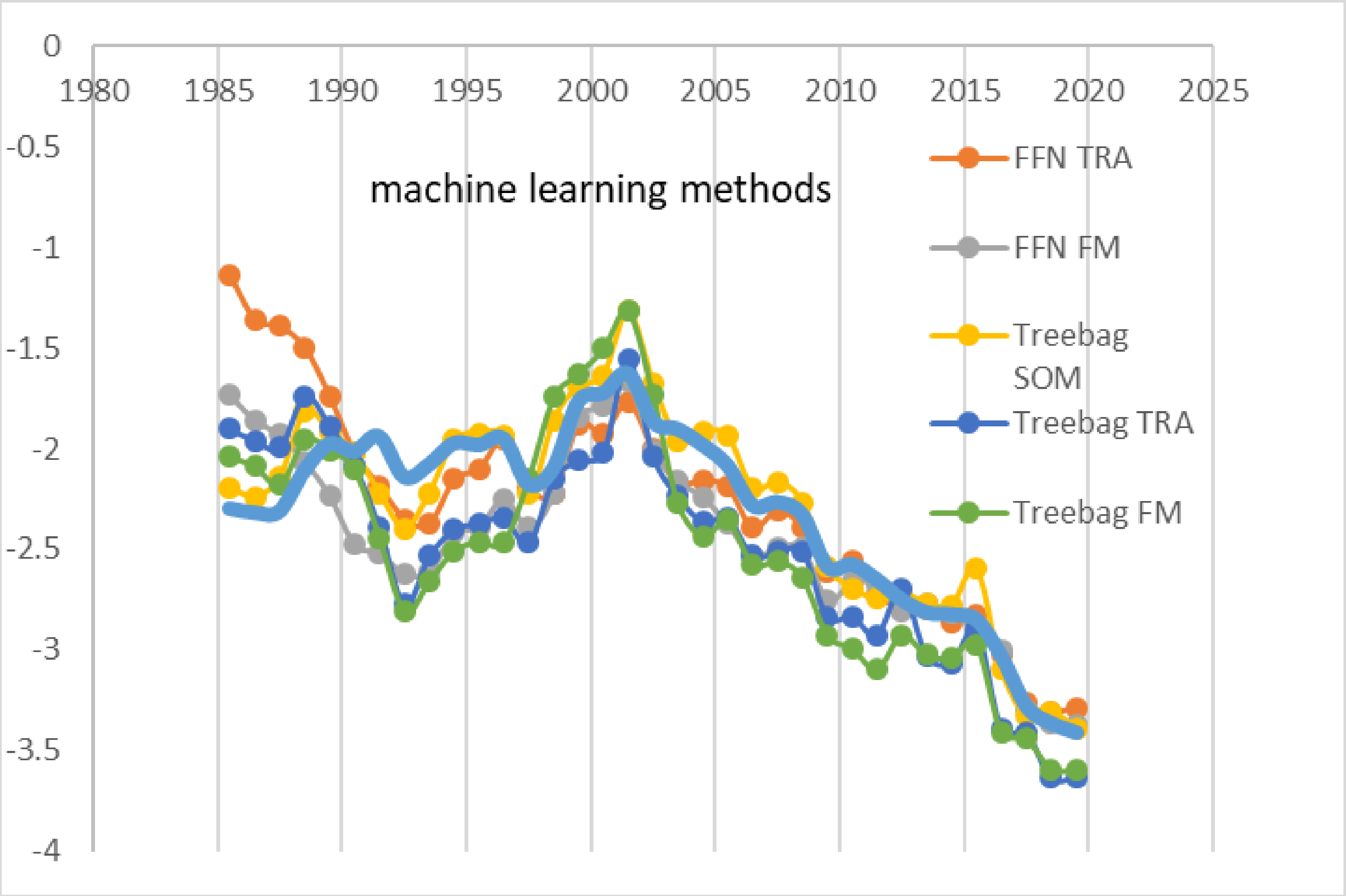
Global anthropogenic CO_2 ocean-atmosphere flux



Global flux +0.57 compared to Gruber et al estimate.

Conclusions

- Correcting "surface" fCO_2 observations to true interface temperatures increases the calculated fluxes, by an amount, still uncertain, but very probably in excess of 0.5 Pg C yr^{-1}
- Globally and at basin level, fluxes can be specified with 90% confidence intervals of around ±0.3 Pg C yr^{-1} after 2000, (and before that in N. Hemisphere).
- Southern ocean and South Pacific contribute much of the uncertainty.
- Corrections make surface fluxes approximately consistent with observed increase in anthropogenic CO_2 calculated from ocean interior observations.



machine learning methods
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
FFN TRA
FFN FM
Treebag SOM
Treebag TRA
Treebag FM