possible links between the ocean carbon sink and fire

1. The ocean carbon sink: status and questions (based on GCP analyses)
2. Possible links between fire aerosols and ocean carbon (with input from SCOR WGs 151 and 167)

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GLOBAL CARBON PROJECT
SCOR
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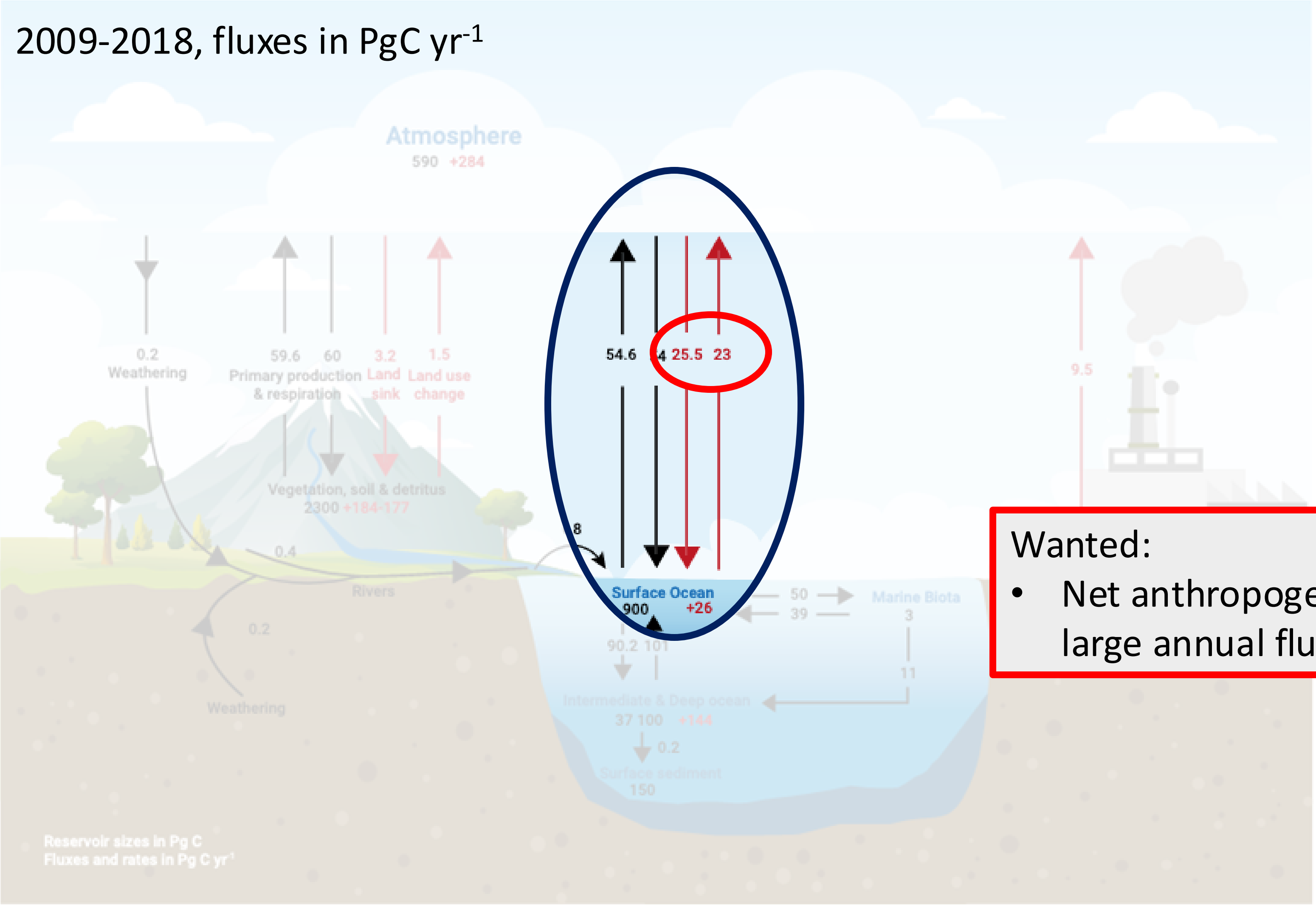
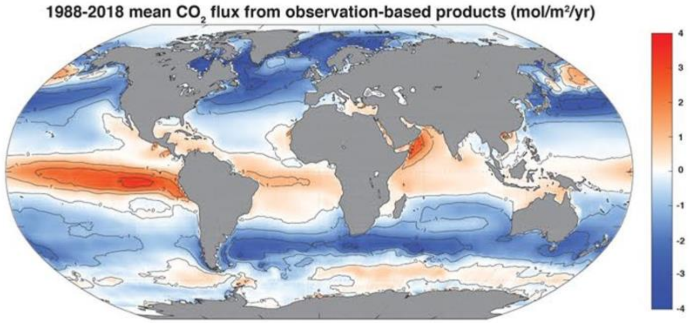
1) Net anthropogenic CO2 uptake





out of ocean

into ocean

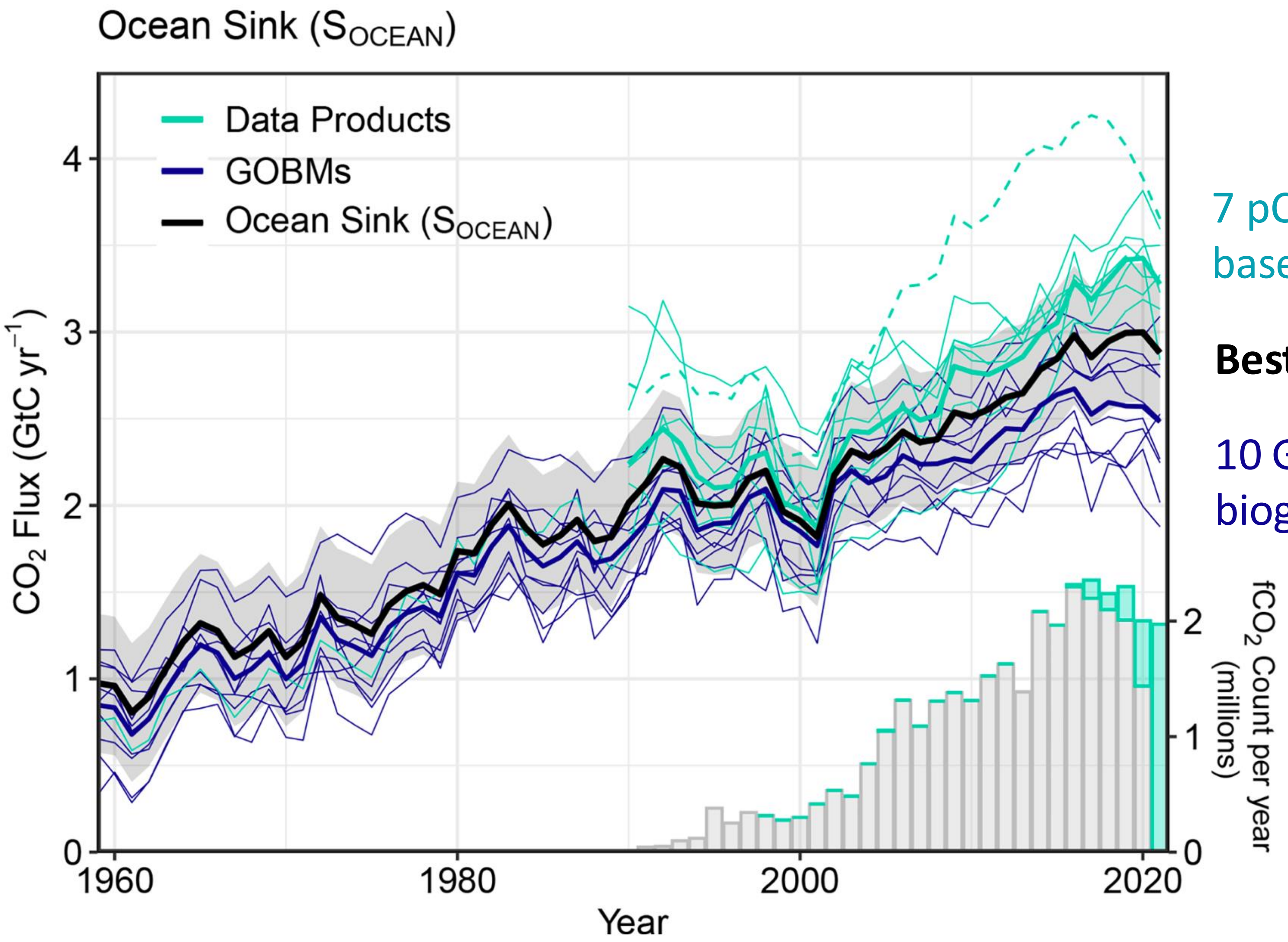
Wanted:

- Net anthropogenic CO_2 uptake, a small residual of large annual fluxes

Integrated ocean carbon research: a summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade, IOC, Technical Series 158, 2021; Numbers: 2009-2018, Friedlingstein et al., 2019; map: Crisp et al., 2022

The Global Carbon Budget ocean sink estimate

How much CO_2 goes into the ocean each year



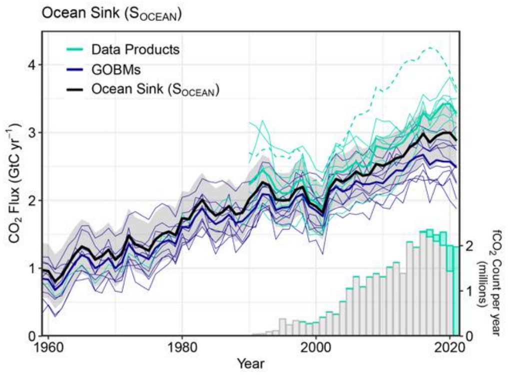
7 pCO_2-observation based data-products

Best estimate

10 Global ocean biogeochemistry models

Global Carbon Budget 2022, Friedlingstein et al., 2022

Methods to estimate the ocean carbon sink



Global ocean biogeochemistry models

Global ocean circulation model with representation of biogeochemistry, forced with observed atm CO_2 and atm reanalysis fields

+ constrained by ocean circulation (transport of C into interior ocean = bottle-neck of ocean C uptake)

pCO_2-observation based data products

Statistical mapping of SOCAT CO_2 observations, 98% gap-filling

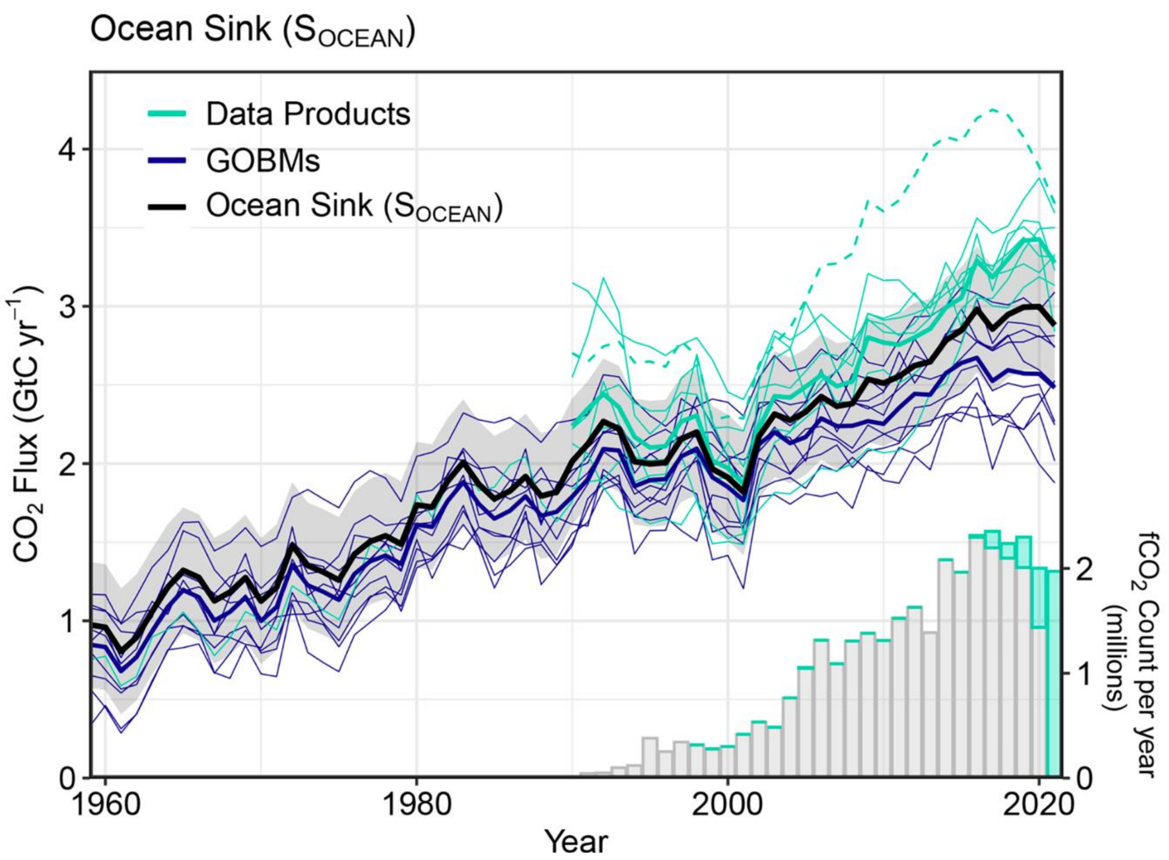
+ closely linked to observations, which carry imprints of variability

- sensitive to uncertainties in gas-exchange parameterization

- no constraint by ocean interior / ocean dynamics

Friedlingstein et al., 2022; Hauck et al., 2020

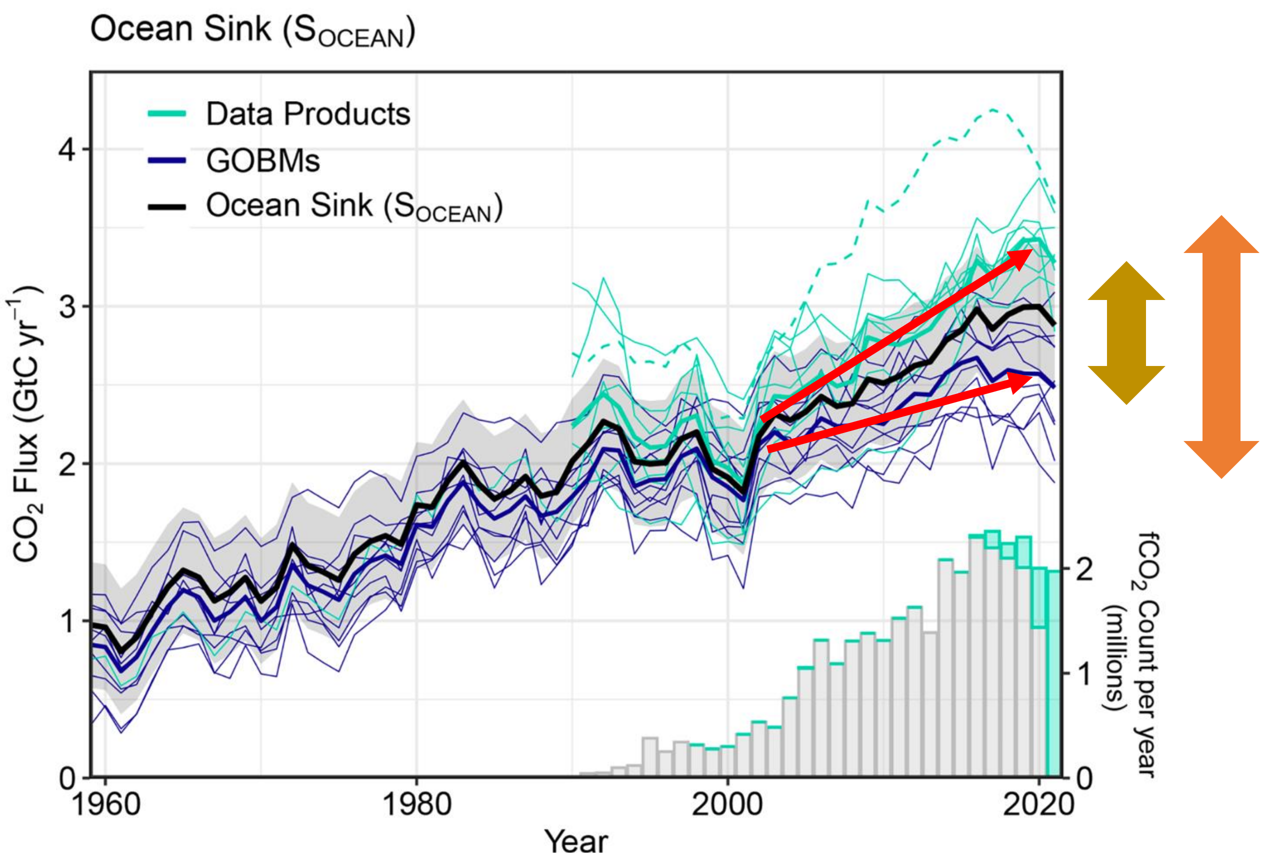
The GCB ocean carbon sink: key results



- In the last decade, 2012-2021, the ocean took up 2.9±0.4 PgC yr^{-1} (26% of all CO_2 emissions).
- The increase in the ocean sink is **driven by atm CO_2 increase**
- The effect of **climate change is much weaker**; without climate change, the ocean sink would have been 5% higher.

Global Carbon Budget 2022, Friedlingstein et al., 2022

Uncertainty and gaps in understanding?

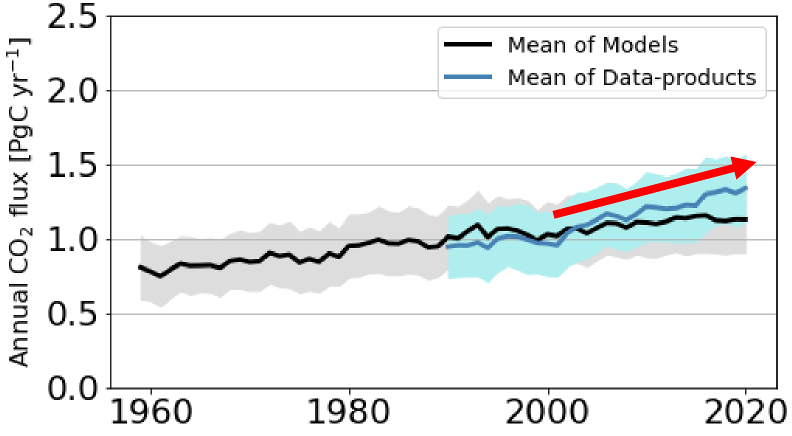


- The **difference between model mean and pCO_2-product mean** (0.8 PgC yr^{-1}) as large as current EU fossil CO_2 emissions
- The **range of all estimates** in 2021 (1.7 PgC yr^{-1}) is twice EU fossil CO_2 emissions
- The **growth rate of the ocean sink** since 2002 differs by a factor of three
- The **discrepancy** between models and pCO_2-products **increases over time**

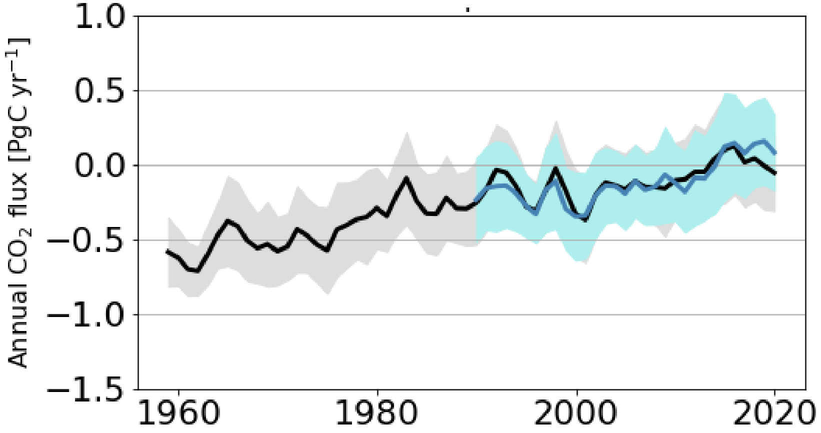
Global Carbon Budget 2022, Friedlingstein et al., 2022

Discrepancy in trends comes from high-latitudes

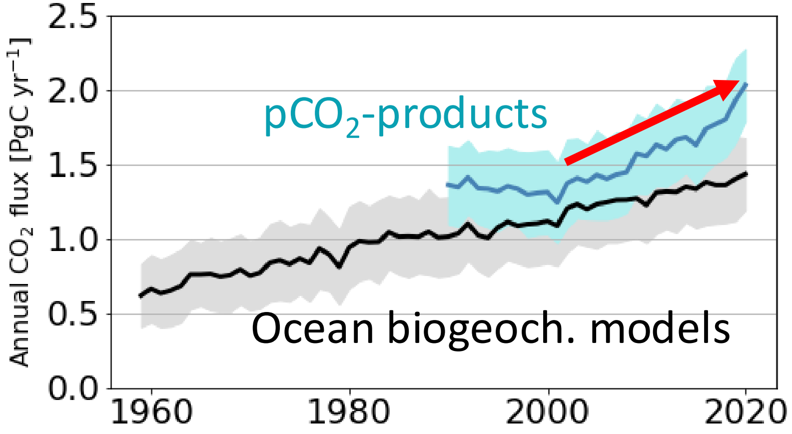
North
north of 30°N



Tropics
30°N - 30°S



South
south of 30°S



Global Carbon Budget 2021, Friedlingstein et al., 2022

Model biases in mean CO_2 flux

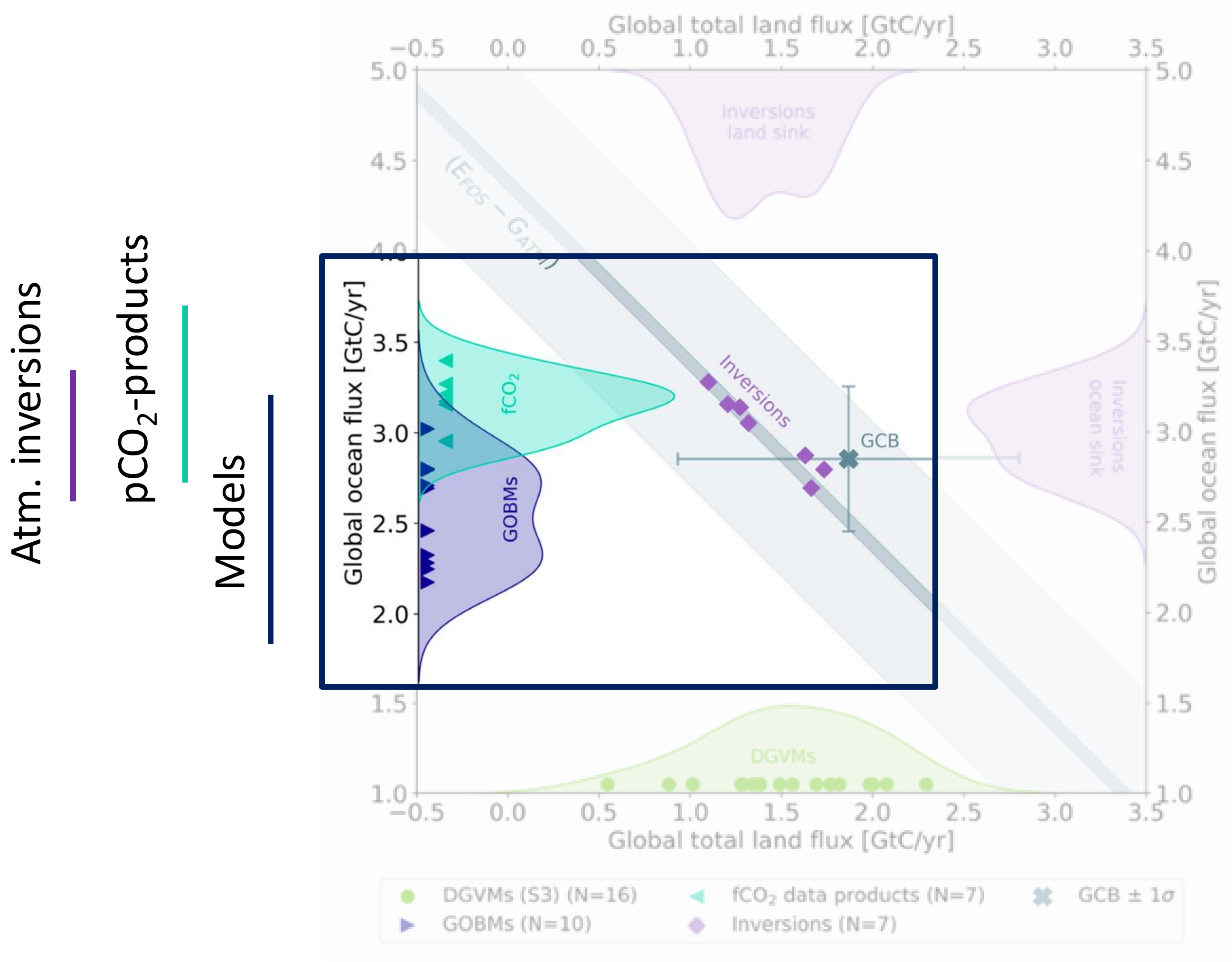


Figure credit: Ingrid Luijkx, Friedlingstein et al., GCB 2022

Majority of models underestimate the ocean CO_2 sink, based on:

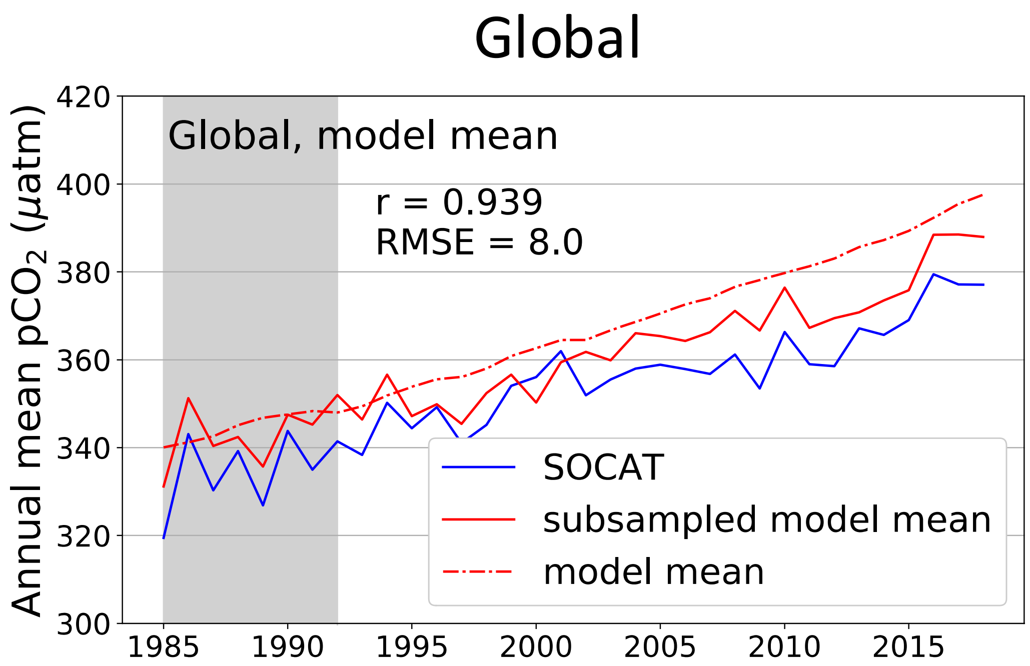
1) Atmospheric inversions
2) observation-based ocean interior anthropogenic carbon accumulation
3) O_2/N_2-based estimate

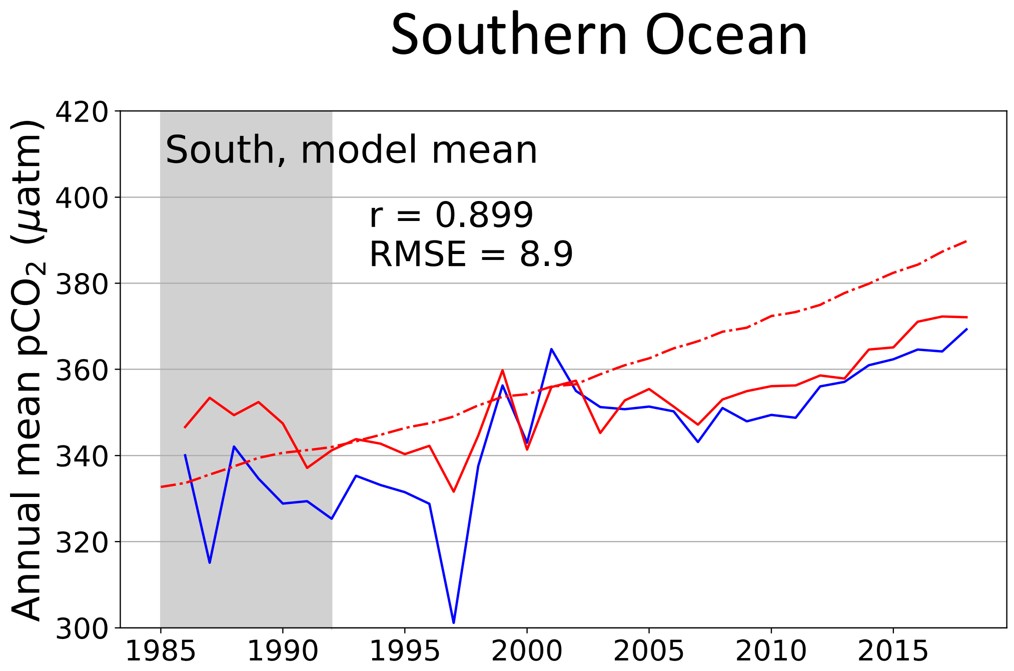
Biases likely related to:

- ocean overturning **circulation** (N Atlantic, Southern Ocean)
- surface ocean **buffering capacity**

Based on: Friedlingstein et al., 2022, Gruber et al., 2019, Tohjima et al., 2019; Terhaar et al., 2022; Terhaar, Goris et al RECCAP model evaluation chapter

Model biases in trends?





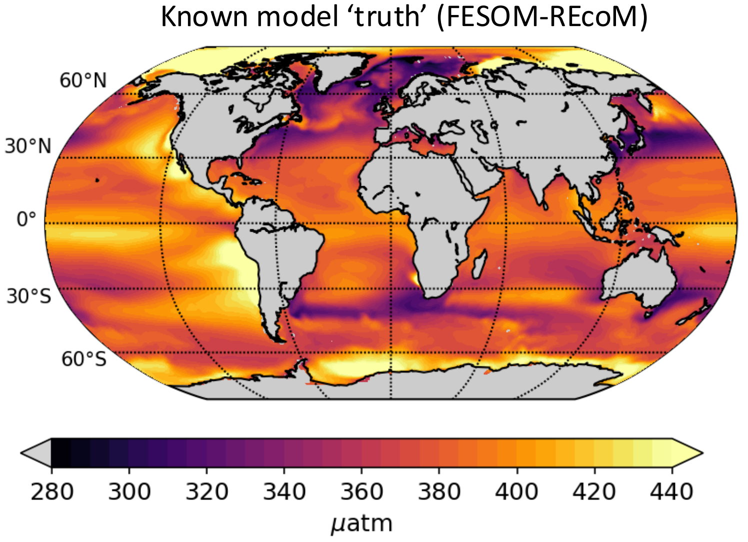
Models compare reasonably well to SOCAT surface ocean CO_2 data and its **temporal evolution** when subsampled for data locations.

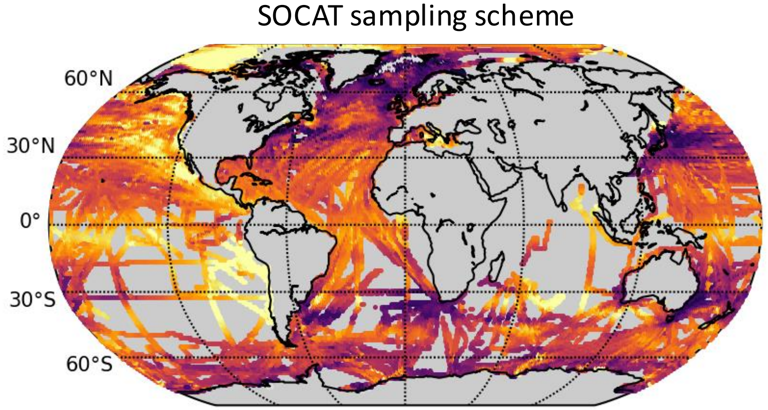
No indication (so far) for an underestimation of the trend.

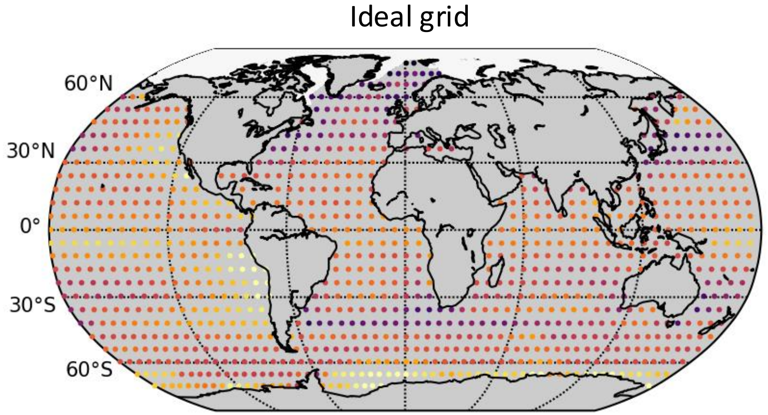
Hauck et al., 2020

pCO_2-product biases in trends?

Model subsampling exercise



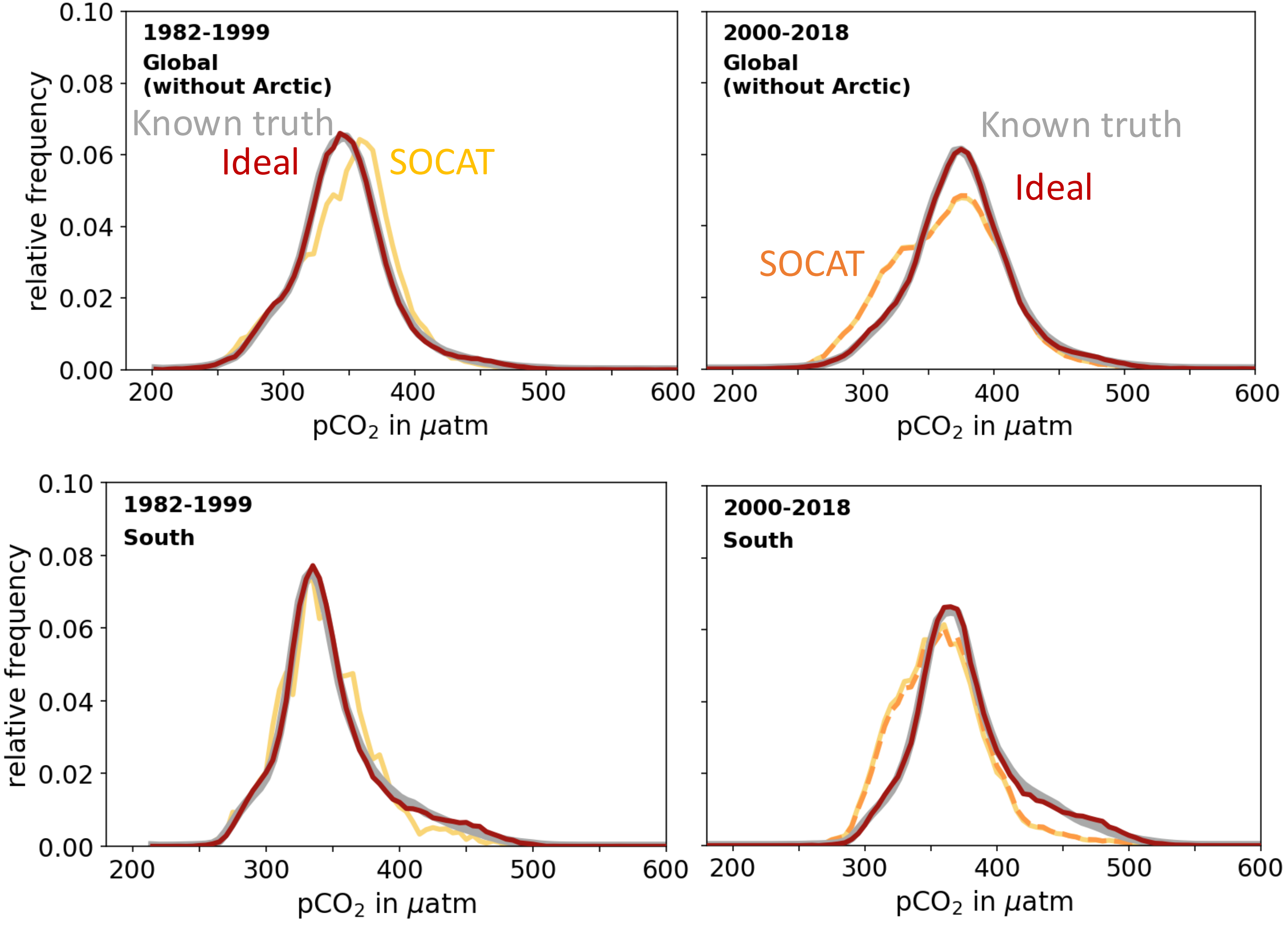




1000 evenly distributed sampling sites

Hauck et al., 2023 Phil. Trans. B

Effect of data sparsity on pCO_2-based estimates



SOCAT pCO_2 distribution **skewed towards low values** after year 2000

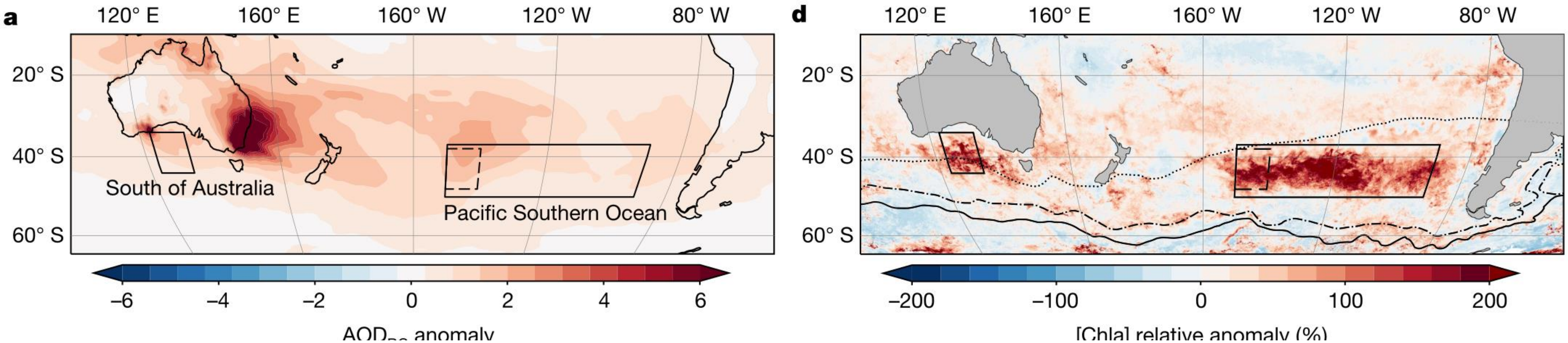
Ideal sampling scheme reproduces pCO_2 distribution

Skewed distribution has its origin in the Southern Ocean

Hauck et al., 2023 Phil. Trans. B

2) Fire induced variations in natural CO_2 fluxes

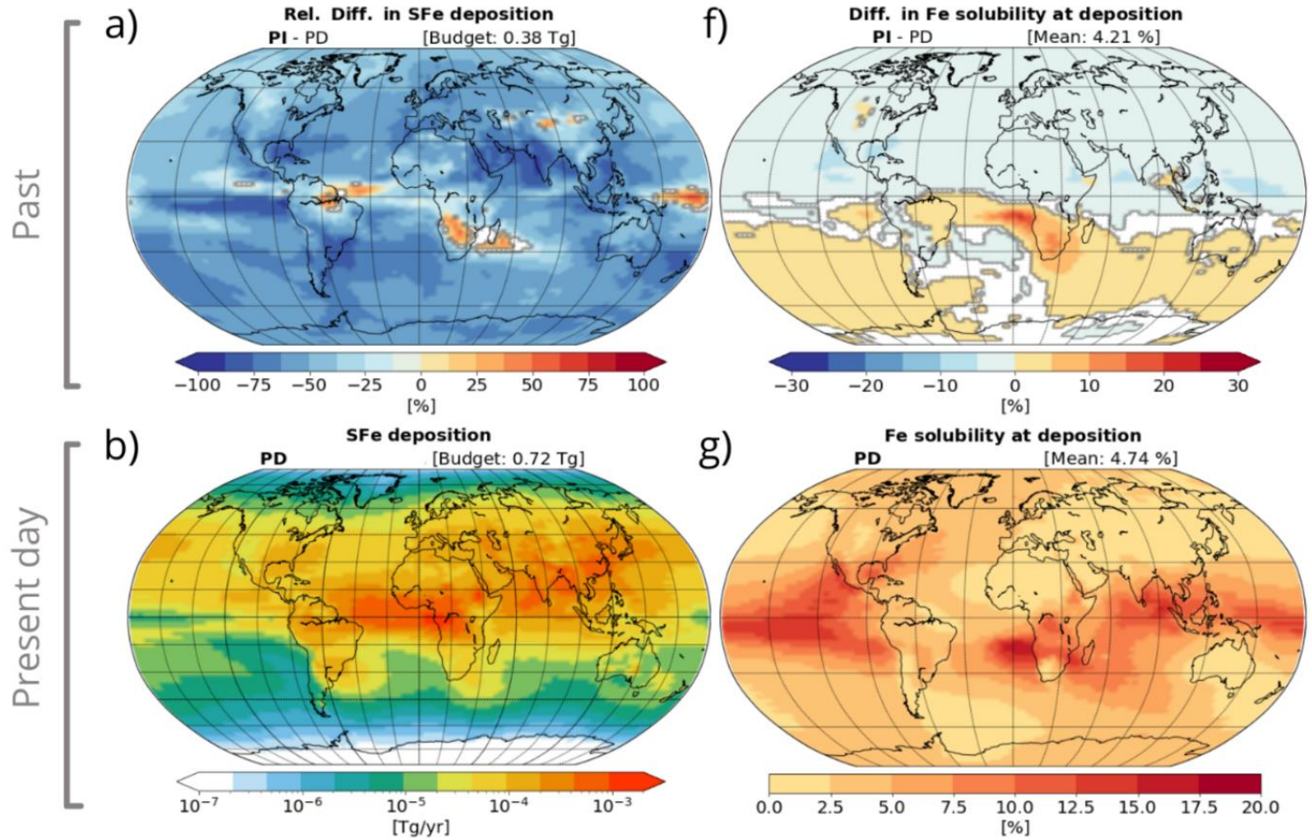
Wanted:
- Effects of climate change and variability on natural and anthropogenic CO_2 fluxes



Several cases now where an ocean reaction to a large fire event could be shown; either related to Fe (Tang et al, 2021, South Pacific) or to N (Ardyna et al, 2022, Arctic Ocean) deposition

Tang et al., 2021

the atmospheric role: more than transport!



Most deposited iron is not soluble (and thus available for growth)

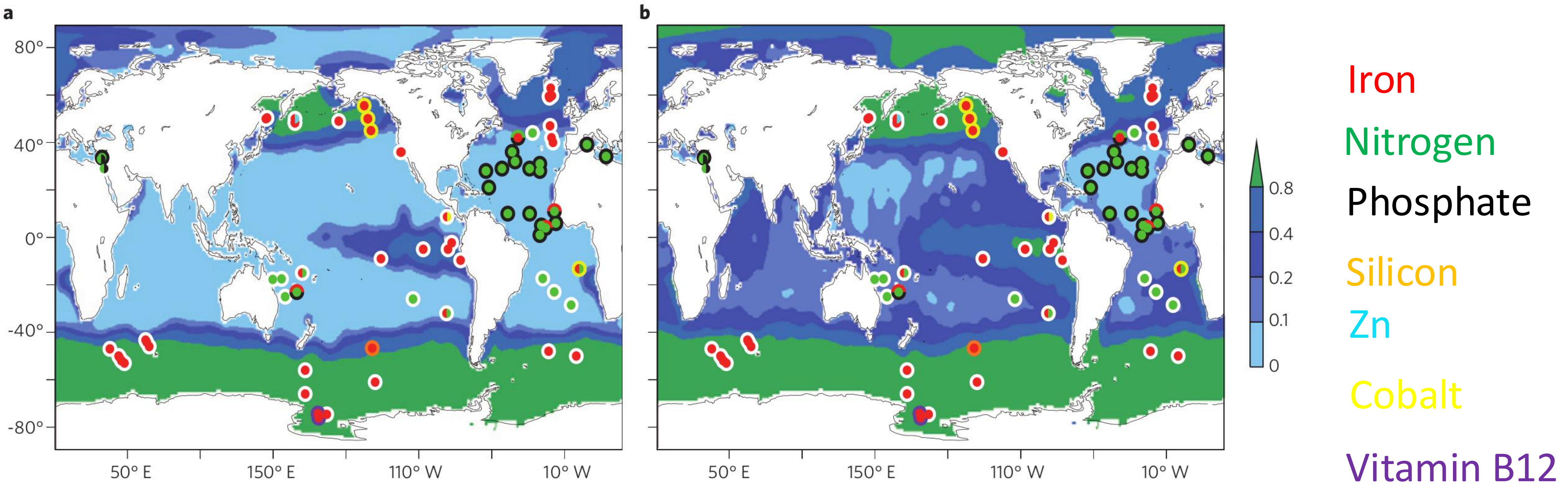
Solubility depends or aerosol source (industrial > fire > lithogenic) but also on chemistry:

lower acidity (industrial pollution) and high organics (fire) lead to increasing solubility in transport

So feedbacks do not only depend on emissions!

Bergas-Massó et al., Earth’s Future, 2023

Conditions on the receiving side

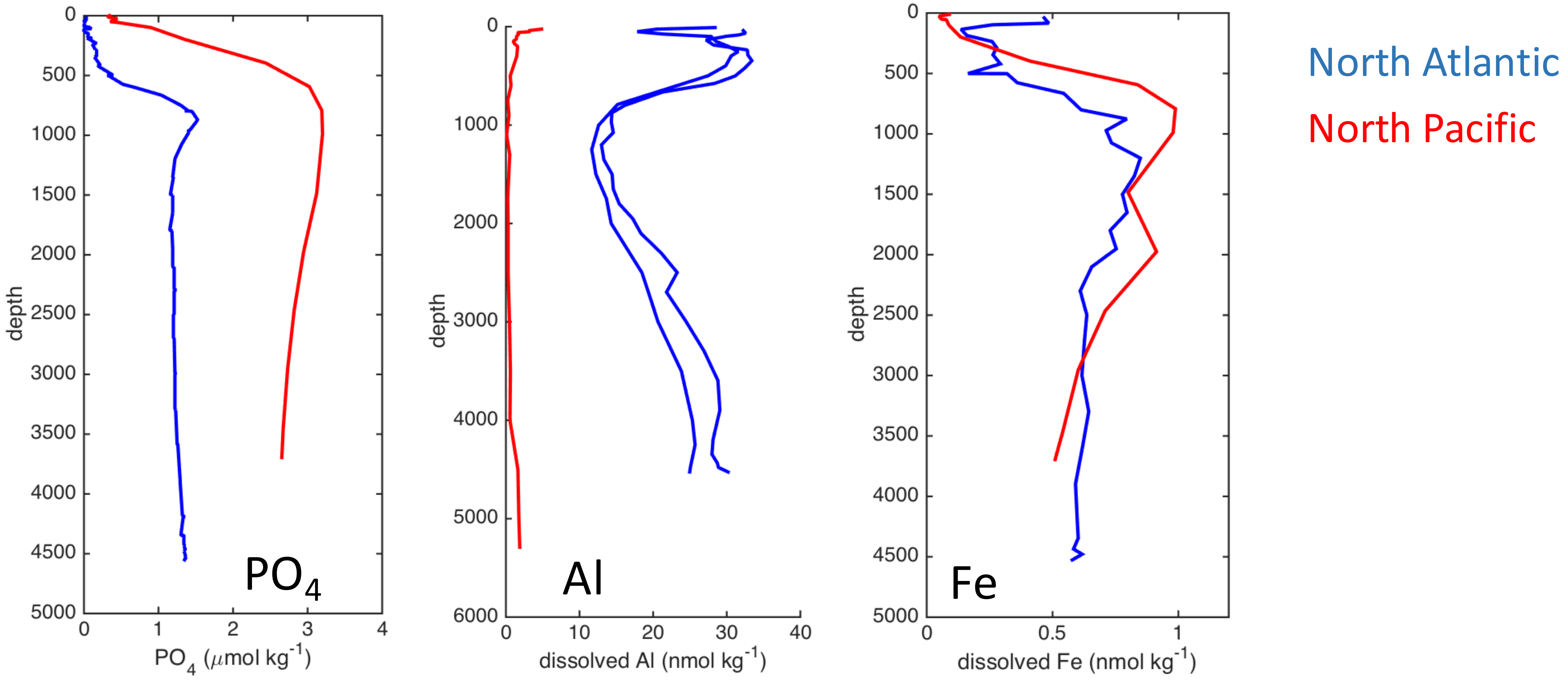


On the ocean side, different element are limiting to growth in different ocean regions

so the effect of deposited aerosols depends on where they arrive

Moore et al, Nat. Geoscience 2013

Recycled vs. scavenged elements

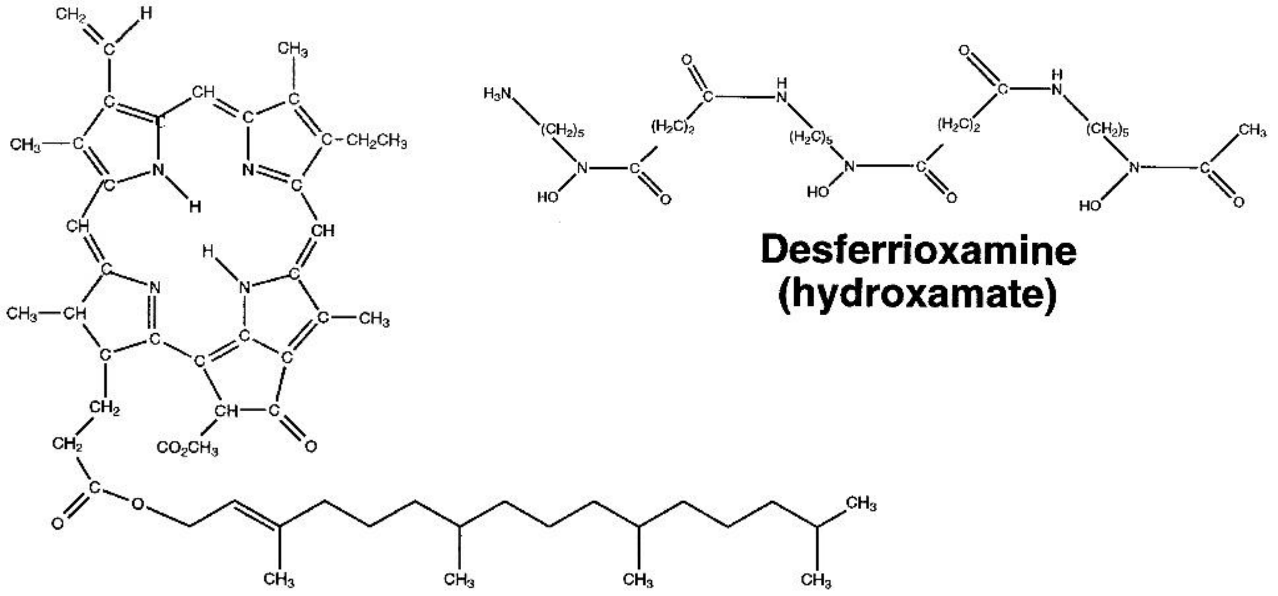


P: long residence time, accumulation with depth and along overturning

Al: Particle reactive, decrease with depth, influenced by local dust

Fe: Particle reactive, but biologically cycled; why no inter-basin gradient?

Fe is complex(ed)



Phaeophytin (porphyrin)

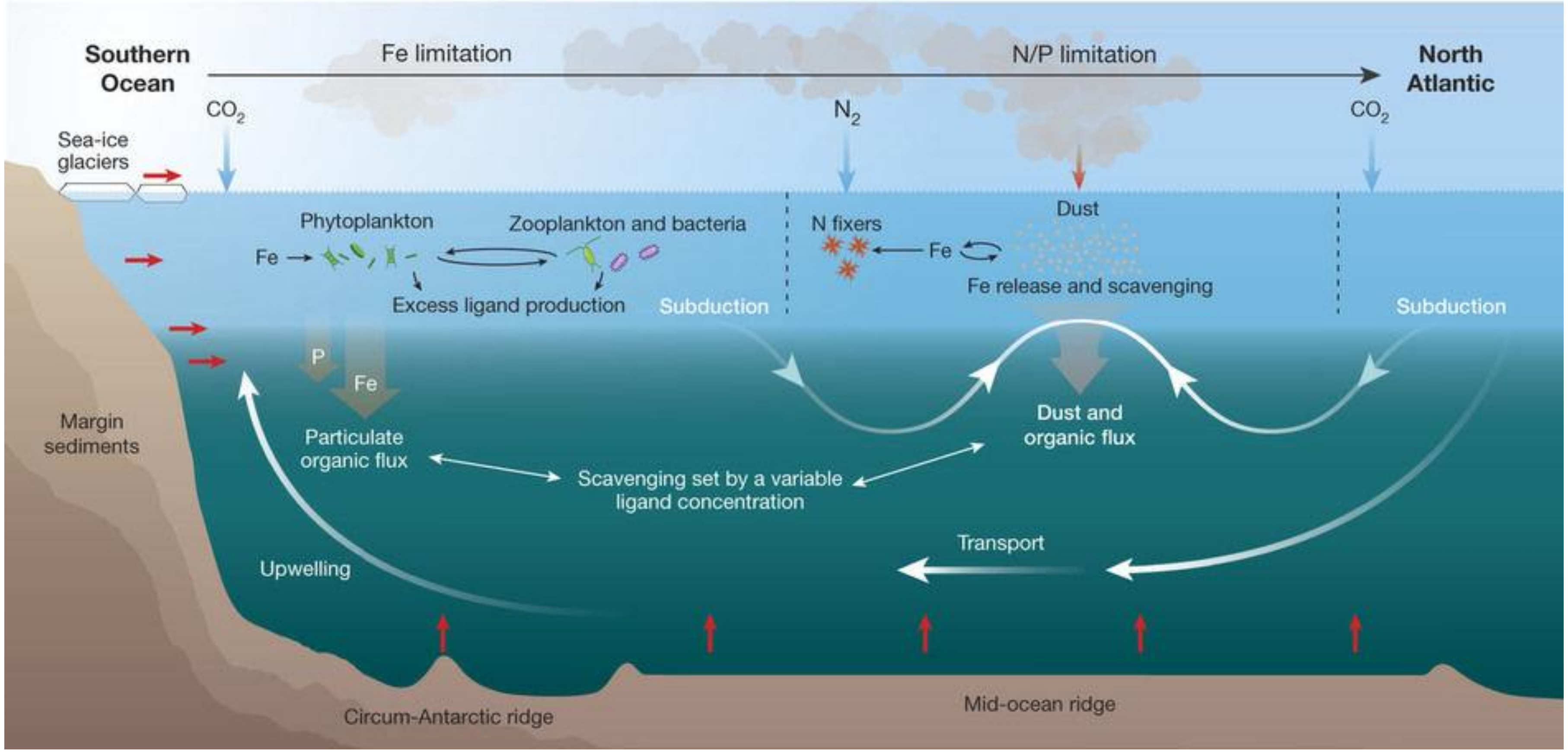
Desferrioxamine (hydroxamate)

The unusual behaviour of Fe is to a large degree by binding to organic ligands; these ligands include smaller molecules, but also to some extent the large pool of not-so-well characterized dissolved organic matter'

Binding is influenced e.g. by pH (feedbacks!)

Witter et al, Mar Chem 2000

Fe is complicated

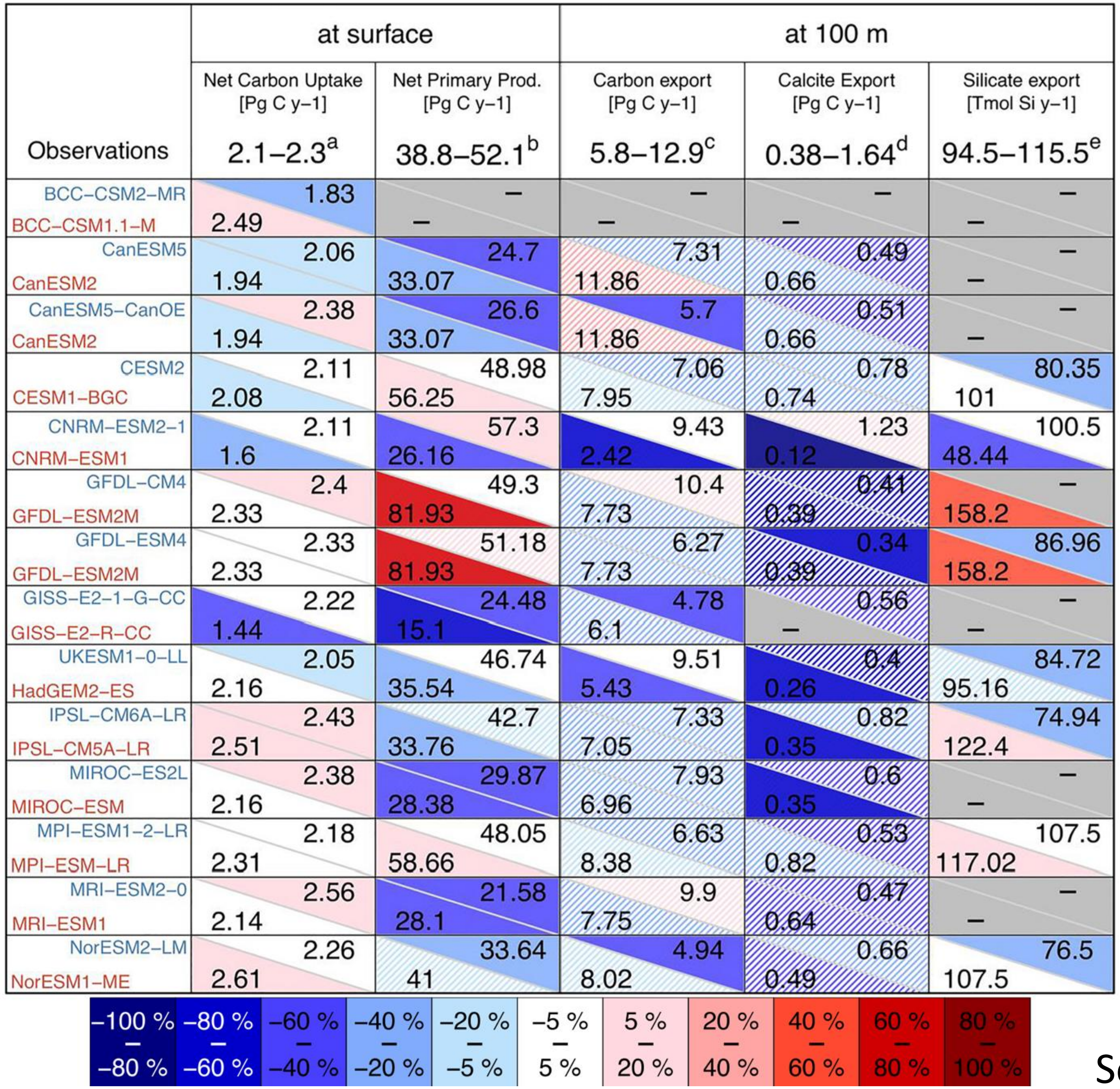


Many (not all) of these aspects are now present in ocean biogeochemical models

Iron is scavenged, but stabilized by ligands. It has many sources: Aerosols, sediments, hydrothermal, rivers. There is active photochemistry occurring. It influences the composition between N-fixers and other phytoplankton, …

Tagliabue et al., 2017

NPP and carbon export in CMIP5/6



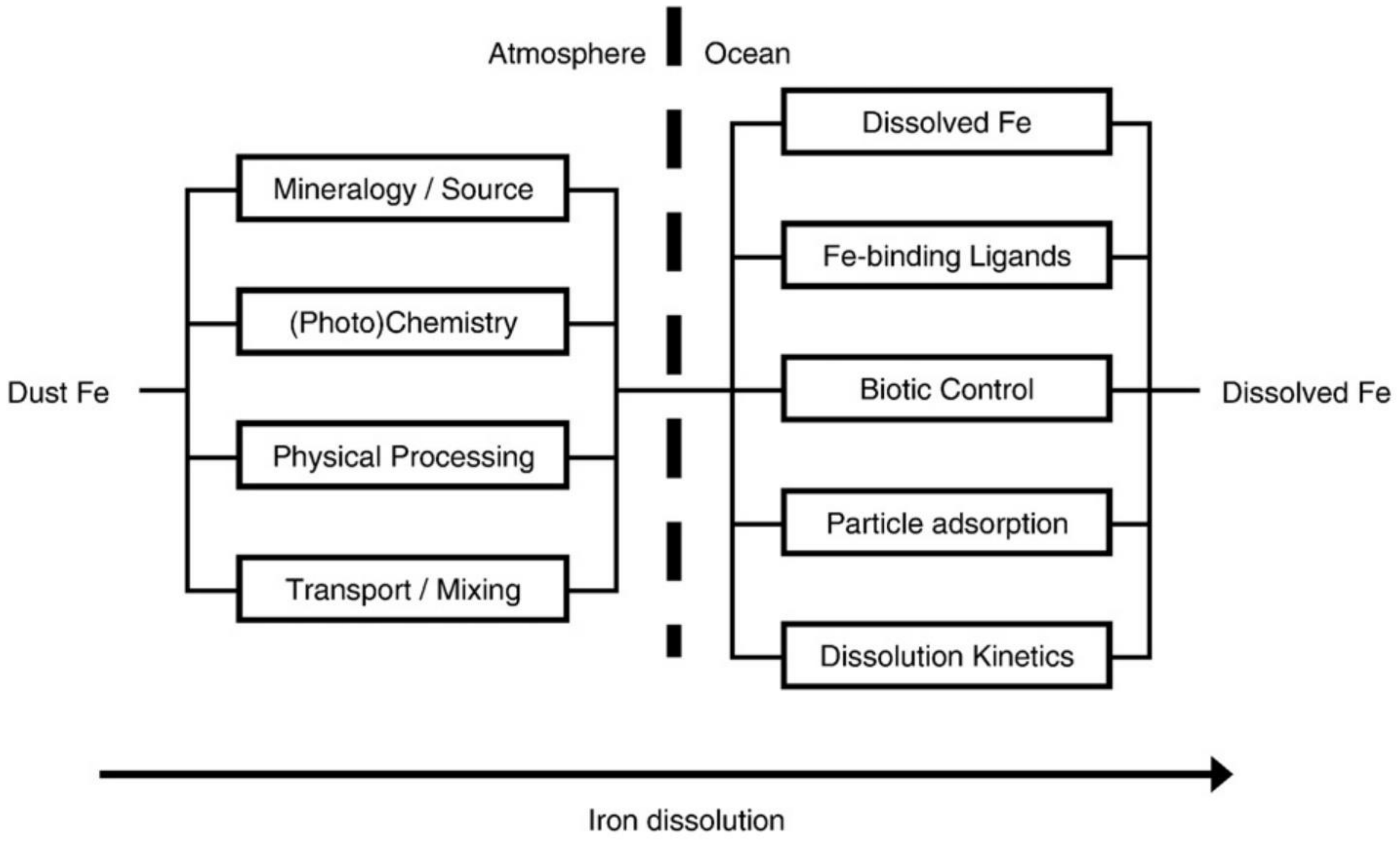
	at surface		at 100 m		
	Net Carbon Uptake [Pg C y−1]	Net Primary Prod. [Pg C y−1]	Carbon export [Pg C y−1]	Calcite Export [Pg C y−1]	Silicate export [Tmol Si y−1]
Observations	2.1–2.3[a]	38.8–52.1[b]	5.8–12.9[c]	0.38–1.64[d]	94.5–115.5[e]
BCC–CSM2–MR / BCC–CSM1.1–M	1.83 / 2.49	– / –	– / –	– / –	– / –
CanESM5 / CanESM2	2.06 / 1.94	24.7 / 33.07	7.31 / 11.86	0.49 / 0.66	– / –
CanESM5–CanOE / CanESM2	2.38 / 1.94	26.6 / 33.07	5.7 / 11.86	0.51 / 0.66	– / –
CESM2 / CESM1–BGC	2.11 / 2.08	48.98 / 56.25	7.06 / 7.95	0.78 / 0.74	80.35 / 101
CNRM–ESM2–1 / CNRM–ESM1	2.11 / 1.6	57.3 / 26.16	9.43 / 2.42	1.23 / 0.12	100.5 / 48.44
GFDL–CM4 / GFDL–ESM2M	2.4 / 2.33	49.3 / 81.93	10.4 / 7.73	0.41 / 0.39	– / 158.2
GFDL–ESM4 / GFDL–ESM2M	2.33 / 2.33	51.18 / 81.93	6.27 / 7.73	0.34 / 0.39	86.96 / 158.2
GISS–E2–1–G–CC / GISS–E2–R–CC	2.22 / 1.44	24.48 / 15.1	4.78 / 6.1	0.56 / –	– / –
UKESM1–0–LL / HadGEM2–ES	2.05 / 2.16	46.74 / 35.54	9.51 / 5.43	0.4 / 0.26	84.72 / 95.16
IPSL–CM6A–LR / IPSL–CM5A–LR	2.43 / 2.51	42.7 / 33.76	7.33 / 7.05	0.82 / 0.35	74.94 / 122.4
MIROC–ES2L / MIROC–ESM	2.38 / 2.16	29.87 / 28.38	7.93 / 6.96	0.6 / 0.35	– / –
MPI–ESM1–2–LR / MPI–ESM–LR	2.18 / 2.31	48.05 / 58.66	6.63 / 8.38	0.53 / 0.82	107.5 / 117.02
MRI–ESM2–0 / MRI–ESM1	2.56 / 2.14	21.58 / 28.1	9.9 / 7.75	0.47 / 0.64	– / –
NorESM2–LM / NorESM1–ME	2.26 / 2.61	33.64 / 41	4.94 / 8.02	0.66 / 0.49	76.5 / 107.5

CMIP5/CMIP6 models also still have quite a span in how complicated the represent the iron cycle;

not only due to this, they have quite a range in mean NPP and export production

Séférian et al., 2020

Open end 1: what is solubility / bioavailability?



Baker and Croot, 2010

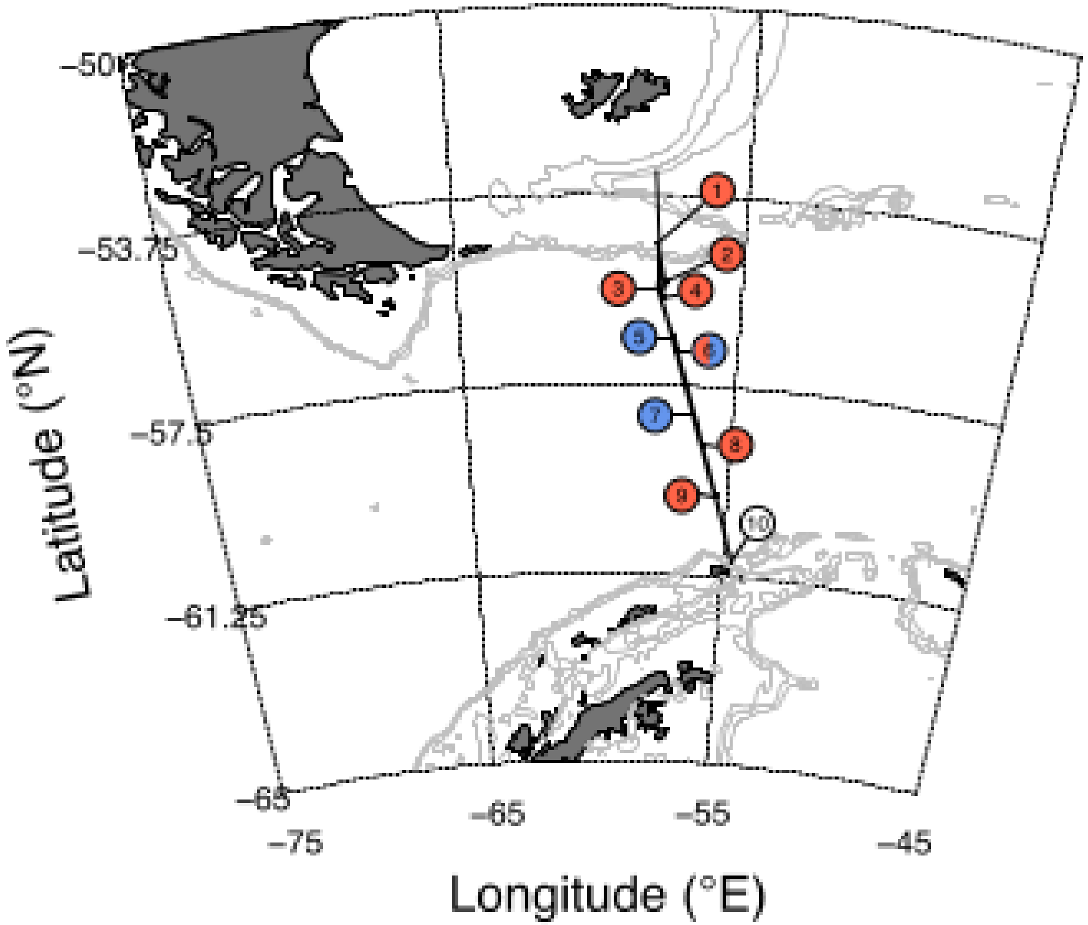
Atmospheric chemistry models can describe the evolution of trace metal solubility over transport

But: how relevant is that, after aerosol particles get deposited on the ocean surface?

Conditions (e.g. pH, ligands) change drastically. Photochemistry happens. Role of this and the sea surface microlayer?

See Meskhidze et al. 2019, Mar Chem.

Open end 2: colimitation, norm rather than exception



Co-limitation by more than one trace metal (here Mn and Fe) has been found in eastern boundary upwelling regions, Southern Ocean, …

Challenge for models to describe several TMs (Fe, Mn, Zn, Co?), hopefully not all as complicated as Fe

Browning et al, 2021

Open end 3: integration within ESMs

Capturing the effects of fire on the marine C cycle in earth system models requires

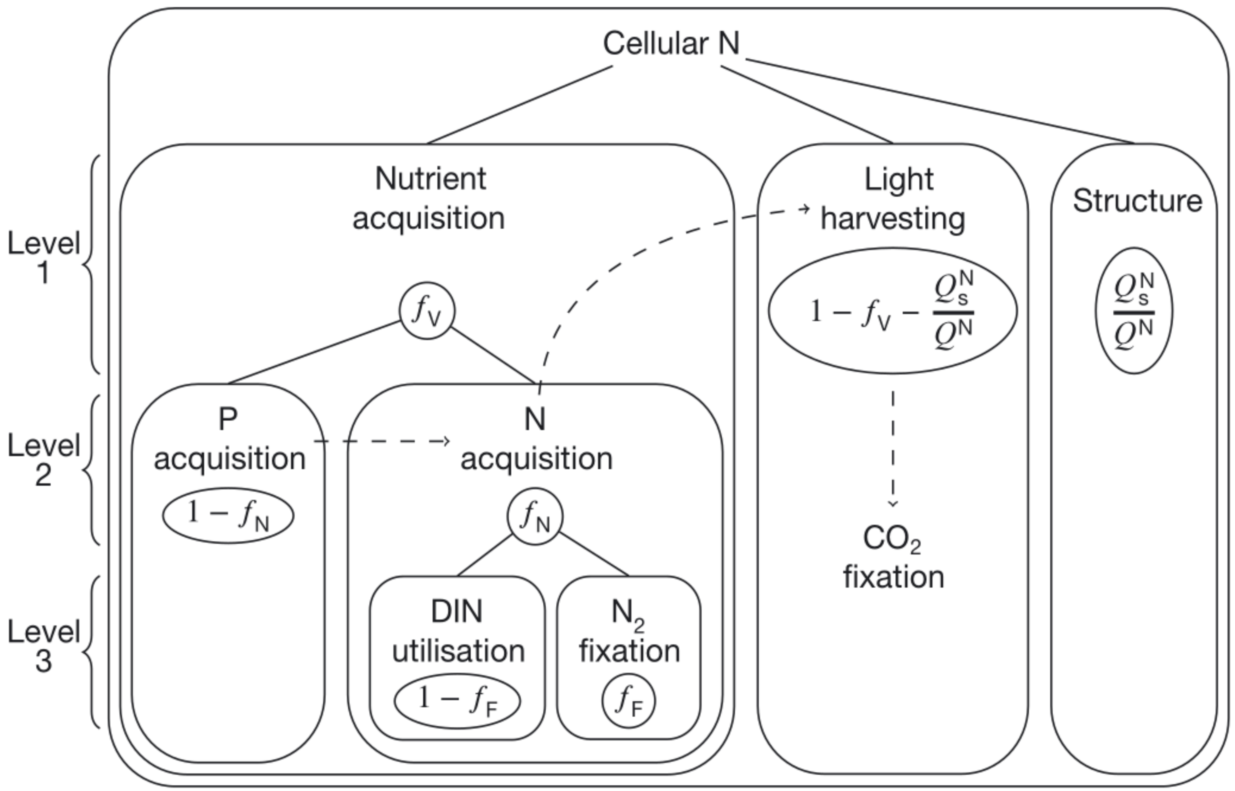
a) a fire-enabled terrestrial ecosystem model
b) an aerosol transport (and ideally chemistry) model
c) a marine biogeochemical model that represent some of the complexities mentioned

Even if the components exist, they each require expertise to judge the model outcomes and interaction on their meaning

So in many cases, a simpler approach is taken: Take output from one model, transplant it into another model. How bad is that?

Two issues with that: consistency, absence of feedbacks

adaptive models allowing for co-limitation



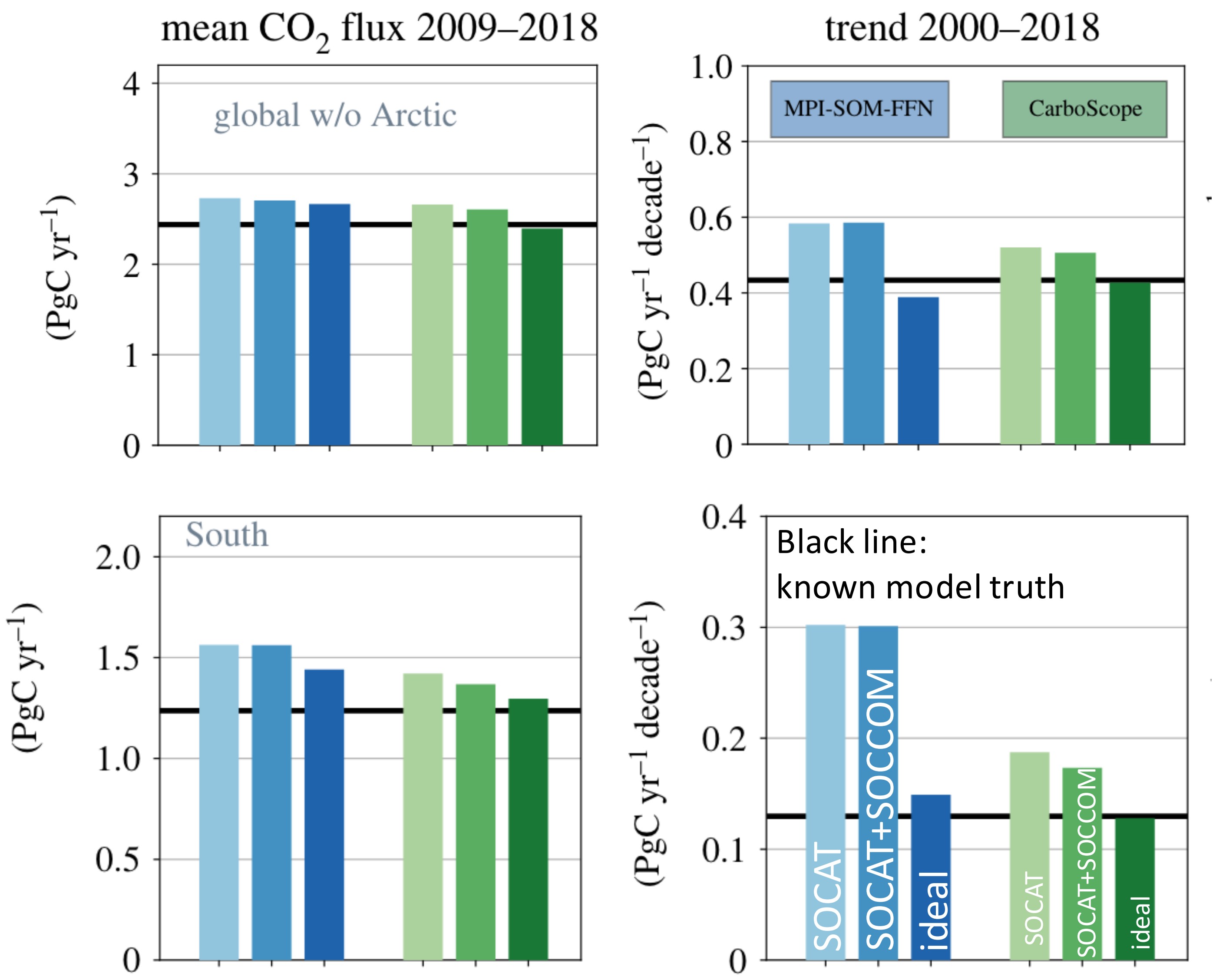
Pahlow et al, 2013

Describing cellular regulations in phytoplankton allows to tackle co-limitation

Examples: optimality-based model (Pahlow 2013), Geider et al. (1998) used in REcoM; extensions for Fe exist

Allow for flexible stoichiometry, bur more importantly regulation, some photophysiology, …
But: role of metals beyond Fe?

Effect of data sparsity on pCO_2-based estimates

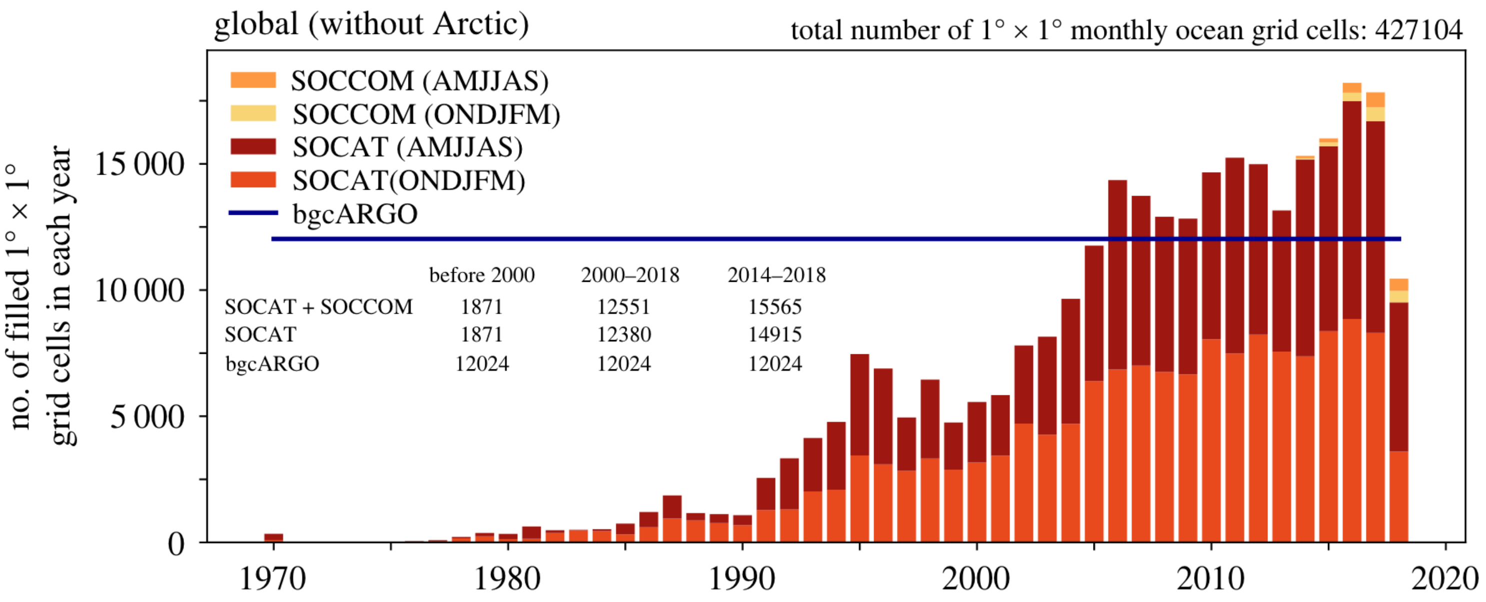


With the ideal sampling, the **bias in the mean CO_2 flux** of 9–12% is reduced to 2–9% globally and from 14–26% to 5–17% in the Southern Ocean

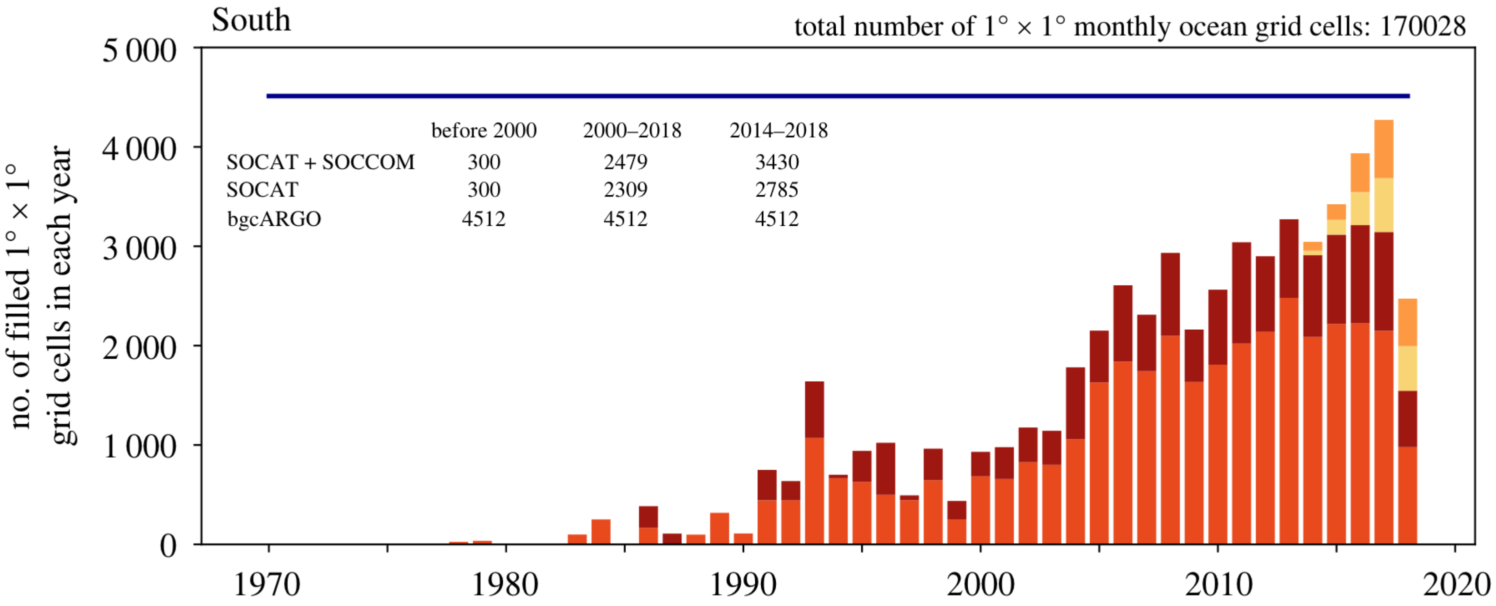
With the ideal sampling, the **bias in the CO_2 flux trend** of +20 to +35% is reduced to -10 to -2% globally and from 50-130% to 0-15% in the Southern Ocean

Hauck et al., 2023, Phil. Trans. B

Total number of observations



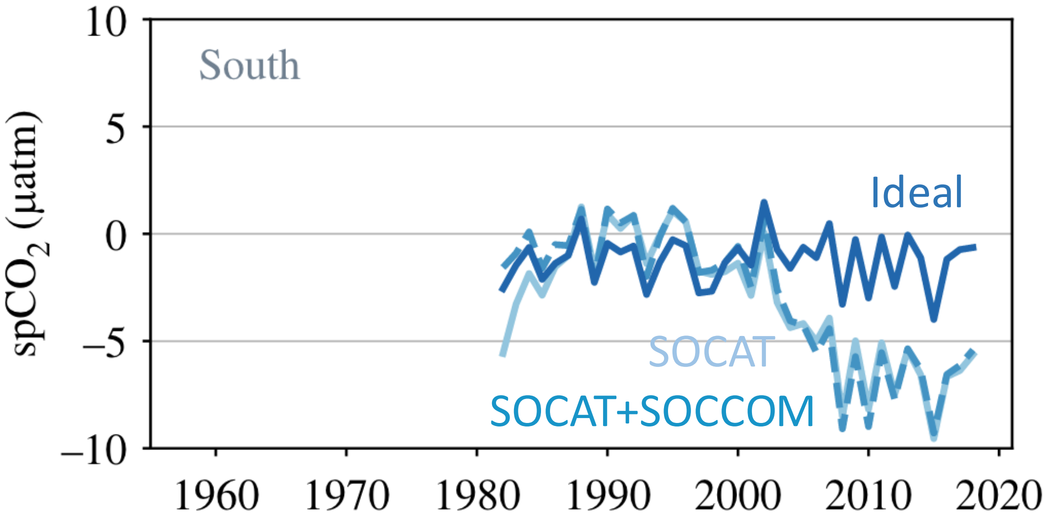
Globally, SOCAT has more observations than the ideal (bgcArgo case)



Not in the Southern Ocean.

Hauck et al., 2023, Phil. Trans. B

pCO_2 biases



The bgcArgo floats are equipped with pH sensors, and hence pCO_2 needs to be derived from pH and a multi-linear regression-derived alkalinity estimate. Currently, this procedure is associated with uncertainties that are substantially larger than for the pCO_2 measurements on ships. Our analysis reveals that **systematic biases of around 5μatm can lead to large errors in reconstructed pCO_2 and CO_2 flux**.

As the array of biogeochemical Argo floats expands, it will be essential to conduct on-going intercomparisons between float and ship-based measurements with the **goal of developing an unbiased multi-platform sampling array** that captures the relevant spatial and temporal variability. This may involve more extensive sampling of surface pH and alkalinity on research vessels and ships of opportunity to allow better assessment of float pH and salinity-derived alkalinity and targeting float locations for purposeful crossover comparisons.

Hauck et al., 2023, Phil. Trans. B