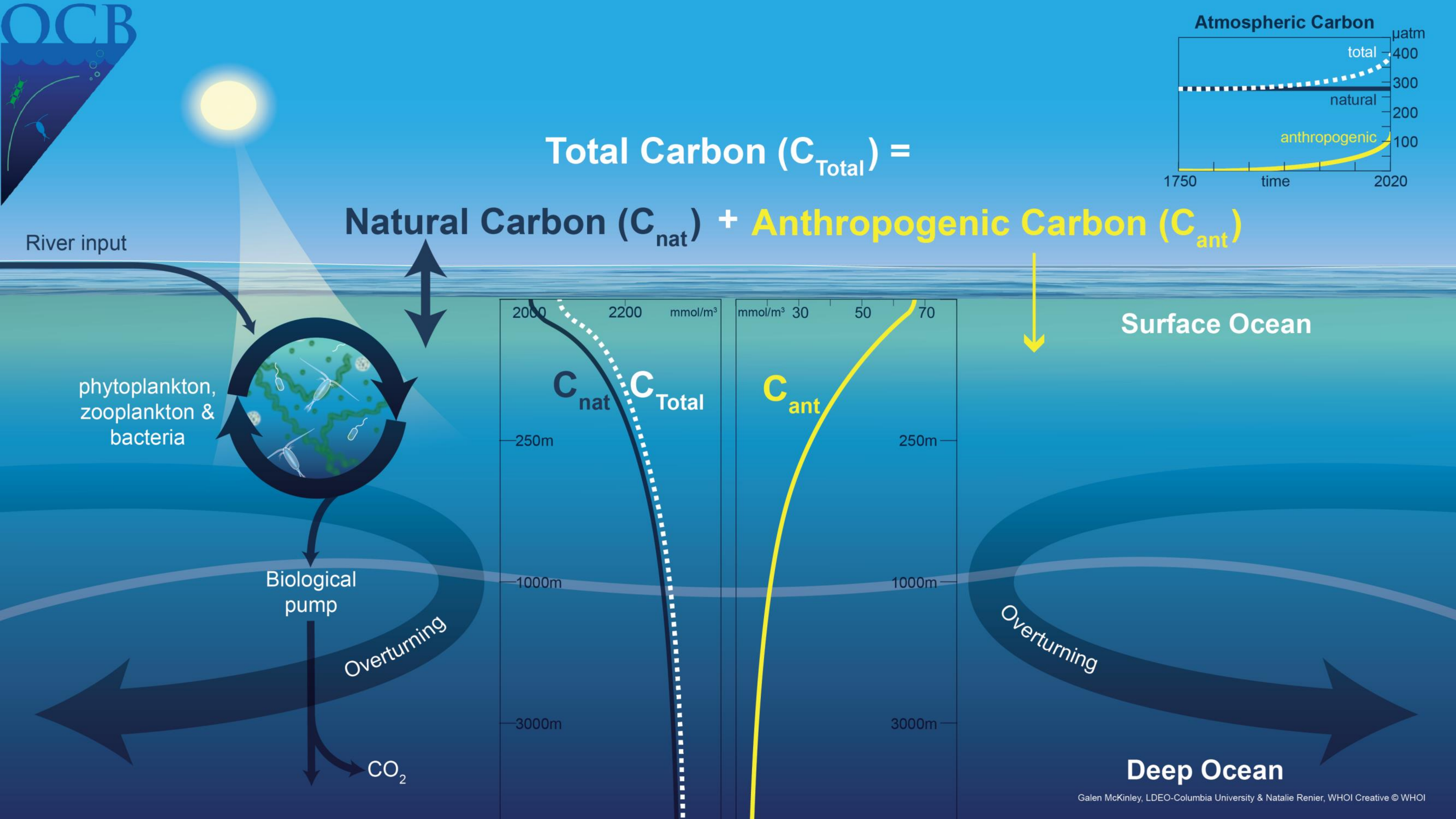
COLUMBIA CLIMATE SCHOOL
LAMONT-DOHERTY EARTH OBSERVATORY

LEAP

Quantifying the Ocean Carbon Cycle

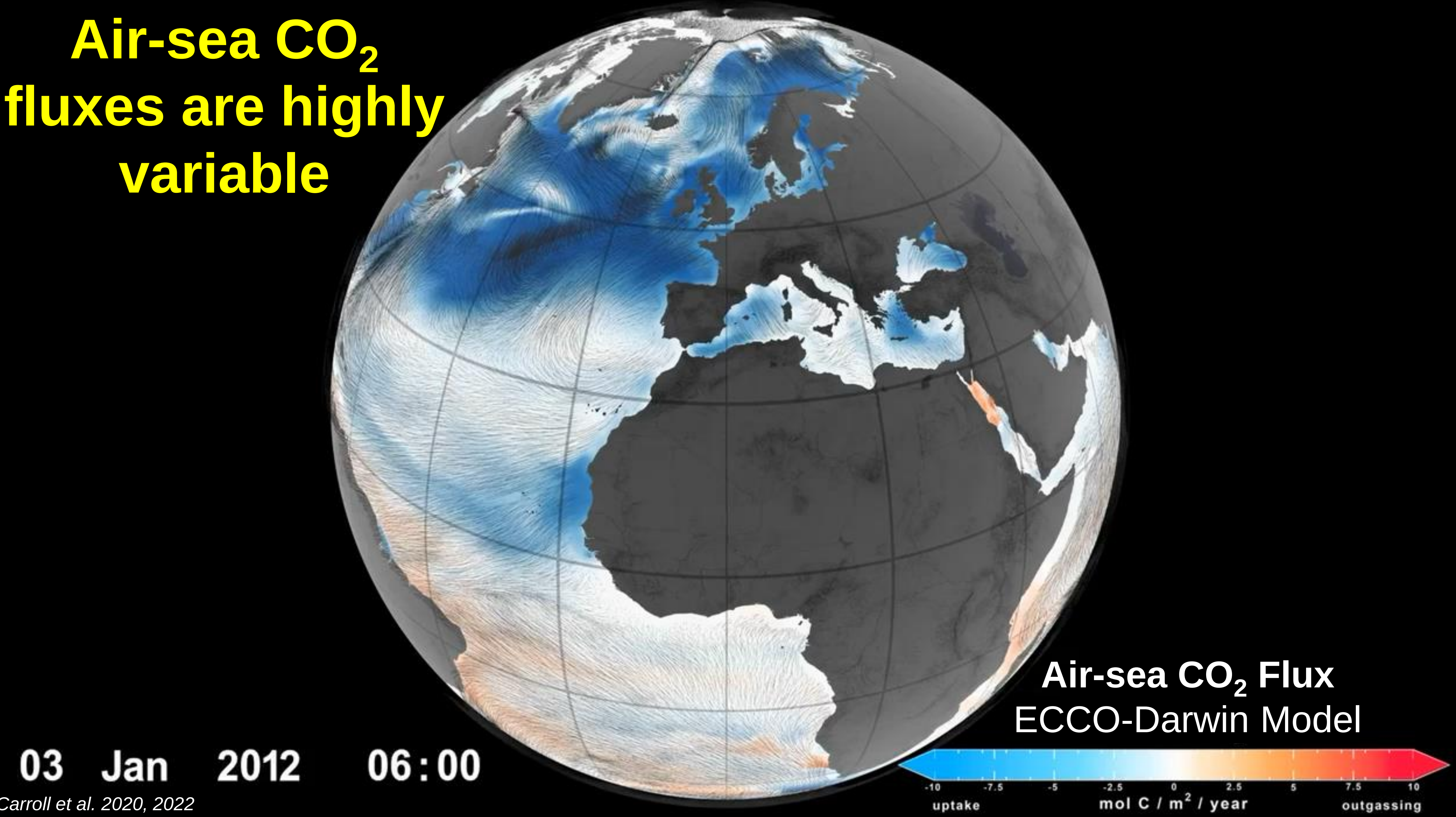
Galen A. McKinley
Professor of Earth and Environmental Sciences
Columbia University and LDEO, New York, USA

Decadal Survey of Ocean Sciences
25 June 2024



Total Carbon (C_{Total}) =
Natural Carbon (C_{nat}) + Anthropogenic Carbon (C_{ant})
Atmospheric Carbon
µatm
total
natural
anthropogenic
400
300
200
100
1750
time
2020
River input
phytoplankton, zooplankton & bacteria
Biological pump
CO_2
Overturning
Overturning
Surface Ocean
Deep Ocean
2000
2200
mmol/m³
mmol/m³
30
50
70
C_{nat}
C_{Total}
C_{ant}
250m
1000m
3000m
250m
1000m
3000m
Galen McKinley, LDEO-Columbia University & Natalie Renier, WHOI Creative © WHOI

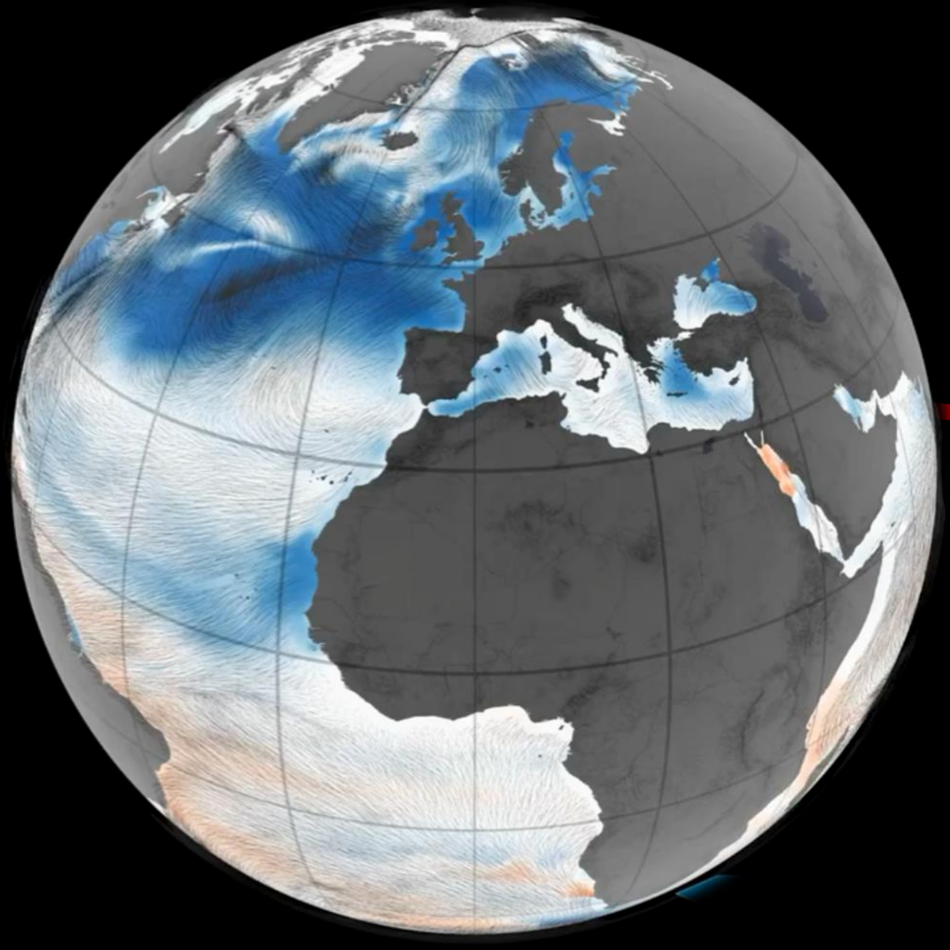
Air-sea CO_2 fluxes are highly variable



Carroll et al. 2020, 2022

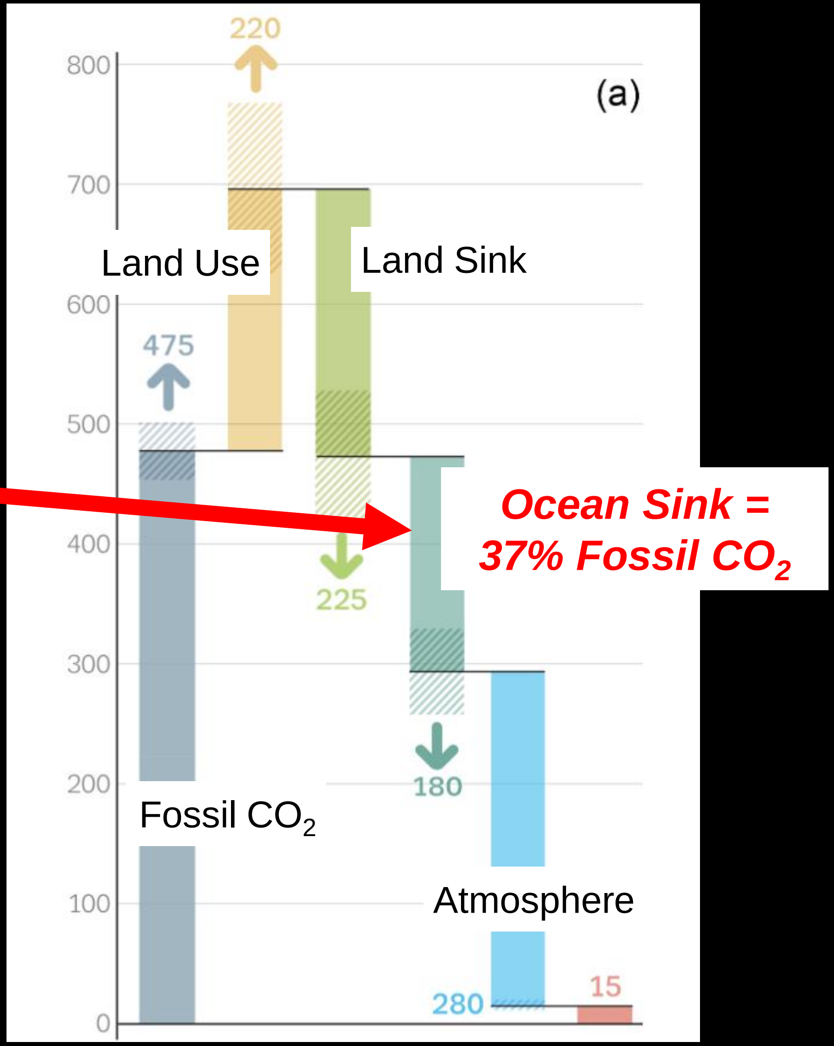
These fluxes add up to significantly mitigate climate change

Σ



Carroll et al. 2020, 2022

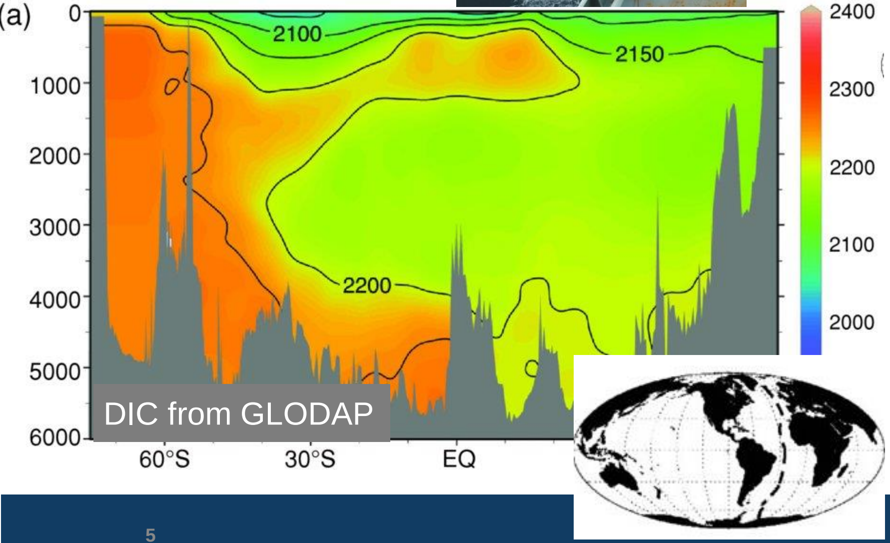
Cumulative Emissions & Sinks 1850-2022



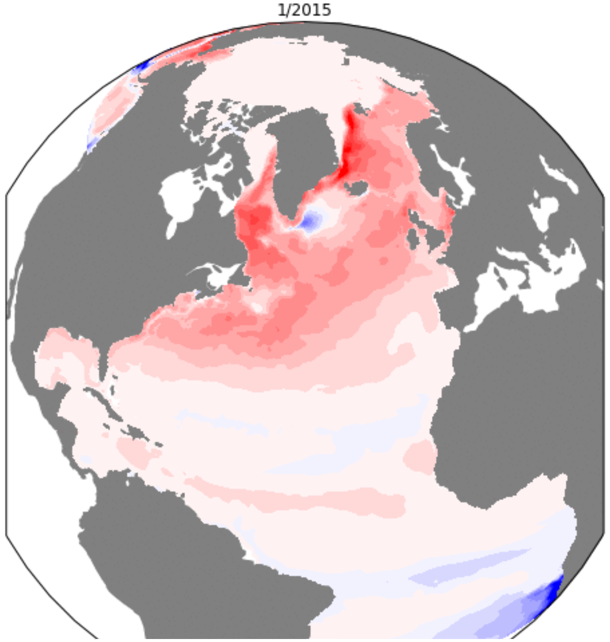
Friedlingstein et al. 2023, ESSD

Three independent approaches constrain the ocean carbon sink

1. Interior observations / products
Interior carbon storage
Decadal closure of global budget
Model validation



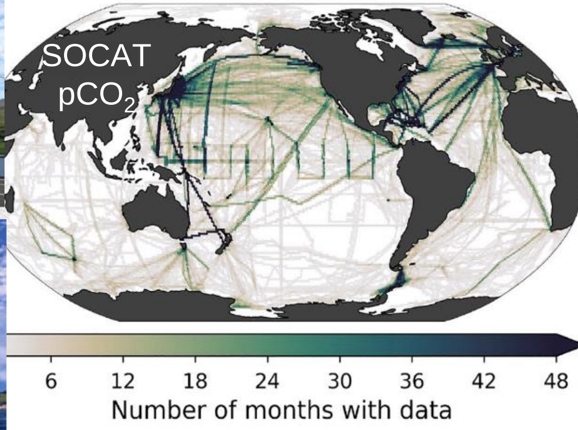
2. Modeling
Air-sea fluxes
Mechanisms
Projections



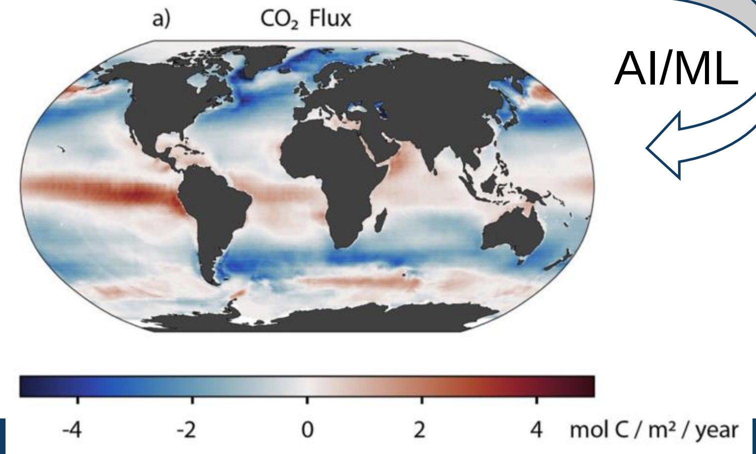
ASTE-BGC
air-sea CO_2 flux

Moseley et al, in prep

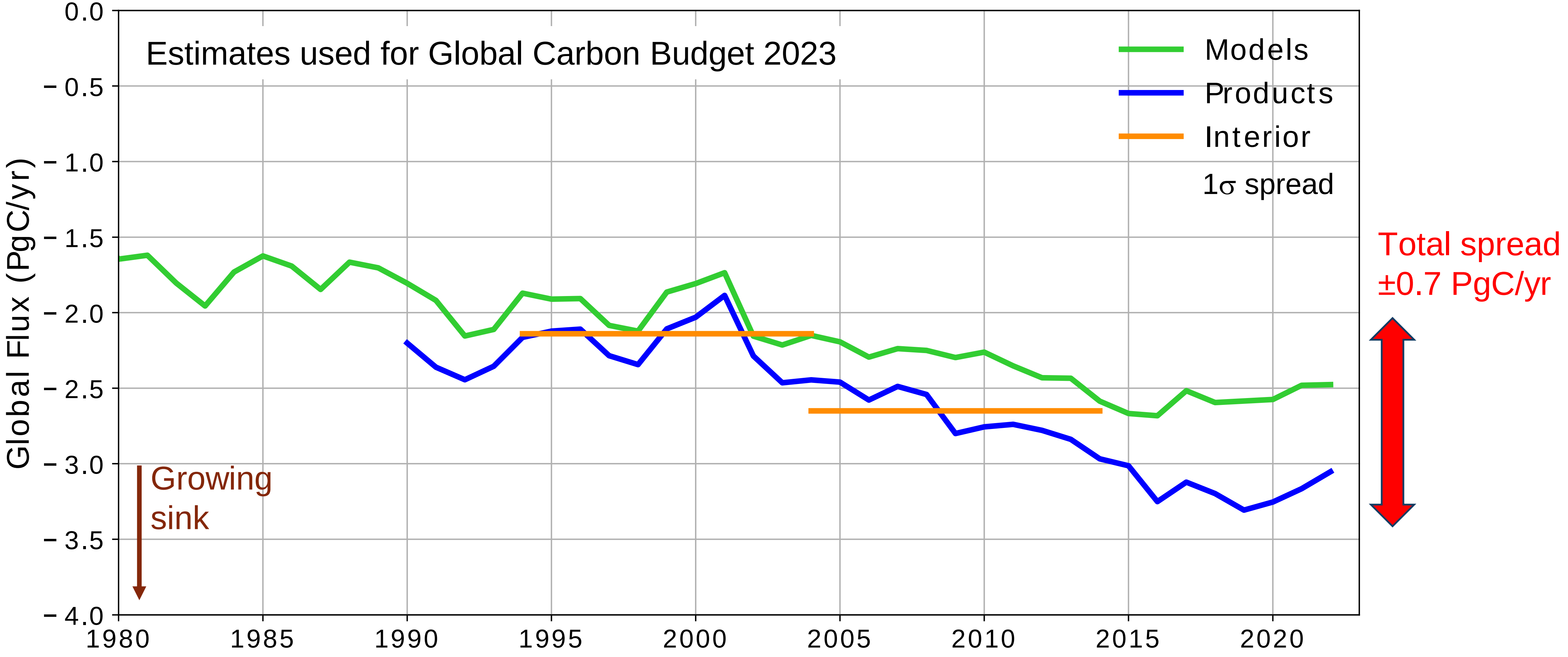
3. Surface data/reconstructions
Air-sea fluxes (~monthly)
Model validation



AI/ML



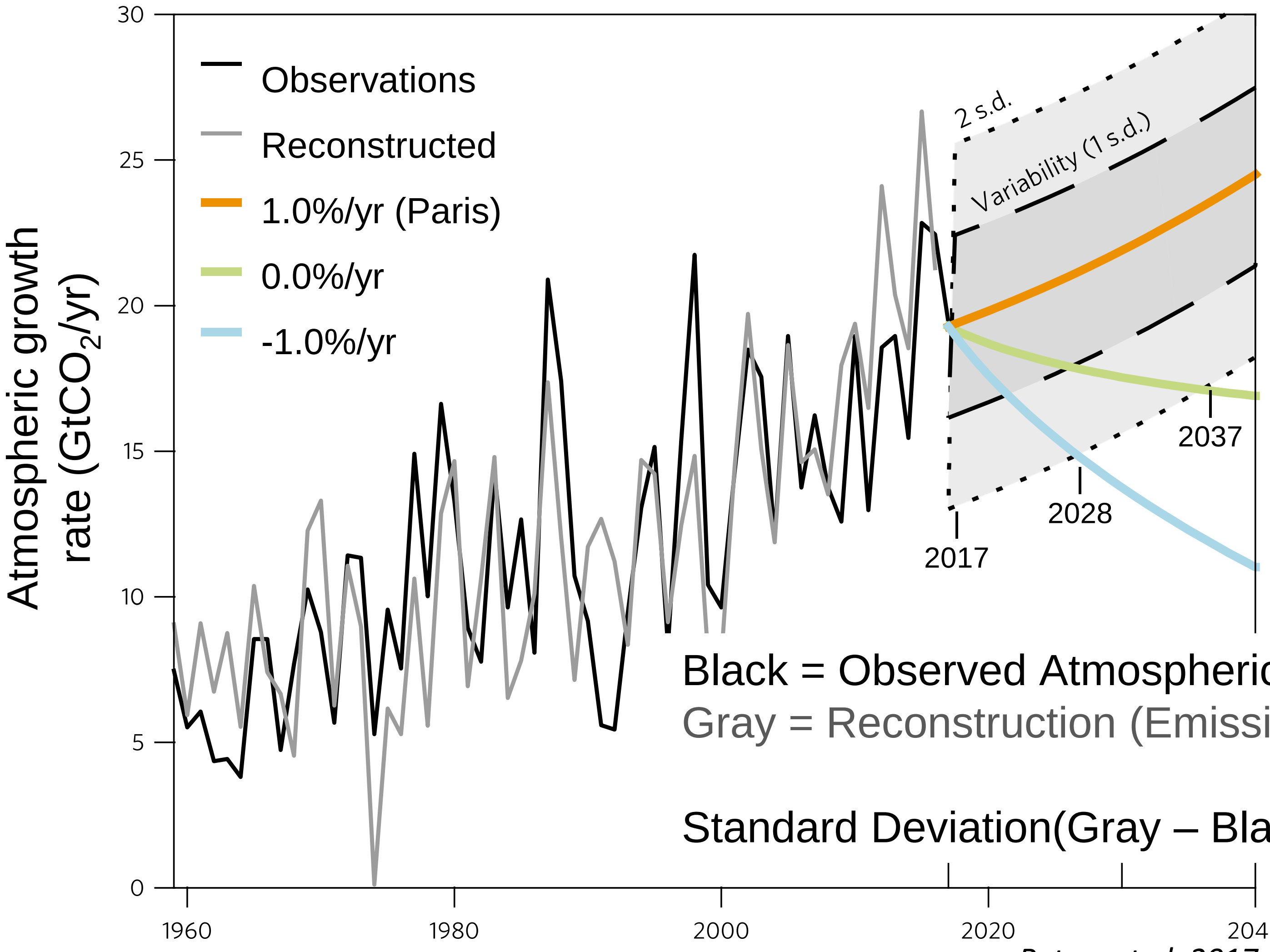
Globally integrated estimates agree to first order .. but large uncertainty remains



Models, products from Friedlingstein et al. 2023
Interior from Müller et al. 2023

These uncertainties are so large as to hamper the potential for carbon cycle science to directly support mitigation

CO_2



Black = Observed Atmospheric Growth Rate
Gray = Reconstruction (Emission–Land–Ocean)

Standard Deviation(Gray – Black) = 3 $GtCO_2$/yr

Peters et al. 2017 Nature Climate Change

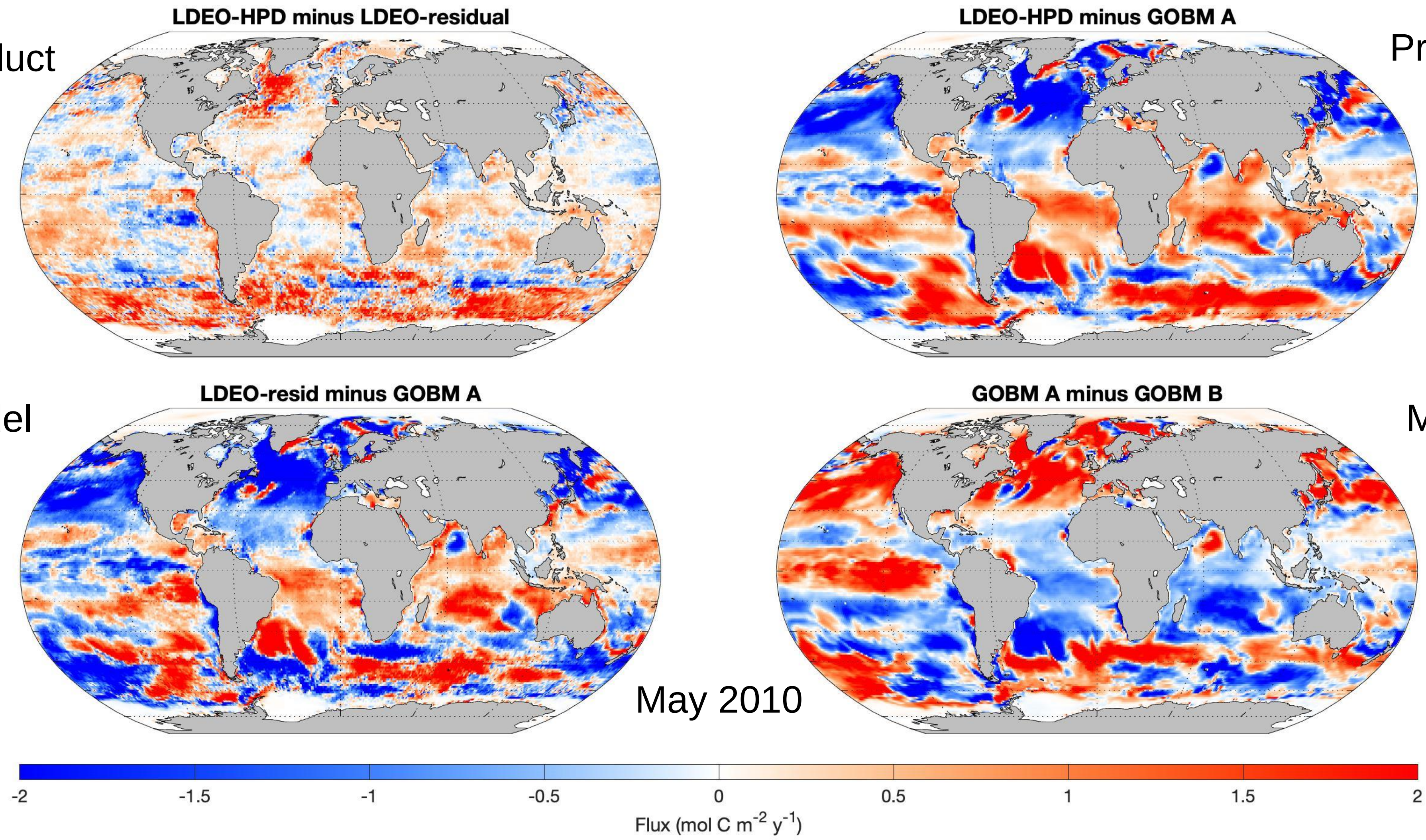
Uncertainties much larger at smaller space-time scales

Product-product

Product-model

Product-model

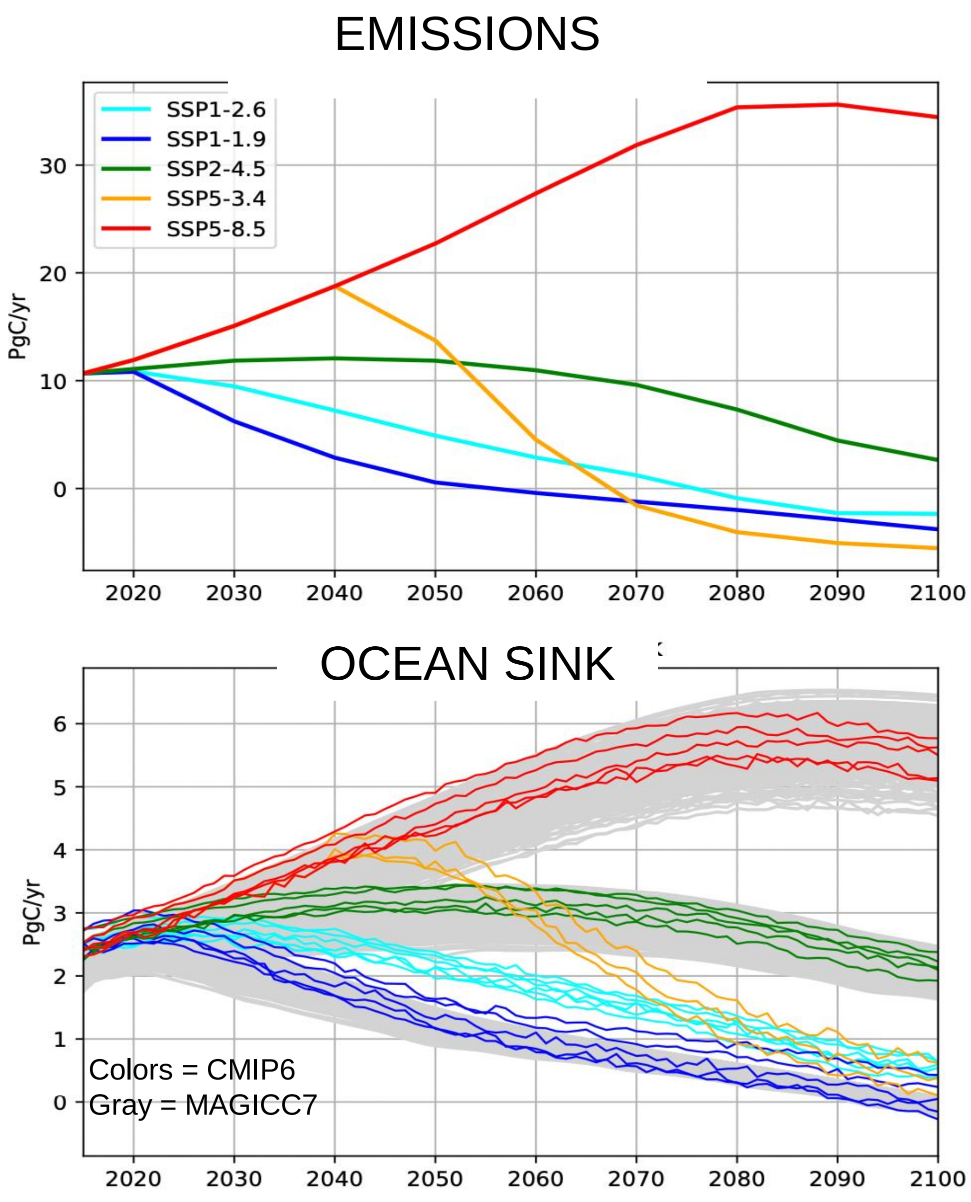
Model-model



Local differences are same magnitude as long-term mean flux

The ocean sink is expected to change significantly in the future

Future Emissions and Ocean Sink



CMIP6

3-6 ensemble means
for each scenario

McKinley et al. 2023, ERL

The ocean sink is expected to change significantly in the future

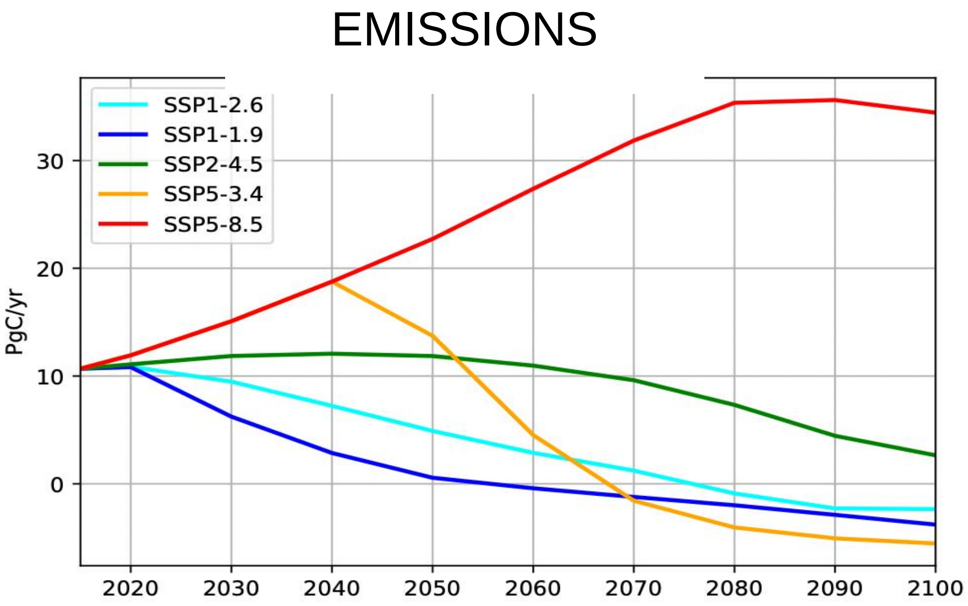
… these predictions can be no better than our mechanistic understanding

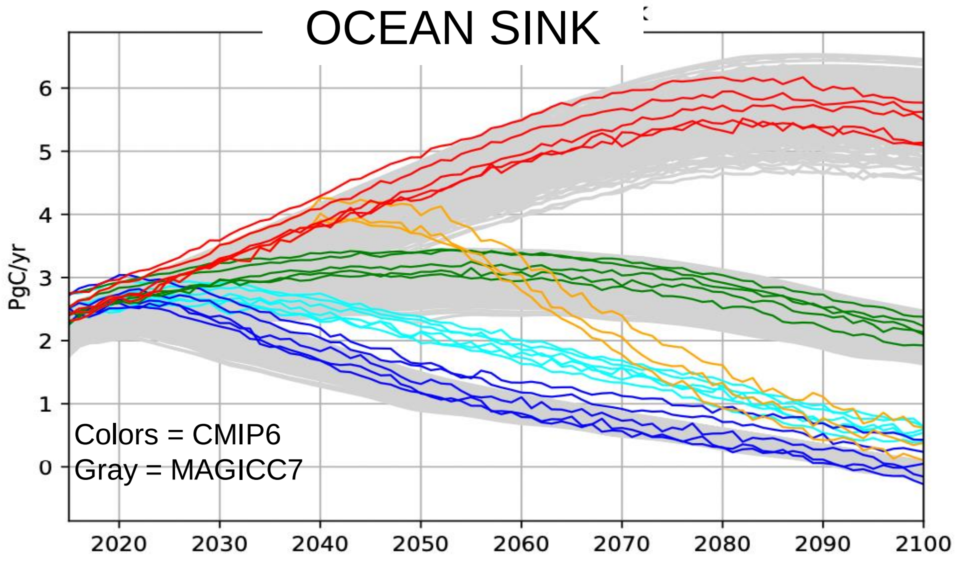
CMIP6

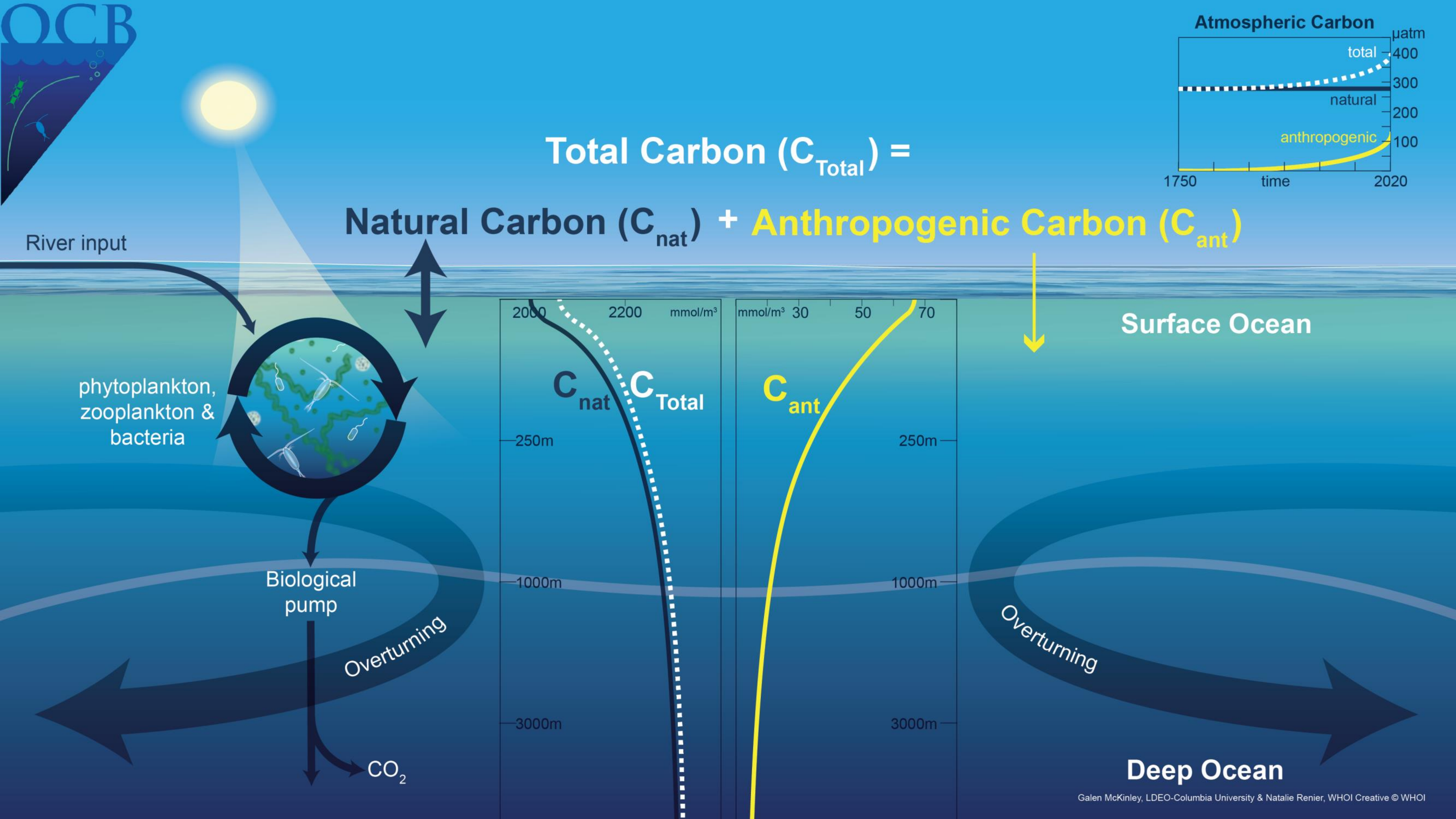
3-6 ensemble means
for each scenario

McKinley et al. 2023, ERL

Future Emissions and Ocean Sink







Atmospheric Carbon
µatm
total
natural
anthropogenic
400
300
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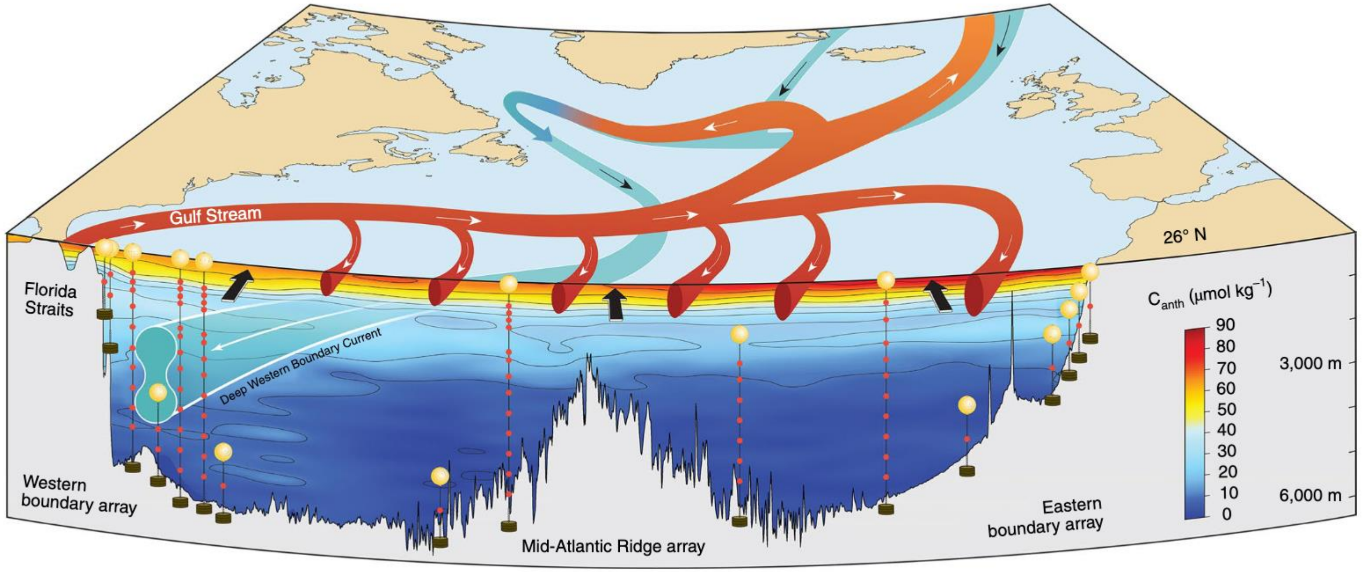
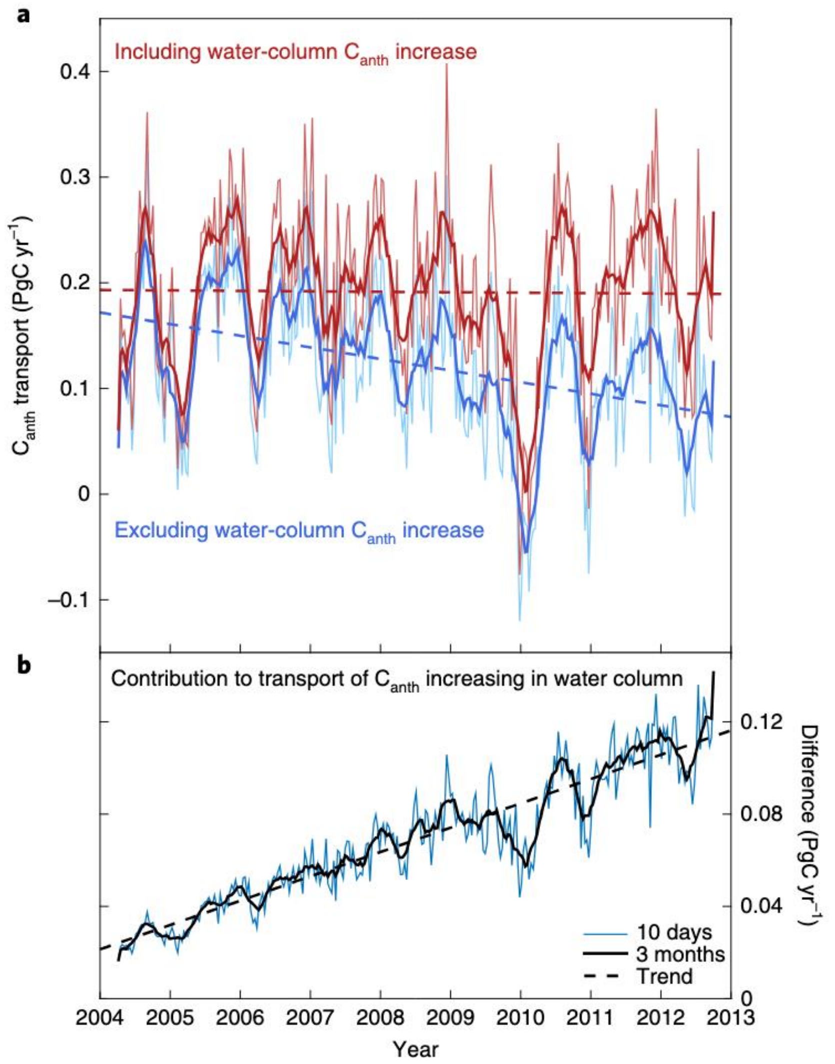
1750
time
2020
Total Carbon (C_{Total}) =
Natural Carbon (C_{nat}) + Anthropogenic Carbon (C_{ant})
River input
phytoplankton, zooplankton & bacteria
Biological pump
CO_2
Overturning
Surface Ocean
2000
2200
mmol/m³
C_{nat}
C_{Total}
mmol/m³
30
50
70
C_{ant}
250m
1000m
3000m
Overturning
Deep Ocean
Galen McKinley, LDEO-Columbia University & Natalie Renier, WHOI Creative © WHOI

Ocean circulation, now and future?

Estimate of C_{anth} transport at RAPID

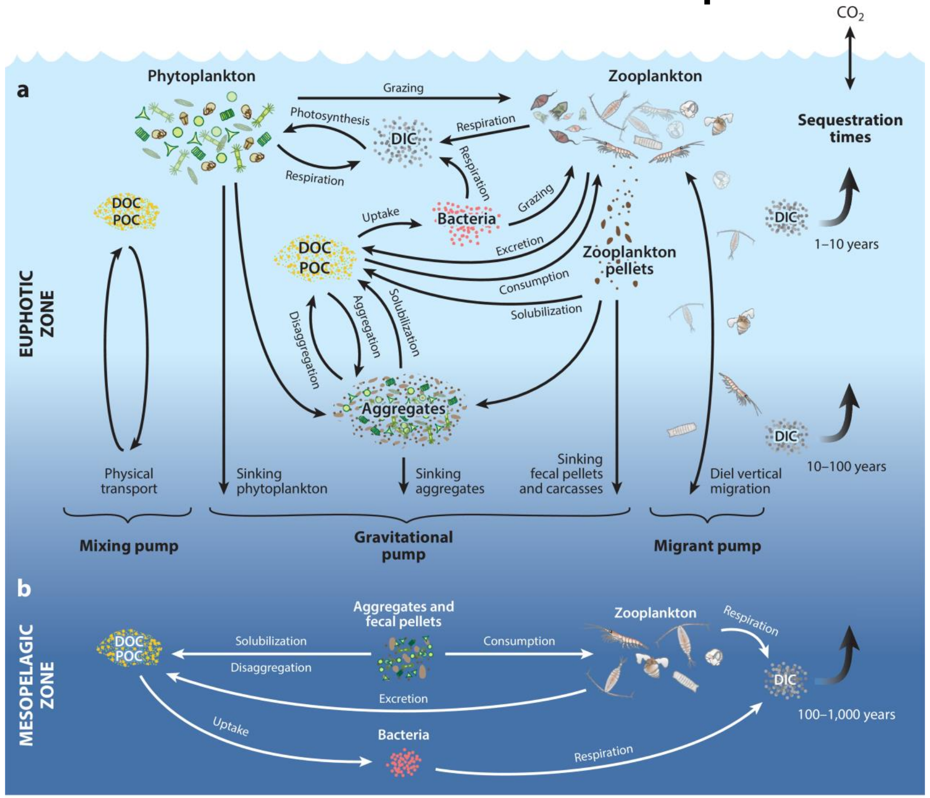


Brown et al. 2022



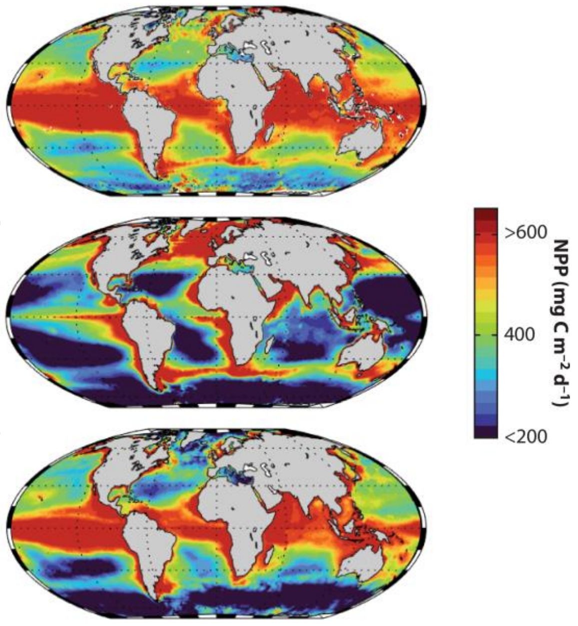
Biological carbon export, now and future?

Estimates of current biological carbon transfer to depth are ***5-12+ PgC/yr***



Siegel DA, et al. 2023
Annu. Rev. Mar. Sci. 15:329–56

Divergent NPP products



Siegel et al 2016, 2023

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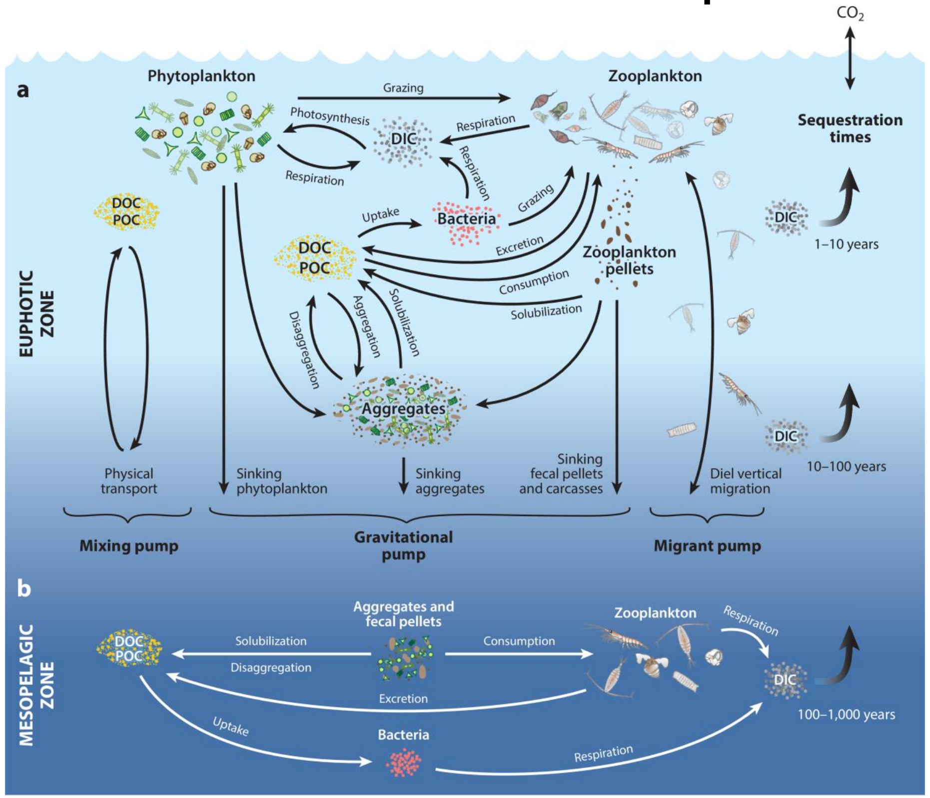

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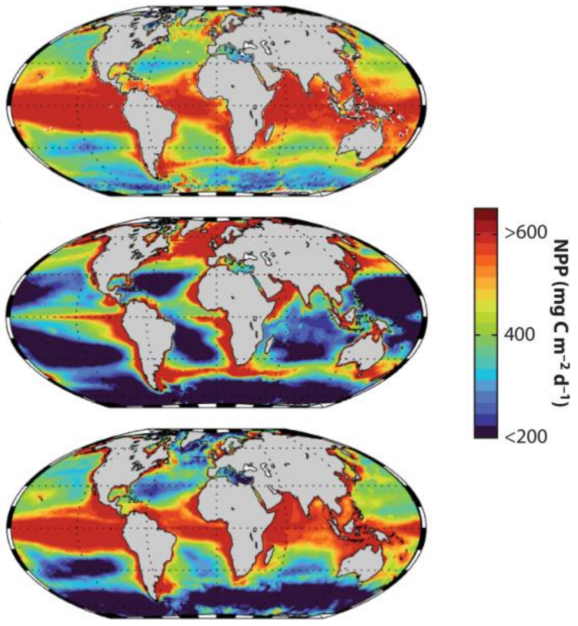
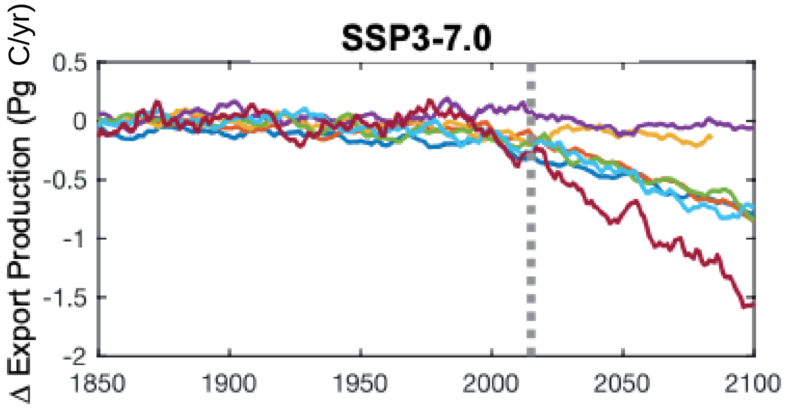
Divergent NPP products



Siegel et al 2016, 2023

.. thus, future projections diverge



Wilson et al. 2022

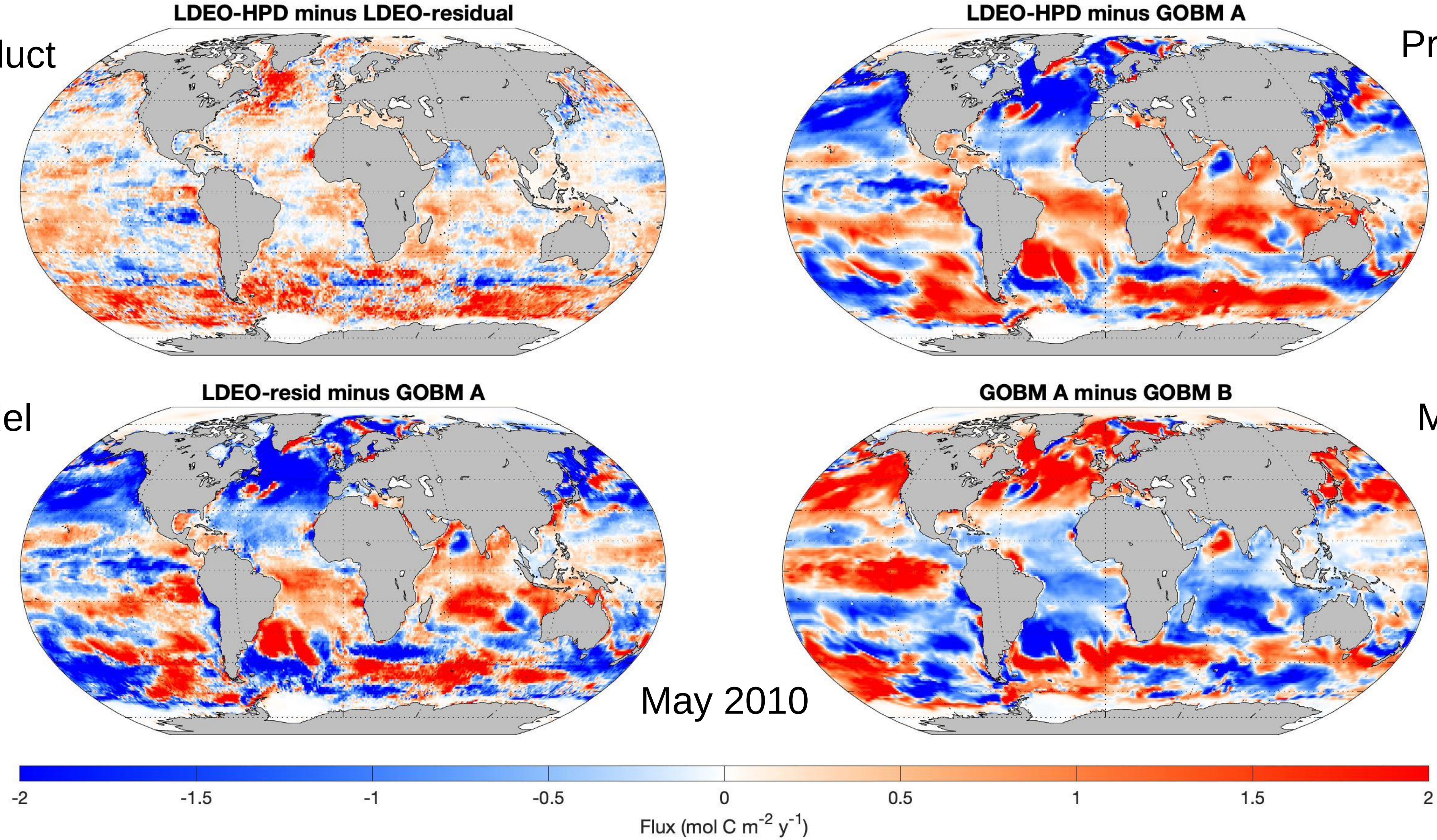
mCDR "additionally" would ideally be referenced to a baseline

Product-product

Product-model

Product-model

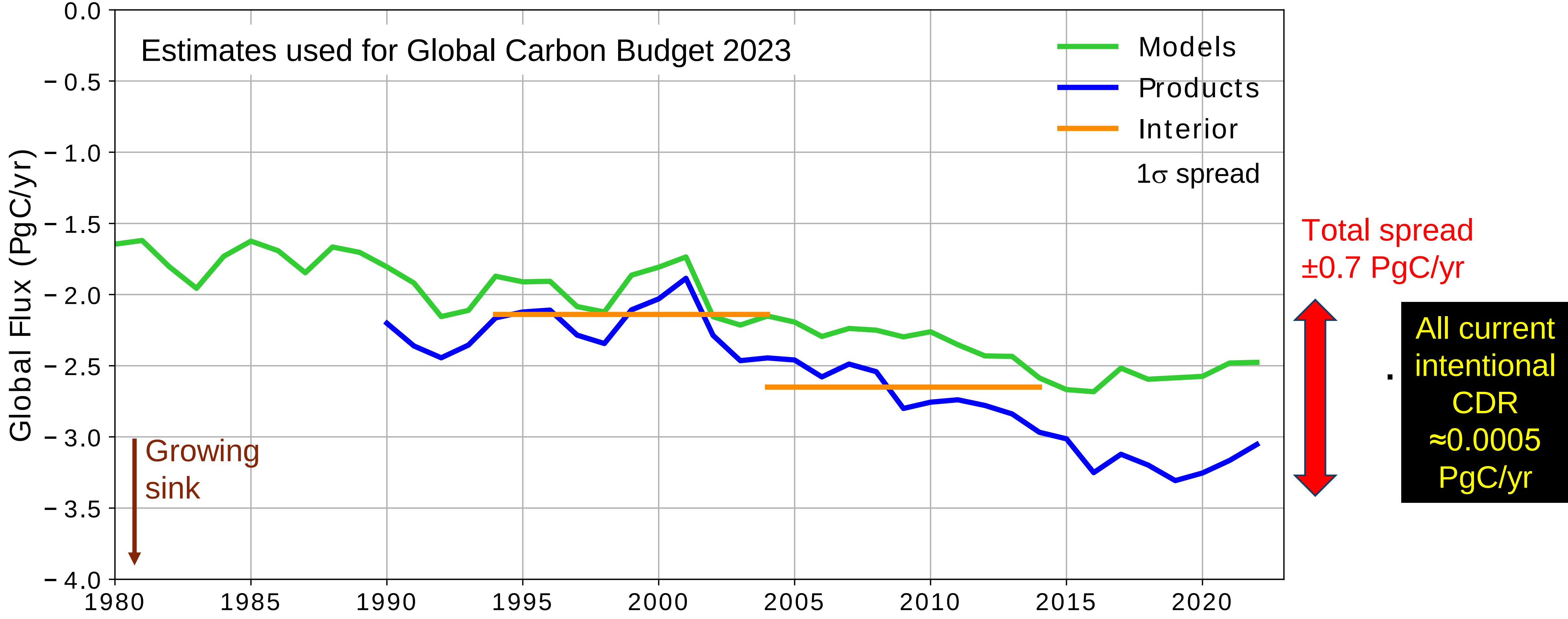
Model-model



May 2010

Local differences are same magnitude as long-term mean flux

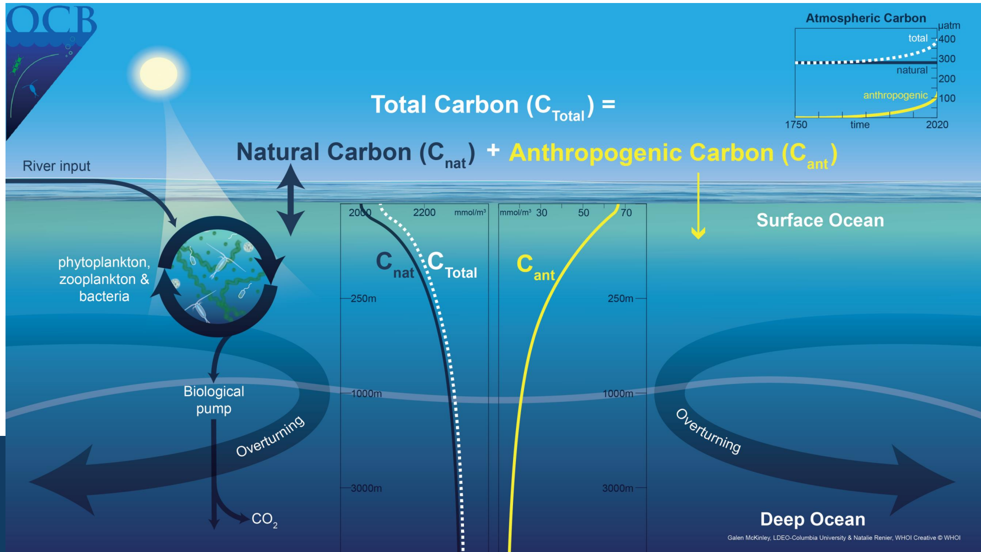
mCDR impacts on the global atmosphere?



Models, products from Friedlingstein et al. 2023
Interior from Müller et al. 2023

Proposed decadal challenge for NSF

- ***How do diverse physical, chemical and biological processes combine across scales to drive the ocean carbon cycle?***
  - (a) Narrow estimates of the annual global integrated sink to within ±0.1 PgC/yr
  - (b) Better constrain carbon cycle projections, especially the natural component
- This will require
  - Observations (ships, moored, autonomous; platforms and sensors)
  - Models (circulation across scales, biological processes)
  - Enabling tools and techniques (data assimilation, machine learning, data and compute systems)
- These efforts will contribute also to
  - mCDR additionality, locally and globally
  - heat uptake and sea level
  - ecosystems, fisheries, climate impacts
  - glacial / interglacial mechanisms



THANK YOU

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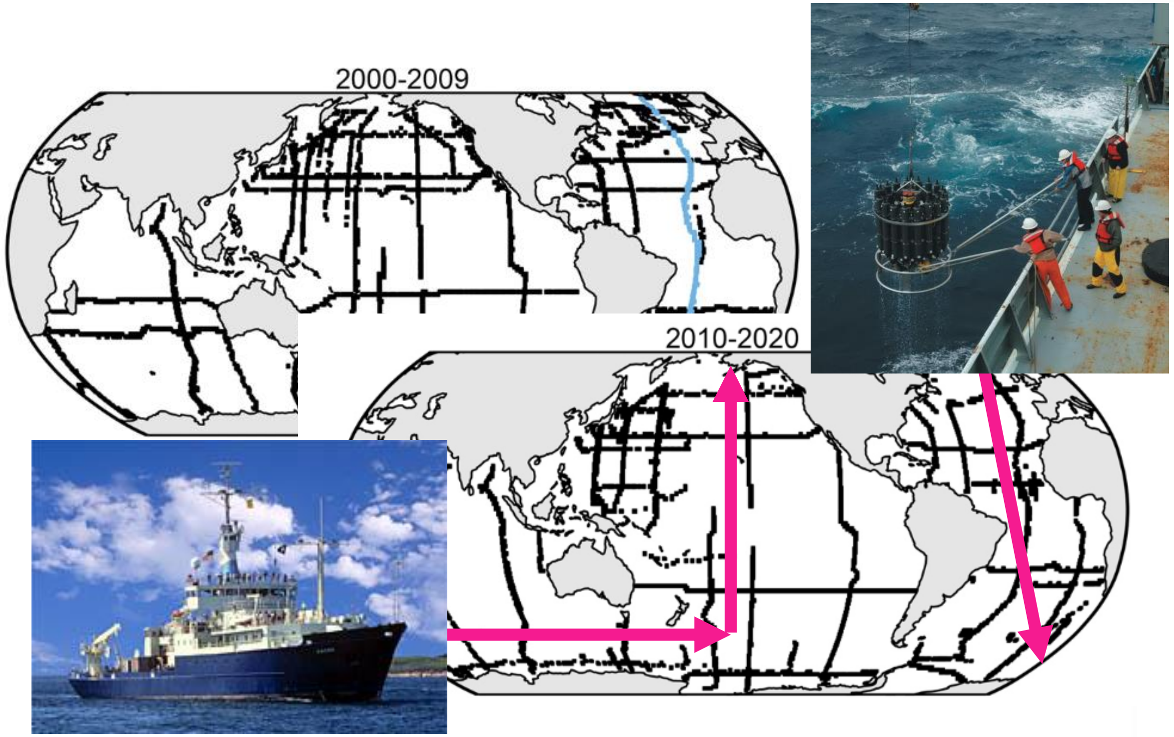
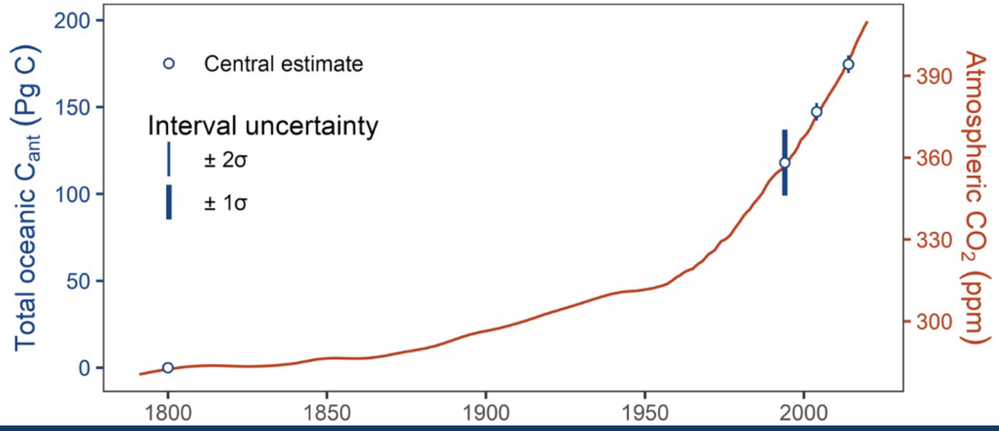
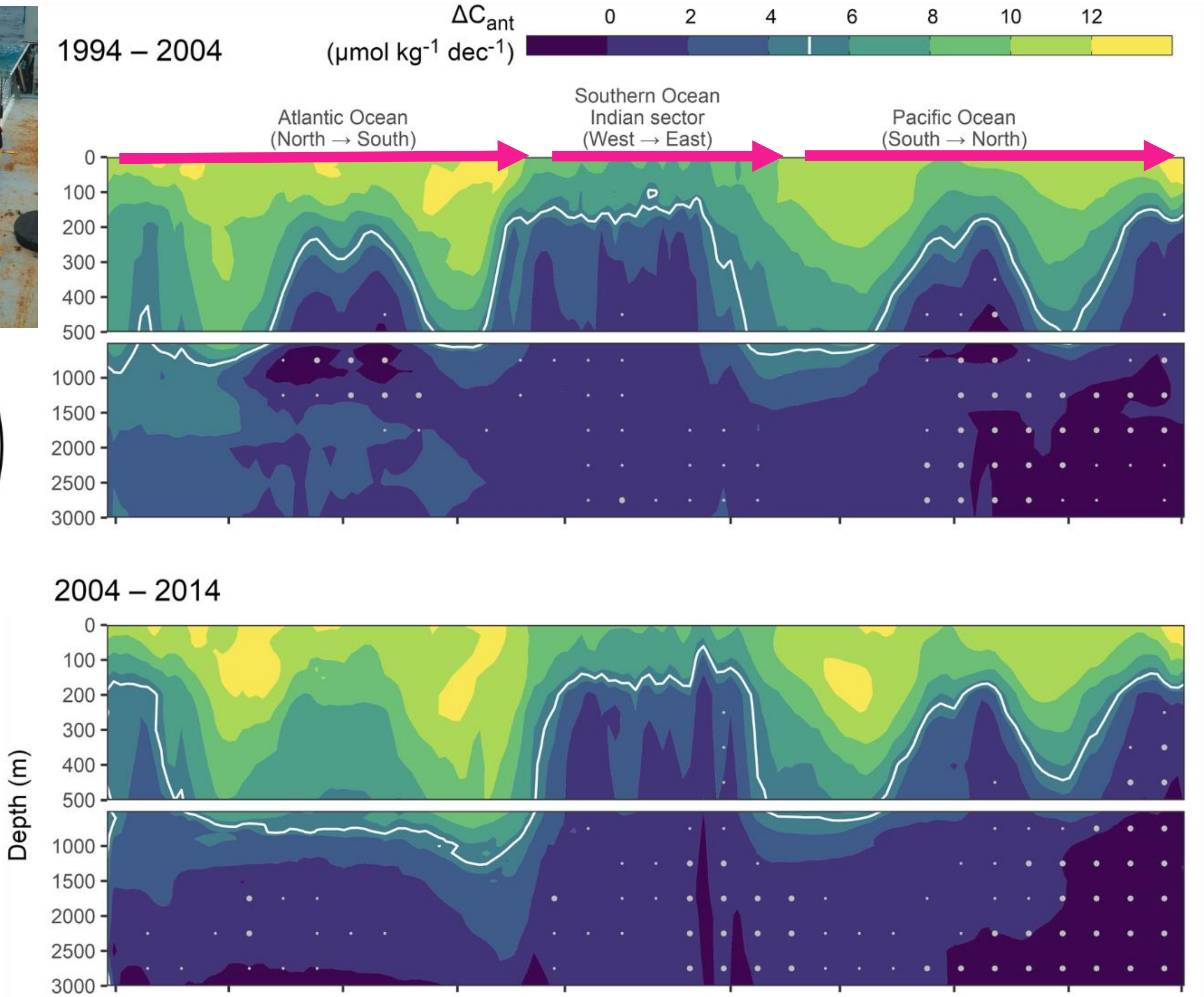
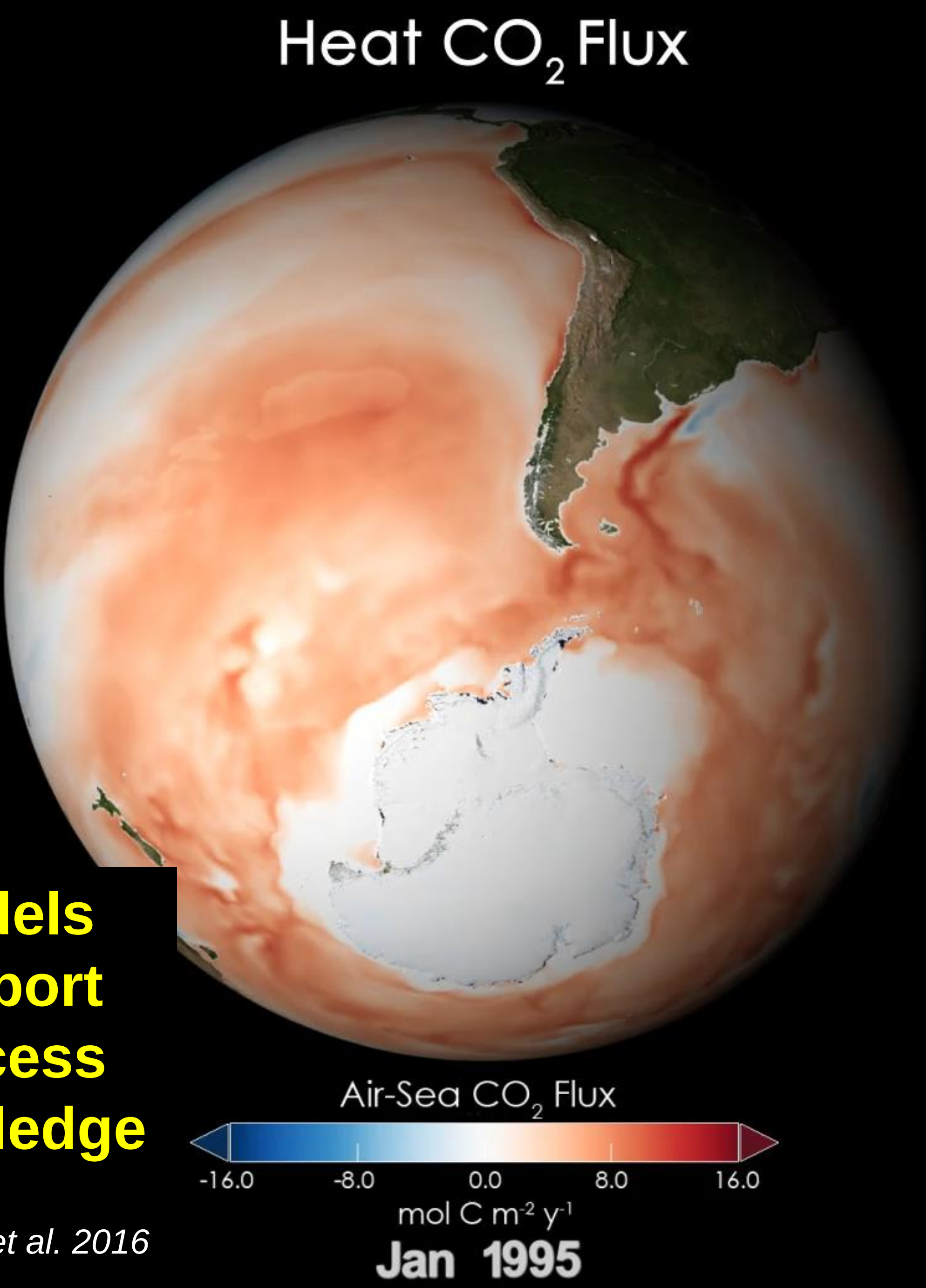
Decadal Interior Data: Shows ocean ***following atmospheric*** pCO_2







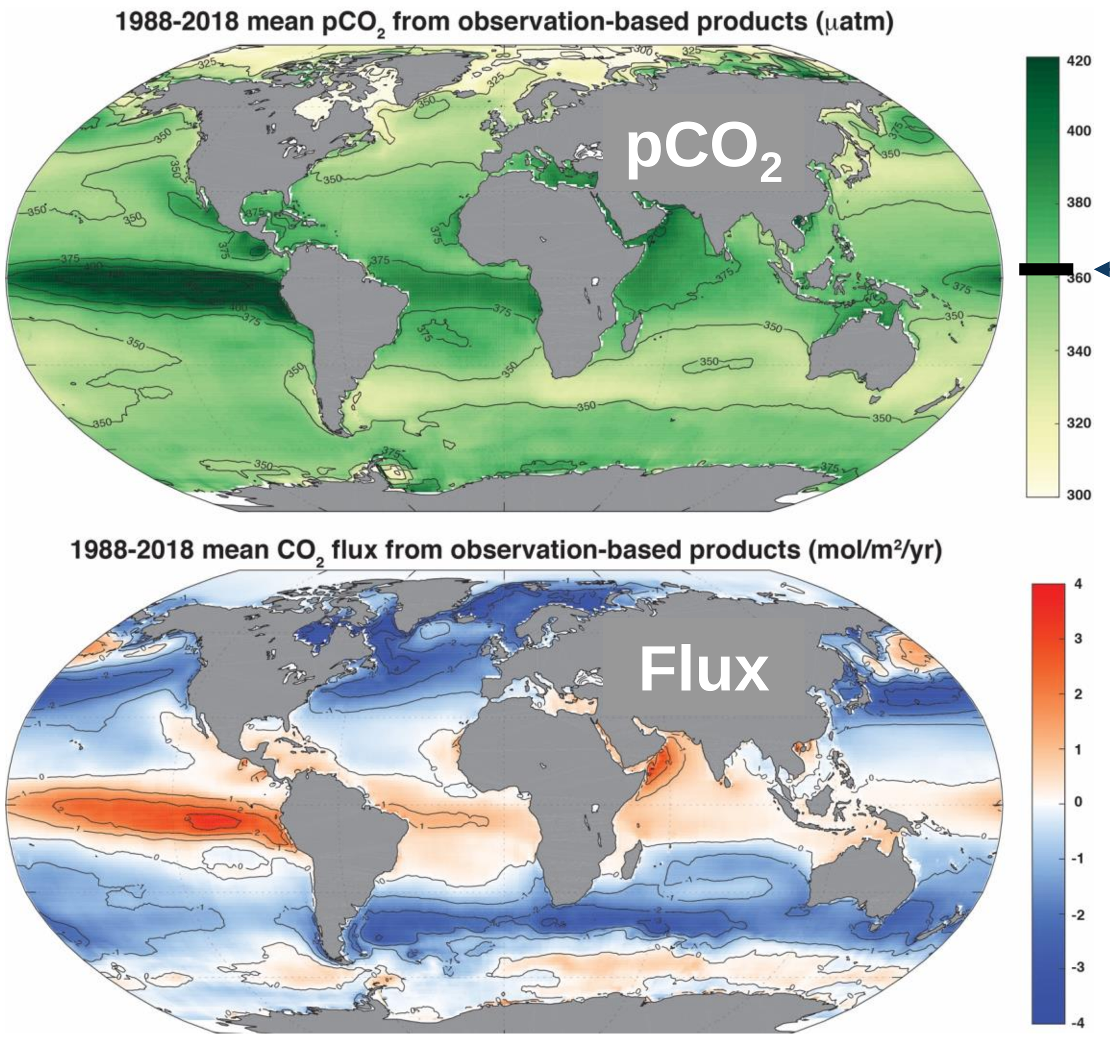
Müller, Gruber et al. 2023, AGU Advances



Models support process knowledge

Lauderdale et al. 2016

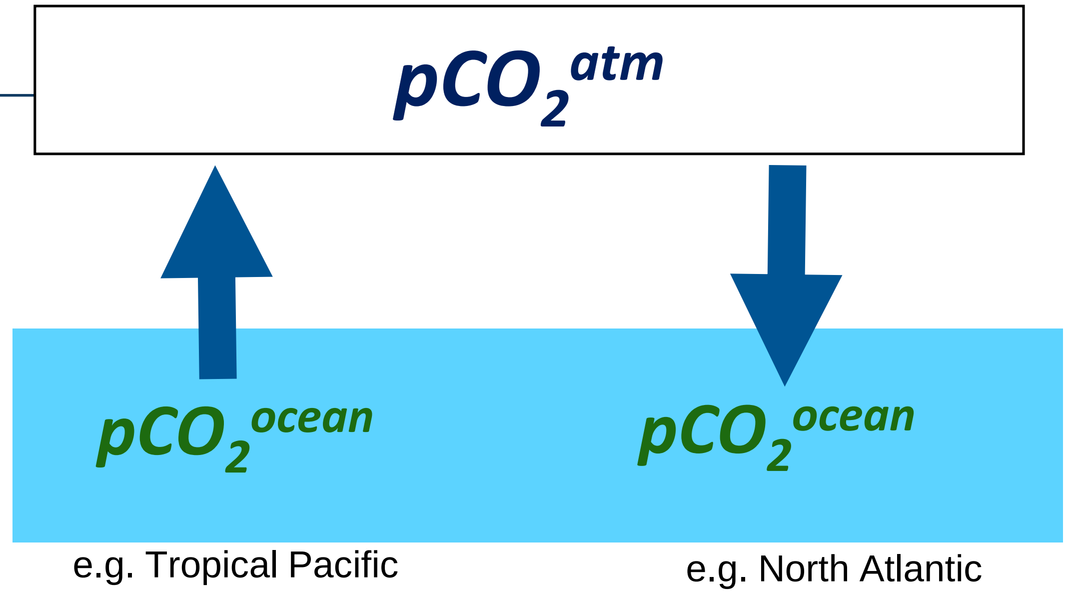
Reconstructions are full-coverage pCO_2 fields derived from data



Crisp et al., 2022, Review of Geophysics

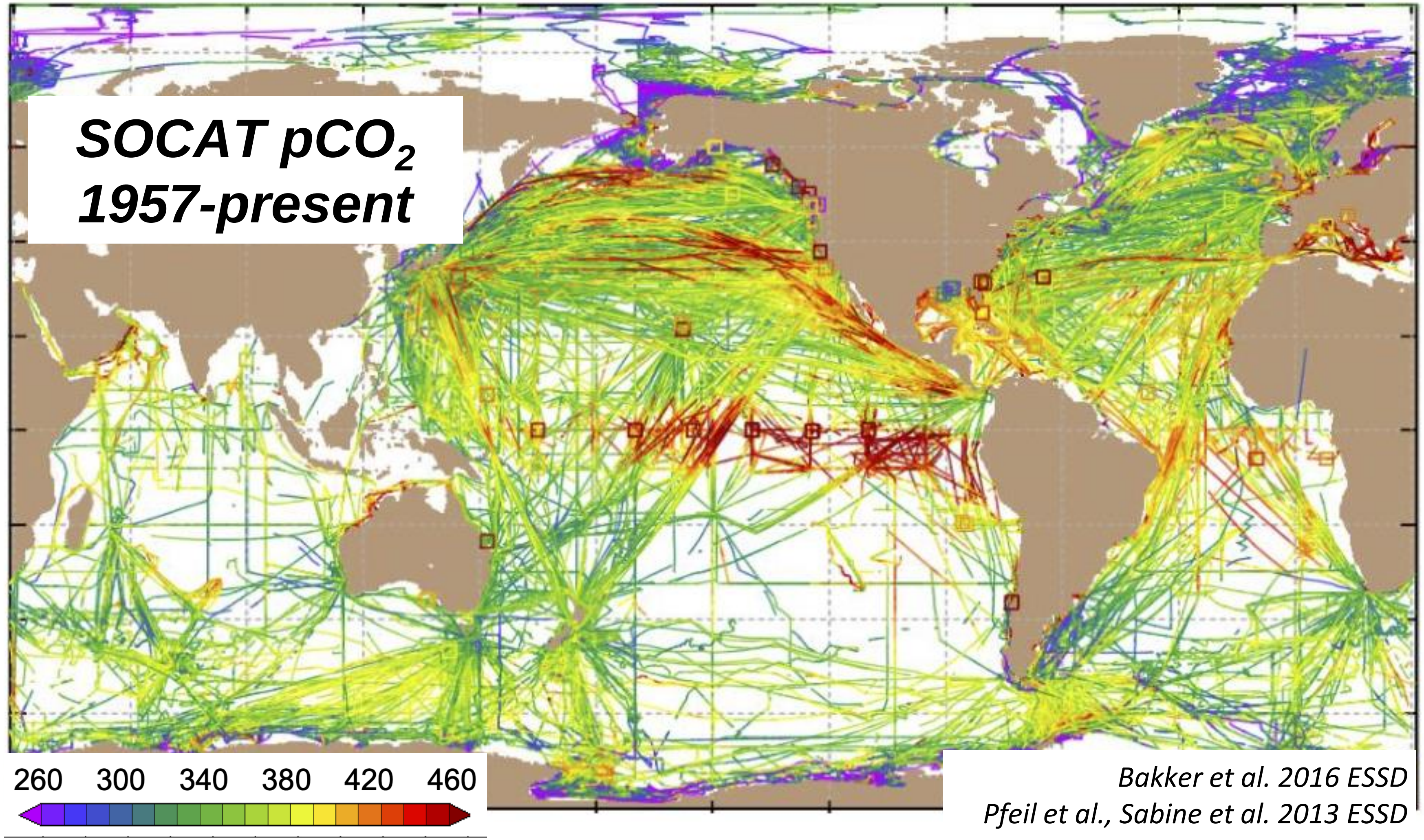
If $pCO_2^{ocean} > pCO_2^{atm}$ flux is out of ocean (positive)

If $pCO_2^{ocean} < pCO_2^{atm}$ flux is into ocean (negative)



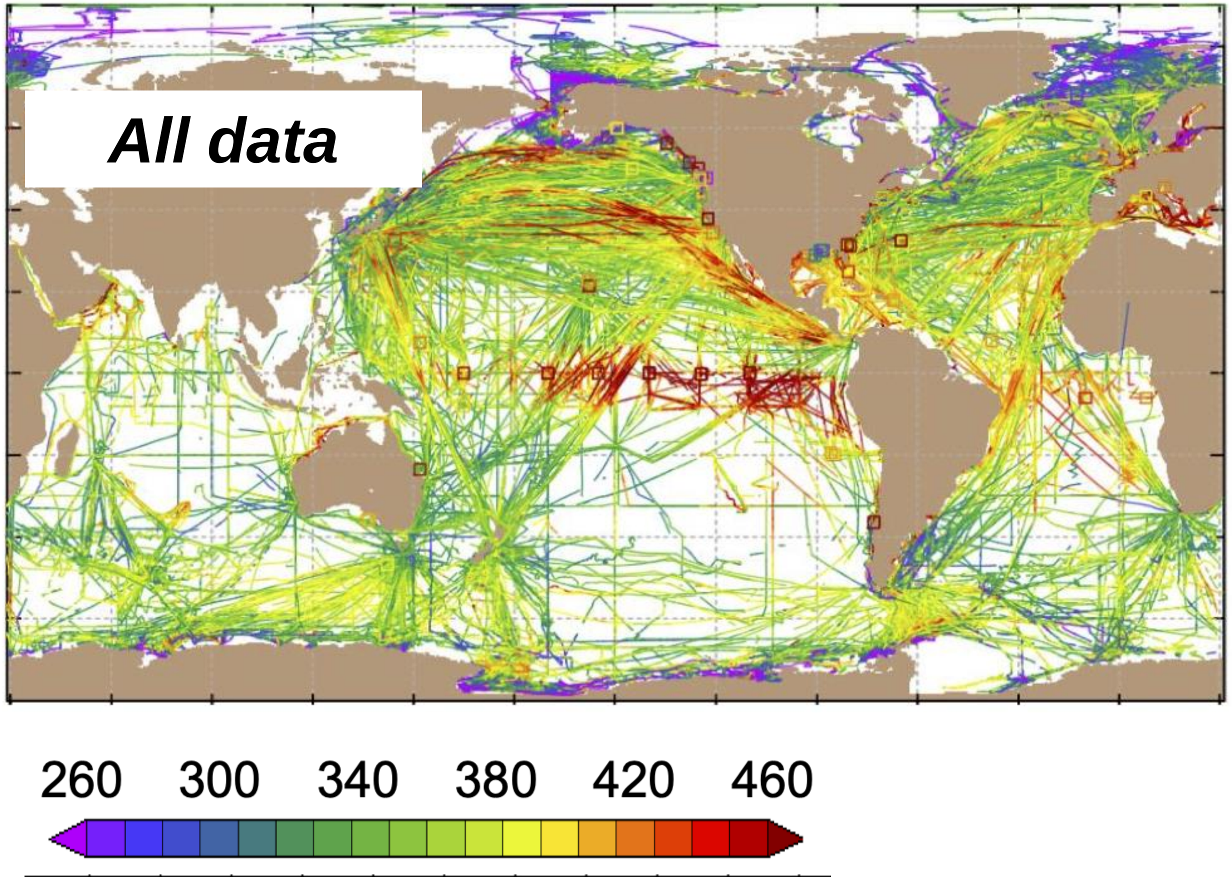
$$Air\ sea\ CO_2\ flux = k_w S_{CO_2}(1 - f_{ice})(pCO_2^{ocean} - pCO_2^{atm})$$

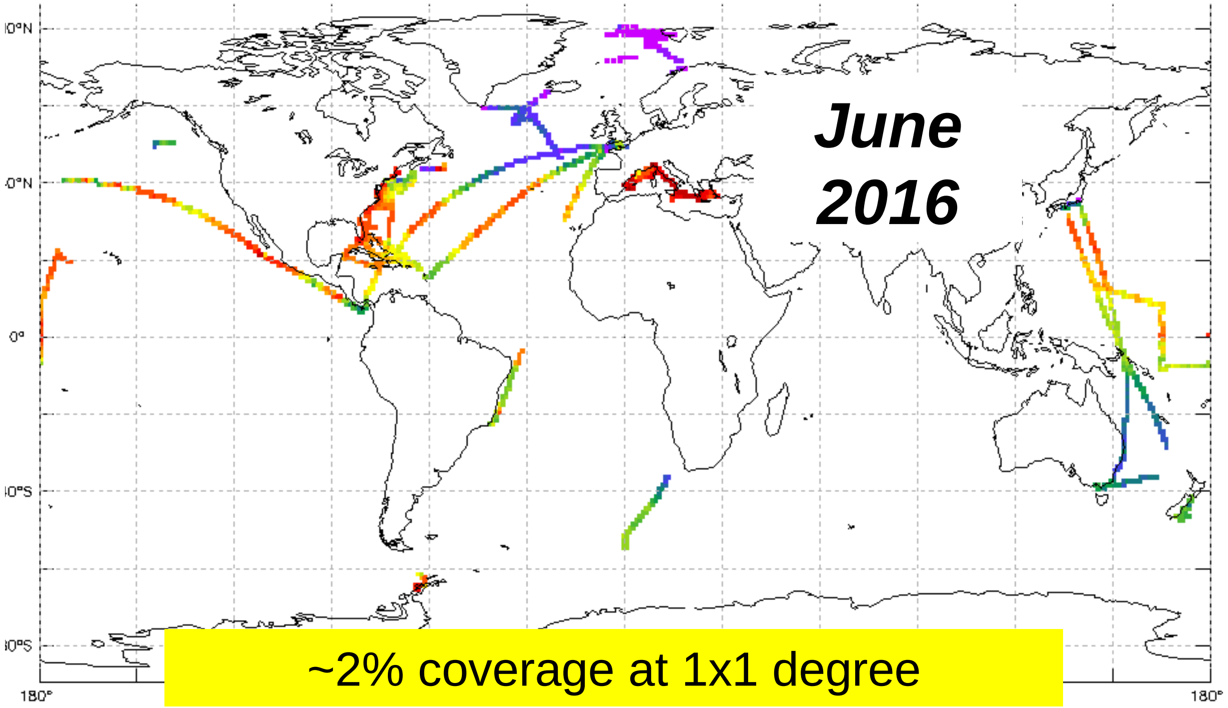
Surface ocean pCO_2 data used in reconstructions



Bakker et al. 2016 ESSD
Pfeil et al., Sabine et al. 2013 ESSD

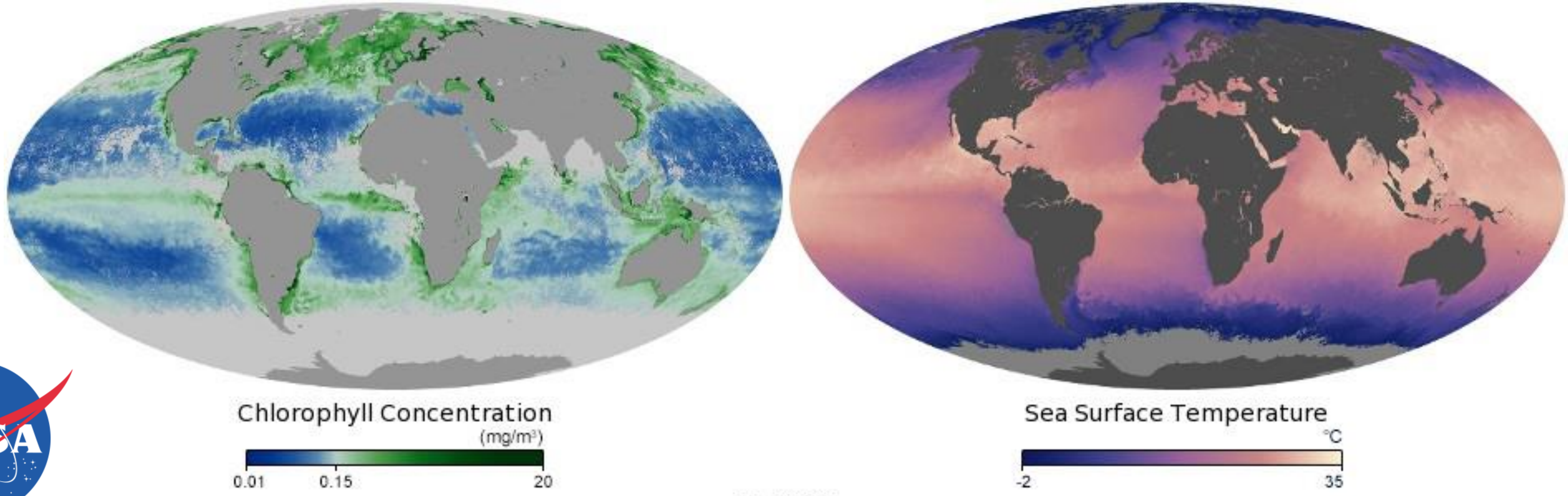
pCO_2 data are very sparse …
How to turn these into full coverage, monthly flux maps?





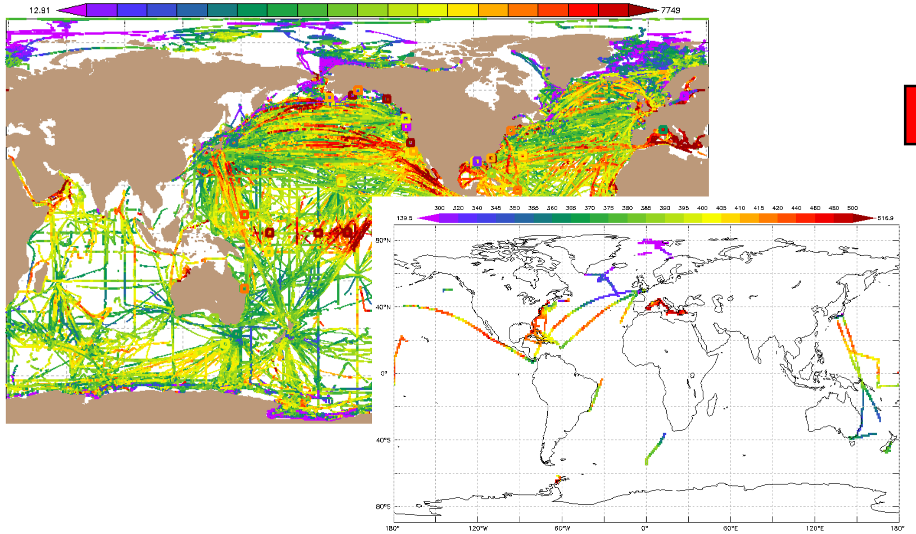
Full coverage data related to pCO_2 do exist

Chlorophyll (Chl) | **Sea Surface Temperature (SST)**

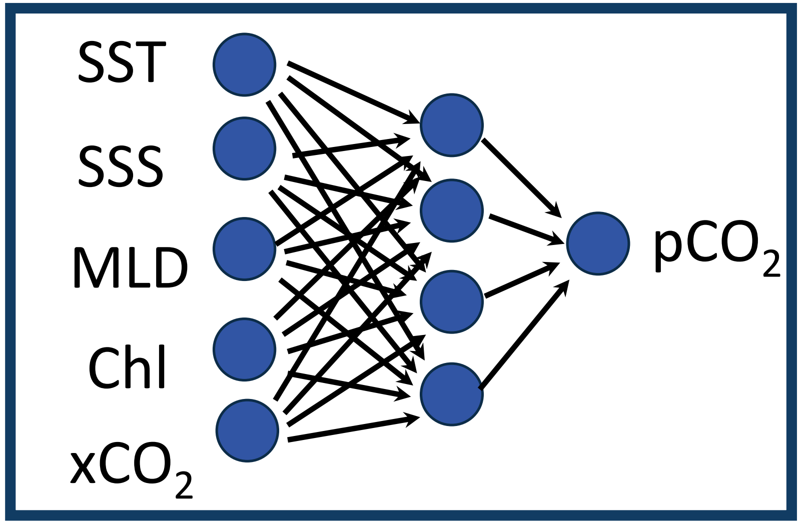


July 2002

Machine learning now common to extrapolate pCO_2 to global

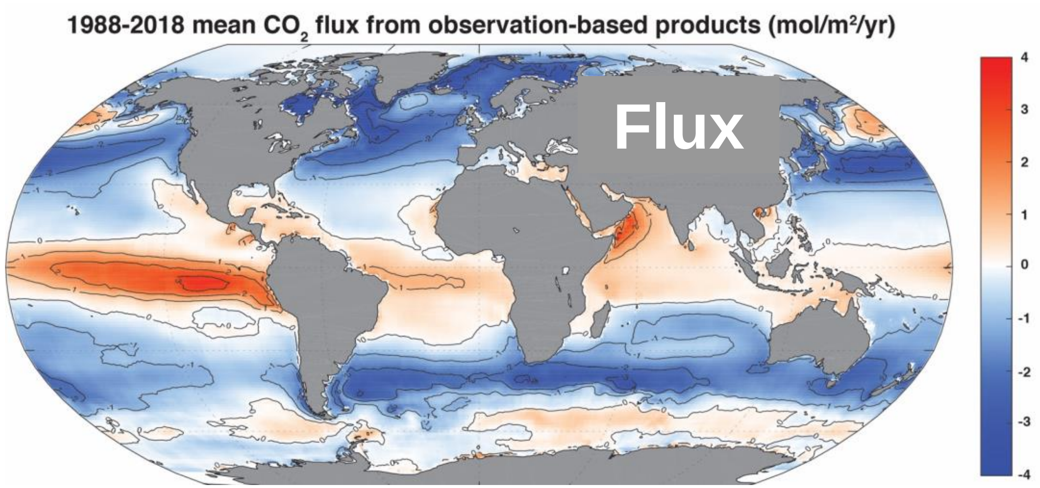


1. Train Machine Learning on sparse data



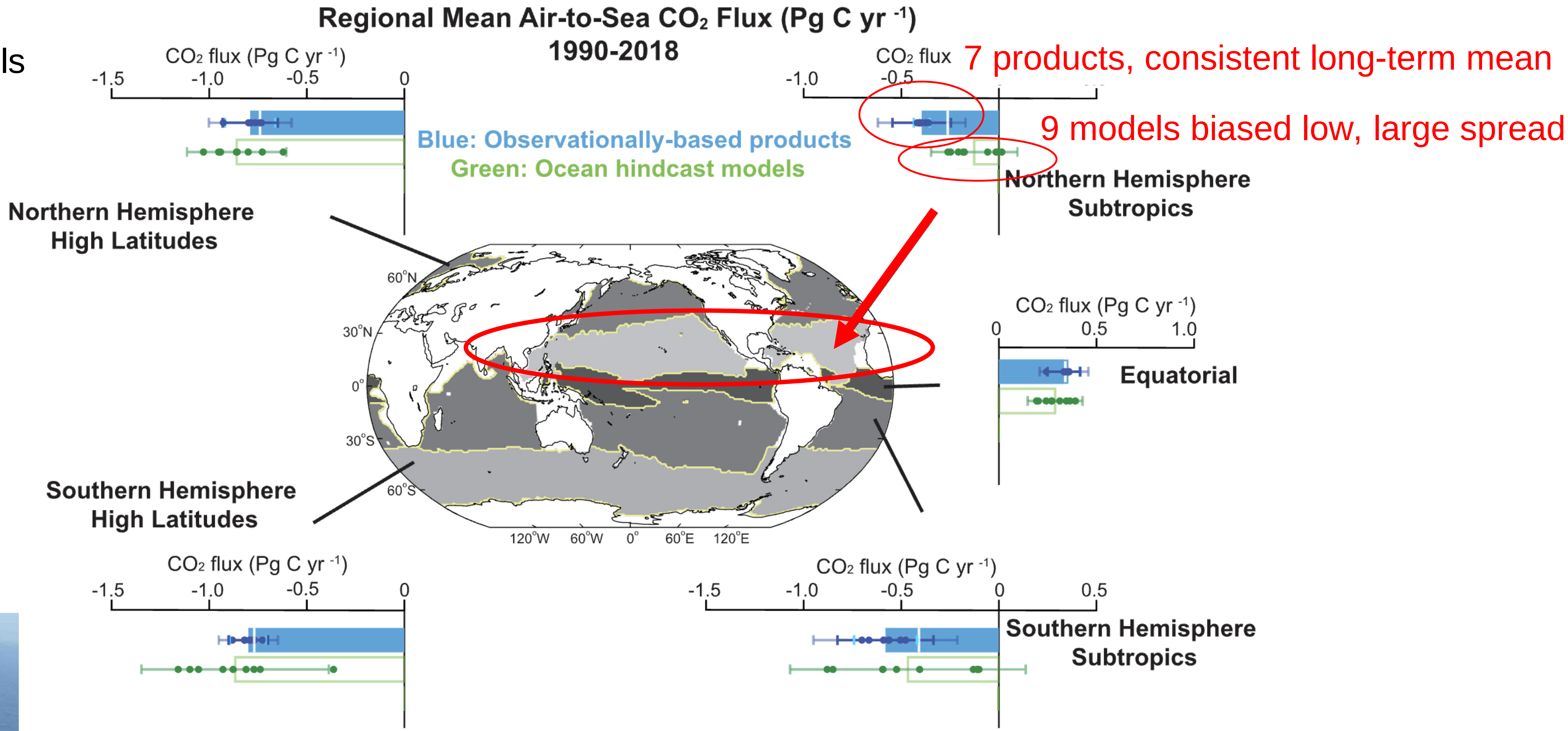
2. Predict $pCO_2 = f(SST, SSS, MLD, Chl, xCO_2)$

3. Calculate Flux from pCO_2



Ocean models have significant mean-state errors

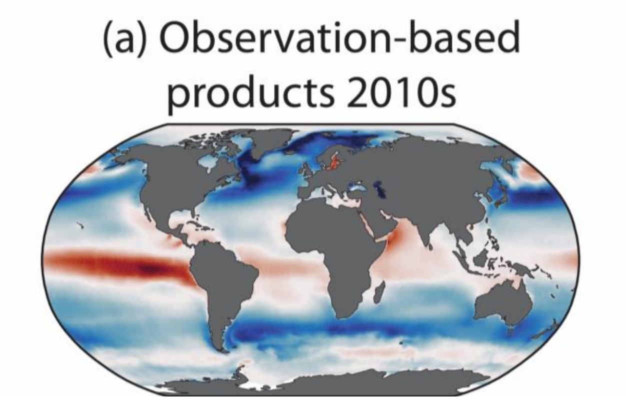
Products and hindcast models for real fluxes 1990-2018



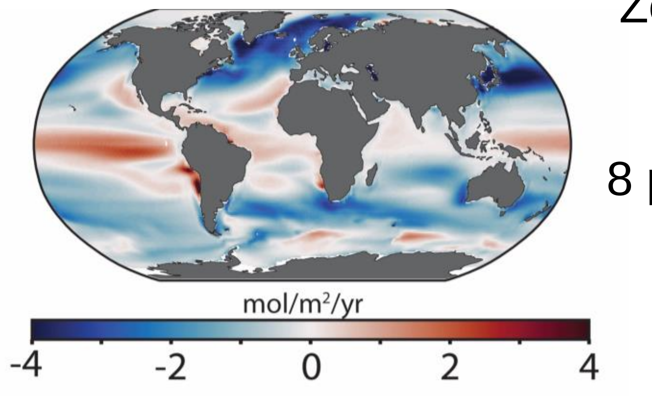
Fay and McKinley 2021

Mean-state biases are retained in CMIP6 projections

Modern = 2010-2020 Flux

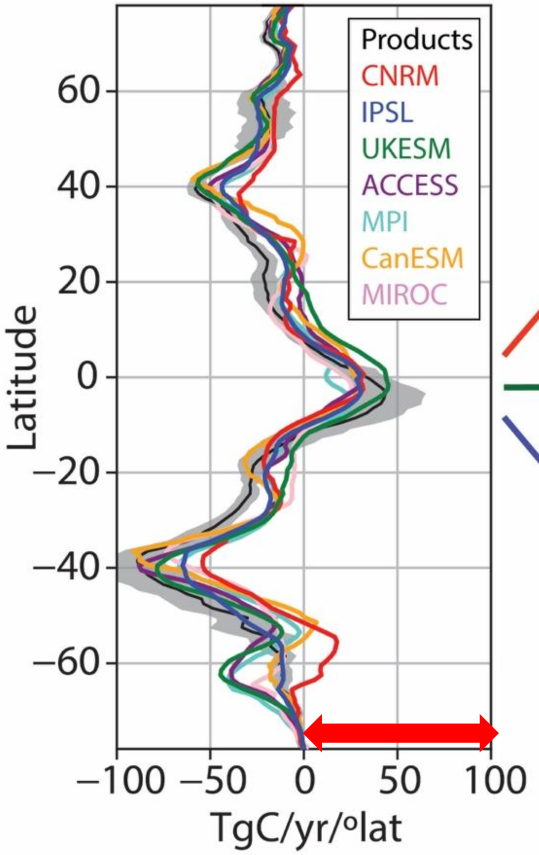


Example CMIP6 (IPSL)

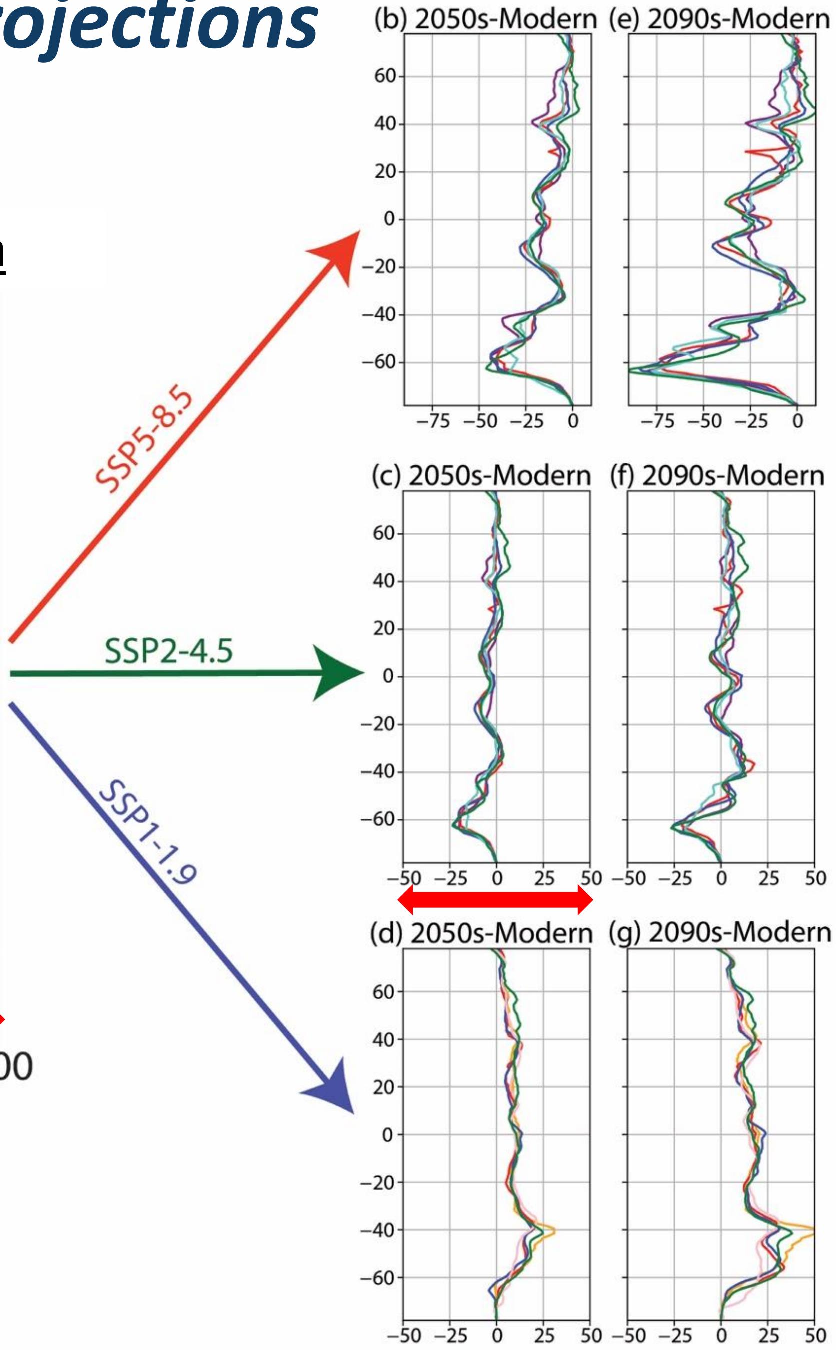


Zonal average of this comparison:
7 models (colors)
8 products (black/gray)

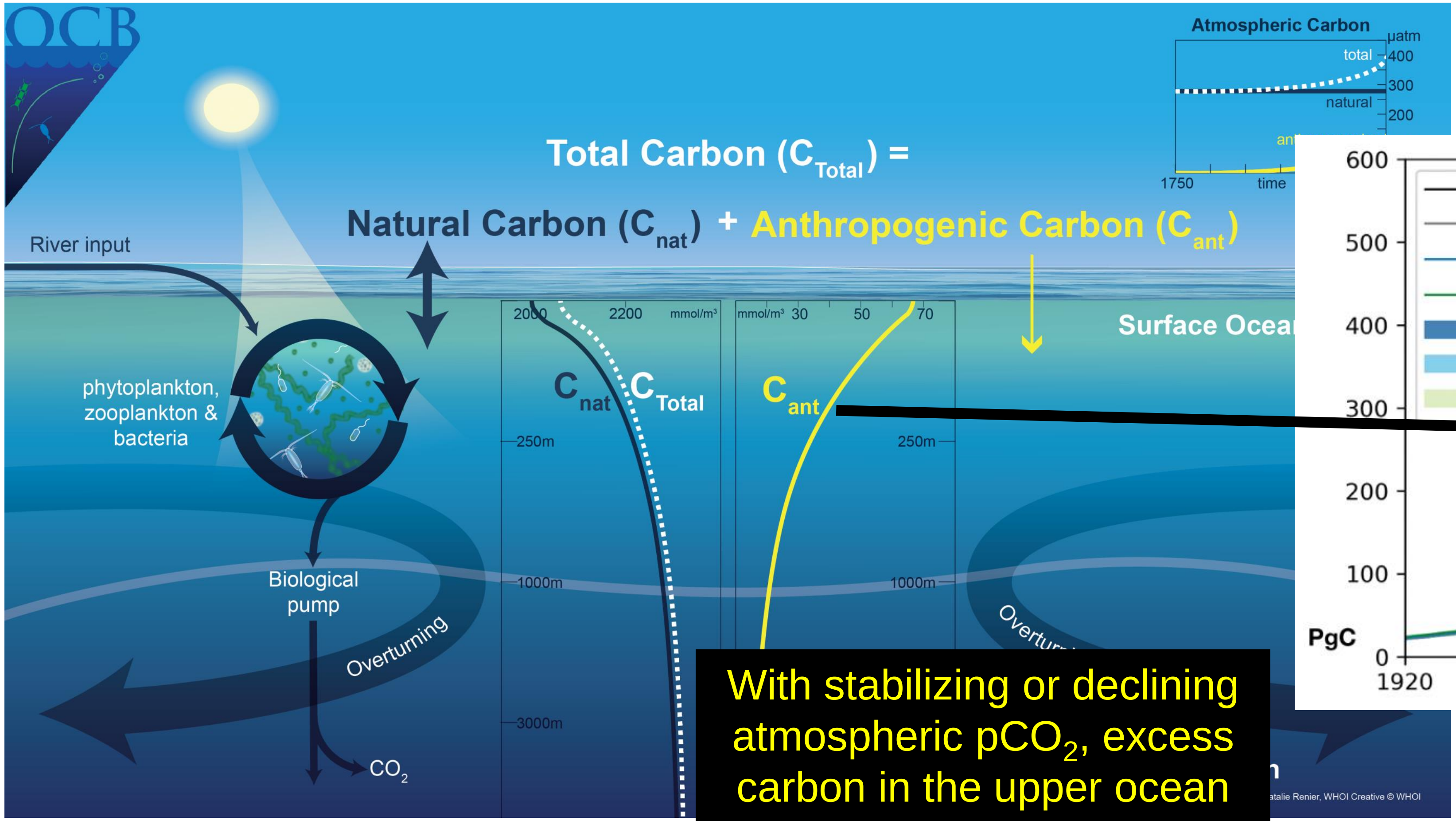
Modern Zonal-mean



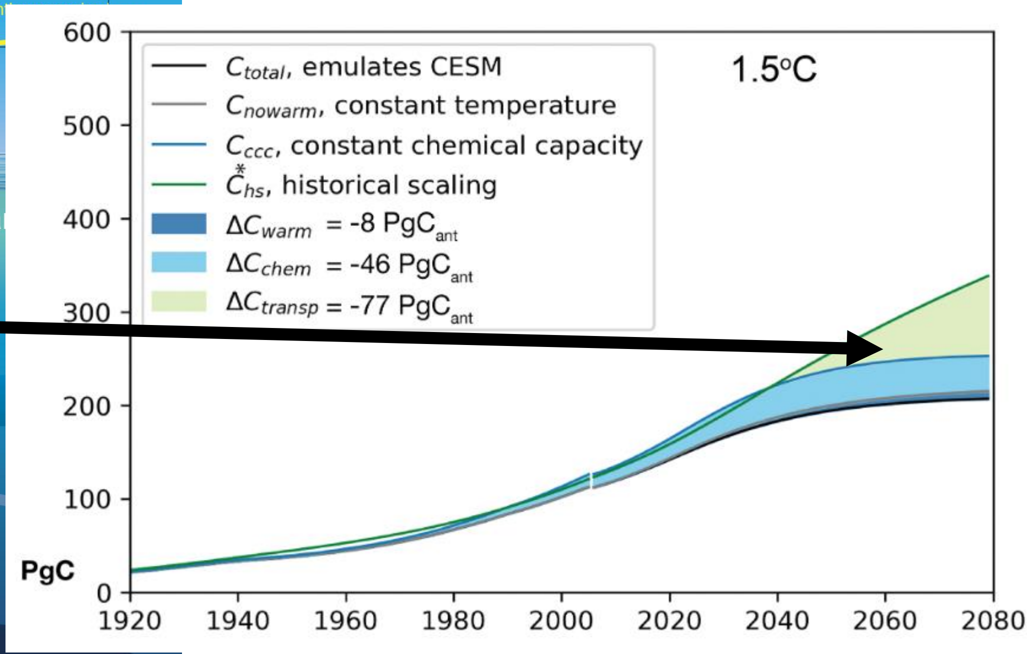
Future Flux change



If we meet climate targets, upper ocean re-circulation will be to dominant negative feedback on future ocean sink



With stabilizing or declining atmospheric pCO_2, excess carbon in the upper ocean will recirculate to surface



Ridge and McKinley 2021 Biogeosciences