The Natural Ocean Carbon Sink

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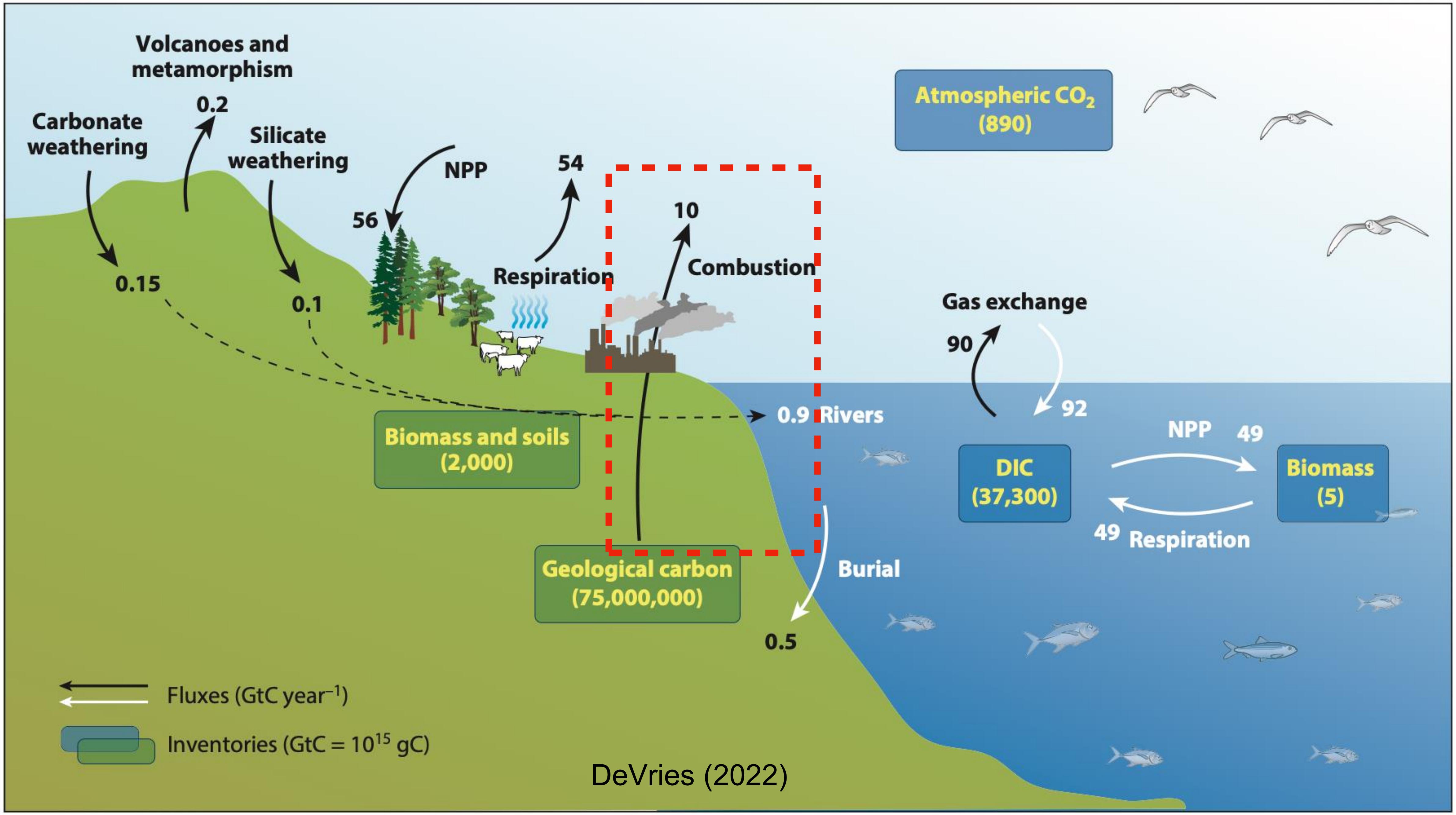
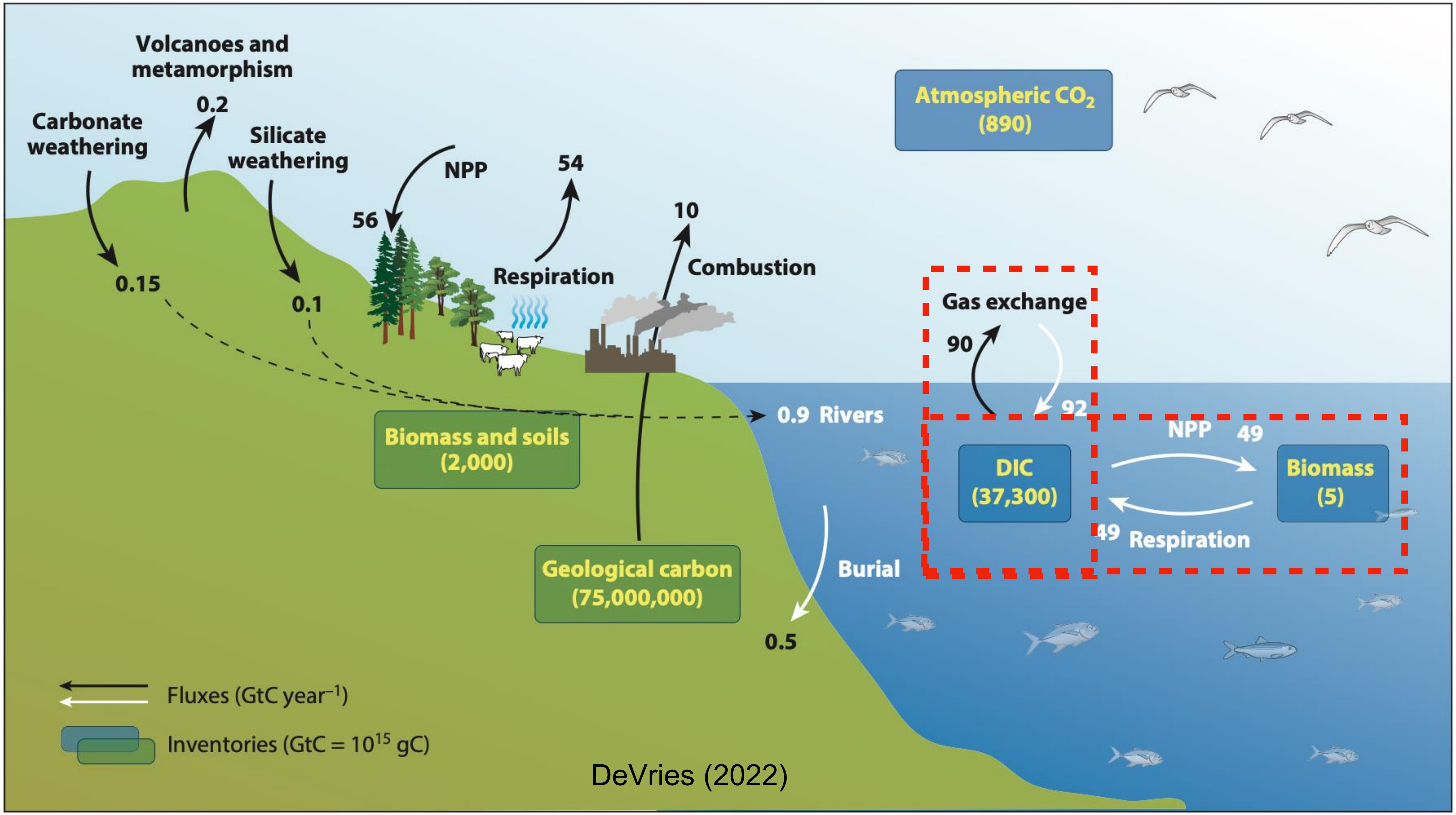
Global Carbon Cycle



DeVries (2022)

- Humans extract/combust ~10 GtC/yr from fossil fuel reserves (highly-concentrated carbon)
- FF industry employs ~30 million people, generates ~$3-4 trillion/year globally
- About half of this accumulates in the atmosphere (5 GtC/yr ~ 2.5 ppm CO_2/yr)
- The remaining 50% is roughly evenly absorbed into the terrestrial biosphere and ocean

Global Carbon Cycle



- The ocean plays a central role in the global carbon cycle as the largest natural carbon reservoir that rapidly exchanges with the atmosphere
- Roughly 90 GtC/yr cycles through air-sea gas exchange as inorganic CO_2
- Roughly 50 GtC/yr cycles through the organic carbon pool by photosynthesis/respiration

The Ocean Carbon "Sink"

The exchange (flux) of CO_2 between the ocean and atmosphere can be conceptualized as consisting of three components: "natural" (preindustrial) exchanges, anthropogenic CO_2 flux due to rising atmospheric CO_2, and climate-driven fluxes driven by climate variability.

The net contemporary sea-air CO_2 flux

"Anthropogenic CO_2" flux (steady climate, increasing CO_2)

"Climate-driven" CO_2 flux (variable climate)

"Natural steady-state" CO_2 flux (pre-industrial steady-state)

$$F_{sea-air} = F_{ant,CO2} + F_{climate} + F_{nat,ss}$$

Gross: ~90 GtC/yr

Net: ~2 GtC/yr

The "ocean carbon sink", or S_{OCEAN} in the Global Carbon Budget

Gross: ~60 GtC/yr

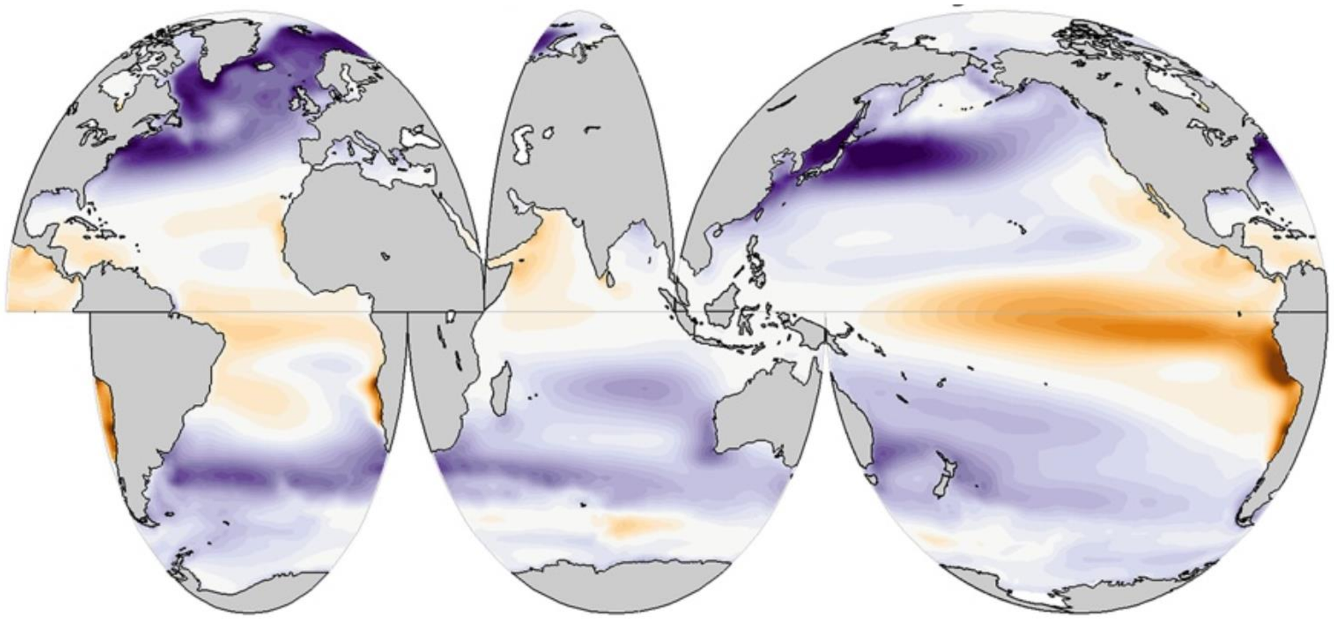
Net: ~-0.6 GtC/yr

Only $F_{sea\text{-}air}$ is directly observable (in theory). In practice, even $F_{sea\text{-}air}$ cannot be measured and must be estimated by models (e.g. "pCO_2 products").

The other terms on the right-hand side of the equation, including S_{OCEAN}, can never be directly observed and must be estimated by models.

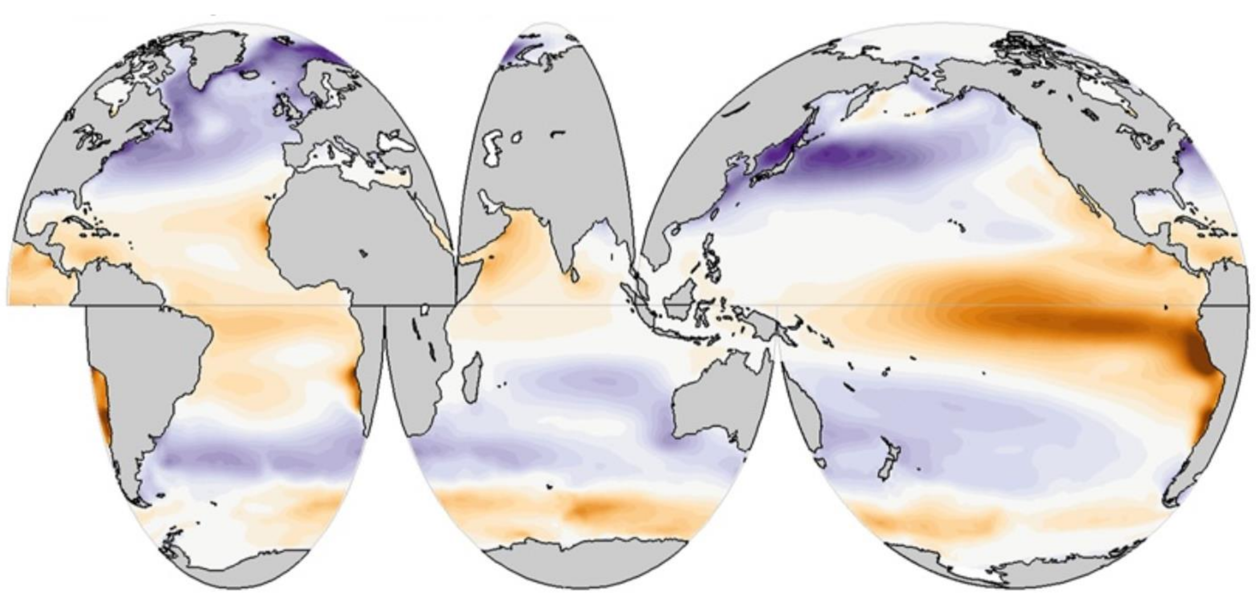
Contemporary and Natural CO_2 Fluxes

$F_{sea\text{-}air}$: Contemporary air-sea CO_2 flux



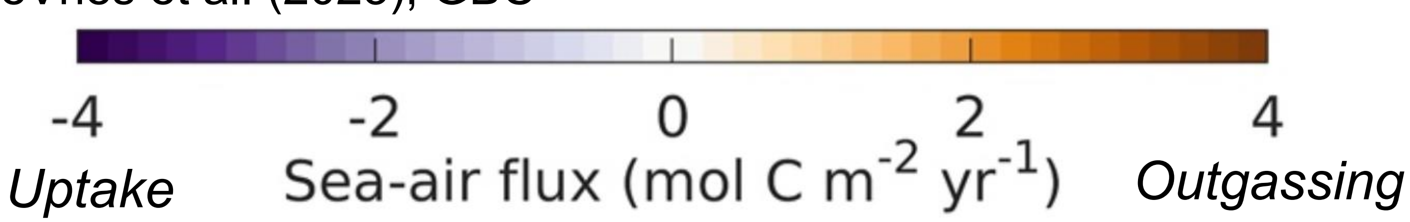
- Gross exchange of ~90 GtC/yr
- Driven by heat exchanges (~4-5 PW sensible heat), biological C cycling (~ 10 GtC/yr export, ~10 TW), and the ocean's overturning circulation (~1-2 TW).
- Compare to global human energy consumption ~20 TW

$F_{nat,ss}$: Preindustrial air-sea CO_2 flux



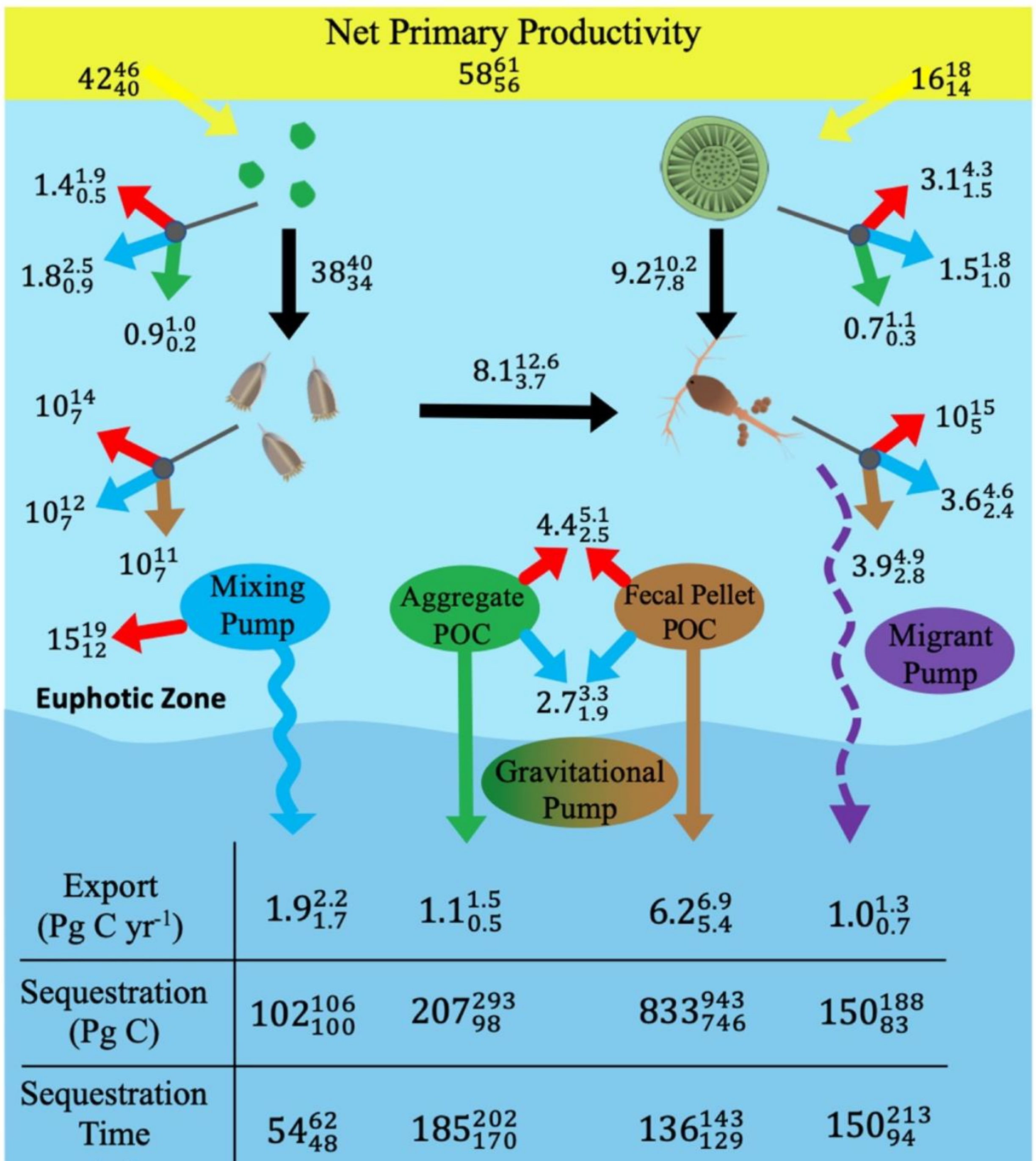
- Gross exchange of ~60 GtC/yr
- Very similar to total contemporary air-sea CO_2 flux
- Estimated net degassing of 0.6 GtC/yr from preindustrial ocean due to excess riverine C inputs

DeVries et al. (2023), GBC



Biological Pump Pathways

A key component of natural CO_2 cycling is the biological pump. The biological pump refers to the production of organic carbon in the surface ocean and its subsequent transport ("export") into the deep ocean, where it is sequestered as respired/remineralized DIC.



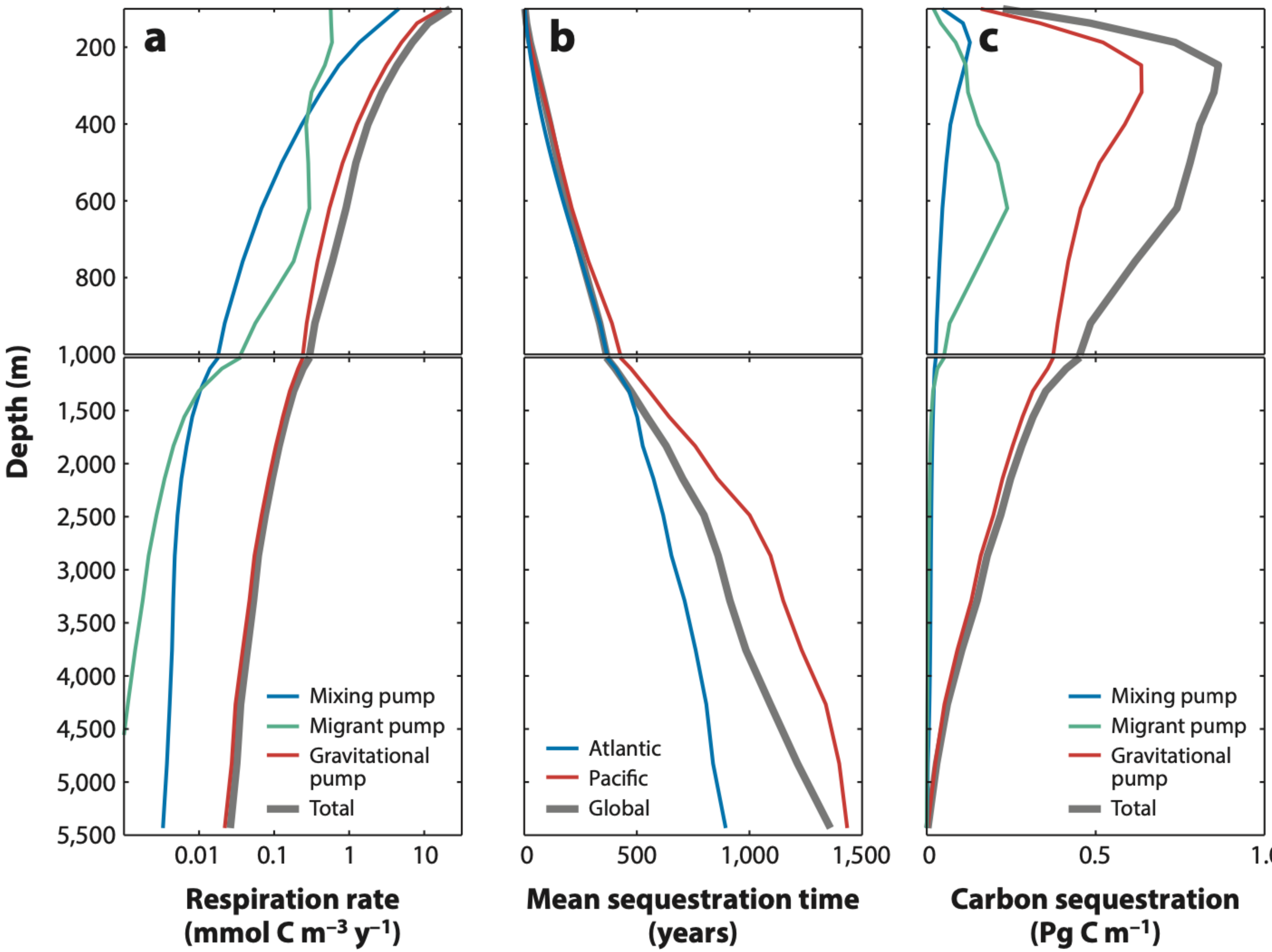
Nowicki et al. (2022)

Three main pathways of carbon export:

- ***Gravitational pump:*** Sinking of particulate organic carbon from all trophic levels of food web
  - Total export ~5-7 GtC/yr
  - Total sequestration ~800-1100 GtC
  - Sequestration time ~150-200 years
- ***Mixing pump:*** Downward mixing of suspended and dissolved organic carbon
  - Total export ~2-3 GtC/yr
  - Total sequestration ~100-150 GtC
  - Sequestration time ~50 years
- ***Migrant pump:*** Daily to seasonal vertical migrations of zooplankton and fish
  - Total export ~1-2 GtC/yr
  - Total sequestration ~150-400 GtC
  - Sequestration time ~100-250 years

Air-sea disequilibrium enhances biological DIC sequestration by ~35-70%.

Biological Pump Sequestration

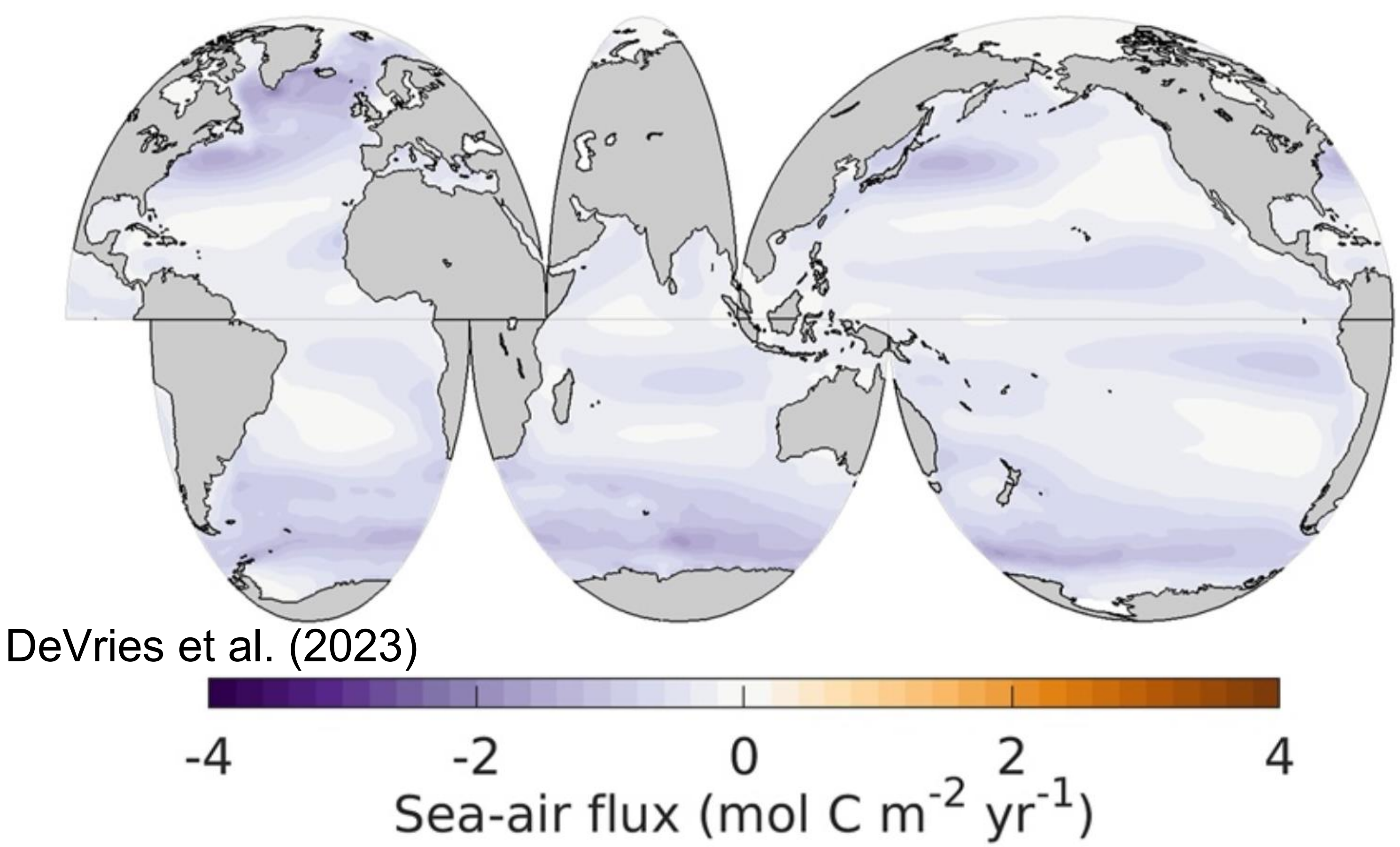


- Sequestration time increases with depth, and is highest in the Pacific Ocean
- About 50% of the carbon sequestration by the biological pump is driven by remineralization in the upper 1000 m
- Low remineralization rates but high sequestration times below 1000 m

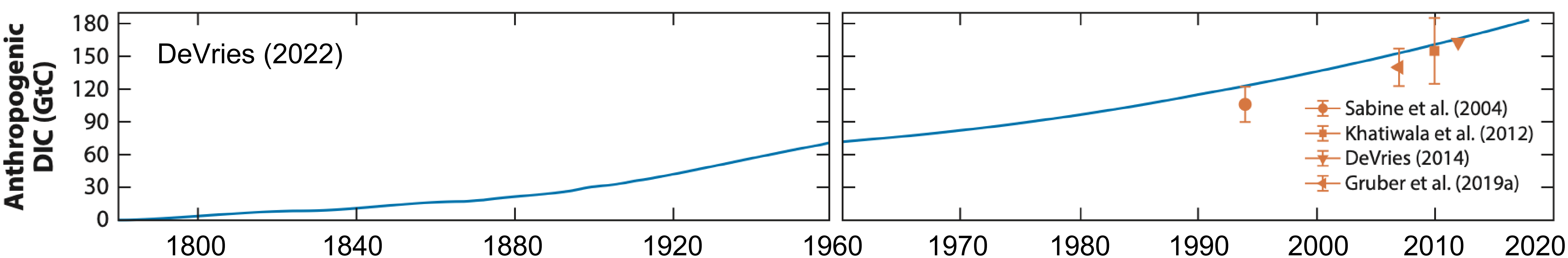
Siegel et al. (2023)

Anthropogenic Carbon Fluxes

F_{ant,CO_2}: Anthropogenic CO_2 flux



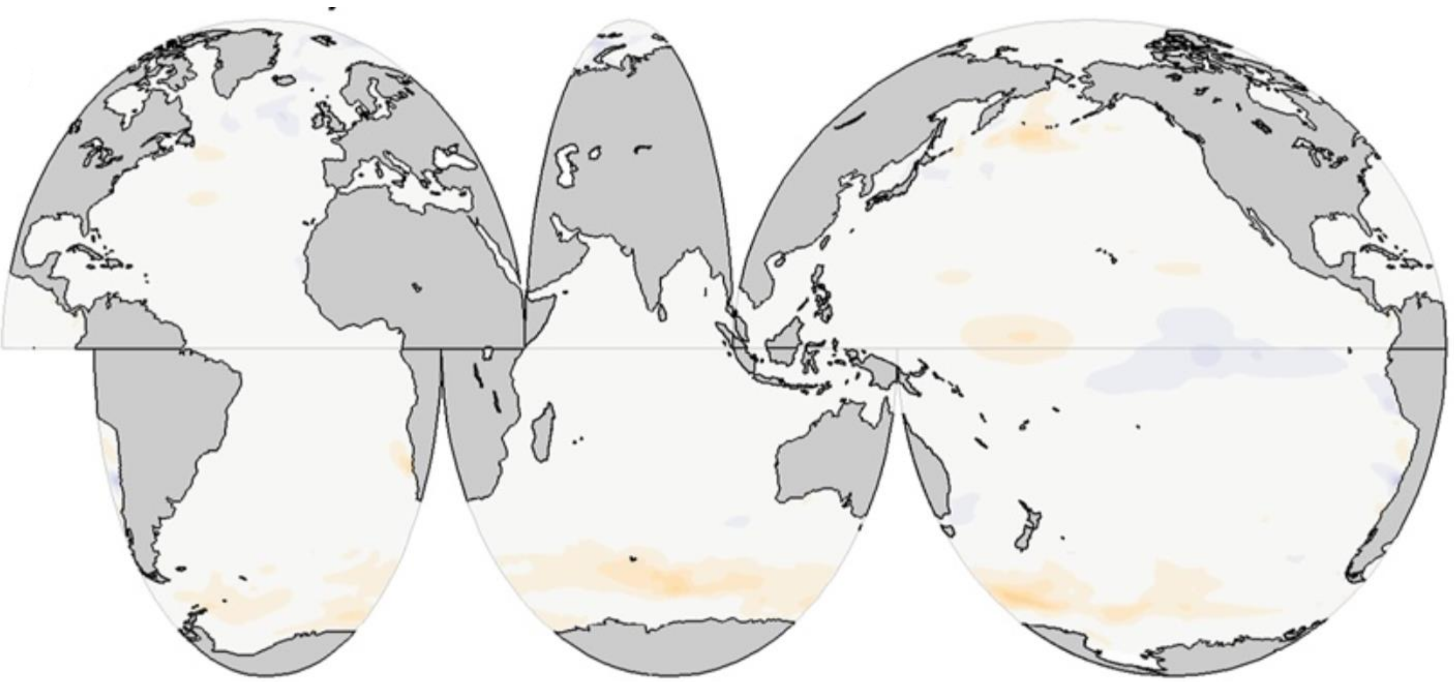
- Gross exchange of ~30 GtC/yr
- Global uptake of ~3 GtC/yr driven by increasing atmospheric CO_2
- Uptake is largest where waters upwell to surface (Southern Ocean, subpolar regions), or are transported rapidly to high latitudes (western boundary currents)
- Biological pump is not important for this uptake



The ocean DIC inventory has increased by ~200 GtC (~0.5%) due to the uptake of anthropogenic CO_2 since the start of the industrial era. Consequent decrease in pH and buffering capacity.

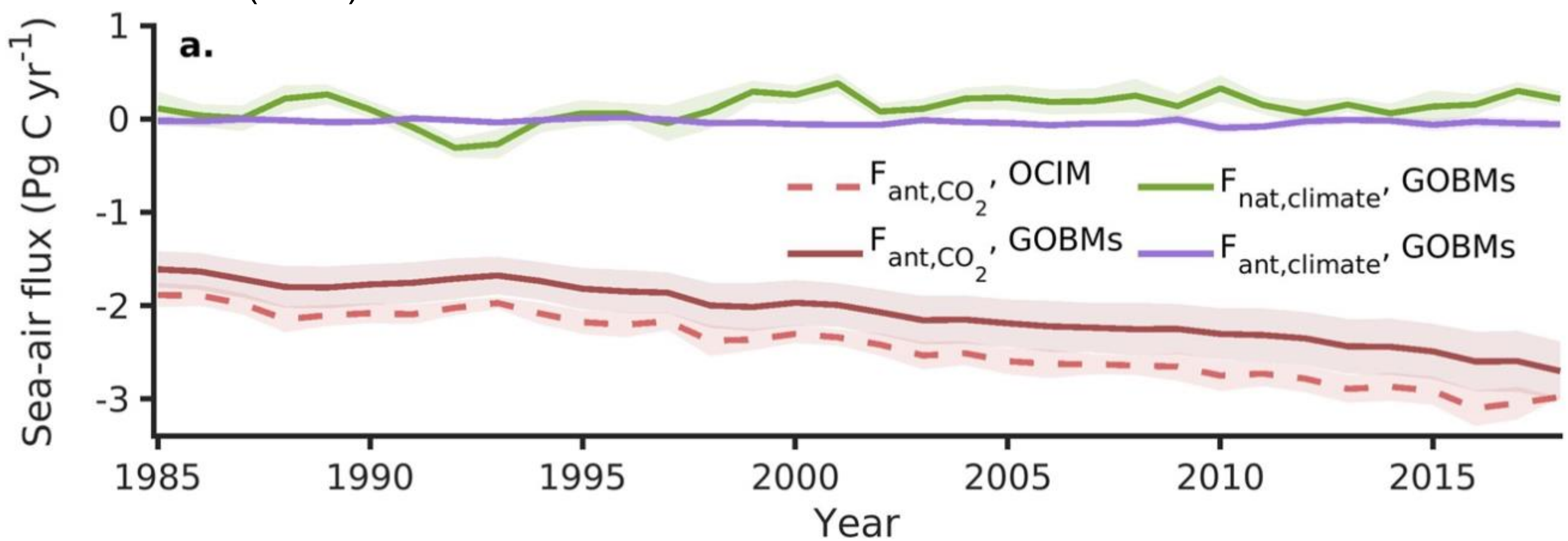
Climate-Driven Carbon Fluxes

$F_{ant,CO2}$: Anthropogenic CO_2 flux



- Small values
- Negligible on long-term, global scale
- Contributes to shorter-term (interannual) variability in the ocean carbon sink

DeVries et al. (2023)



Climate-driven fluxes (green) are small and variable

Anthropogenic fluxes (green) are large and steadily increasing

For perspective: El Nino events release the energy equivalent of millions of hydrogen bombs (per NOAA). But, the impact on global atmospheric CO_2 is relatively minor.

Ocean Carbon Sink Components: Current Best Estimates

Table 3
"Best Estimate" of Ocean Carbon Sink Components Averaged Over the Time Period 2001–2018

Sea-air CO_2 flux component	Value ($PgC\ yr^{-1}$)	Reported uncertainty	Additional uncertainty (estimated)	Source
$F_{sea\text{-}air}$	−1.9	±0.2	±0.6	pCO_2 products
★ $F_{ant,CO2}$	−2.7	±0.1	±0.3	OCIM
$F_{land\text{-}sea,ss}$	+0.65	±0.3	–	Regnier et al. (2022)
★ $F_{climate}$	+0.1	±0.1	±0.3	GOBMs

DeVries et al. (2023)

Global Carbon Project
REgional Carbon Cycle Assessment and Processes
Phase 2
RECCAP2

★The largest term in the carbon sink is $F_{ant,CO2}$. This is a counterfactual that can only be estimated by models. Data assimilation models (e.g. OCIM) can provide the best estimate of this quantity.

★The other component relevant for S_{OCEAN} is $F_{climate}$. Our best estimates come from biogeochemical models run in hindcast mode. They produce very small values of $F_{climate}$, but they may underestimate $F_{climate}$.

★Will we eventually have a F_{CDR} term?