

Reimagining the Modeling of Ocean Biosphere Dynamics: From Missing Processes to Earth System Prediction

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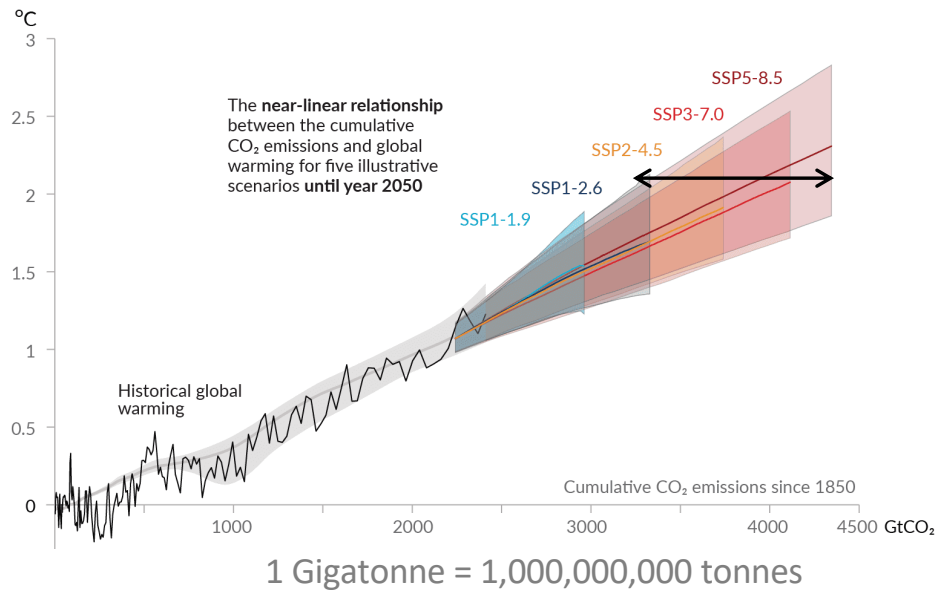
MAX-PLANCK-INSTITUT
FÜR MARINE MIKROBIOLOGIE



Climate change is essentially a CO₂ problem (as well as N₂O, CH₄) ...

– every tonne of CO₂ emissions adds to global warming

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO₂ emissions (GtCO₂)



IPCC AR6 WGI Summary for Policymakers

TCRE: transient climate response to CO₂ emissions

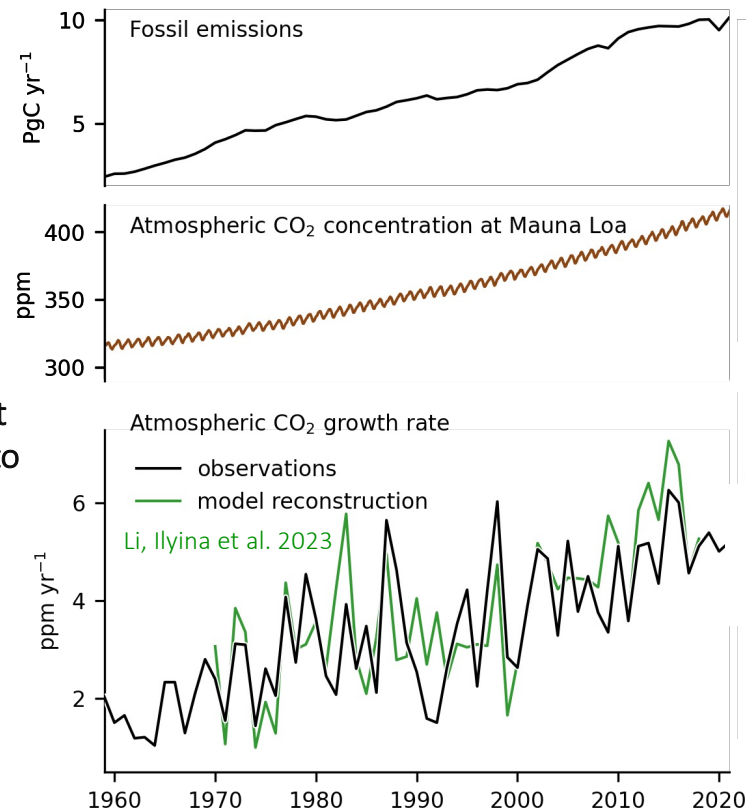
- Large uncertainty in CO₂ emissions compatible with a given climate target
- Spread in model projections due to uncertain physical and biogeochemical feedbacks on climate
- Ongoing assessment of TCRE (led by C. Jones, P. Friedlingstein, T. Ilyina, R. Seferian et al.) to develop interpretive model framework to combine multiple lines of evidence.

Where does the anthropogenic carbon go?

Only half of the emitted CO₂ stays in the atmosphere;
oceans currently absorb one third

Longer-term changes follow emissions pace; **ocean is the largest sink for emitted CO₂ on centennial to millennial timescales**

Interannual changes are driven by the response of carbon sinks to climate variability



*Global Carbon Budget; Friedlingstein et al. incl. Ilyina
IPCC AR6 WG1; Ilyina – Contributing Author*

Knowledge gaps

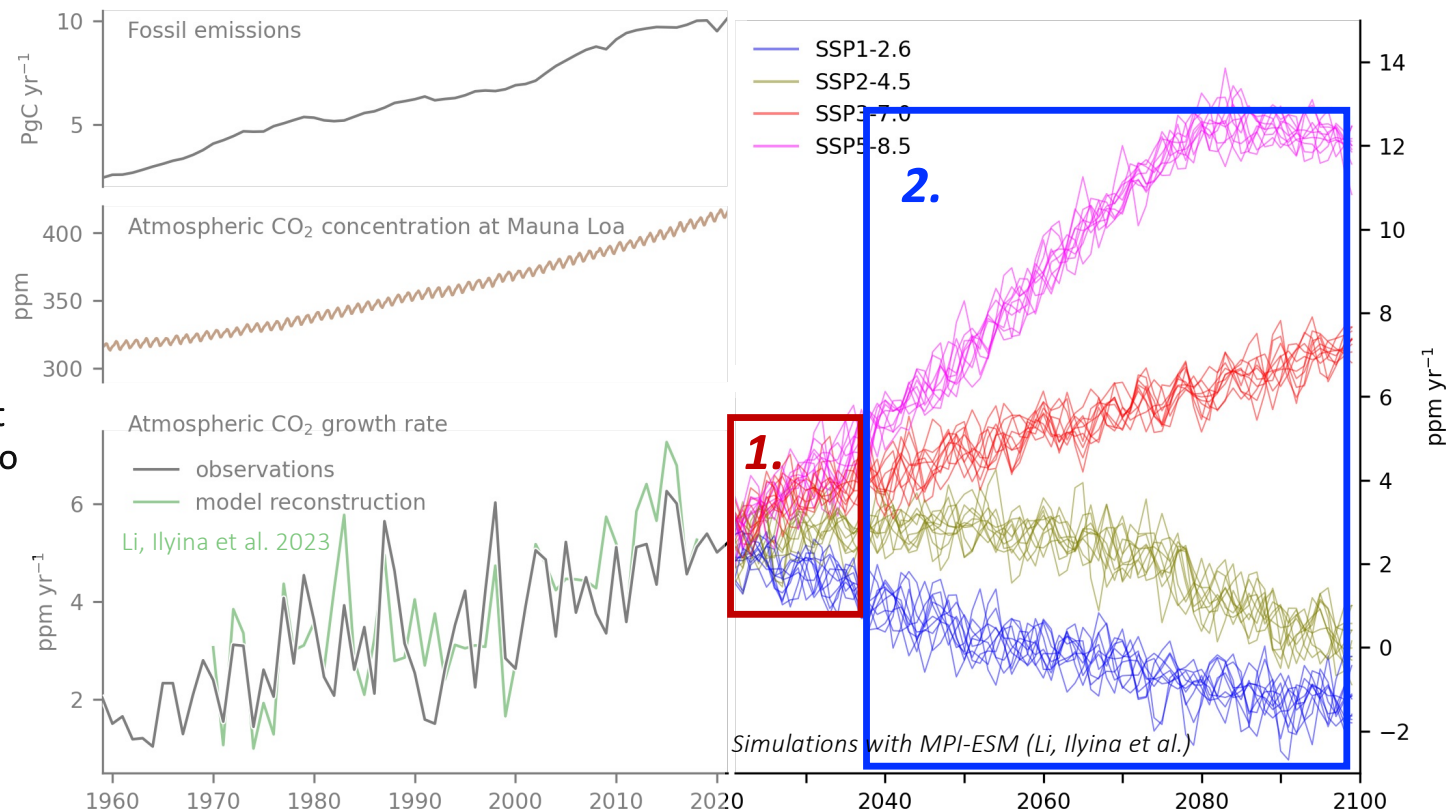
1. Indiscernible changes on decadal timescales

2. Unknown response to rapid and strong changes in emission

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Ilyina et al. 2021
Li, Ilyina et al. 2016; 2019; 2023
Spring and Ilyina 2020
Spring et al. 2020

Ilyina 2022
Li and Ilyina 2018
Fröb et al. incl. Ilyina 2020
Maher et al. incl. Ilyina 2019

Paulsen et al. 2017; 2018
Maerz et al. 2020; in prep.
Mathis et al. 2022; 2024
Liu et al. 2024

Nielsen et al. 2022; 2024
Lacroix et al. 2021a; b
Kwiatkowski et al. 2020

Ocean is the largest climate-relevant carbon sink

→ small changes in ocean carbon impact climate

→ complex interactions limit our understanding
(Earth system models are powerful tools)

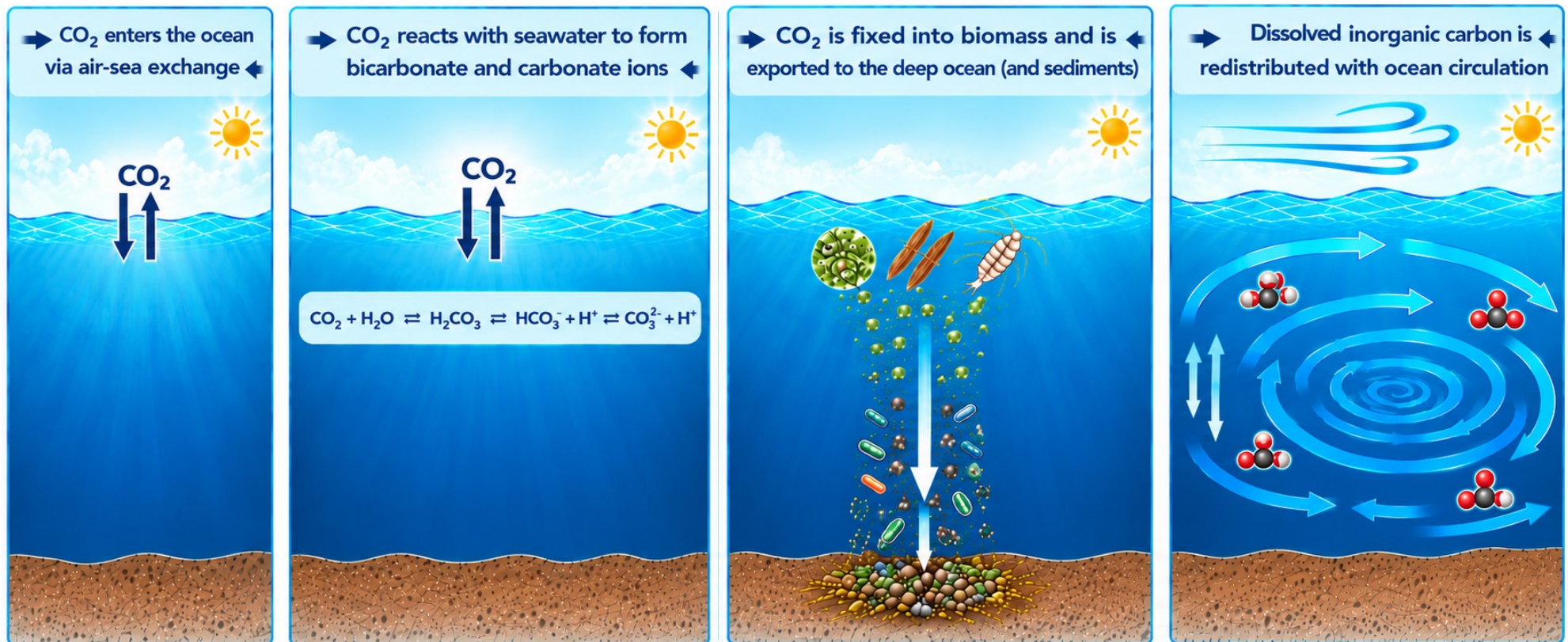
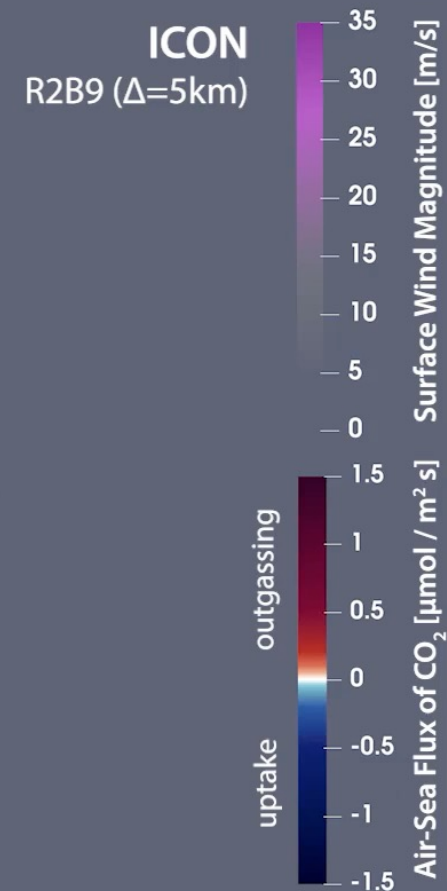
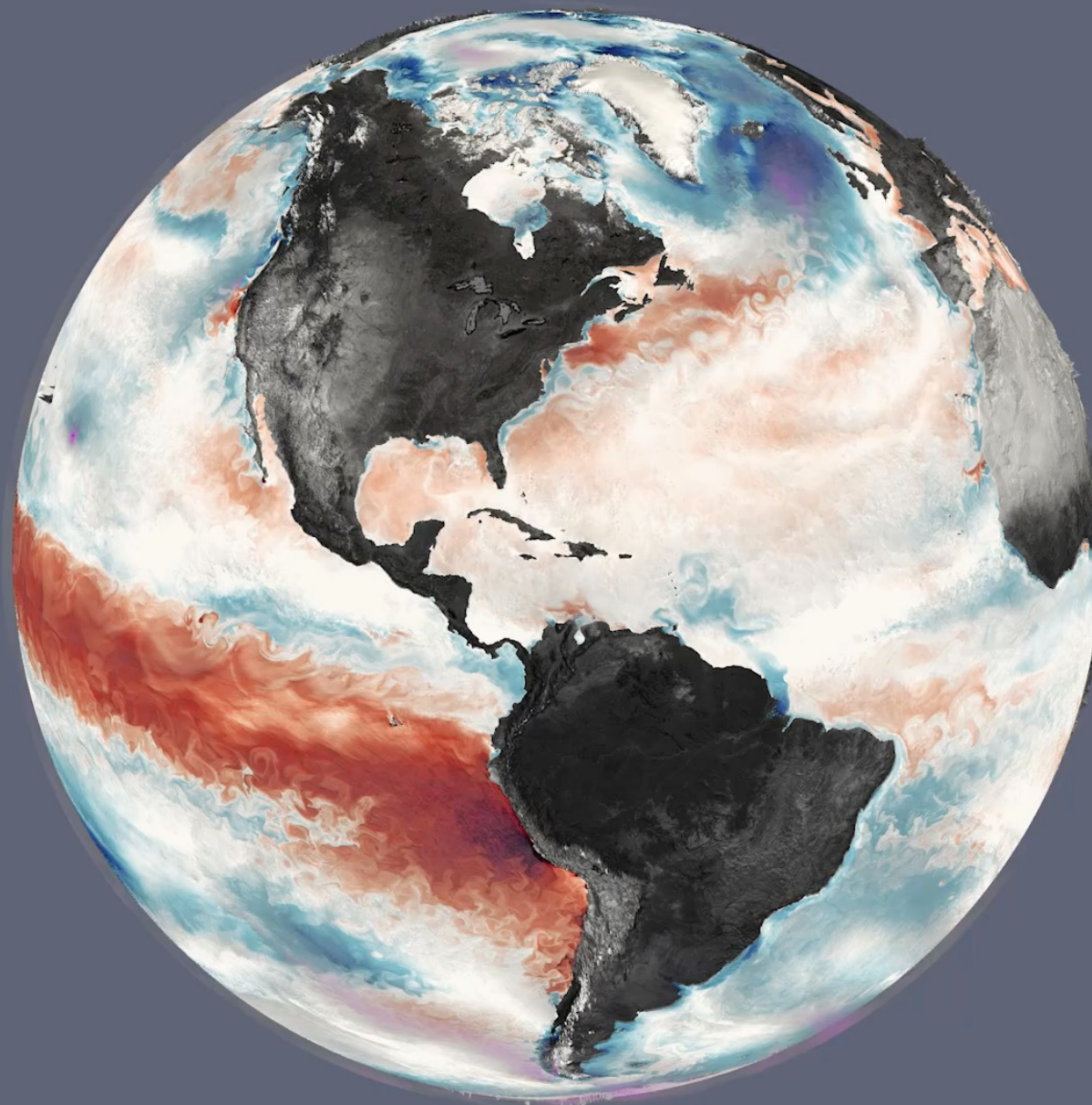


Figure produced with help of AI



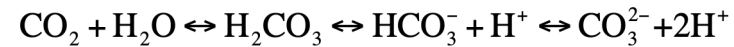
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Credit: MPI-M/DKRZ 2023

Components of an ocean biogeochemical model

Carbonate chemistry:

mass balance equations,
chemical fields integrated over time/space



$$[\text{CO}_2] = K_0(T, S) \cdot p\text{CO}_2$$

$$K_1 = \frac{[\text{HCO}_3^-][\text{H}^+]}{[\text{CO}_2]} \quad K_2 = \frac{[\text{CO}_3^{2-}][\text{H}^+]}{[\text{HCO}_3^-]}$$

accurate representation in ESMs is challenging



Biology:

semi-empirical process parameterizations,
extended NPZD approaches

$$\frac{\partial \text{Phy}}{\partial t} = G_{\text{phy}} - F_{\text{pz}} - M_{\text{phy}} - E_{\text{phy}},$$

$$\frac{\partial \text{Zoo}}{\partial t} = G_{\text{zoo}} - M_{\text{zoo}} - E_{\text{zoo}},$$

G – growth F – grazing M – mortality E – exudation

Transport of tracers (prognostic variables):

advection and diffusion, computed by the Ocean
General Circulation Model in the same manner as
for temperature and salinity

$$\frac{\partial U}{\partial t} - fV + gH \frac{\partial \zeta}{\partial x} + \int_{-H}^{\zeta} \frac{\partial}{\partial x} p' dz = 0$$

$$\frac{\partial V}{\partial t} + fU + gH \frac{\partial \zeta}{\partial y} + \int_{-H}^{\zeta} \frac{\partial}{\partial y} p' dz = 0$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = Q_{\zeta}$$

Components of an ocean biogeochemical model

– as interactive component of
Earth system models

HAMburg Ocean Carbon Cycle model (Ilyina et al. 2013; Maier-Reimer and Hasselmann 1987)
– a tool to test our ideas

Carbonate chemistry:

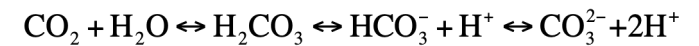
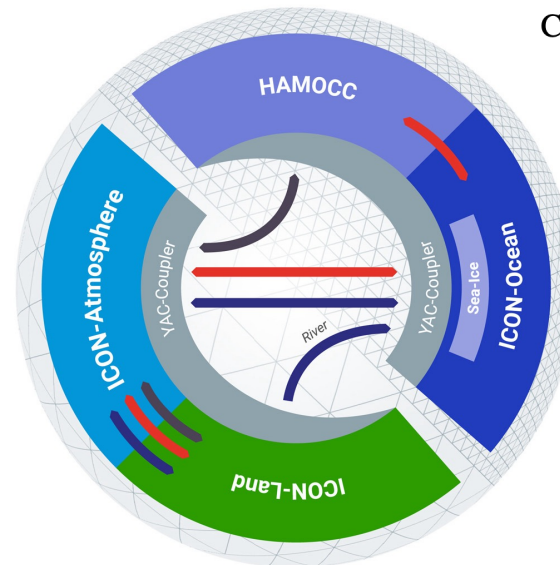
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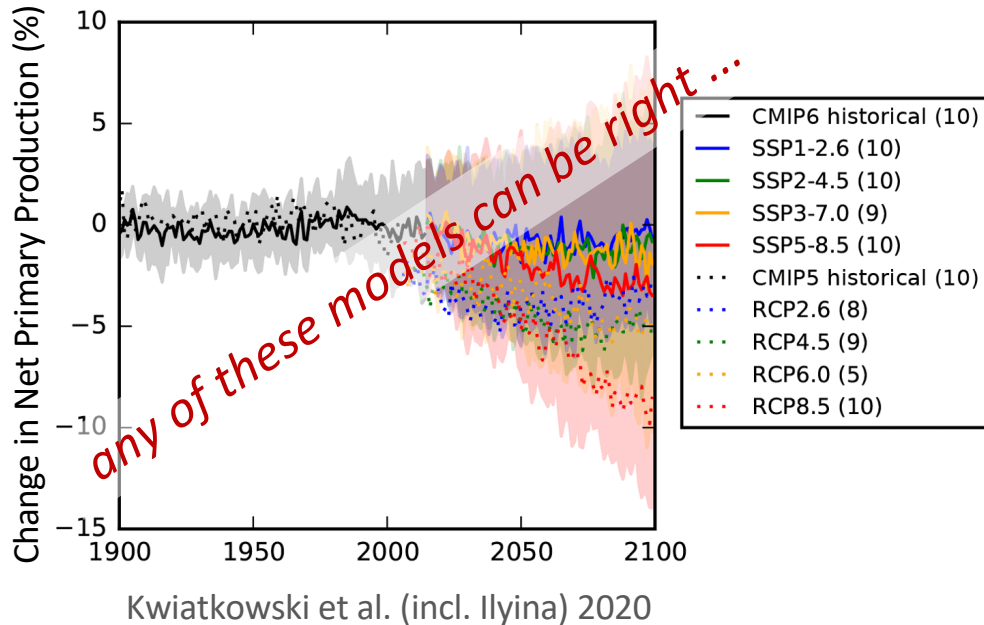
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Why do ESMs fail to accurately represent marine biological processes?



- Vastly different estimates of primary production, export fluxes
→ ***uncertain estimates of carbon storage in the ocean***
- ESMs do not embrace biological empirical evidence to date
→ ***underrepresenting complexity of marine life***
- **integration of tracers is computationally expensive**
e.g. in HAMOCC now: ~30 tracers; 2+ phytoplankton, 1 zooplankton, rates of many processes represented with invariable coefficients, no microbes ...

IPCC AR6: *High confidence* that feedbacks to climate will arise from alterations to marine biology
But *low confidence* in the magnitude or even sign of these biological feedbacks

Two approaches to address knowledge gaps:

1. By improving climate physics; effects of physical climate and ocean processes

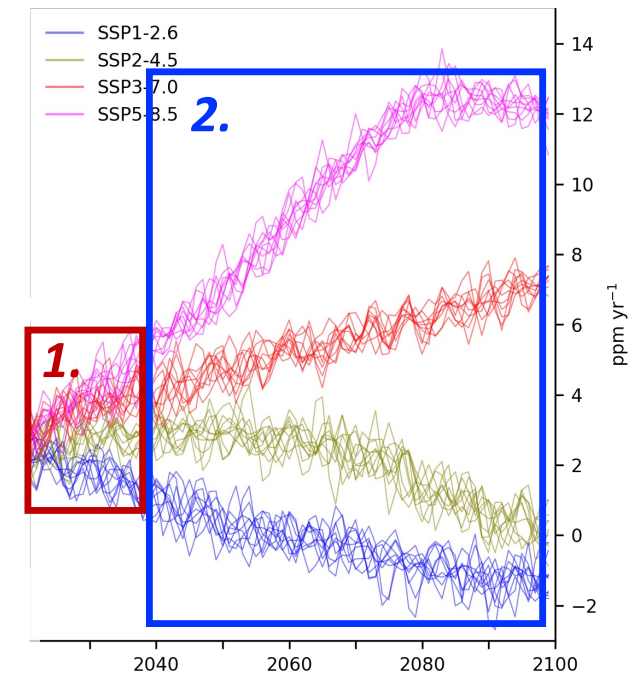
Indiscernible changes on decadal timescales

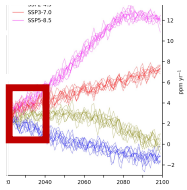
- Unraveling response to climate **variability**: Spring et al. 2020

2. By introducing missing biological processes; enhancing process complexity

Unknown response to rapid and strong changes in emission

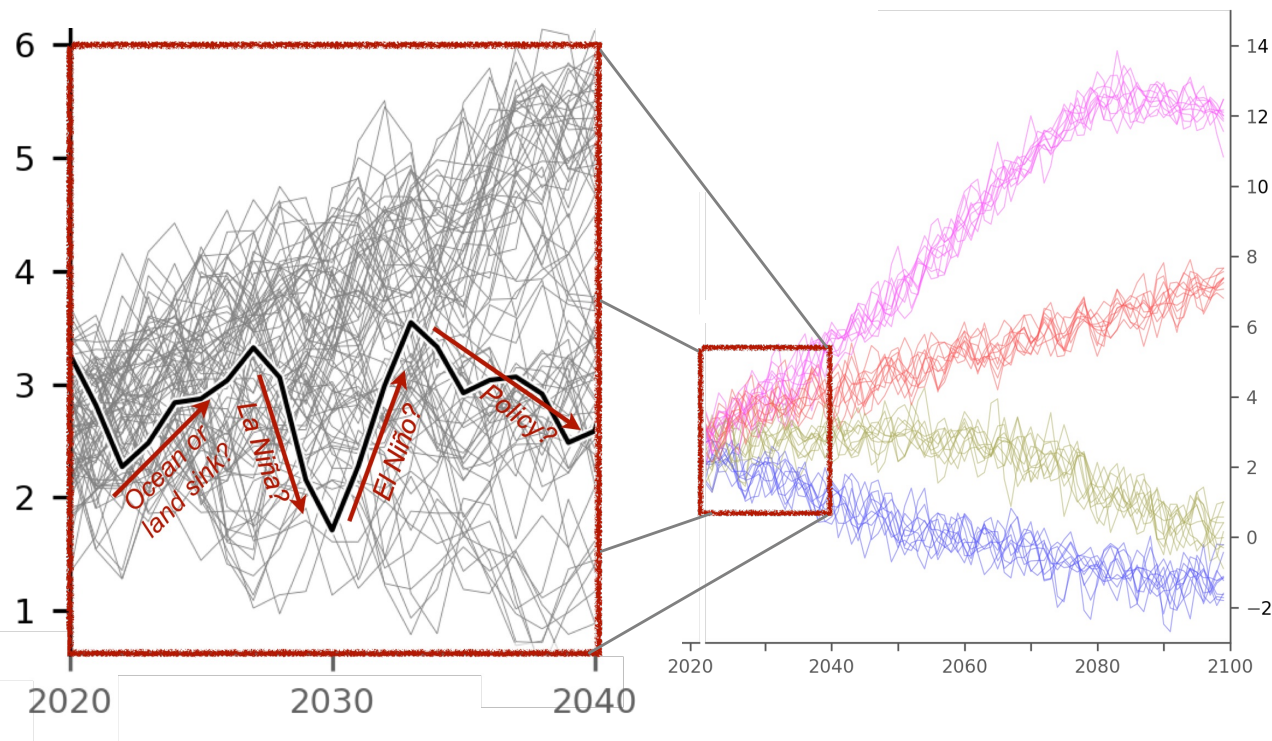
- **N₂ fixation** by *Trichodesmium*: Paulsen et al. 2017; 2018
- Structure of **marine aggregates**: März et al. 2020; 2025



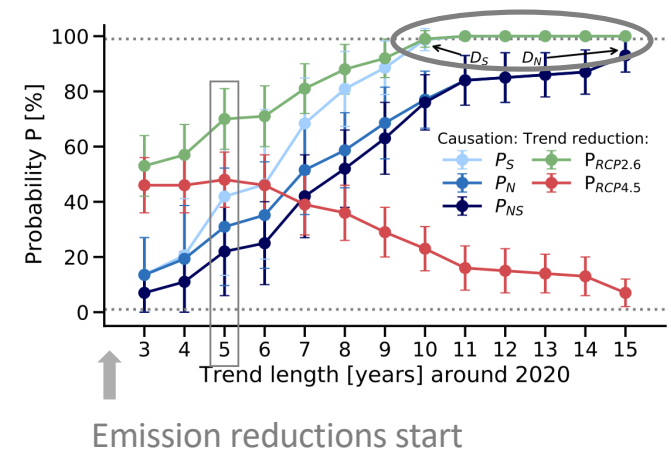


When do CO₂ emission reductions become measurable?

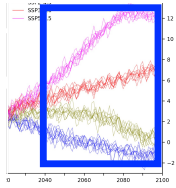
- Certainty of causation of CO₂ emissions reductions is delayed due to climate variability by 10-15 years (faster than for temperature)
- Three-out-of-ten chance that atm. CO₂ rises stronger during the five years after emission reduction



Probabilities of trend reduction in atm. CO₂ between periods of varying trend length before and after emission reductions start in 2020

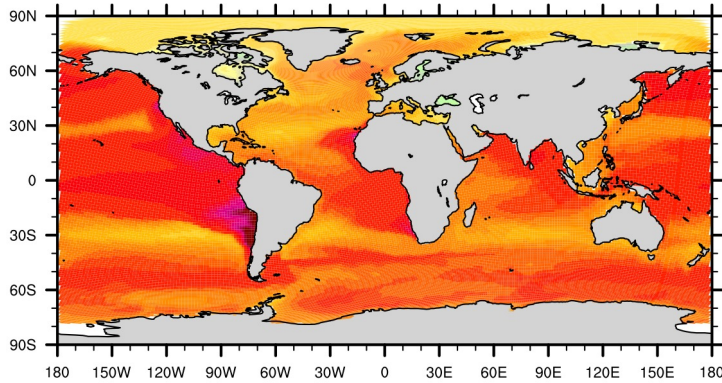


Spring et al. *Environ. Res. Letters* 2020

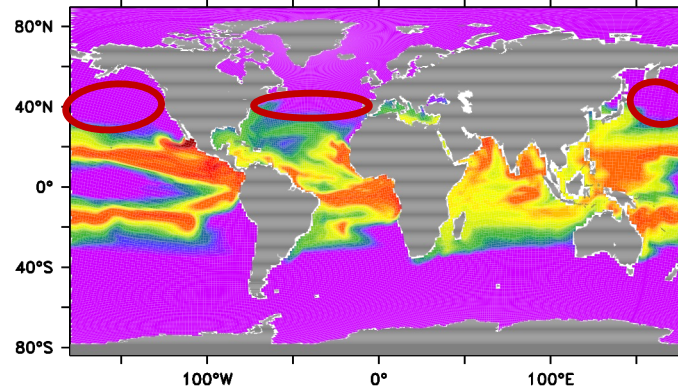


Including missing biological processes: **N₂ fixation** → is the main supply of bioavailable new N to the ocean's euphotic zone

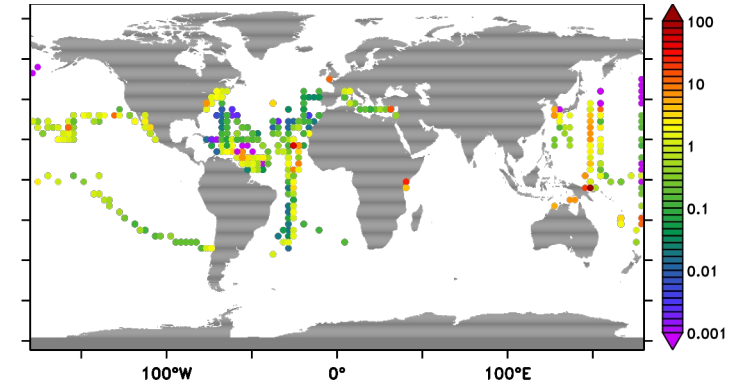
N₂ fixation at const rate



Prognostic N₂ fixation by *Trichodesmium*



Observations



Unrealistically high N₂ fixation rates

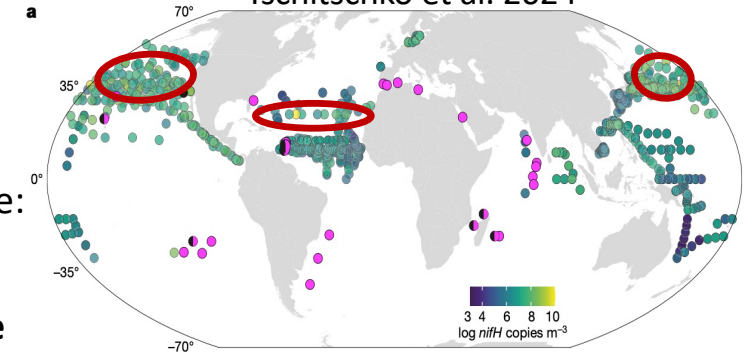
Paulsen et al., 2017, 2018: Improved N₂ fixation and N₂O fluxes

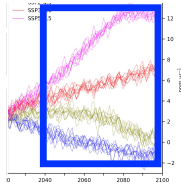
Co-limitation of *Trichodesmium* growth by iron and phosphate:

→ less biomass in a warmer stratified ocean

→ **decreased biological carbon storage under climate change**

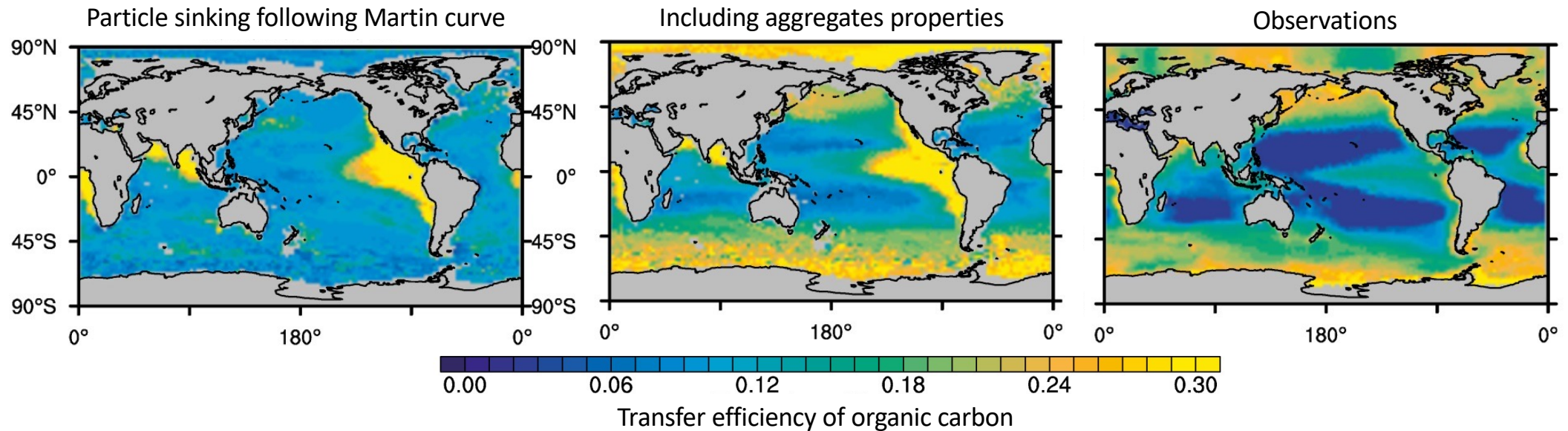
Tschitschko et al. 2024





*Including missing biological processes: **marine aggregates***

→ the primary vehicles of organic carbon transport into the deep ocean

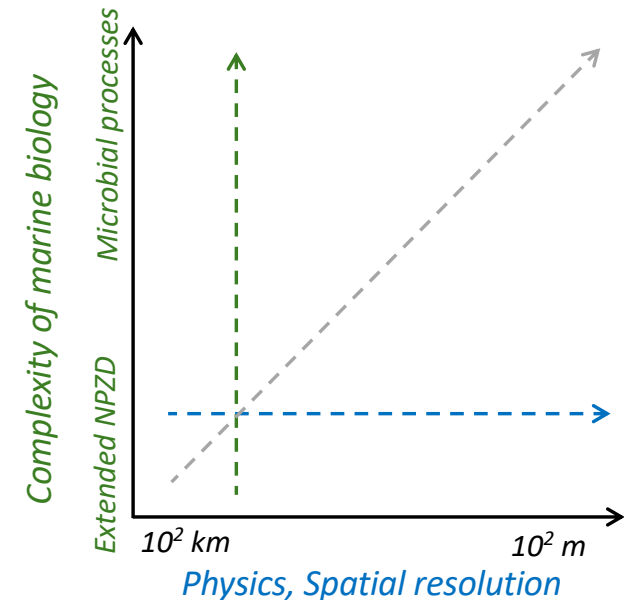


Maerz et al. 2020: Improvements by including measurable properties of marine aggregates (e.g. size, porosity, microstructure, excess-density) from microscale modeling and lab work (Ahmerkamp et al. 2022)

→ **increased biological carbon sequestration efficiency under climate change (Maerz et al. 2025)**

The asymmetry: resolving physics vs. representing biology

1. 😊 Effects of physical climate processes; higher resolution
😞 Unresolved complexity of biological processes
- +
2. 😊 Embracing biological complexity
😞 Unresolved physics in coarser resolution
- =
3. 😊 😊 The next frontier: not simply resolving more, but discovering and representing more



09 2026

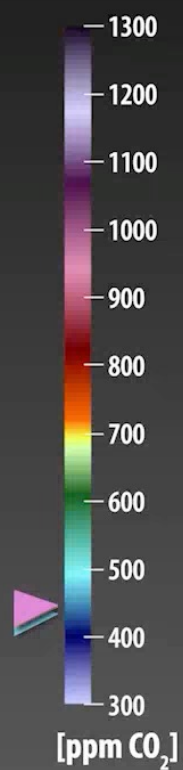
SSP1-2.6

SSP2-4.5

MPI-ESM LR

SSP3-7.0

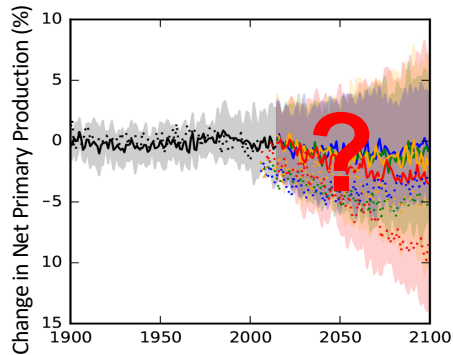
SSP5-8.5



Color: Simulated CO₂ Concentration
Height: Relative Seasonal Cycle

CC-BY NC-ND4.0: DKRZ / MPI-MM / MPI-M / UHH

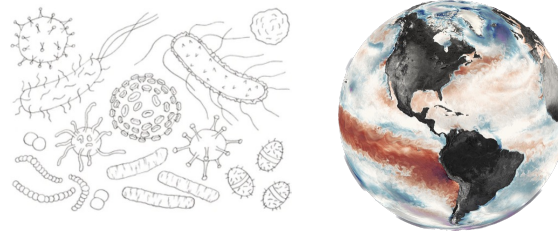
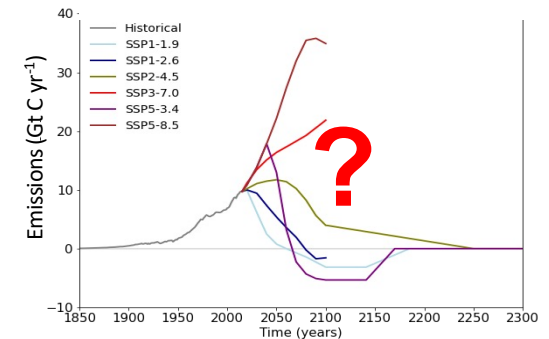
The real frontier: reimagining the modeling of coean biosphere dynamics



Missing predictive dynamics of marine microbial feedbacks under global change



From modeling what we know to building models to connect discovery with prediction



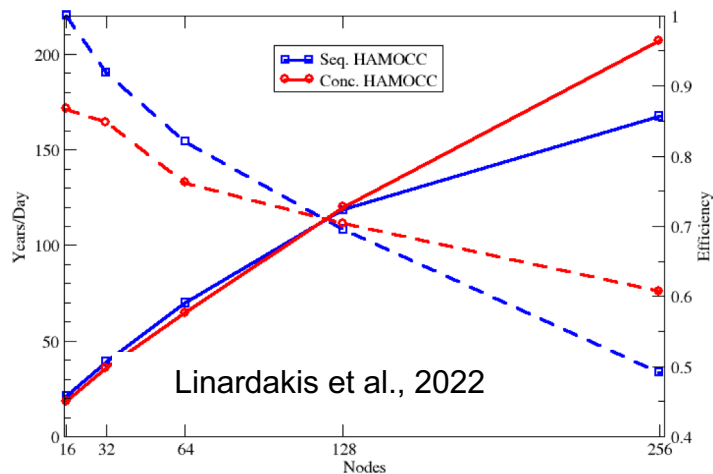
1. *How to bridge the gap between micro and macro scales?*
2. *How to incorporate marine microbial life in an Earth system model?*
3. *What is the response under strong and rapid global change?*

Vision for future work: from discovery to prediction—and back again



Why now

- Emerging technology, i.e. software engineering and AI offers new ways to address challenges of computing and storage resources
- DKRZ (German Climate Computing Center; MPG owns 55%) is a major partner

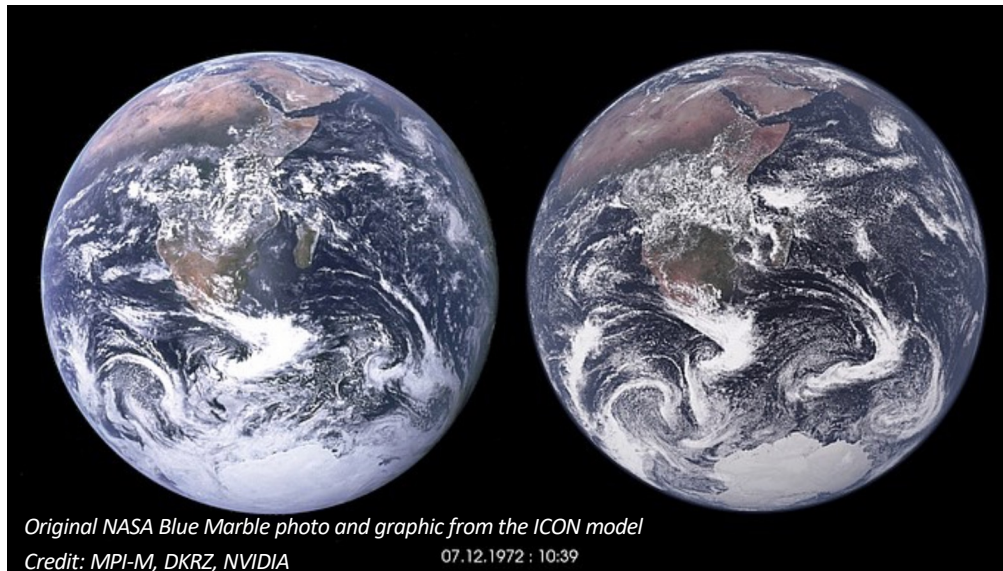


Concurrent representation of obgc tracers:

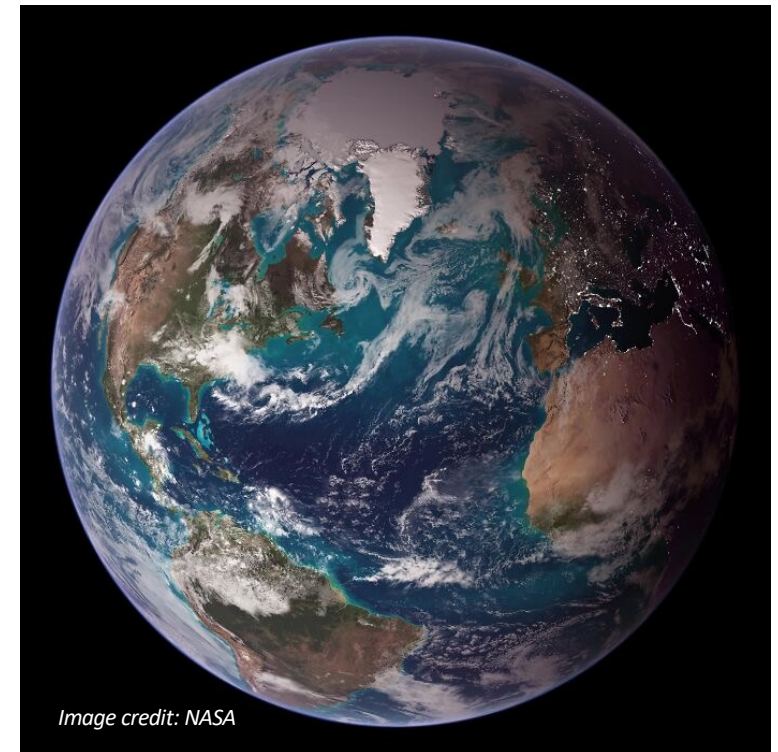
- Increased turnaround achieved by concurrent integration of tracer transport; porting onto GPUs
- Enabled **high resolution** coupled simulations (5km and 1km in testing)
- Heterogeneous hardware (GPU+CPU) opens opportunity for **increasing complexity** (larger number of tracers)

New perspective – boost the representation of marine life and its feedbacks in ESMs to predict the health of our planet under anthropogenic pressures

The Blue Marble



The Marble is Green



Thank you for your attention



Ocean Biosphere Dynamics, Sep 2026

