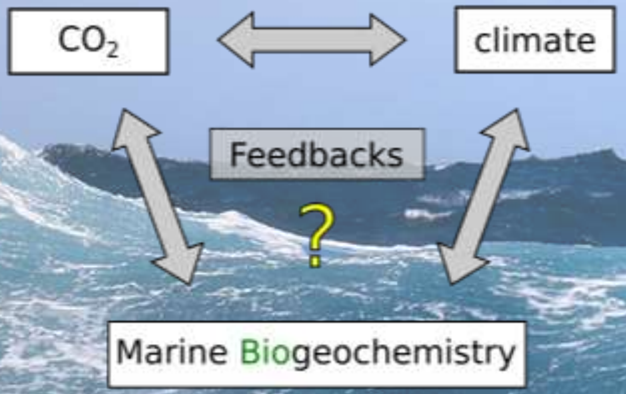
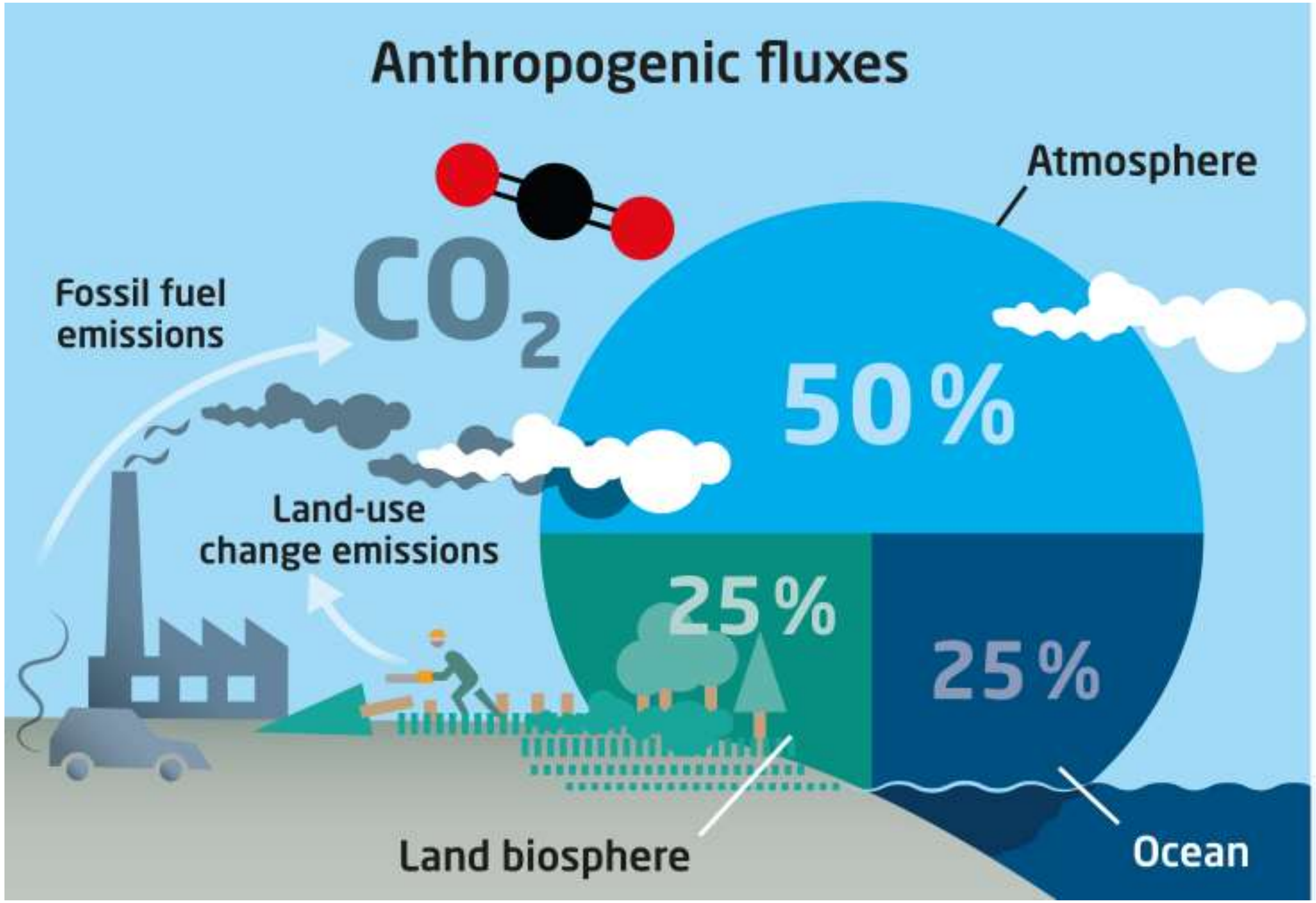


Regulated Ecosystem Model (REcoM)
Recent advances and plans ahead

Judith Hauck, Christopher Danek, Özgür Gürses, Miriam Seifert, Christoph Völker, Ying Ye

natESM Focus Workshop on Ocean Biogeochemistry

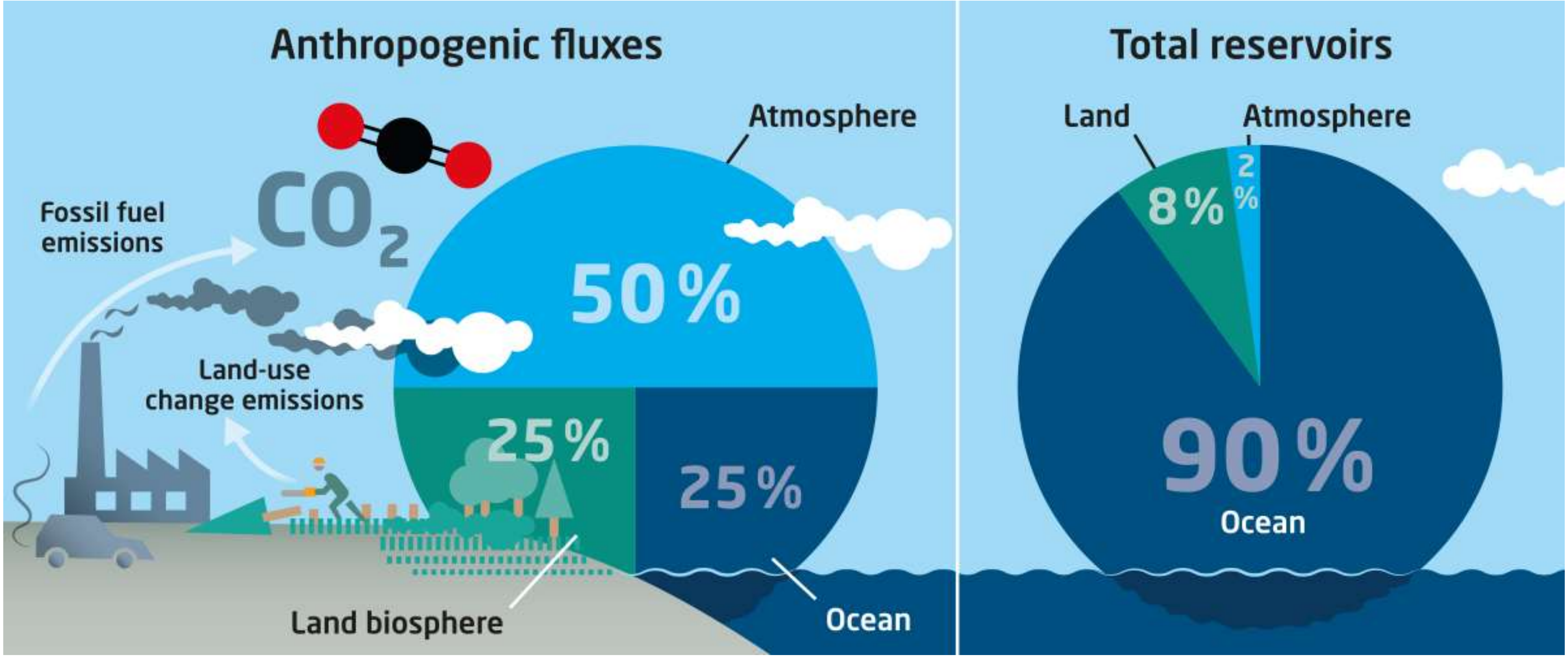
Ocean carbon



GLOBAL CARBON PROJECT

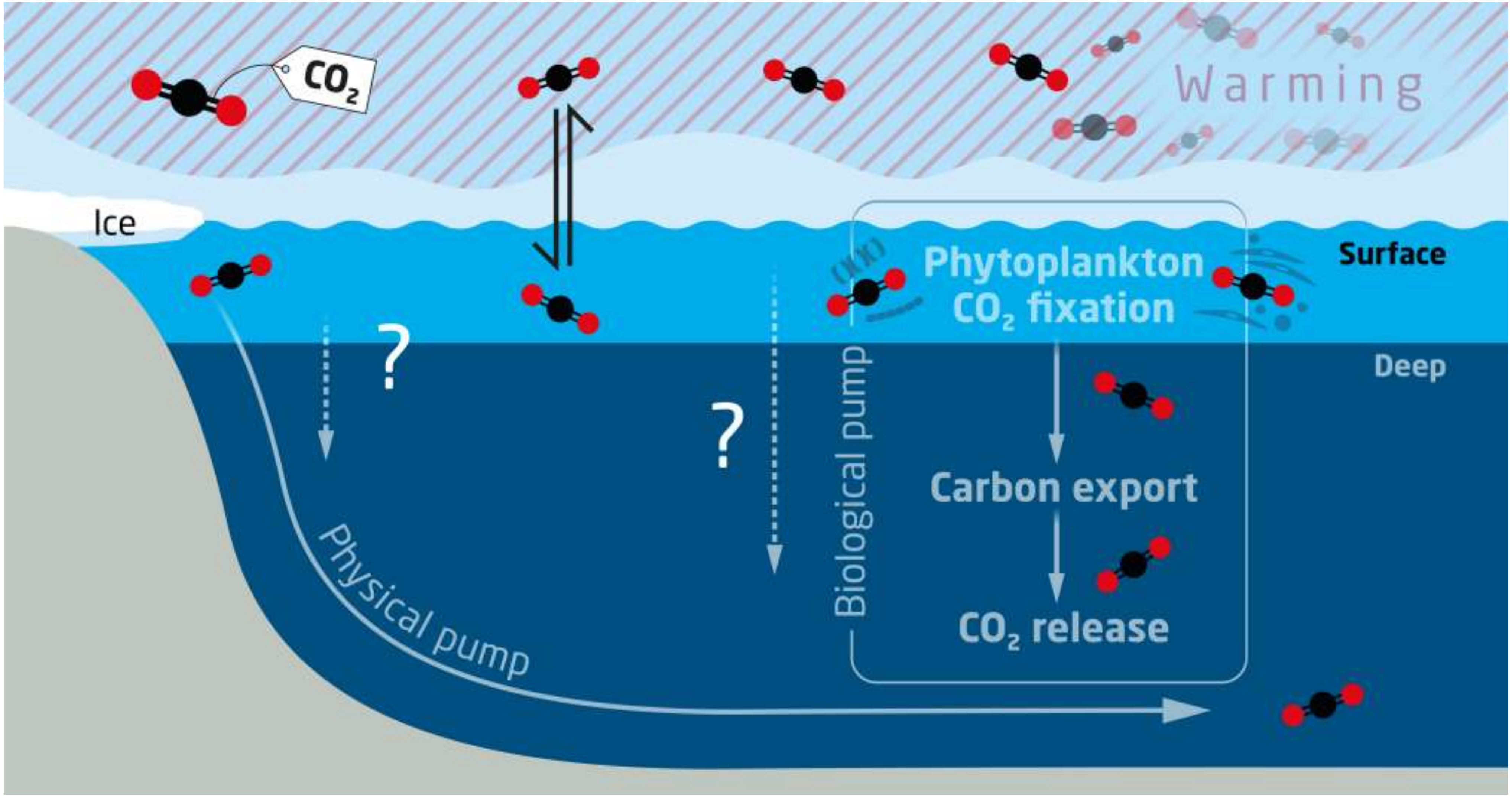
Friedlingstein et al. (2025), Hauck et al. (2020)

Ocean carbon



Friedlingstein et al. (2025), Hauck et al. (2020)

Ocean carbon under change



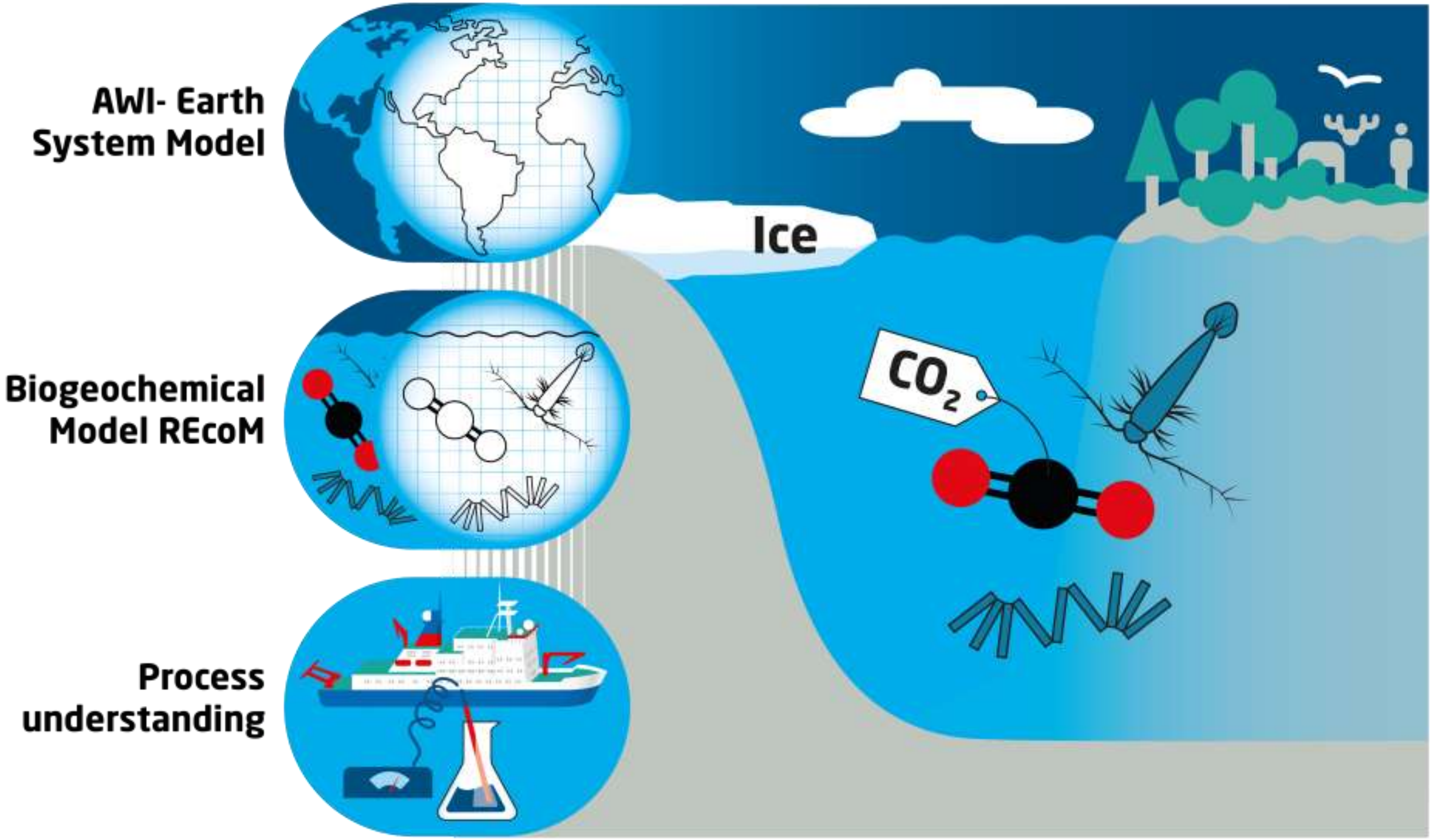
Marine ecosystem drivers

Warming, acidification, nutrients, oxygen, plankton productivity

SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD

SUSTAINABLE DEVELOPMENT GOAL 14
Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Ocean carbon & modelling



FESOM2 Finite volumE Sea ice-Ocean Model

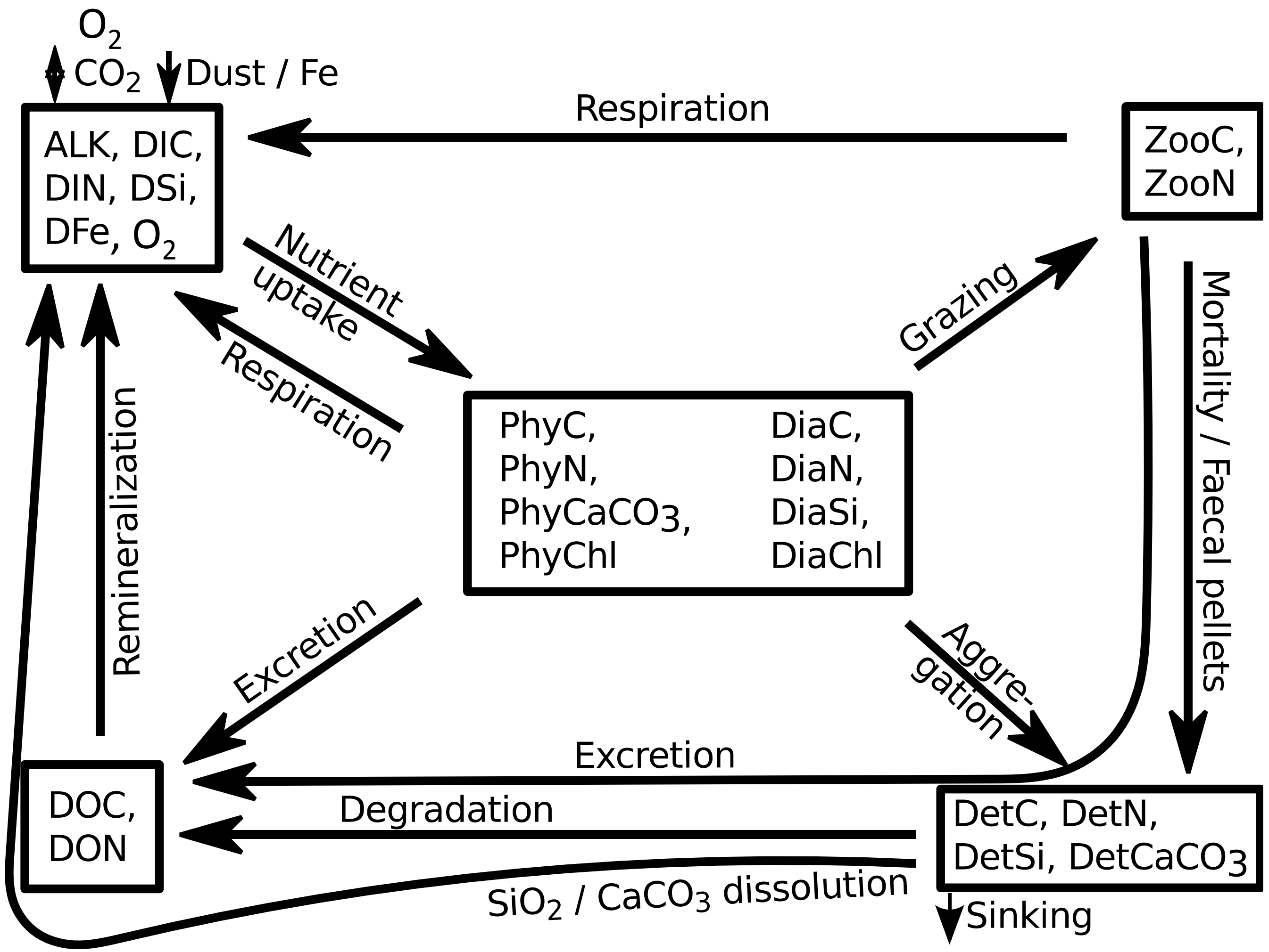
REcoM Regulated Ecosystem Model

CMIP6 Interim data available in concentration- and emission-driven mode

Preparing for CMIP7

Seifert et al. (2020, 2022, 2023), Karakus et al. (2021, 2022, 2025), Gürses et al. (2023)

REcoM Regulated Ecosystem Model



"Regulated Ecosystem"

- Photosynthesis, nitrate assimilation, chlorophyll synthesis are described based on environmental conditions and internal stoichiometry of the cells (Geider et al., 1998)
- Silicate assimilation added by Hohn (2009)
- Comprehensive representation of iron chemistry (e.g. Ye et al., 2020)
- Biogeochemical cycling of carbon, nitrogen, silicon, iron, oxygen

Hauck et al., 2013, Gürses et al., 2023

Geider model

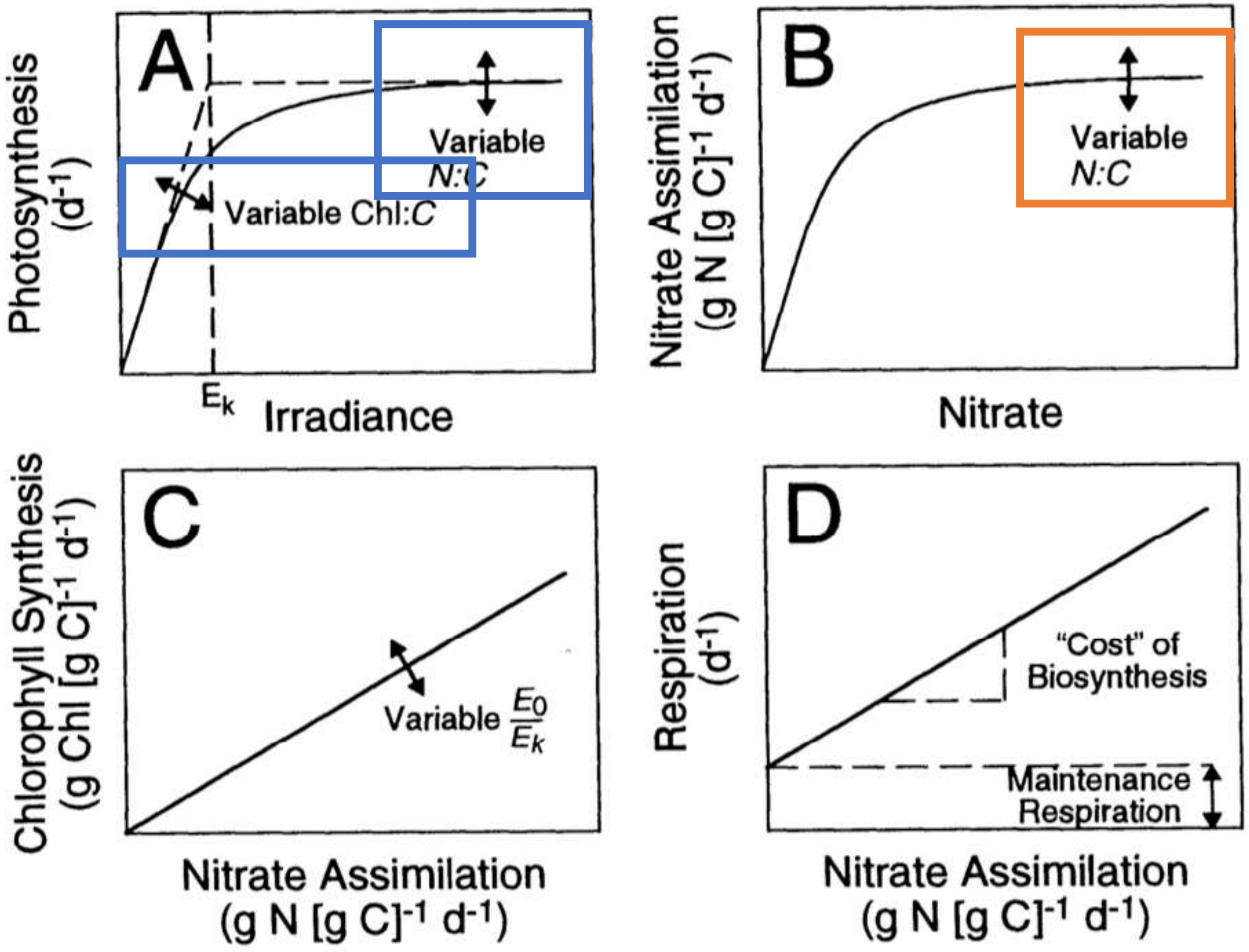
Photosynthesis is a saturating function of irradiance

Initial slope increases with increasing Chl:C

Light-saturated rate increases with increasing N:C

Chlorophyll synthesis coupled to protein synthesis and thus to nitrate assimilation

Chl synthesis downregulated at high light (high light saturation E0/Ek)



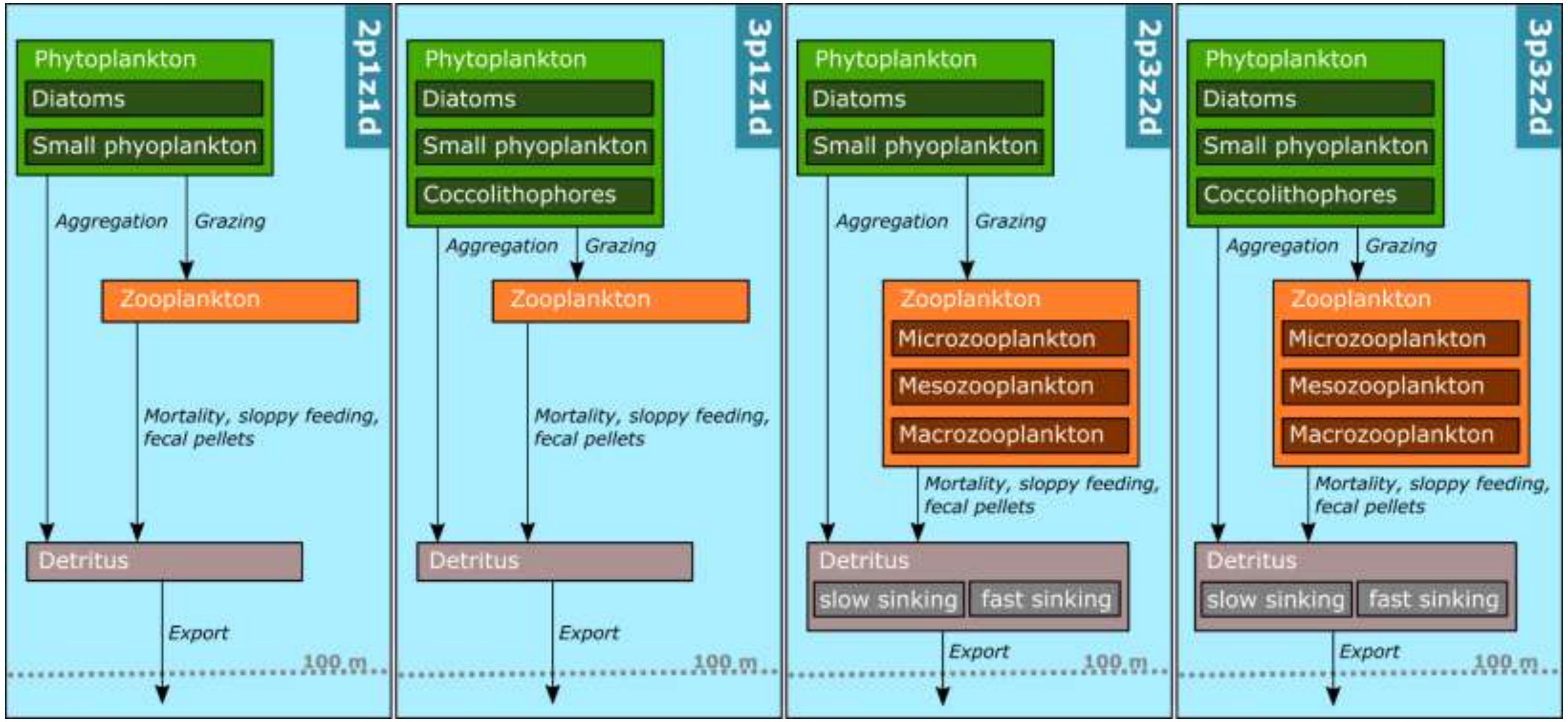
Nitrate assimilation is a saturating function of nitrate concentration

Maximum uptake rate is downregulated at high values of N:C

Major respiratory costs are associated with protein synthesis (reduction of nitrate to ammonium, incorporation of ammonium into amino acids and polymerization of amino acids into proteins)

Geider et al (1998)

Various levels of complexity

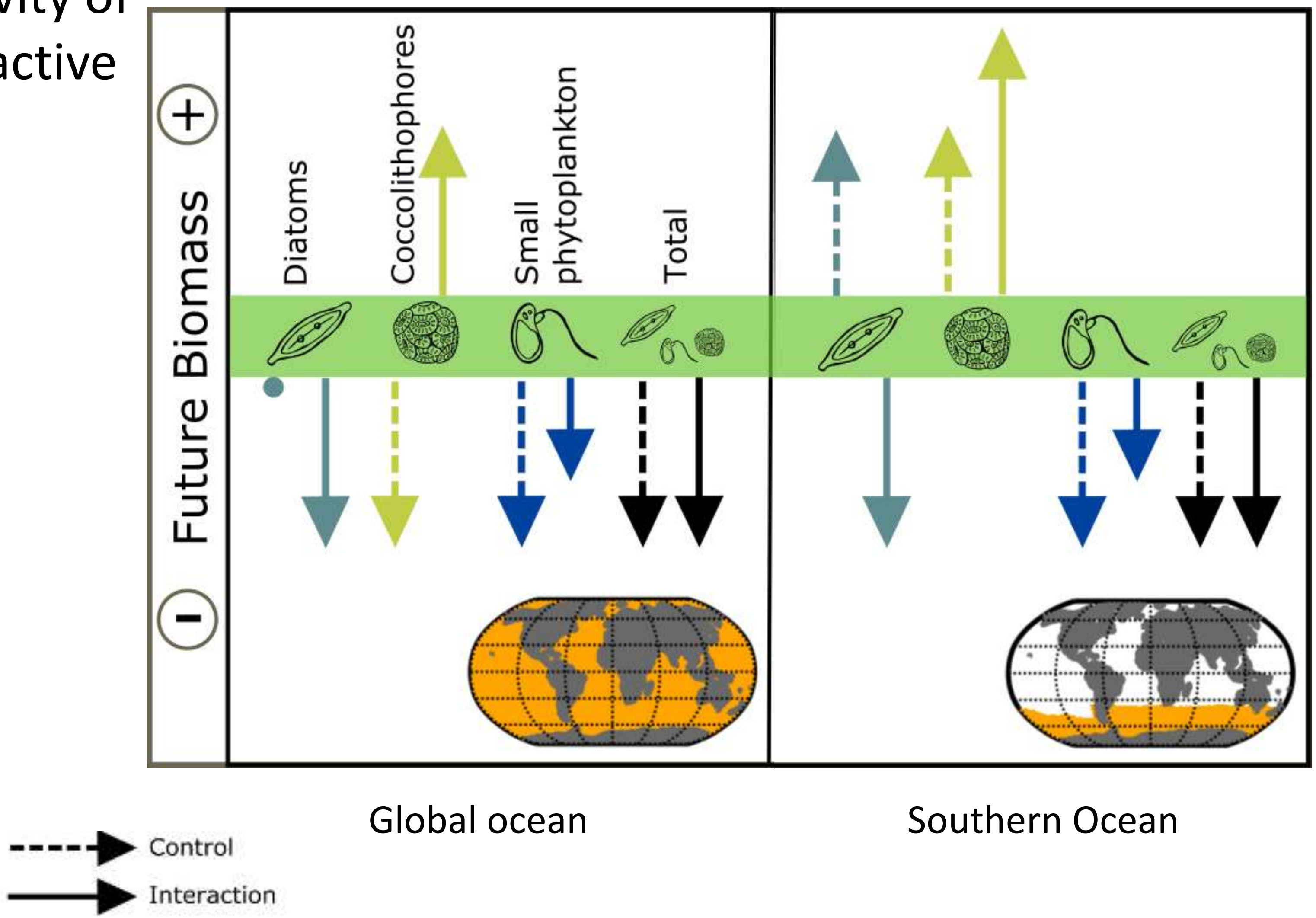


tracers	22	25	30	33
Wall clock time per simulated year (1152 CPUs)	35 min	39	46	50

Seifert et al., in prep.

REcoM features

- Explicit calcifiers, CO_2-sensitivity of phytoplankton growth, interactive effects of drivers



Seifert et al., 2022, 2023

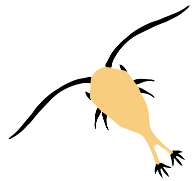
REcoM features

- Explicit calcifiers, CO_2-sensitivity of phytoplankton growth, interactive effects of drivers (Seifert et al.)
- Three zooplankton groups, and particle-sinking scheme that accounts for ballast minerals, seawater viscosity, and oxygen-dependent remineralization

Microzooplankton
(e.g., ciliates)

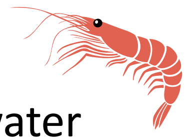
Fast-growing herbivore group, main grazer of (small) phytoplankton

Mesozooplankton
(e.g., copepods)



Grazes on larger phytoplankton and microzooplankton, fast sinking fecal pellets

(Polar) macrozooplankton
(krill)

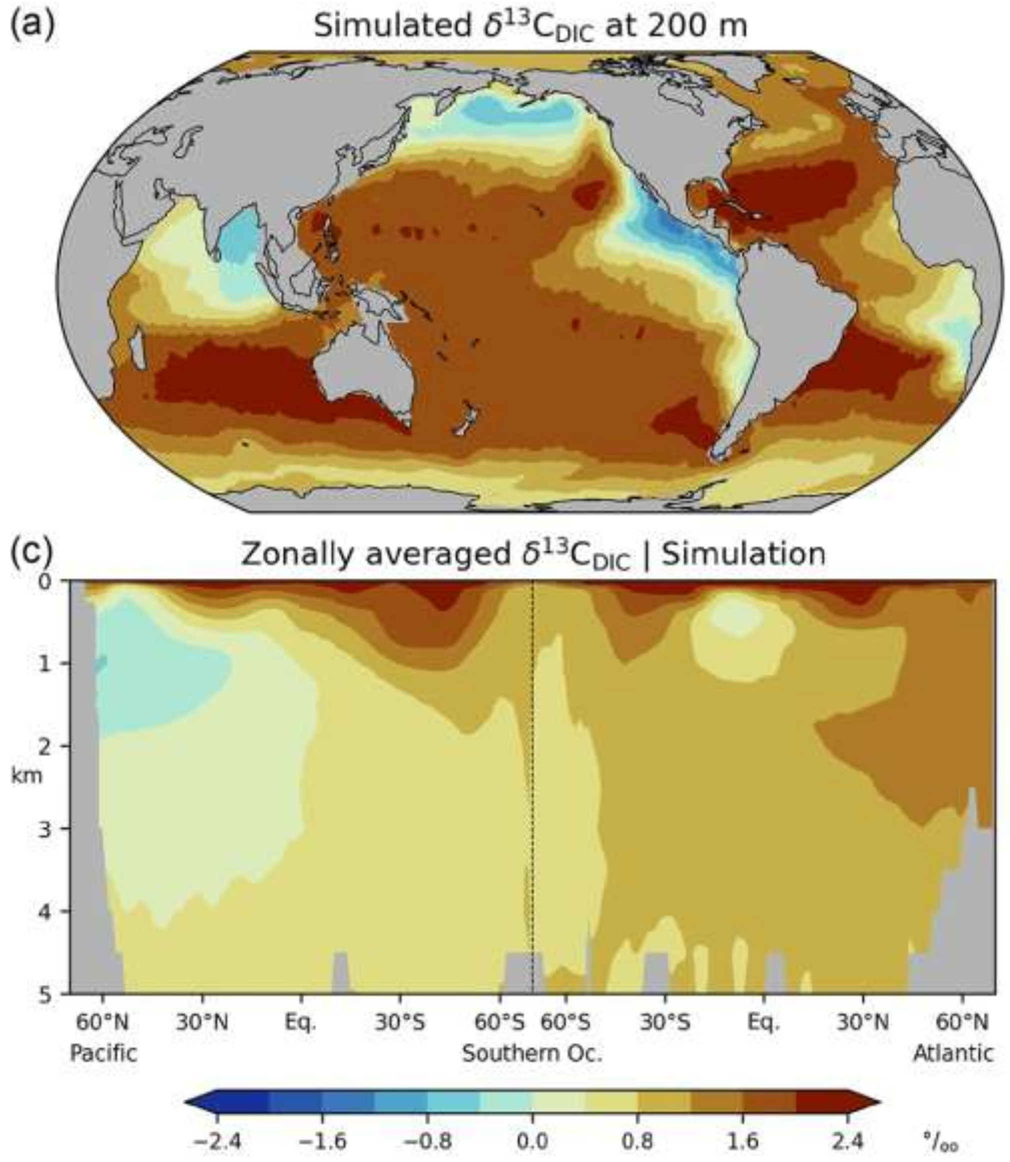


Slow-growing, cold-water species, fast-sinking fecal pellets with high C:N ratio

Karakus et al., 2022, 2023, 2025

REcoM features

- Explicit calcifiers, CO_2-sensitivity of phytoplankton growth, interactive effects of drivers (Seifert et al.)
- Three zooplankton groups, and advanced particle-sinking (Karakus et al.)
- Carbon isotopes (Butzin et al., 2024)
- CFCs



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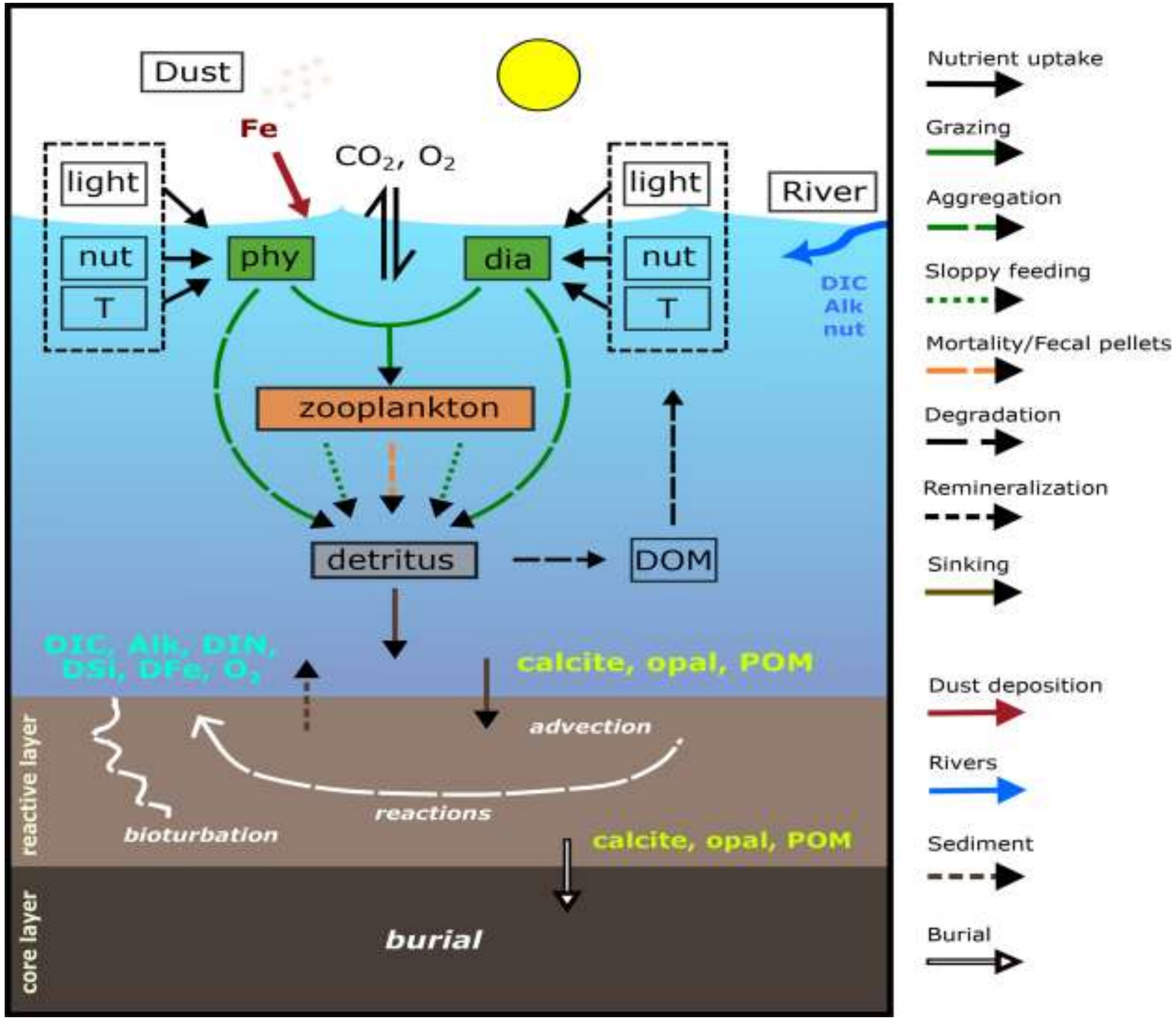
- CFCs
- Coupled to sediment model MEDUSA (Ye et al., 2025)



REcoM features

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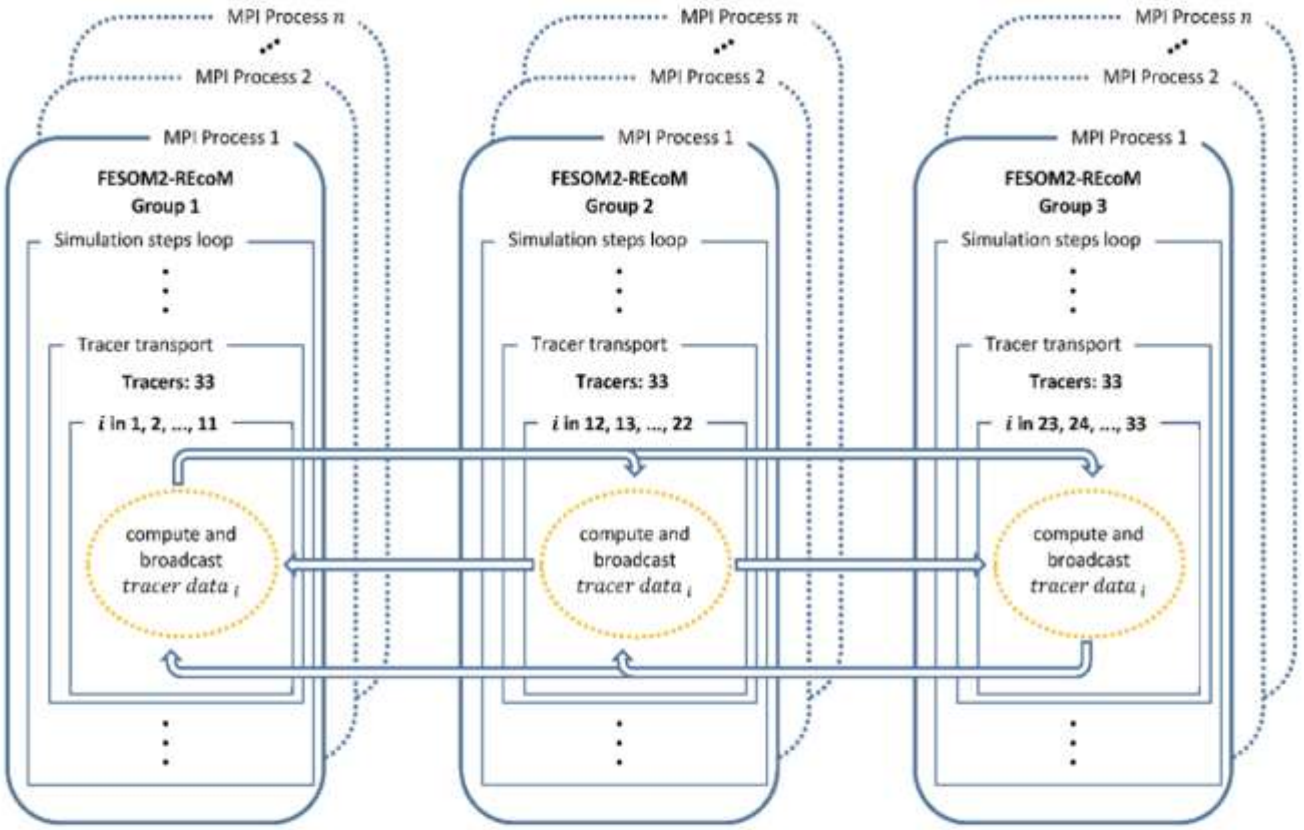
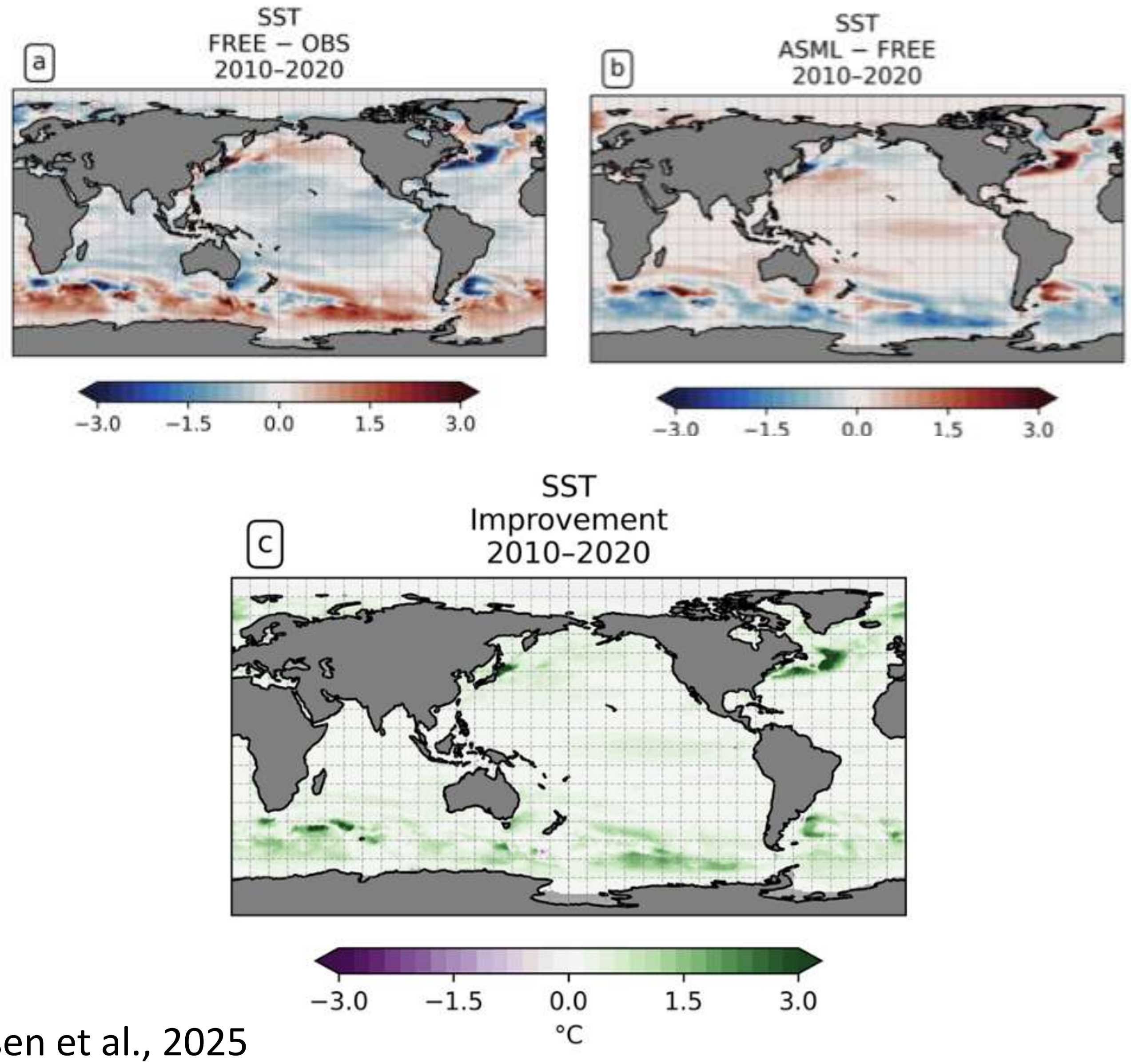
- Tracer parallelization (Himstedt, 2025)



REcoM features

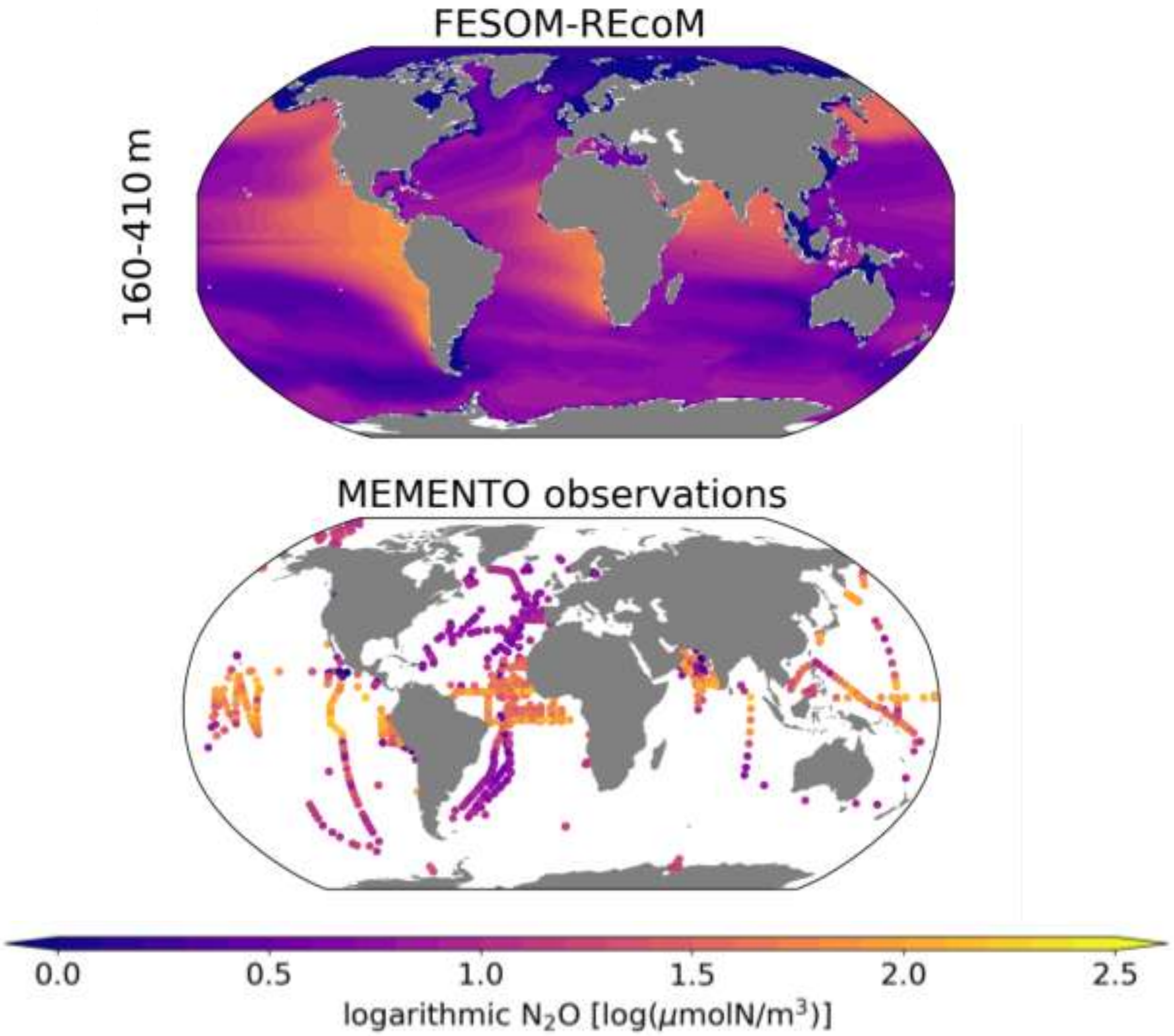
- Explicit calcifiers, CO_2-sensitivity of phytoplankton growth, interactive effects of drivers (Seifert et al.)
- Three zooplankton groups, and advanced particle-sinking (Karakus et al.)
- Carbon isotopes (Butzin et al., 2024), CFCs
- Coupled to sediment model MEDUSA (Ye et al., 2025)
- Tracer parallelization (Himstedt, 2025)
- Data-assimilation (ensemble Kalman filter, PDAF)



Bunsen et al., 2025

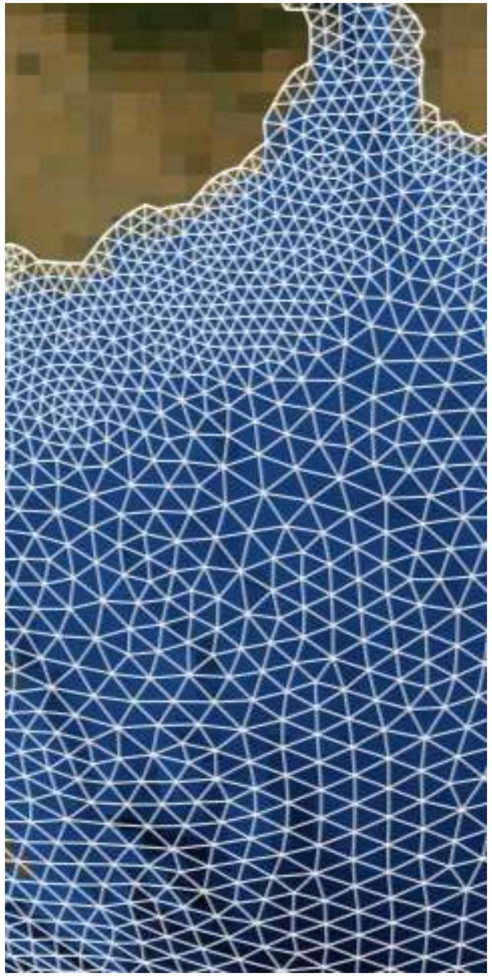
REcoM features

- Explicit calcifiers, CO_2-sensitivity of phytoplankton growth, interactive effects of drivers (Seifert et al.)
- Three zooplankton groups, and advanced particle-sinking (Karakus et al.)
- Carbon isotopes (Butzin et al., 2024), CFCs
- Coupled to sediment model MEDUSA (Ye et al., 2025)
- Tracer parallelization (Himstedt, 2025)
- Data-assimilation (ensemble Kalman filter, PDAF)
- Adding marine N_2O emissions, MSc thesis M. Vollmayr (split reactive nitrogen into redox states, model production of N_2O)



Interfaces/Integration

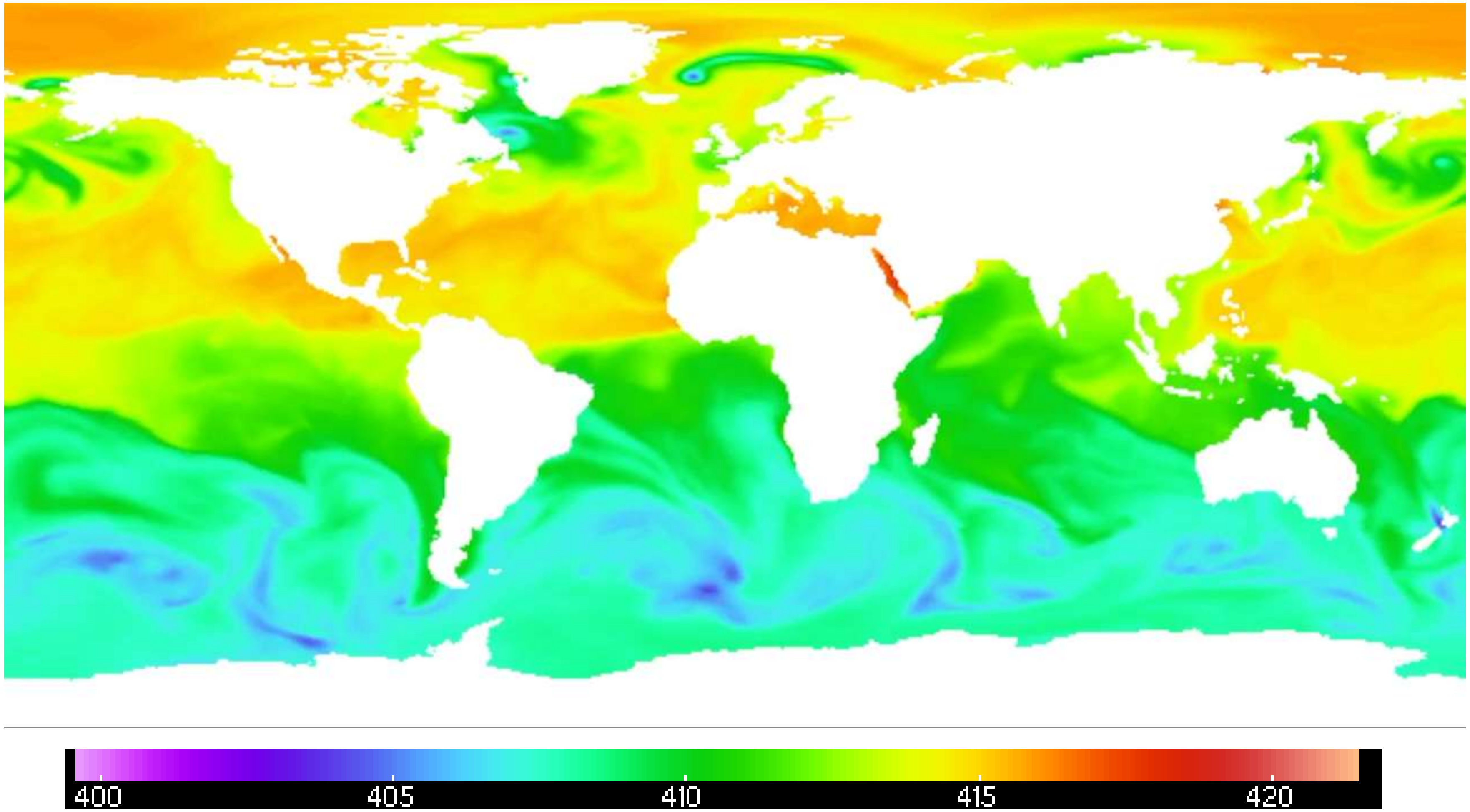
- Coupled to FESOM, AWI-CM/ESM (versions 1, 2, 3), MITgcm



Interfaces/Integration

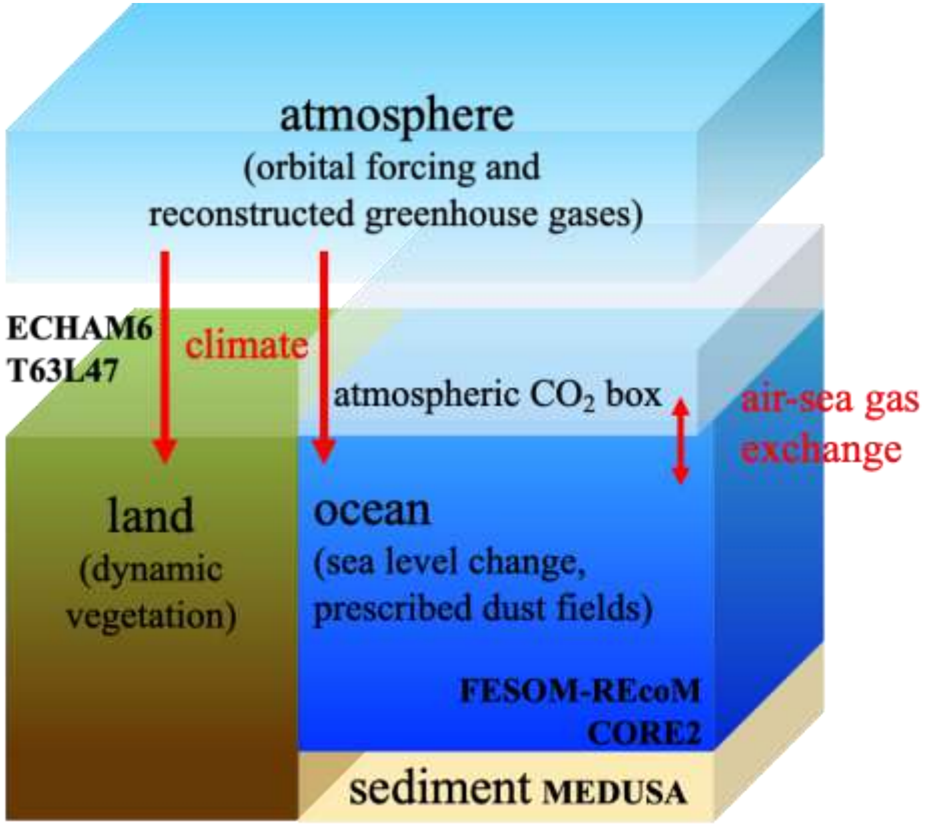
- Coupled to FESOM, AWI-CM/ESM (versions 1, 2, 3), MITgcm

Atmospheric CO_2 in AWI-ESM3 (work in progress)

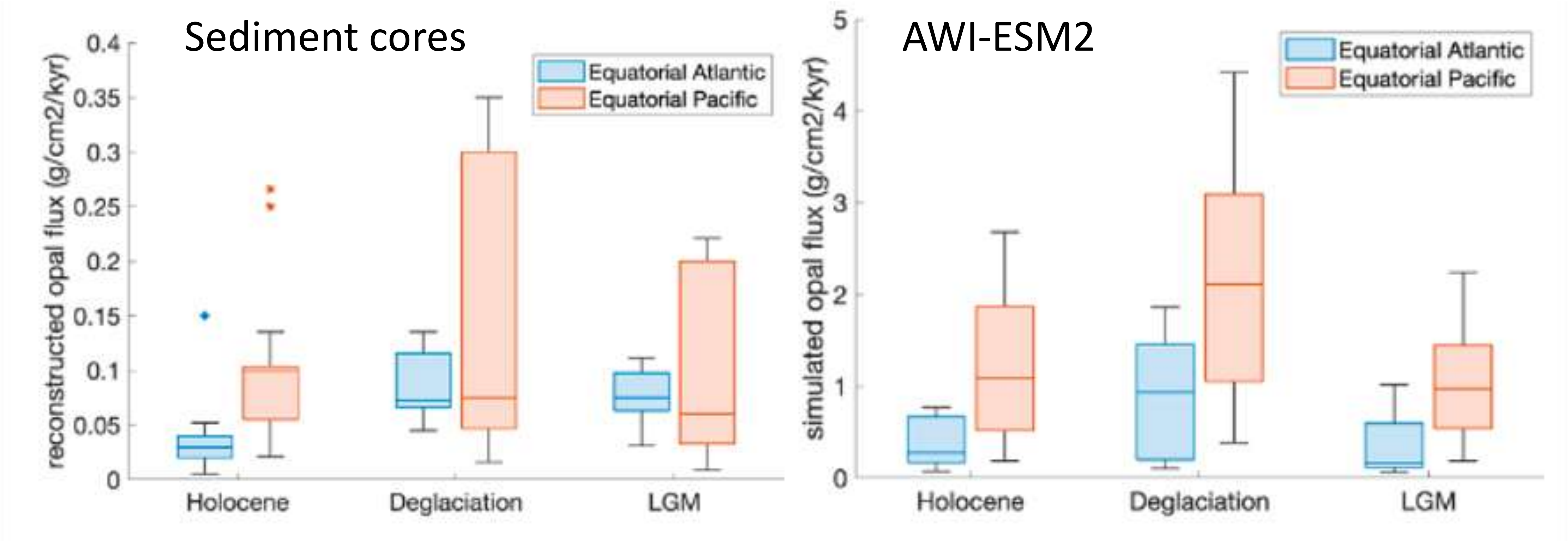


Interfaces/Integration

- Coupled to FESOM, AWI-CM/ESM (versions 1, 2, 3), MITgcm
- Coupled set-up for paleo reconstruction



Silicon redistribution after Heinrich Stadials stimulated low-latitude diatom growth



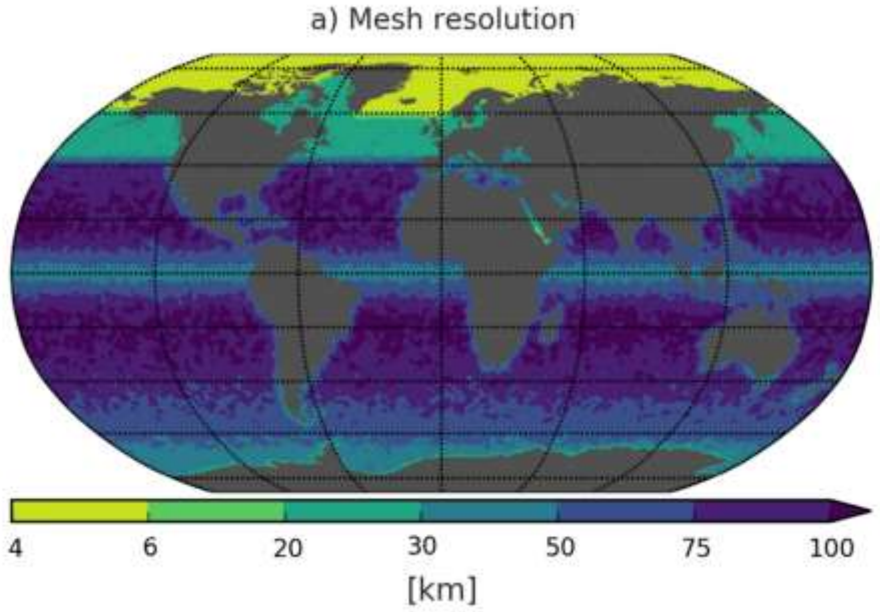
- AWI-ESM reproduces patterns of opal deposition observed in sediment cores from equatorial regions for the PI, LGM and deglacial periods.
- Higher opal deposition during deglaciation due to redistribution of Si from Southern Ocean surface waters

Ye et al., submitted

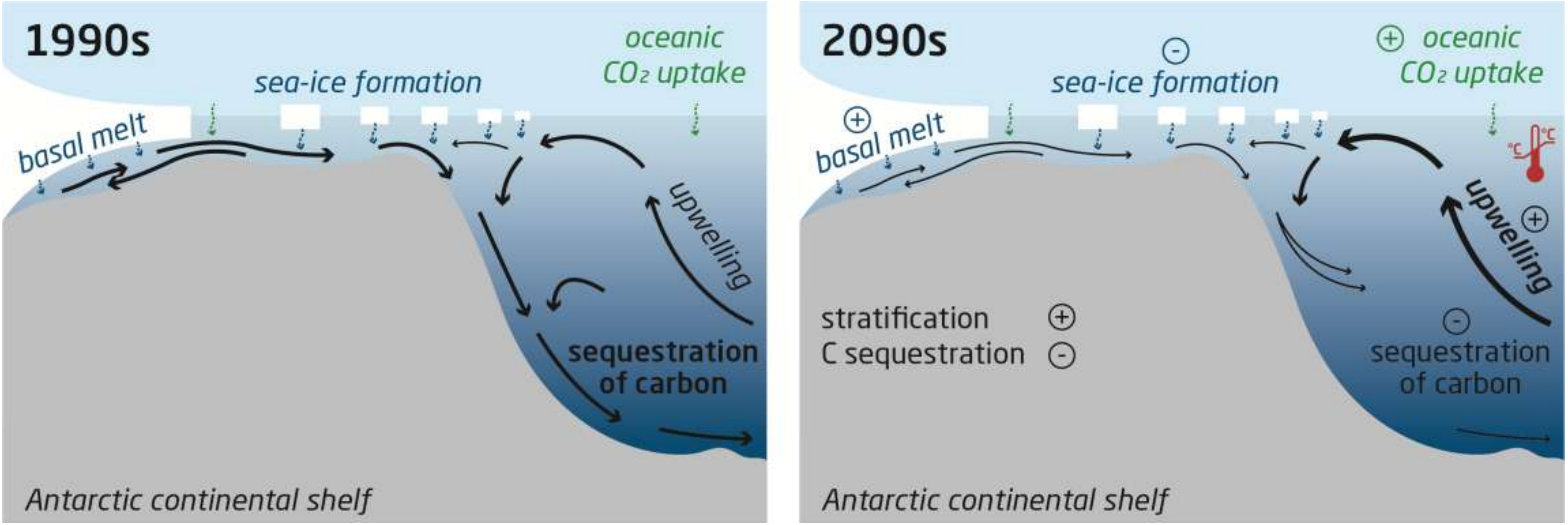
Interfaces/Integration

- Coupled to FESOM, AWI-CM/ESM (versions 1, 2, 3), MITgcm
- Coupled set-up for paleo reconstruction
- Sprint proposal in review: implement REcoM into FABM (Framework for Aquatic Biogeoch. Models)
- Exploiting FESOM flexible mesh to resolve physical processes in regions of interest (Southern Ocean, Arctic, coasts)

Arctic Ocean: 4.5 km resolution



Abruptly attenuated carbon sequestration

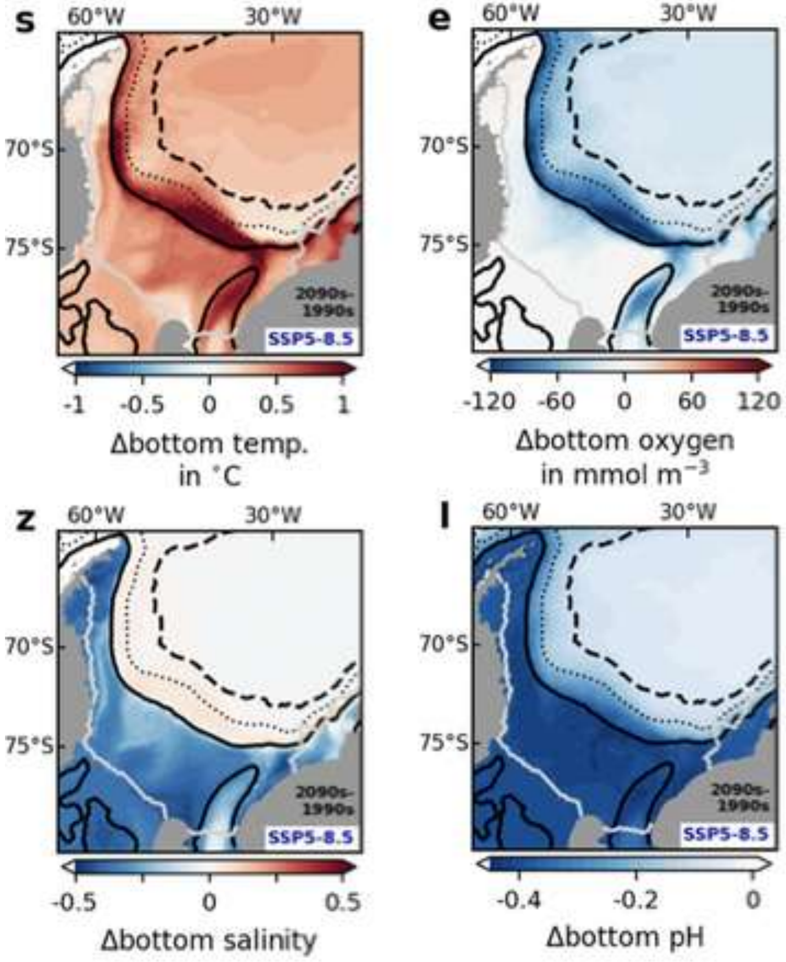


→ A variety of changes lower the density and volume of newly formed bottom waters and reduce the associated carbon transport to the abyss.

Nissen et al. (2022), Nature Communications; Nissen et al. (2023), Journal of Climate

Regime shift Weddell Sea shelves

Tipping point cascade from physics to ecosystems initiated on Weddell Sea continental shelves, avoidable in a 2°C scenario: from “dense shelf” to “warm shelf”



Erosion of density differences shelf vs. open ocean

→ Flushing of shelf with warm deep water
→ Increase ice-shelf basal melt rates
→ Impacts on

- Global sea level
  destabilization of ice sheets
- ocean circulation and climate
  AABW: heat and carbon transfer to depth
- Ecosystems
  deep ocean oxygenation
  acidification and oxygen decrease on the shelves

Nissen et al., 2023

Regime shift Weddell Sea shelves

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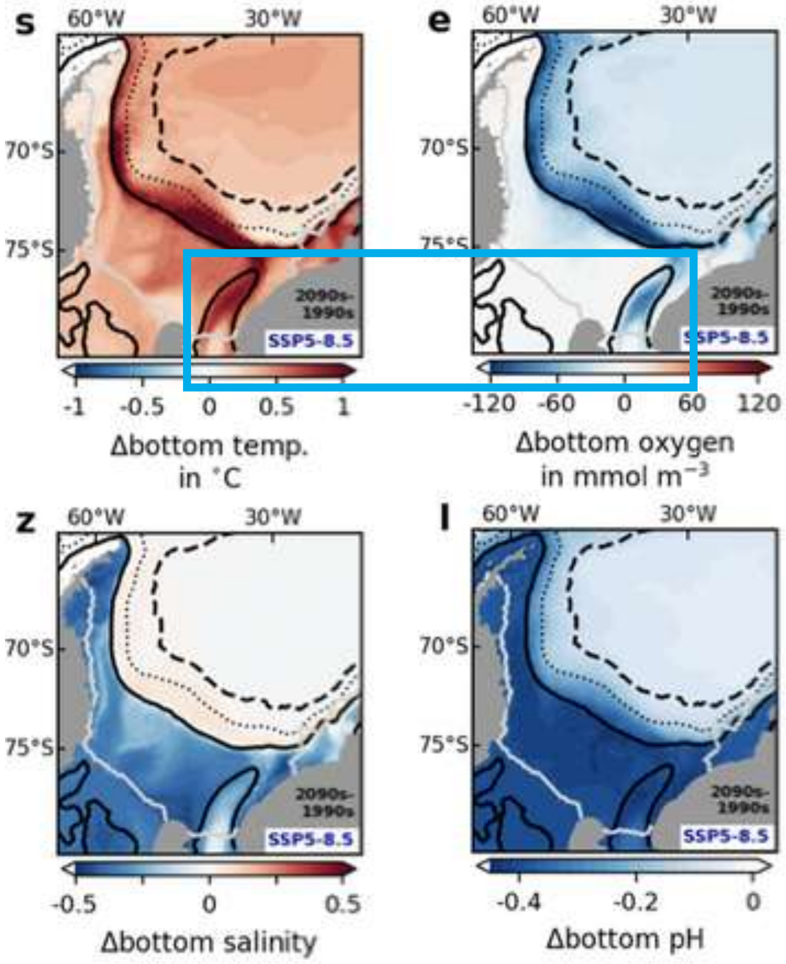


A vast icefish breeding colony discovered in the Antarctic

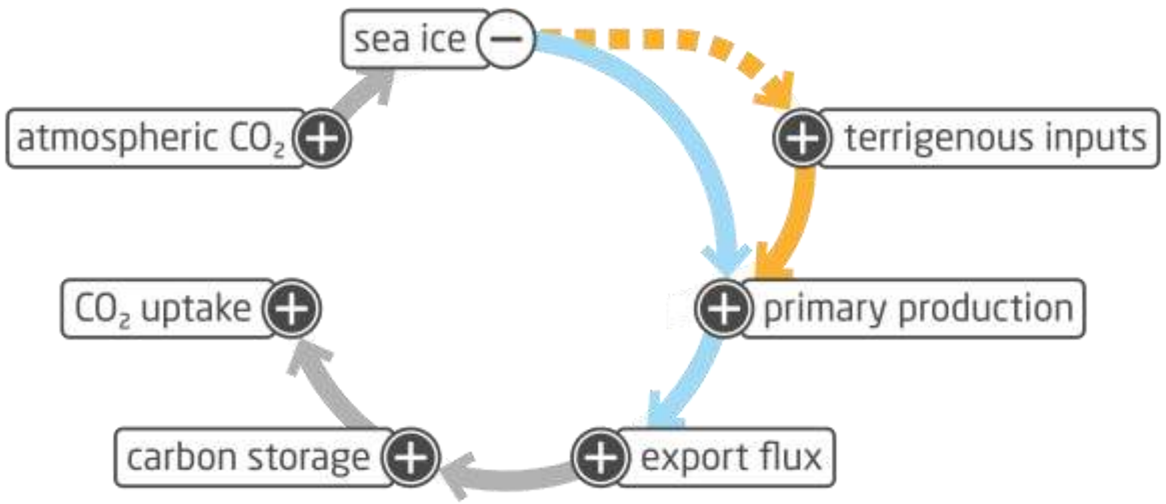
Purser et al., 2022

Nissen et al., 2023

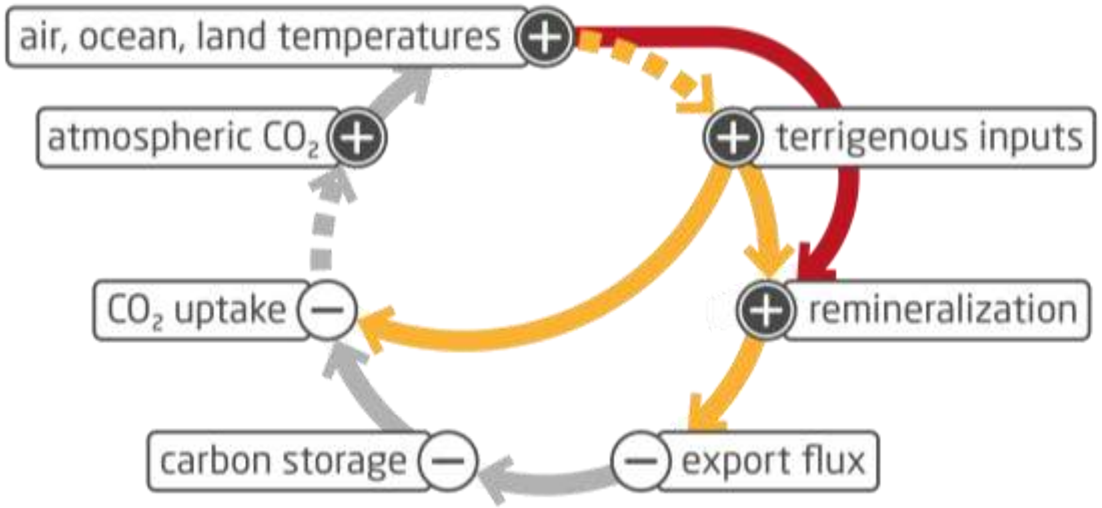
Arctic land-ocean carbon coupling

- Despite increased primary production, **the efficiency of the Arctic Ocean's biological carbon pump is projected to decrease by 40%**, largely due to enhanced remineralization.
- Terrigenous inputs lead to intense outgassing on the Arctic coasts.

Negative feedback loop



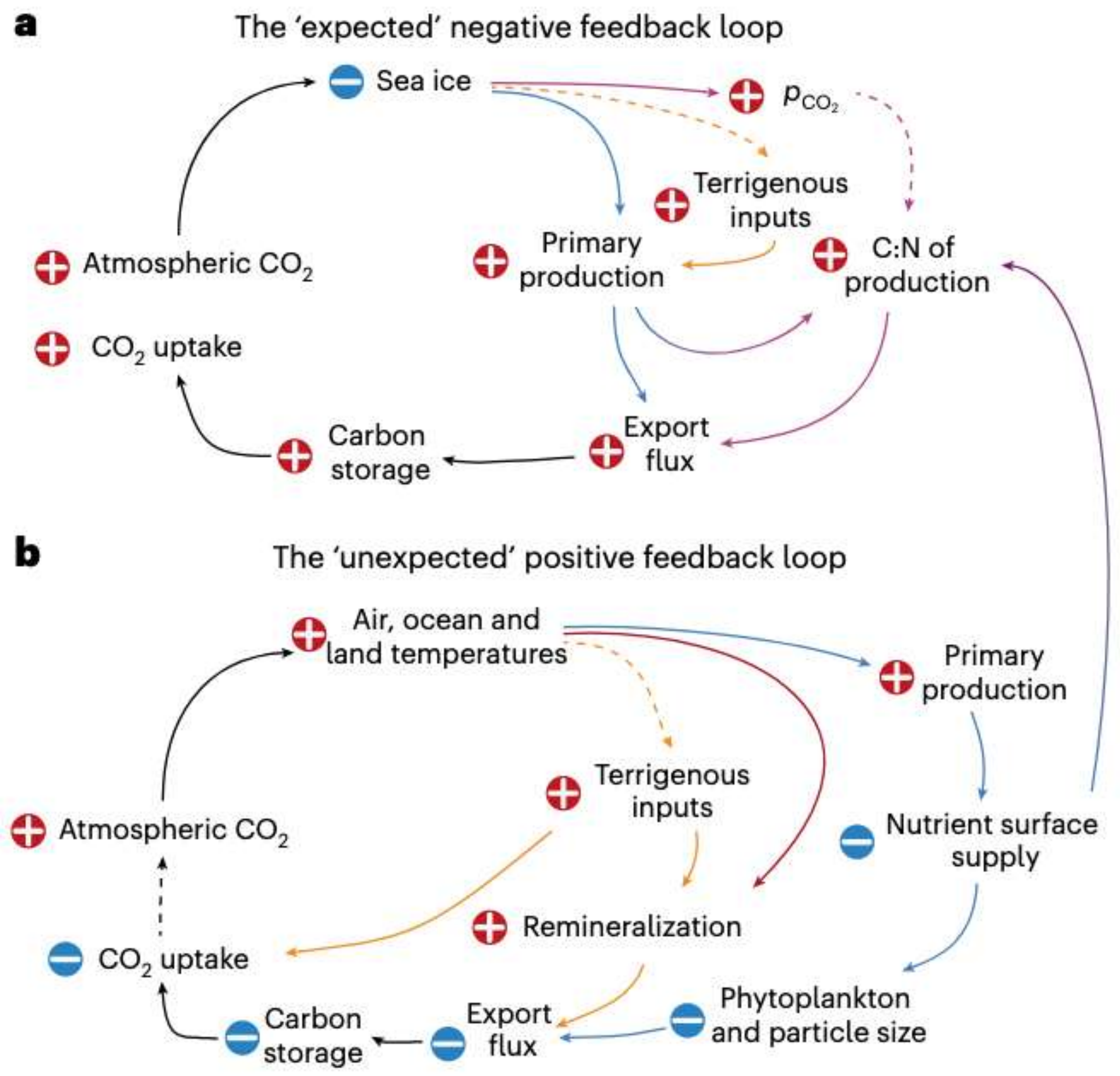
Positive feedback loop



Oziel et al. (2025), Nature Climate Change

Arctic land-ocean carbon coupling

The full picture is more complicated and involves stoichiometry changes.

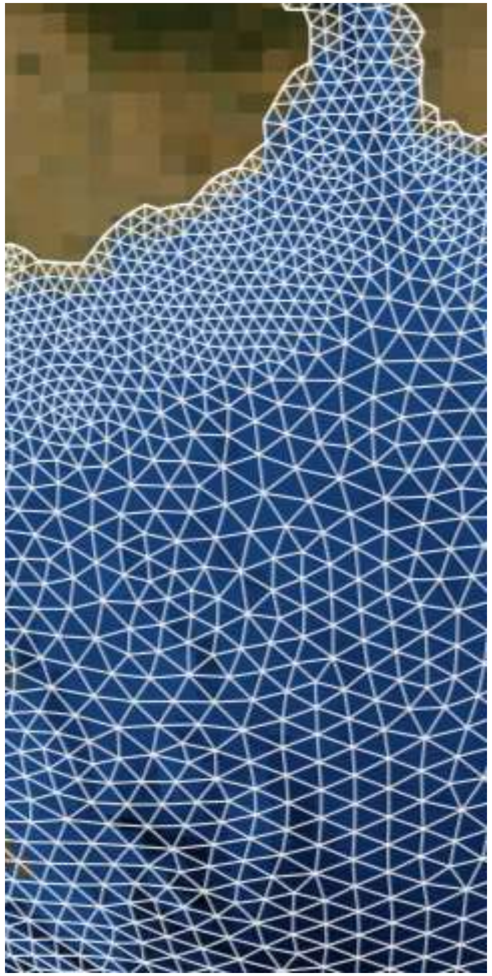


Oziel et al. (2025), Nature Climate Change

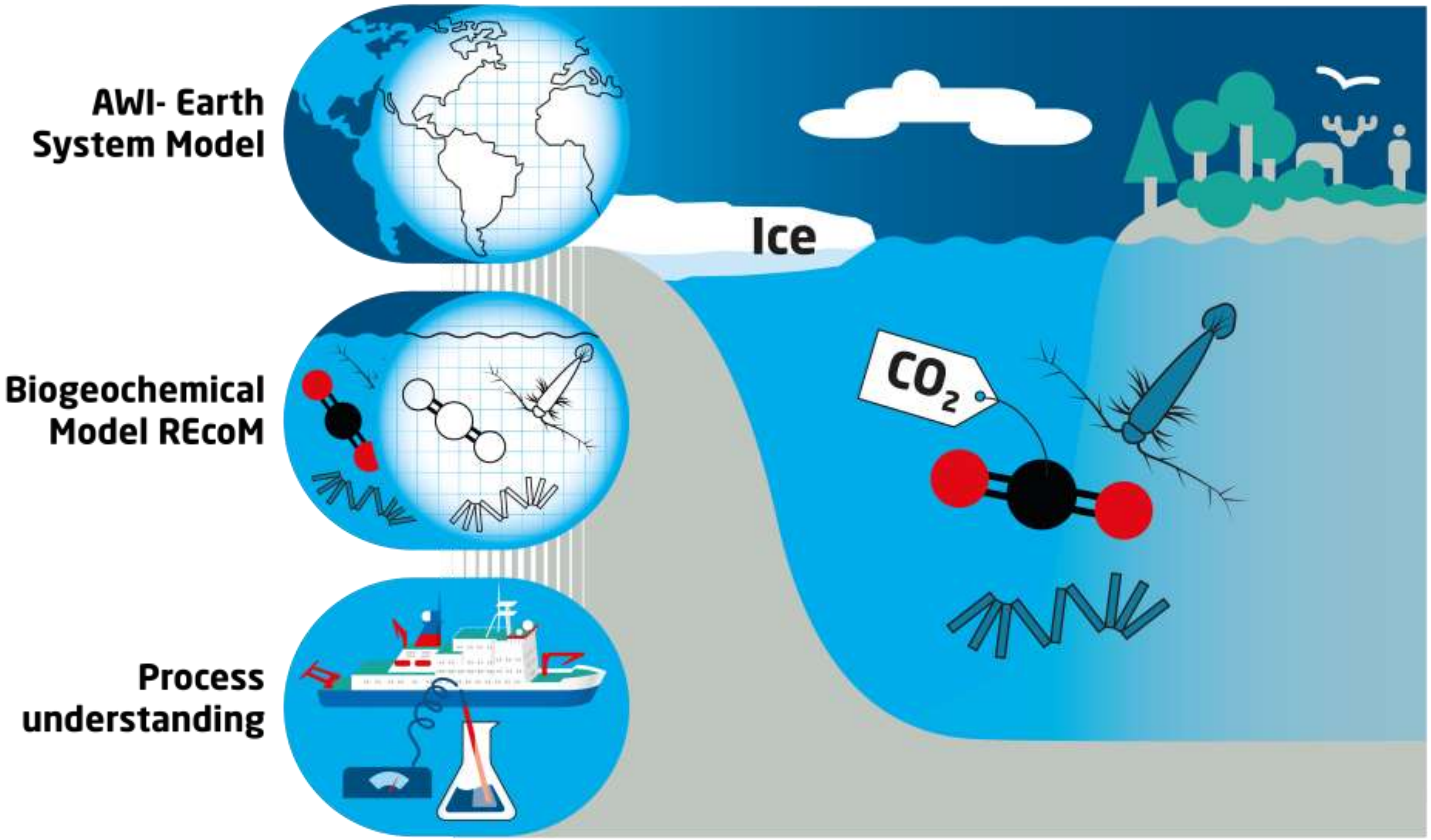
Interfaces/Integration

- Coupled to FESOM, AWI-CM/ESM (versions 1, 2, 3), MITgcm
- Coupled set-up for paleo reconstruction
- Sprint proposal in review: implement REcoM into FABM
- Exploiting FESOM flexible mesh to resolve physical processes in regions of interest (Southern Ocean, Arctic, coasts)

- Running on supercomputers at AWI, DKRZ (Levante), NHR
- REcoM GitHub repository used as submodule in FESOM
- Planned: continuous integration



Model application in emission-driven AWI-ESM

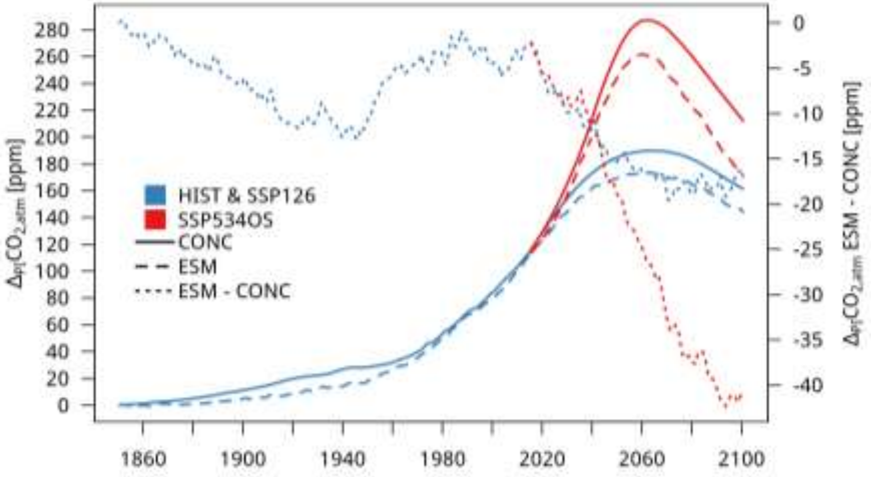


FESOM2
Finite volumE
Sea ice-Ocean Model

REcoM
Regulated
Ecosystem Model

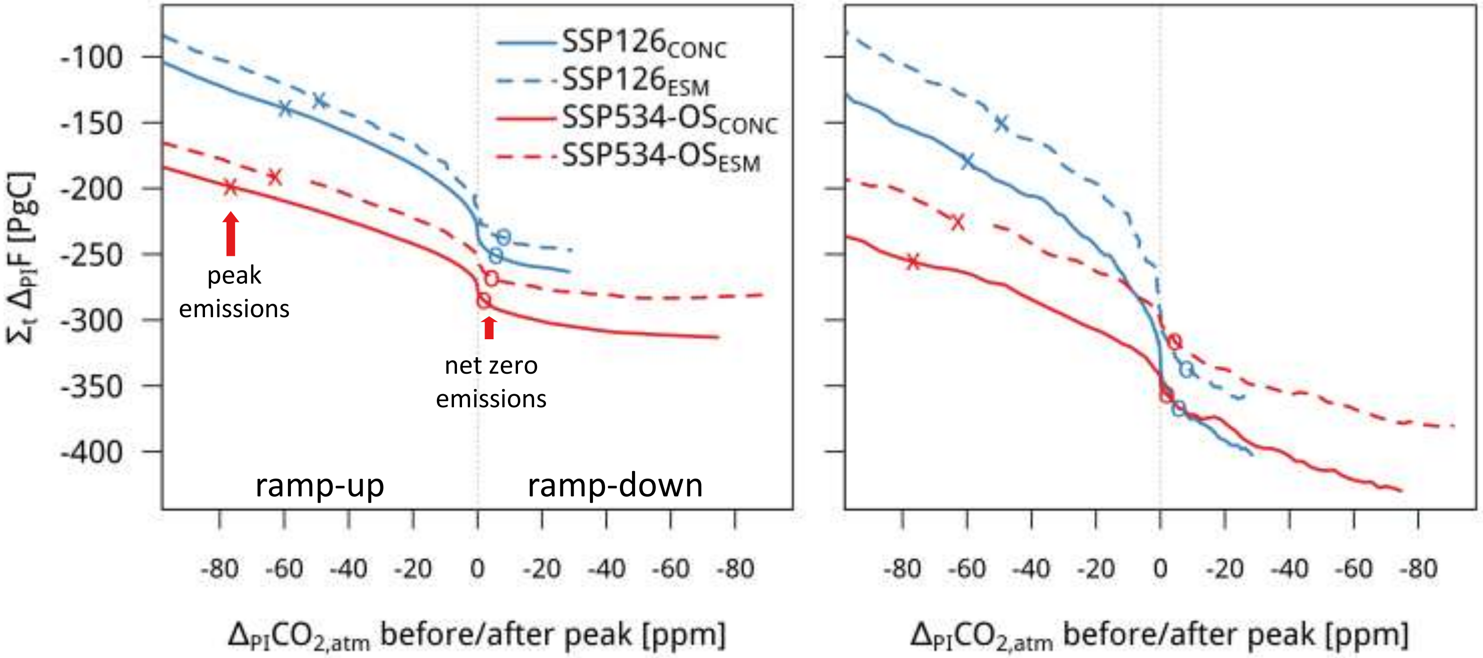
Future carbon cycle in emissions-driven ESMs

Atmospheric CO_2



ocean CO_2 sink

natural terrestrial CO_2 sink



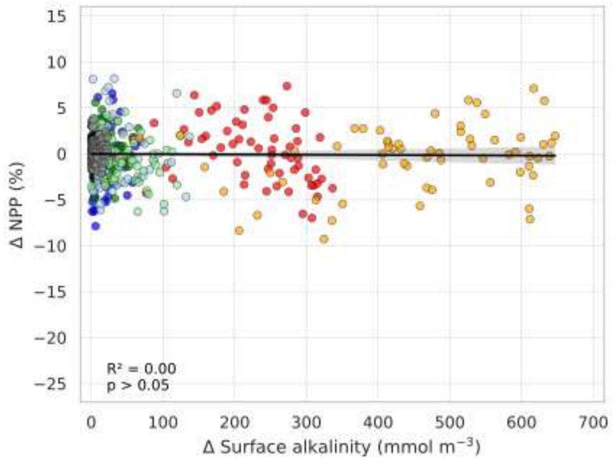
- Differences between emissions- and concentration-driven simulations largest in overshoot scenarios
- Peak in atmospheric CO_2 decisive for pathway-dependent change in ocean and land sink

Danek et al. in prep

Ocean alkalinity enhancement and phytoplankton

Effects of OAE on net primary production

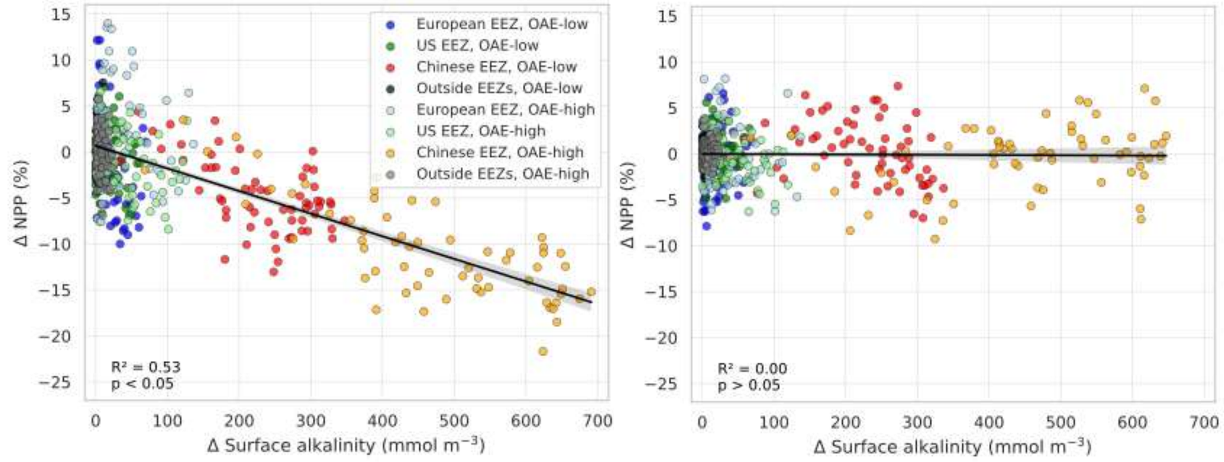
Without carbonate system effects on phytoplankton



Ocean alkalinity enhancement and phytoplankton

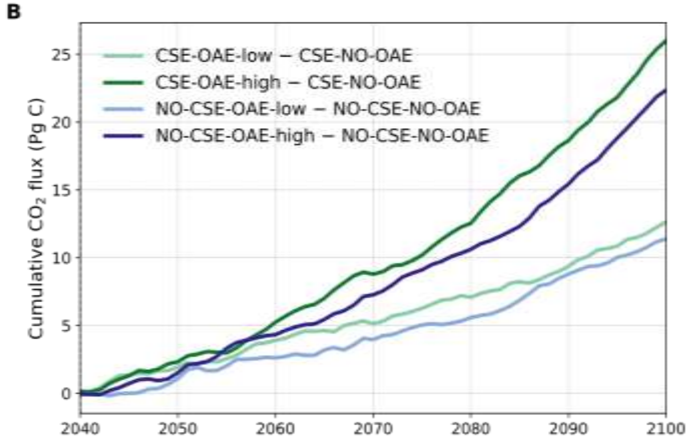
Effects of OAE on net primary production

With carbonate system effects on phytoplankton | **Without carbonate system effects on phytoplankton**



Indirect effects of OAE **decrease phytoplankton NPP by up to 15%** in the model version with carbonate system effects on phytoplankton

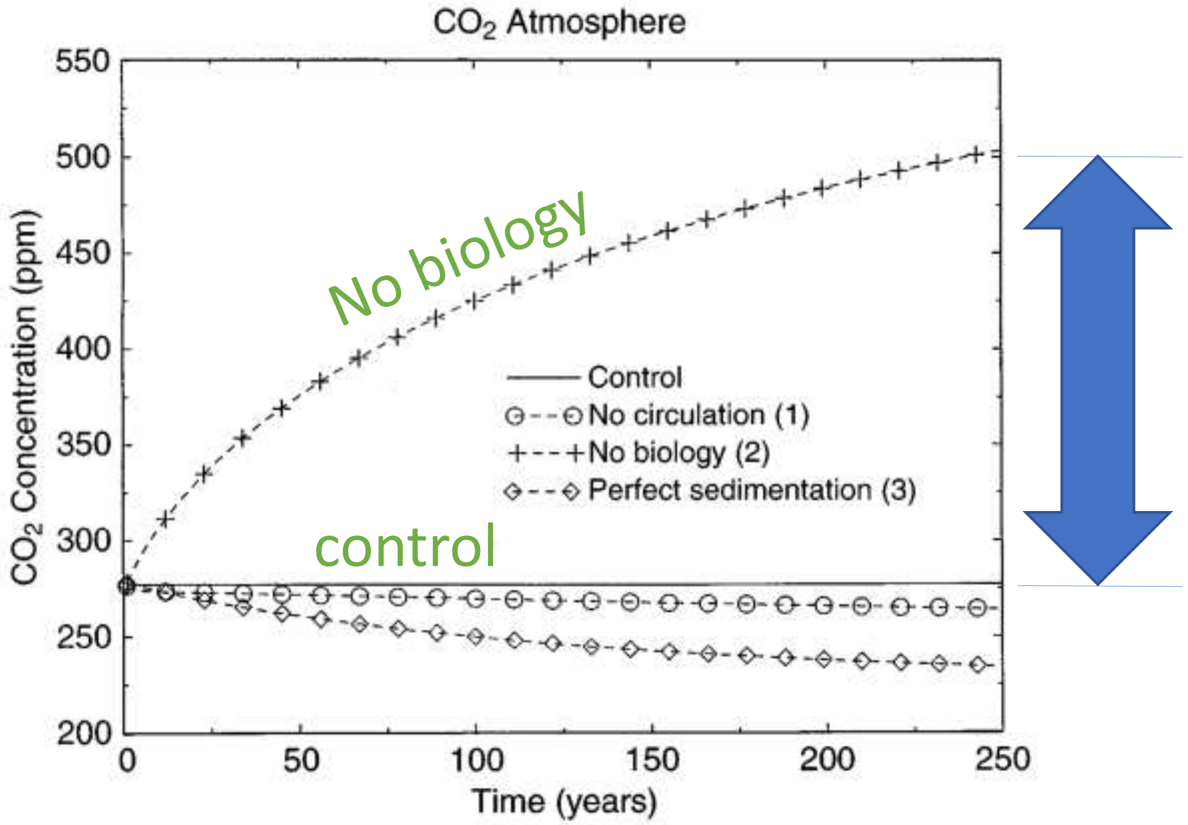
Effects of phytoplankton on OAE efficiency



Stronger CO_2 uptake by the ocean with carbonate system effects on phytoplankton

Seifert et al., Biogeosciences, accepted

Role of ocean biology for atmospheric CO_2



Effect of biology, ca 220 ppm
Preindustrial control experiment

500/280 = 1.8 “nearly twofold higher”

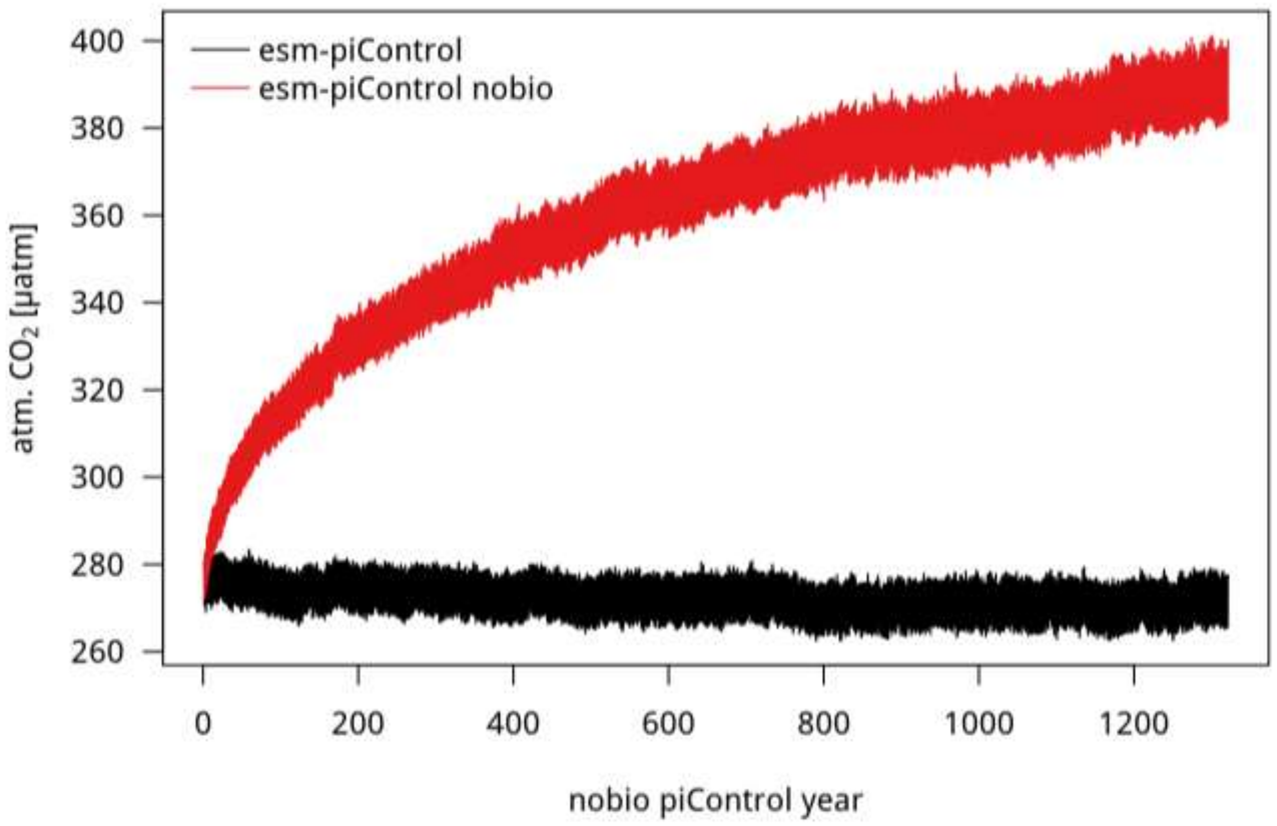
The absolute change is related to the amount of biological carbon in the ocean.
The relative change is not transferable to the present-day with higher atmospheric CO_2.

Land feedbacks missing, how does that compare to state-of-the-art models?

Maier-Reimer et al., 1996

Role of ocean biology for atmospheric CO_2

No-biology experiments in emission-driven AWI-ESM



Atmospheric CO_2

Rising by 120 µatm in 1300 years

→ Lower and slower than in Maier-Reimer et al.

→ Less diffuse ocean models and land carbon feedbacks

Hauck et al. in prep

On-going & outlook

Other on-going projects:
- Southern Ocean freshwater effects on carbon (SOFIA)
- Quantifying and addressing ventilation biases
- Mapping polar plankton habitats and their change
- Sprint proposal in review: implement REcoM into FABM
- Coastal set-up

Within REcoM:
- Additional calcifiers and improved representation of alkalinity
- New phytoplankton types: phaeocystis, second diatom
- Tracer for terrestrial POC
- Plankton response to warming and heatwaves
- Marine nitrogen cycling
- pH/temperature-controlled trace metal cycling

FESOM2 Finite volumE Sea ice-Ocean Model
REcoM Regulated Ecosystem Model
OCEAN PEAK
OceanICU Understanding Ocean Carbon
POMP
PALMOD GERMAN CLIMATE MODELING INITIATIVE
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Thank you!

Universität Bremen