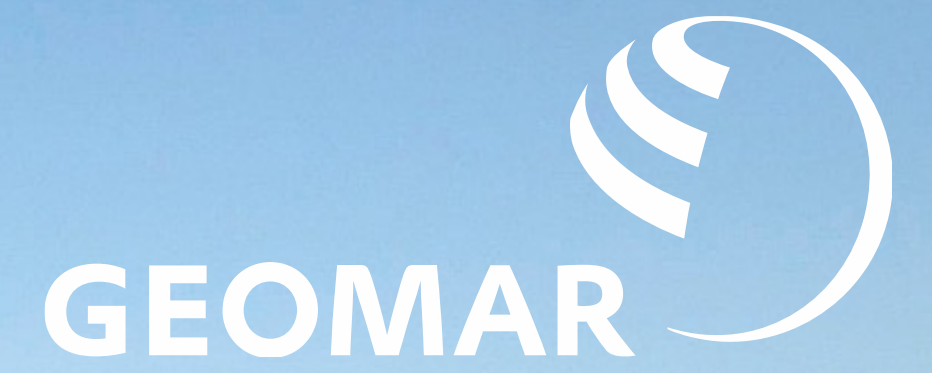


	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6
	Monday, July 22nd	Tuesday, July 23rd	Wednesday, July 24th	Thursday, July 25th	Friday, July 26th	Saturday, July 27th
08:30-09:00	Welcome					
09:00-09:30	Polar hydrography and circulation (Waterman/Chidichimo)	Observations (Waterman)	Atmosphere-ice-ocean interactions (Kushner/Bracegirdle)	Sea ice (Bitz/Smith)	Ocean-ice sheet interactions (Myers/Colleoni)	Biogeochemical processes (Frenger/Tedesco)
09:30-10:00						
10:00-10:30	Break	Break	Break	Break	Break	Break
10:30-11:00	Polar hydrography and circulation (Waterman/Chidichimo)	Numerical modelling (Bitz)	Atmosphere-ice-ocean interactions (Kushner/Bracegirdle)	Sea ice (Bitz/Smith)	Ocean-ice sheet interactions (Myers/Colleoni)	Biogeochemical processes (Frenger/Tedesco)
11:00-11:30						
11:30-12:00	Discussion	Discussion	Discussion	Discussion	Discussion	Discussion
12:00-12:30						
12:30-13:00	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch
13:00-13:30						
13:30-14:00	Research projects	EMODnet and data management	Research projects	Social activity (snorkeling and boat tour in the marine reserve area)	Research projects	Research projects
14:00-14:30						
14:30-15:00						
15:00-15:30						
15:30-16:00						
16:00-16:30	Research projects					
16:30-17:00						
17:00-17:30						
17:30-18:00	Posters and drinks				Posters and drinks	
18:00-18:30						
			Dinner?			Dinner?

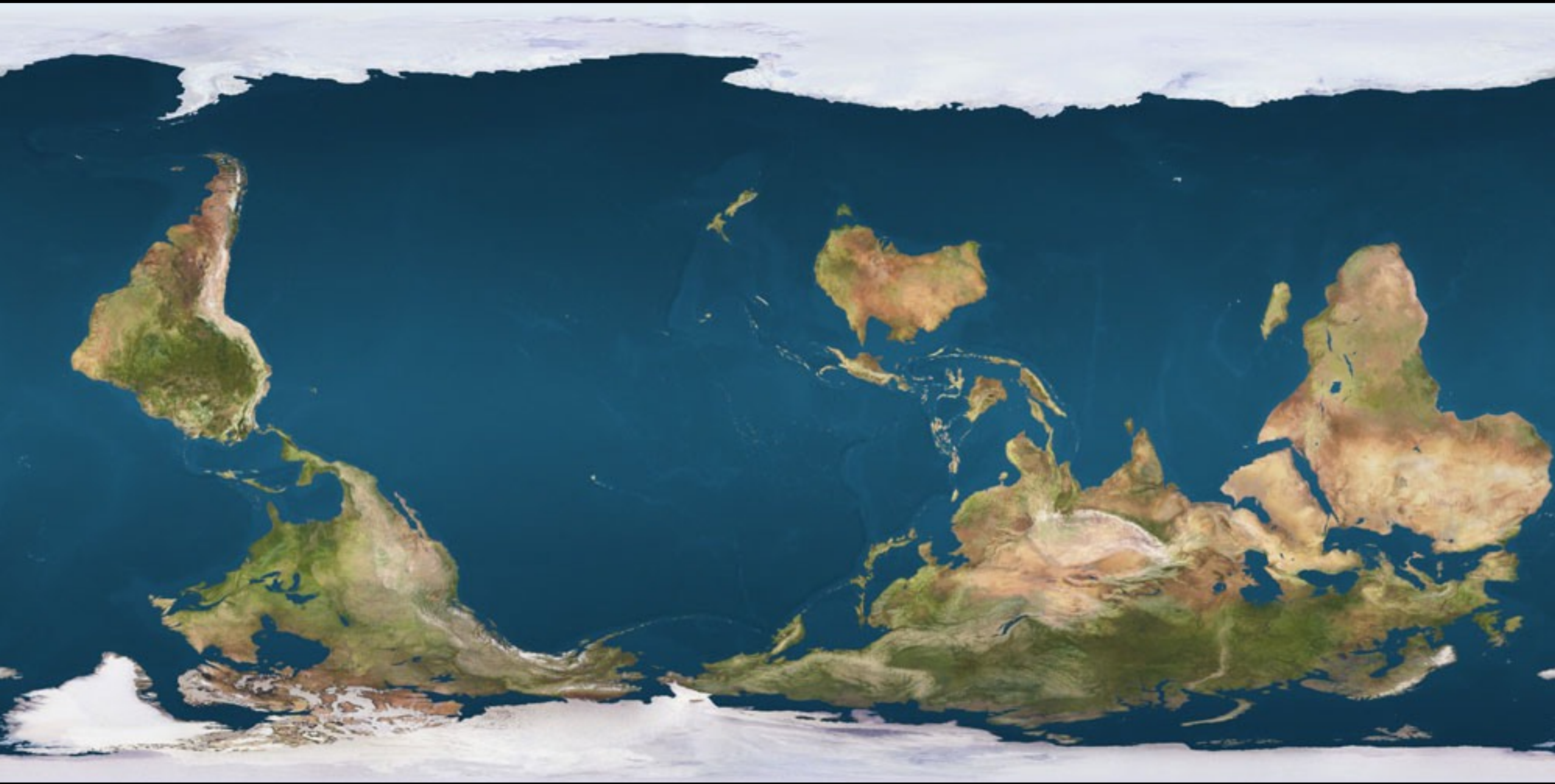
HELMHOLTZ



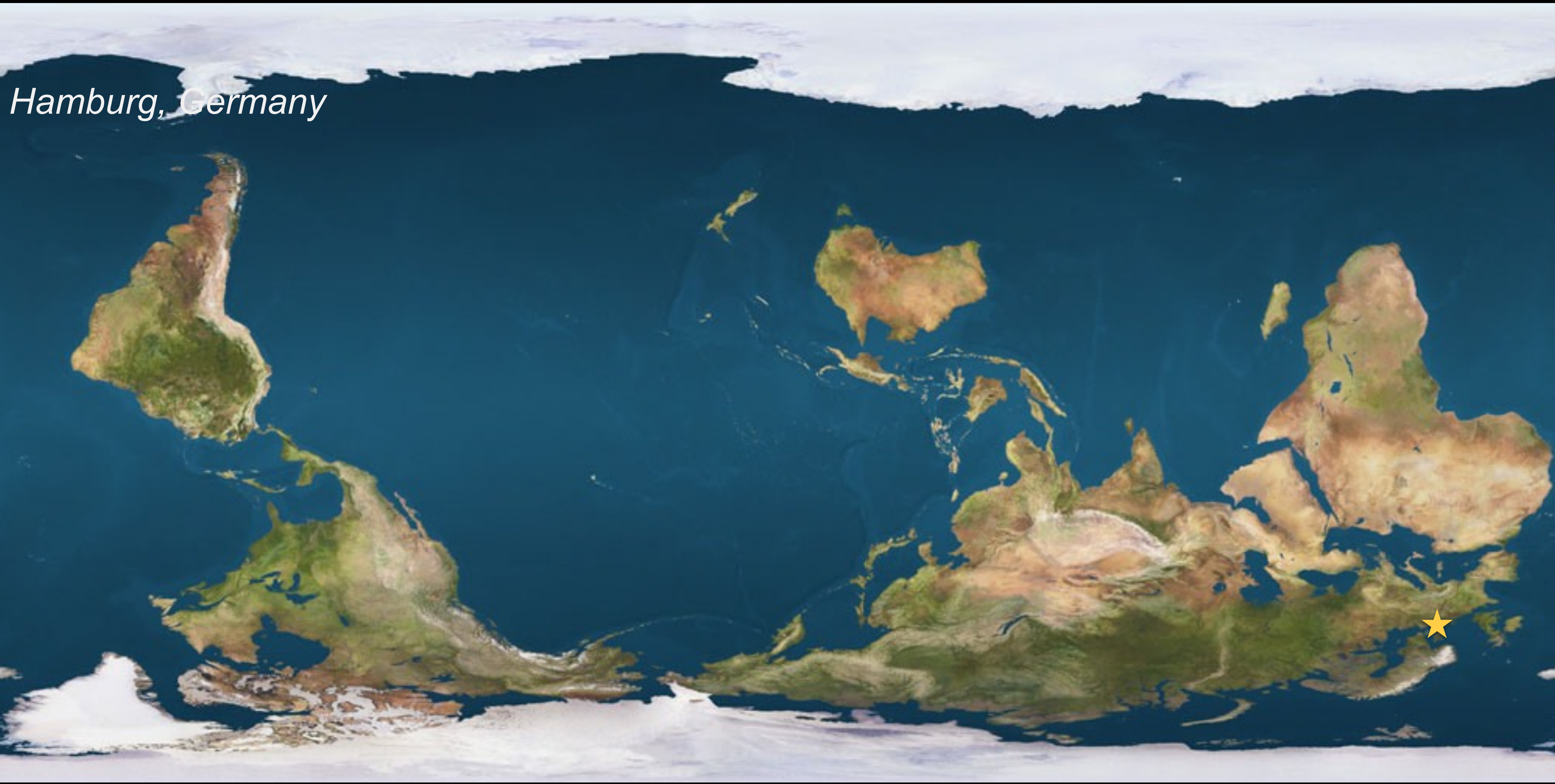
Brief info CV

Ivy Frenger





Hamburg, Germany



Hamburg, Germany

► “Diplom” (Bachelor/Master): Meteorology, Hamburg University

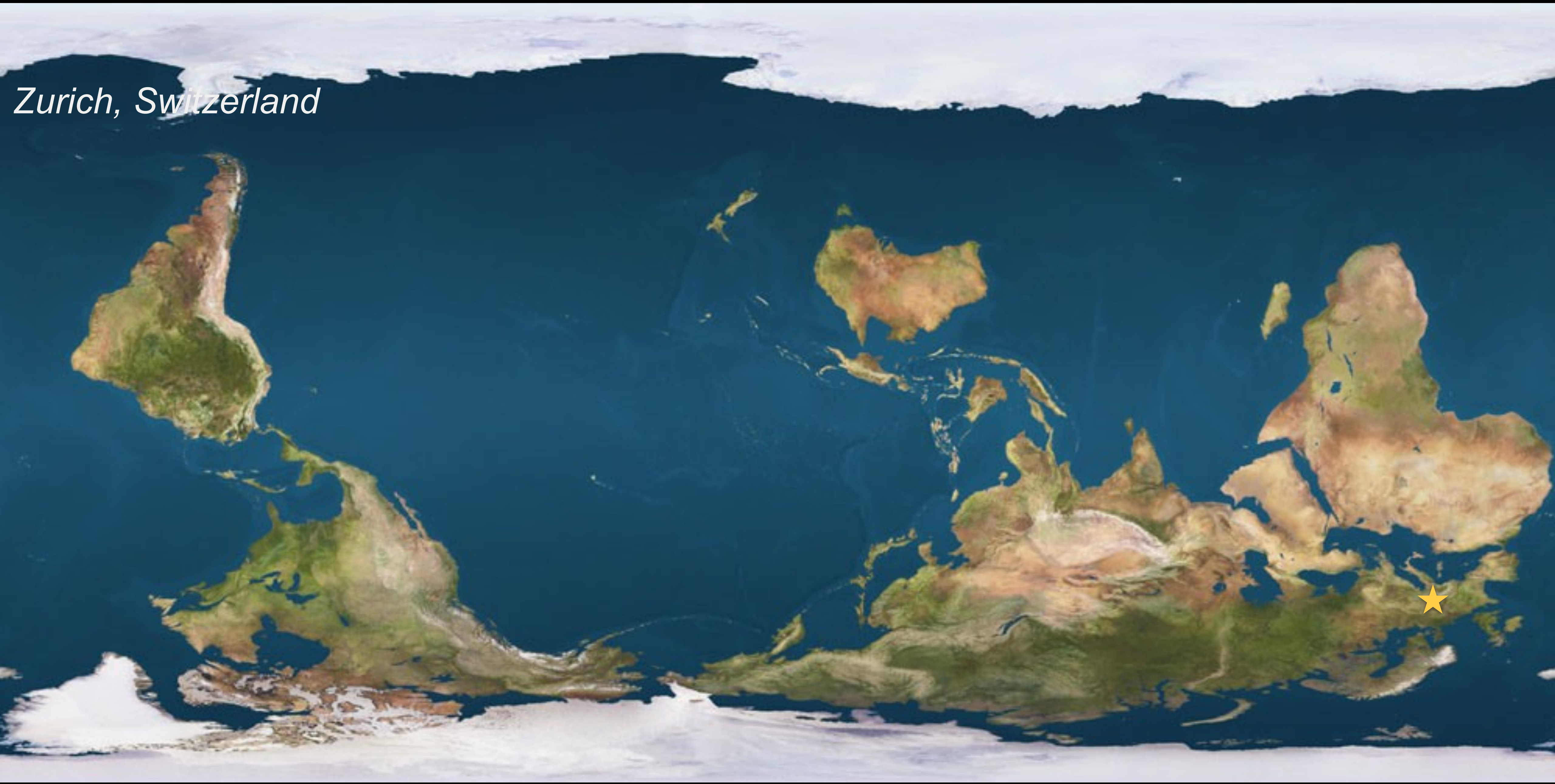


Hamburg, Germany

- ▶ “Diplom” (Bachelor/Master): Meteorology, Hamburg University
- ▶ Oceanography, Dalhousie University, Halifax, Canada
- ▶ Value of “atmospheric education”



Zurich, Switzerland



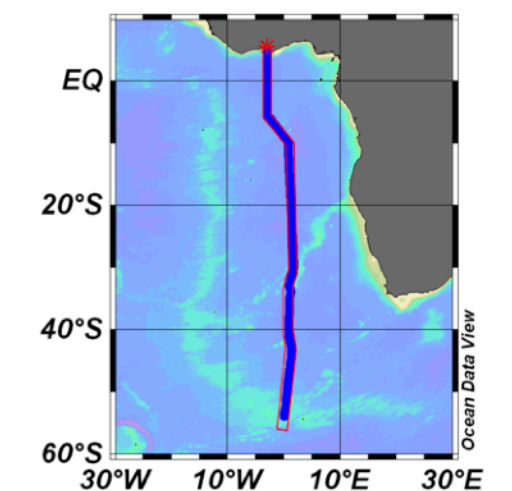
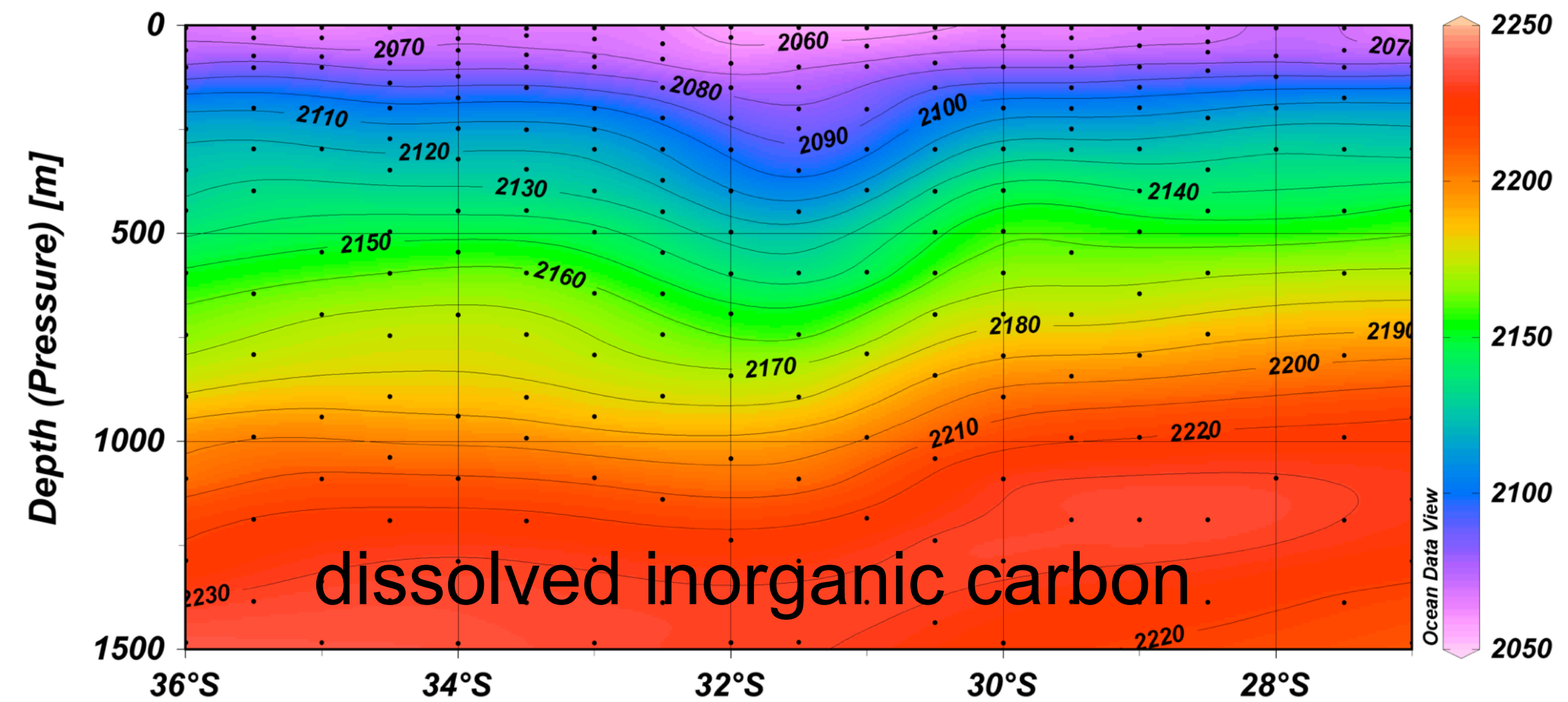
Zurich, Switzerland

► PhD: Oceanography, Marine Biogeochemistry, ETHZ



Zurich, Switzerland

- ▶ PhD: Oceanography, Marine Biogeochemistry, ETHZ
- ▶ Southern Ocean, mesoscale eddies, cruise: A13.5, insights in situ observations



<https://www.pmel.noaa.gov/>

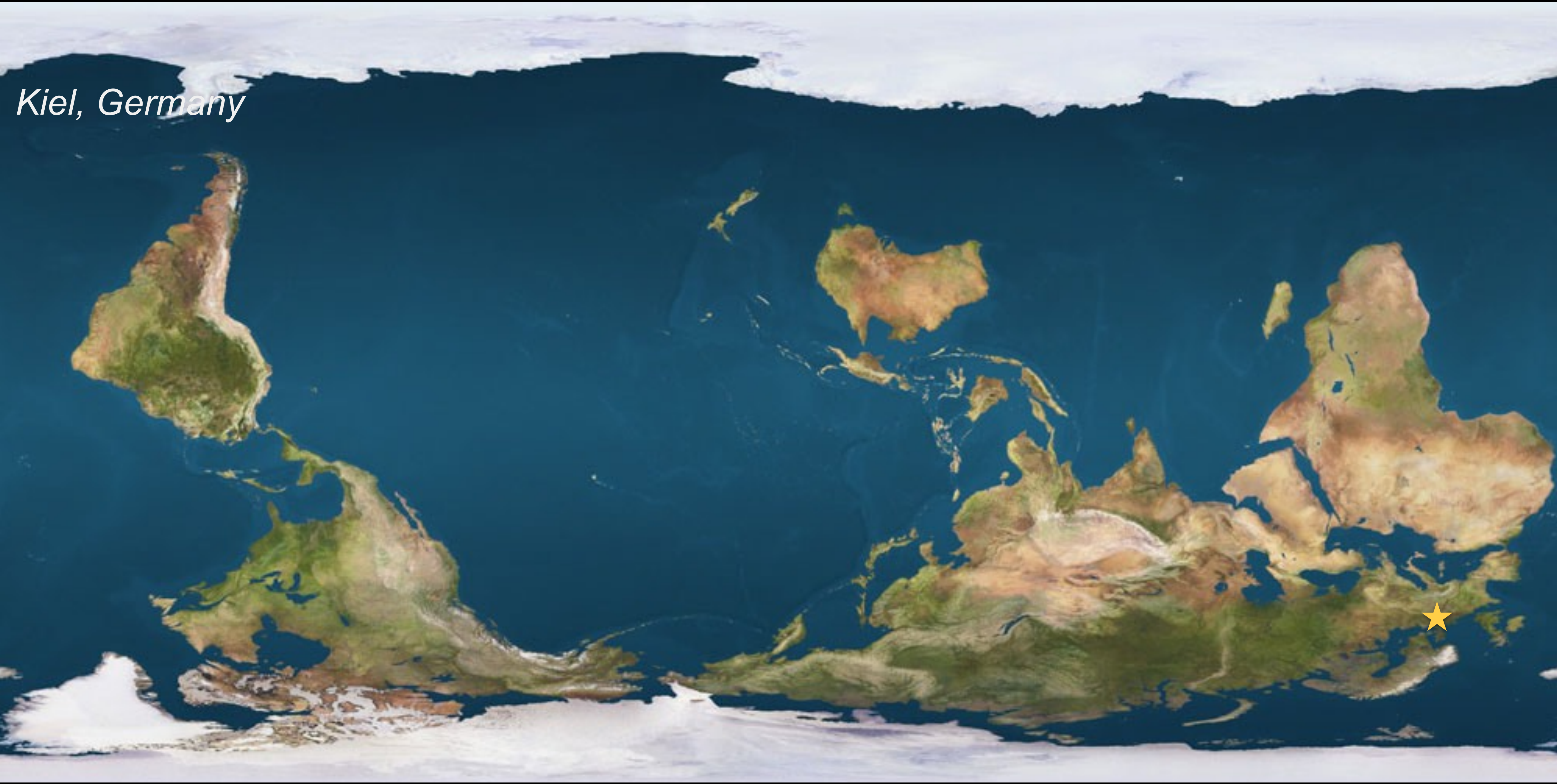
https://en.wikipedia.org/wiki/South-up_map_orientation

Princeton, NJ, US

- ▶ *Postdoc: Oceanography, Marine Biogeochemistry*
- ▶ *Modelling center GFDL; US science community.*



Kiel, Germany



Kiel, Germany

- ▶ *Postdoc, research scientist on soft money*
- ▶ *ERCStG research group lead*



HELMHOLTZ



Biogeochemical processes and their physical drivers part I

Ivy Frenger

Summer School on Polar Climates

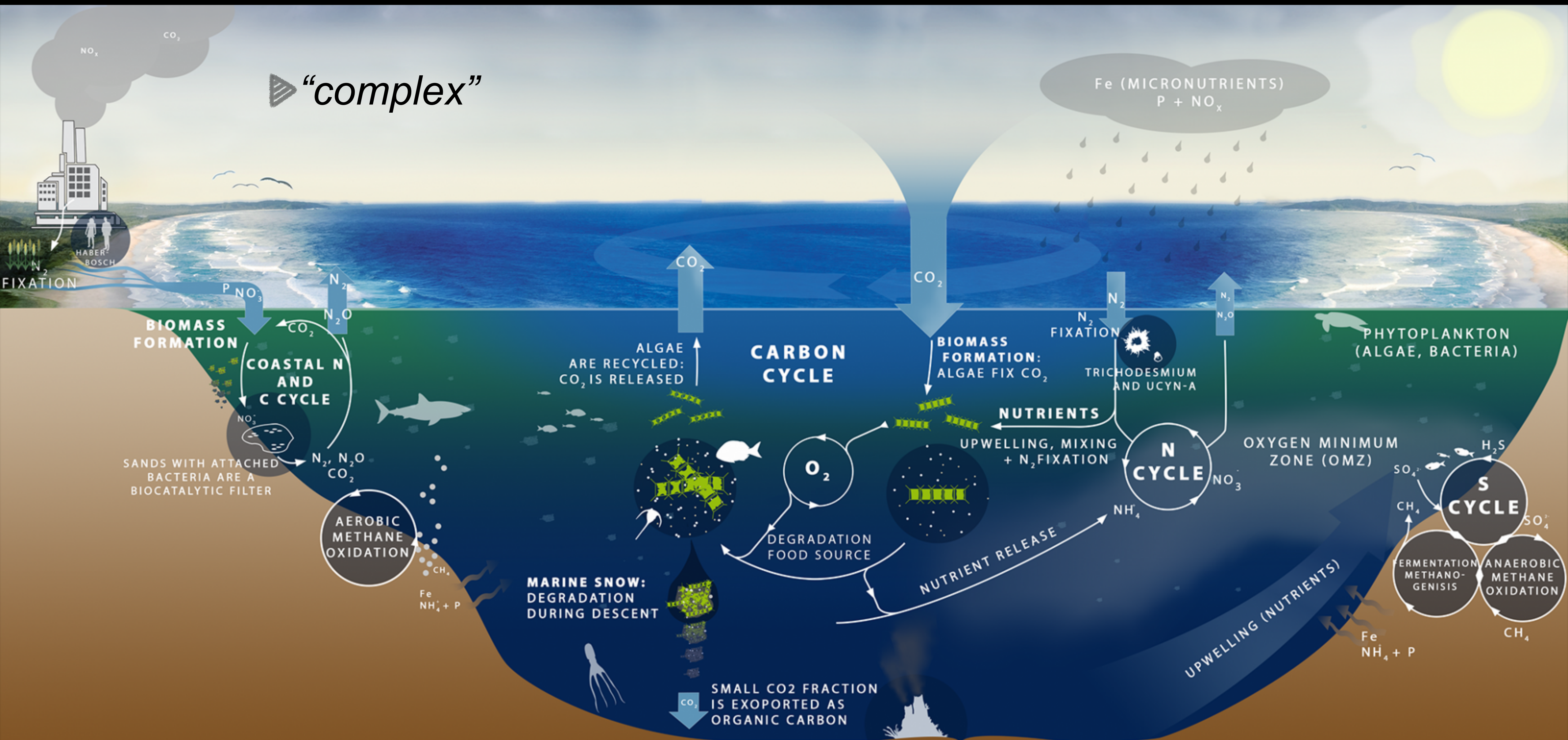
BACKGROUND

Marine biogeochemistry

What is it concerned about:

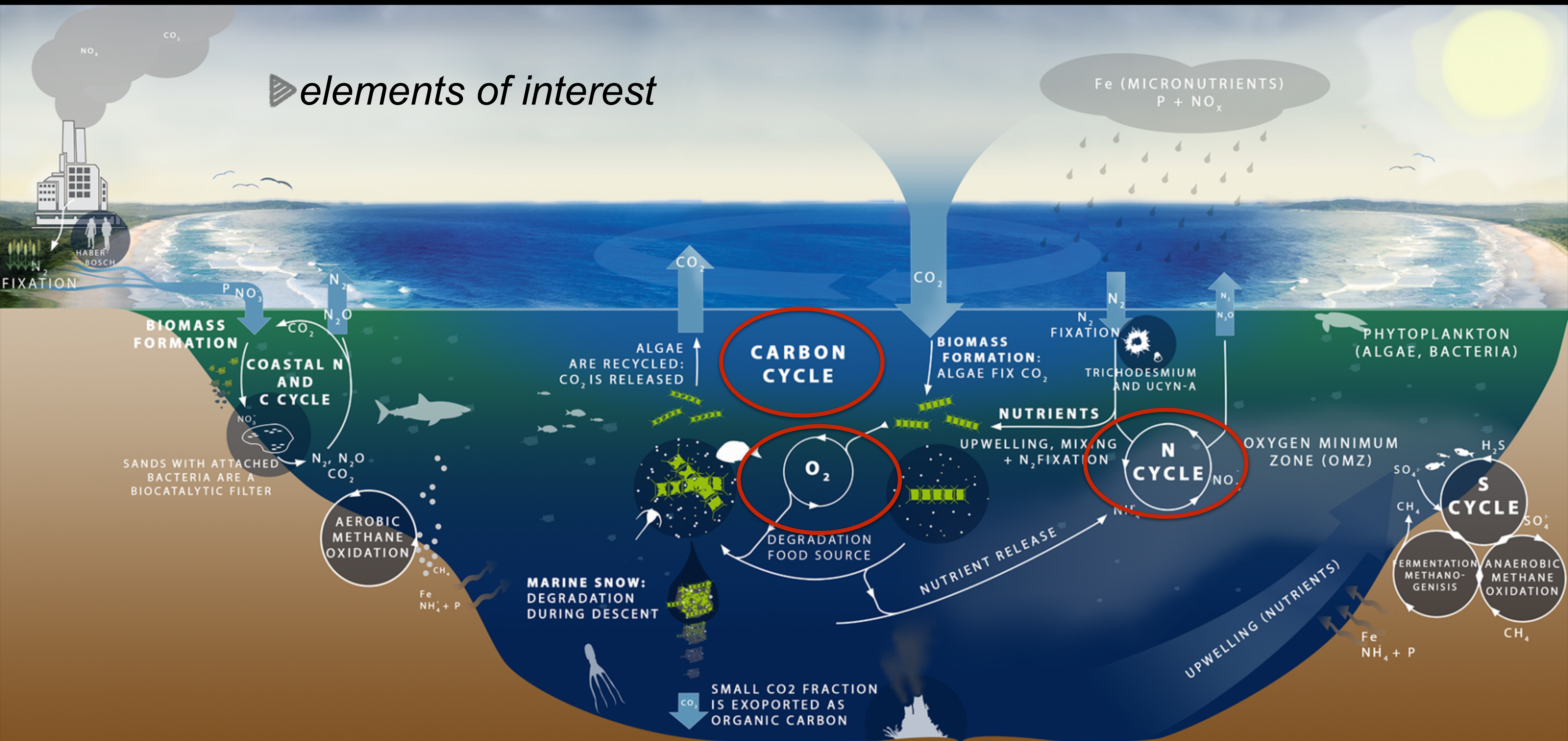
Processes, that drive element cycling in the ocean

BACKGROUND



BACKGROUND

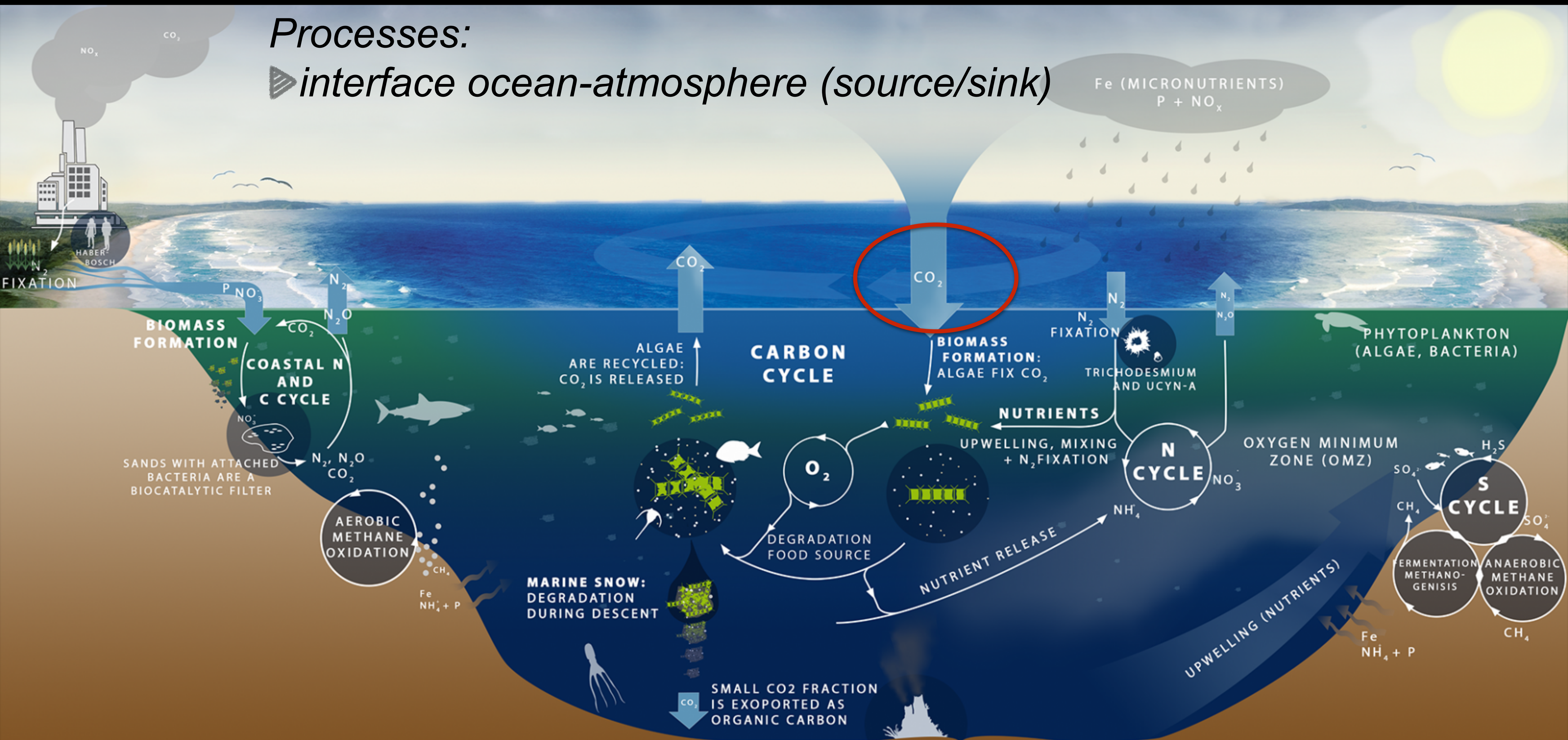
elements of interest



BACKGROUND

Processes:

▶ *interface ocean-atmosphere (source/sink)*

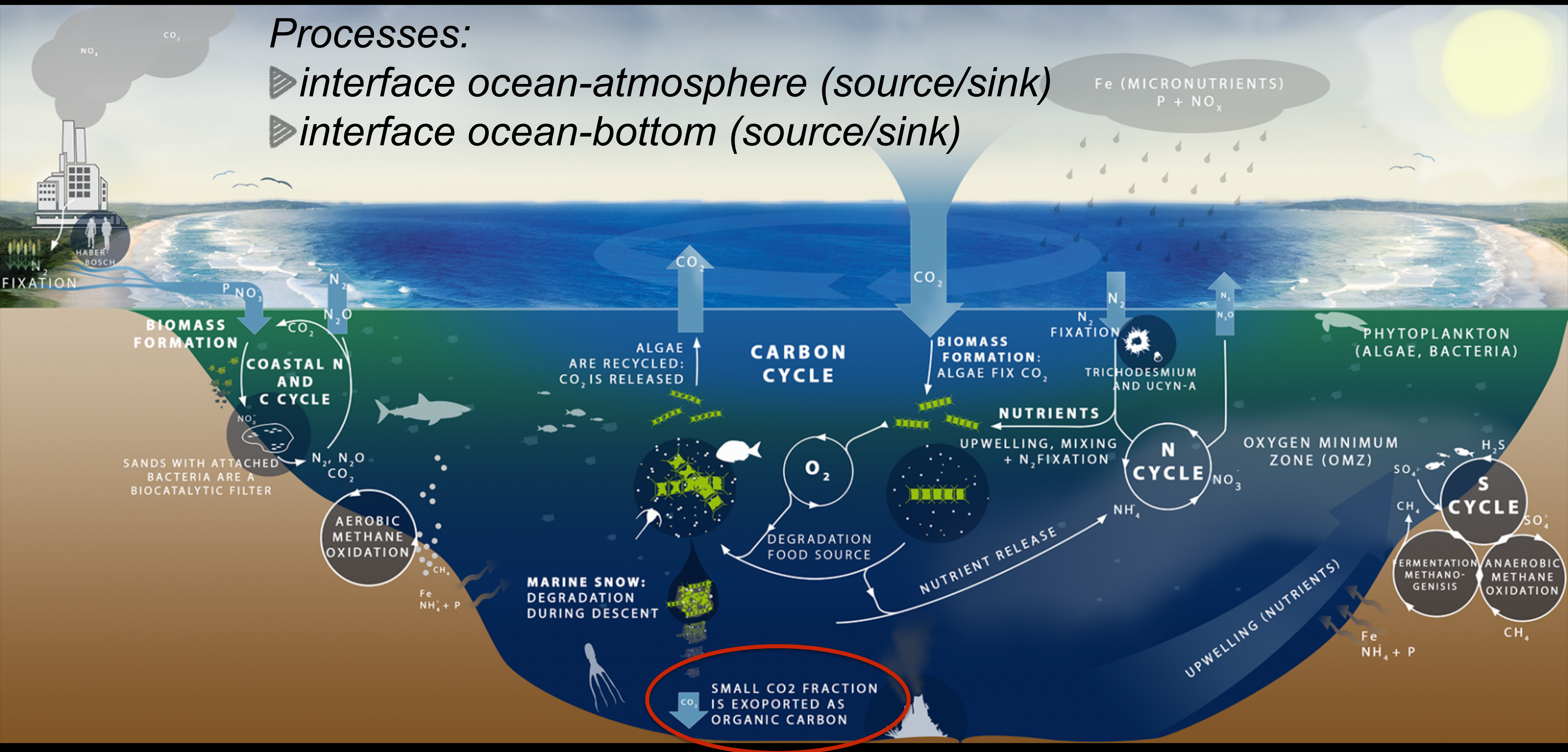


BACKGROUND

Processes:

▶ interface ocean-atmosphere (source/sink)

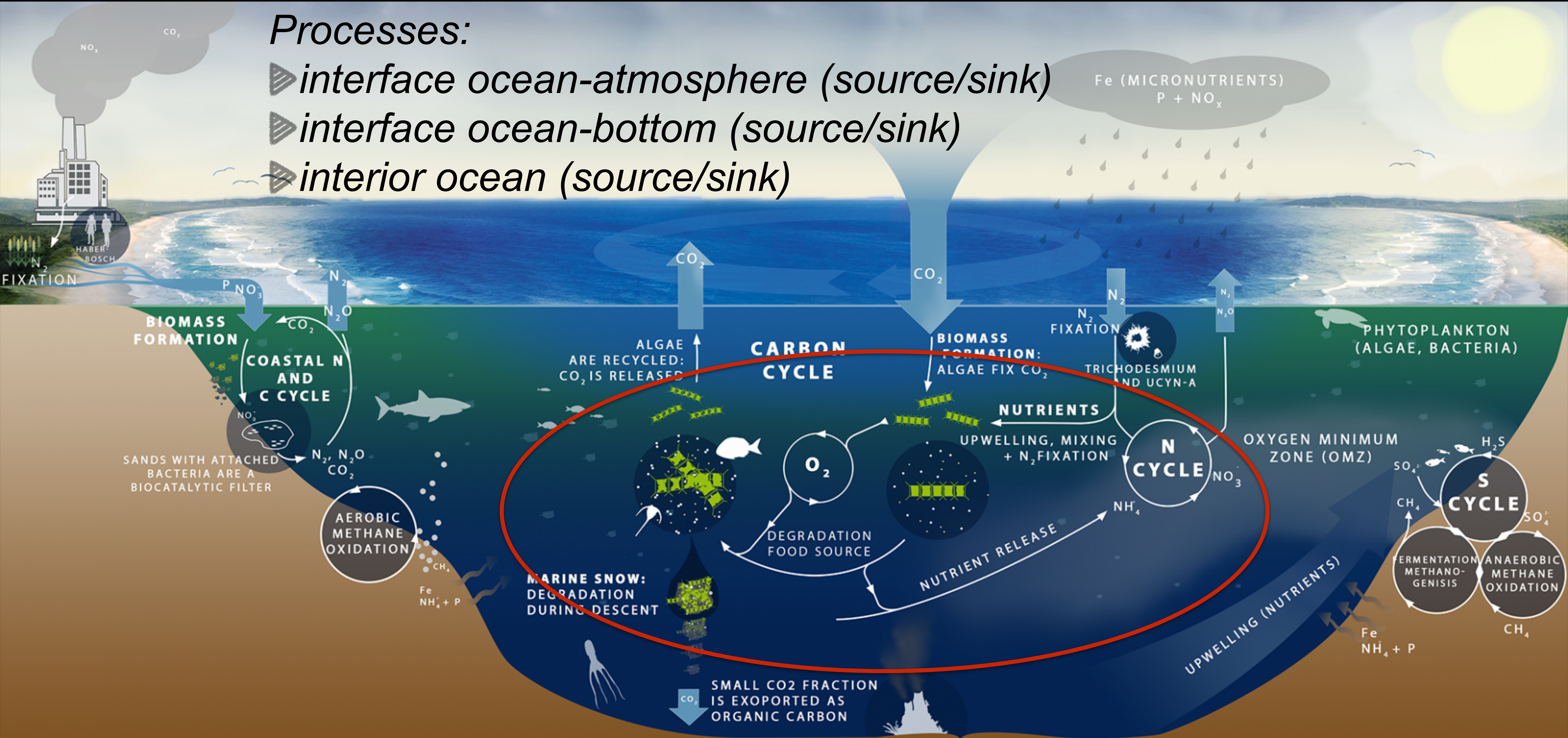
▶ interface ocean-bottom (source/sink)



BACKGROUND

Processes:

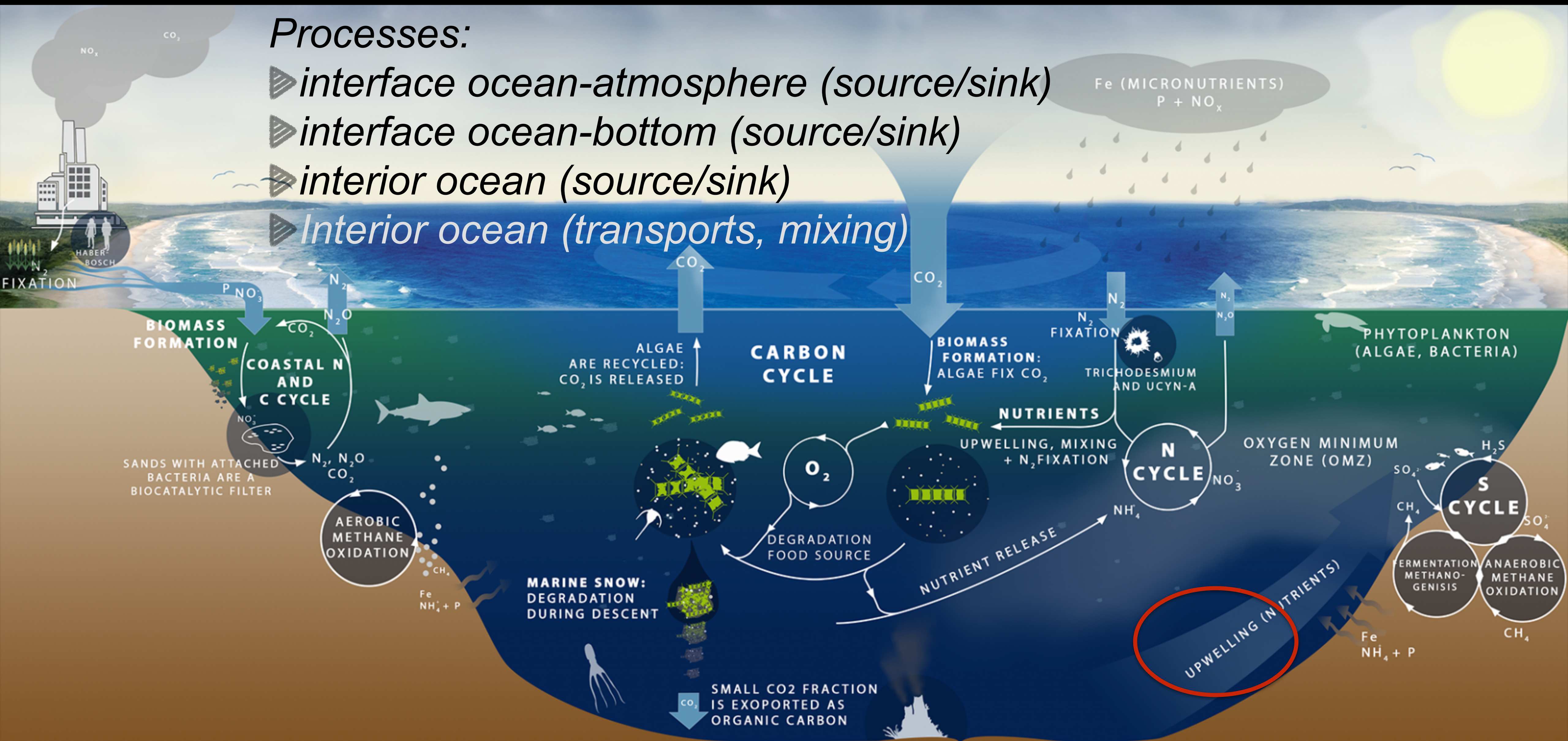
- ▶ interface ocean-atmosphere (source/sink)
- ▶ interface ocean-bottom (source/sink)
- ▶ interior ocean (source/sink)



BACKGROUND

Processes:

- ▶ interface ocean-atmosphere (source/sink)
- ▶ interface ocean-bottom (source/sink)
- ▶ interior ocean (source/sink)
- ▶ Interior ocean (transports, mixing)



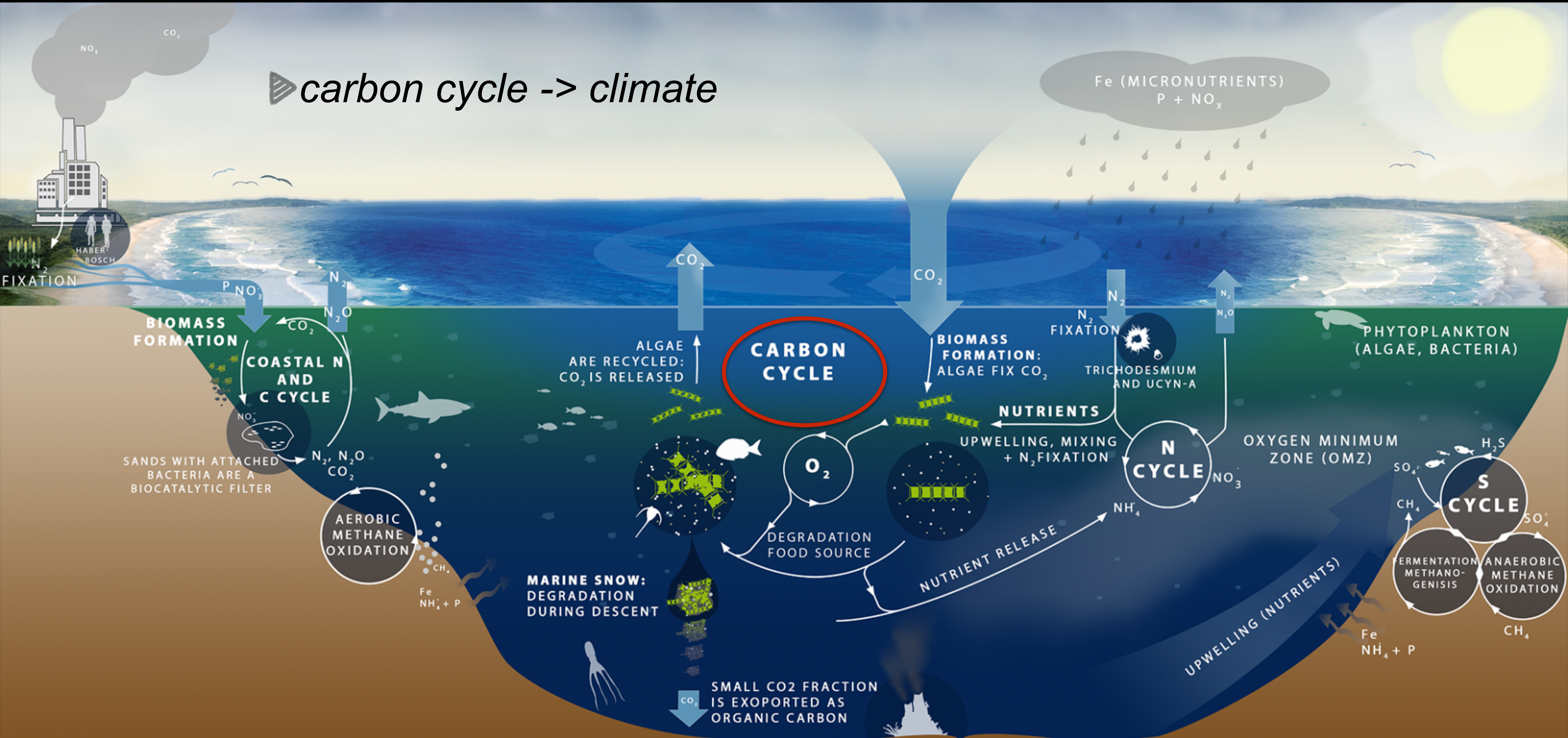
BACKGROUND

Marine biogeochemistry

Why do we care

BACKGROUND

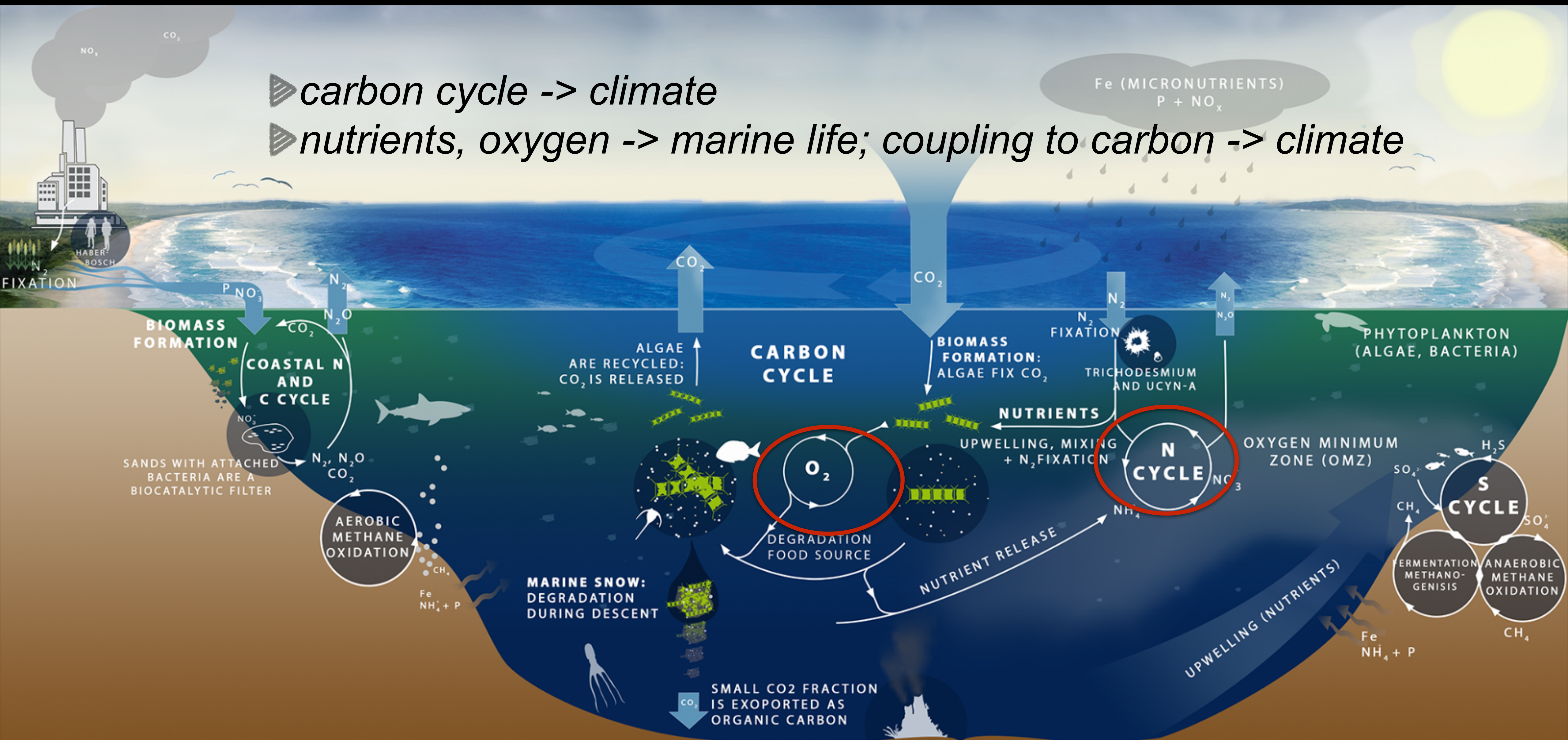
▶ carbon cycle -> climate



BACKGROUND

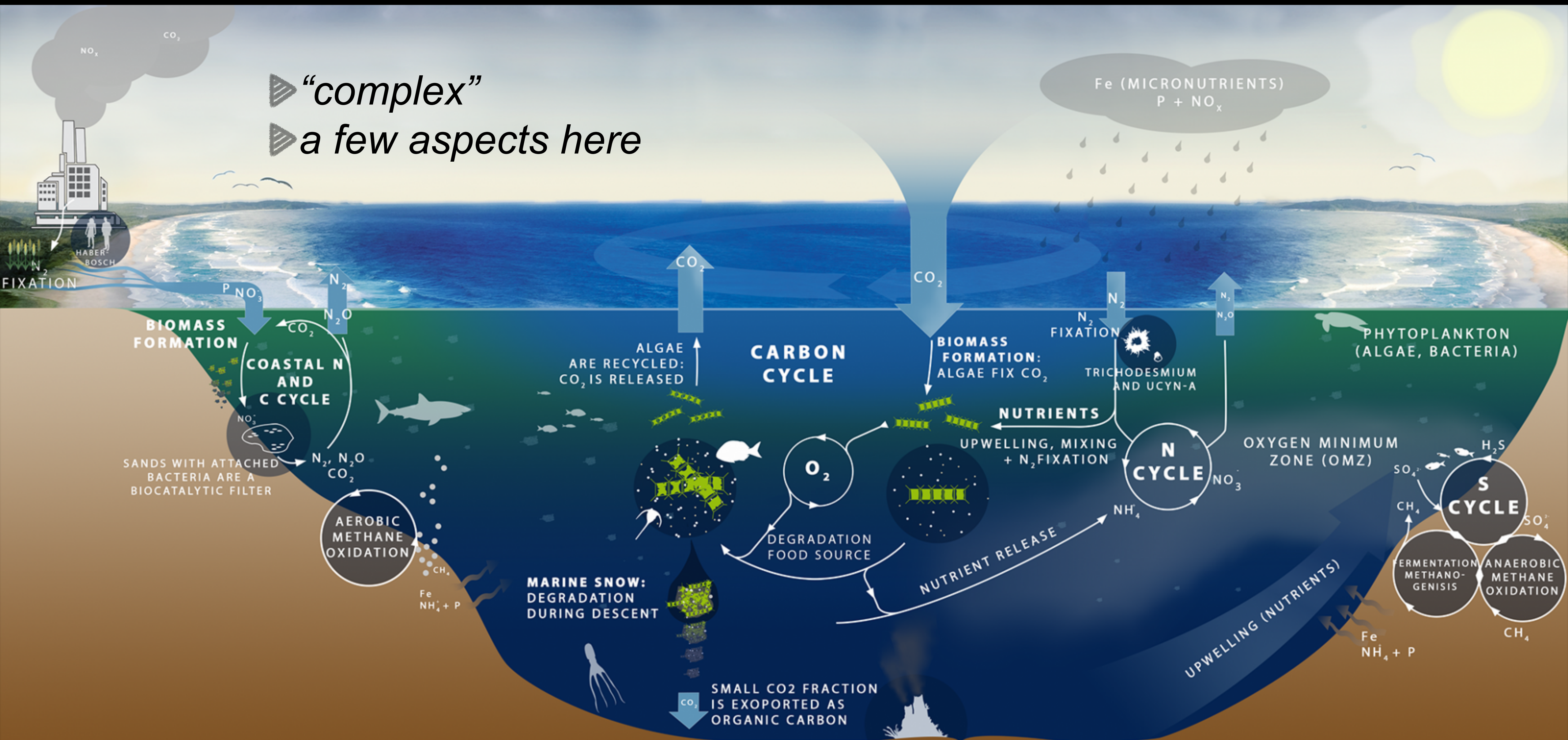
▶ carbon cycle -> climate

▶ nutrients, oxygen -> marine life; coupling to carbon -> climate



BACKGROUND

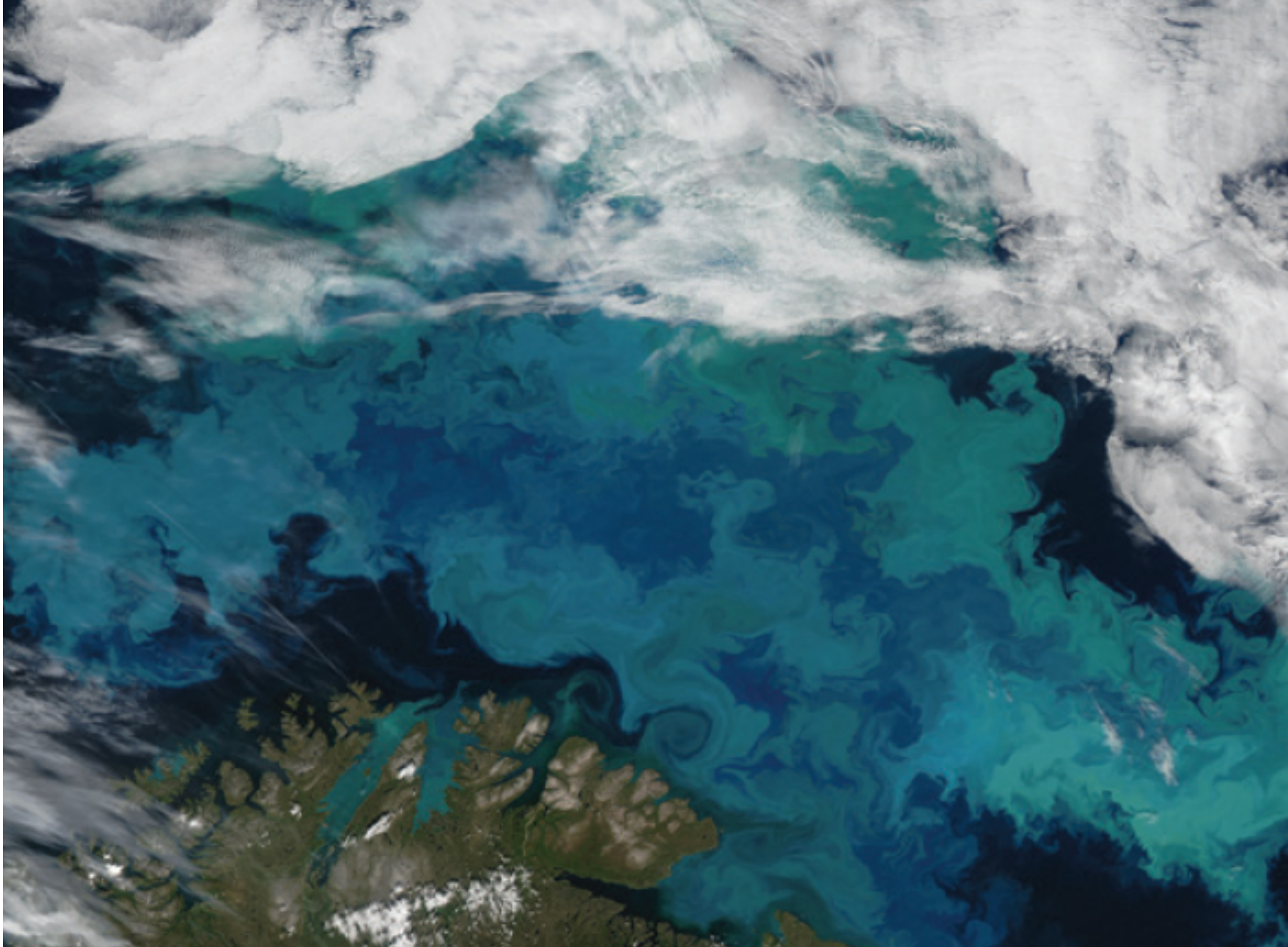
► “complex”
► a few aspects here



*Have you worked with biogeochemical variables before?
Analyzed, interpreted etc, such as ...*

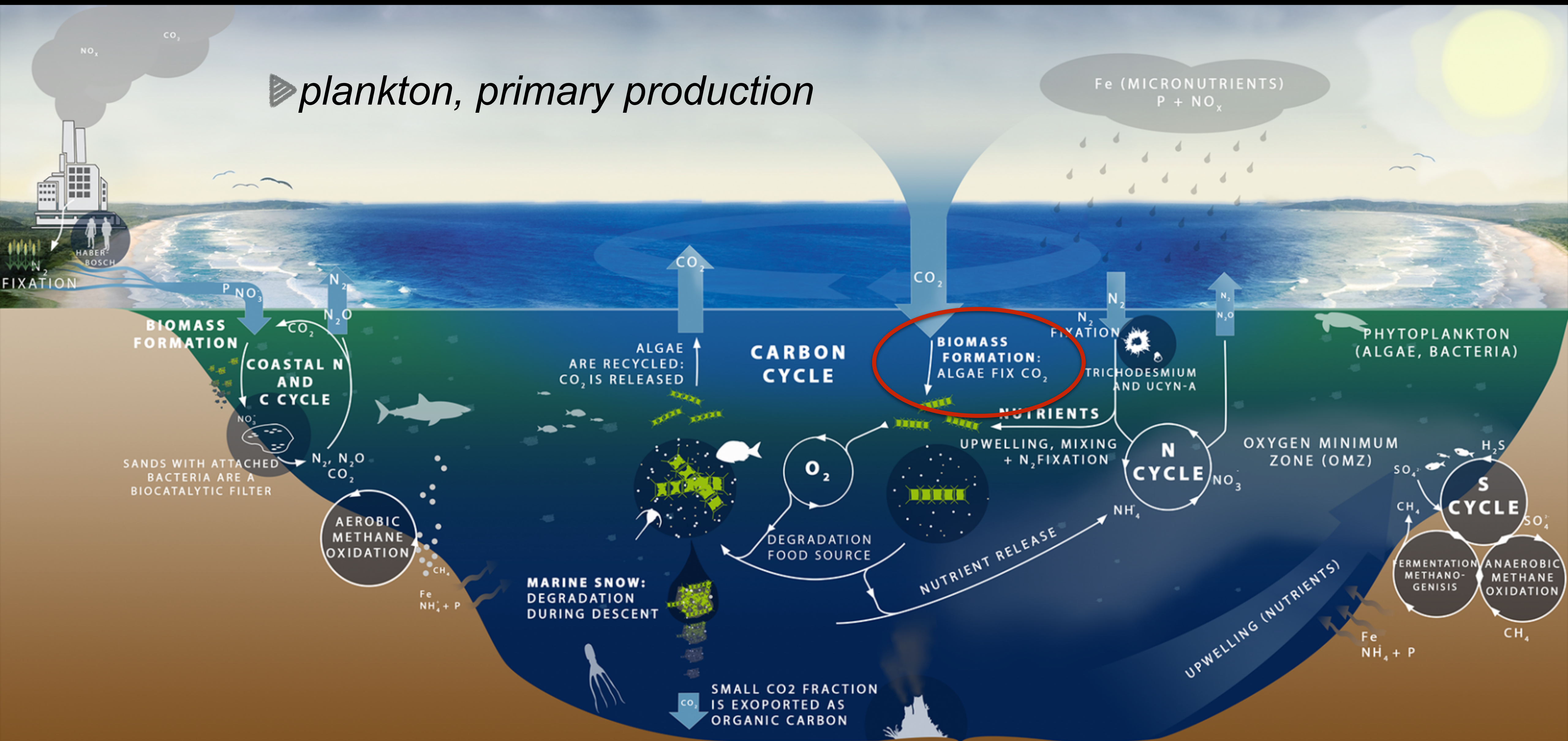
- ▶ *carbon*
- ▶ *plankton*
- ▶ *...*
- ?

BACKGROUND



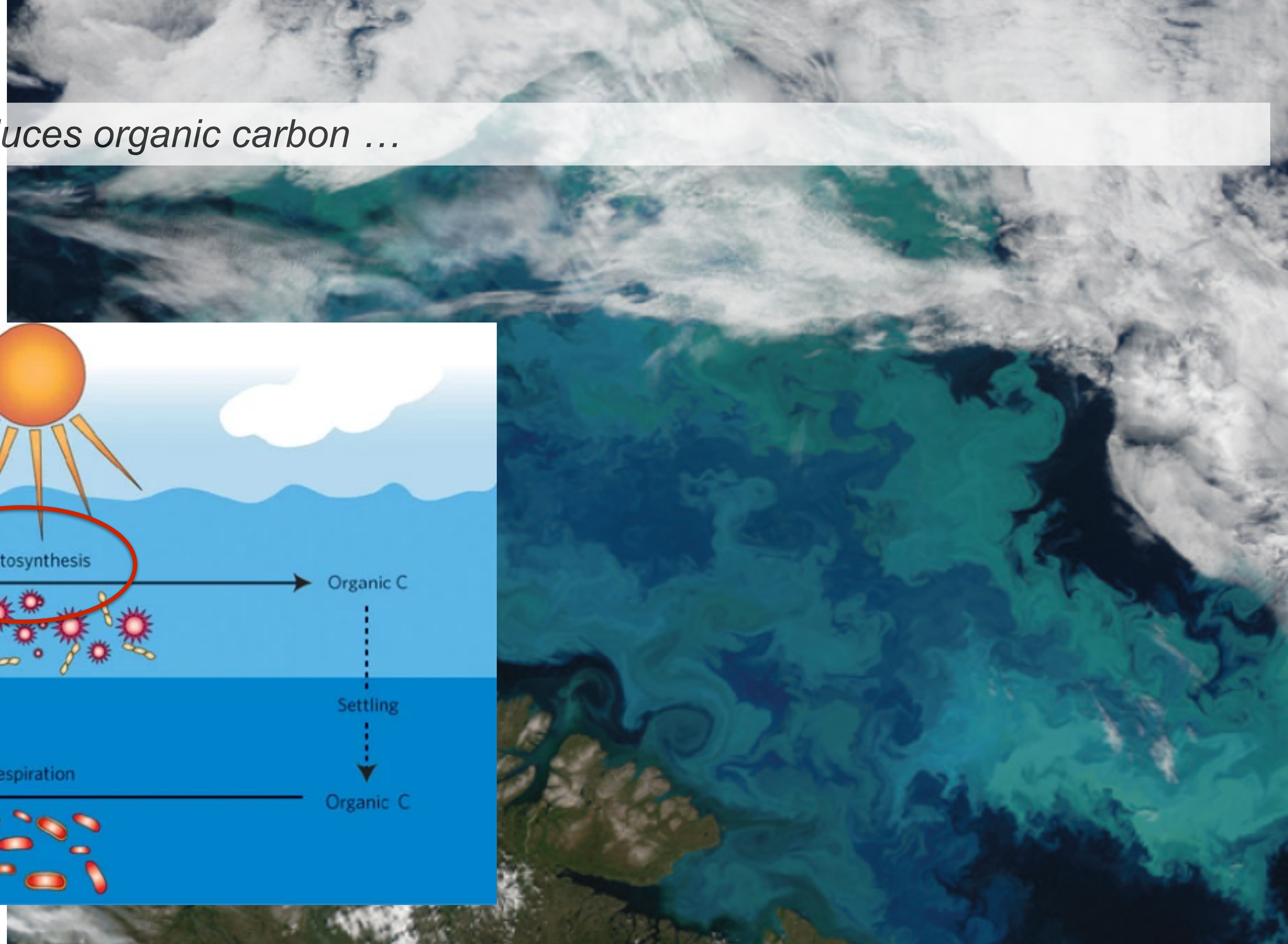
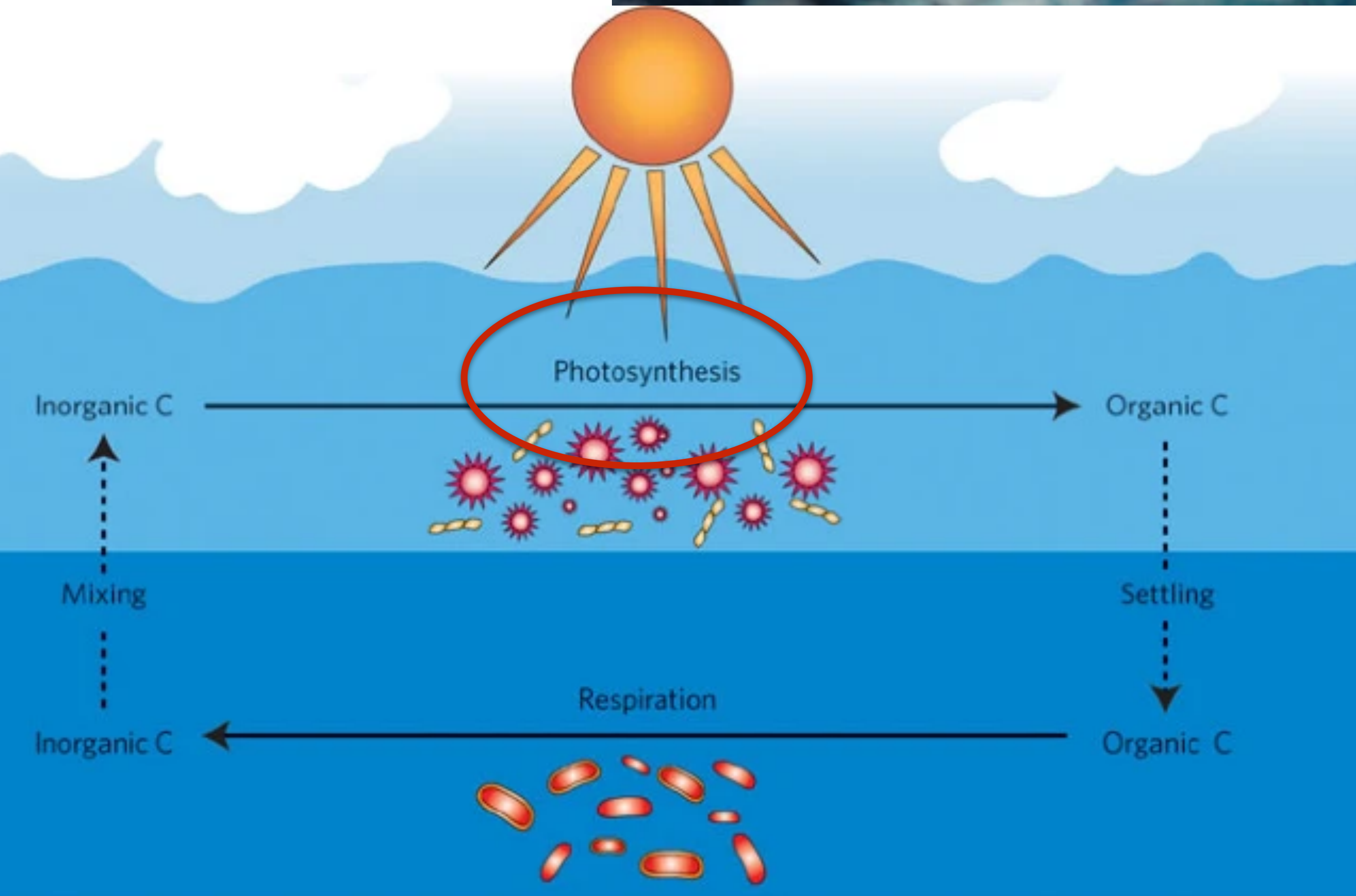
BACKGROUND

▶ plankton, primary production



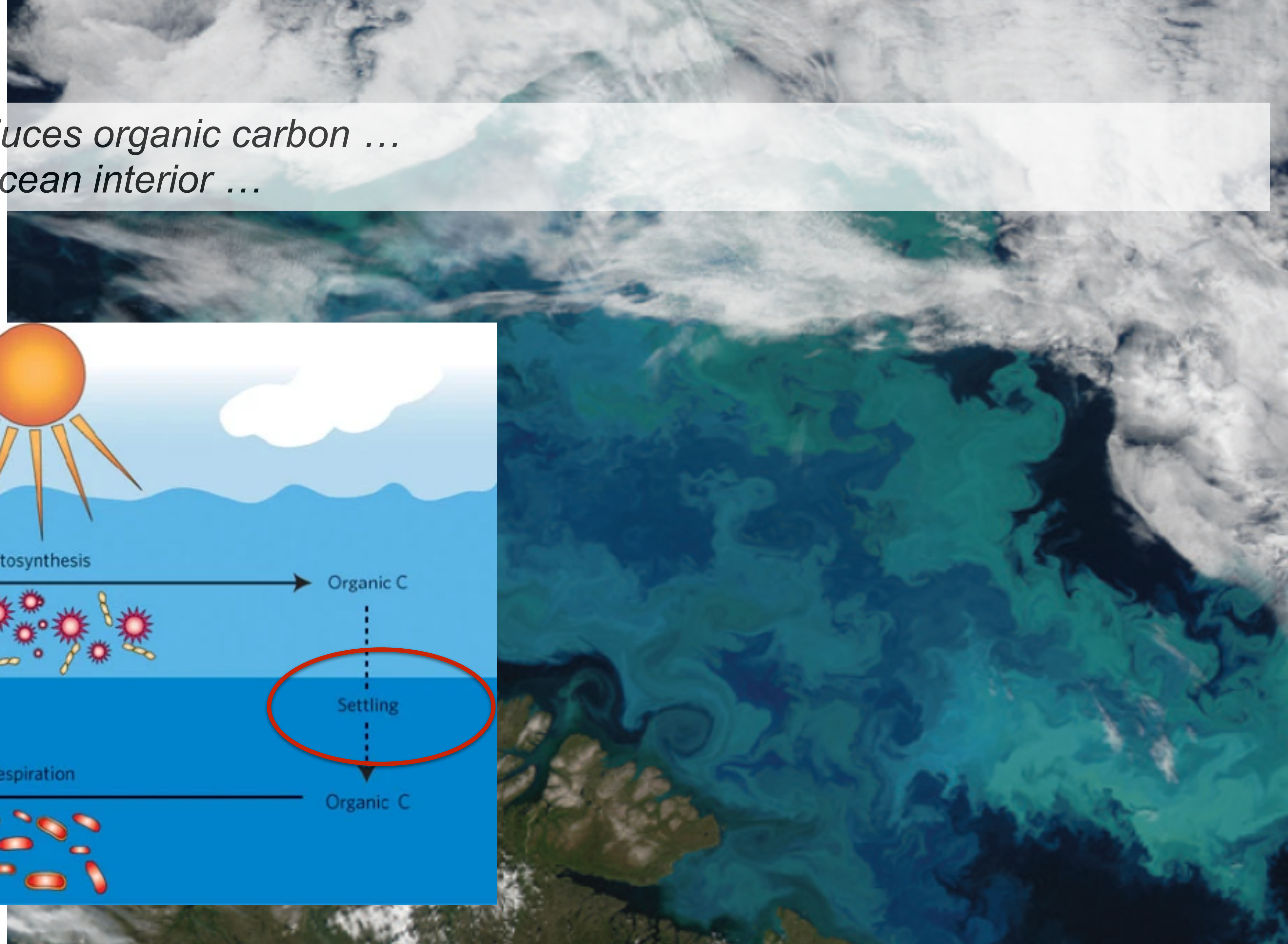
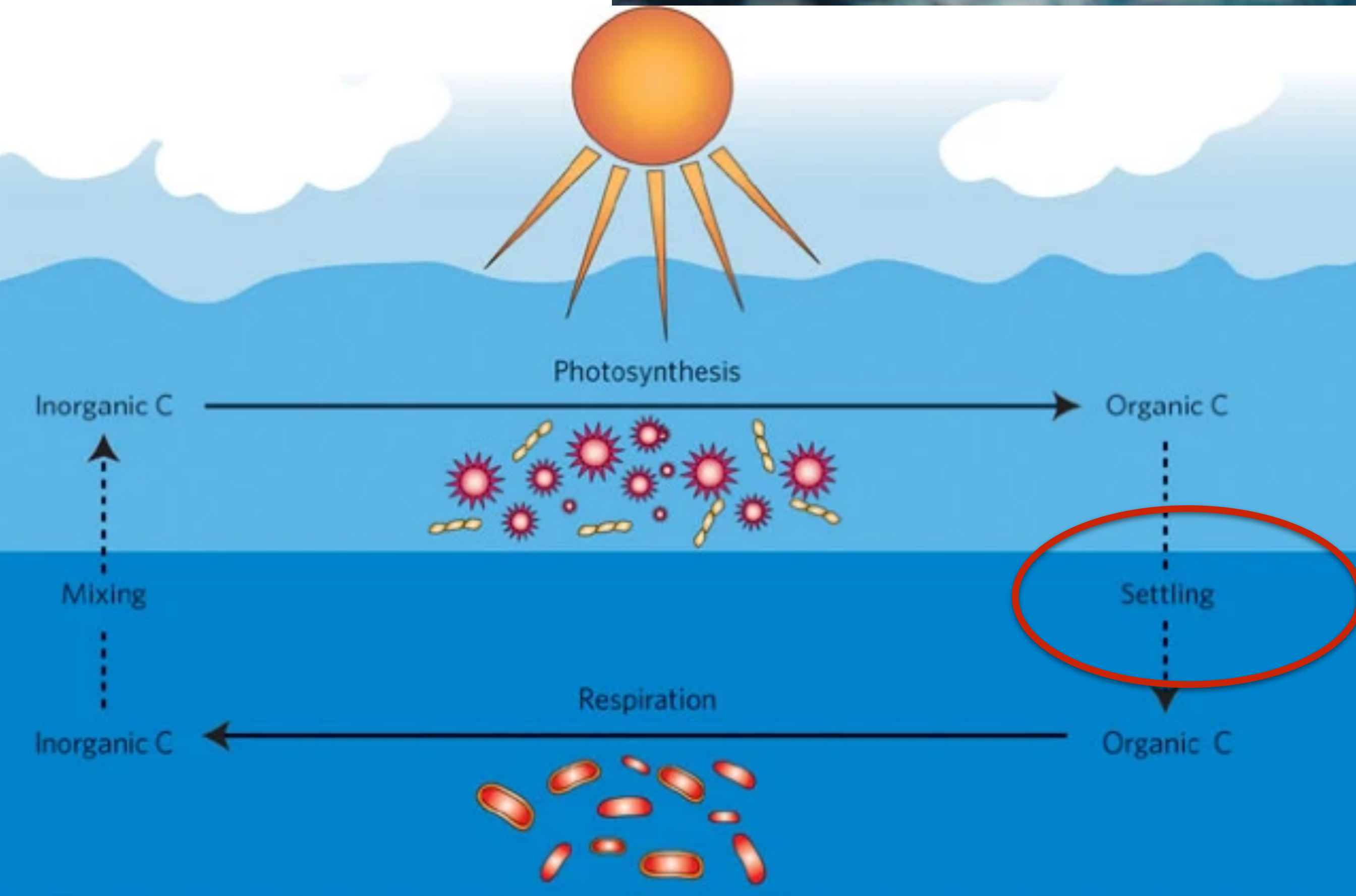
BACKGROUND

► *phytoplankton produces organic carbon ...*



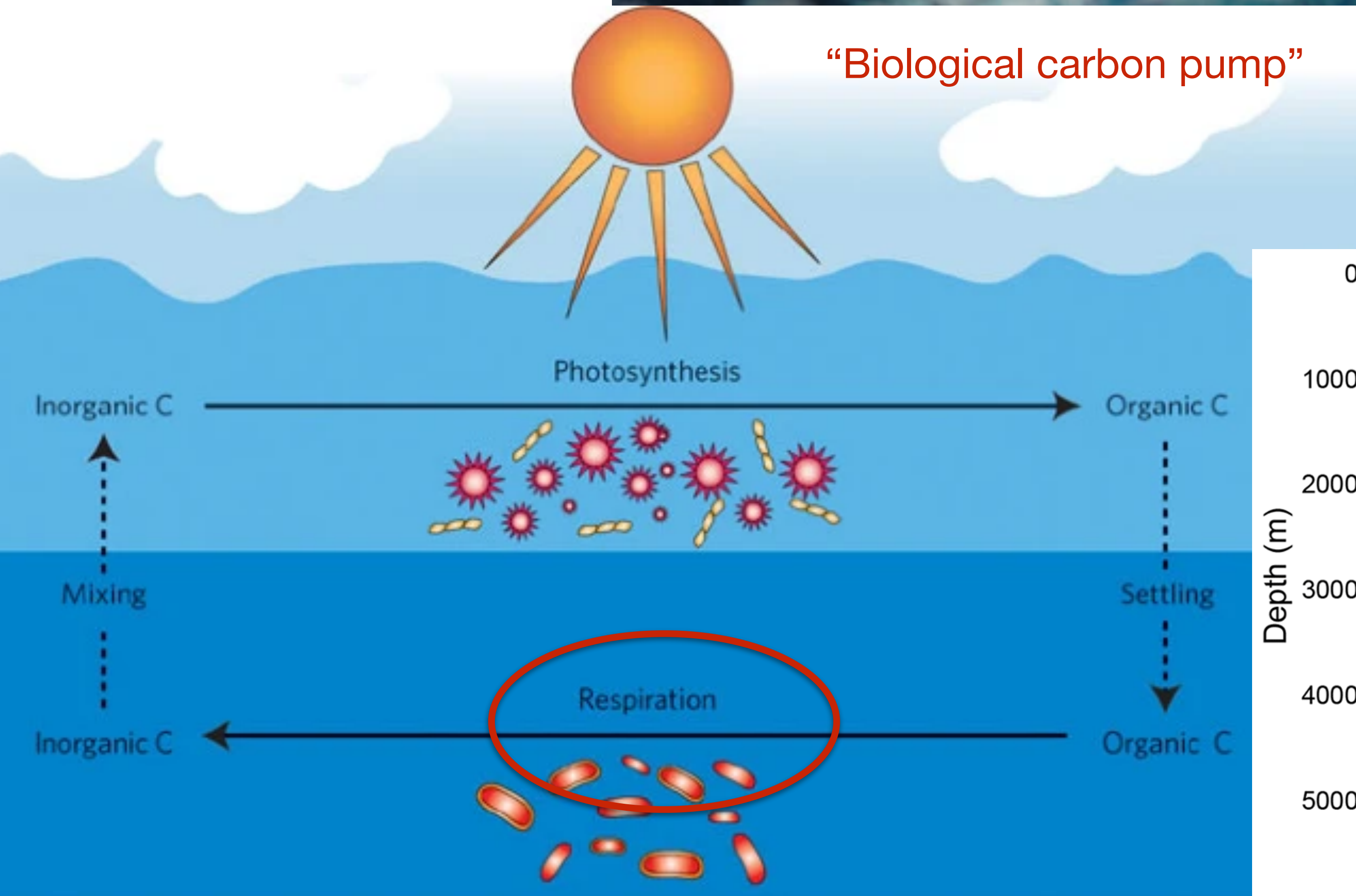
BACKGROUND

- ▶ phytoplankton produces organic carbon ...
- ▶ transferred to the ocean interior ...



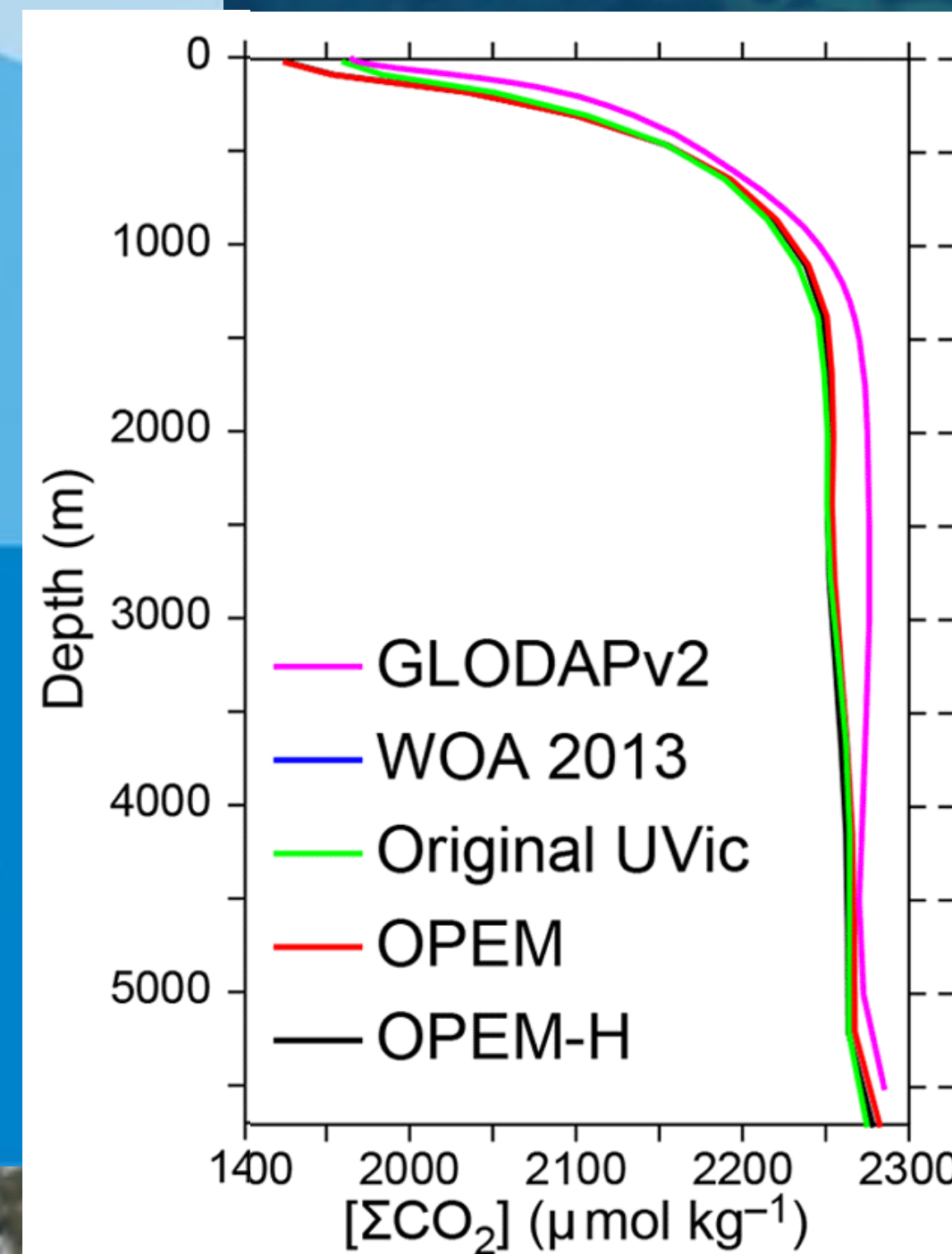
BACKGROUND

- ▶ phytoplankton produces organic carbon ...
- ▶ transferred to the ocean interior ...
- ▶ respired/remineralized back to inorganic carbon ...



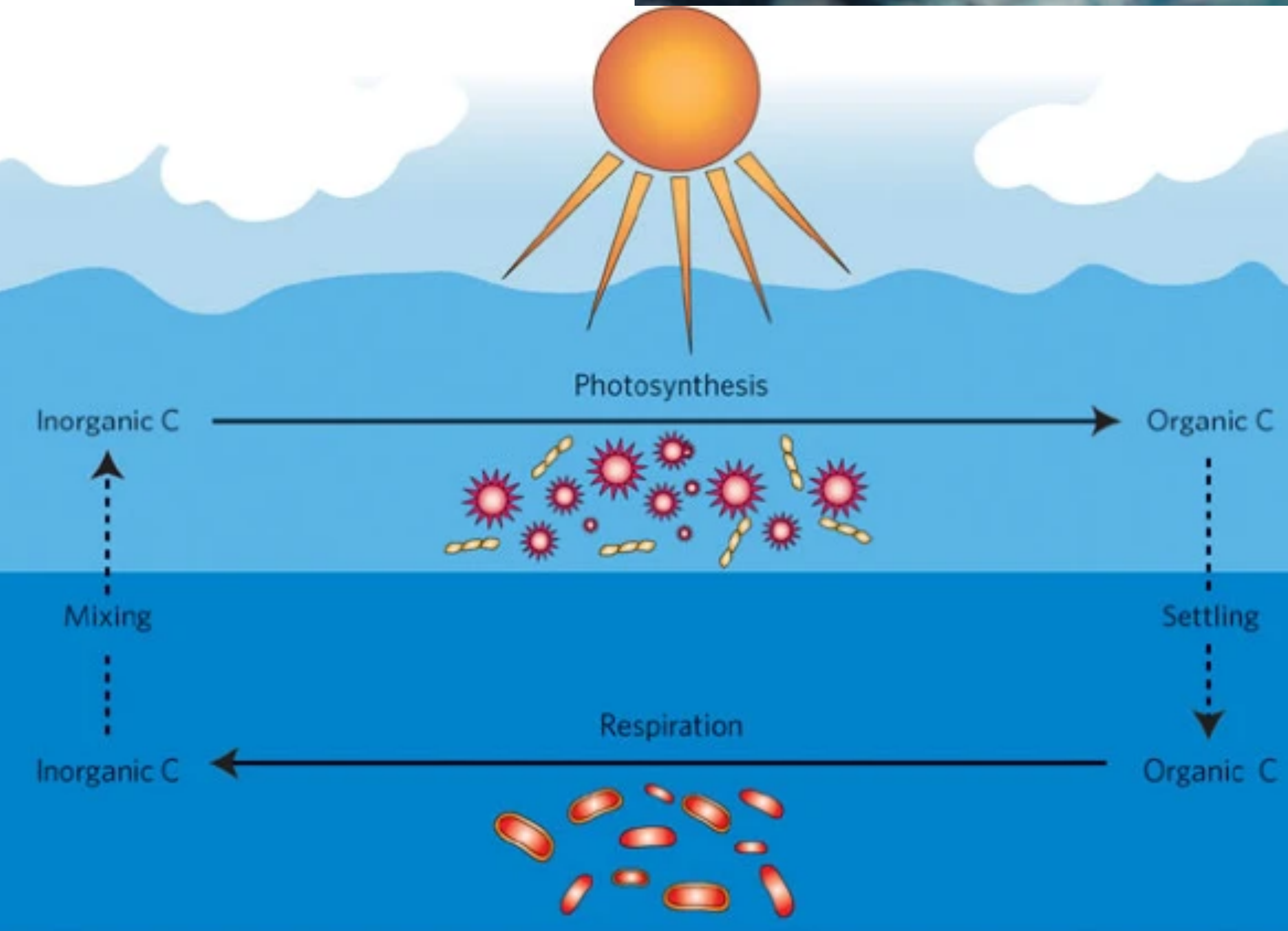
“Biological carbon pump”

Pahlow et al, 2020

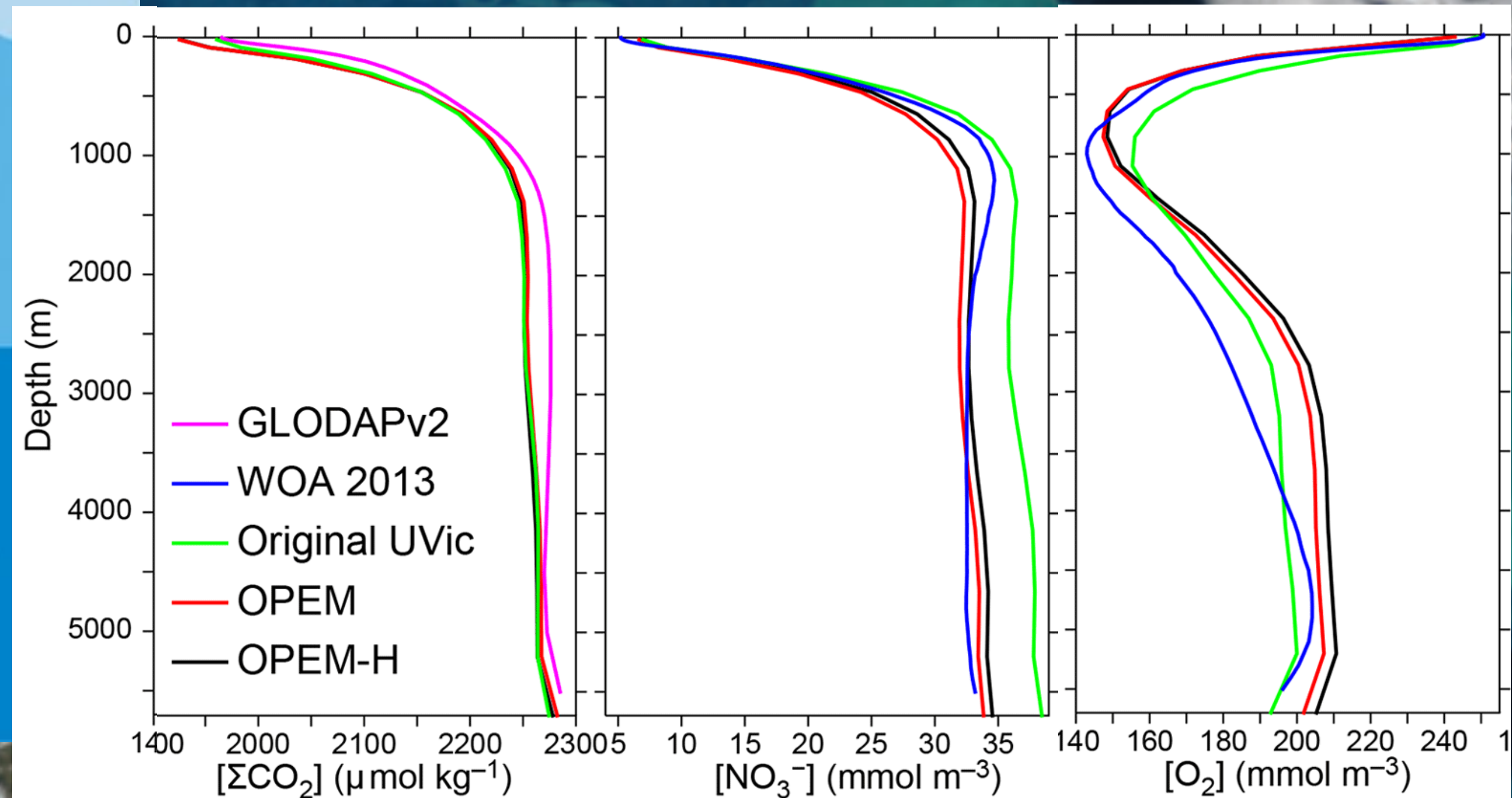


BACKGROUND

- ▶ phytoplankton produces organic carbon ...
- ▶ transferred to the ocean interior ...
- ▶ respired/remineralized back to inorganic carbon ...

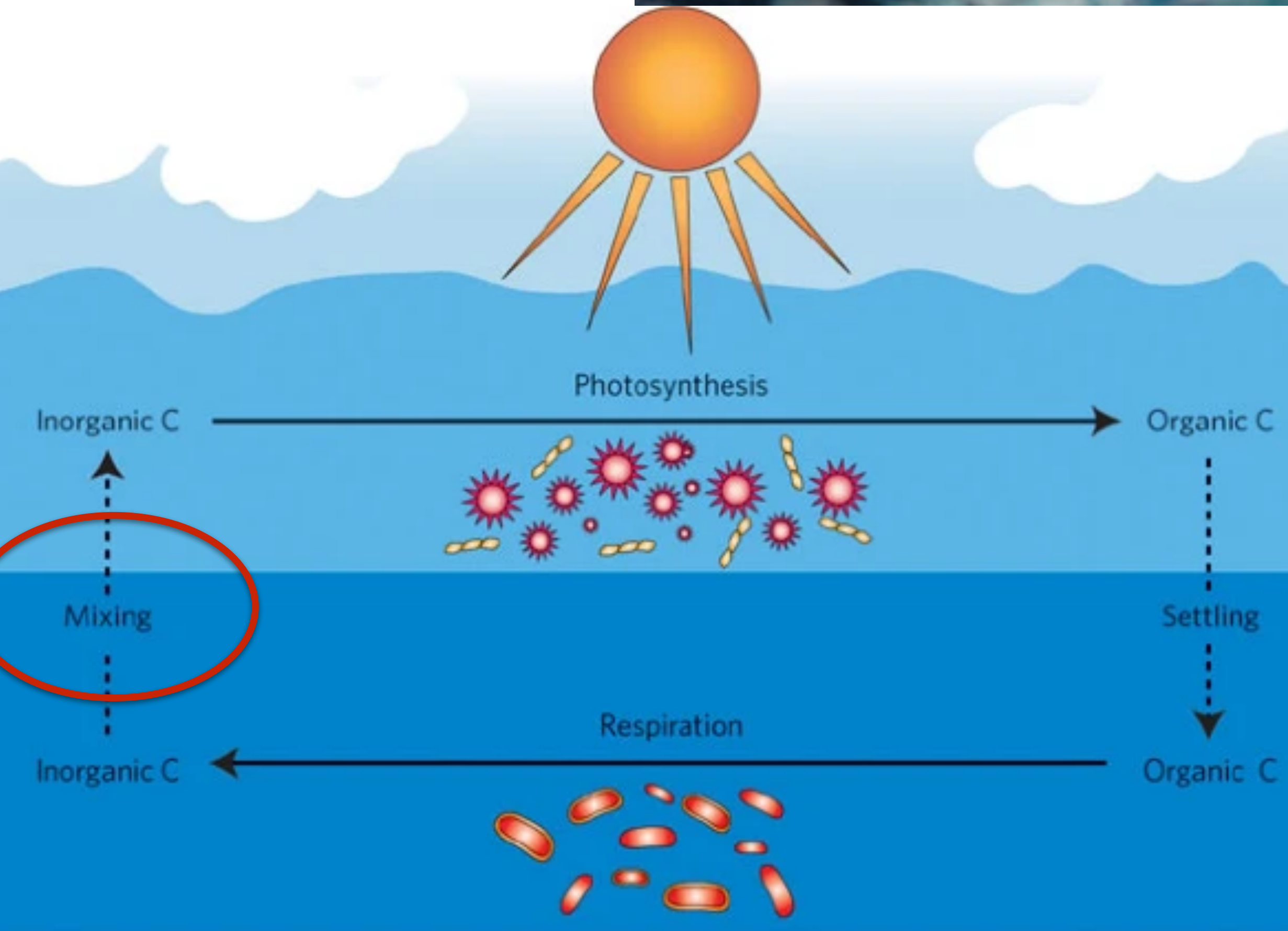


Pahlow et al, 2020

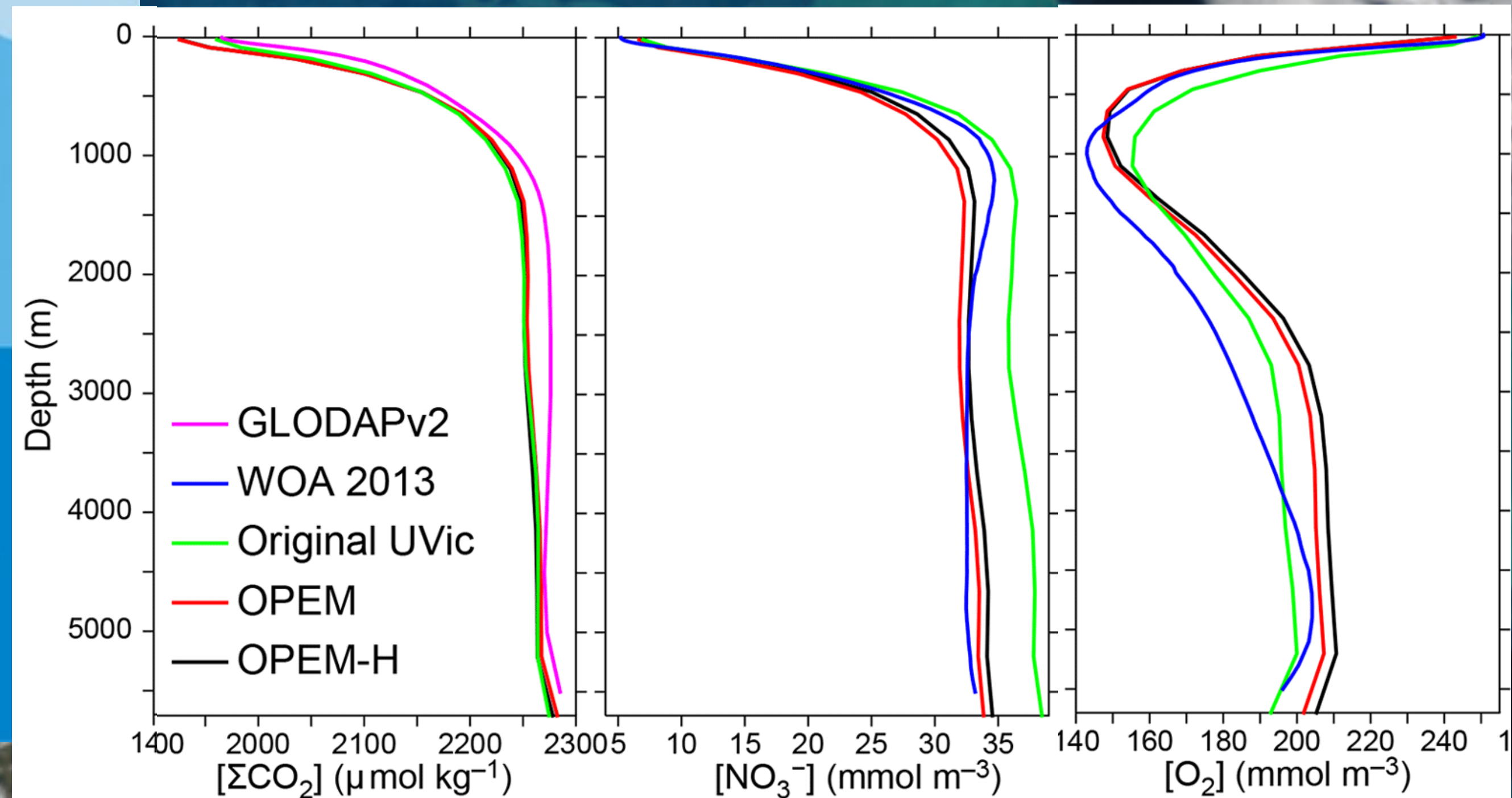


BACKGROUND

- ▶ phytoplankton produces organic carbon ...
- ▶ transferred to the ocean interior ...
- ▶ respired/remineralized back to inorganic carbon ...
- ▶ brought back to surface and exchange to atmosphere with circulation/mixing ...

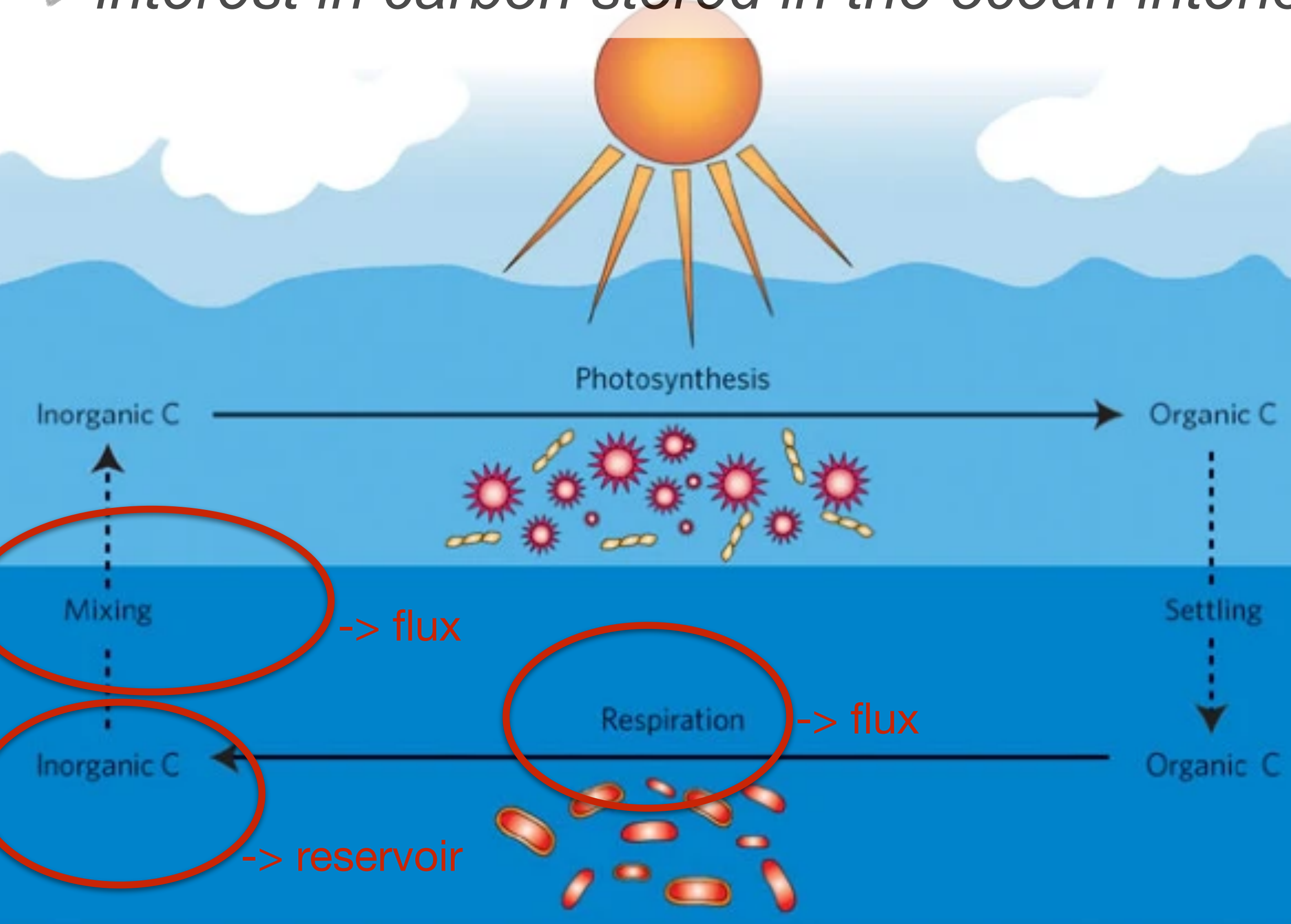


Pahlow et al, 2020

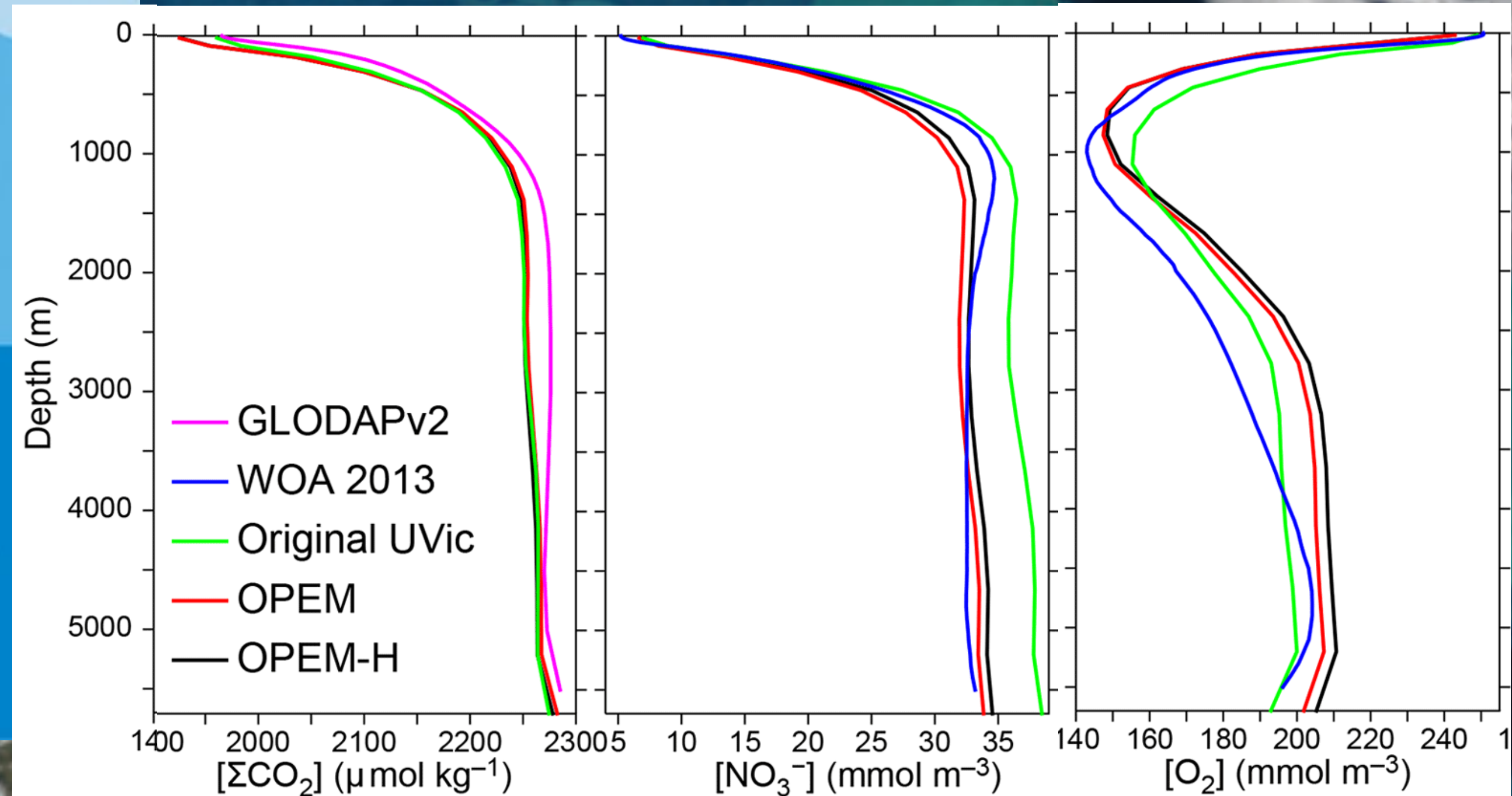


BACKGROUND

- ▶ phytoplankton produces organic carbon ...
- ▶ transferred to the ocean interior ...
- ▶ respired/remineralized back to inorganic carbon ...
- ▶ brought back to surface and exchange to atmosphere with circulation/mixing ...
- ▶ interest in carbon stored in the ocean interior? -> Δ flux vs Δ reservoir

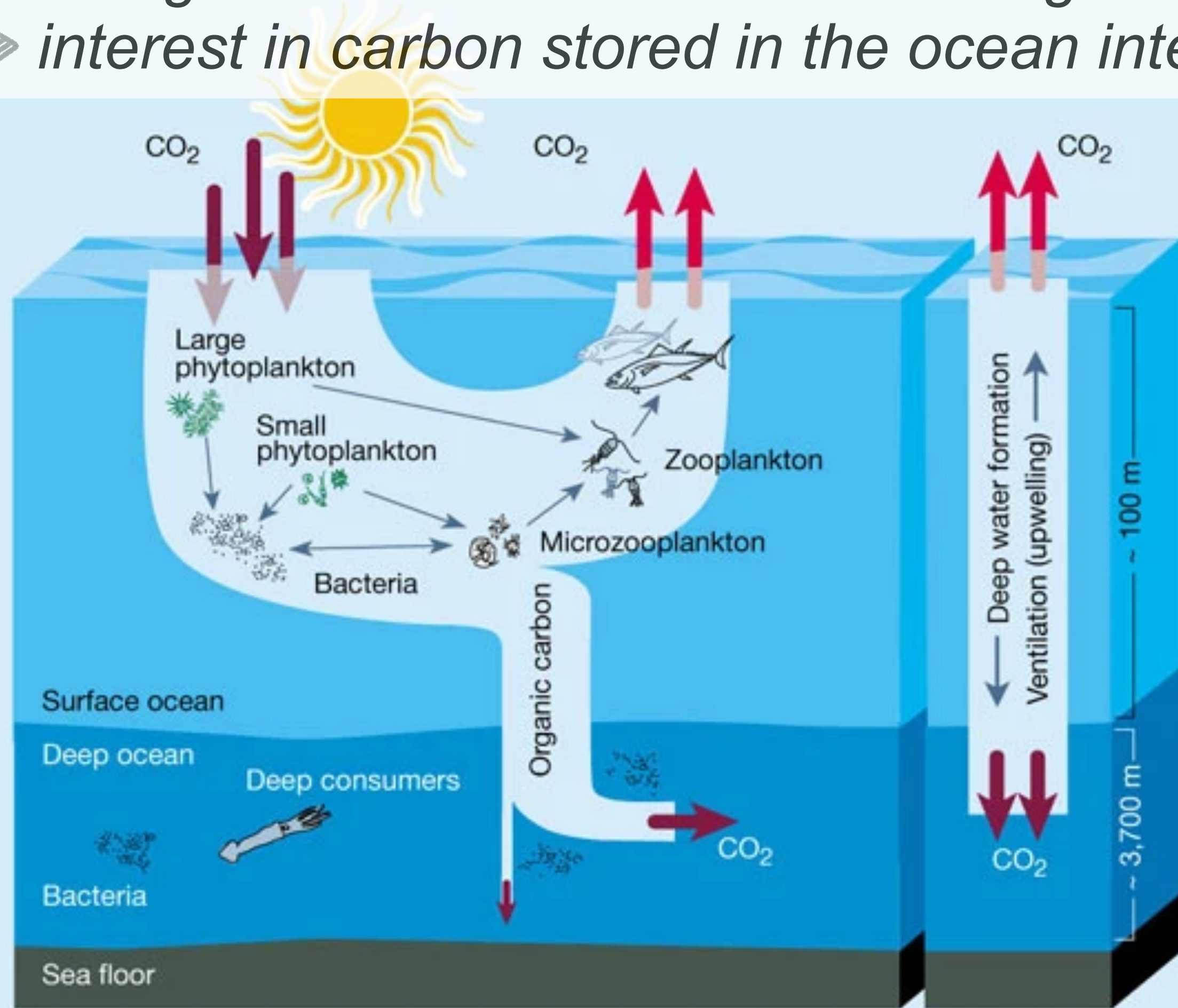


Pahlow et al, 2020



BACKGROUND

- ▶ phytoplankton produces organic carbon ...
- ▶ transferred to the ocean interior ...
- ▶ respired/remineralized back to inorganic carbon ...
- ▶ brought back to surface and exchange to atmosphere with circulation/mixing ...
- ▶ interest in carbon stored in the ocean interior? -> Δ flux vs Δ reservoir; carbon chemistry

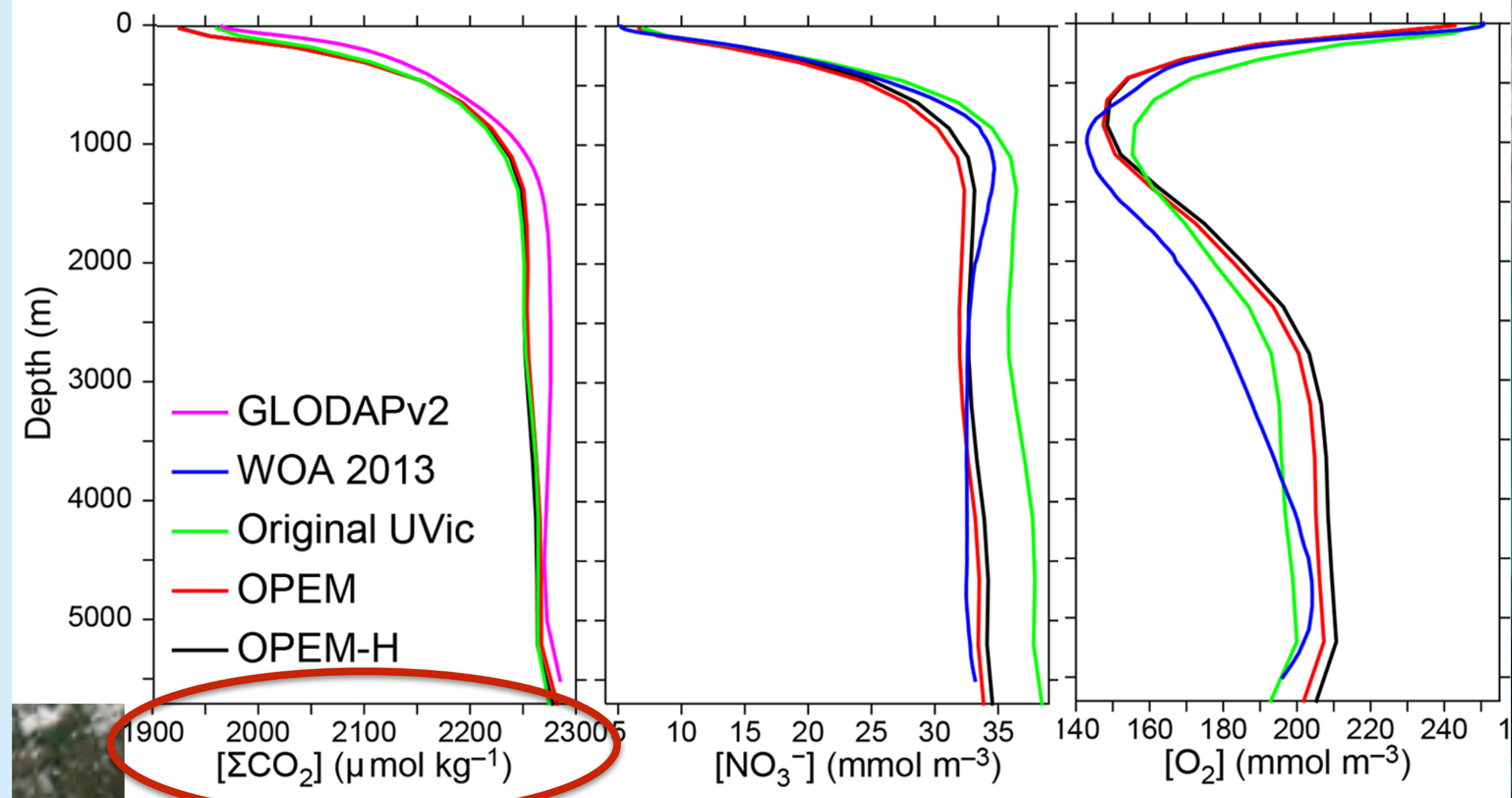


Chisholm et al, 2000

Biology

Physio-chemical

Pahlow et al, 2020



BACKGROUND

“History-one-liner”:

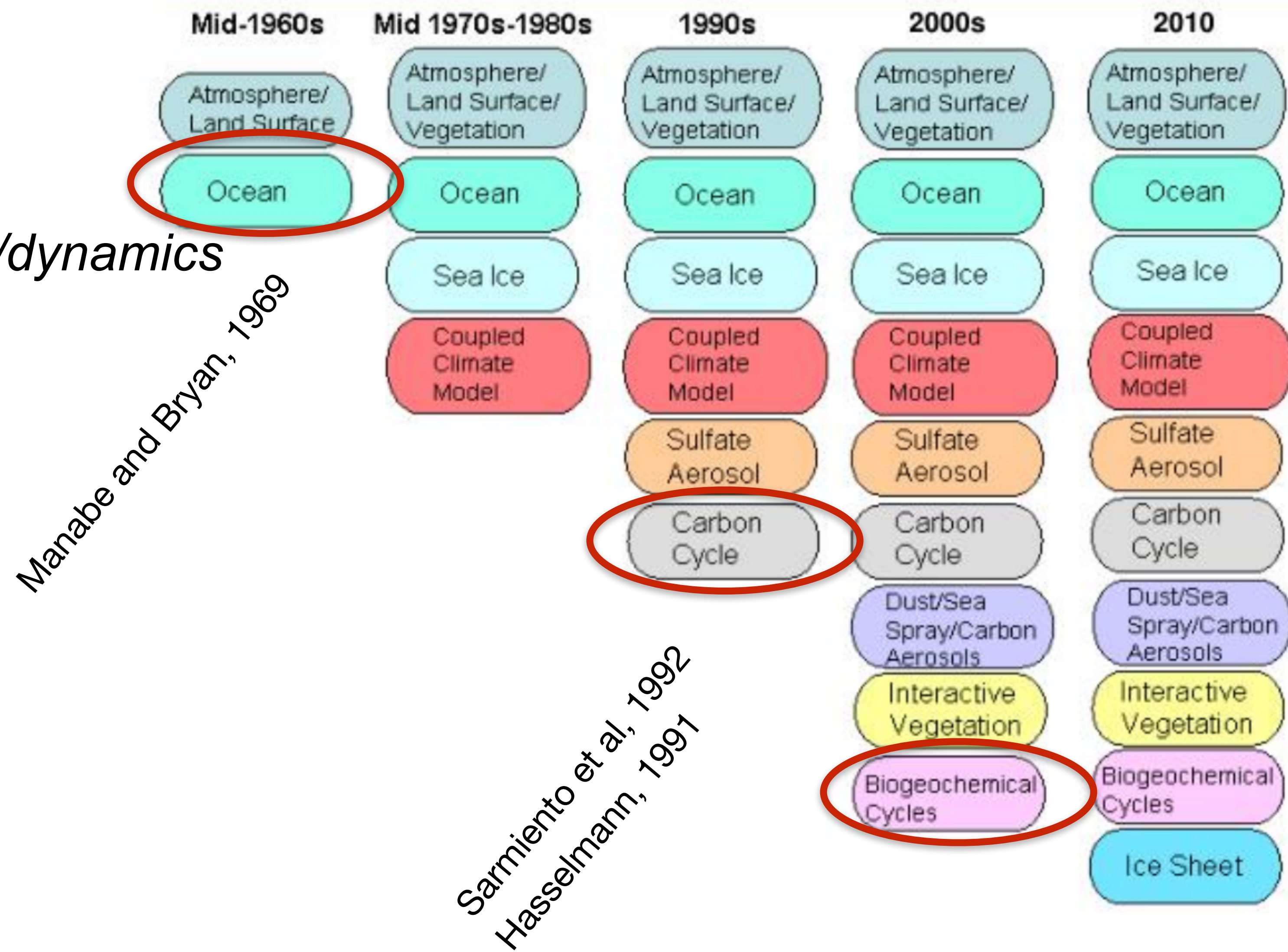
Marine biogeochemistry “lags” physics/dynamics

BACKGROUND

“History-one-liner”:
Marine biogeochemistry “lags” physics/dynamics

► Modeling

Earth system model development



BACKGROUND

“History-one-liner”:

Marine biogeochemistry “lags” physics/dynamics

▶ *Modeling*

▶ *Observations, e.g., Argo*



Background

Characteristics

Global relevance

Anthropogenic climate change

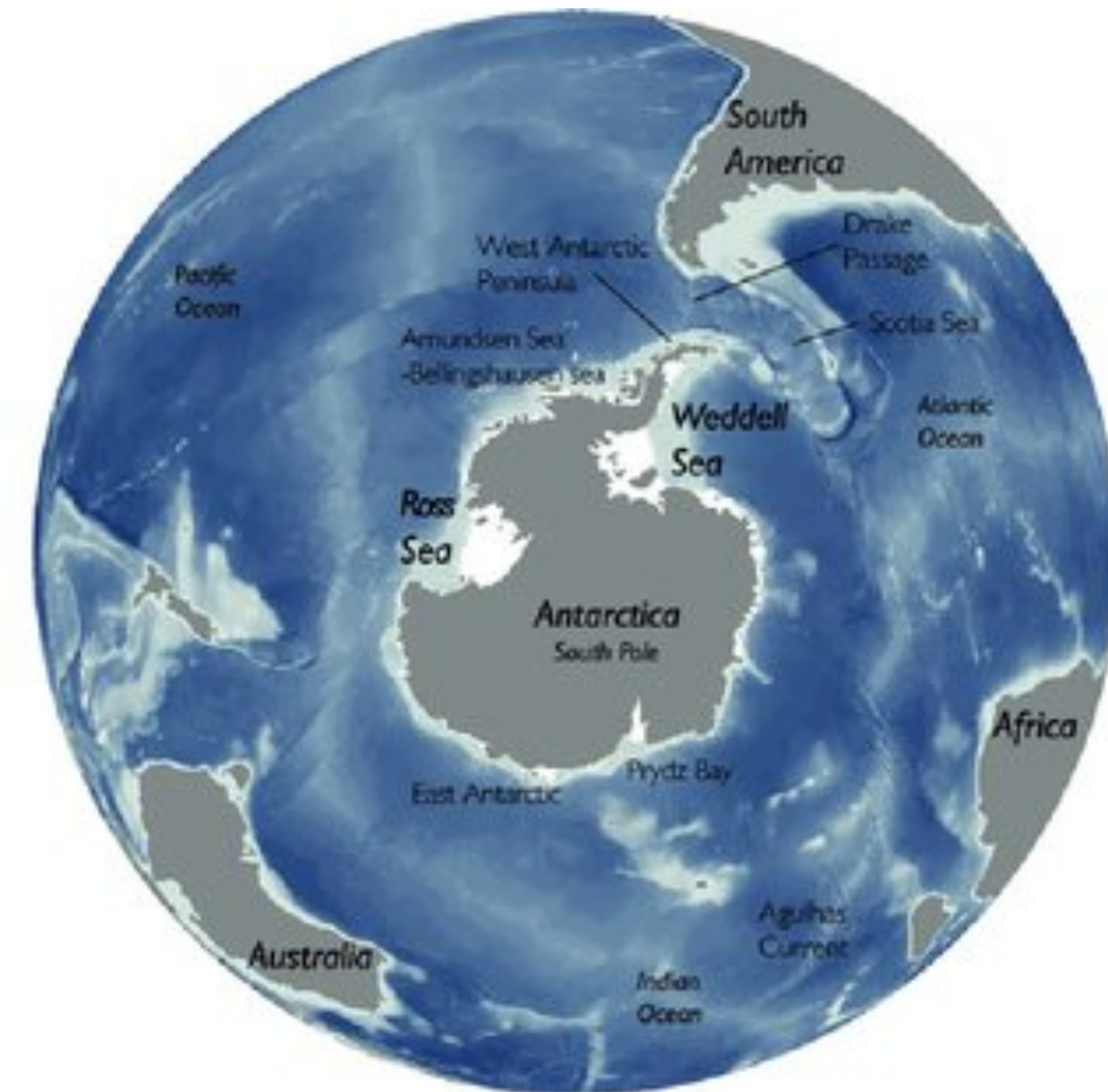
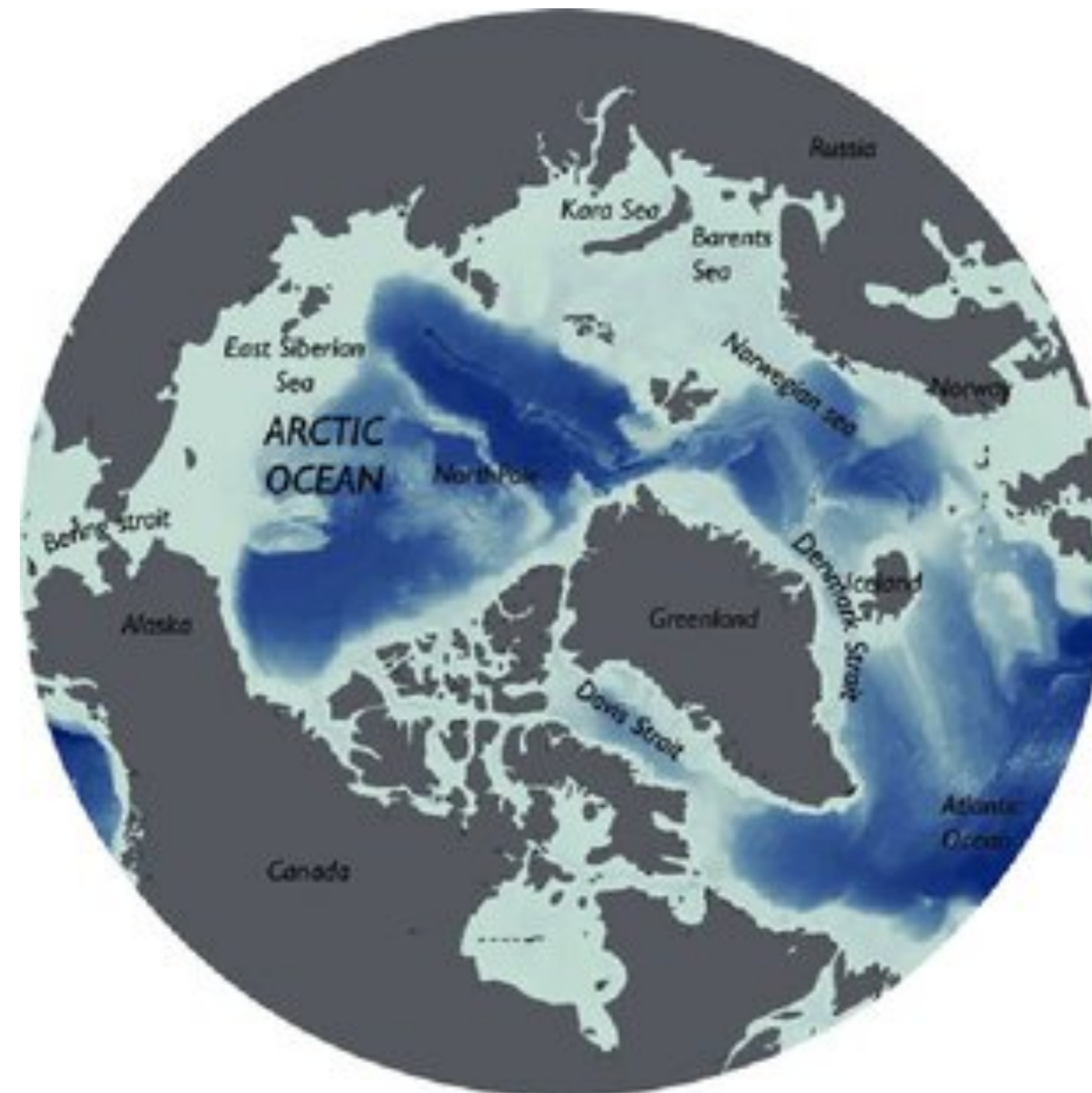
CHARACTERISTICS

Differences. e.g.,

- ▶ *Arctic: ocean enclosed by land*
- ▶ *Antarctic: land enclosed by ocean*

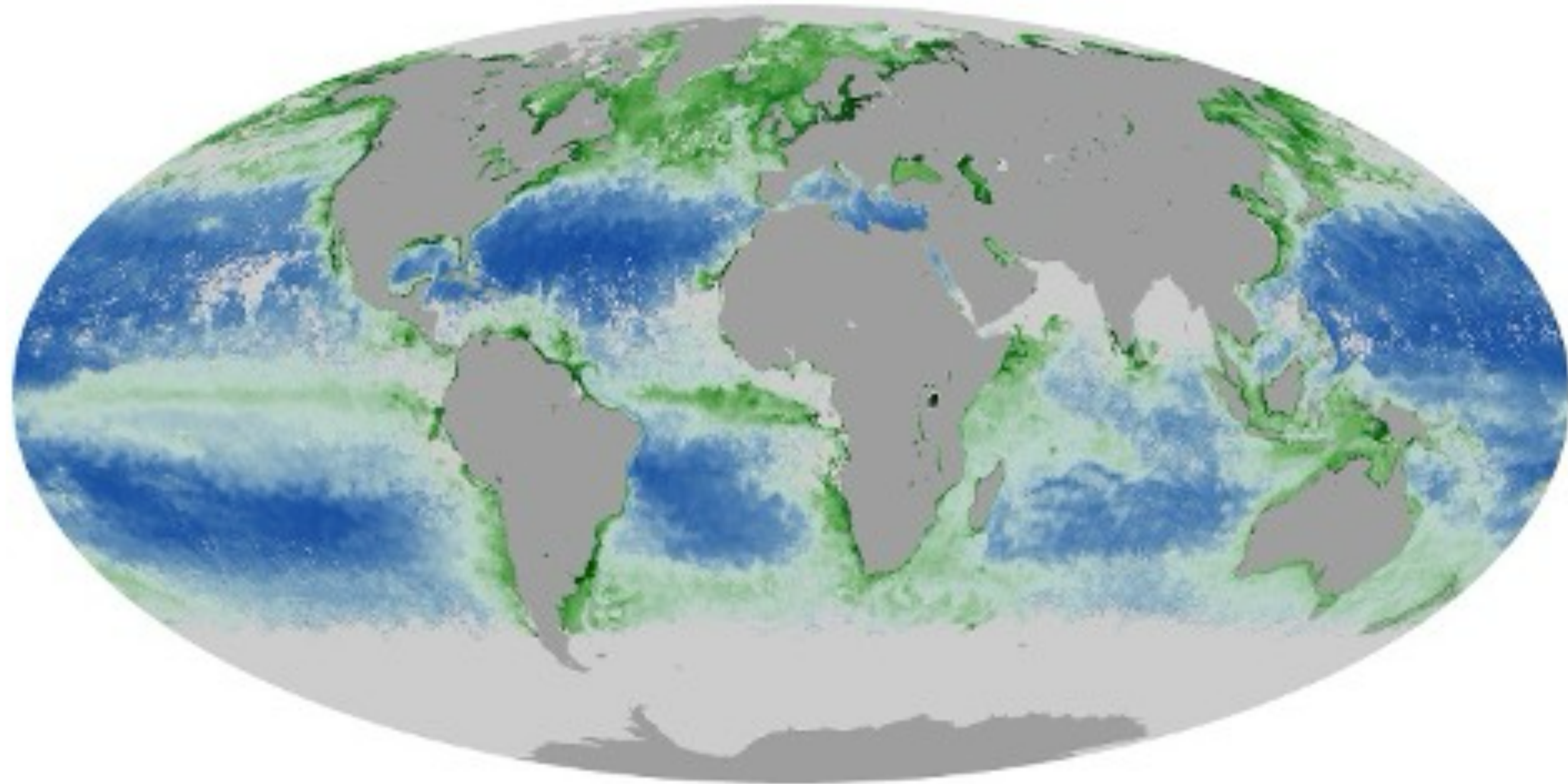
Similarities, e.g.,

- ▶ *Sea ice ...*



CHARACTERISTICS

Polar oceans
▶ *phytoplankton*



Chlorophyll Concentration
(mg/m³)

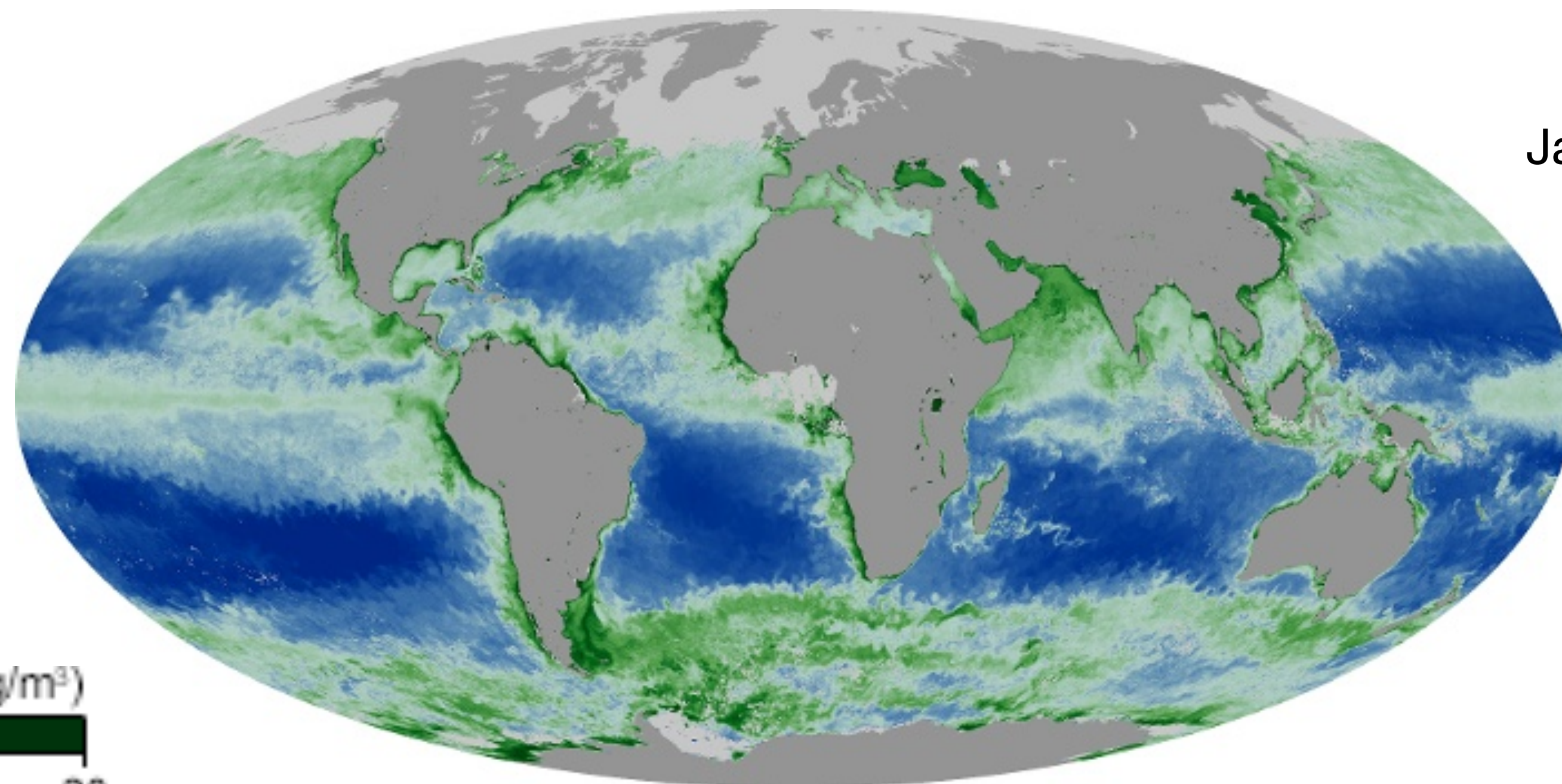
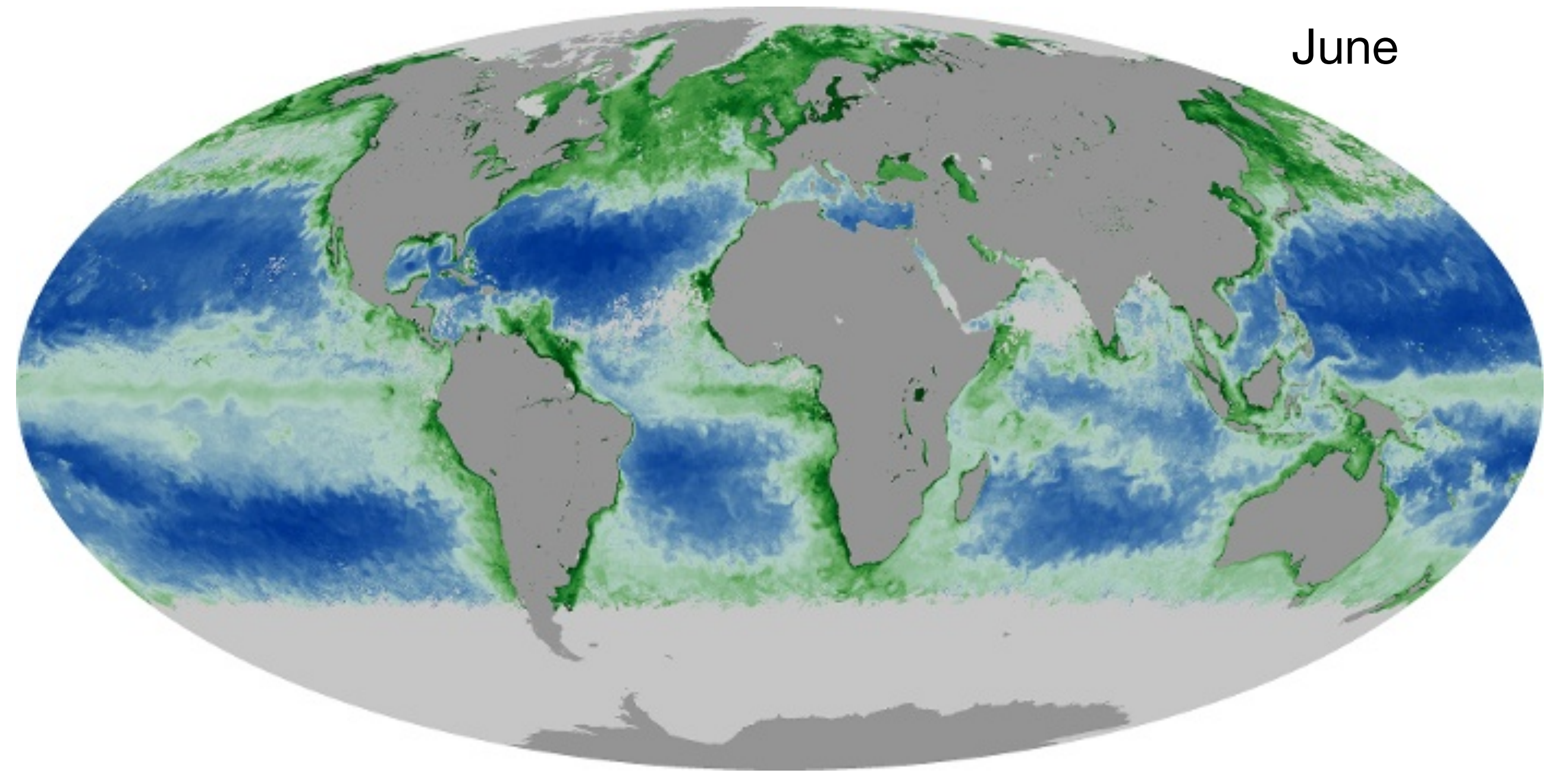


July 2002

CHARACTERISTICS

Polar oceans

- ▶ *phytoplankton:*
seasonality, blooms



(mg/m³)



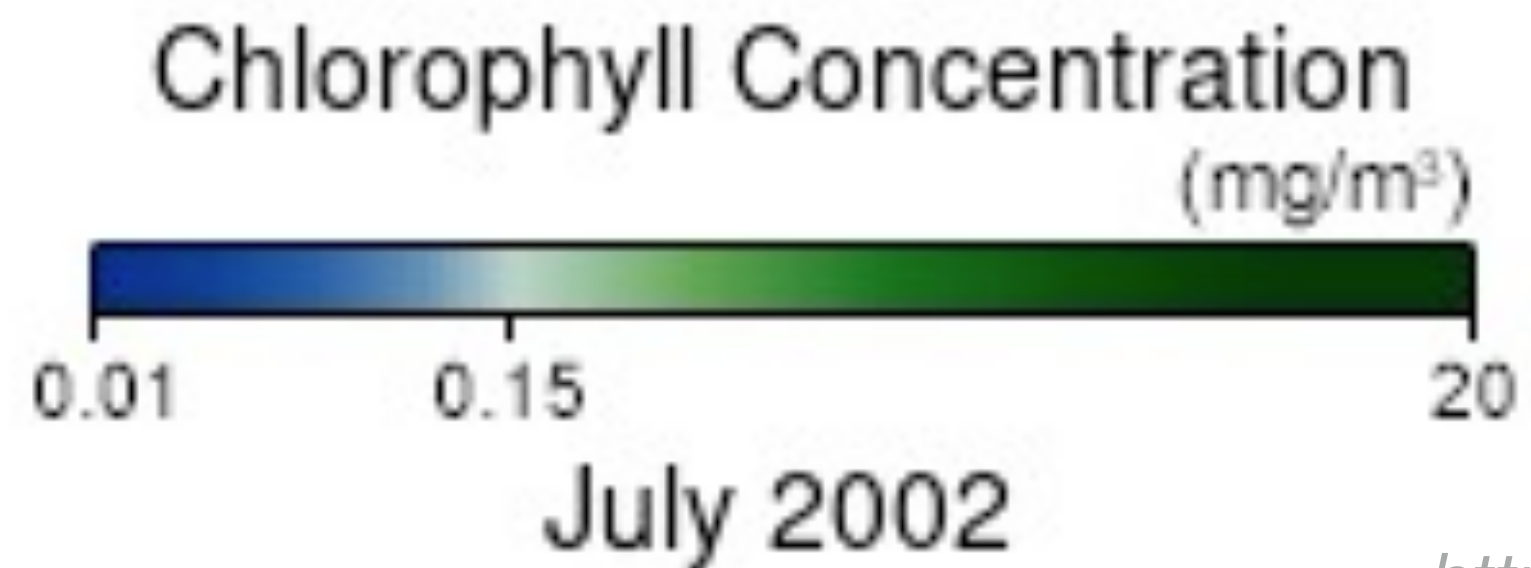
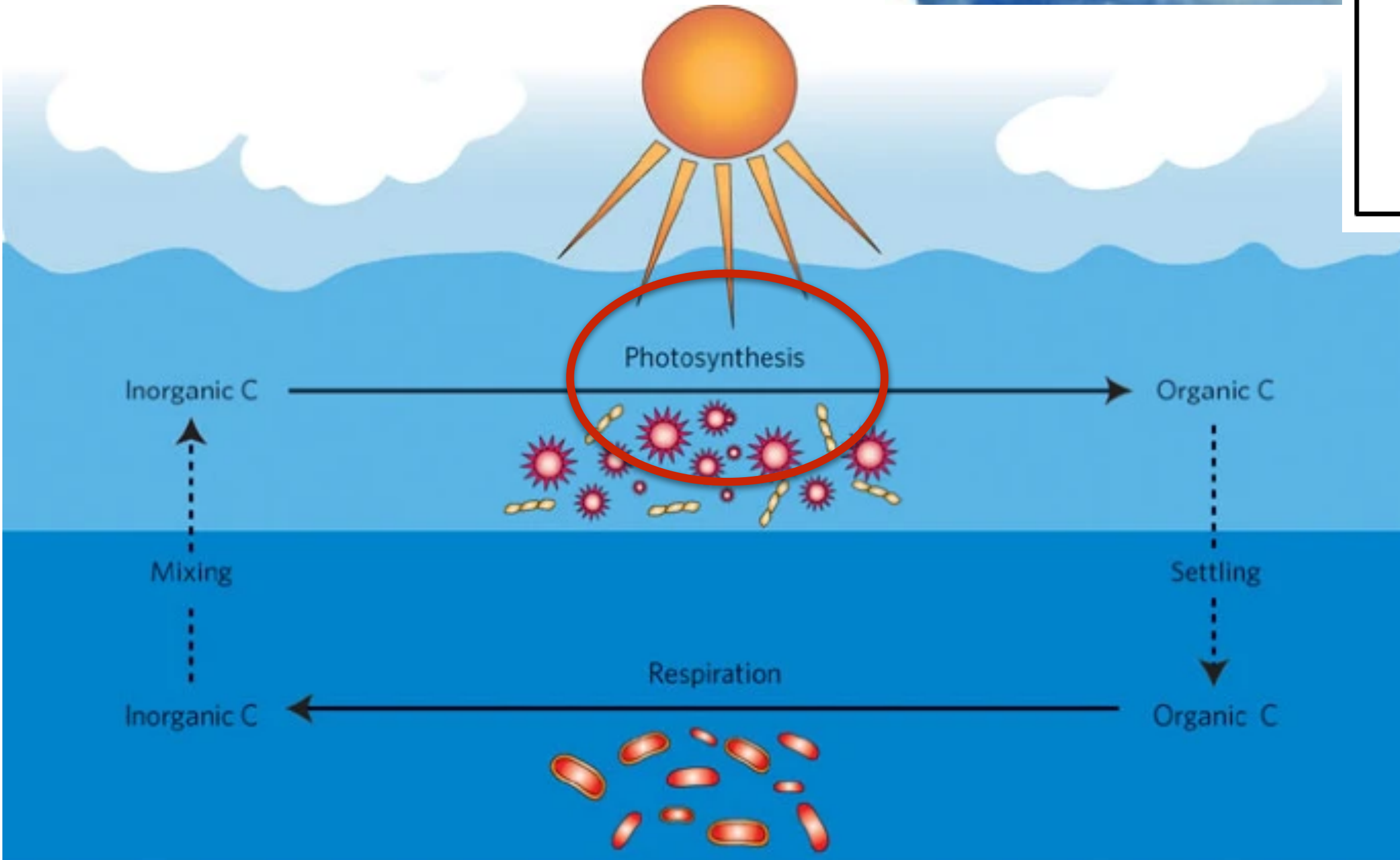
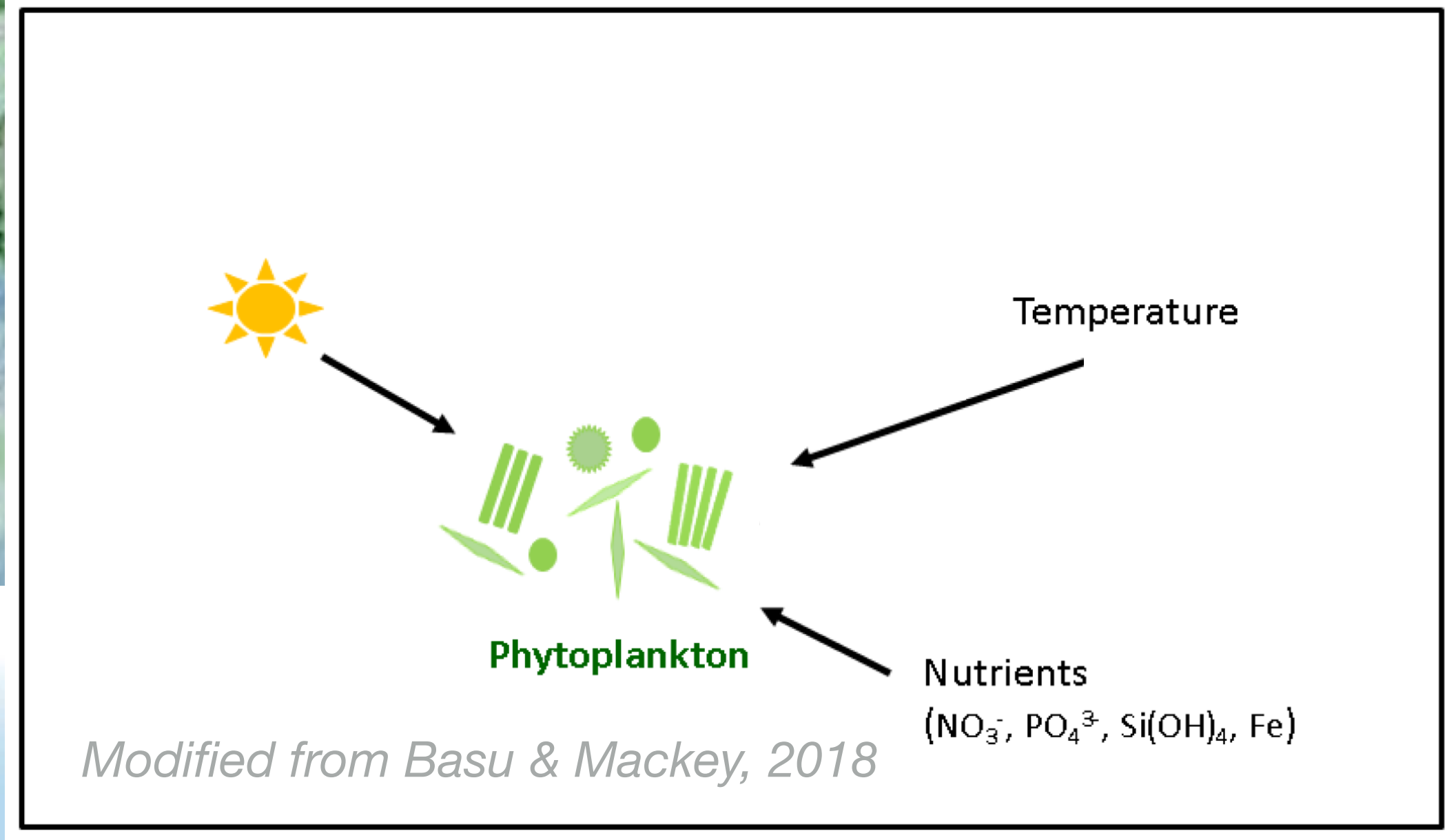
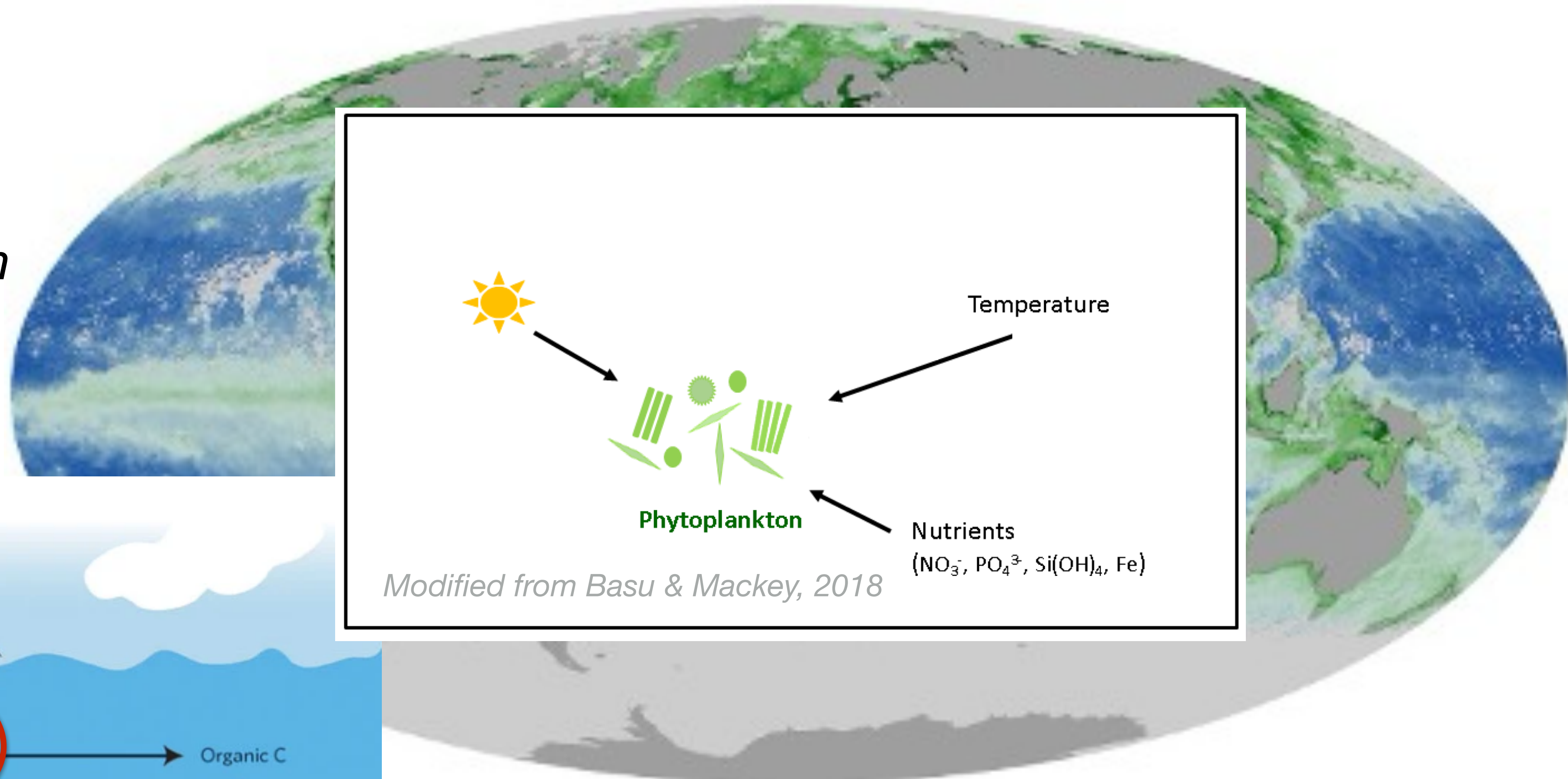
*What does phytoplankton need to grow?
("growth" or "limiting" factors)*

In polar oceans?

CHARACTERISTICS

Polar oceans

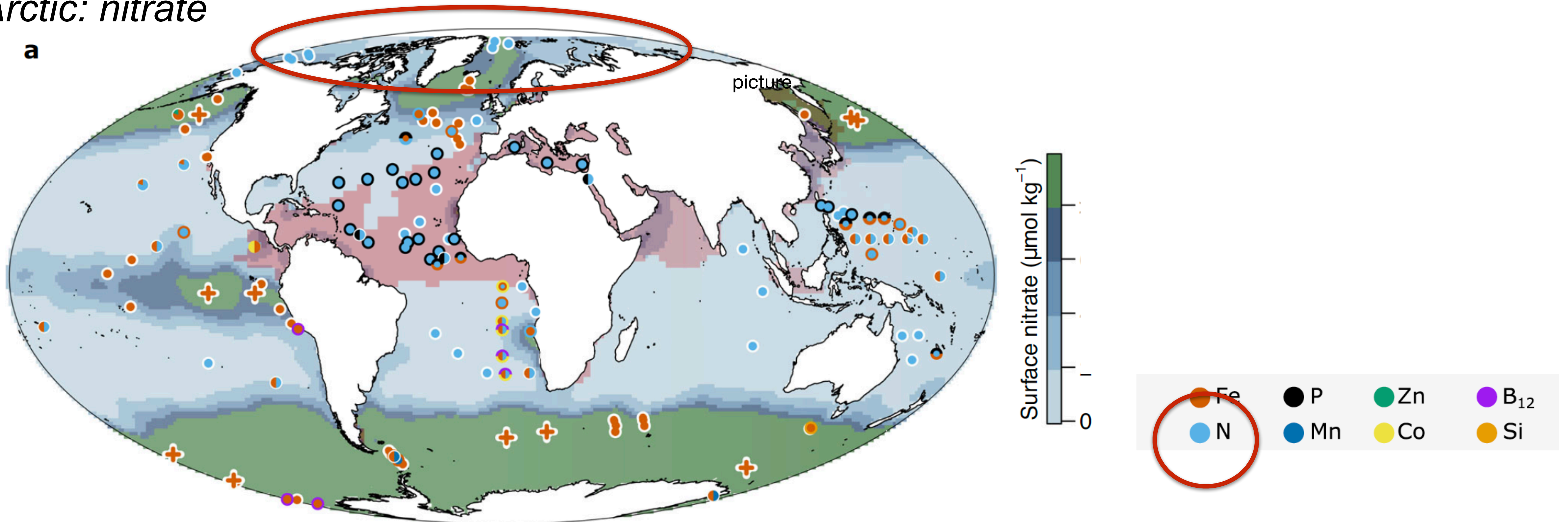
- ▶ *phytoplankton: seasonality, blooms*
- ▶ *what does phytoplankton need to grow? (“growth” or “limiting” factors)? In polar oceans?*



CHARACTERISTICS

Polar oceans

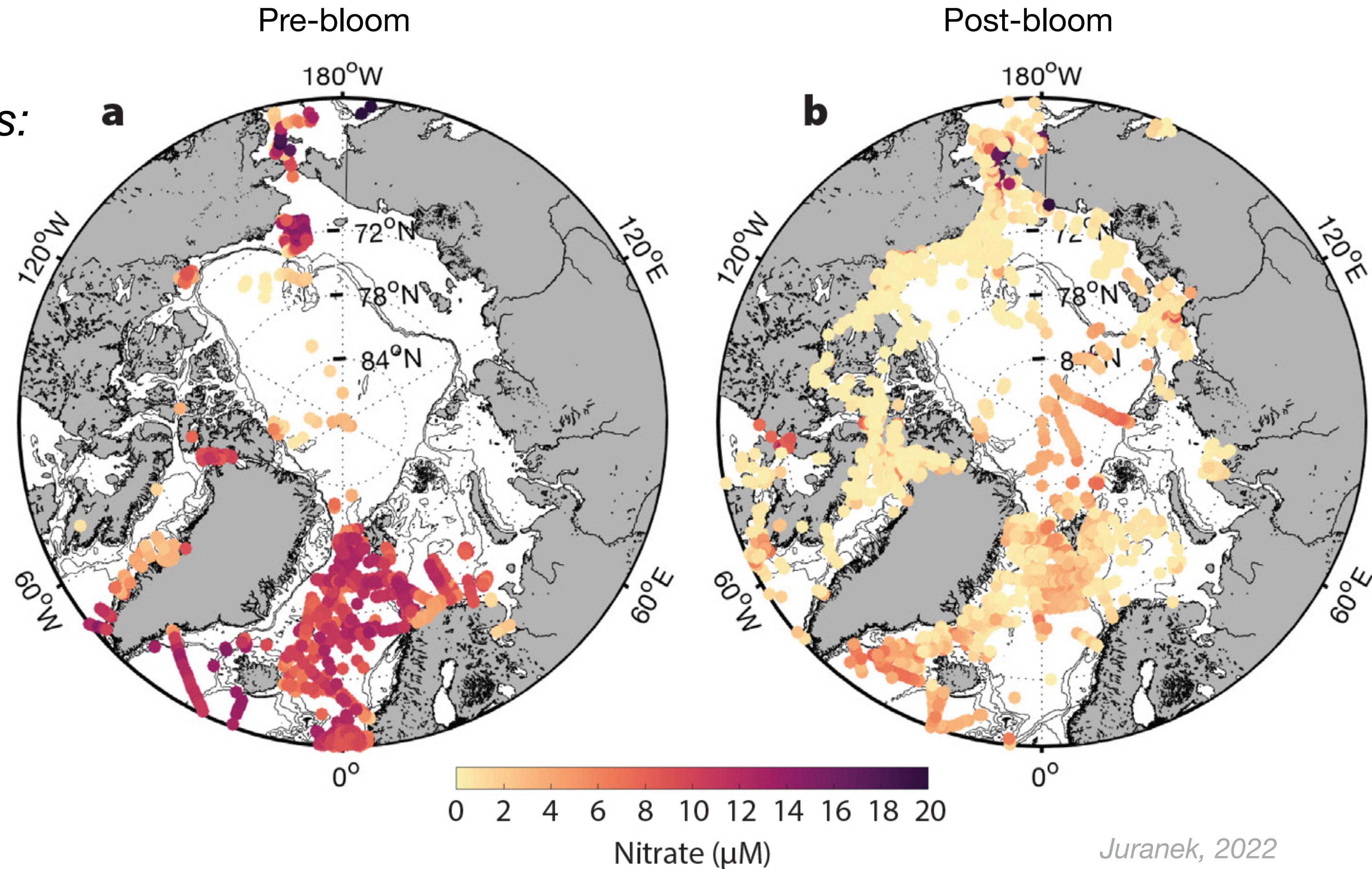
- ▶ primary production: seasonality, blooms
- ▶ “growth” or “limiting” factors: light; Arctic: nitrate



CHARACTERISTICS

Polar oceans

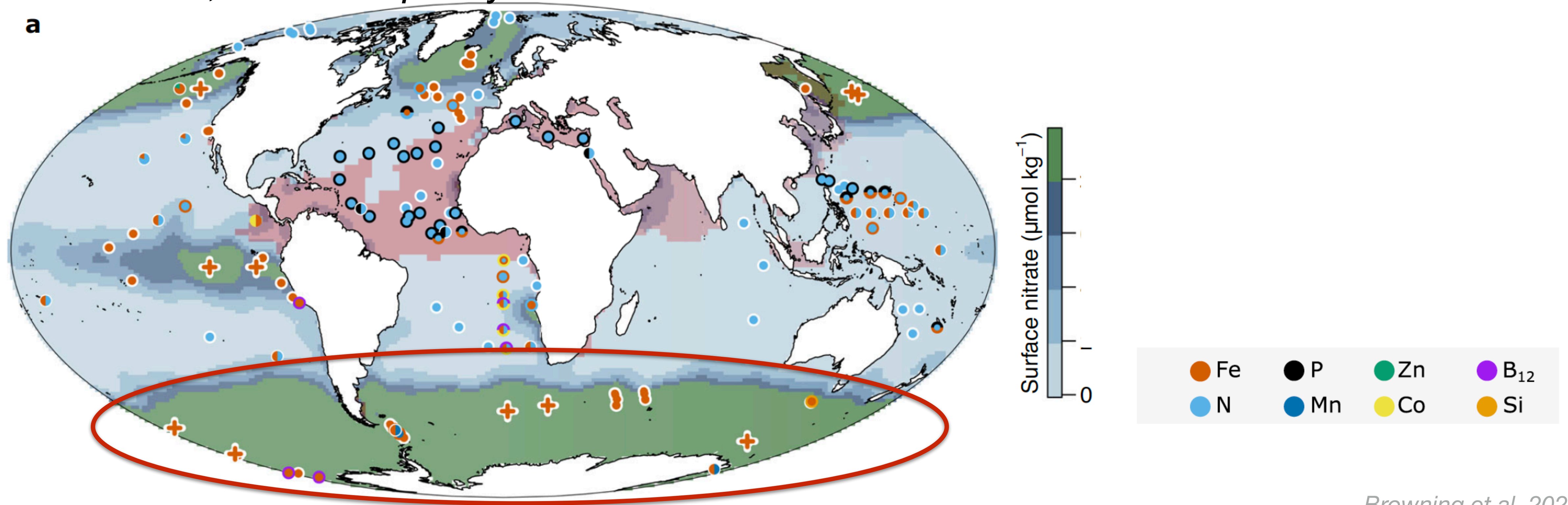
- ▶ *primary production: seasonality, blooms*
- ▶ *“growth” or “limiting” factors: light;*
Arctic: nitrate



CHARACTERISTICS

Polar oceans

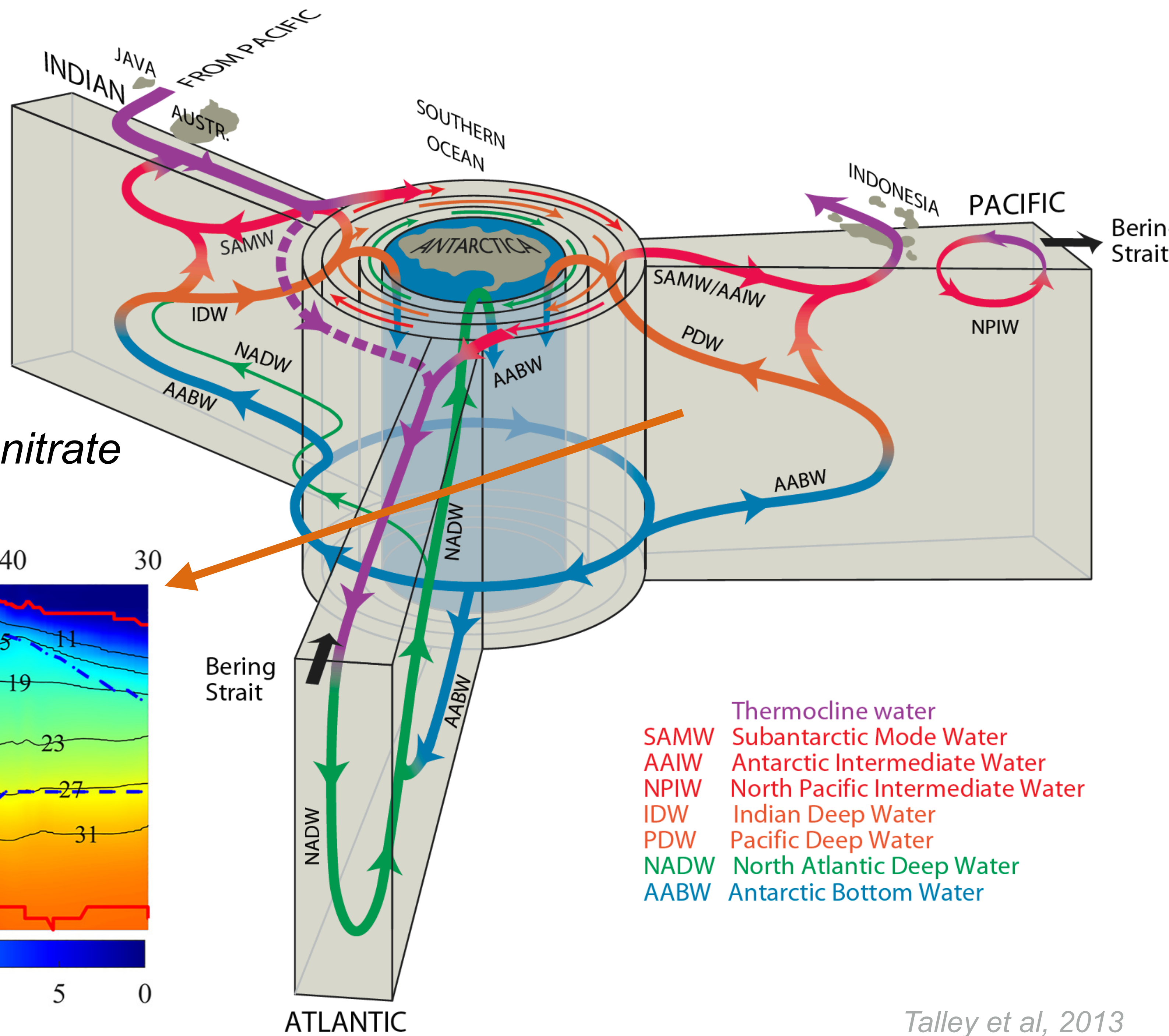
- ▶ *primary production: seasonality, blooms*
- ▶ *“growth” or “limiting” factors: light;*
Arctic: nitrate, Antarctic: plenty of nitrate



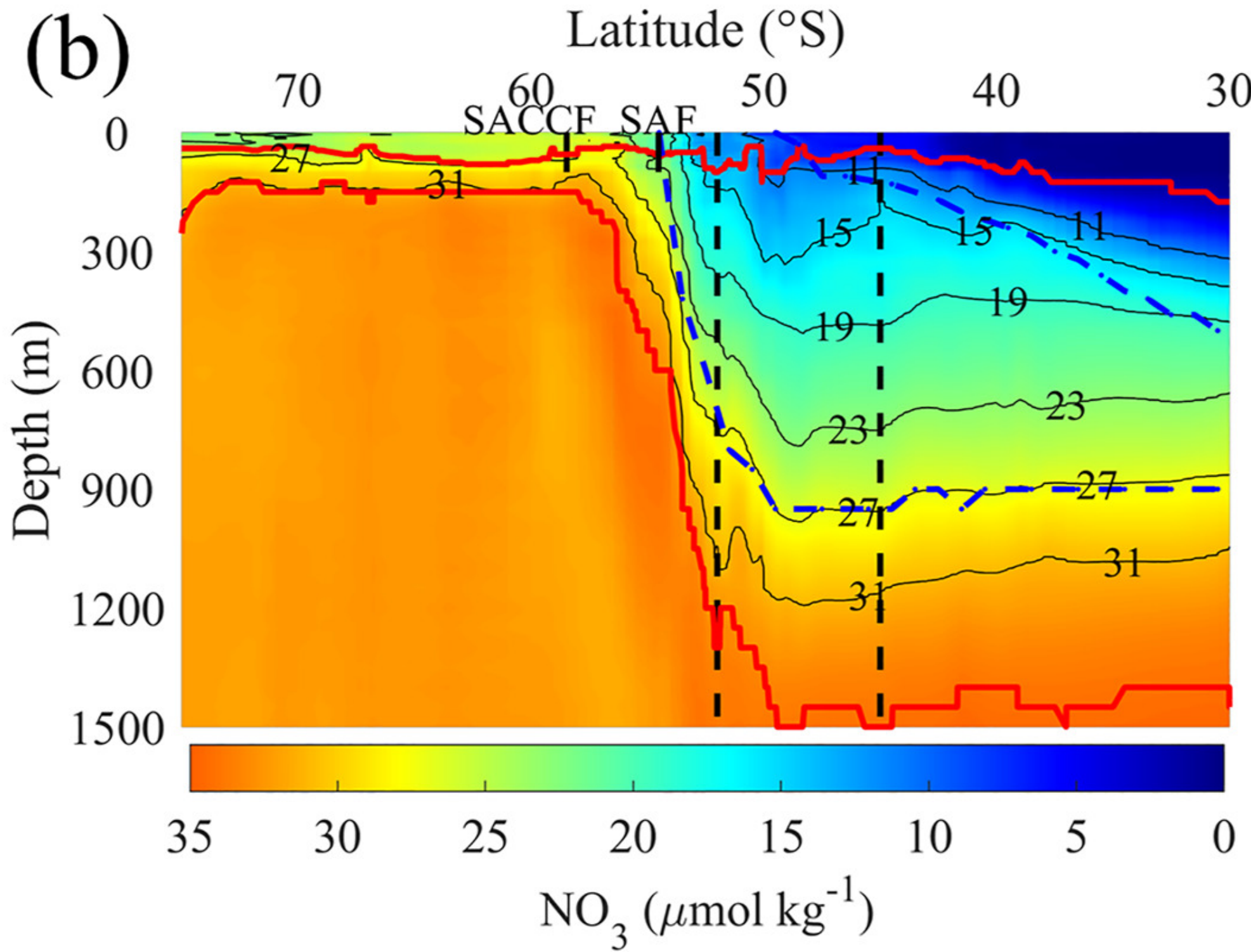
CHARACTERISTICS

Polar oceans

- ▶ primary production: seasonality, blooms
- ▶ “growth” or “limiting” factors: light;
- Arctic: nitrate, Antarctic: plenty of nitrate



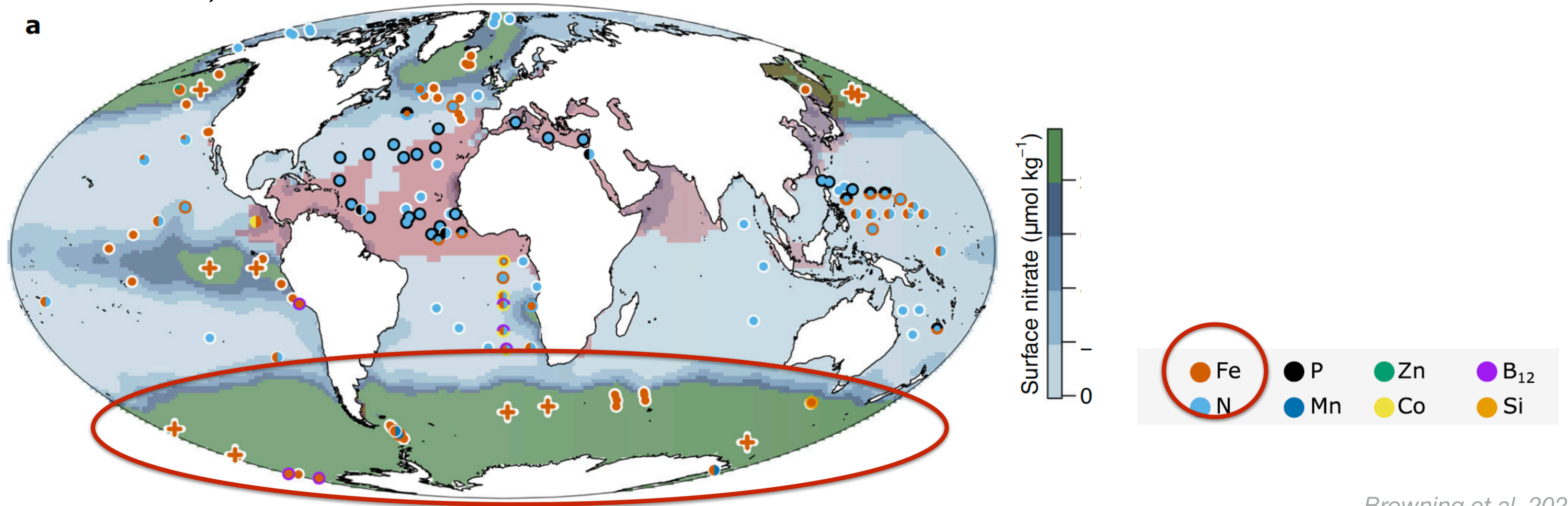
- Thermocline water
- SAMW Subantarctic Mode Water
- AAIW Antarctic Intermediate Water
- NPIW North Pacific Intermediate Water
- IDW Indian Deep Water
- PDW Pacific Deep Water
- NADW North Atlantic Deep Water
- AABW Antarctic Bottom Water



CHARACTERISTICS

Polar oceans

- ▶ primary production: seasonality, blooms
- ▶ “growth” or “limiting” factors: light; Arctic: nitrate, Antarctic: iron

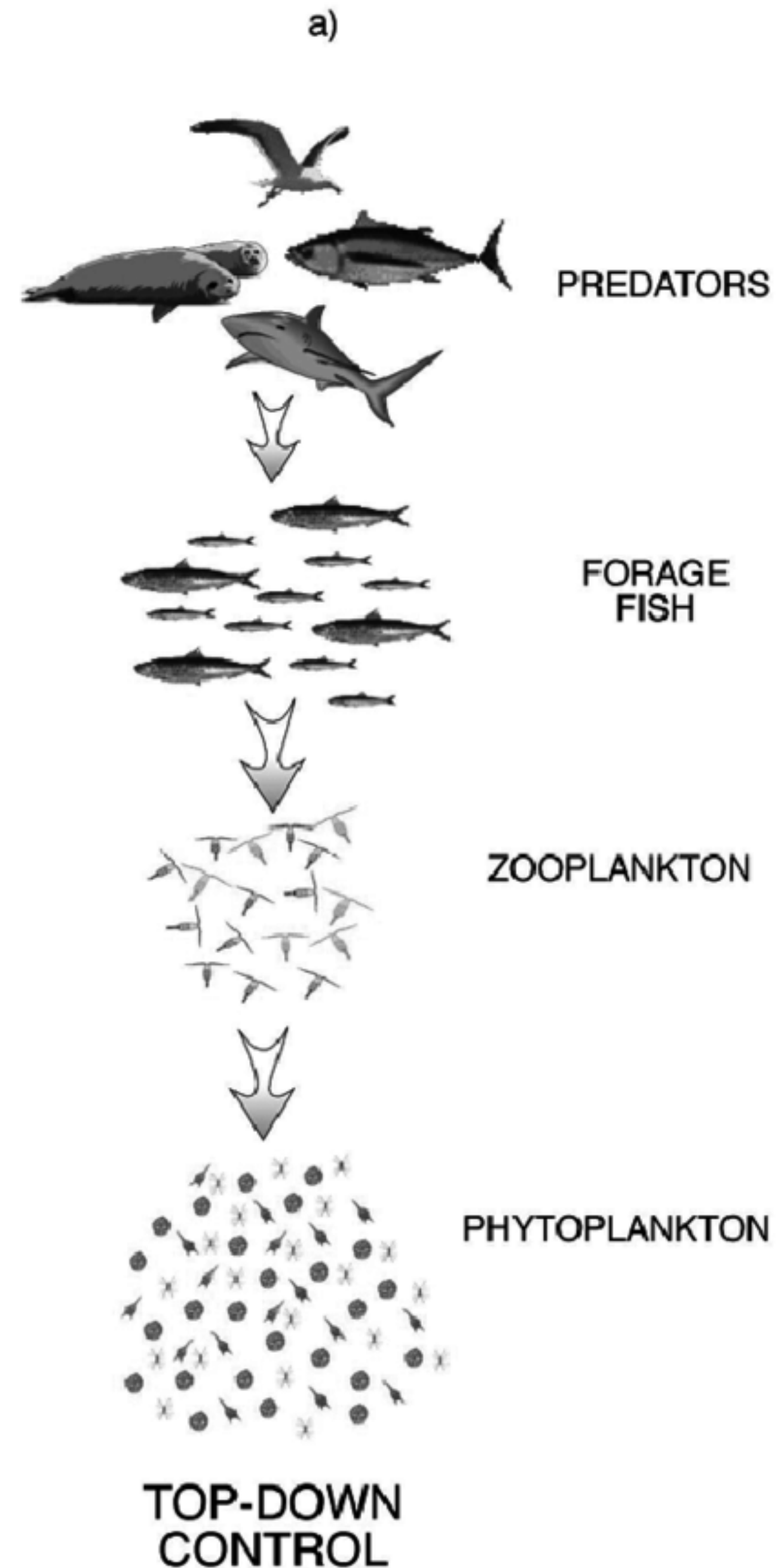


CHARACTERISTICS

Polar oceans

- ▶ *primary production: seasonality, blooms*
- ▶ *“growth” or “limiting” factors: light; Arctic: nitrate, Antarctic: iron*

Role of higher trophic levels for element cycling?

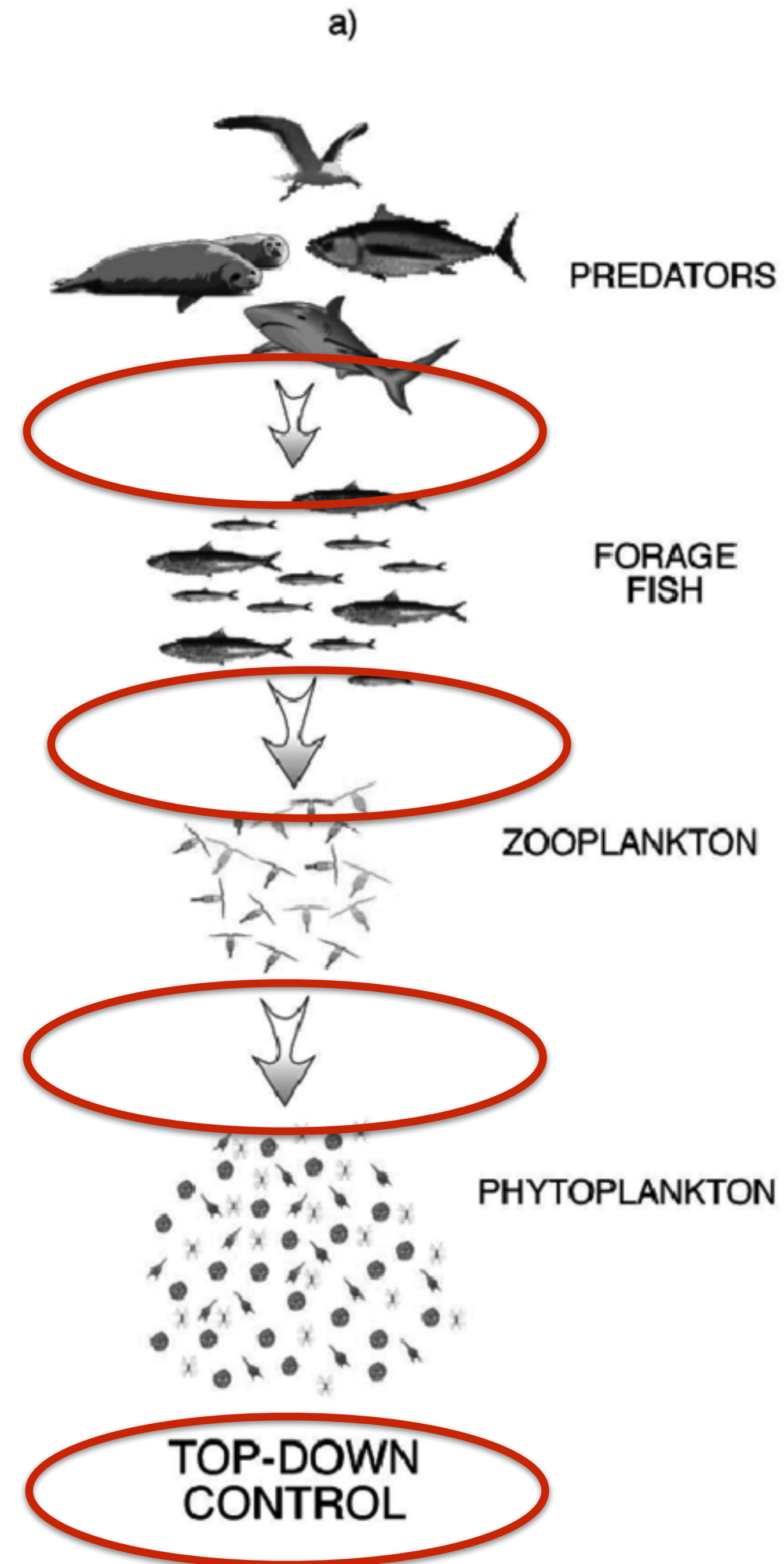


CHARACTERISTICS

Polar oceans

- ▶ *primary production: seasonality, blooms*
- ▶ *“growth” or “limiting” factors: light; Arctic: nitrate, Antarctic: iron*

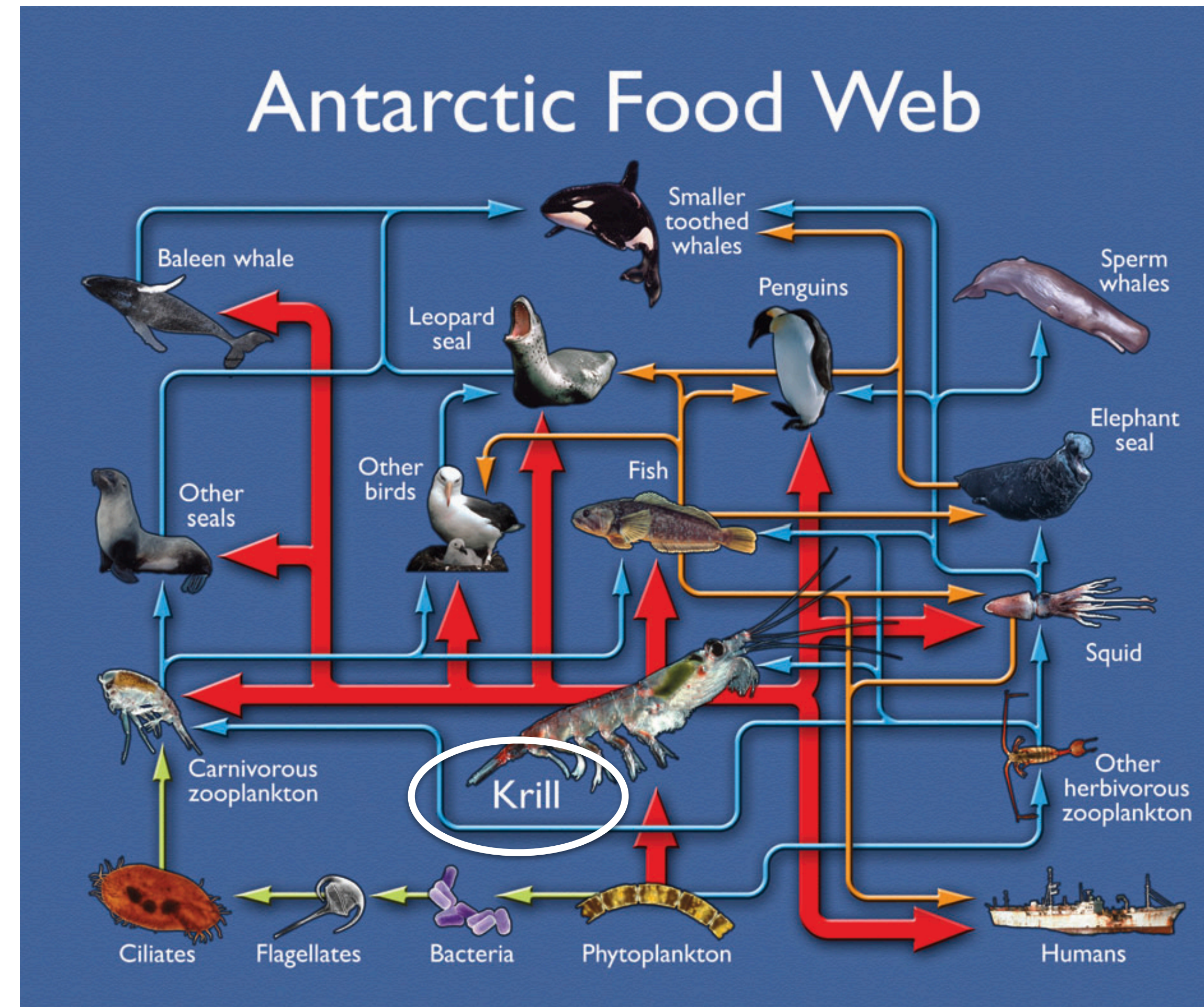
Role of higher trophic levels for element cycling?



CHARACTERISTICS

► E.g.,. Antarctic: krill central, “macrozooplankton”, feeds on phytoplankton

Antarctic



McBride, 2014

CHARACTERISTICS

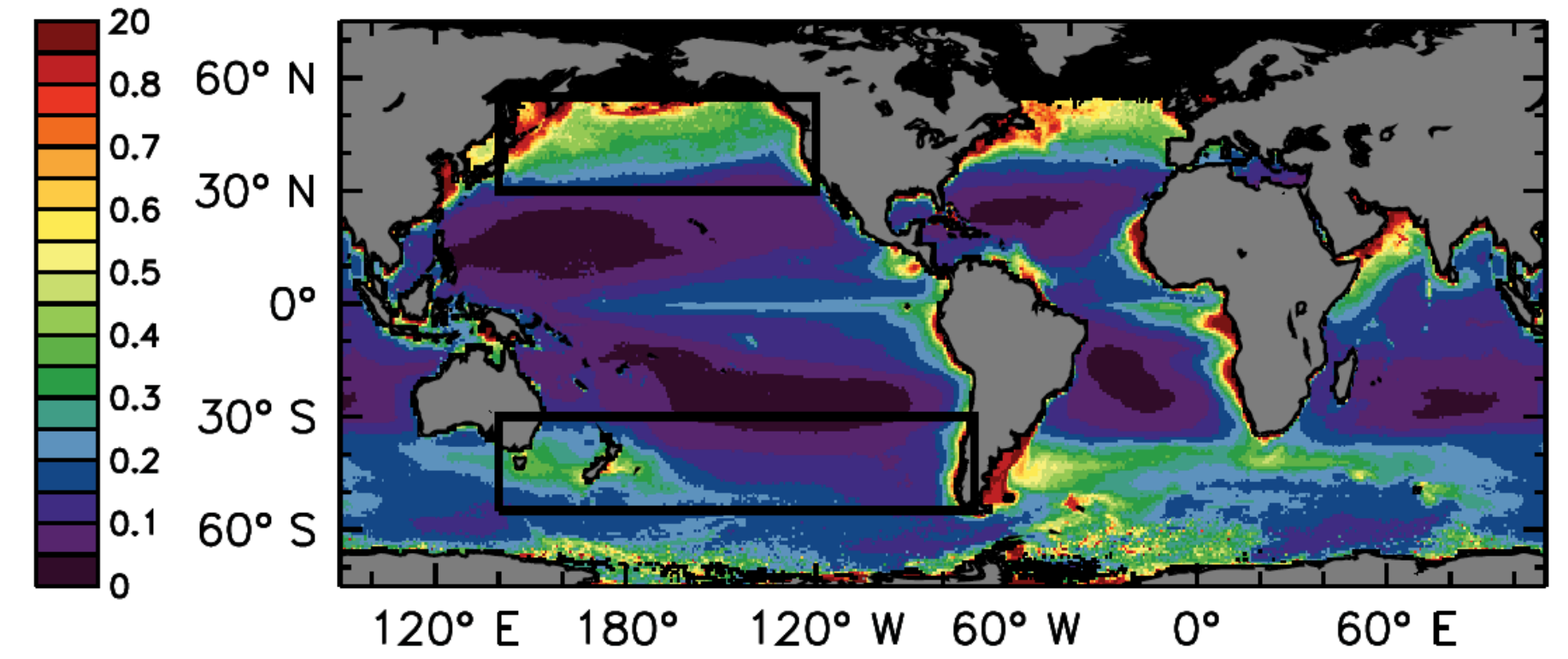
► *E.g., Antarctic: krill central*

Chlorophyll, austral summer

SeaWiFS data

Nov–Jan

Observations



CHARACTERISTICS

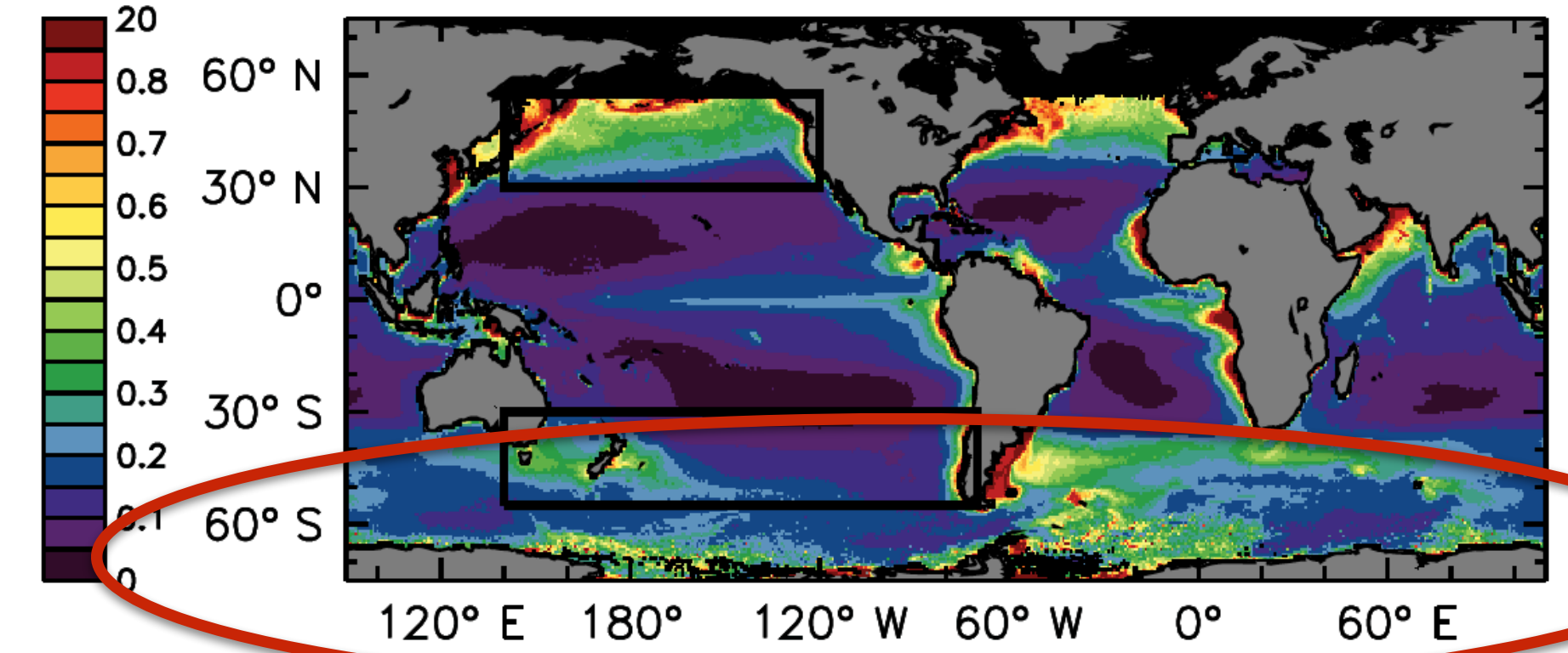
► *E.g., Antarctic: krill central*

Chlorophyll, austral summer

SeaWiFS data

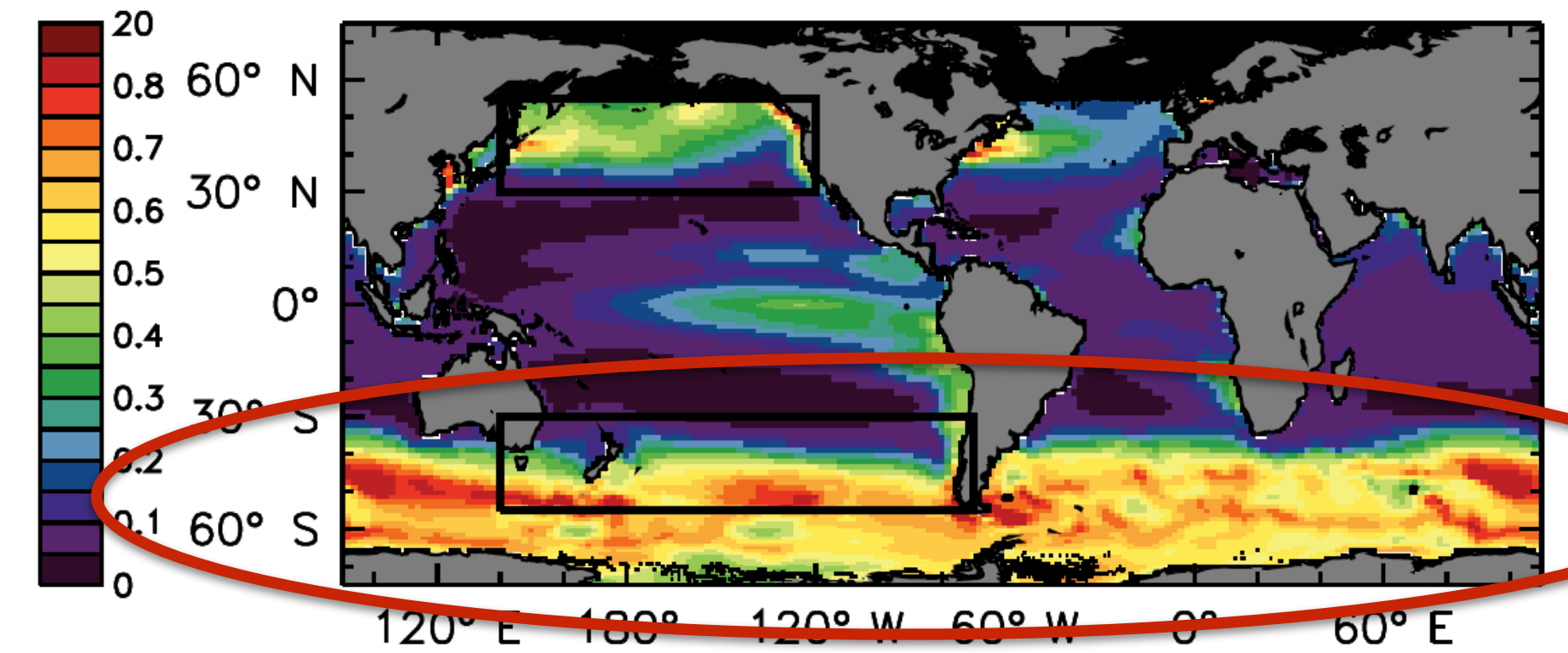
Nov–Jan

Observations



Model without
“krill”

PlankTOM6



CHARACTERISTICS

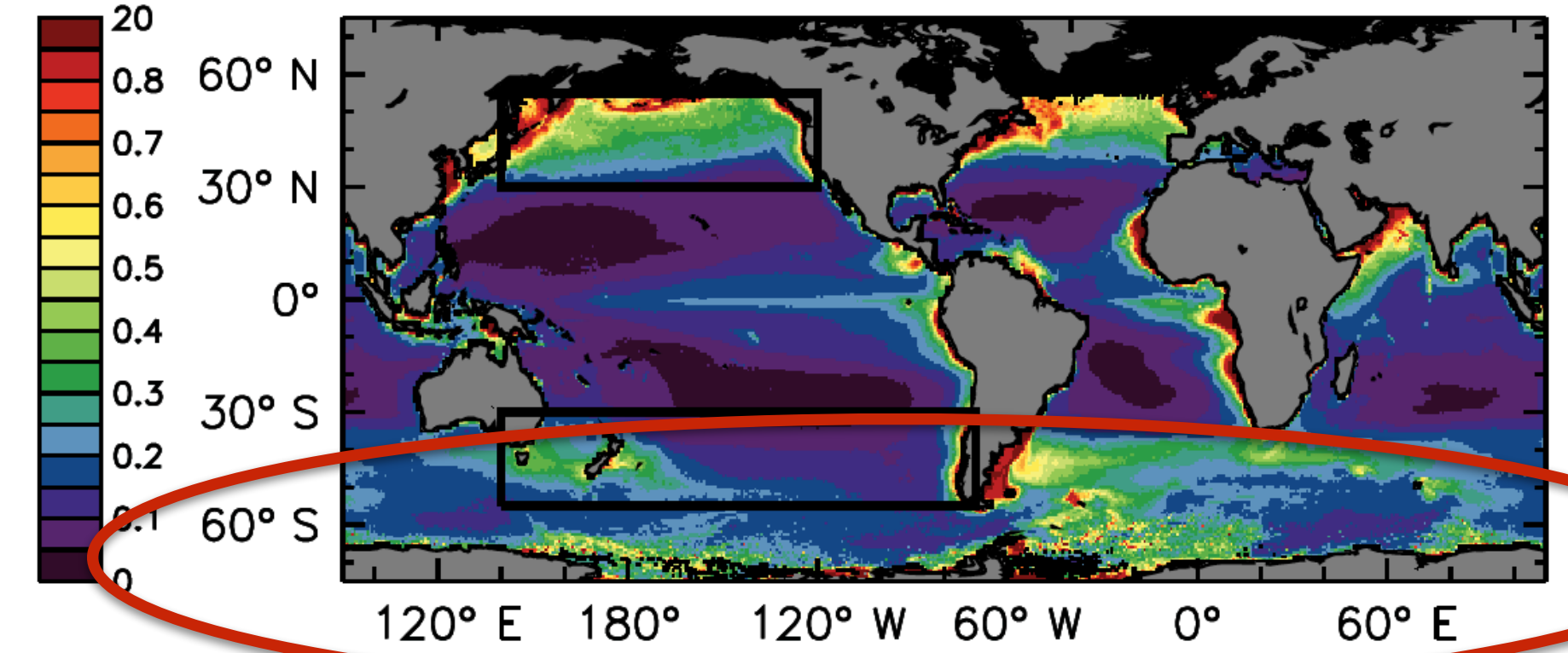
► *E.g., Antarctic: krill central*

Chlorophyll, austral summer

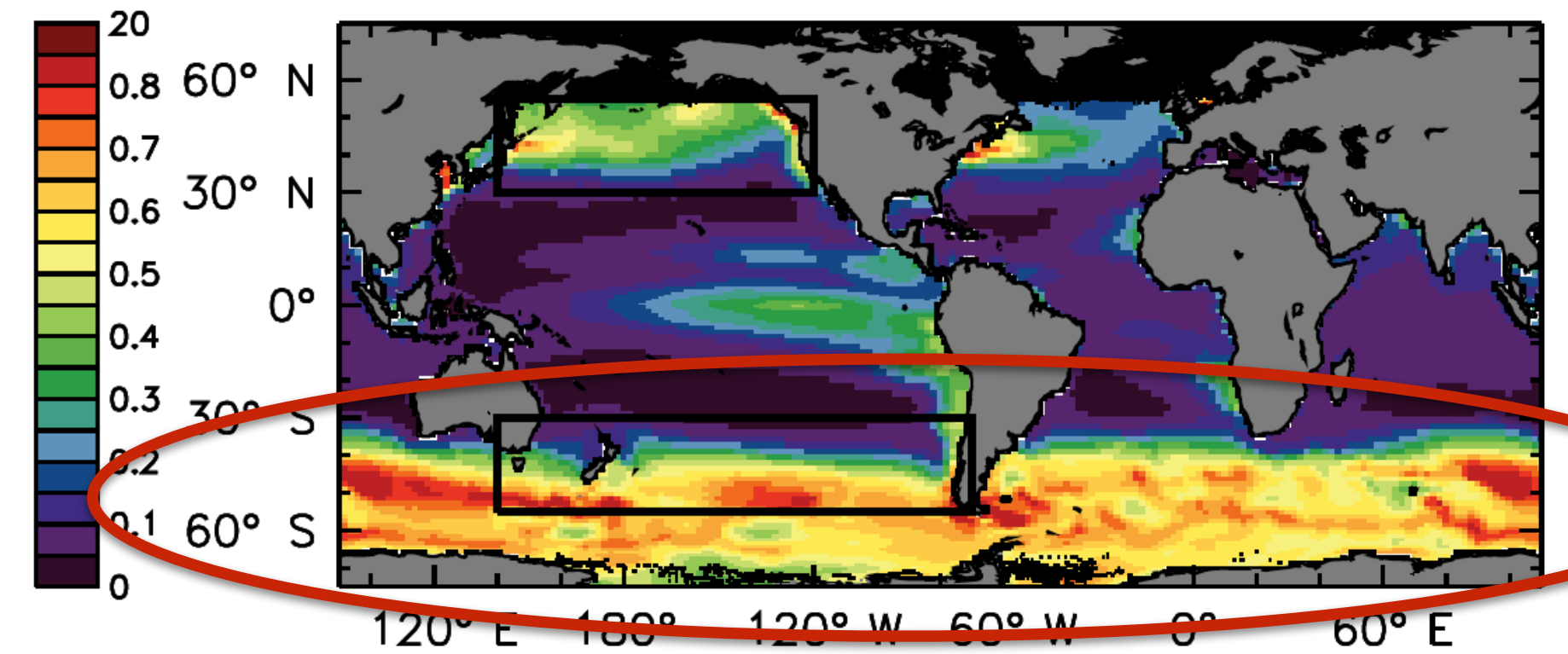
SeaWiFS data

Nov–Jan

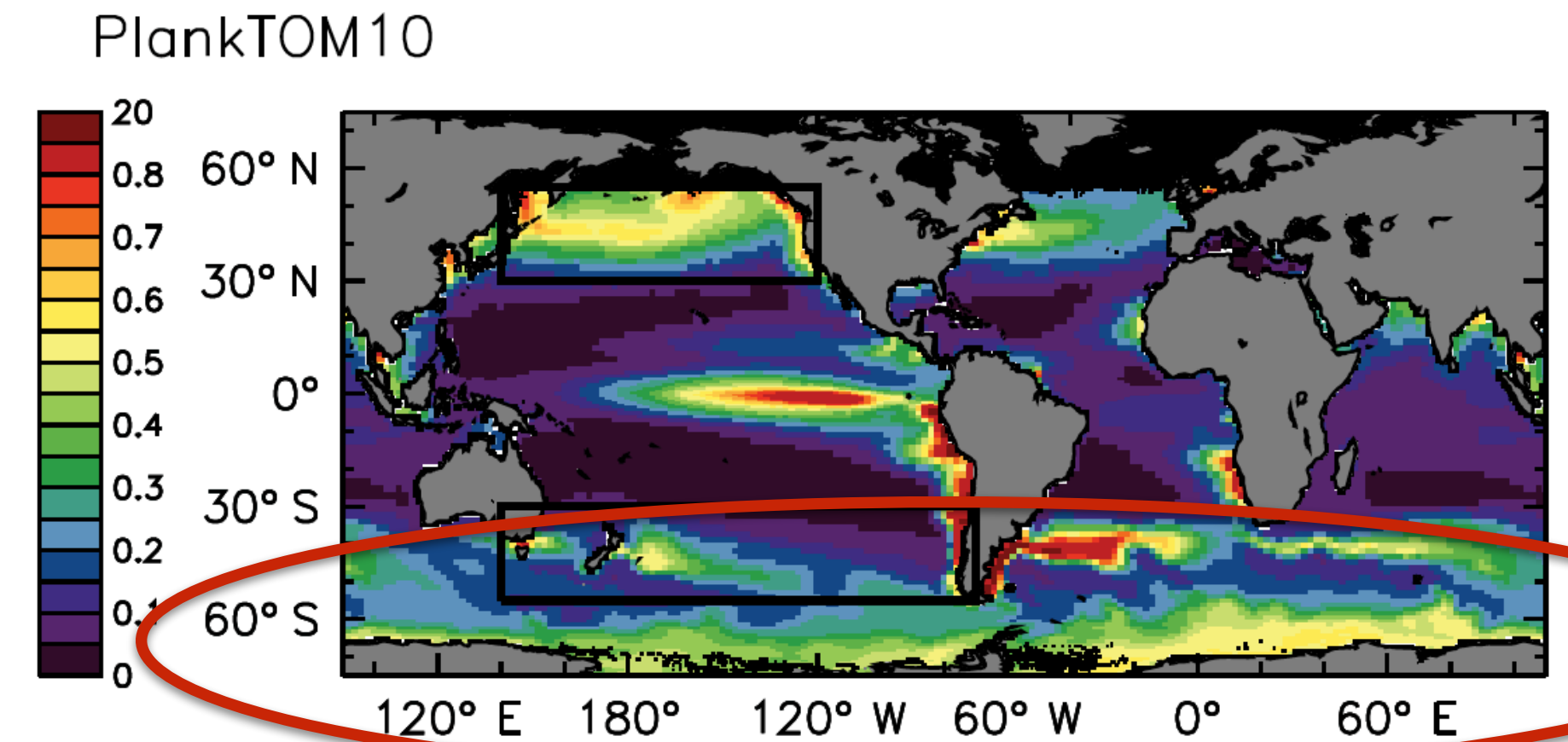
Observations



Model without
“krill”



Model with
“krill”

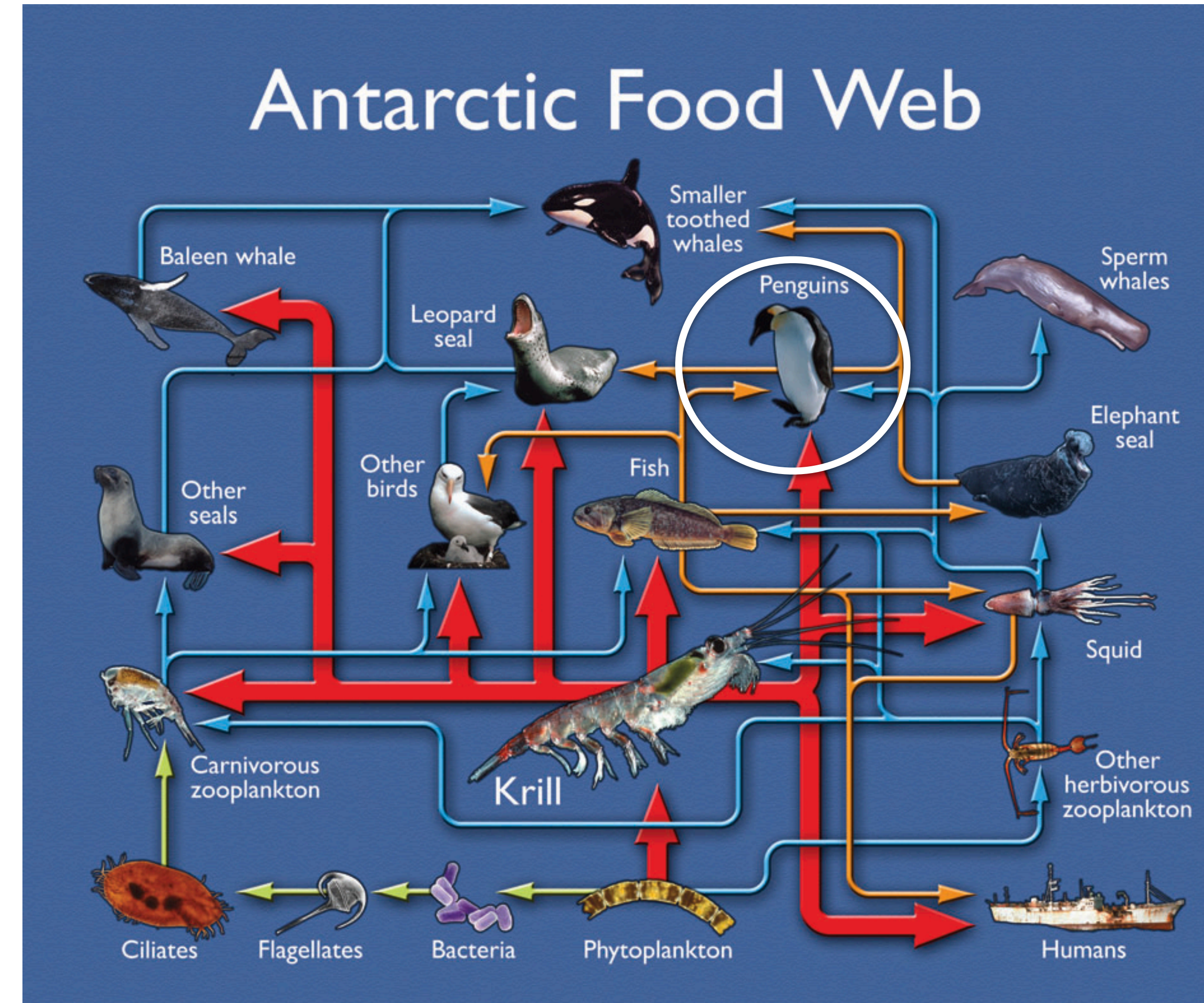
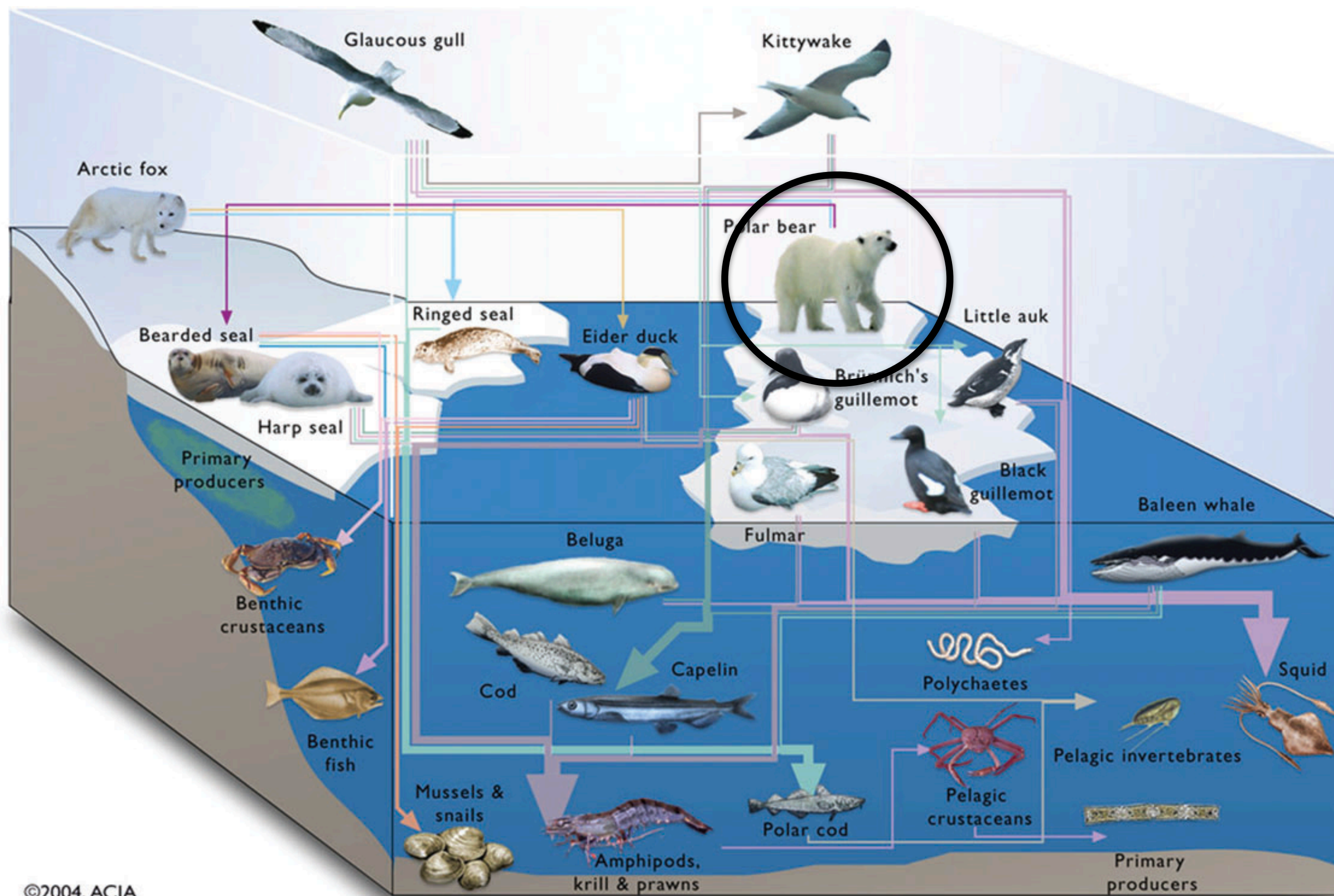


CHARACTERISTICS

► Food webs differ

Arctic

Antarctic

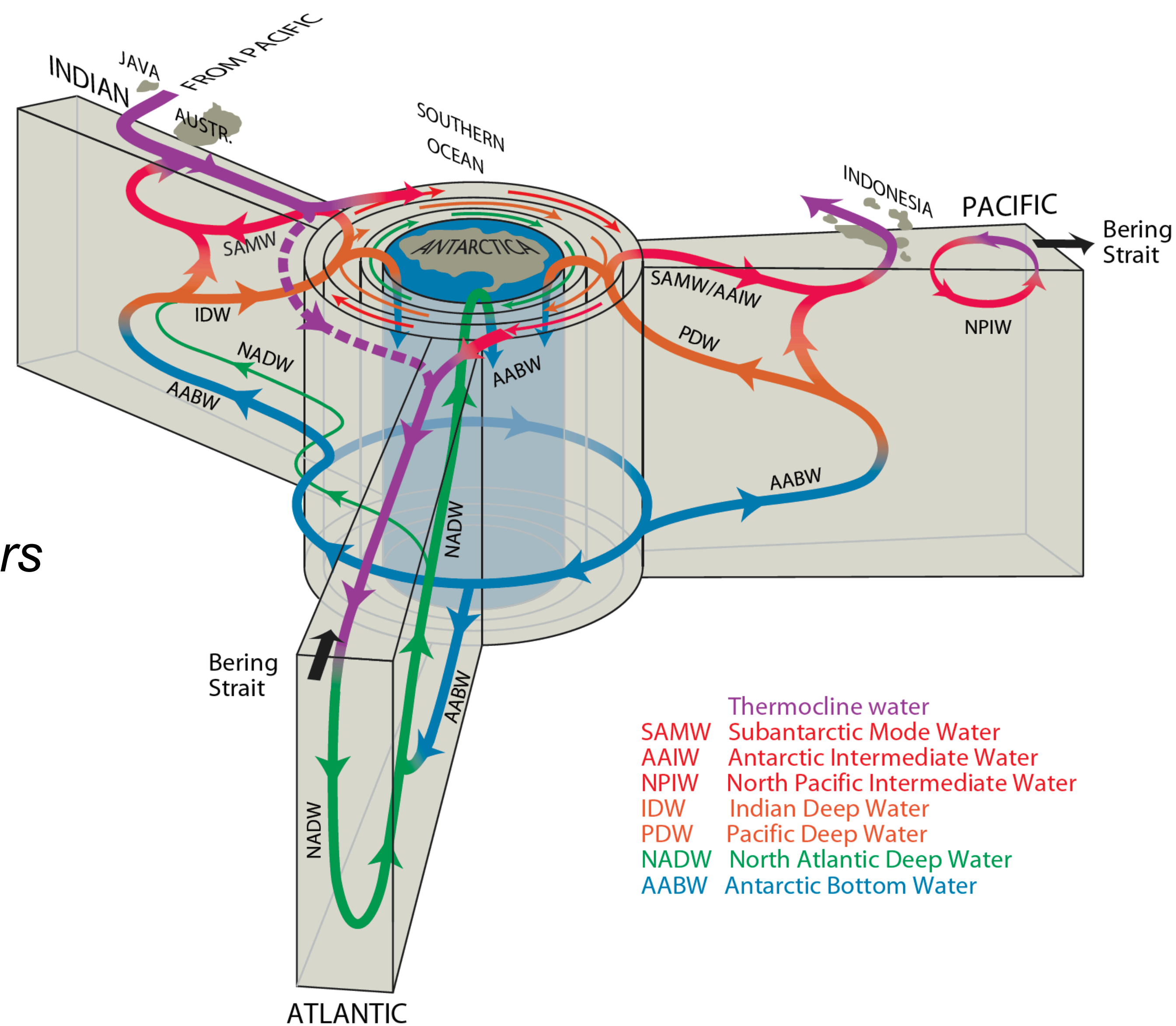


CHARACTERISTICS

Water mass properties:

Antarctic:

► *upwelling of low oxygen, high nitrate, high carbon waters*



CHARACTERISTICS

Water mass properties:

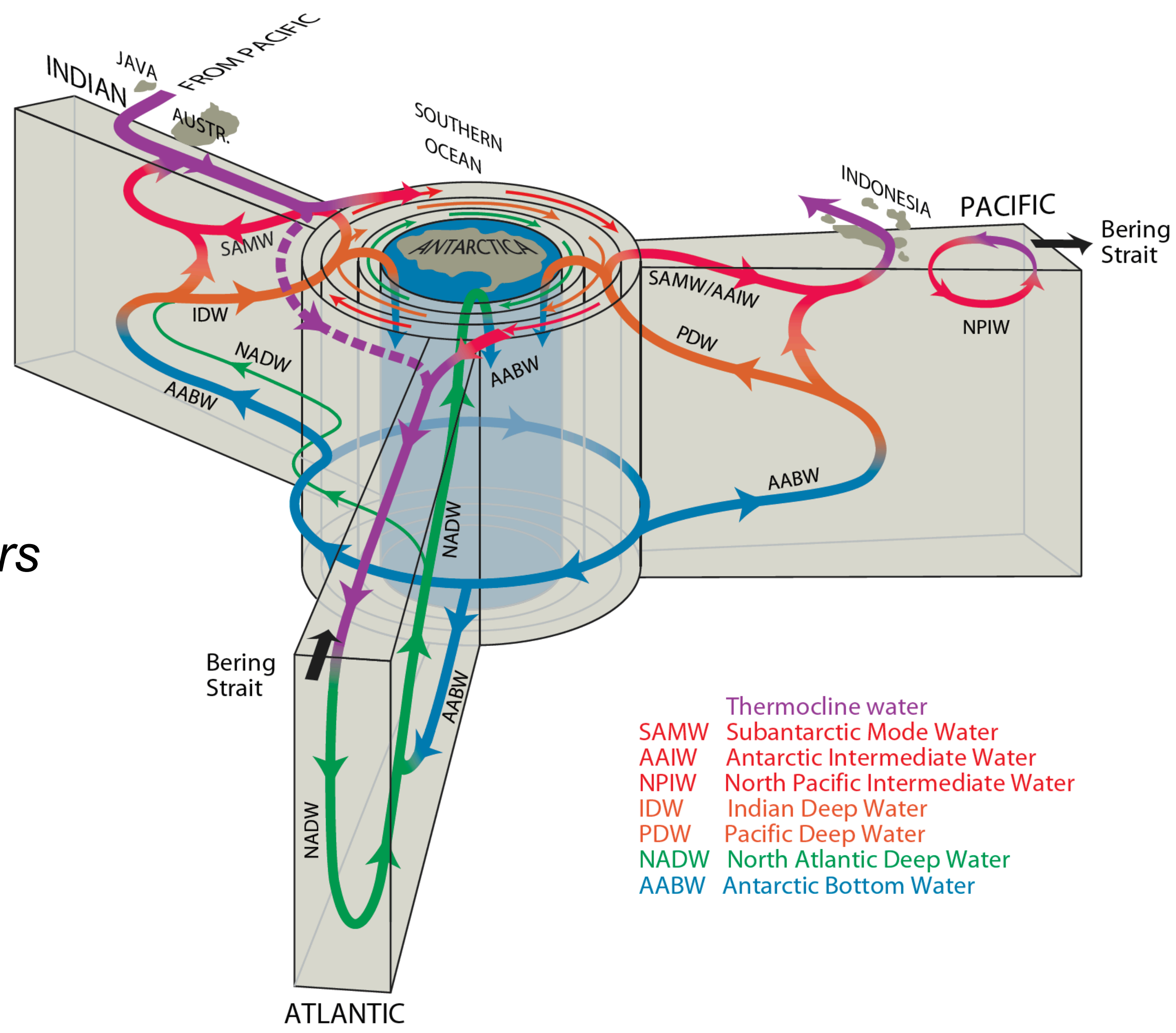
Antarctic:

► upwelling of low oxygen, high nitrate, high carbon waters

↓
consumed

↓
remineralized

↓
remineralized,
cool



- Thermocline water
- SAMW Subantarctic Mode Water
- AAIW Antarctic Intermediate Water
- NPIW North Pacific Intermediate Water
- IDW Indian Deep Water
- PDW Pacific Deep Water
- NADW North Atlantic Deep Water
- AABW Antarctic Bottom Water

CHARACTERISTICS

Water mass properties:

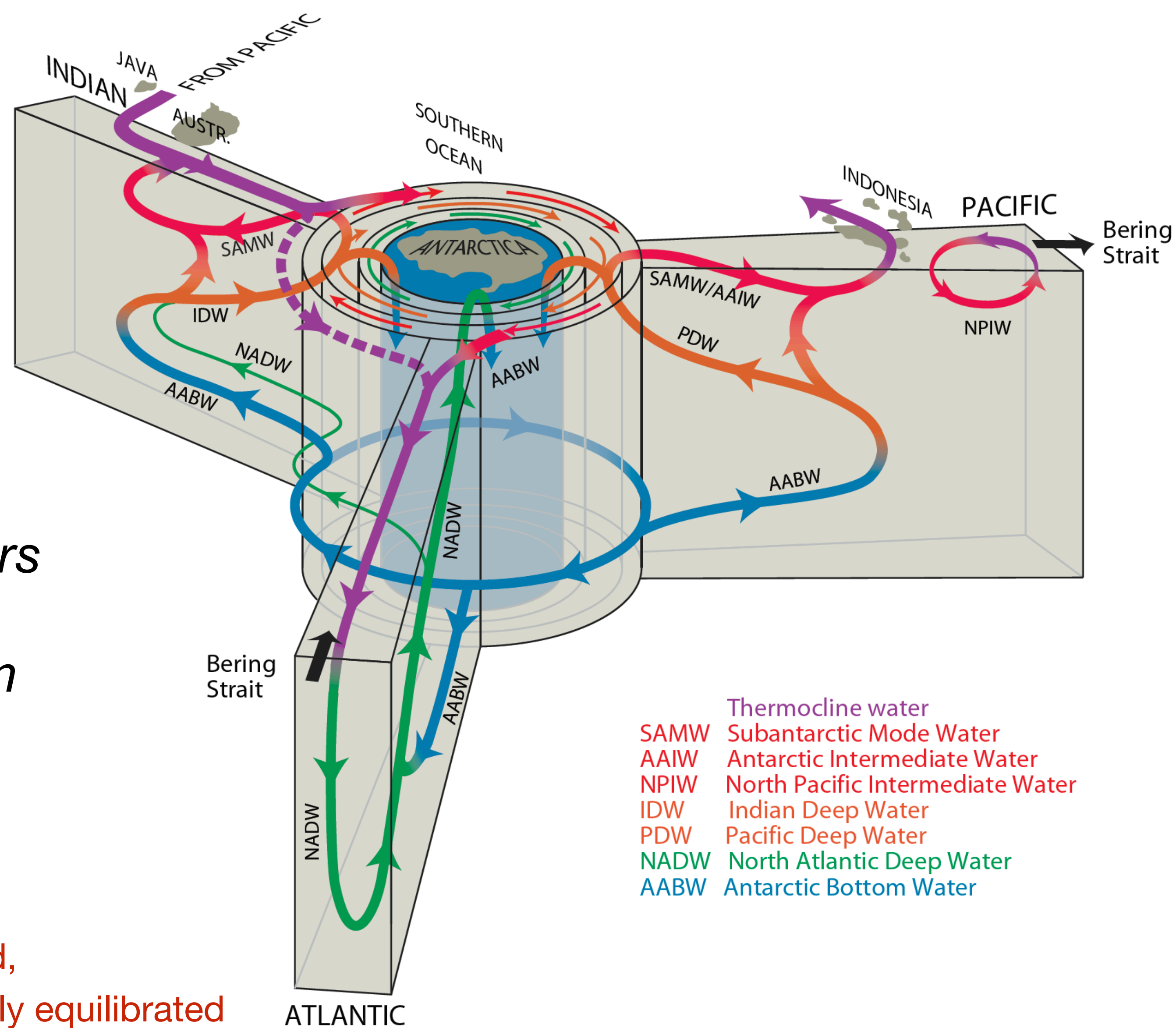
Antarctic:

- ▶ *upwelling of low oxygen, high nitrate, high carbon waters*
- ▶ *subduction of oxygenated waters, with nitrate and carbon*

↓
air-sea exchange

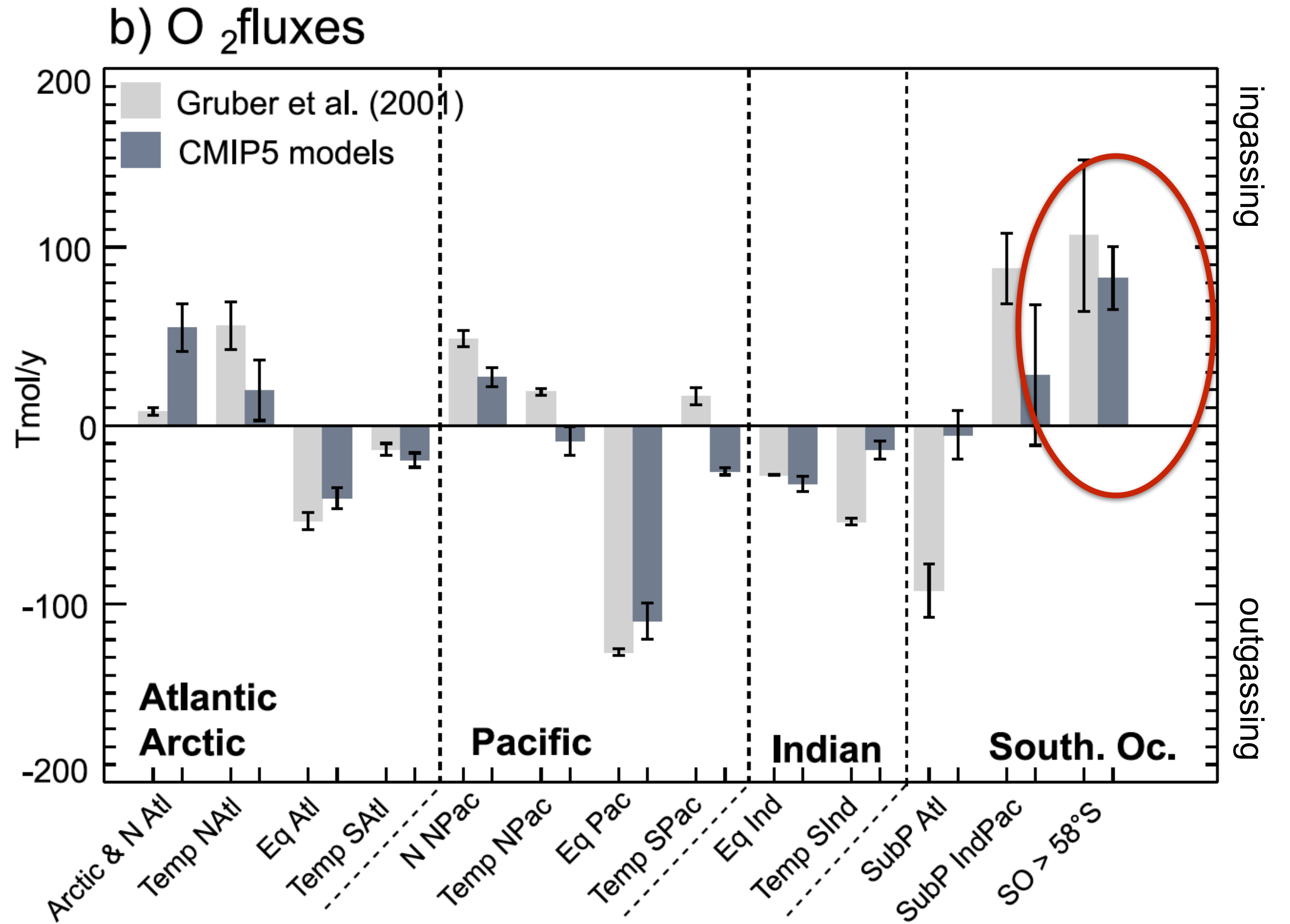
↓
not used up

↓
cooled,
not fully equilibrated



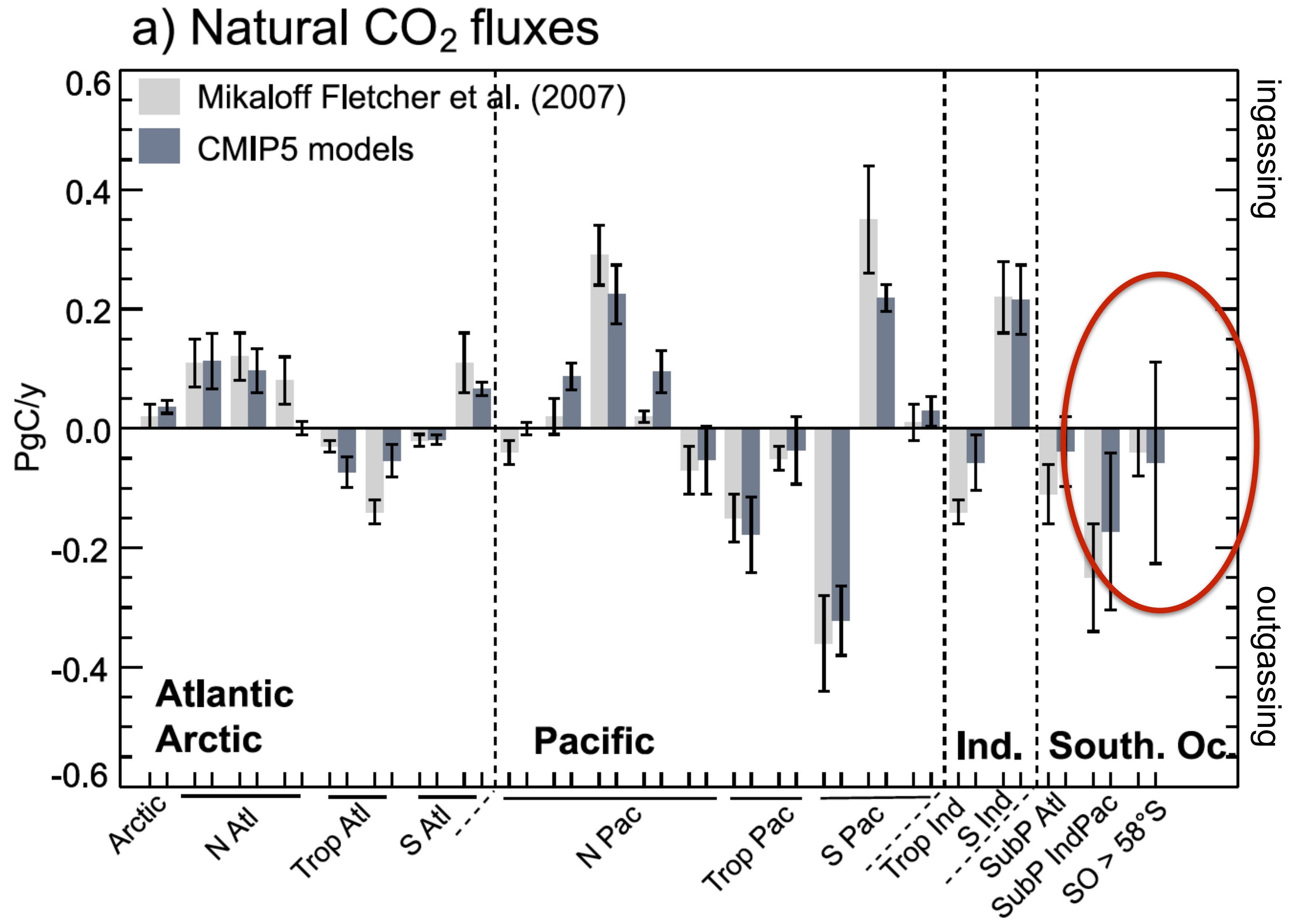
CHARACTERISTICS

► *Reflected in air-sea fluxes*



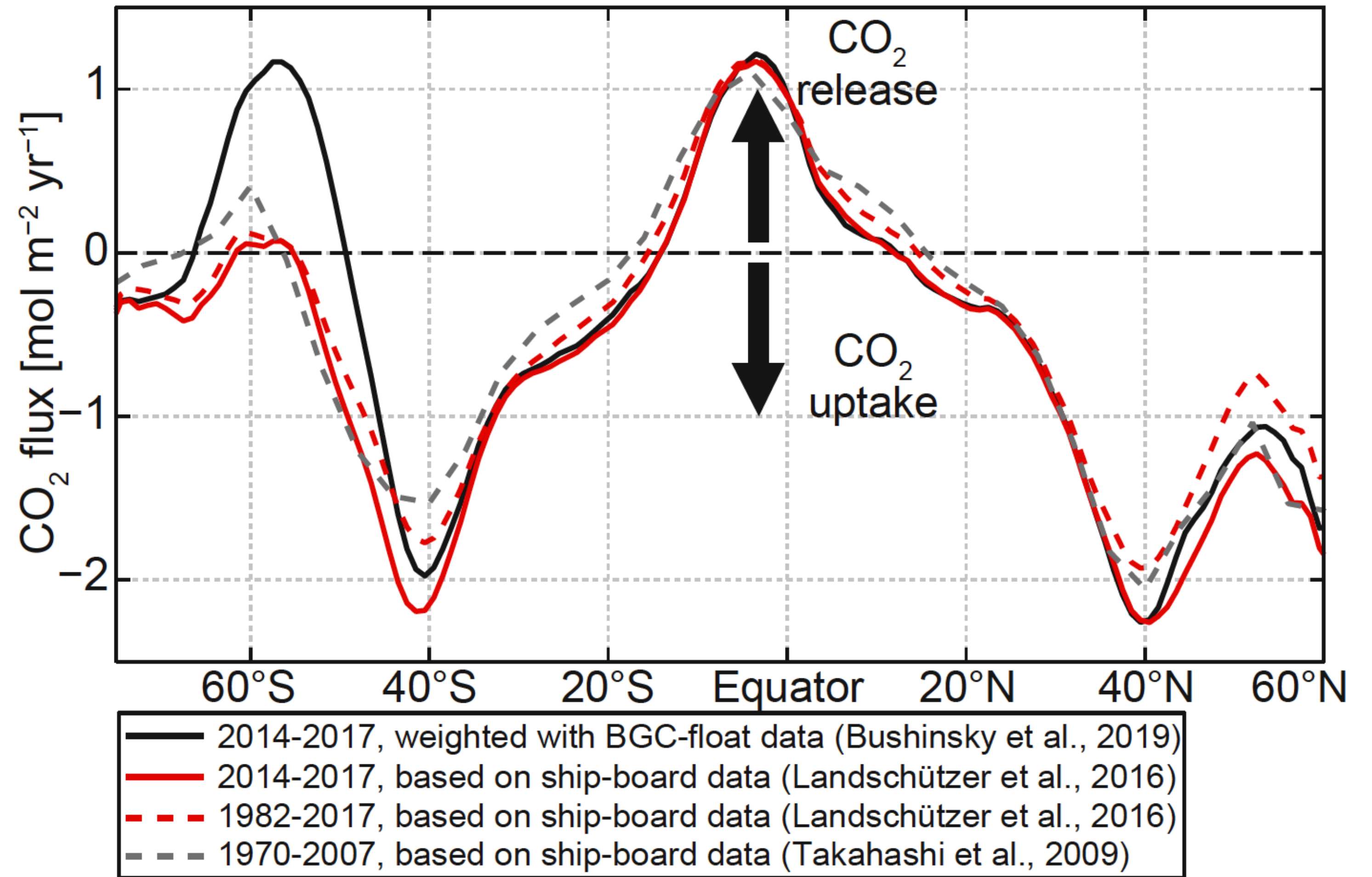
CHARACTERISTICS

► *Reflected in air-sea fluxes*



CHARACTERISTICS

- Reflected in air-sea fluxes
- Sidenote: uncertain (Antarctic & Arctic)



Chen et al, 2022, see also Bushinsky et al, 2019, Gray et al, 2018

Background

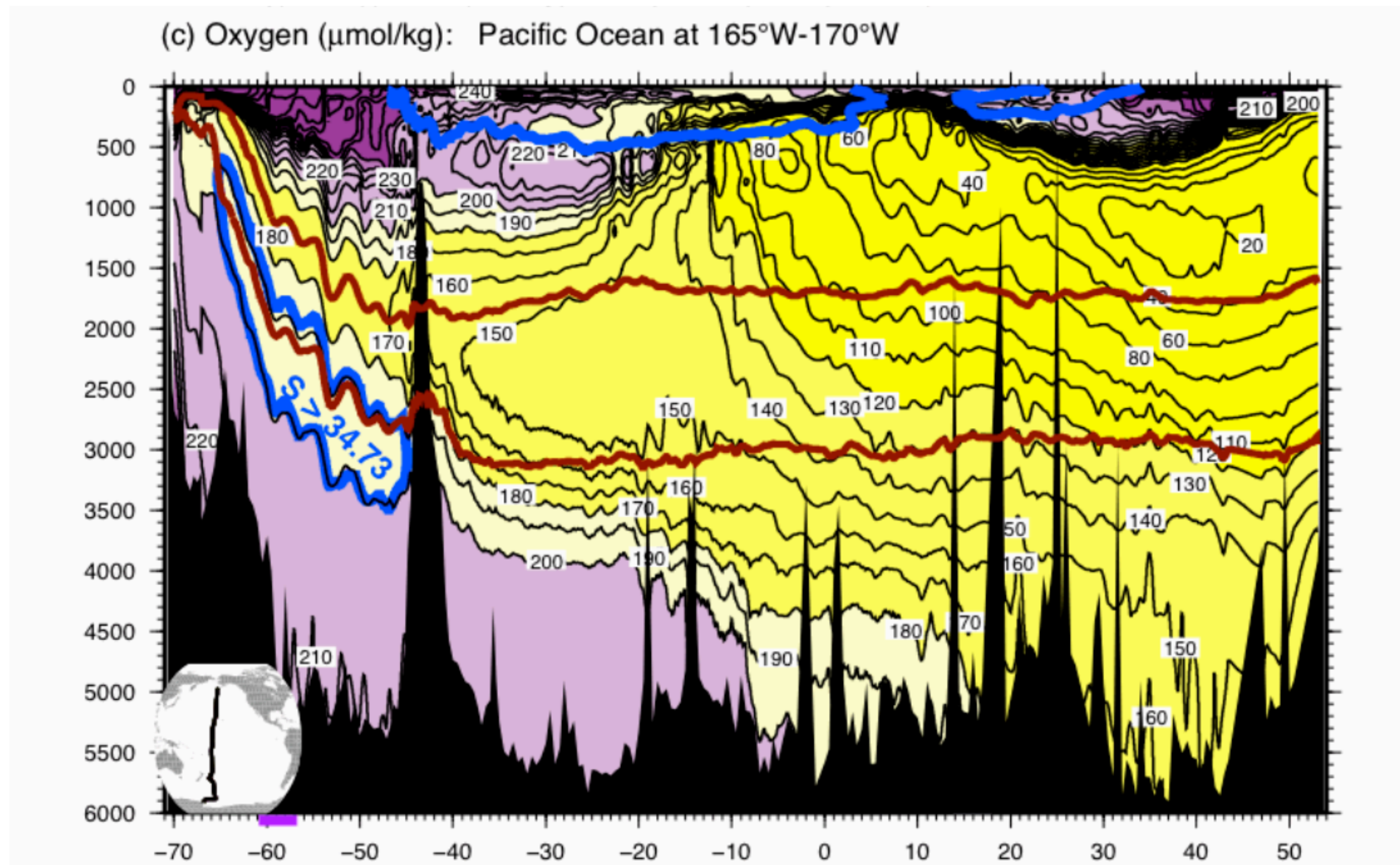
Characteristics

Global relevance

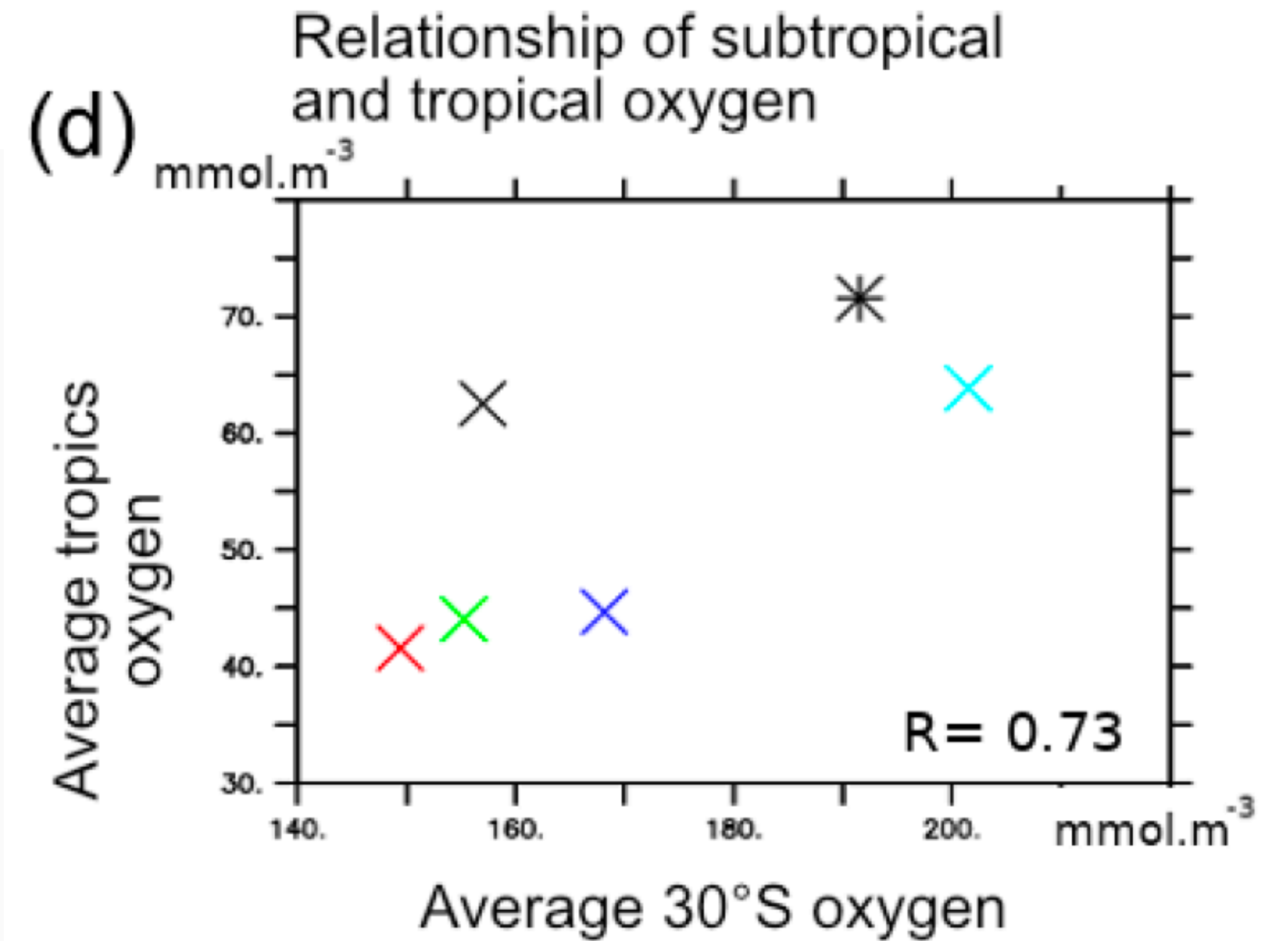
Anthropogenic climate change

GLOBAL IMPORTANCE

► Ventilation of thermocline waters



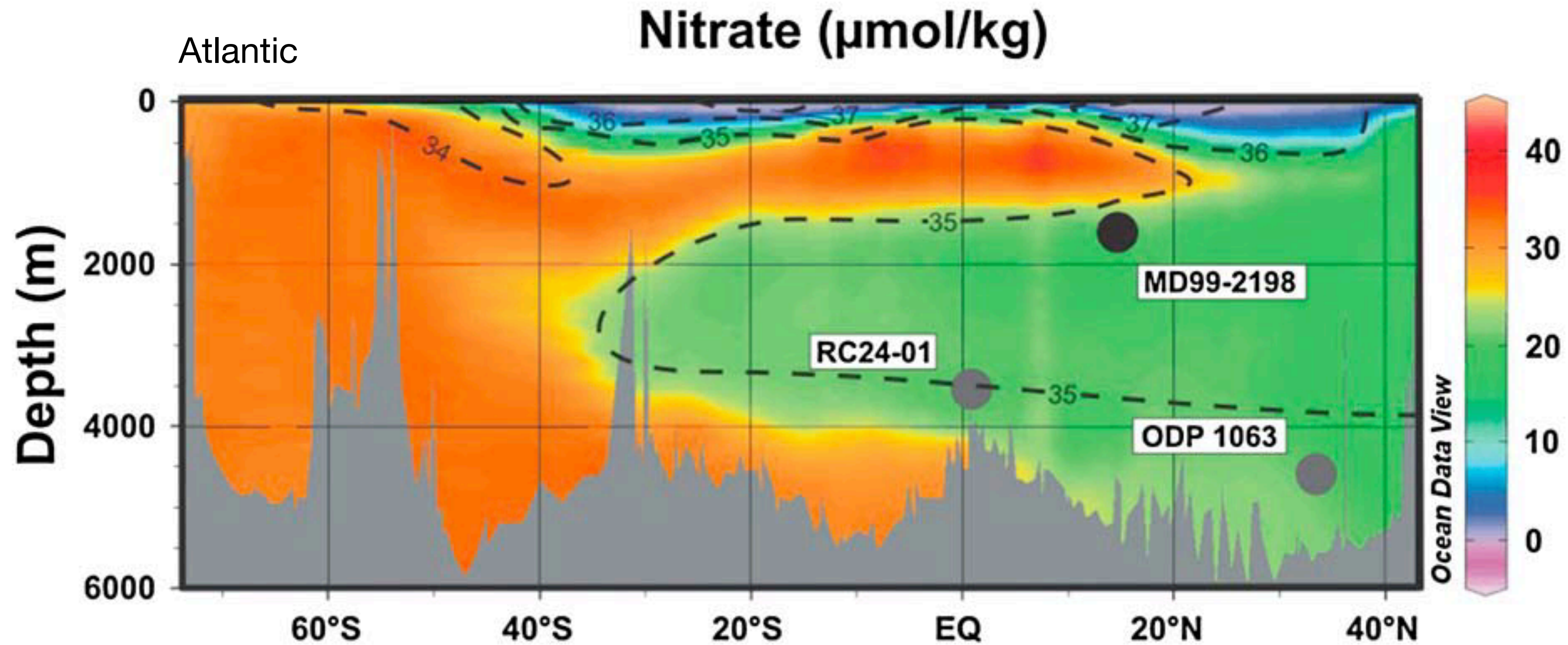
Talley et al, 2013



Duteil et al, 2021

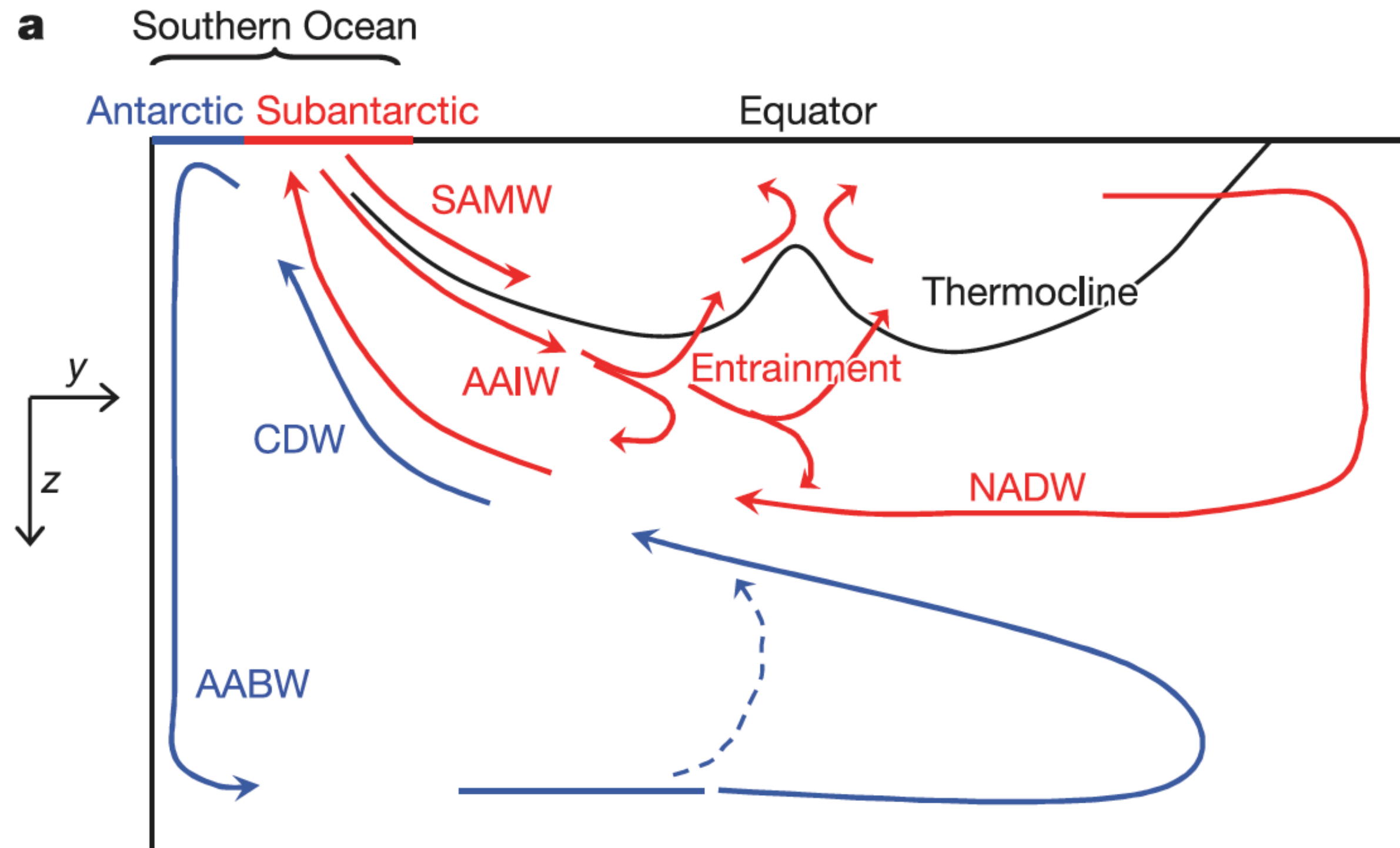
GLOBAL IMPORTANCE

- ▶ *Ventilation of thermocline waters*
- ▶ *Nutrient supply to lower latitudes*



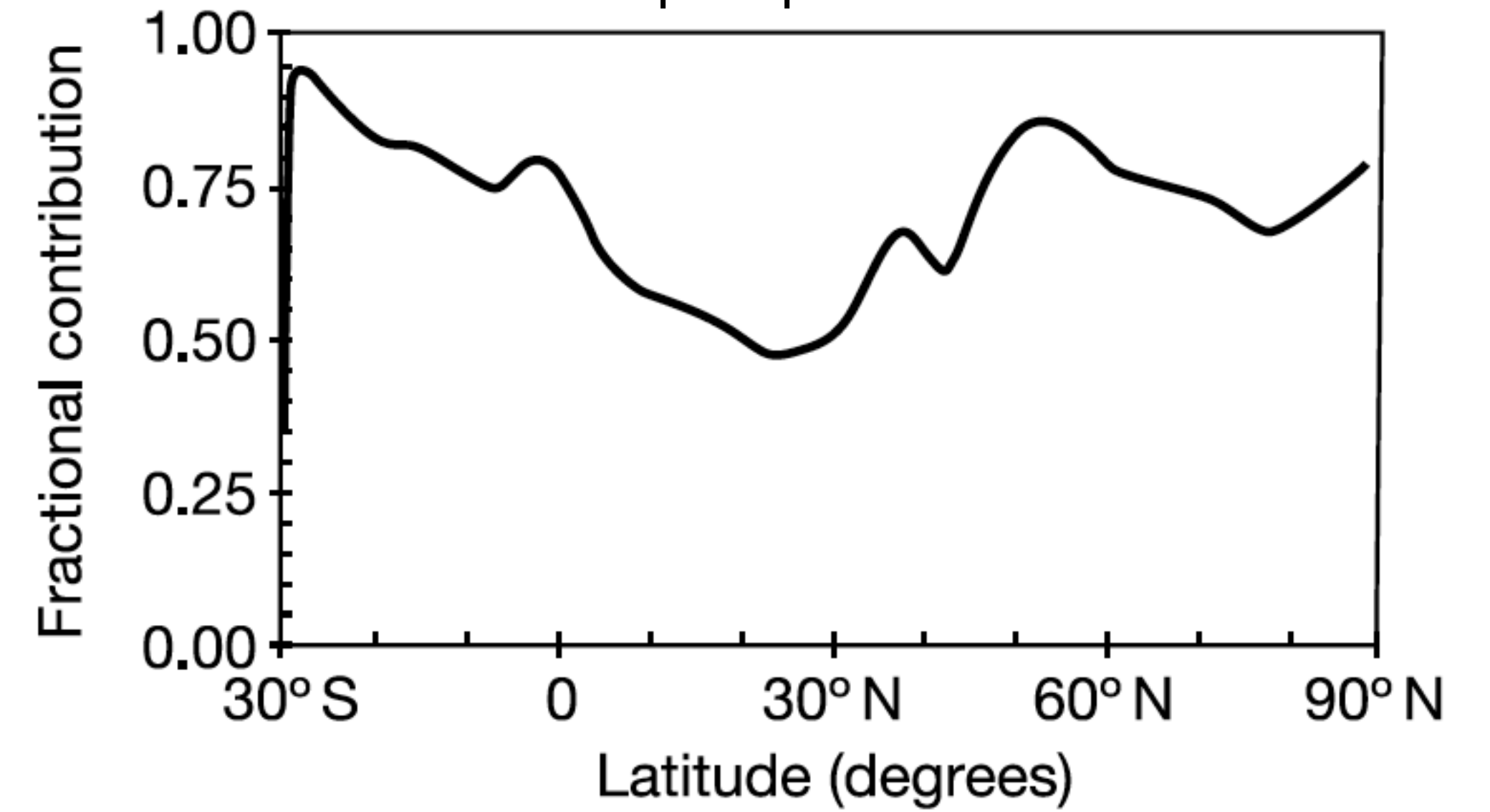
GLOBAL IMPORTANCE

- ▶ *Ventilation of thermocline waters*
- ▶ *Nutrient supply to lower latitudes*



Marinov et al, 2006

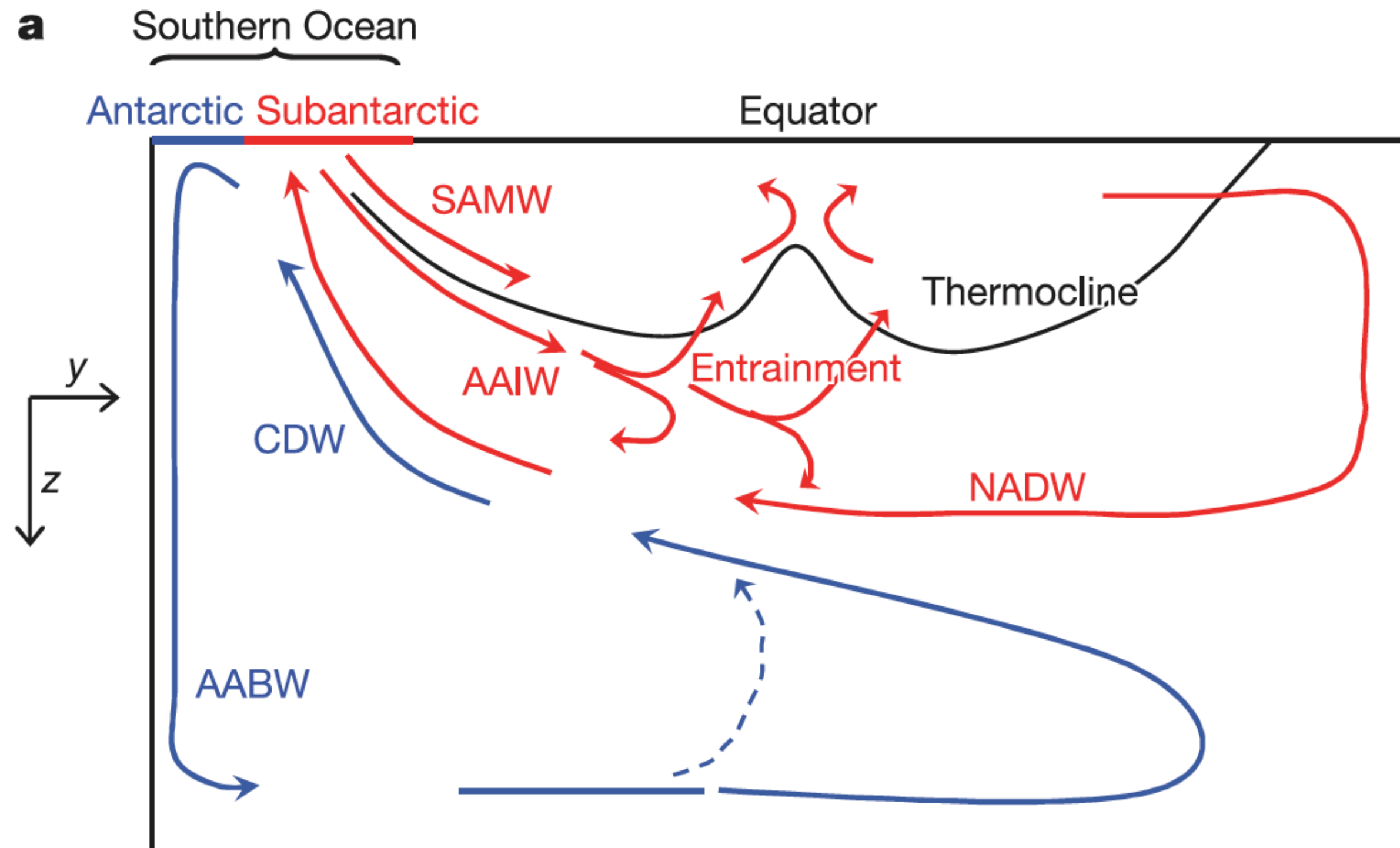
Fractional contribution of Southern Ocean nutrient supply to export production



Sarmiento et al, 2004

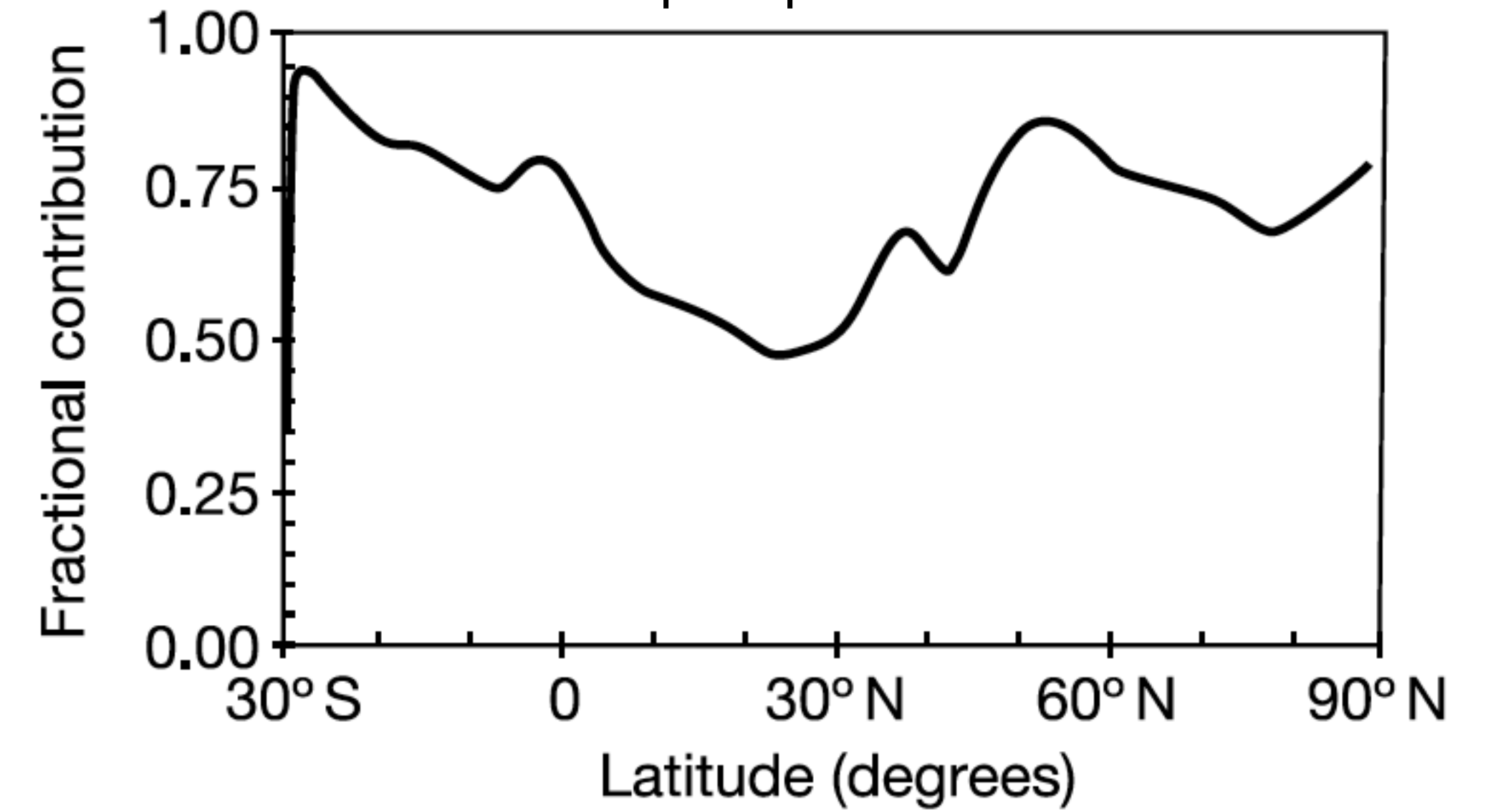
GLOBAL IMPORTANCE

- ▶ *Ventilation of thermocline waters*
- ▶ *Nutrient supply to lower latitudes*
- ▶ *Sequestration of carbon for long time scales*



Marinov et al, 2006

Fractional contribution of Southern Ocean nutrient supply to export production



Sarmiento et al, 2004

Background

Characteristics

Global relevance

Anthropogenic climate change

ANTHROPOGENIC CLIMATE CHANGE

Tagliabue et al, 2022

Primary production

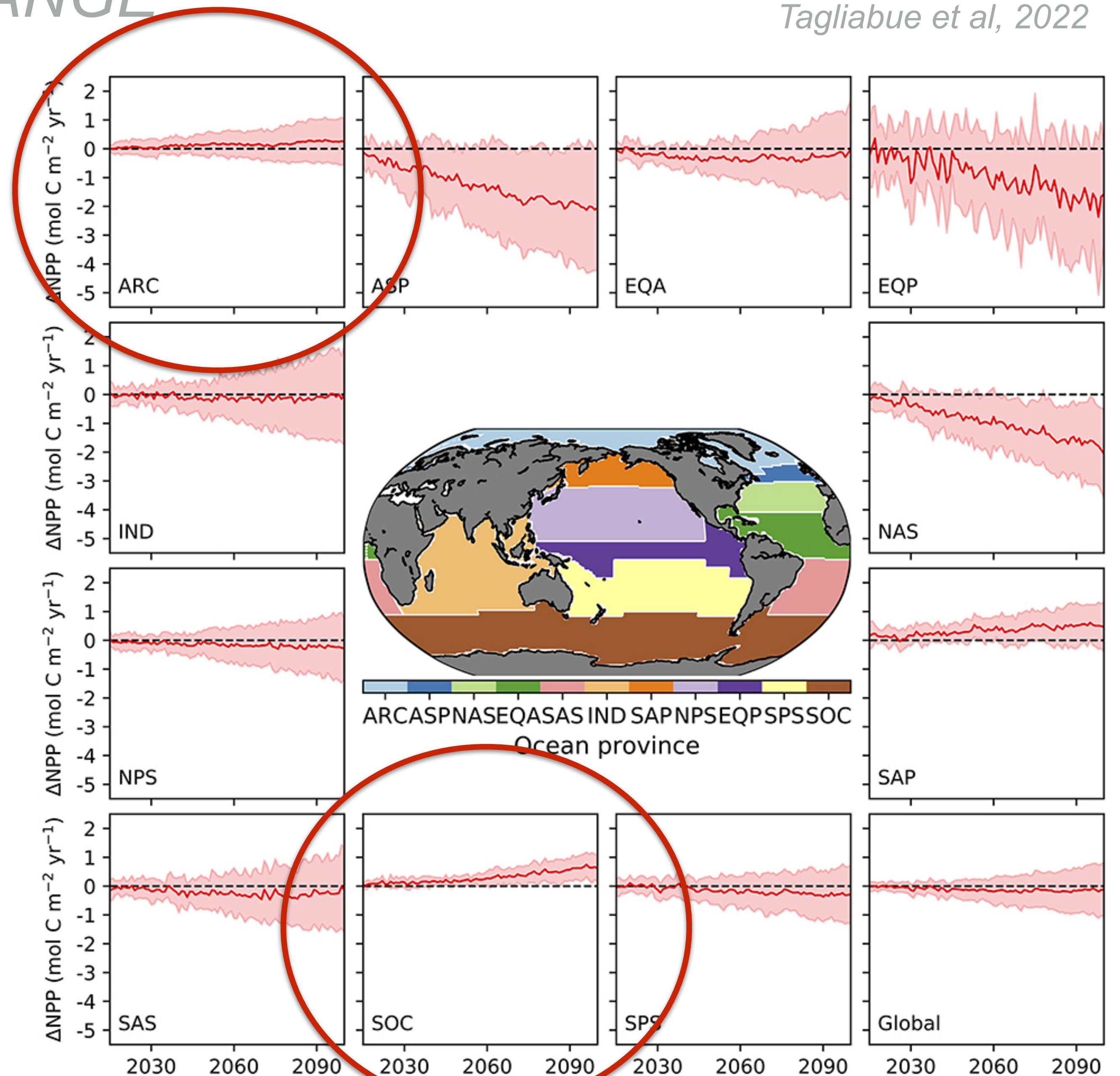
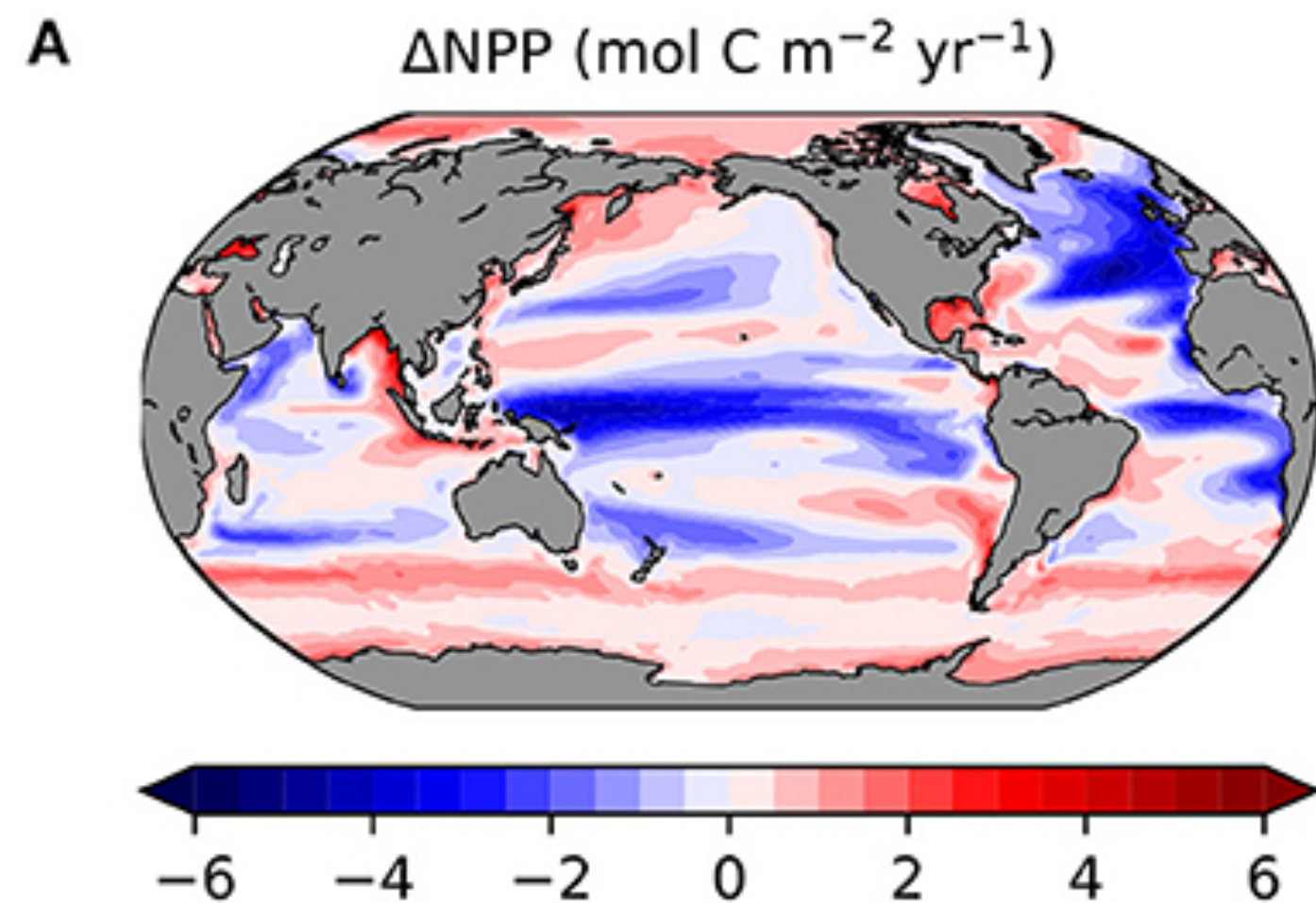
► Increase projected.

What stimulates more production?

► Warming, sea-ice retreat

► Arctic: more upward mixing of nitrate with storms over ice-free areas?

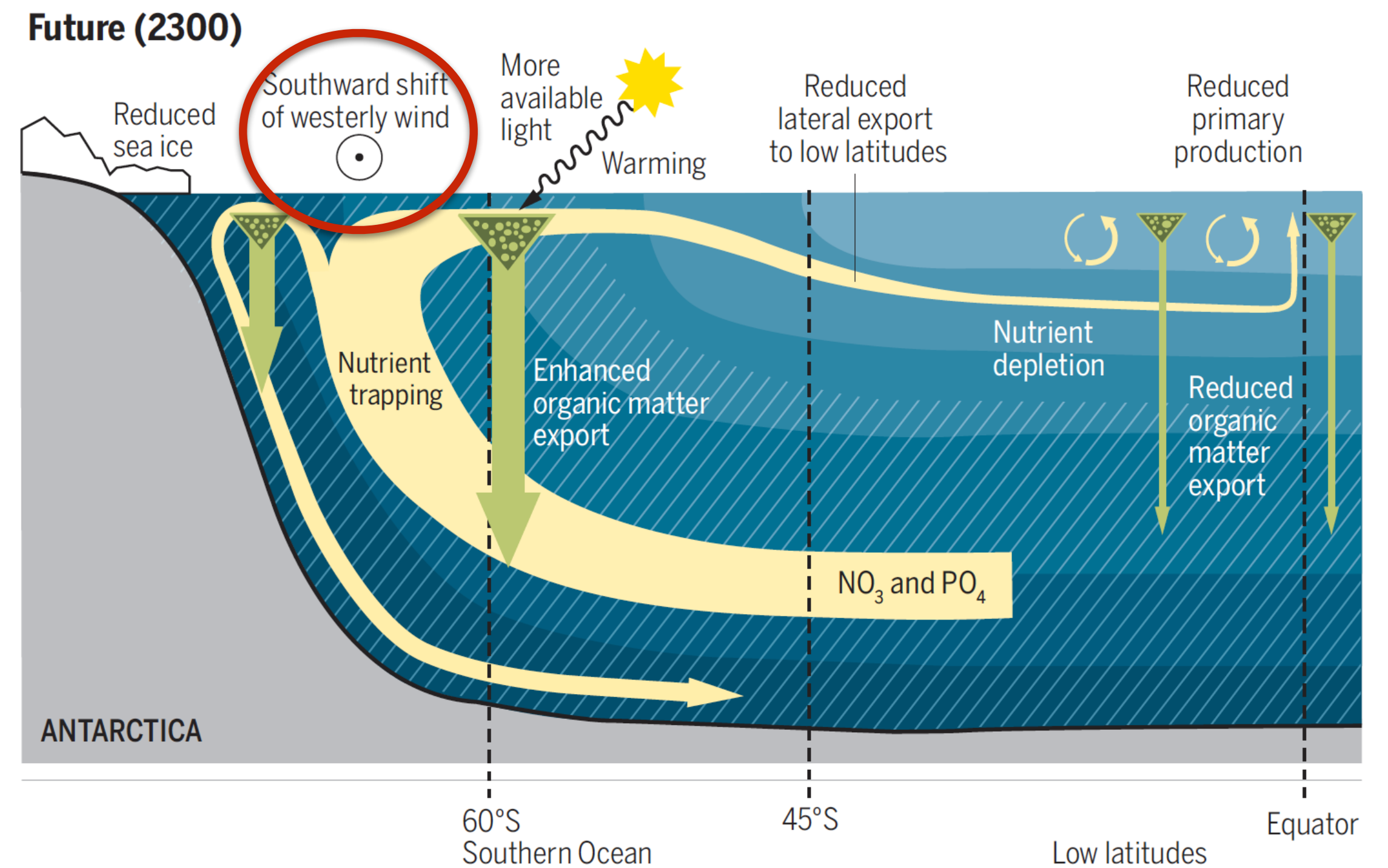
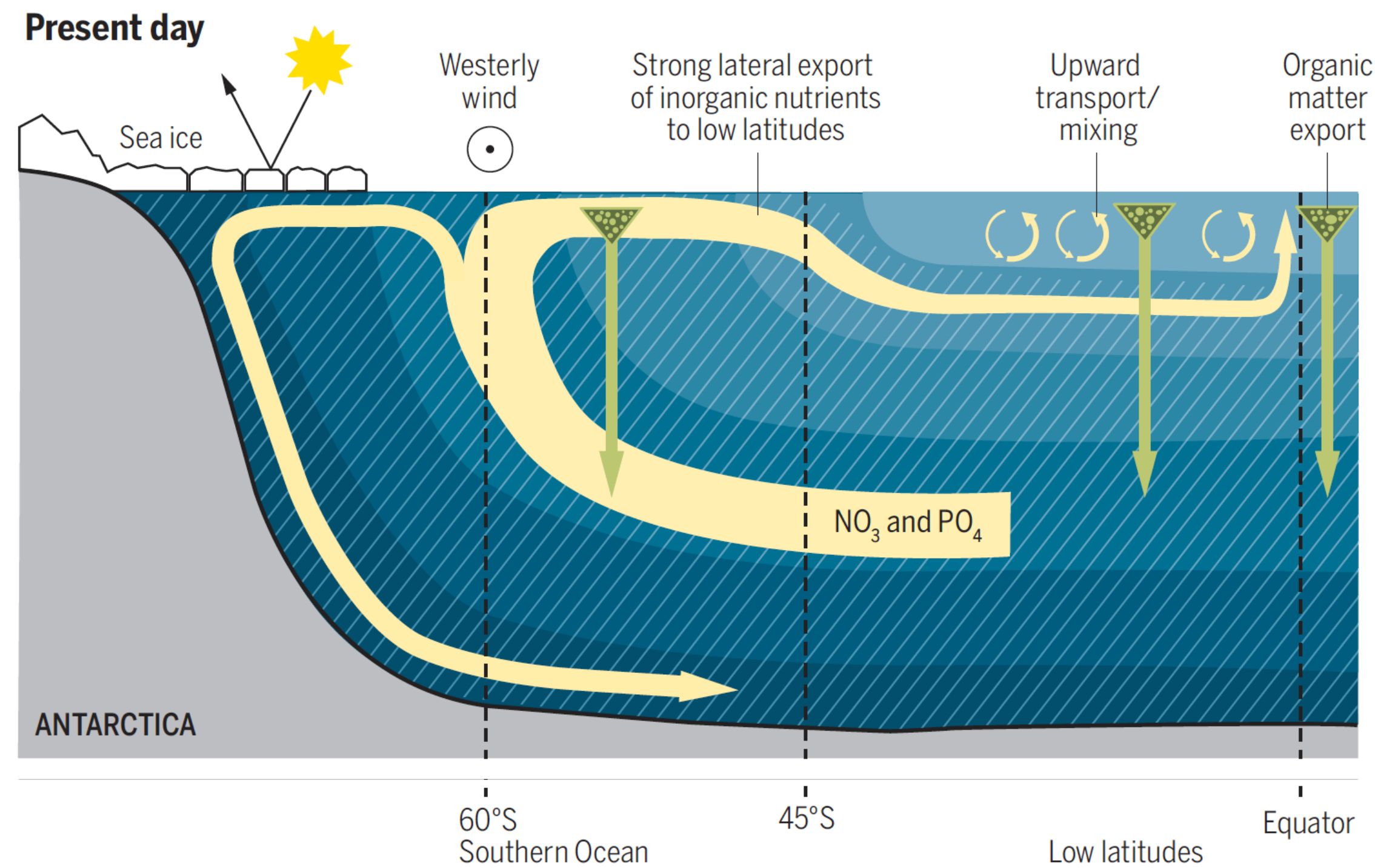
Antarctic: Shoaling of mixed layers?



ANTHROPOGENIC CLIMATE CHANGE

Primary production

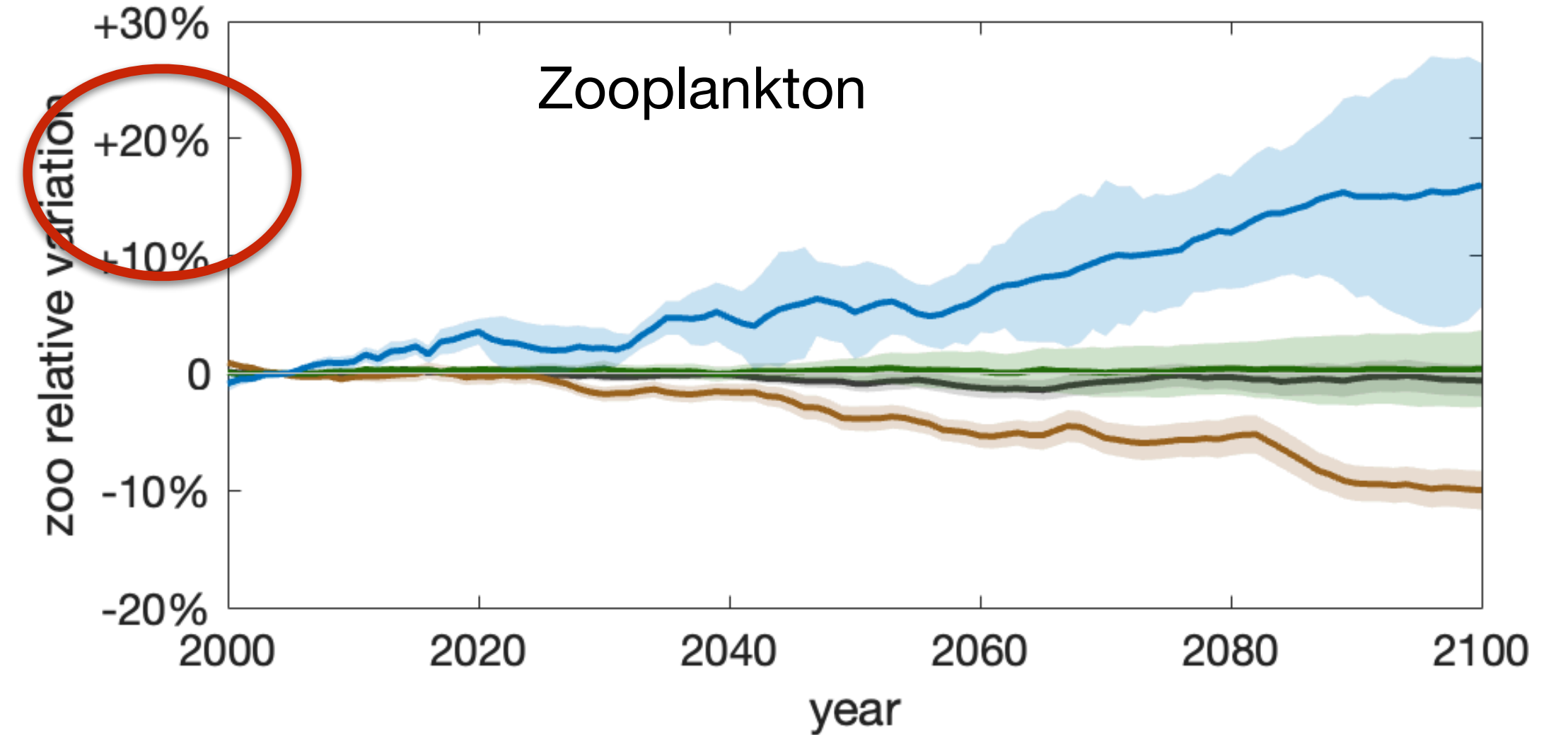
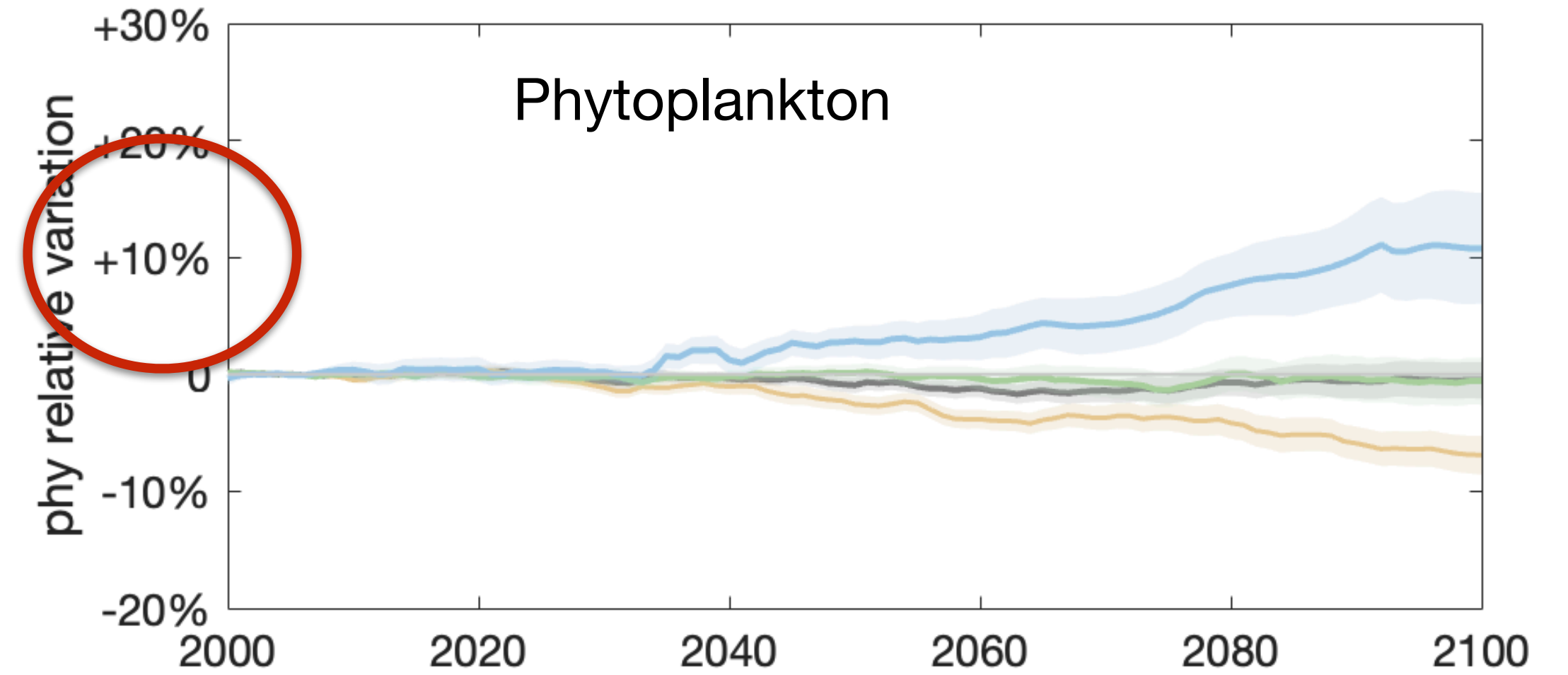
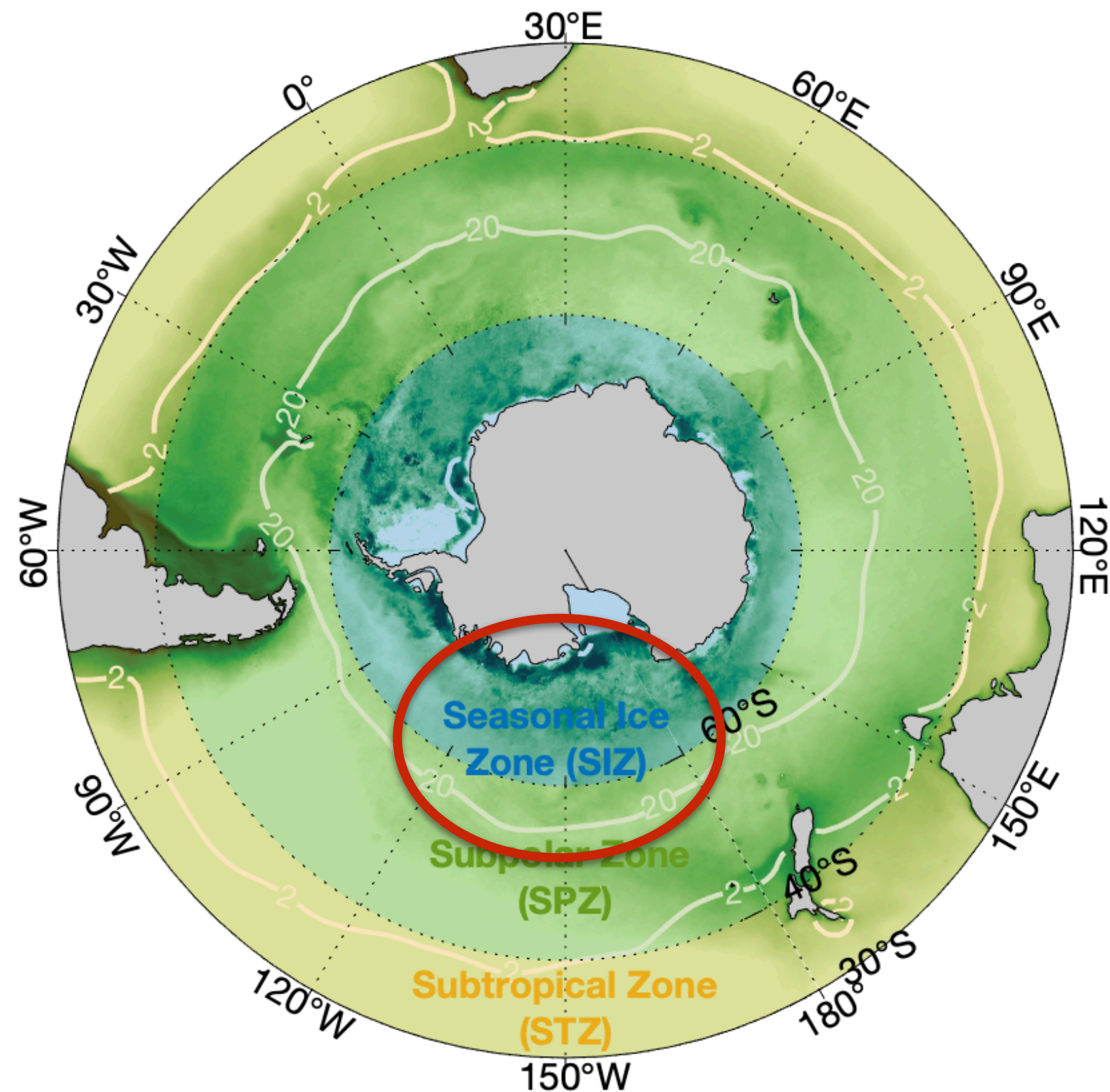
- ▶ Increase projected.
- ▶ Antarctic: Nutrient “robbing”?



ANTHROPOGENIC CLIMATE CHANGE

Primary production

- ▶ Increase projected.
- ▶ Antarctic:
Nutrient “robbing”? Trophic amplification?



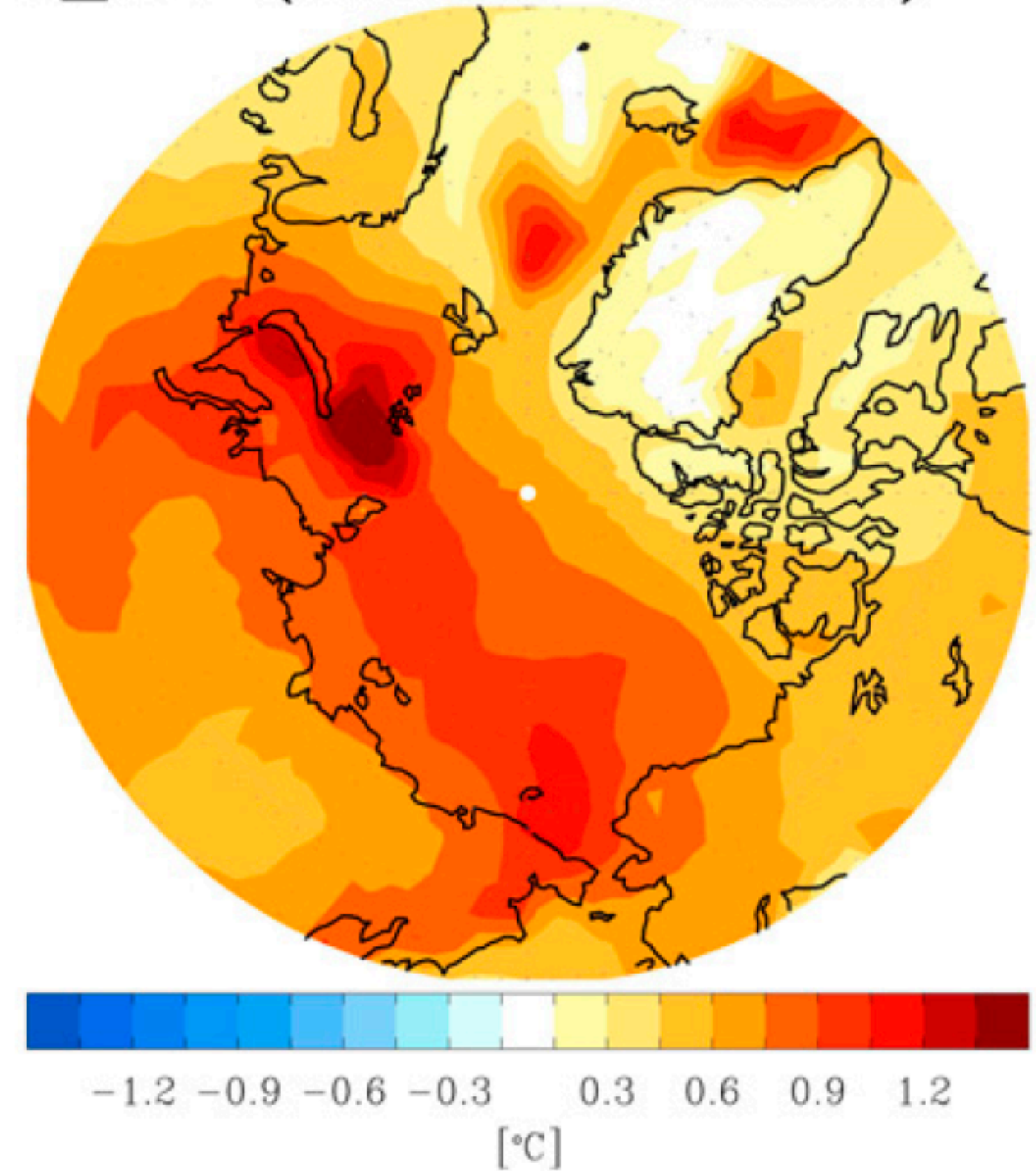
ANTHROPOGENIC CLIMATE CHANGE

Primary production

- ▶ Increase projected.
- ▶ Antarctic:
Nutrient “robbing”? Trophic amplification?
- ▶ Arctic:
Feedback phytoplankton - climate?

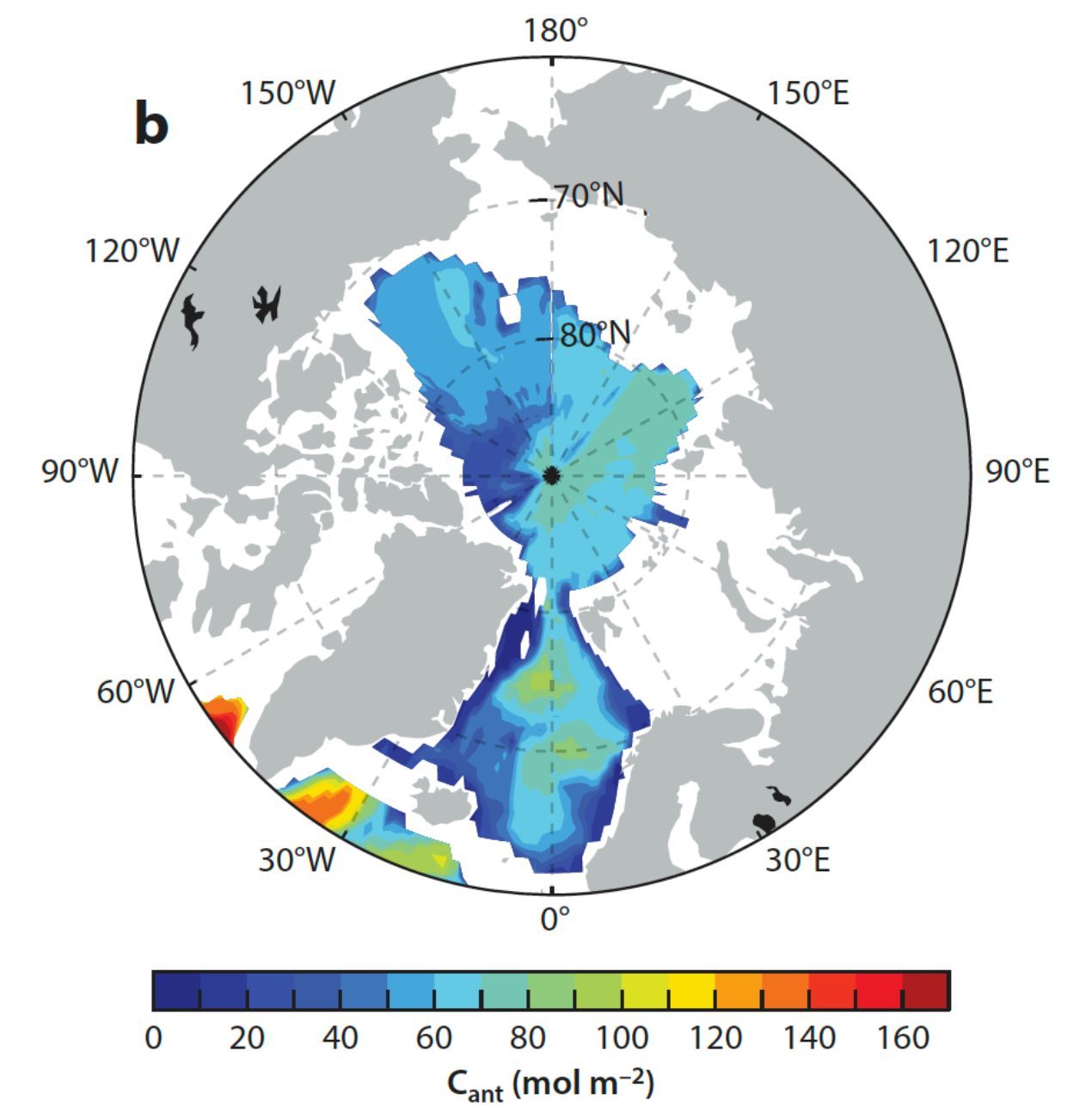
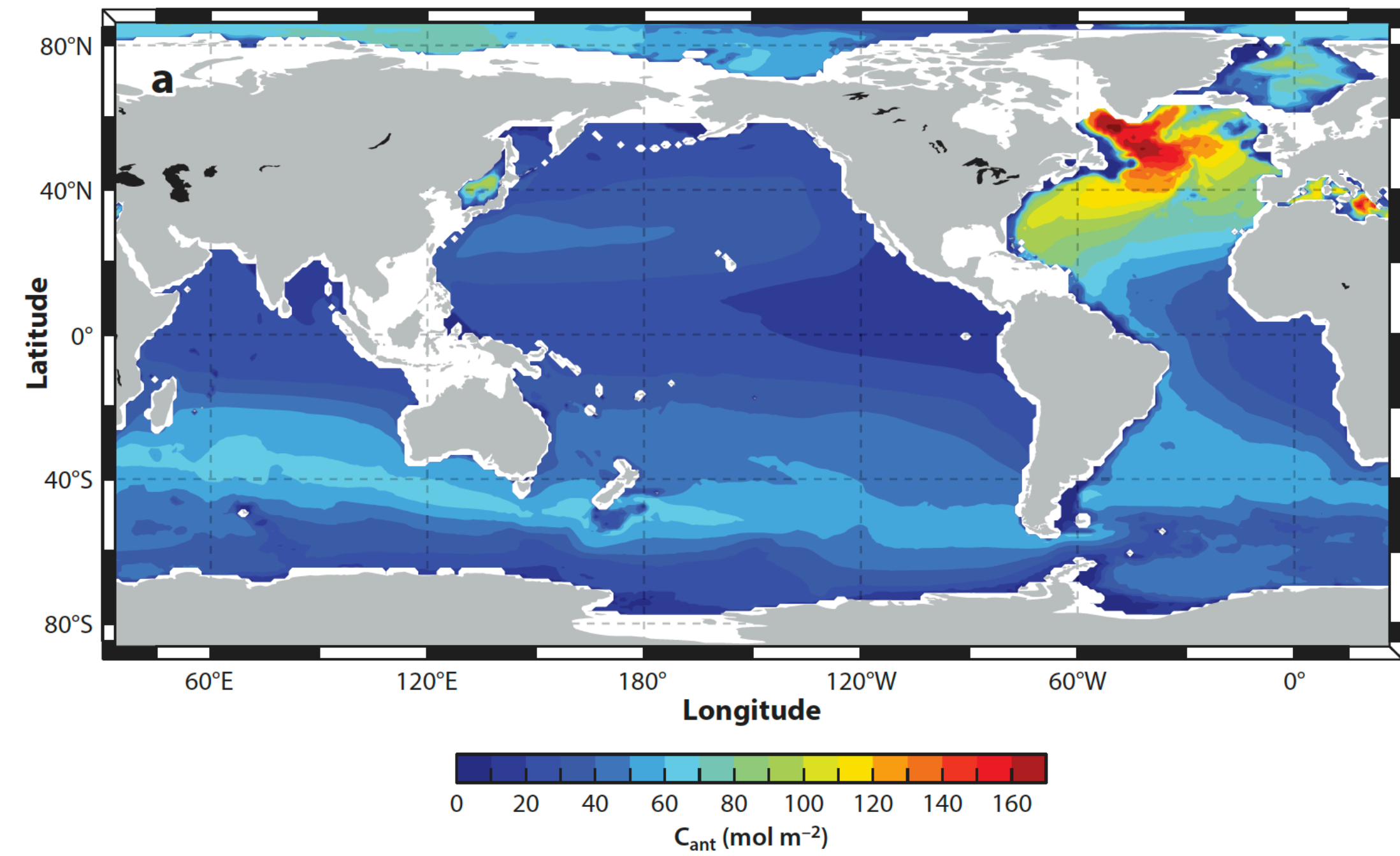
Simulation with consideration of phytoplankton effect on shortwave radiation versus not

A $T_{sfc} (ECO.on - ECO.off)$



ANTHROPOGENIC CLIMATE CHANGE

Anthropogenic carbon uptake

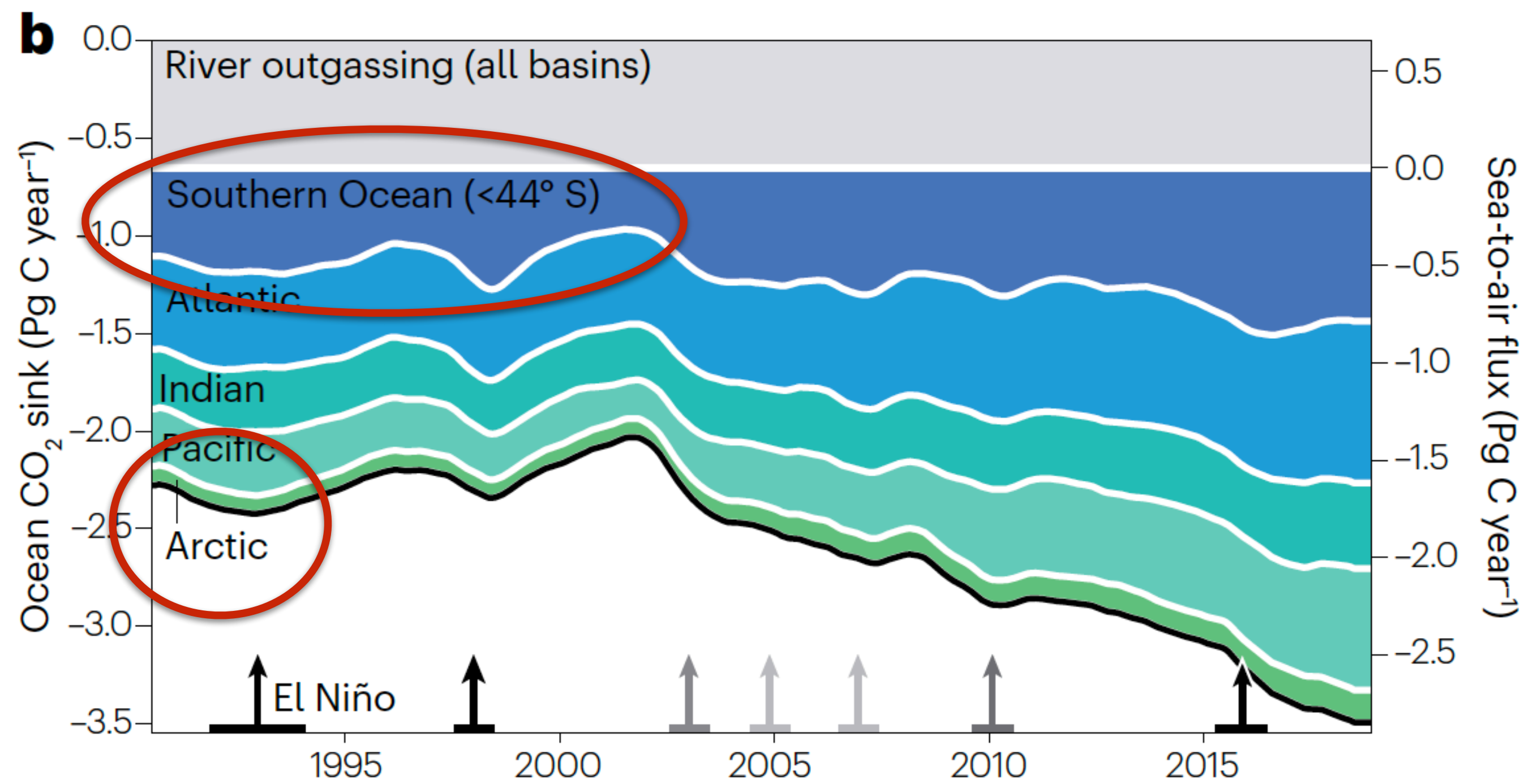


Talley et al, 2016

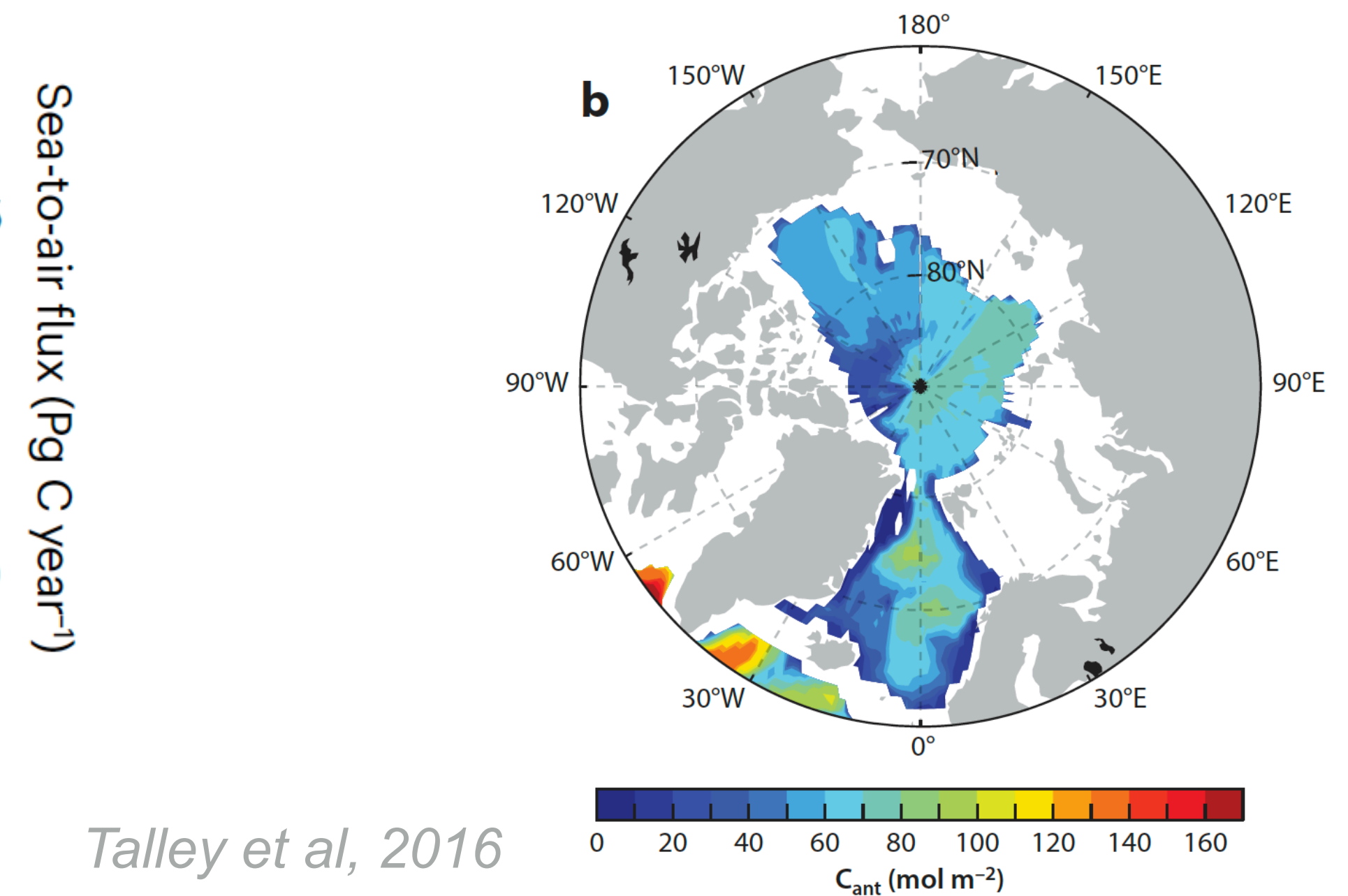
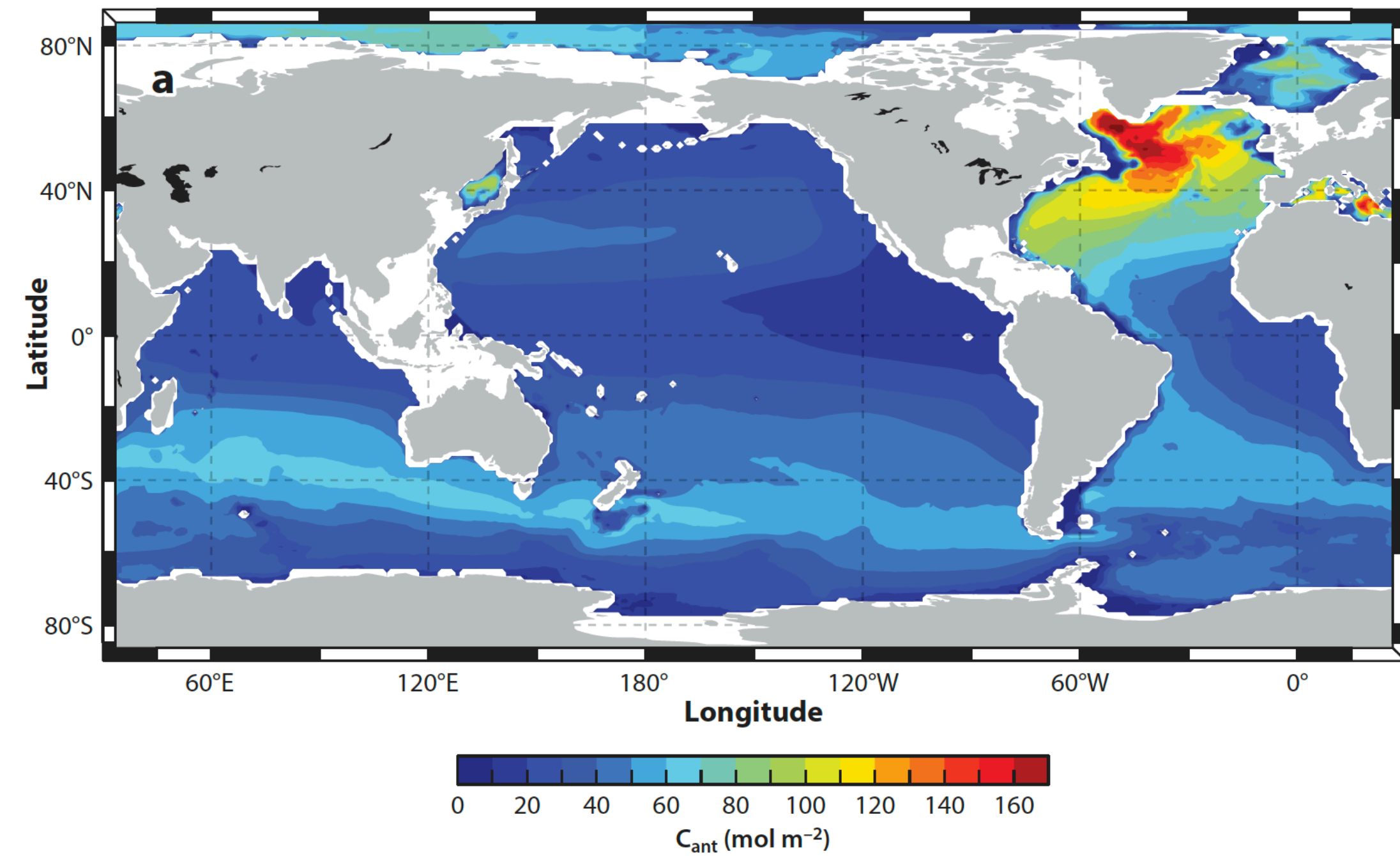
ANTHROPOGENIC CLIMATE CHANGE

Anthropogenic carbon uptake

► Southern Ocean more important than Arctic.



Gruber et al, 2023

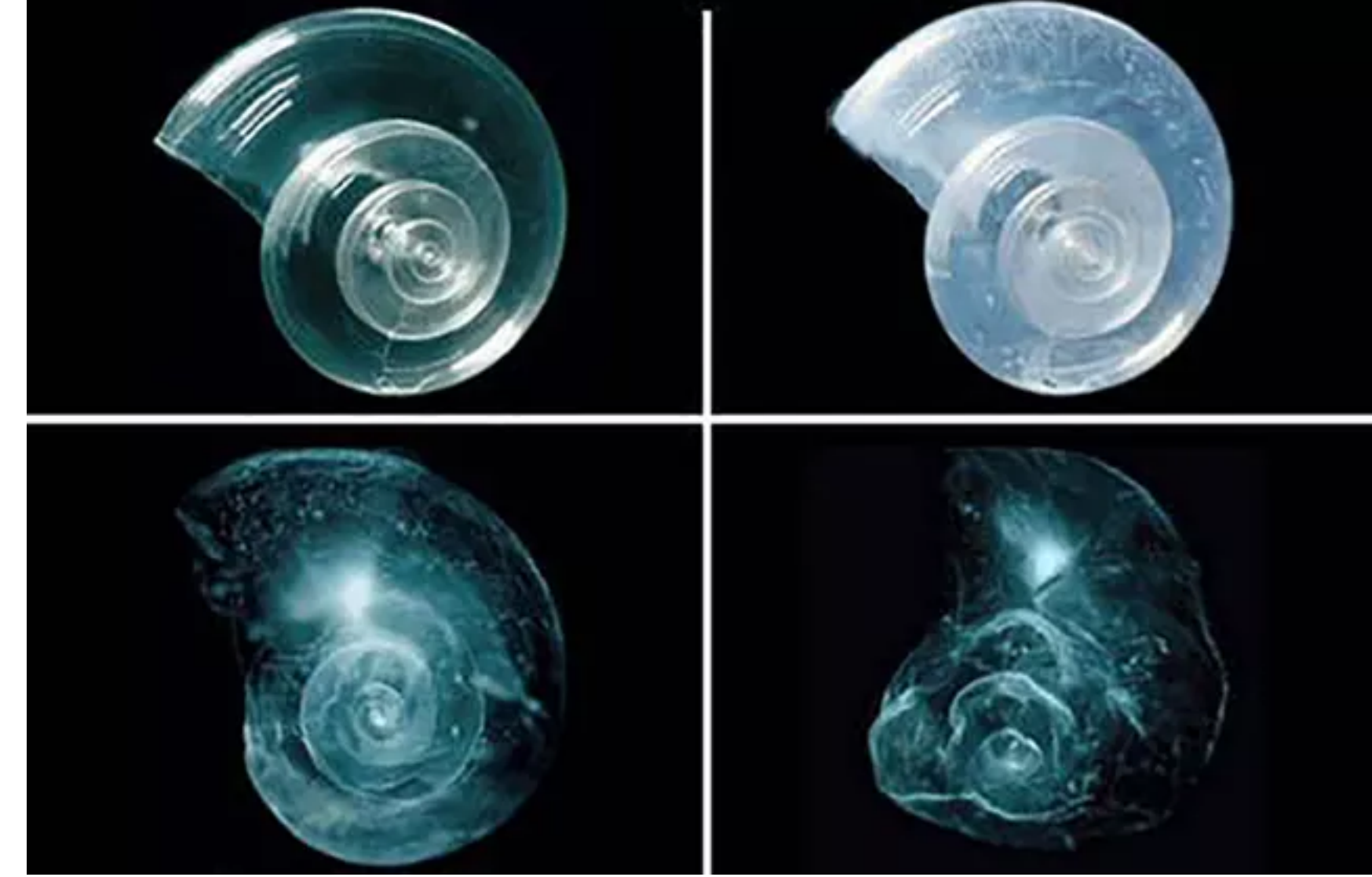


Talley et al, 2016

ANTHROPOGENIC CLIMATE CHANGE

Anthropogenic carbon uptake

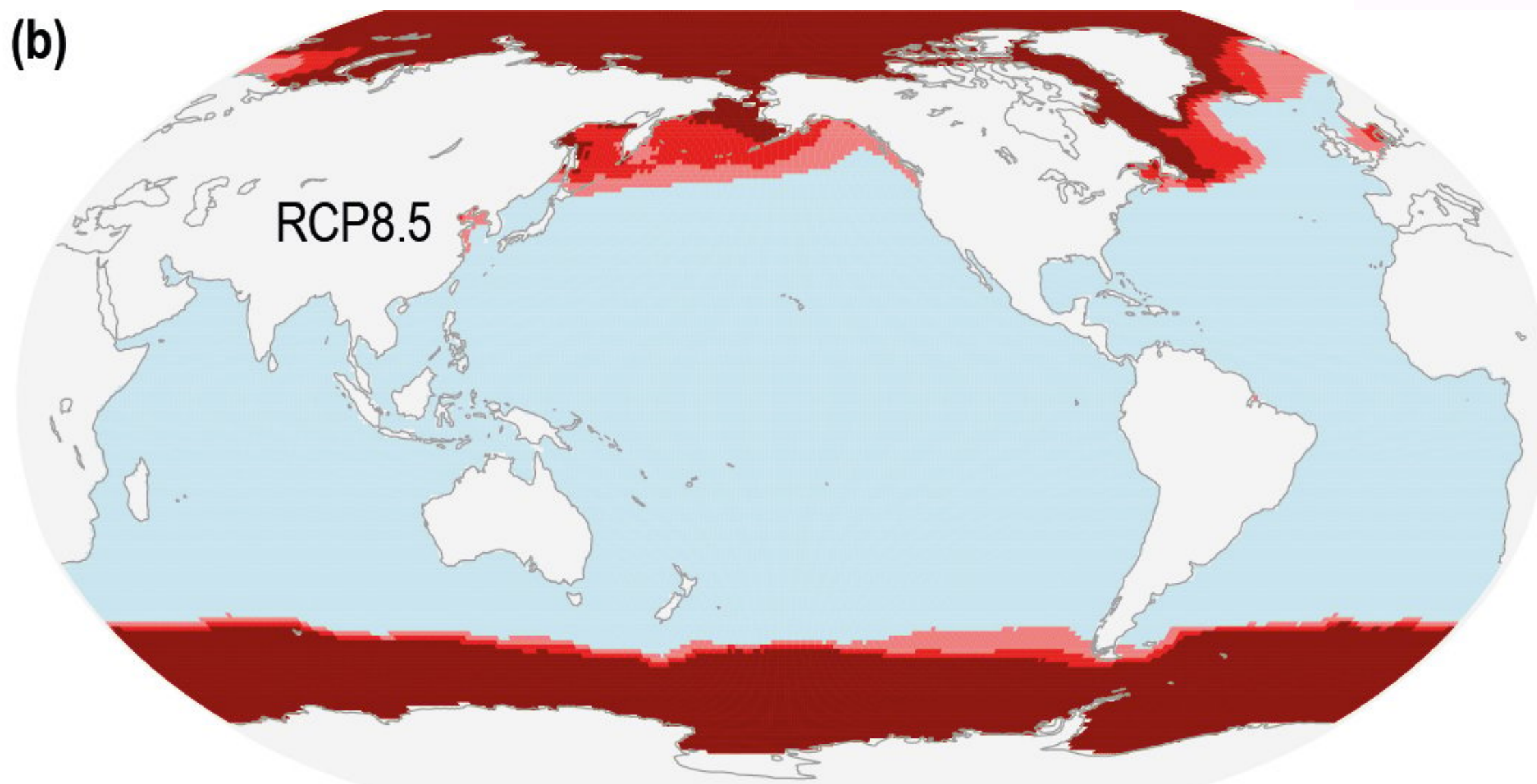
- ▶ Southern Ocean more important than Arctic.
- ▶ At the cost of acidification



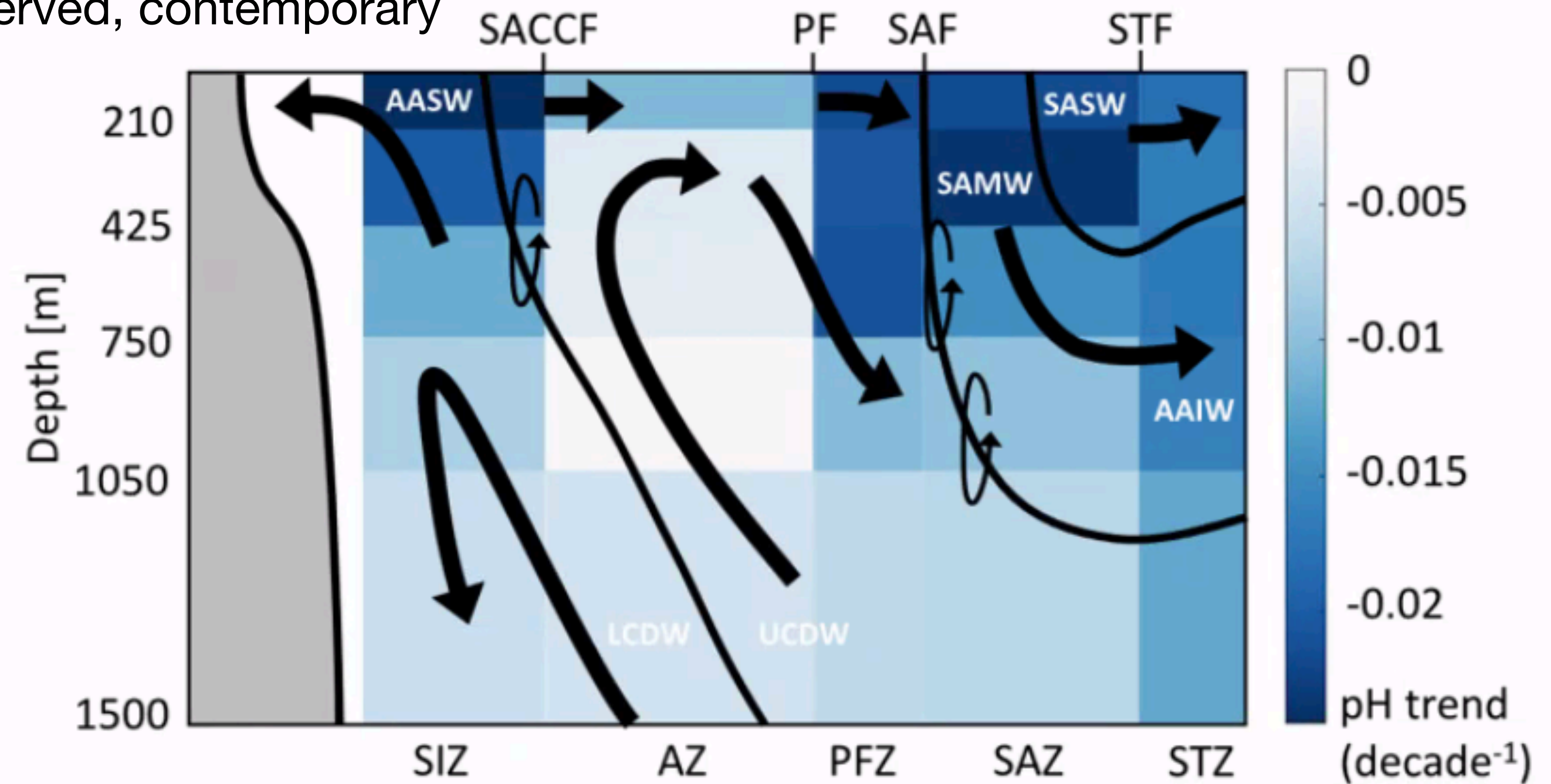
<https://www.nps.gov/articles/oceanacidification.html>

Climate models, end of century
aragonite undersaturation

(b)



Observed, contemporary



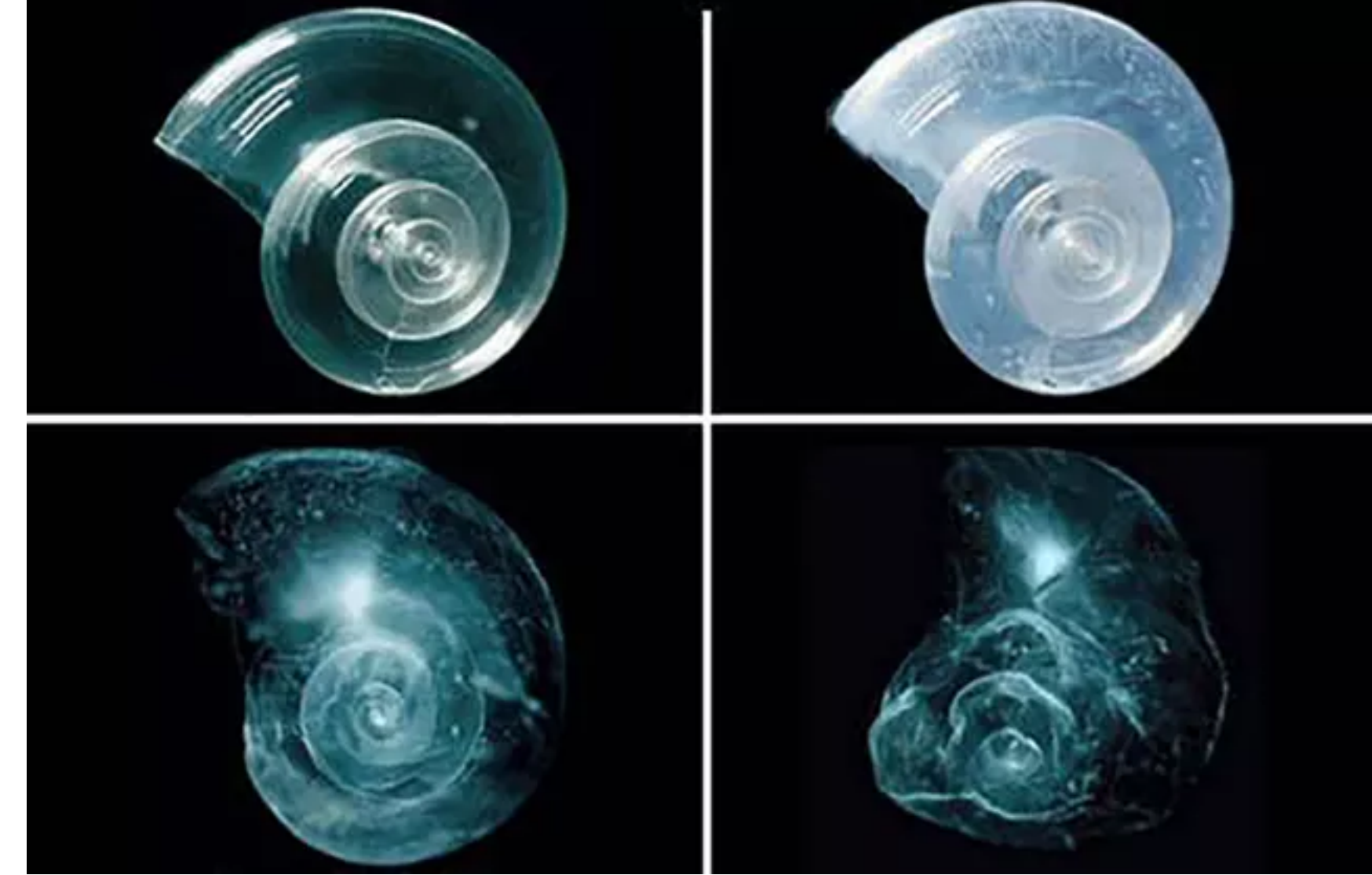
Mazloff et al, 2023

<https://www.ipcc.ch/srocc/chapter/chapter-3-2>

ANTHROPOGENIC CLIMATE CHANGE

Anthropogenic carbon uptake

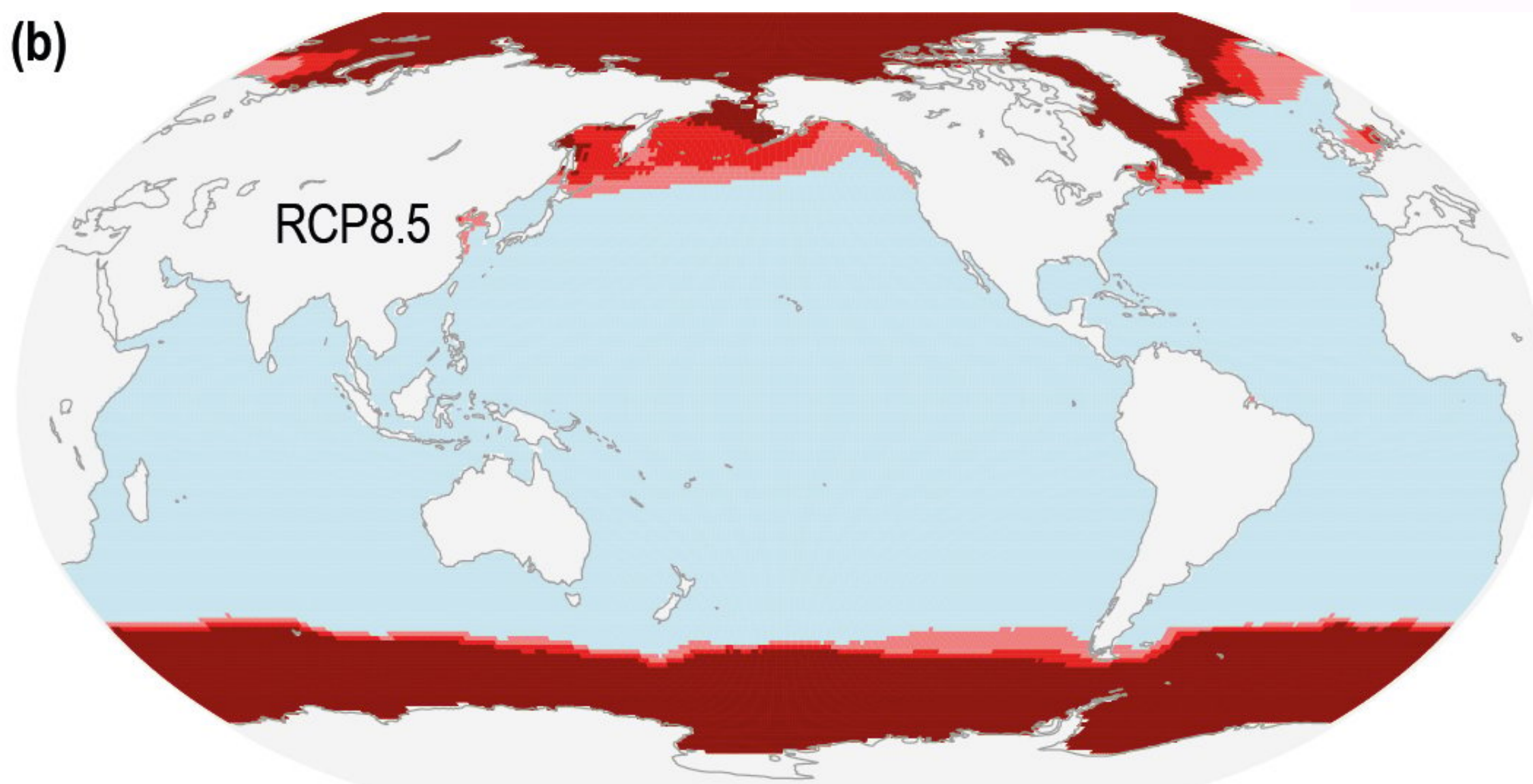
- ▶ Southern Ocean more important than Arctic.
- ▶ At the cost of acidification
- ▶ Loss of oxygen



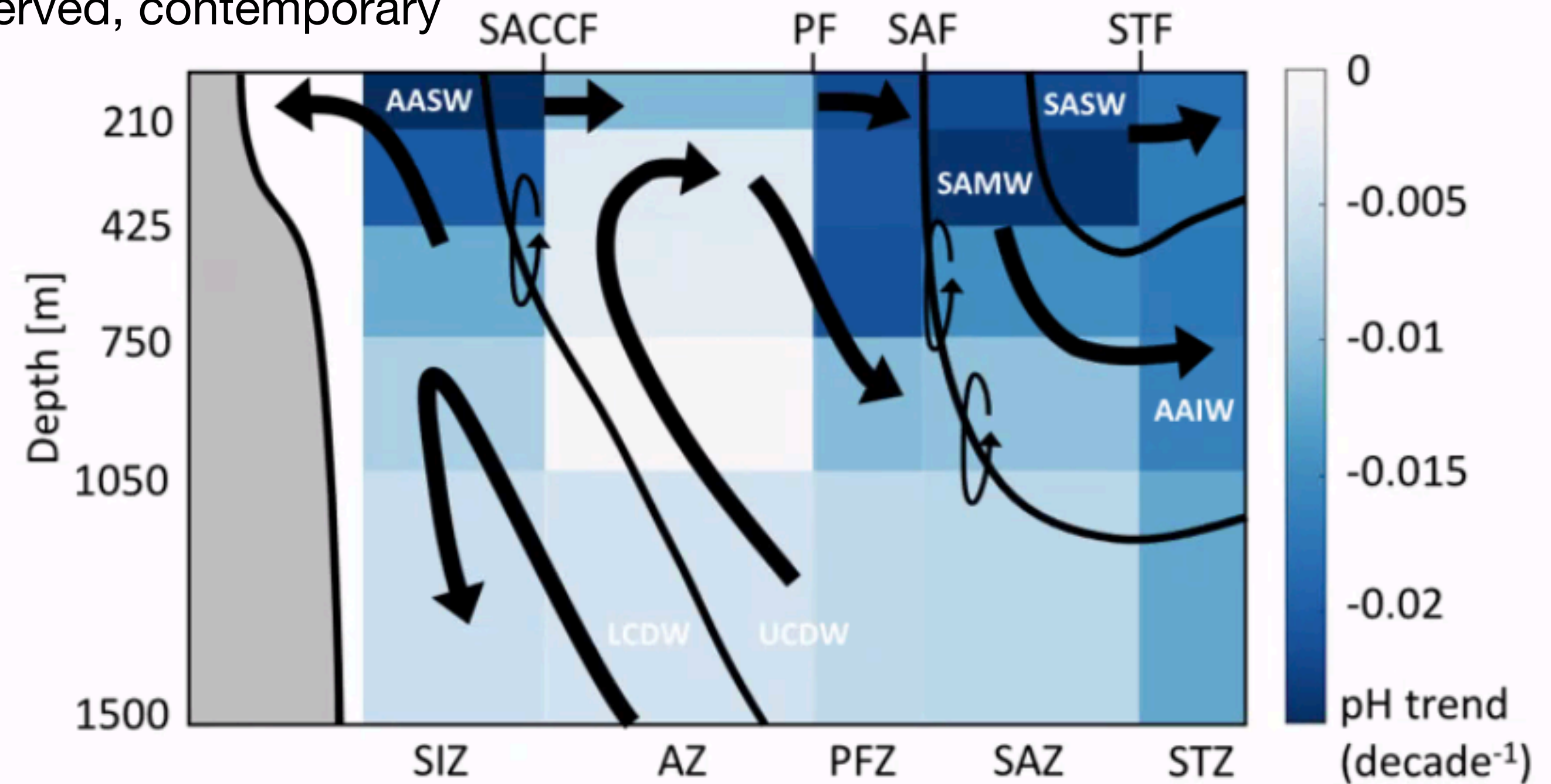
<https://www.nps.gov/articles/oceanacidification.html>

Climate models, end of century
aragonite undersaturation

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Observed, contemporary



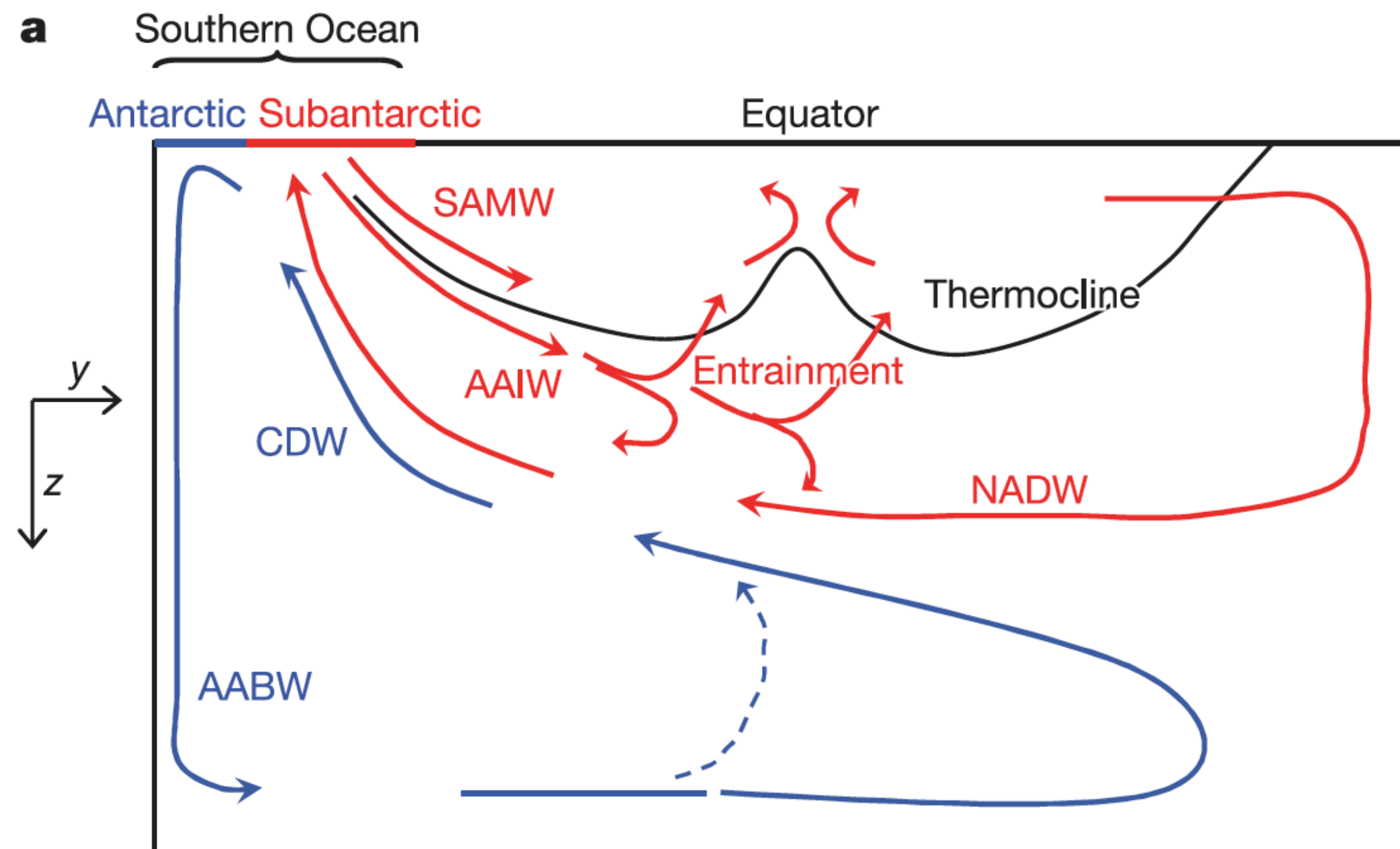
Mazloff et al, 2023

<https://www.ipcc.ch/srocc/chapter/chapter-3-2>

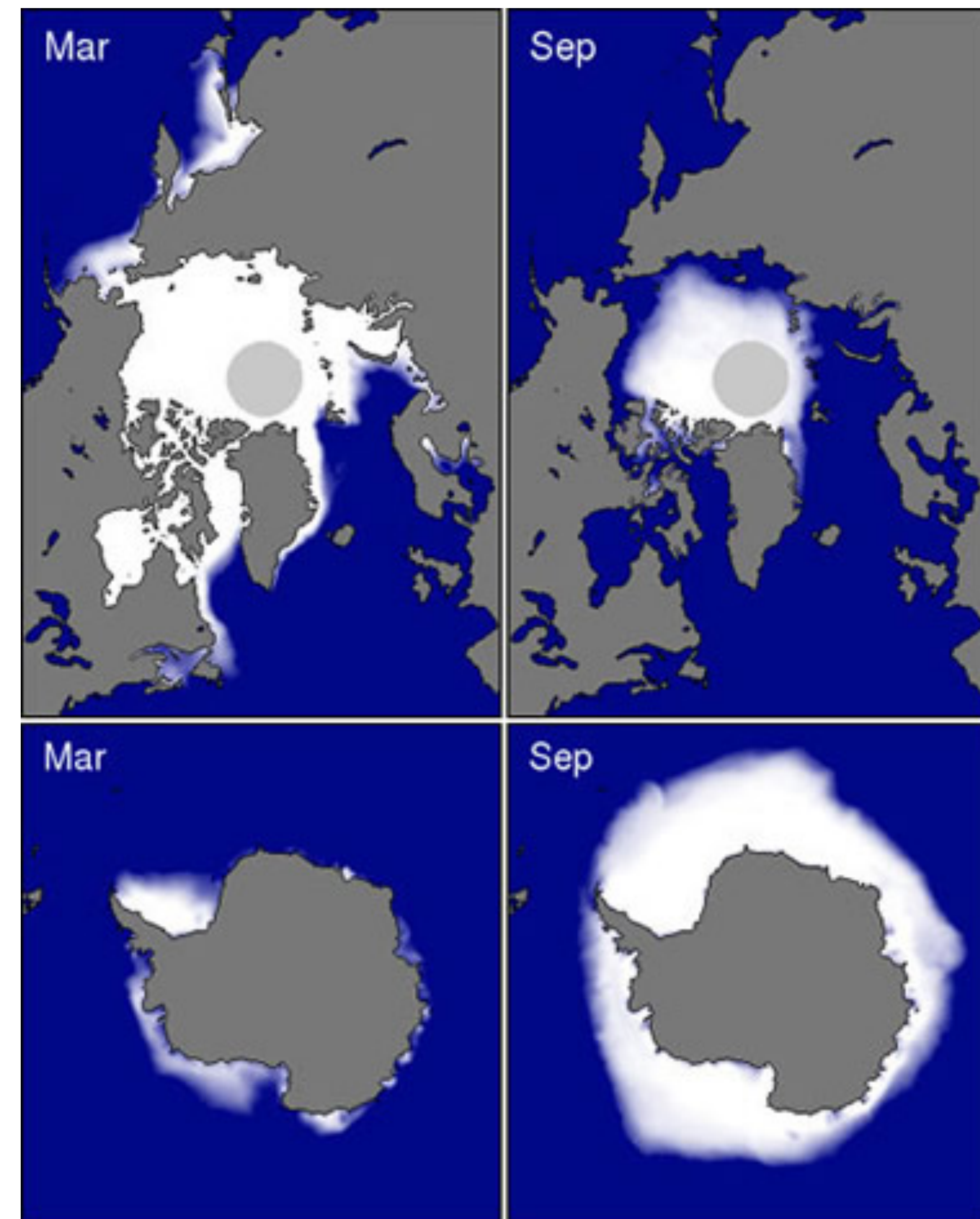
ANTHROPOGENIC CLIMATE CHANGE

Anthropogenic carbon uptake

- ▶ Southern Ocean more important than Arctic.
- ▶ At the cost of acidification
- ▶ Changes of biogeochemical divide?



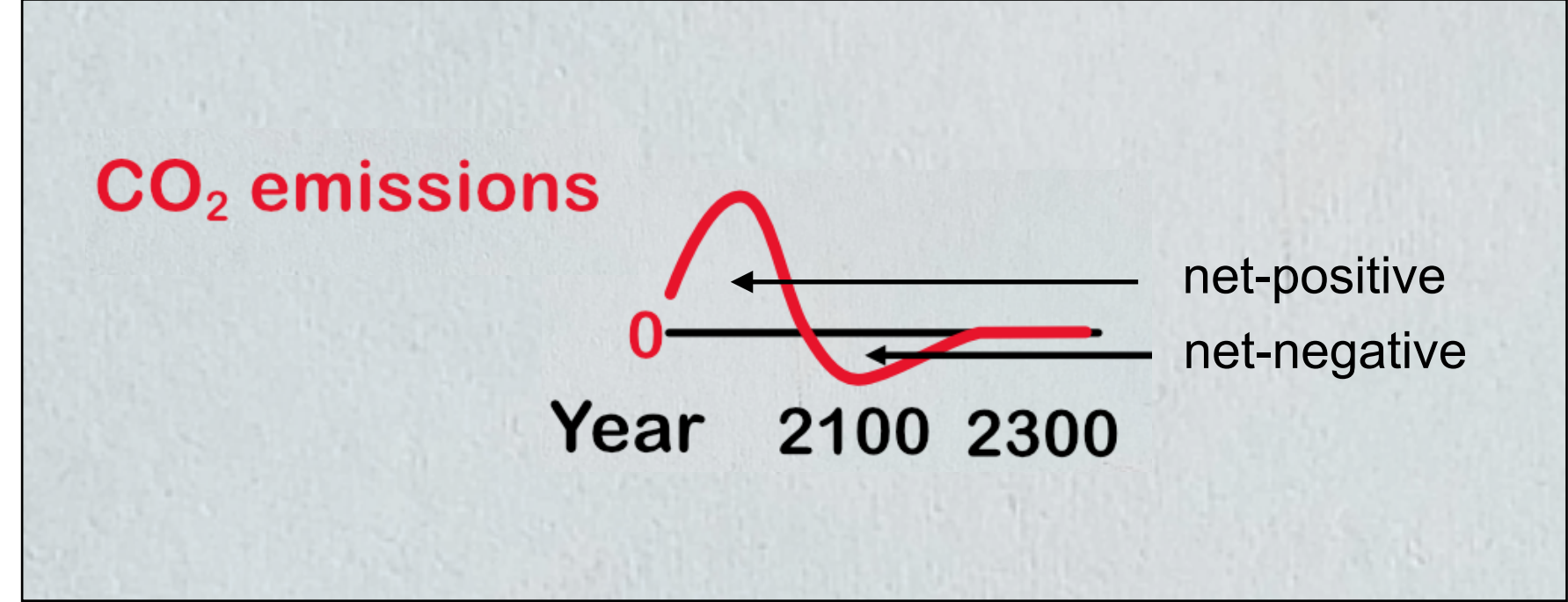
Marinov et al, 2006



...

ANTHROPOGENIC CLIMATE CHANGE

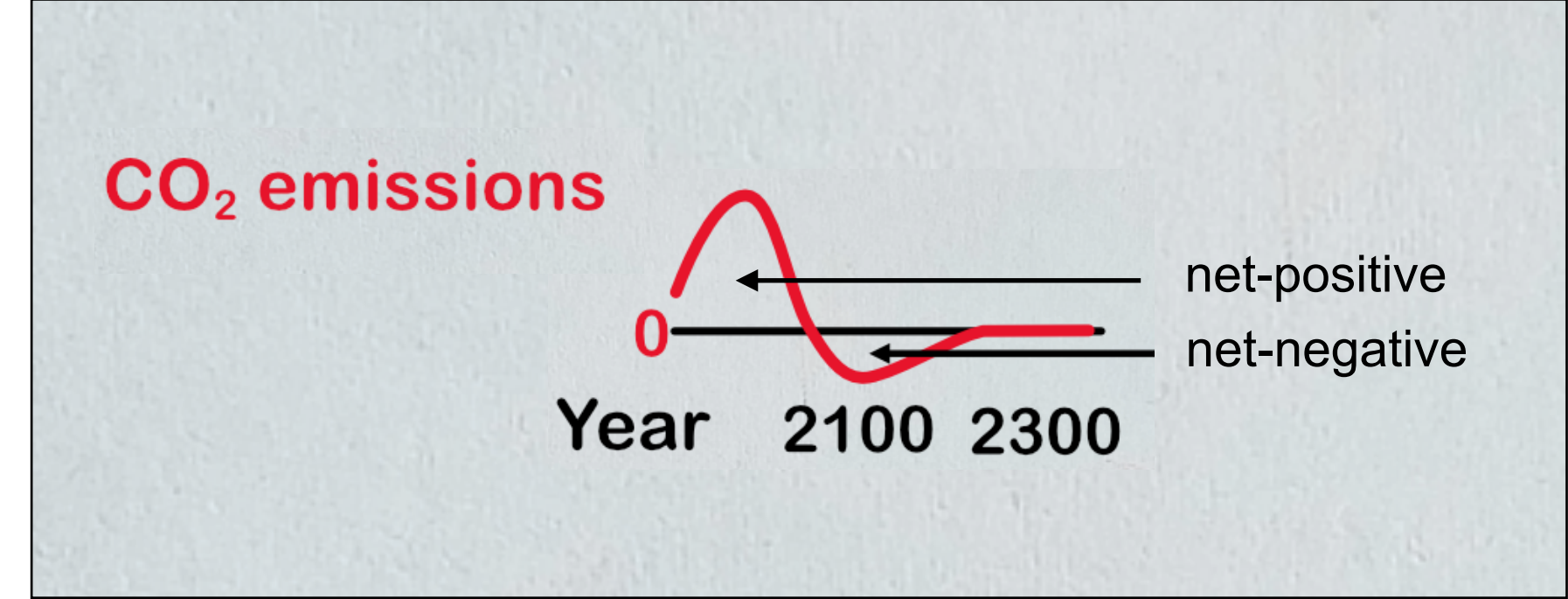
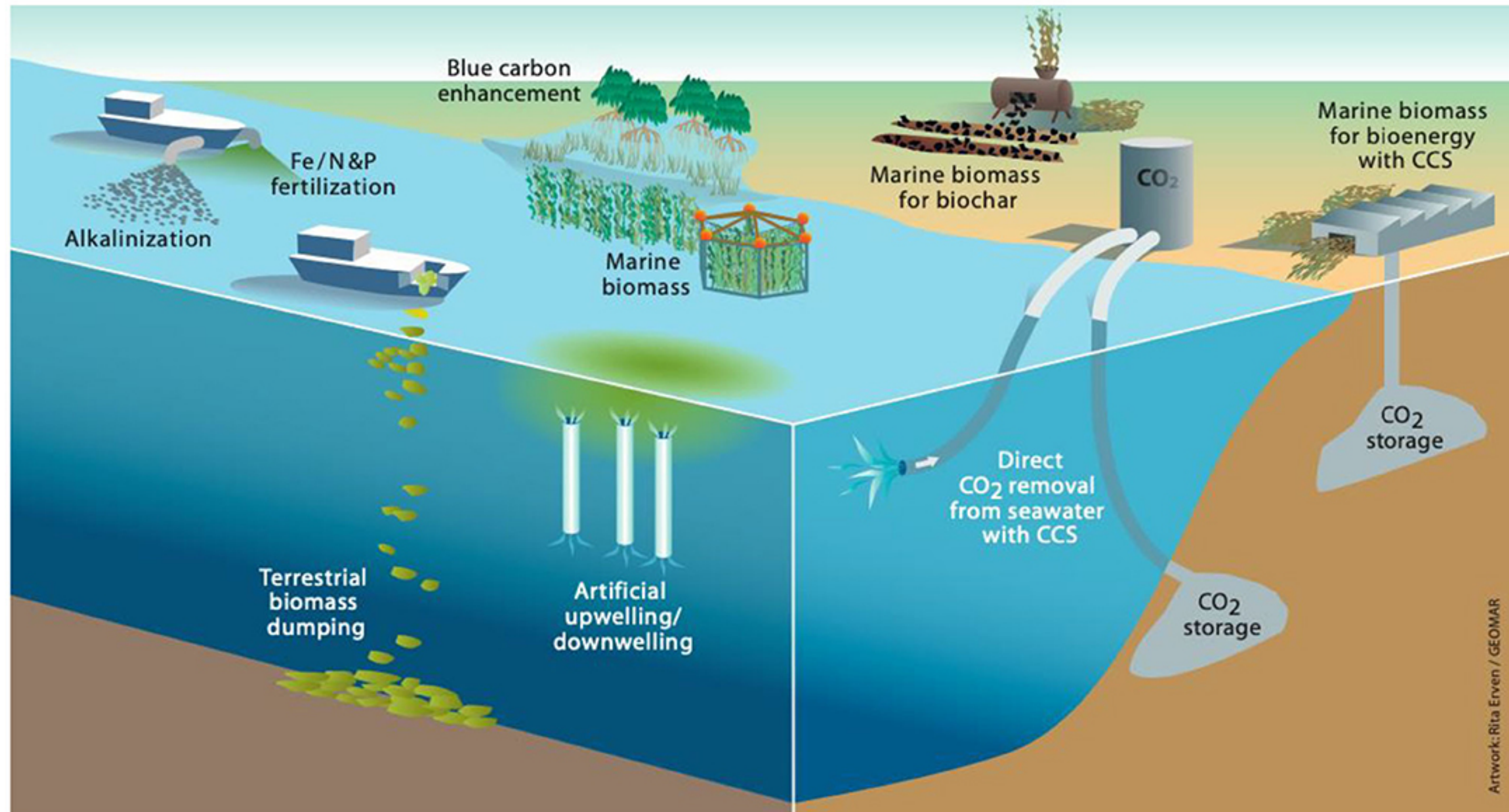
Beyond increasing CO2 emissions



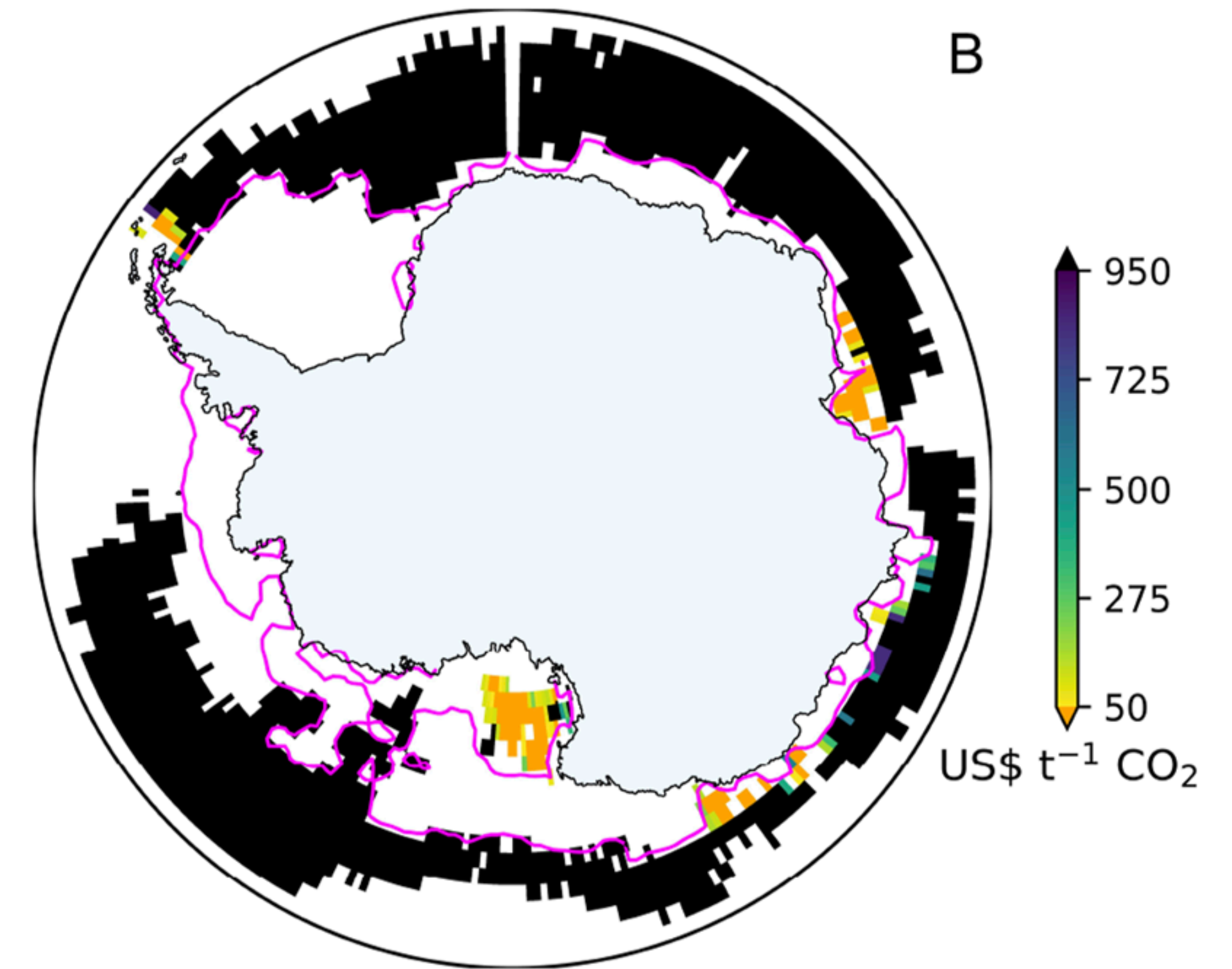
ANTHROPOGENIC CLIMATE CHANGE

Beyond increasing CO2 emissions

- How to get there: carbon dioxide removal (CDR)
Example Antarctic



Engineering biology: Iron fertilization



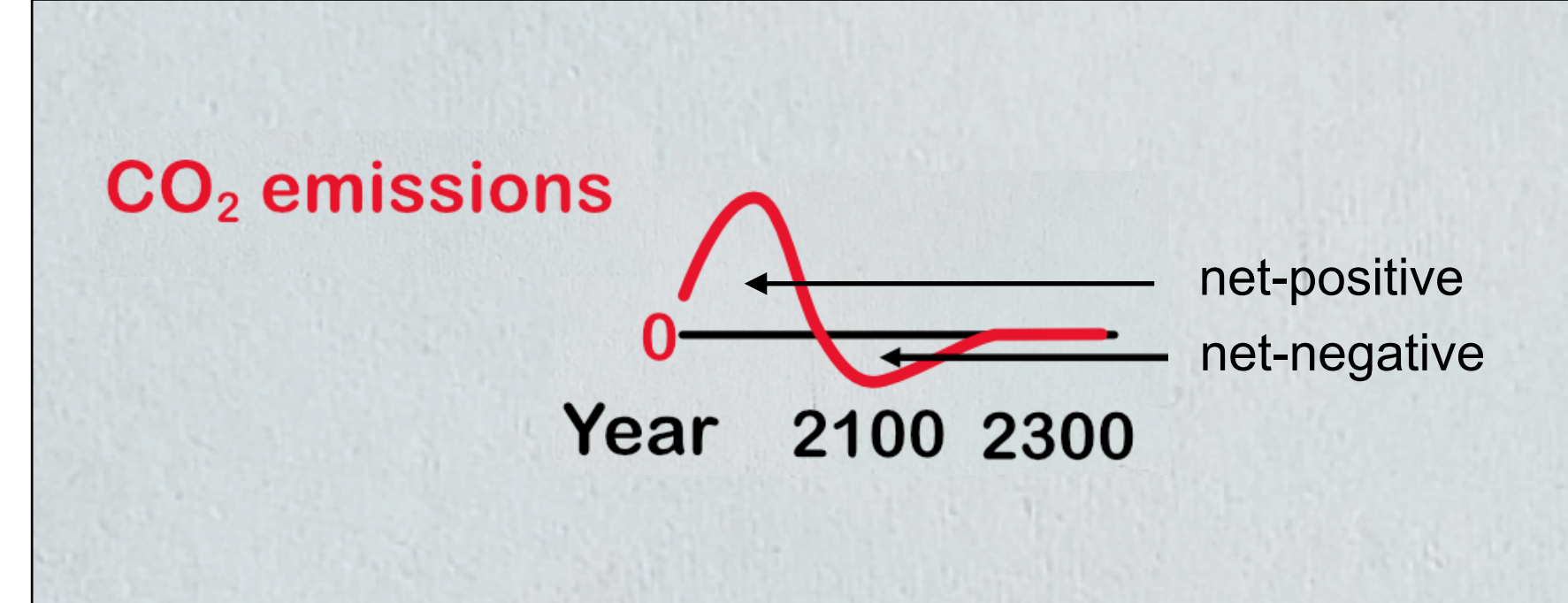
Boettcher et al, 2021

Bach et al, 2023

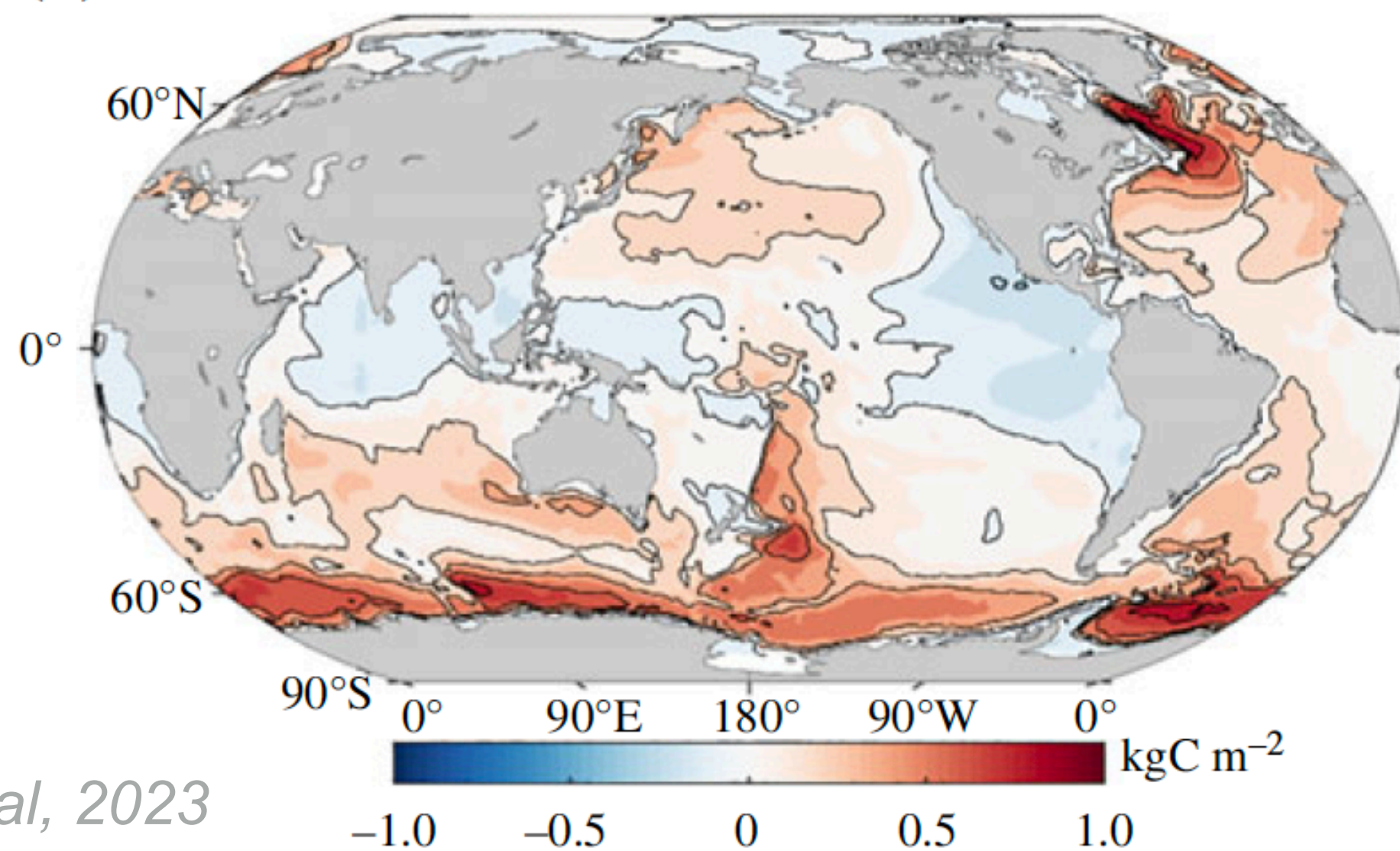
ANTHROPOGENIC CLIMATE CHANGE

Beyond increasing CO₂ emissions

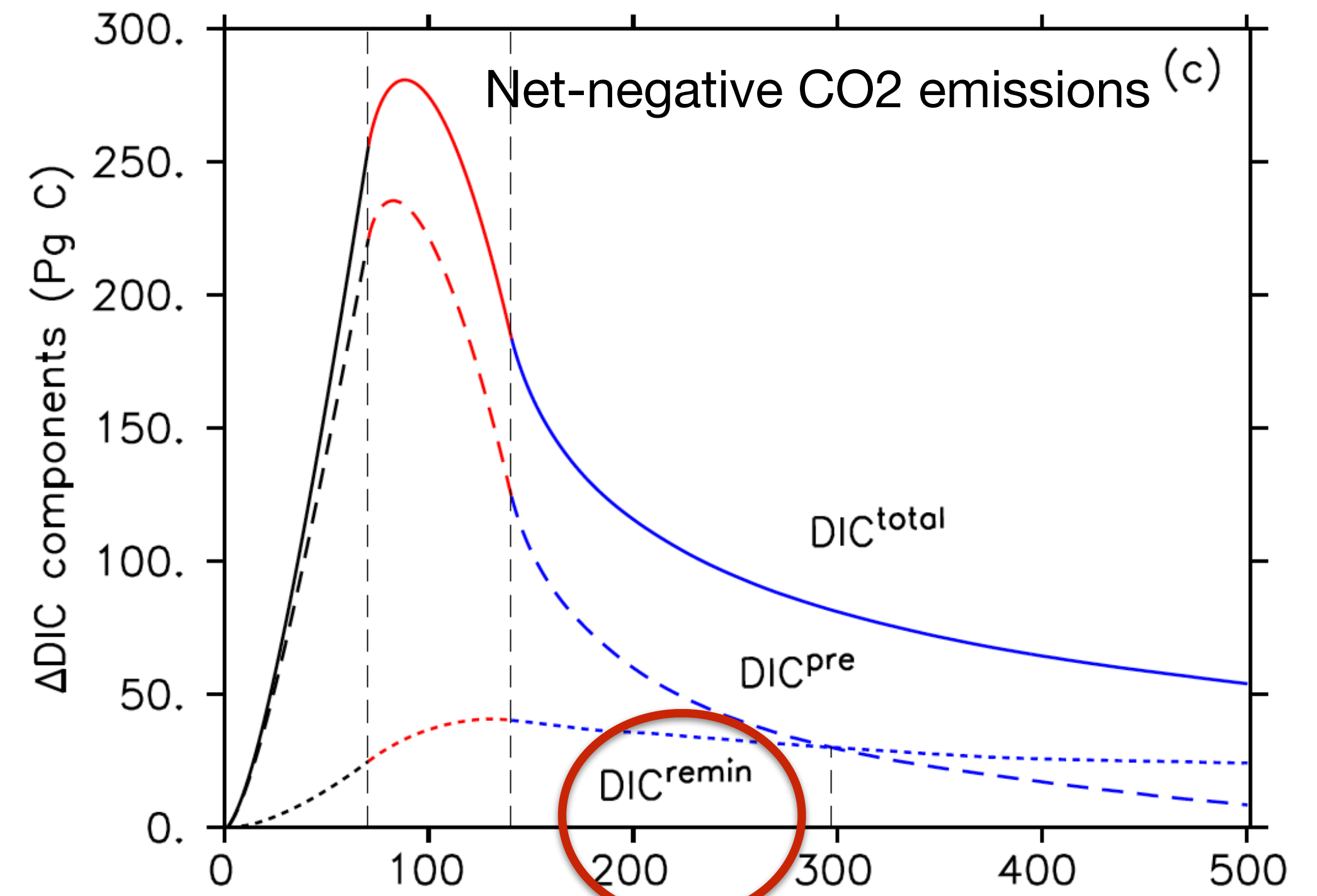
- ▶ How to get there: carbon dioxide removal (CDR)
Example Antarctic
- ▶ Under net-negative CO₂ emissions:
- how is carbon retained in the ocean, or lost from the ocean?



(d) regenerated carbon storage due to climate change



Williams et al, 2023



Biologically processed carbon

Koeve et al, accepted

Background

Characteristics

Global relevance

Anthropogenic climate change

-> up next: sea-ice biogeochemistry