Paleoclimate

source: NASA

Link to Slides

Yesterday's Summary

Yesterday's Summary

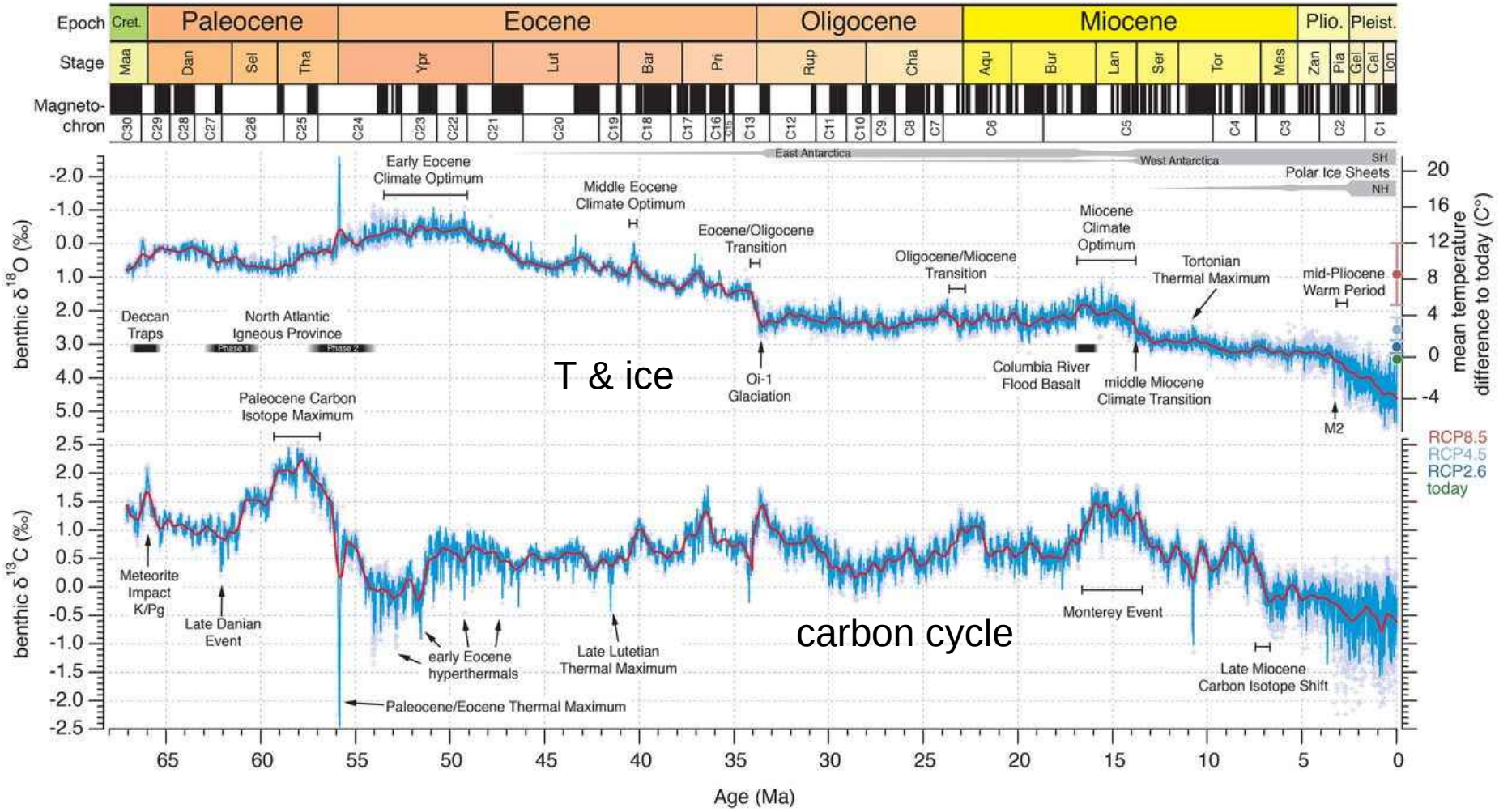
- Eocene Hothouse was very hot
- Equable climate led to warm poles
- PETM was extreme warm event caused by GHG

- Cenozoic climate dominated by CO_2

- Cooling was accompanied by CO_2 reduction and changes in weathering and fauna

- Temperature proxies: $\delta^{18}O$, $\Delta 47$, Mg/Ca, TEX86
- Carbon proxies: $\delta^{13}C$ & $\delta^{11}B$

additional info: PETM

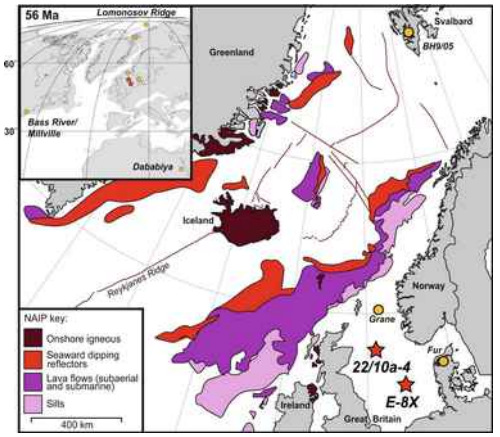


CENOGRID
Westerhold et al. (2020), Science

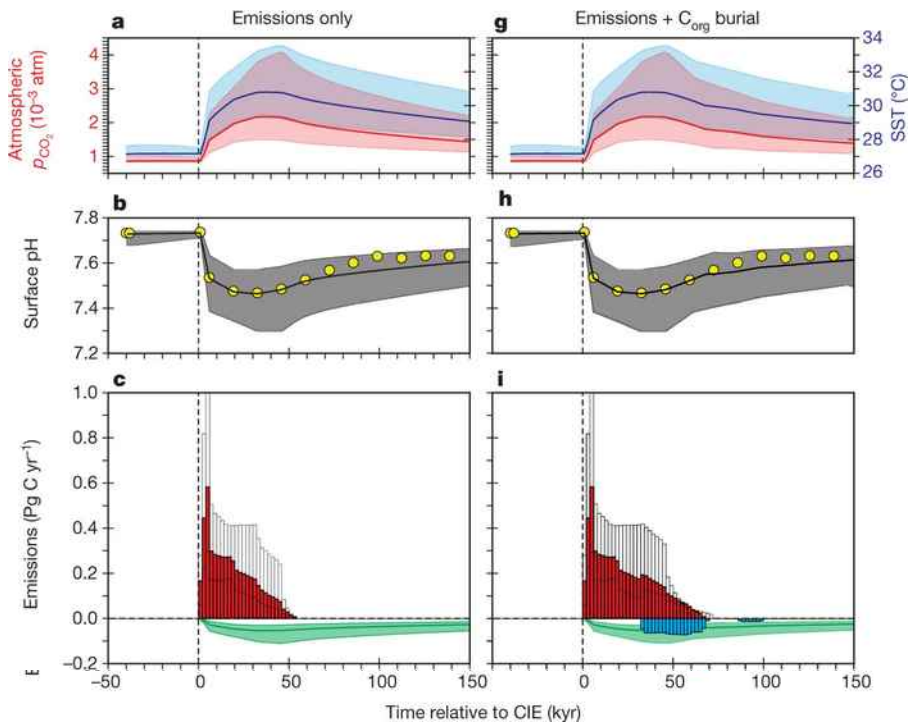
additional info: PETM

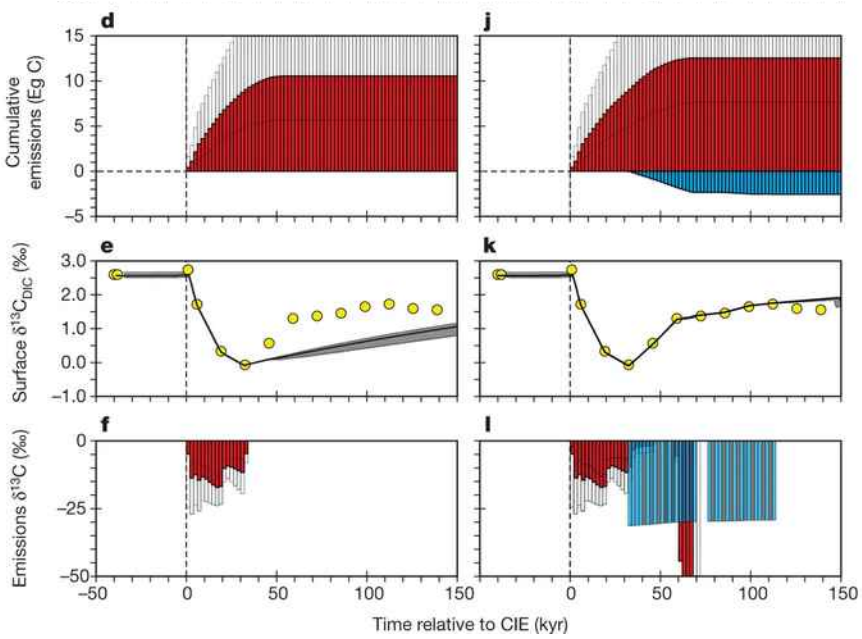
North Atlantic Igneous Province

visitbelfast.com



Kender et al. (2021), Nat. Comm.

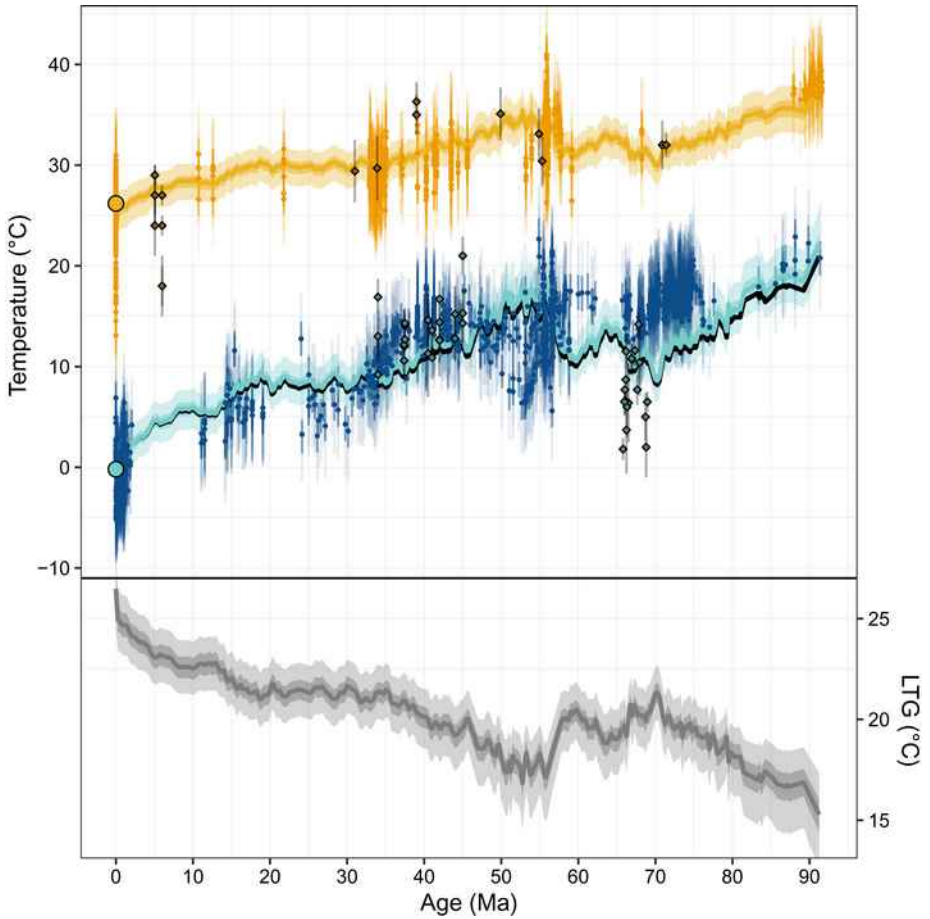


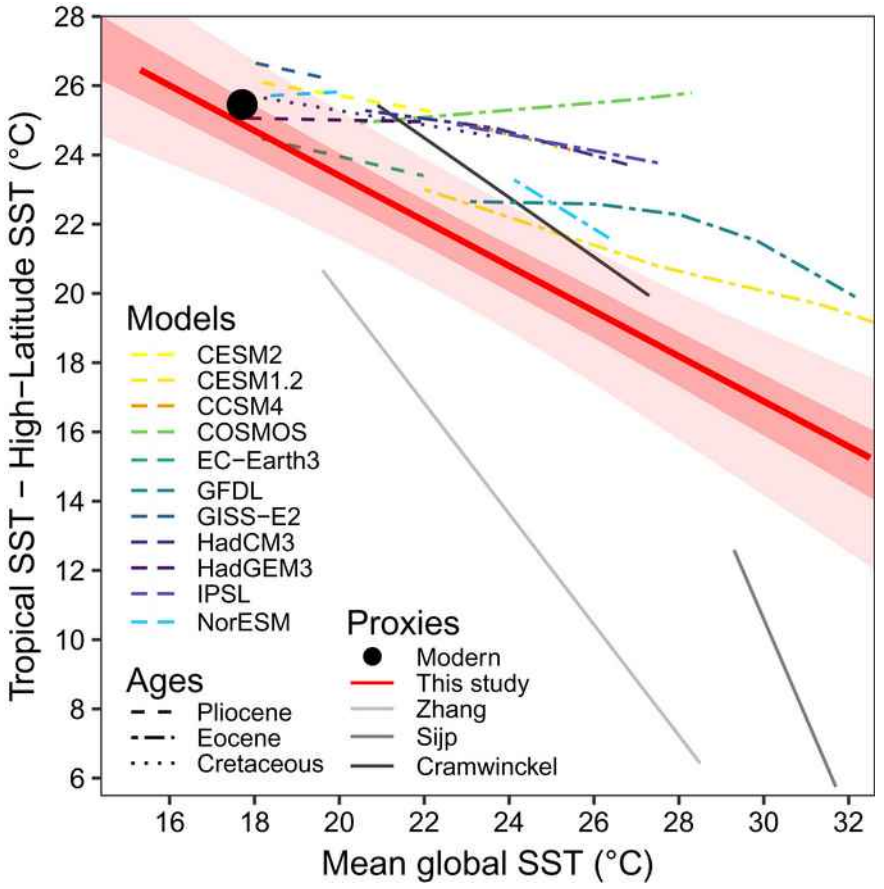


modern emissions: ~ 10 PgC/yr

Gutjahr et al. (2017), Nature

additional info: lat. T gradients





polar amplification factor ~ 1.5

Gaskell et al. (2022)
PNAS

source: NASA Earth Observatory

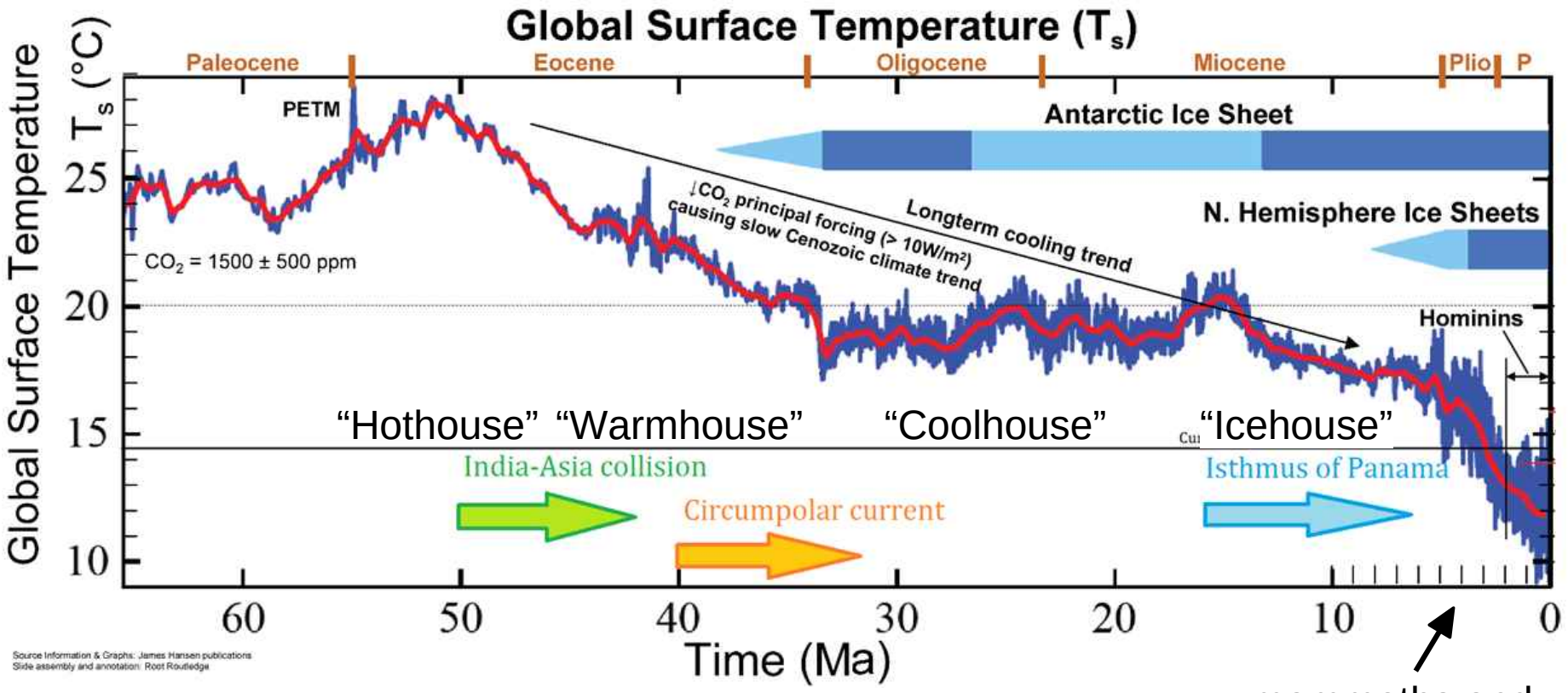
Lecture Progress

Monday	Introduction	Earth History
Tuesday	Proxies I	Cenozoic Hot & Warm House
Wednesday	Specific Climate System components	Pleistocene G-IG climate
Thursday	Proxies II & Climate System Interactions	Abrupt Climate Change
Friday	Current Climate Change	Future & Synthesis

Today's Overview

- Pleistocene Climate
- Glacial-Interglacial Cycles
- Glacial Ice Sheets
- The oceans in the climate system
  - ocean surface
  - deep ocean
  - ocean biochemistry
- Orbital Forcing
- The Mid-Pleistocene Transition

Cenozoic Climate



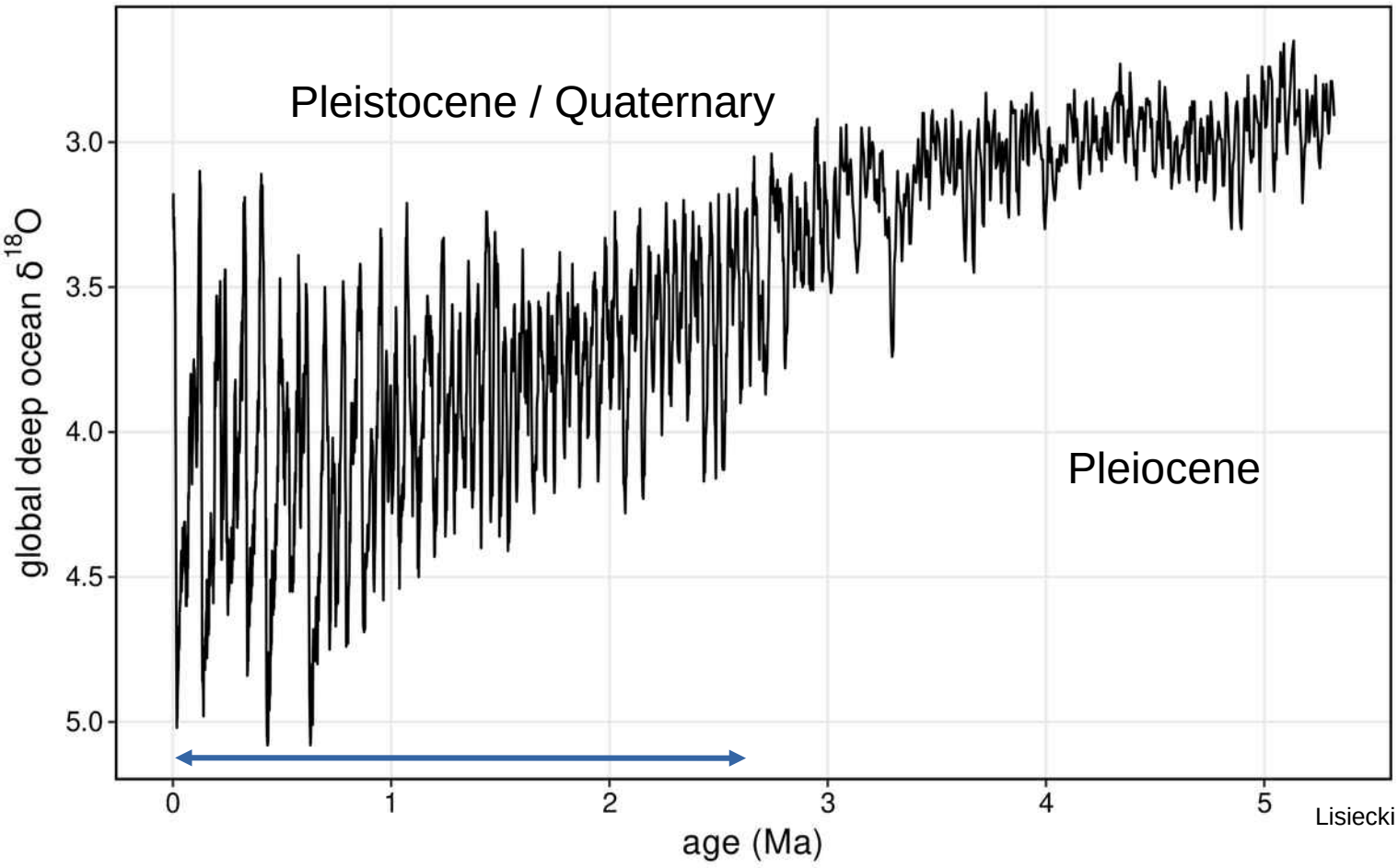
modern mammals

mammoths and saber-toothed cats

better records with plenty marine sediment cores

Earle (2016), opentextbc.ca
after James Hansen and Root Routledge

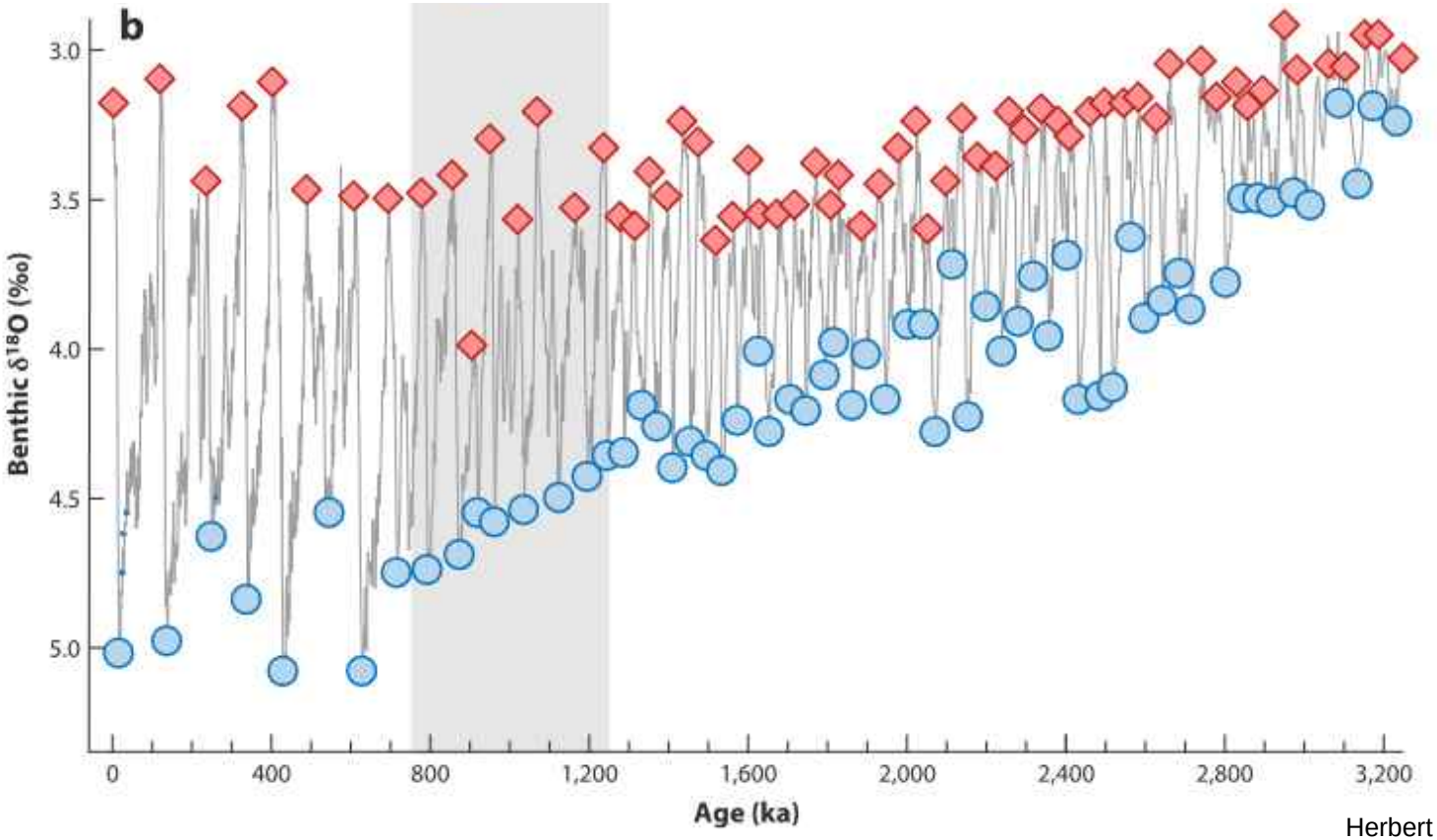
Plio-Pleistocene Climate



Lisiecki & Raymo 2004

Plio-Pleistocene Climate

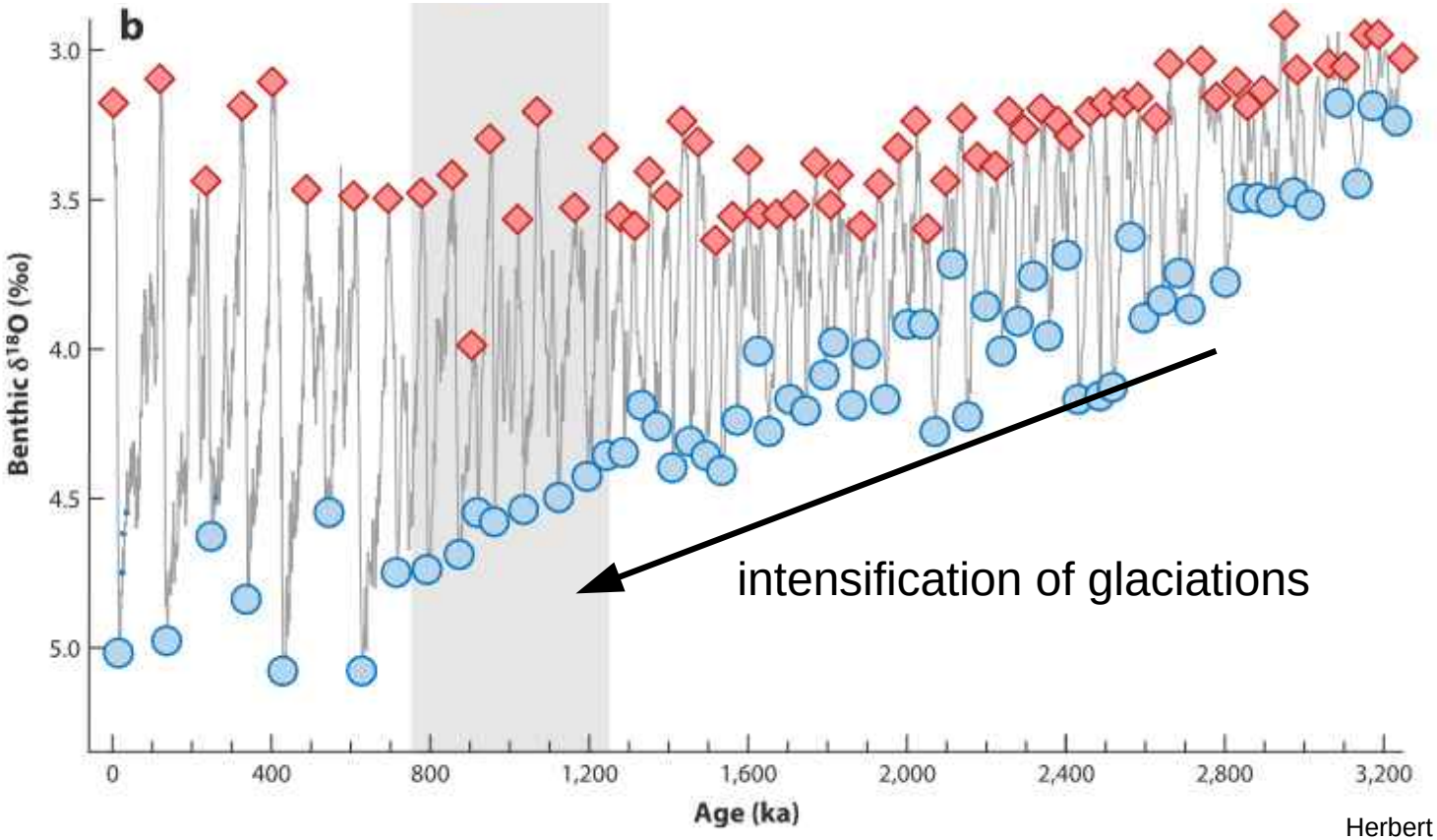
^{18}O in peak glacials vs. interglacials



Herbert 2015

Pleistocene Climate

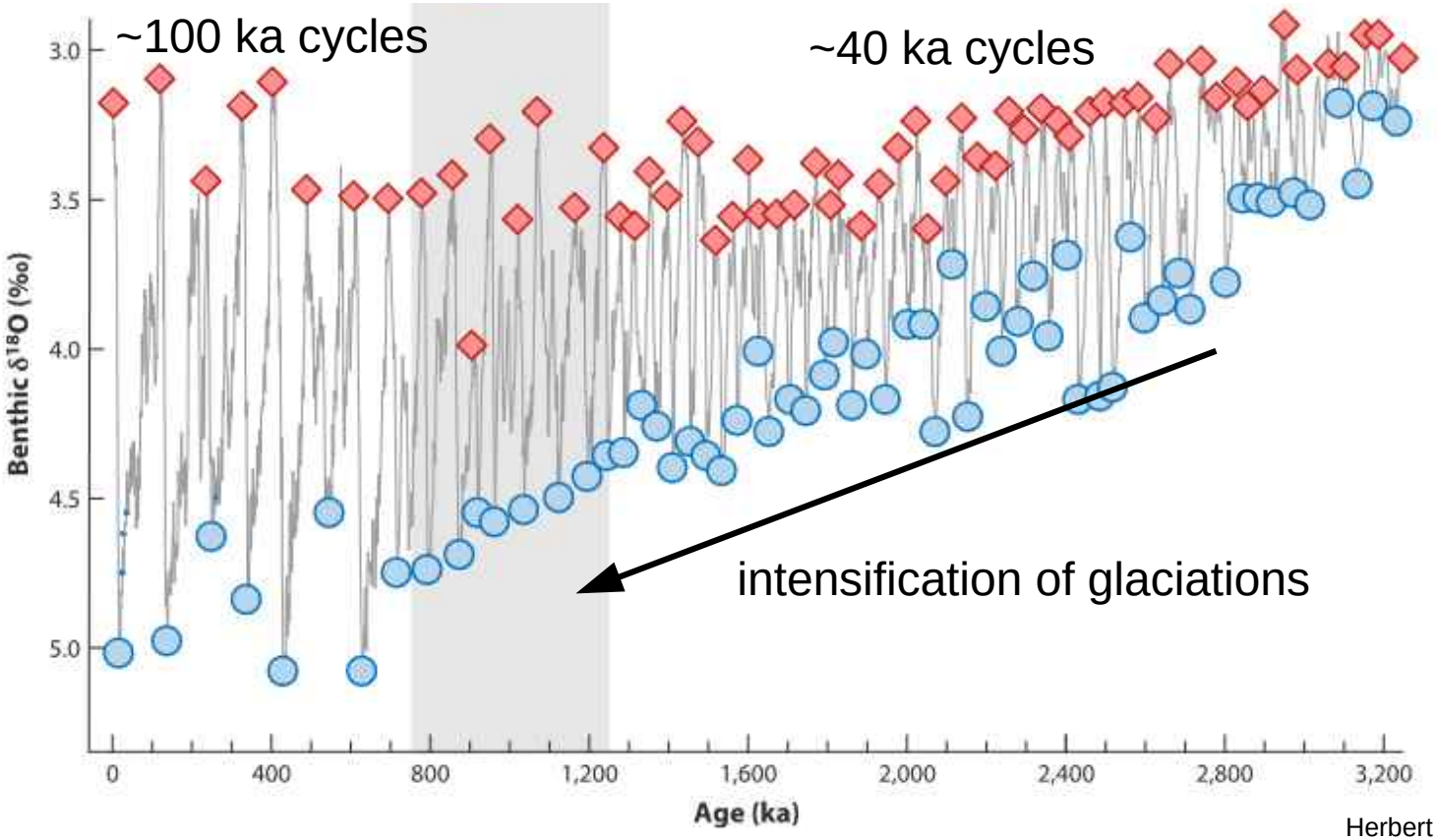
^{18}O in peak glacials vs. interglacials



Herbert 2015

Pleistocene Climate

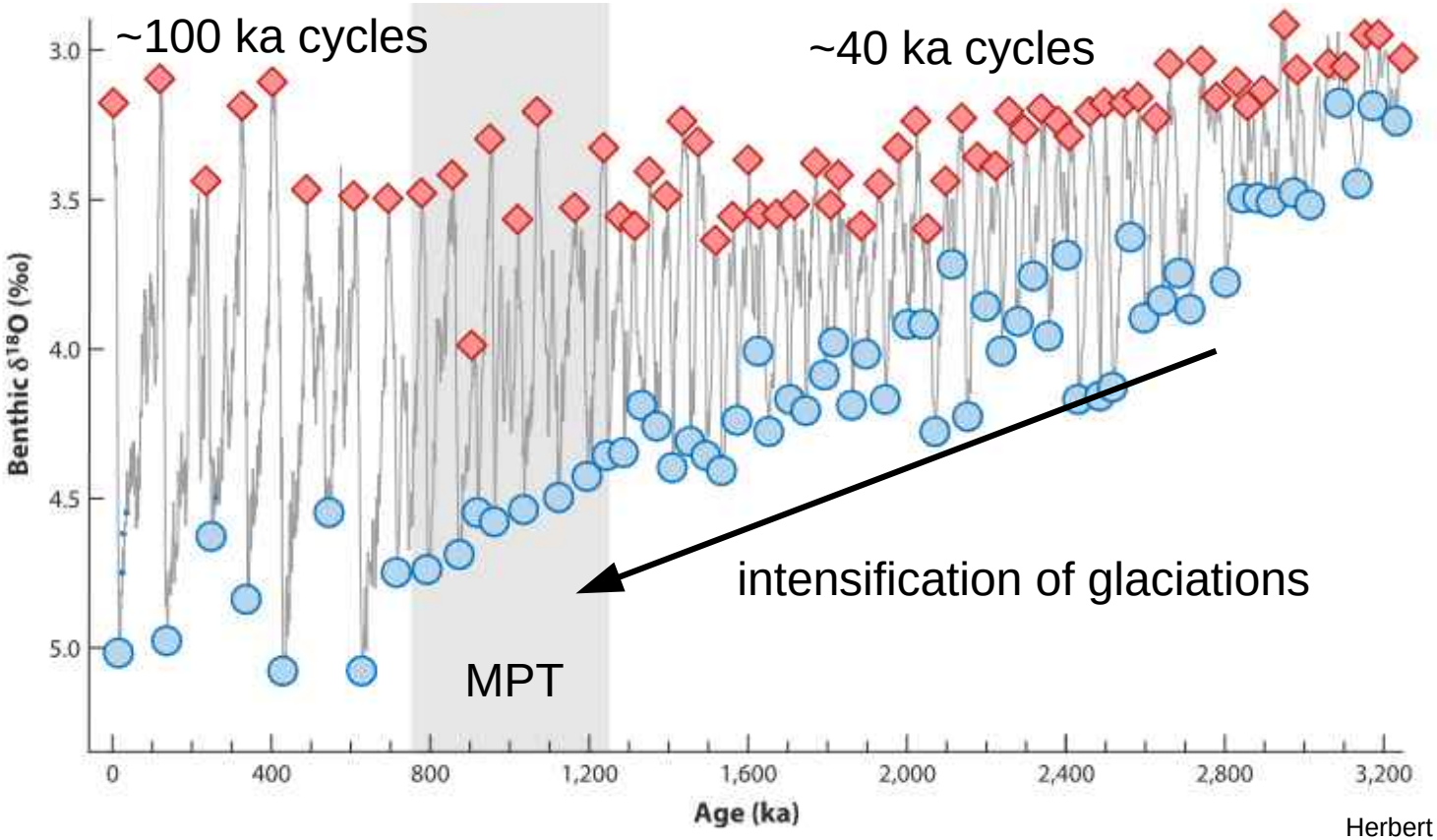
^{18}O in peak glacials vs. interglacials



Herbert 2015

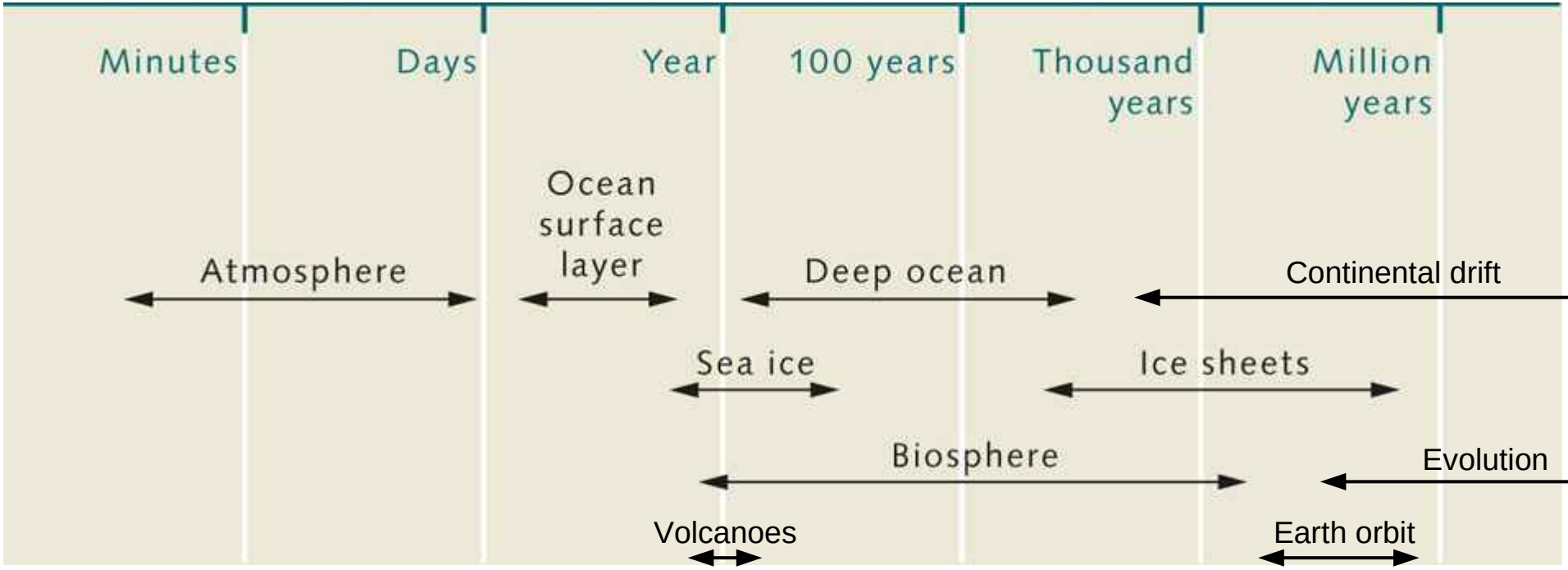
Pleistocene Climate

^{18}O in peak glacials vs. interglacials



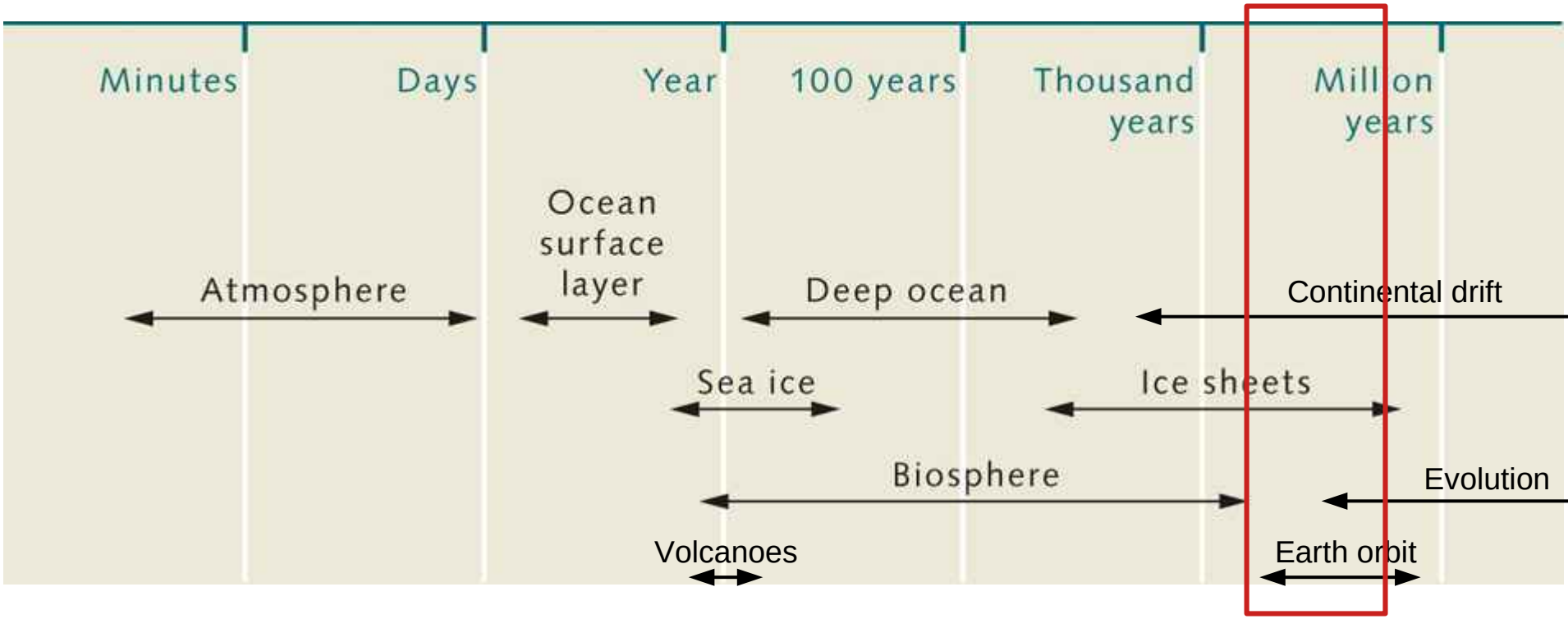
Herbert 2015

Pleistocene Climate



Wold Ocean Review,
after Meincke and Latif 1995,
modified

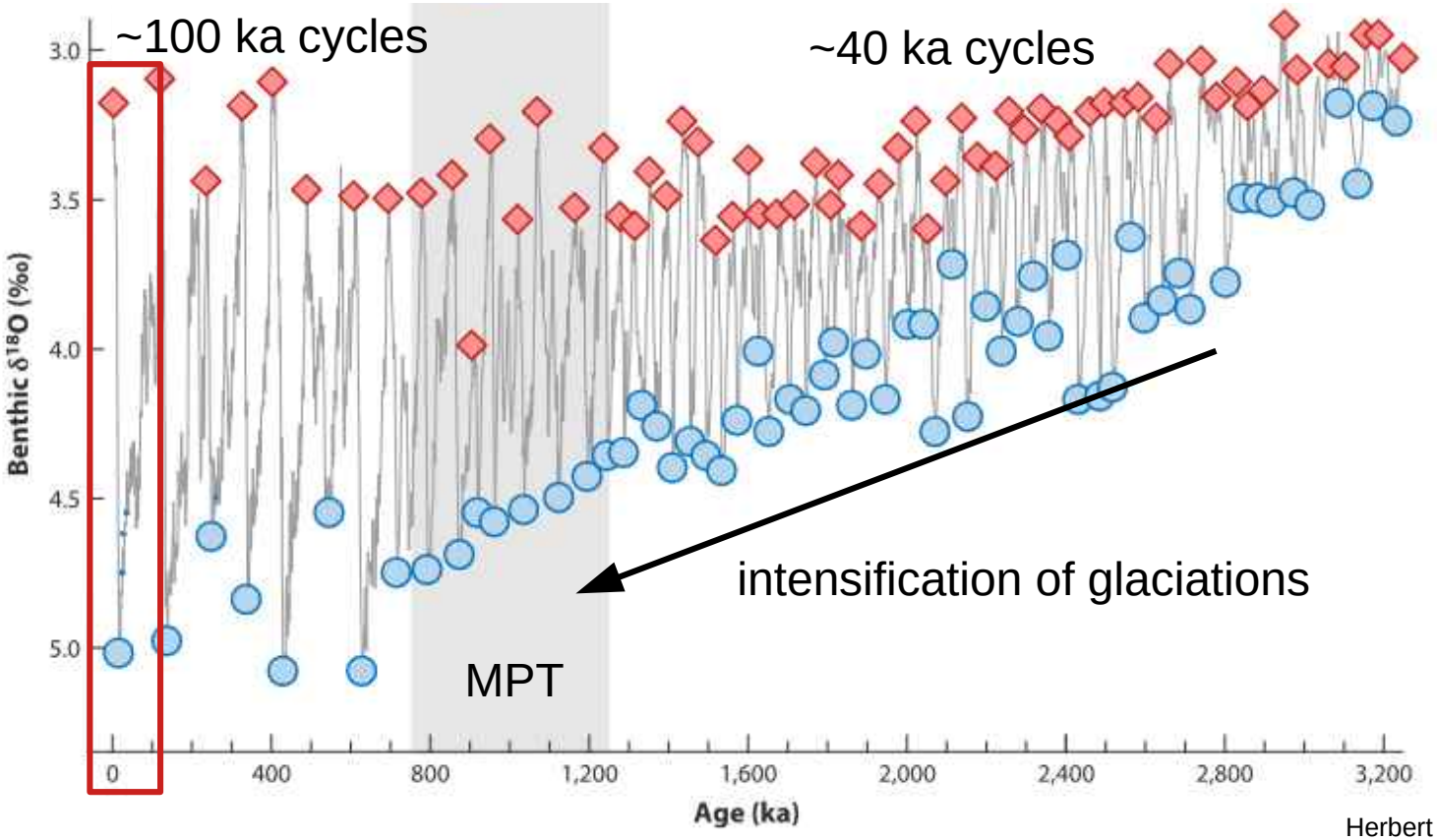
Pleistocene Climate



Wold Ocean Review,
after Meincke and Latif 1995,
modified

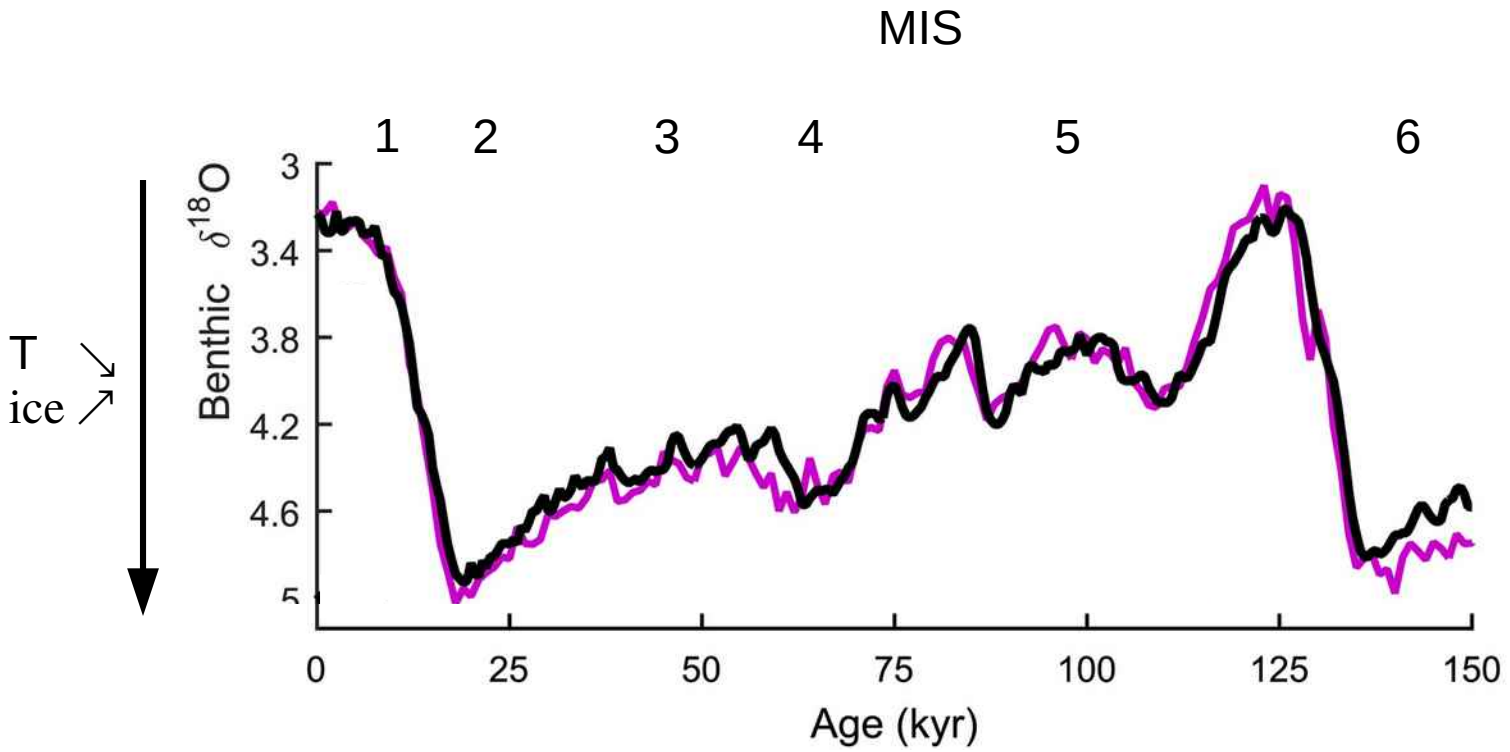
Last Glacial Cycle

^{18}O in peak glacials vs. interglacials



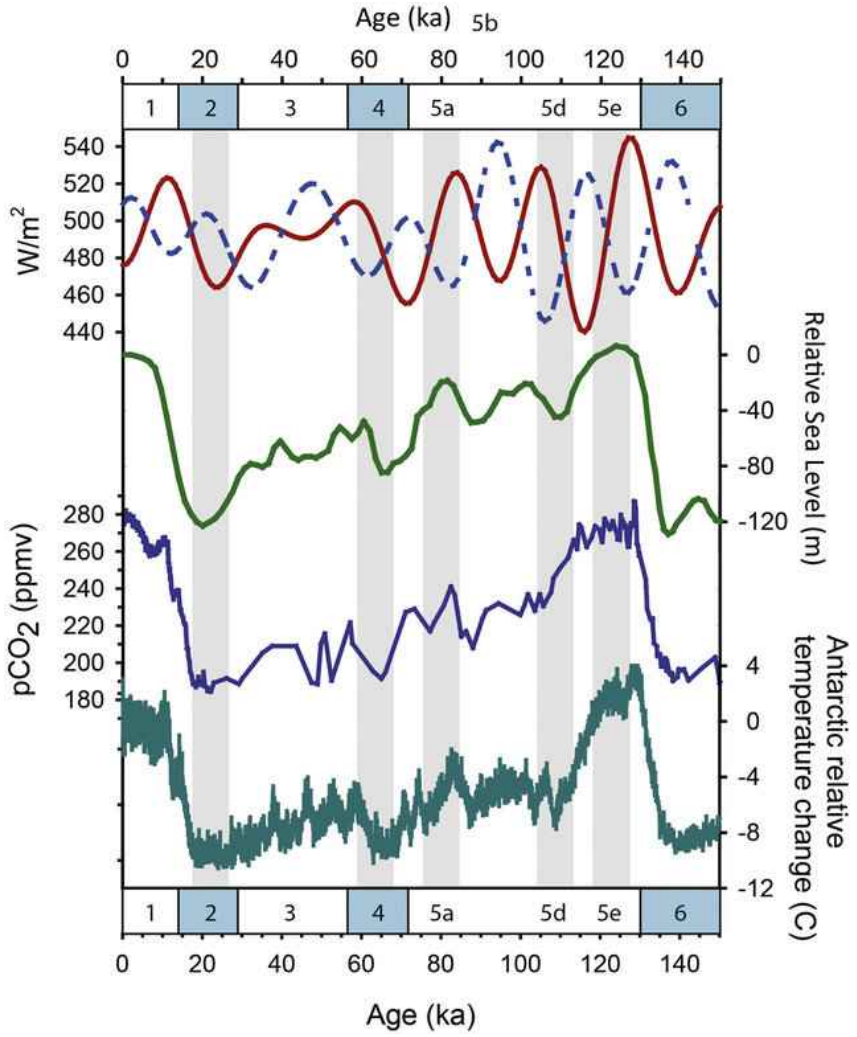
Herbert 2015

Last Glacial Cycle



Lisiecki & Stern (2016)
Paleoceanography & Paleoclimatology

Last Glacial Cycle



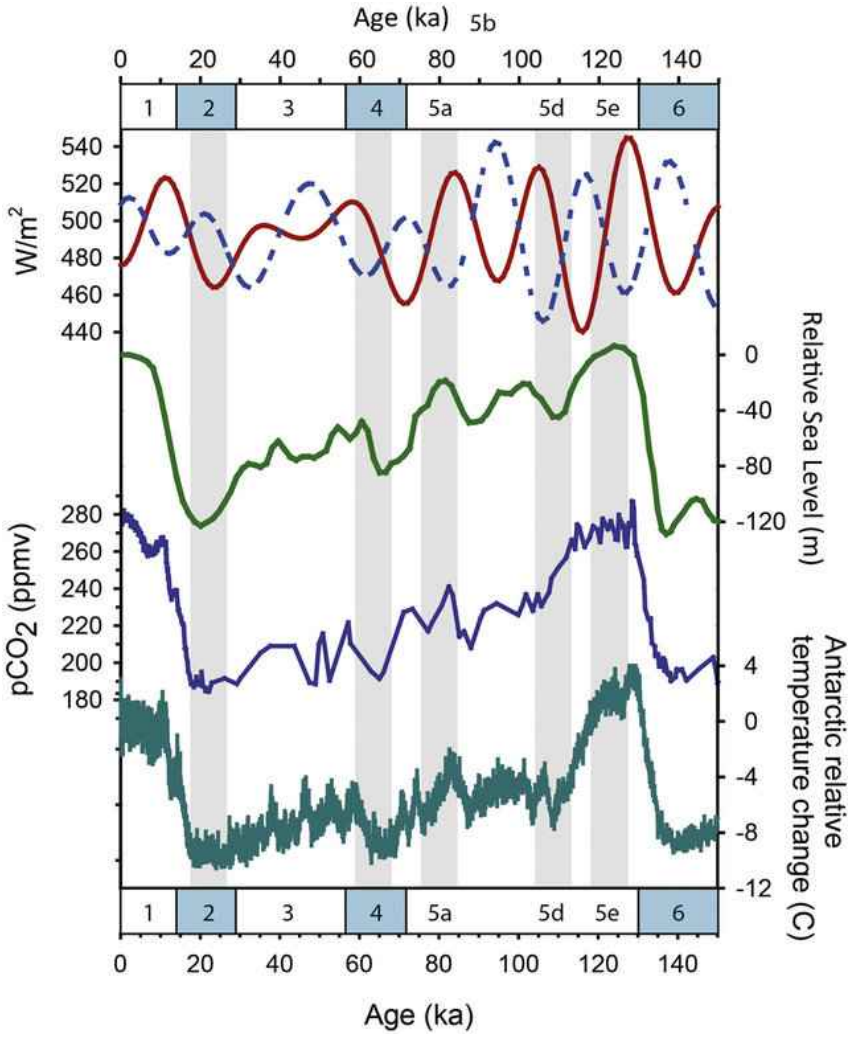
Kohfeld & Chase (2017)
Earth and Planetary Science Letters

Last Glacial Cycle

~ 120 m SLE

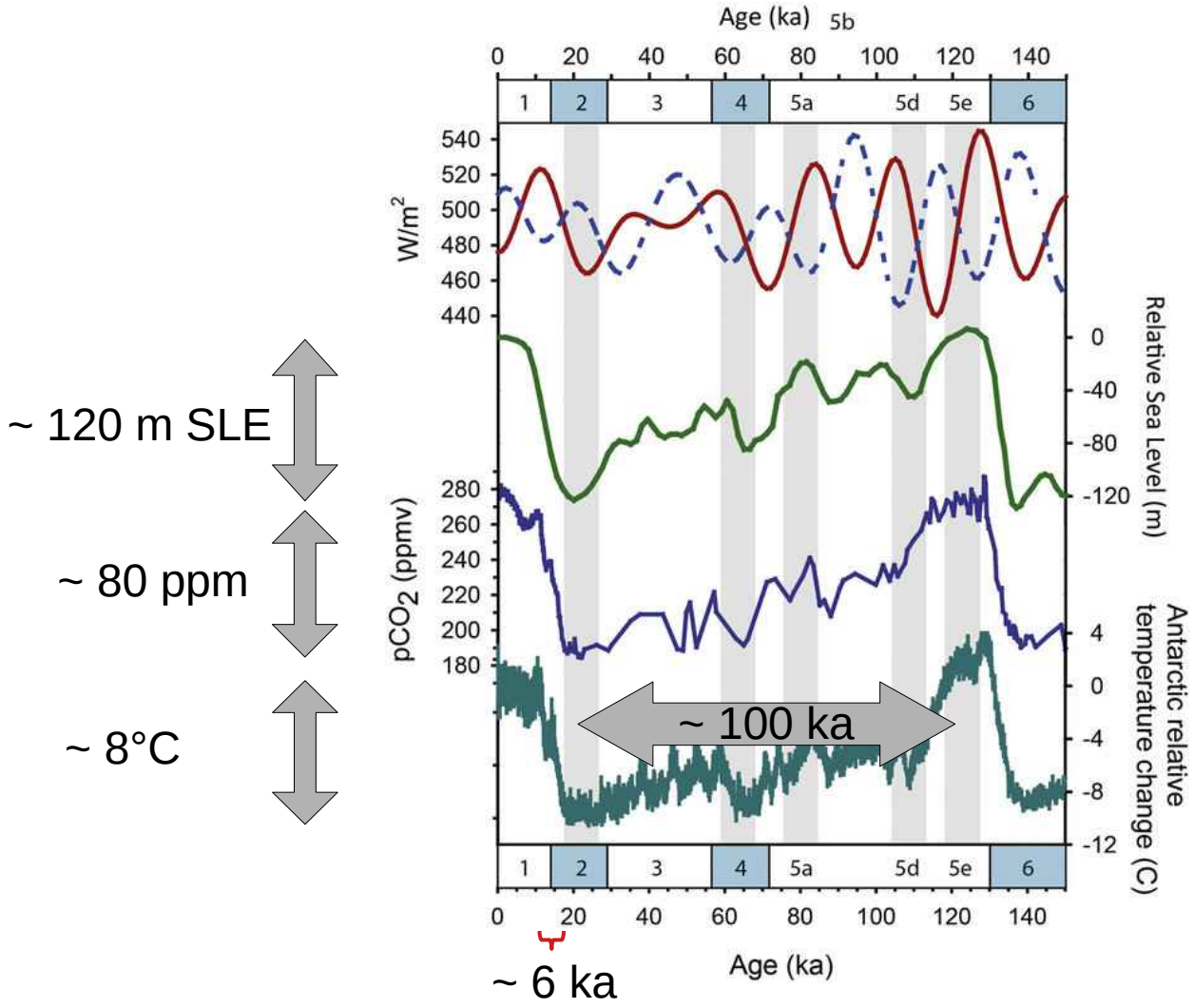
~ 80 ppm

~ 8°C



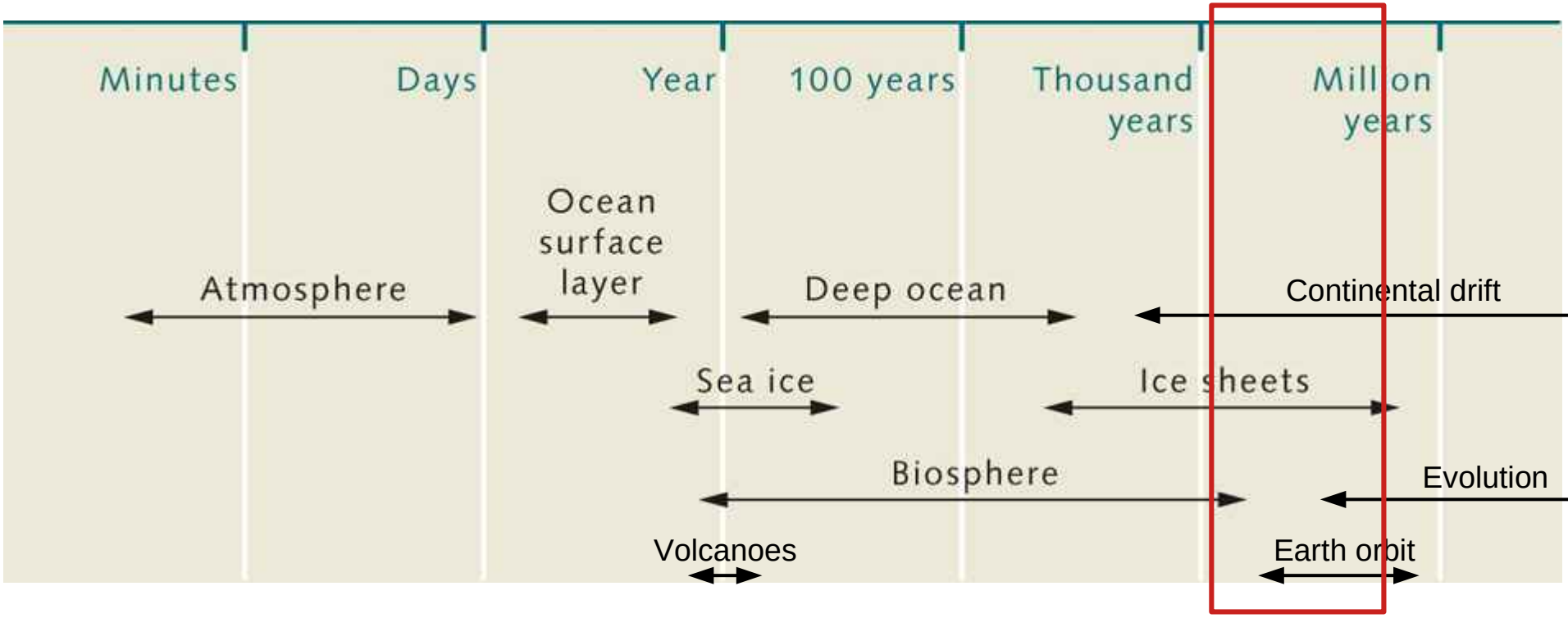
Kohfeld & Chase (2017)
Earth and Planetary Science Letters

Last Glacial Cycle



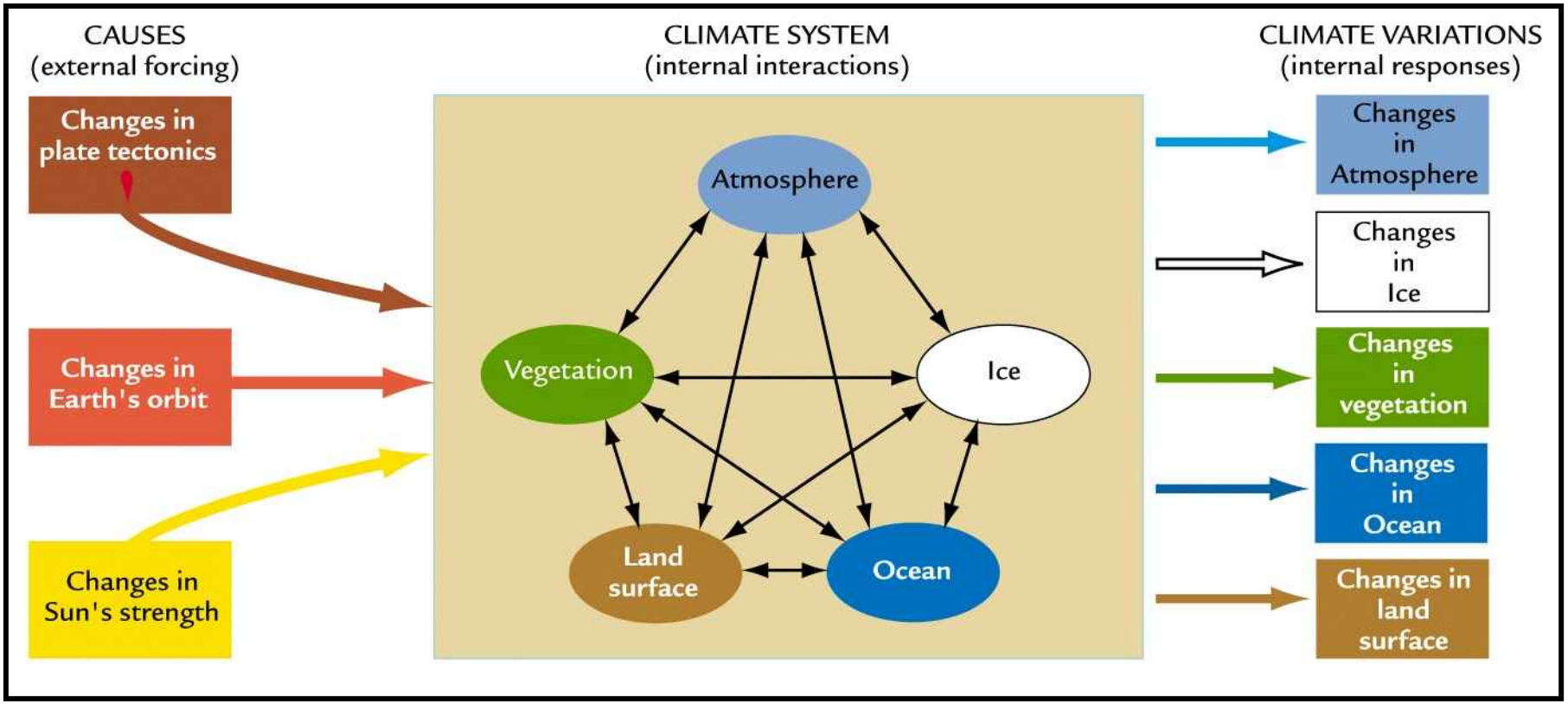
Kohfeld & Chase (2017)
Earth and Planetary Science Letters

Last Glacial Cycle



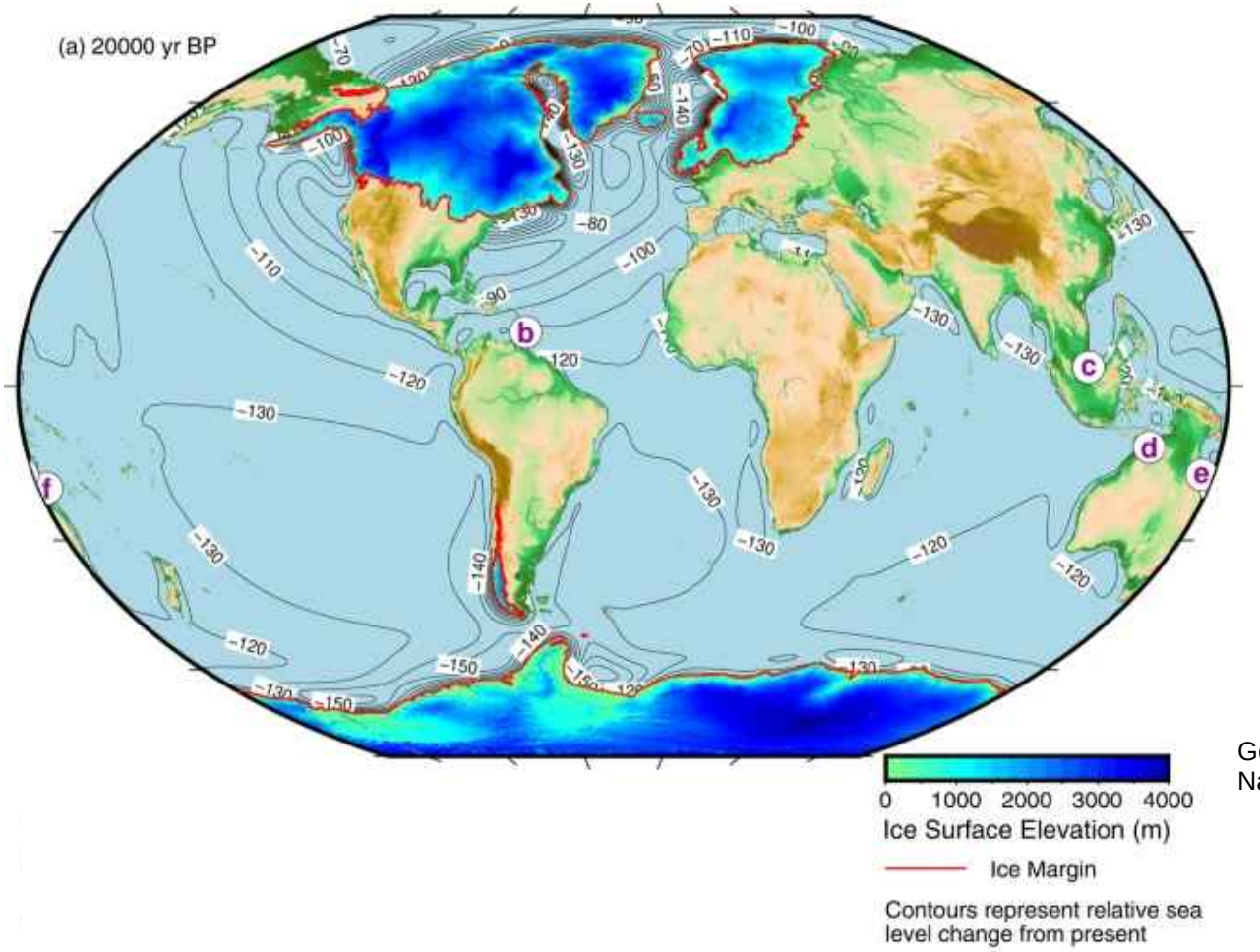
Wold Ocean Review,
after Meincke and Latif 1995,
modified

Last Glacial Cycle



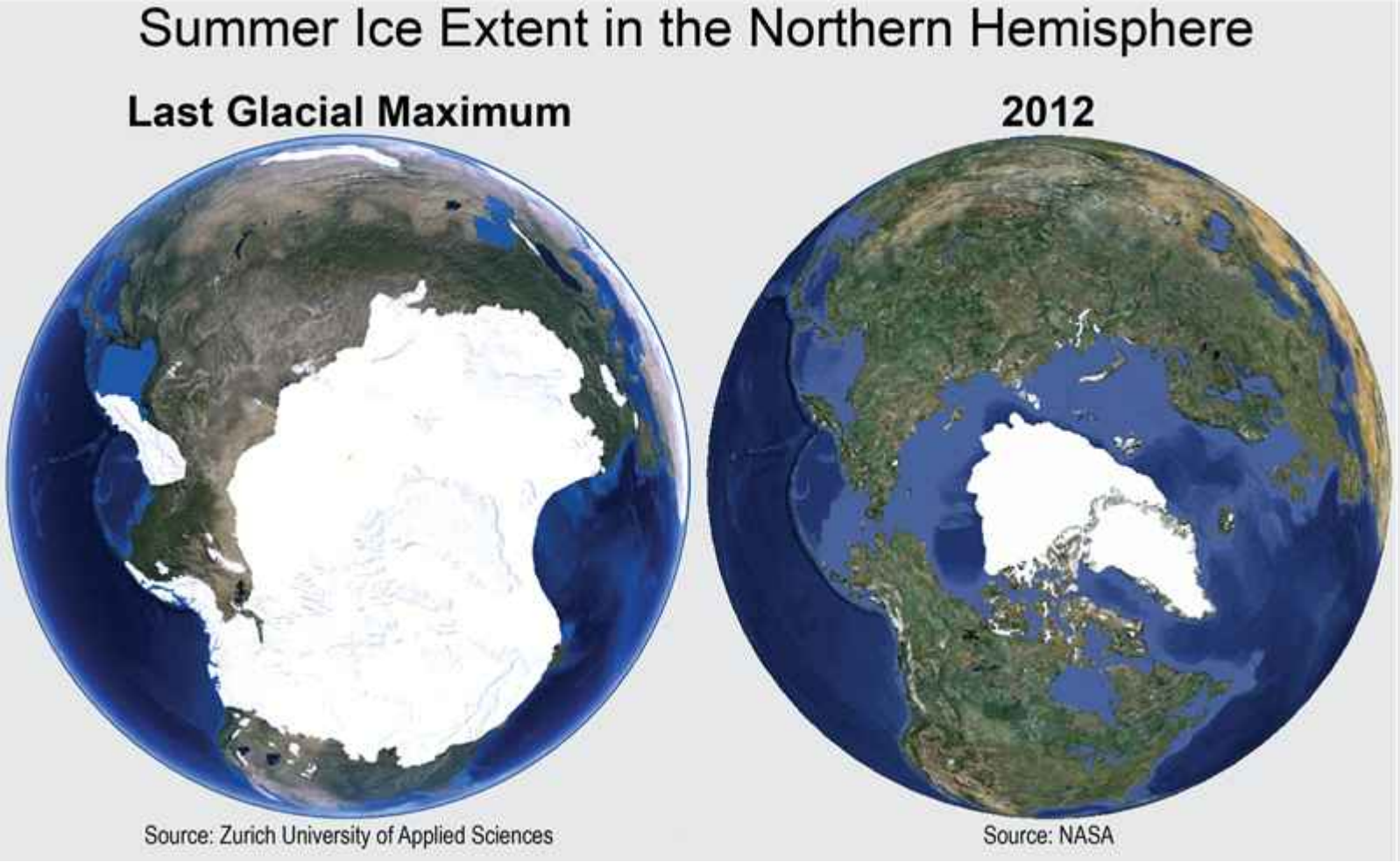
NOAA

Last Glacial Cycle



Gowan et al. (2021)
Nature Communications

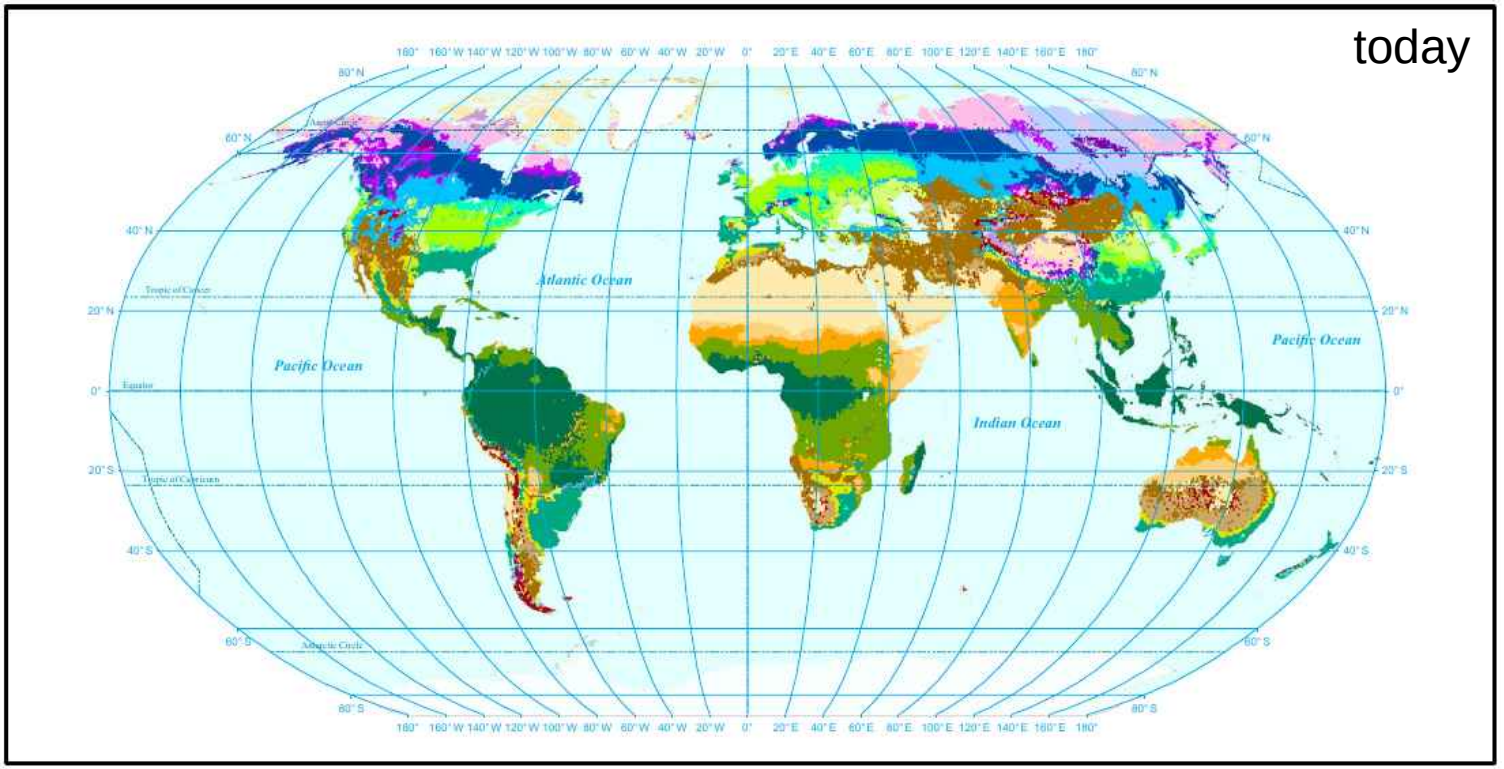
Last Glacial Cycle



Last Glacial Cycle

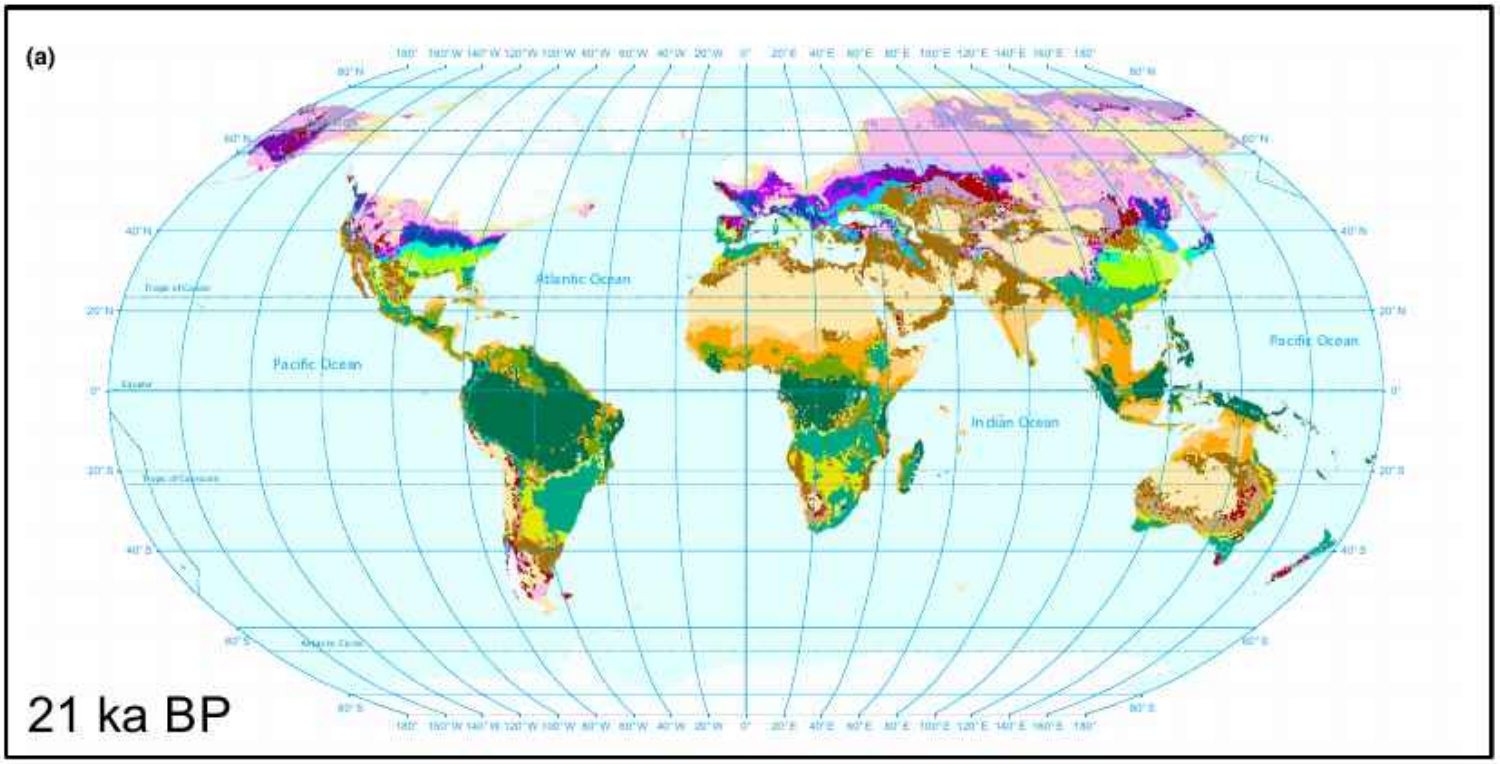
UVA Today
University of Virgina

Last Glacial Cycle



Allen et al. (2020)
Journal of Biogeography

Last Glacial Cycle



Legend

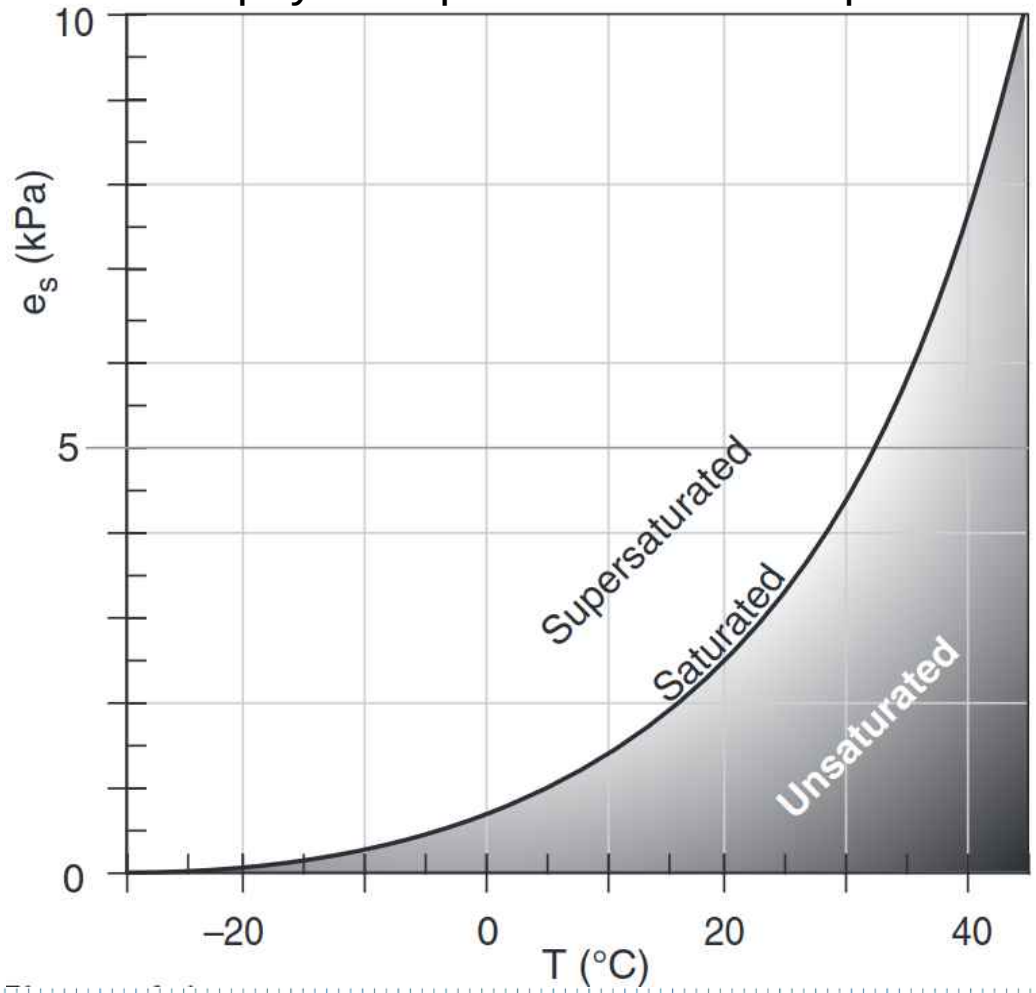
- Desert
- Semi-desert
- Tropical Grassland
- Savanna
- Tropical Raingreen Forest
- Tropical Evergreen Forest
- Temperate Shrubland
- Unclassified
- Warm Temperate Woodland
- Temperate Broad-leaved Evergreen Forest
- Temperate Summergreen Forest
- Temperate Needle-leaved Evergreen Forest
- Temperate Mixed Forest
- Temperate Parkland
- Steppe
- Ice sheet
- Boreal Parkland
- Boreal Evergreen Needle-leaved Forest
- Boreal Summergreen Needle-leaved Forest
- Boreal Summergreen Broad-leaved Forest
- Boreal Woodland
- Shrub Tundra
- Tundra
- Ocean or lake

UNIL | Université de Lausanne

Allen et al. (2020)
Journal of Biogeography

Last Glacial Cycle

Clauius-Clapeyron equation for water vapour saturation



$$e_s \approx e_o \cdot \exp\left[\frac{L}{\Re_v} \cdot \left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$$

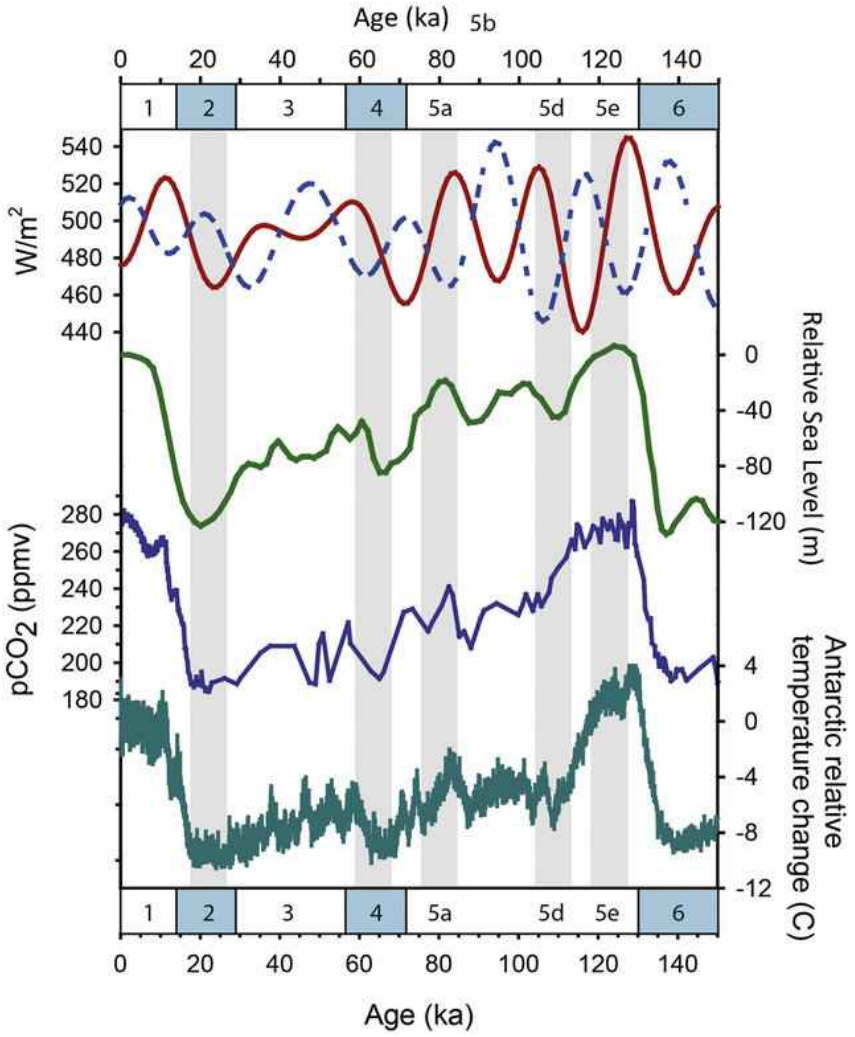
Roland Stull (2015), University of British Columbia,
"Practical Meteorology: An Algebra-based Survey
of Atmospheric Science"

Last Glacial Cycle

~ 120 m SLE

~ 80 ppm

~ 8°C



ice sheets & land

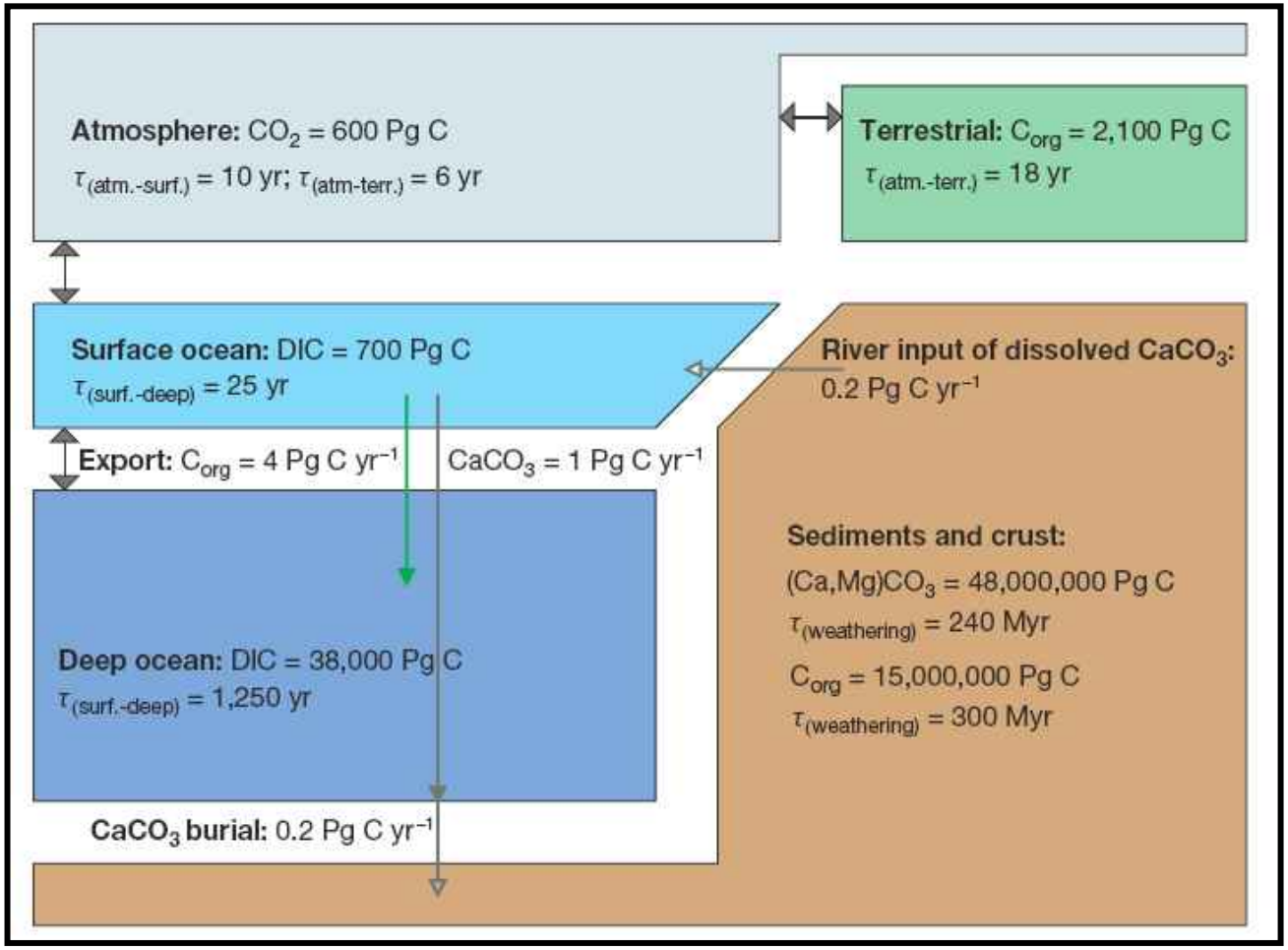
albedo ↗

CO_2 ↘

~ 7 – 12 ppm

Kohfeld & Chase (2017)
Earth and Planetary Science Letters

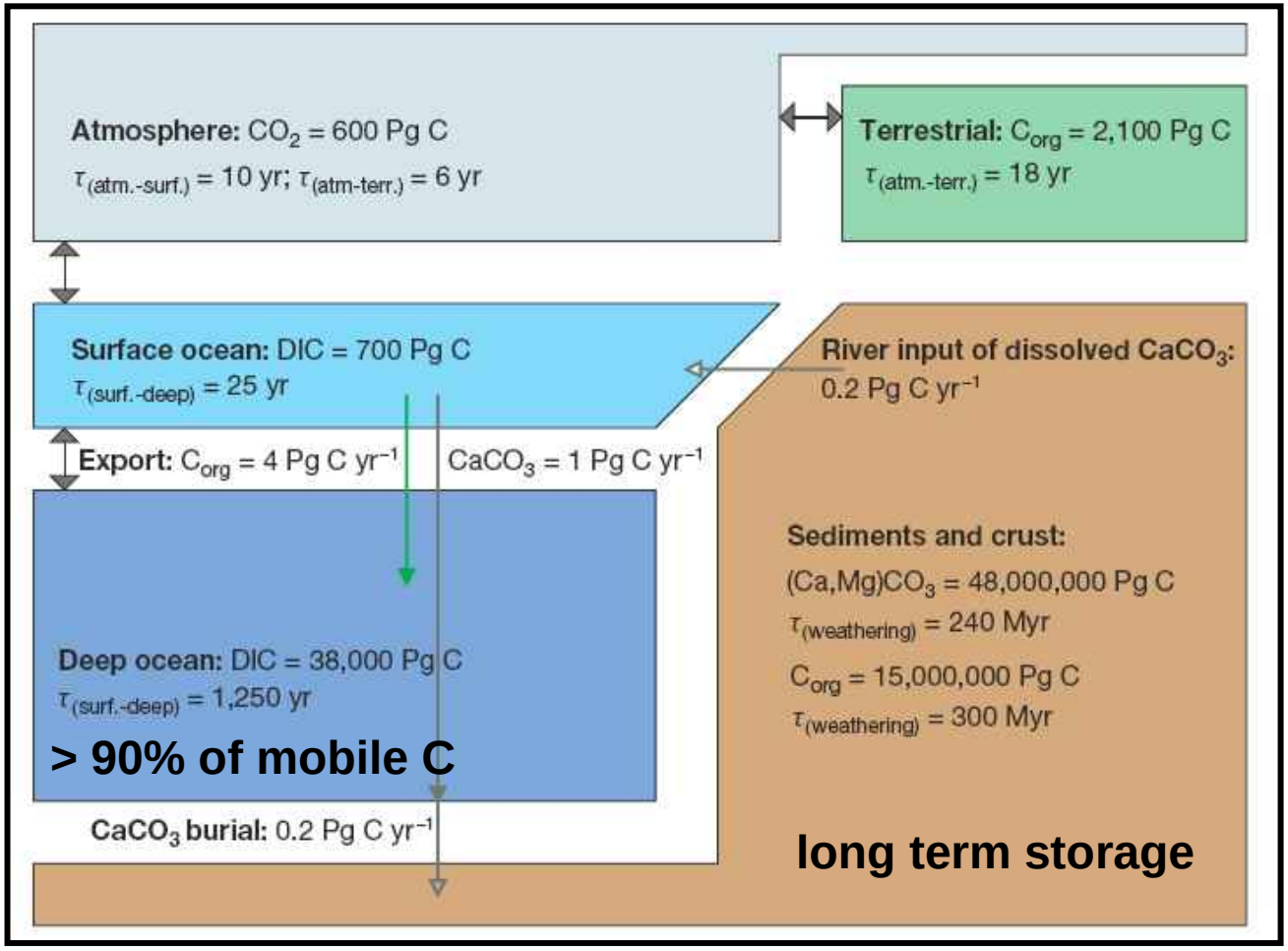
Last Glacial Cycle



Sigman & Boyle, 2000

Pg C = Gt = 10^{12} g C

Last Glacial Cycle

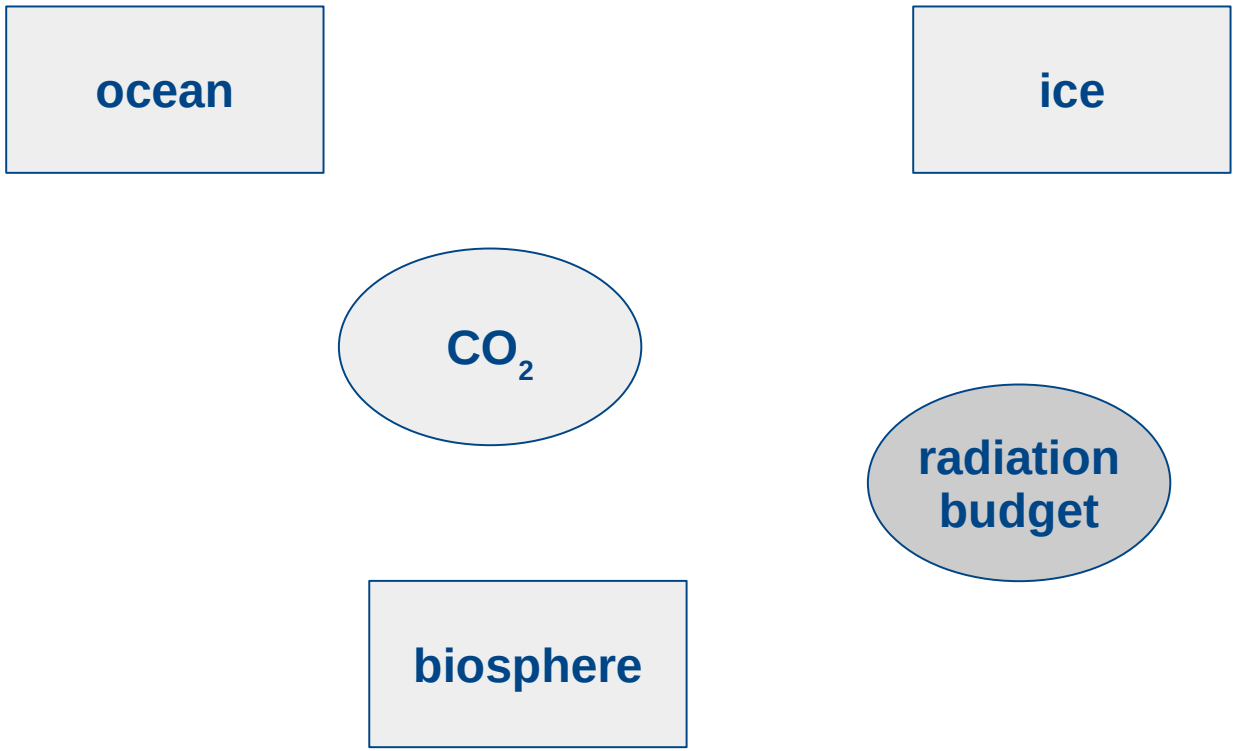


Sigman & Boyle, 2000

Pg C = Gt = 10^{12} g C

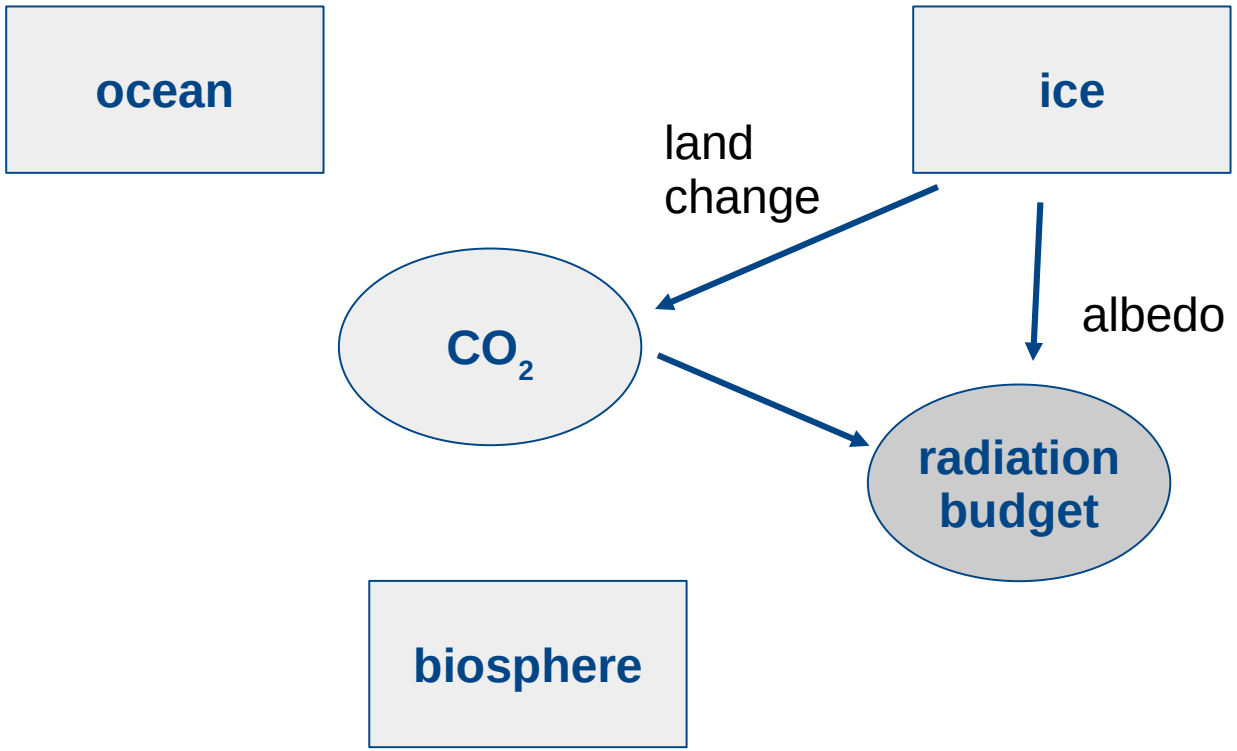
Last Glacial Cycle

most relevant climate players



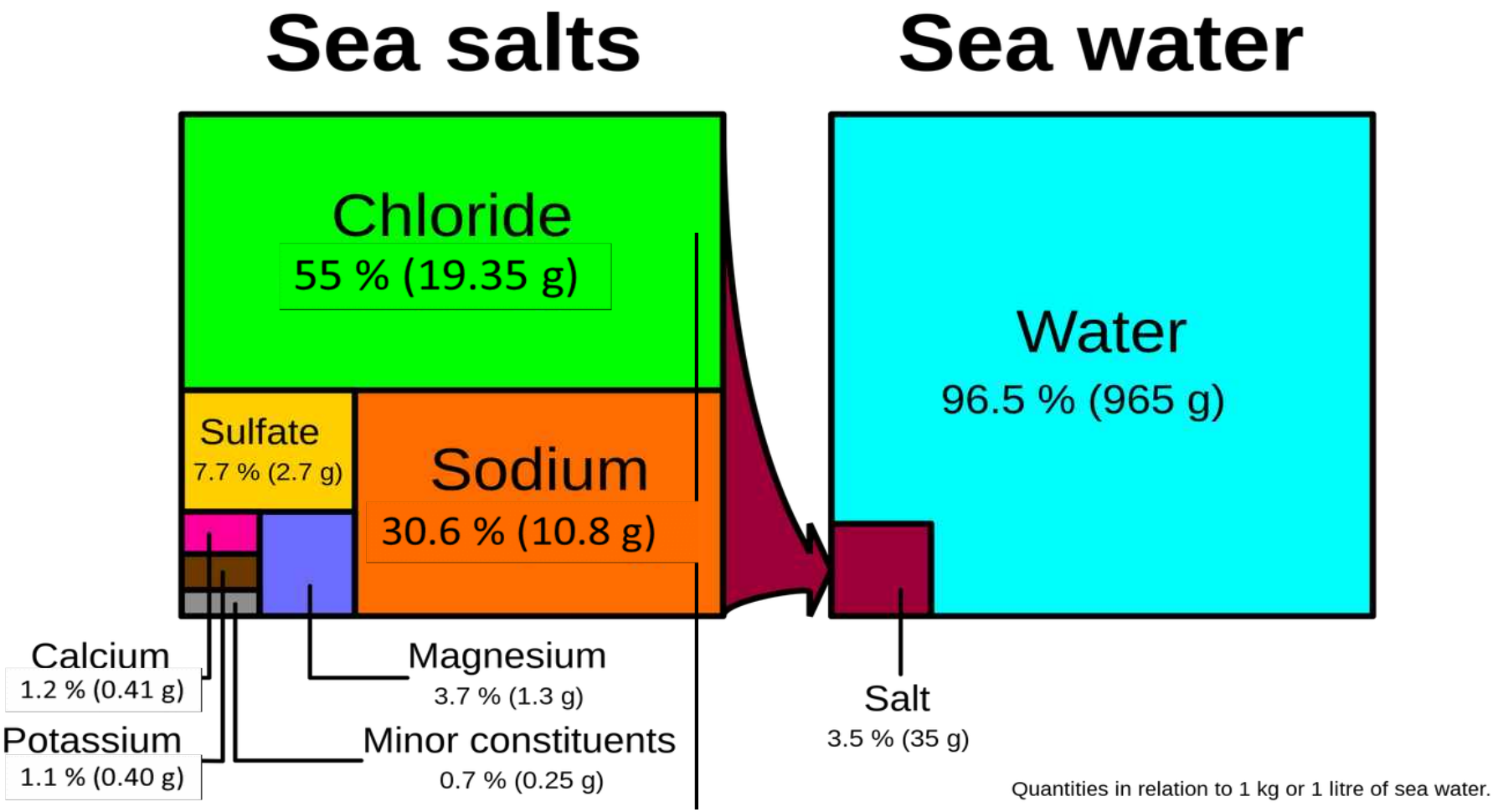
Last Glacial Cycle

most relevant climate players

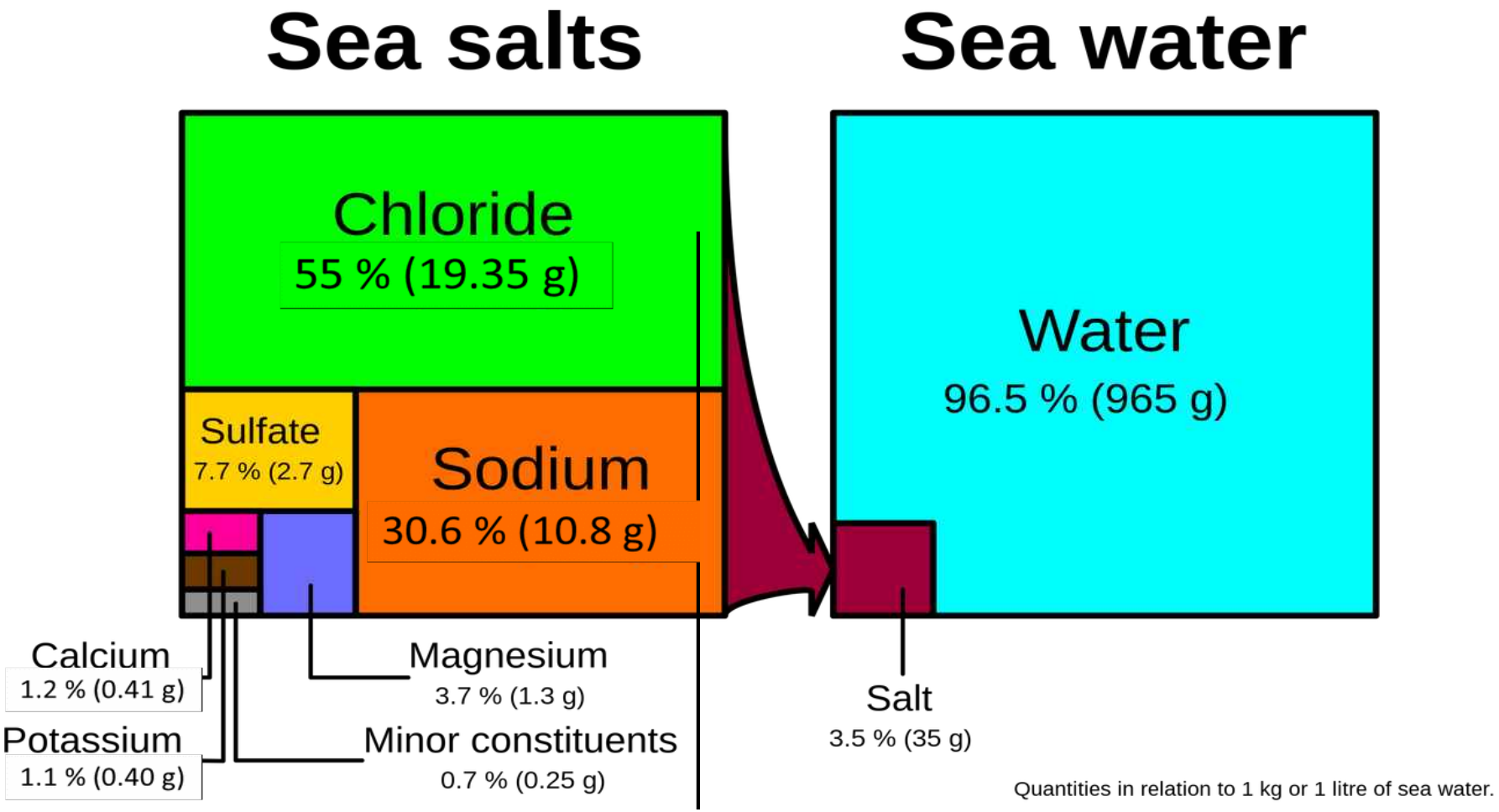


Oceans Basics for G-IG Cycles

Sea Water


Sea salts
Sea water
Chloride
55 % (19.35 g)
Sulfate
7.7 % (2.7 g)
Sodium
30.6 % (10.8 g)
Water
96.5 % (965 g)
Calcium
1.2 % (0.41 g)
Potassium
1.1 % (0.40 g)
Magnesium
3.7 % (1.3 g)
Minor constituents
0.7 % (0.25 g)
Salt
3.5 % (35 g)
Quantities in relation to 1 kg or 1 litre of sea water.

Sea Water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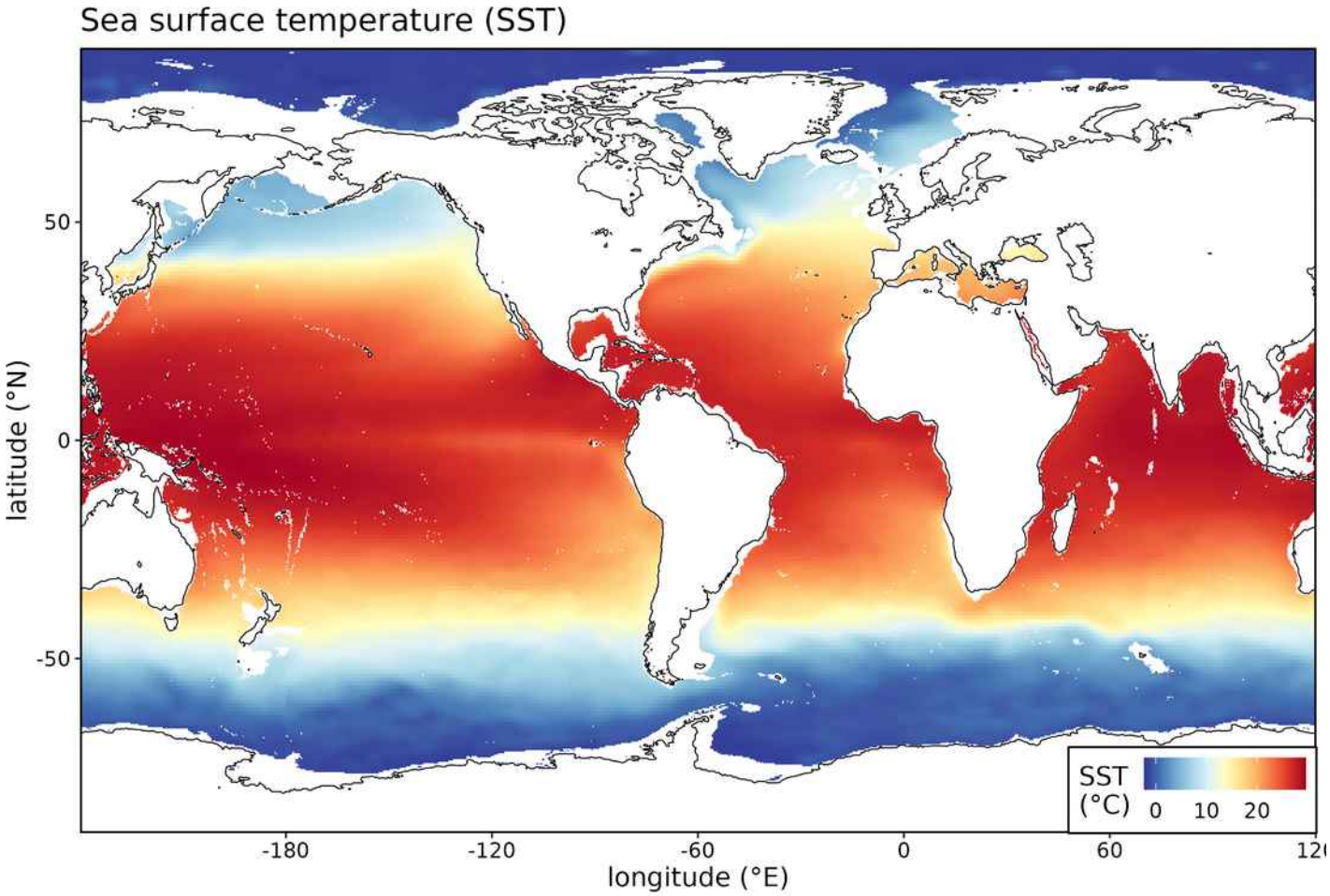
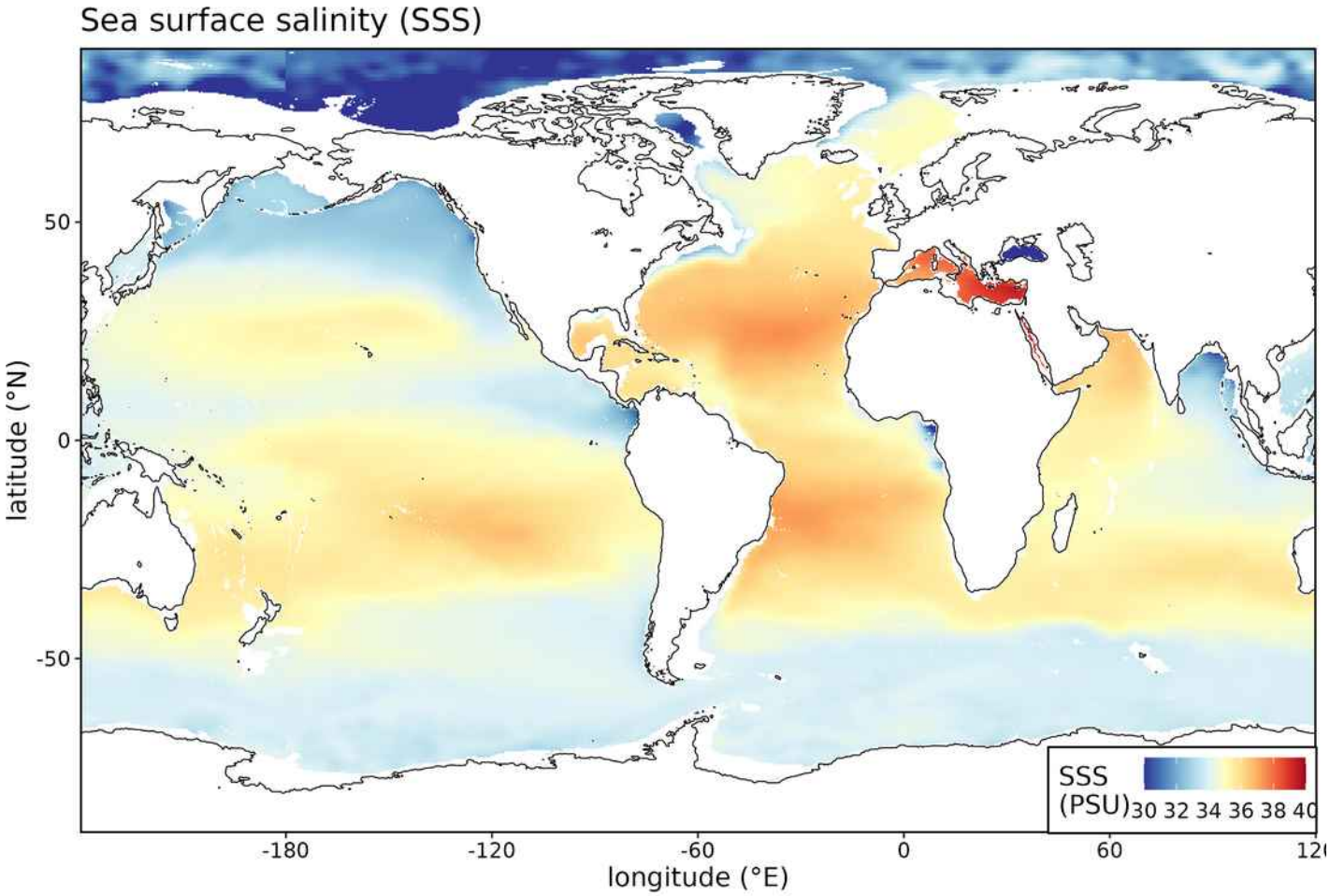
Minor constituents
0.7 % (0.25 g)
Salt
3.5 % (35 g)
Quantities in relation to 1 kg or 1 litre of sea water.
(including organic molecules)

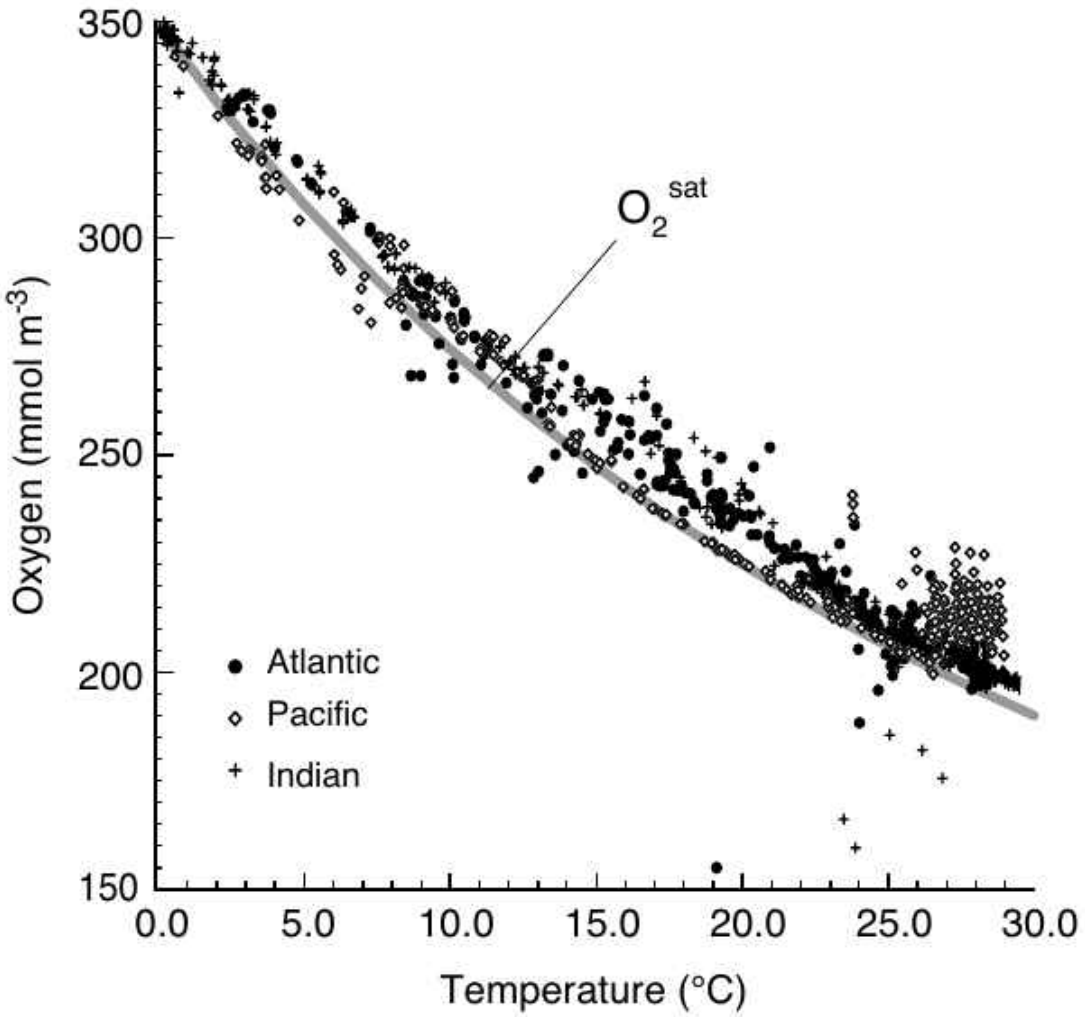
The Sea Surface



The Sea Surface

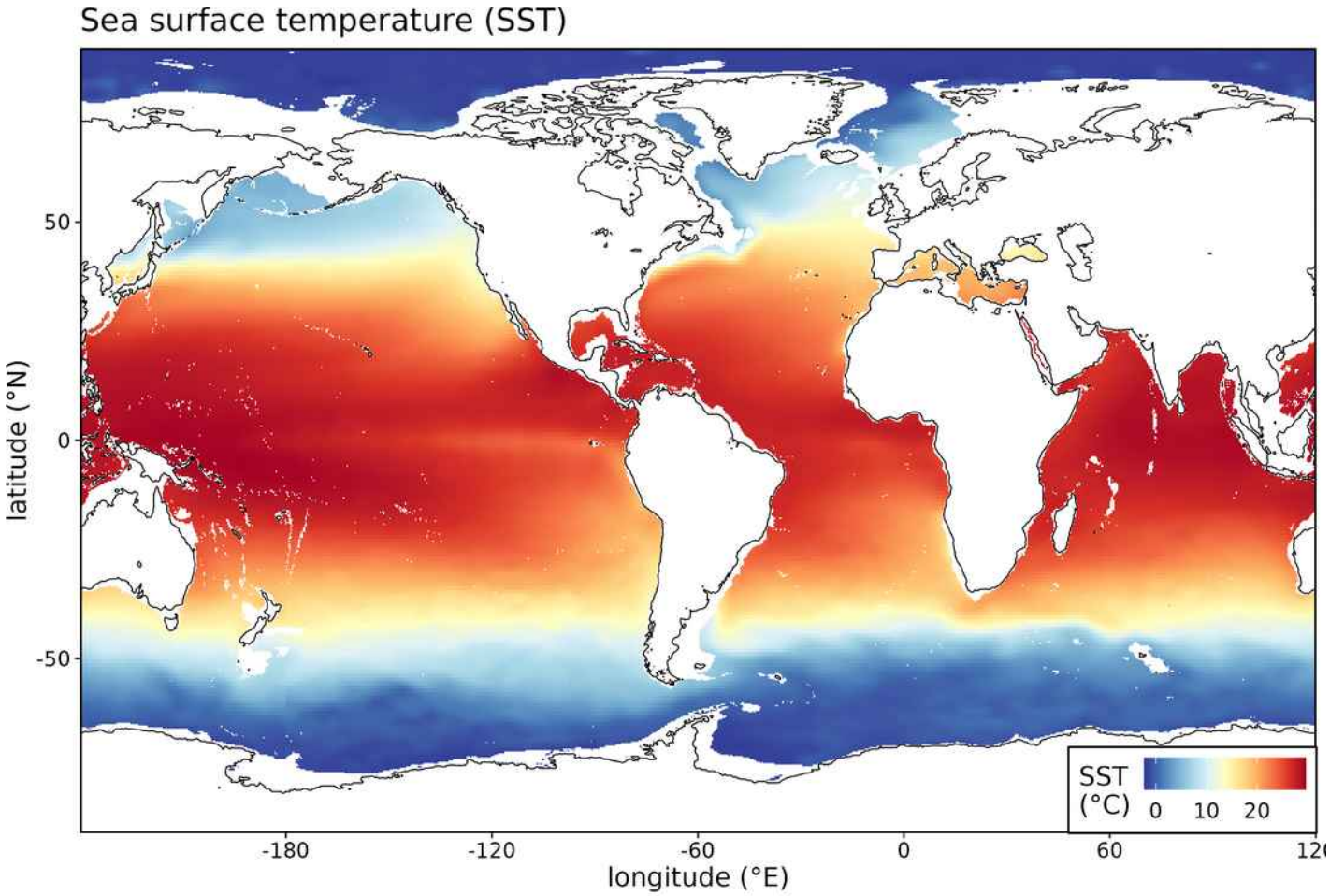


The Sea Surface

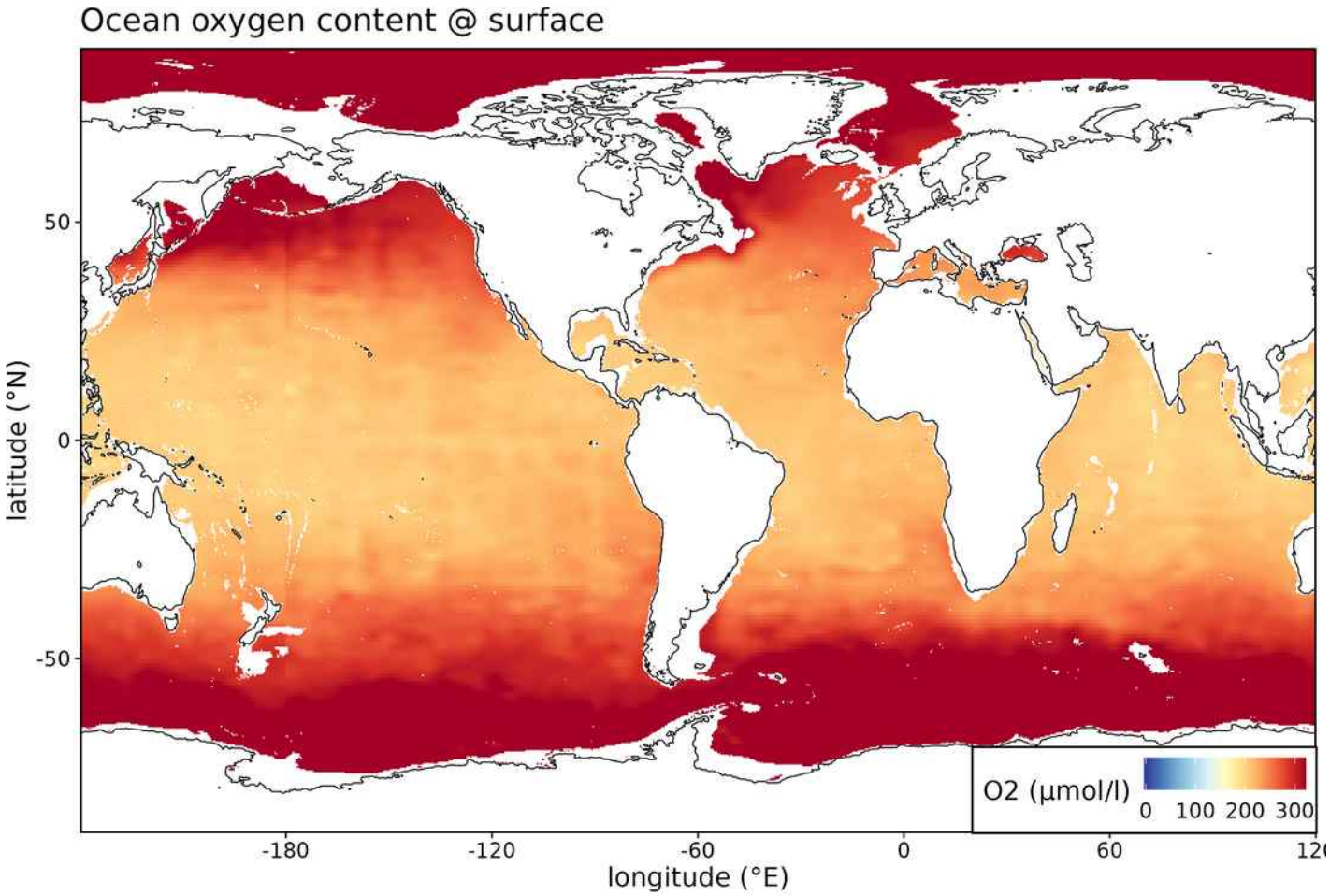


Sarmiento & Gruber (2006), Ocean Biogeochemical Dynamics

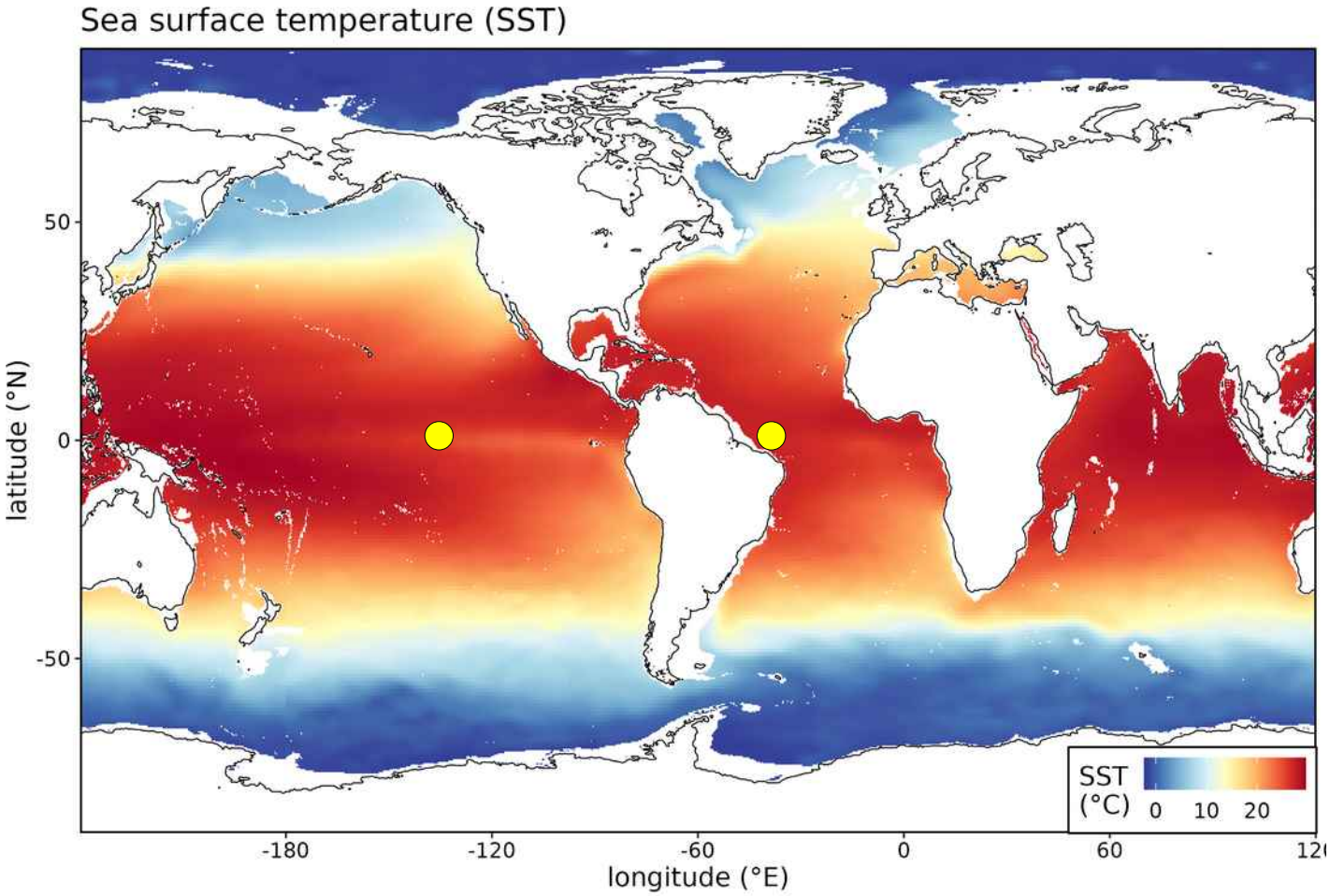
The Sea Surface



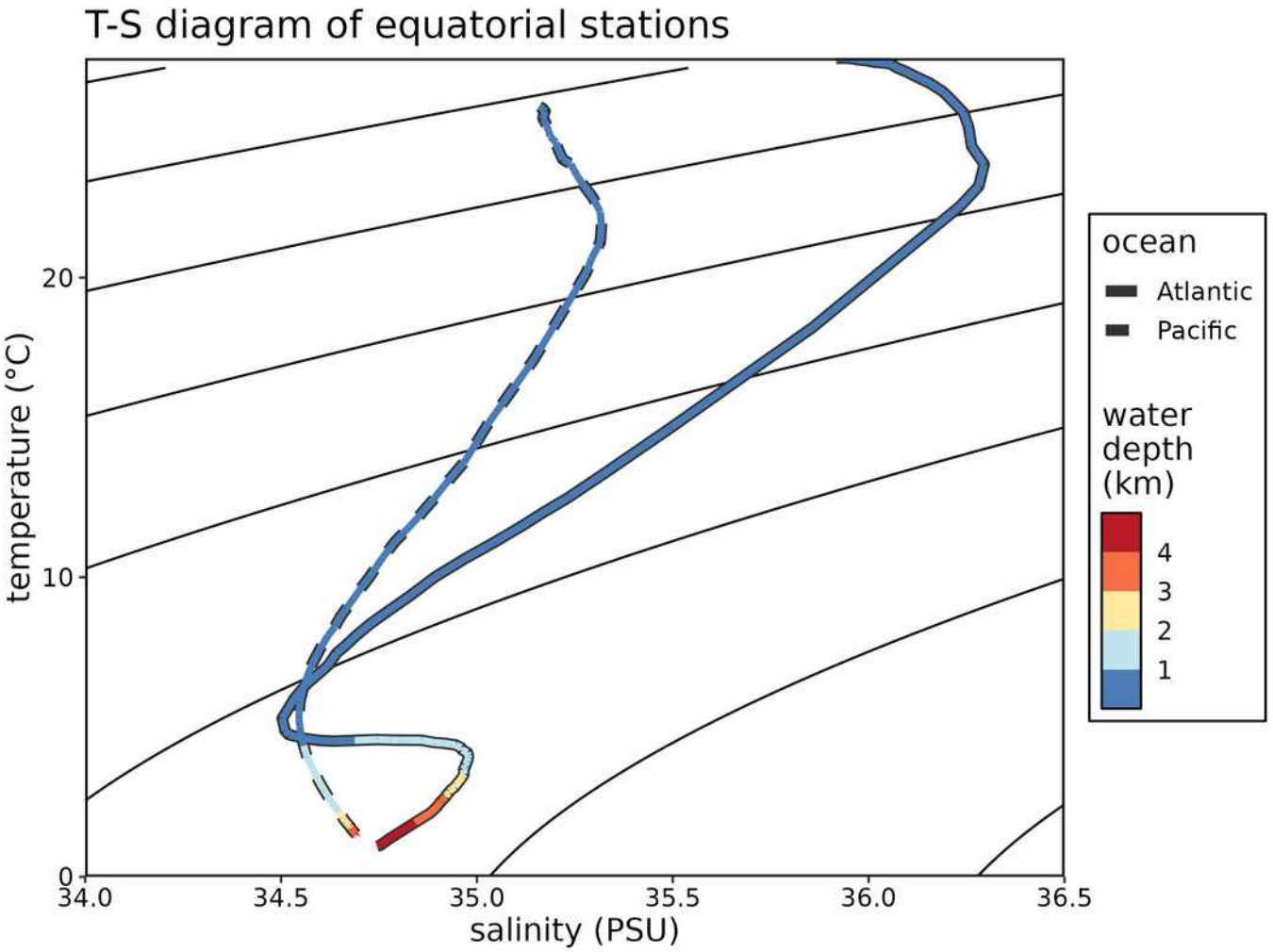
The Sea Surface



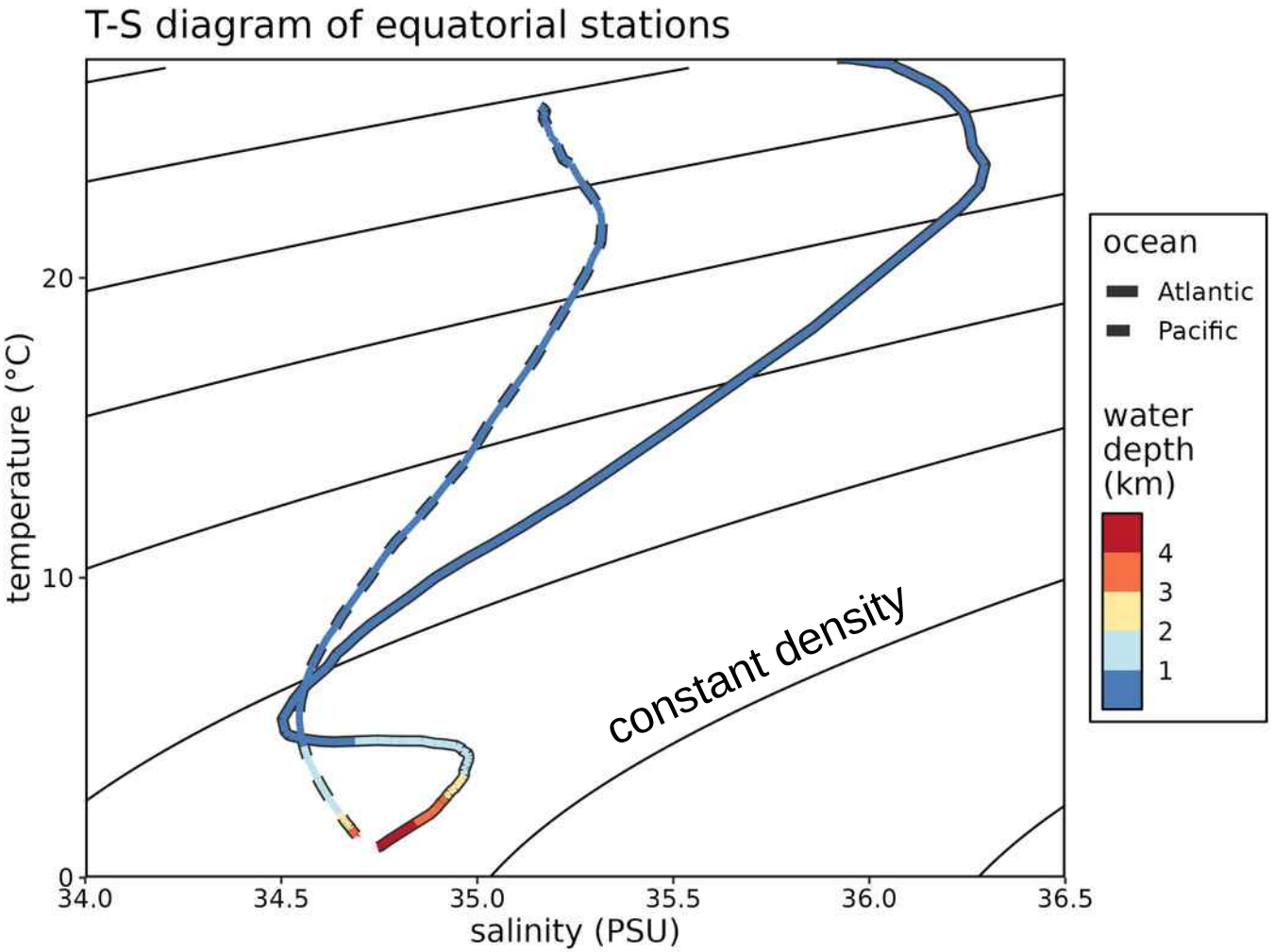
The Water Column



The Water Column

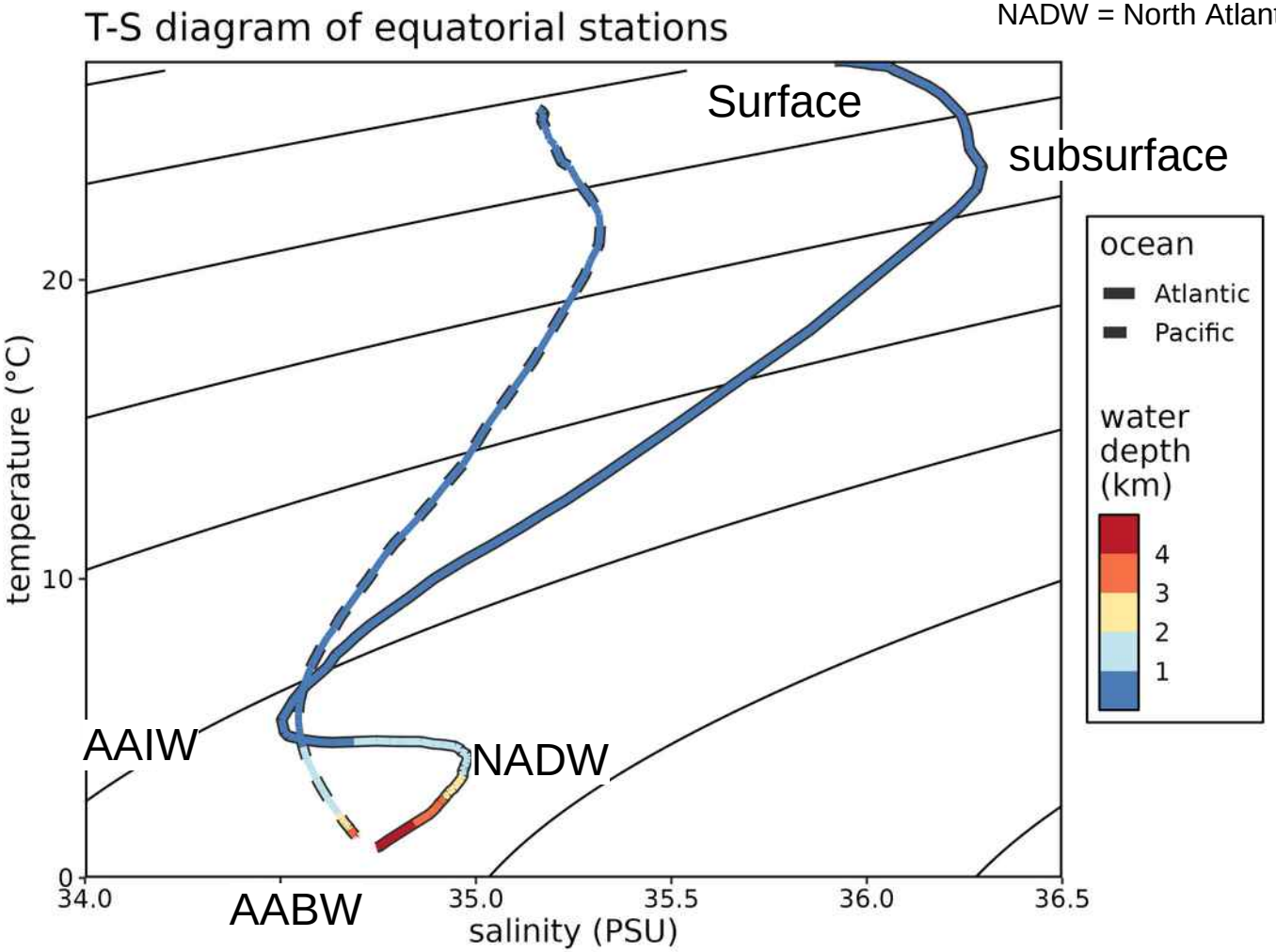


The Water Column

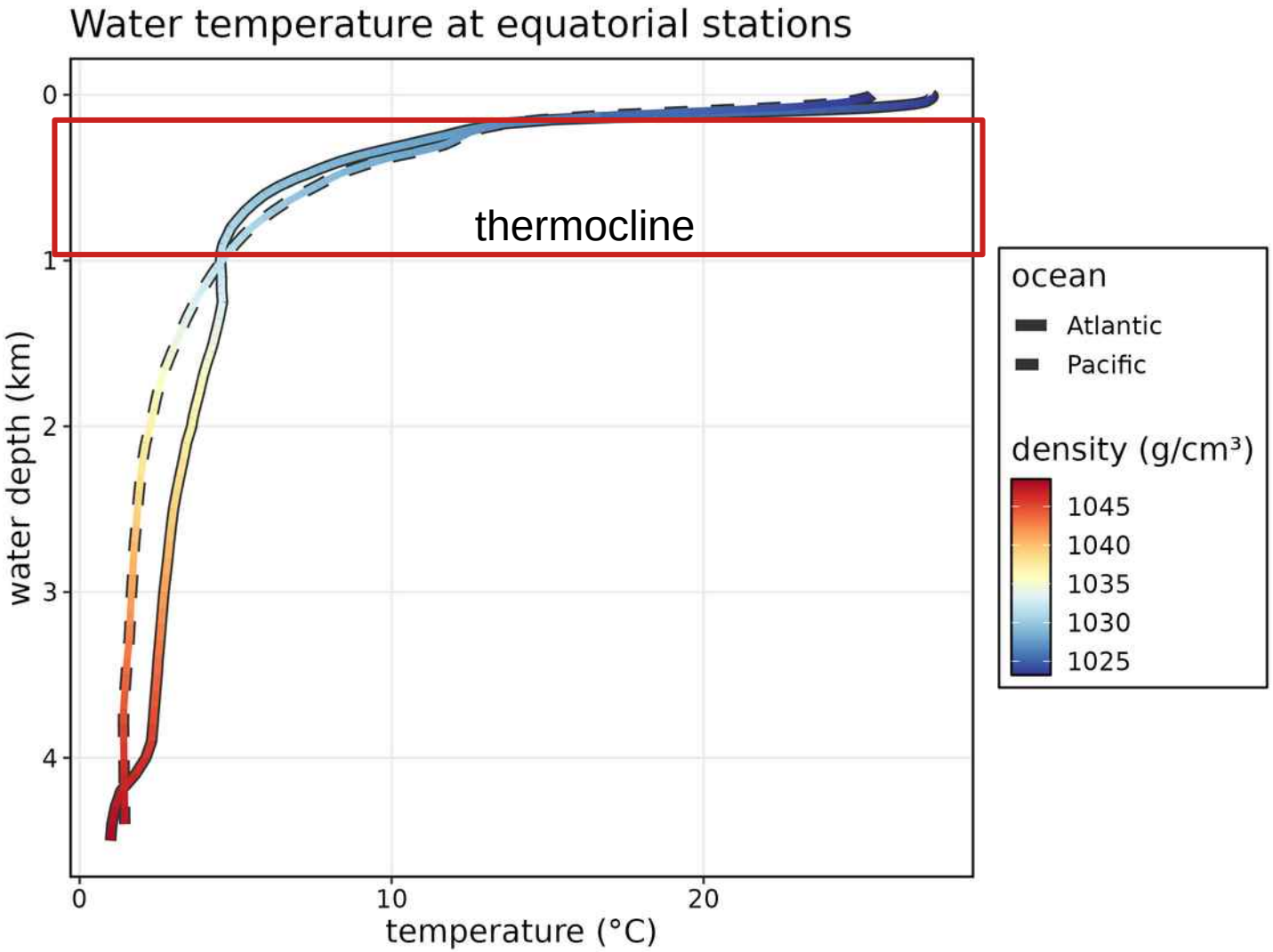


The Water Column

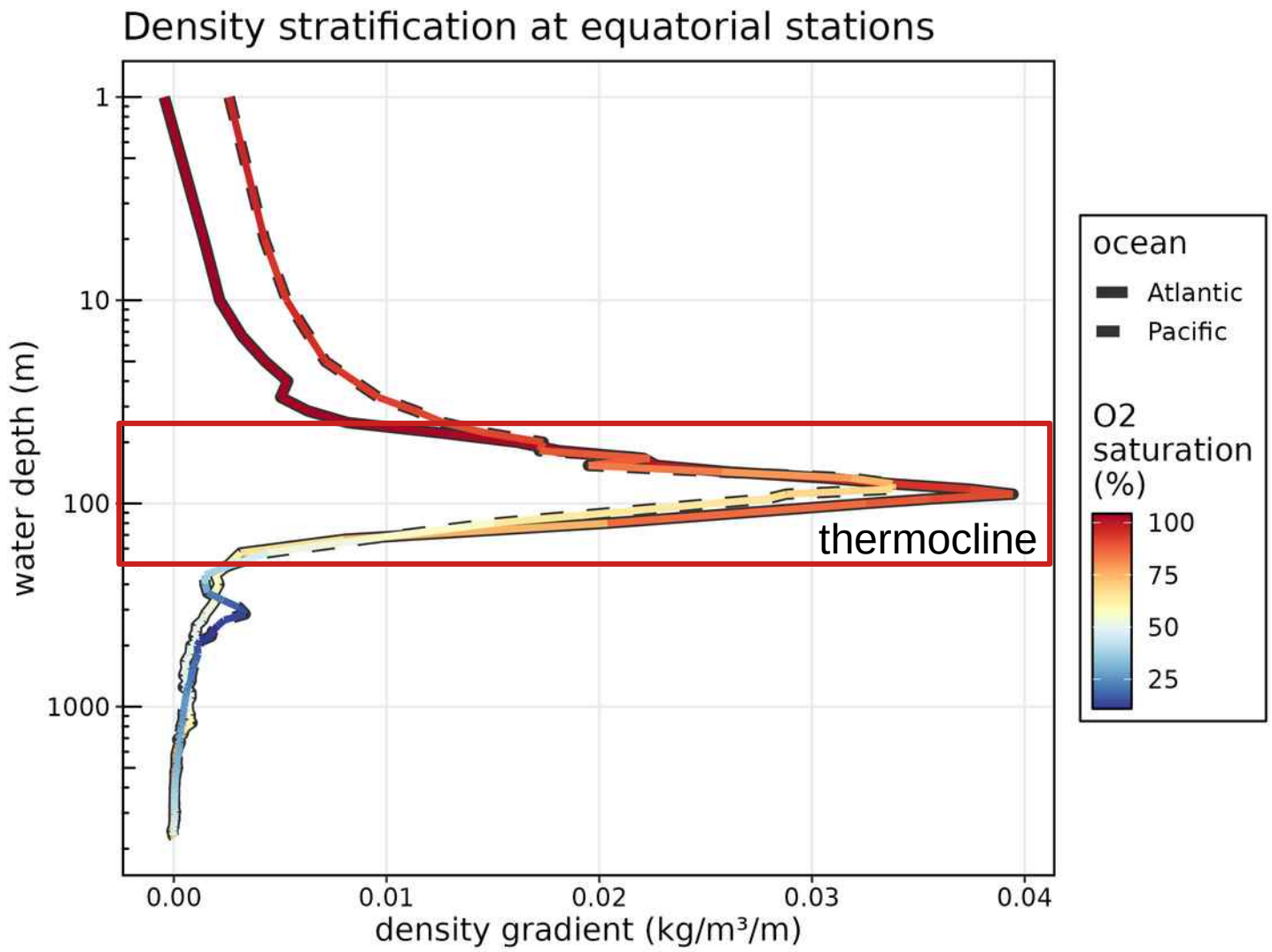
AAIW = Antarctic Intermediate Water
AABW = Antarctic Bottom Water
NADW = North Atlantic Deep Water



The Water Column



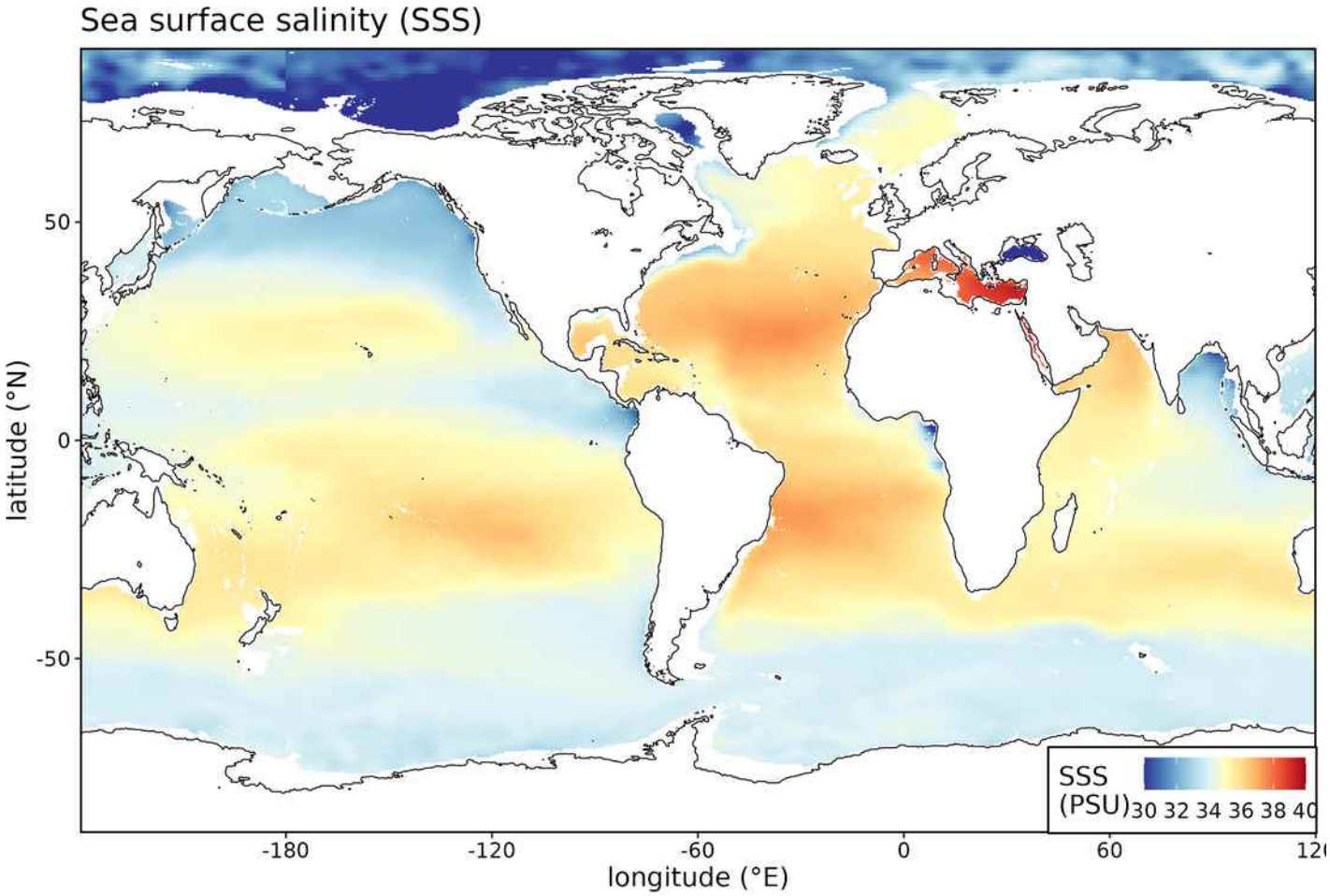
The Water Column



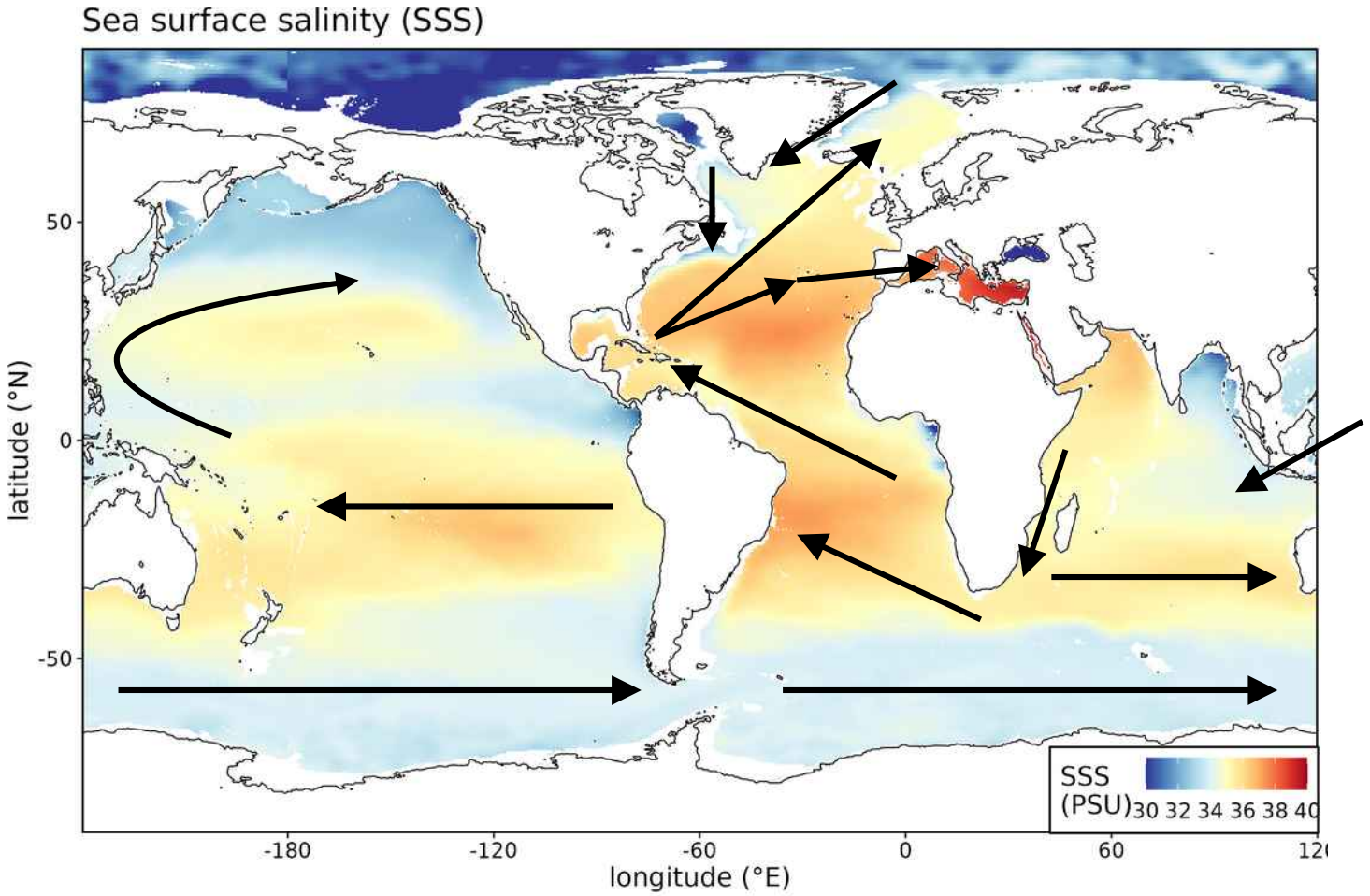
Surface Ocean Currents

NASA: Perpetual Ocean
https://www.youtube.com/watch?v=CCmTY0PKGDs

Surface Ocean Currents

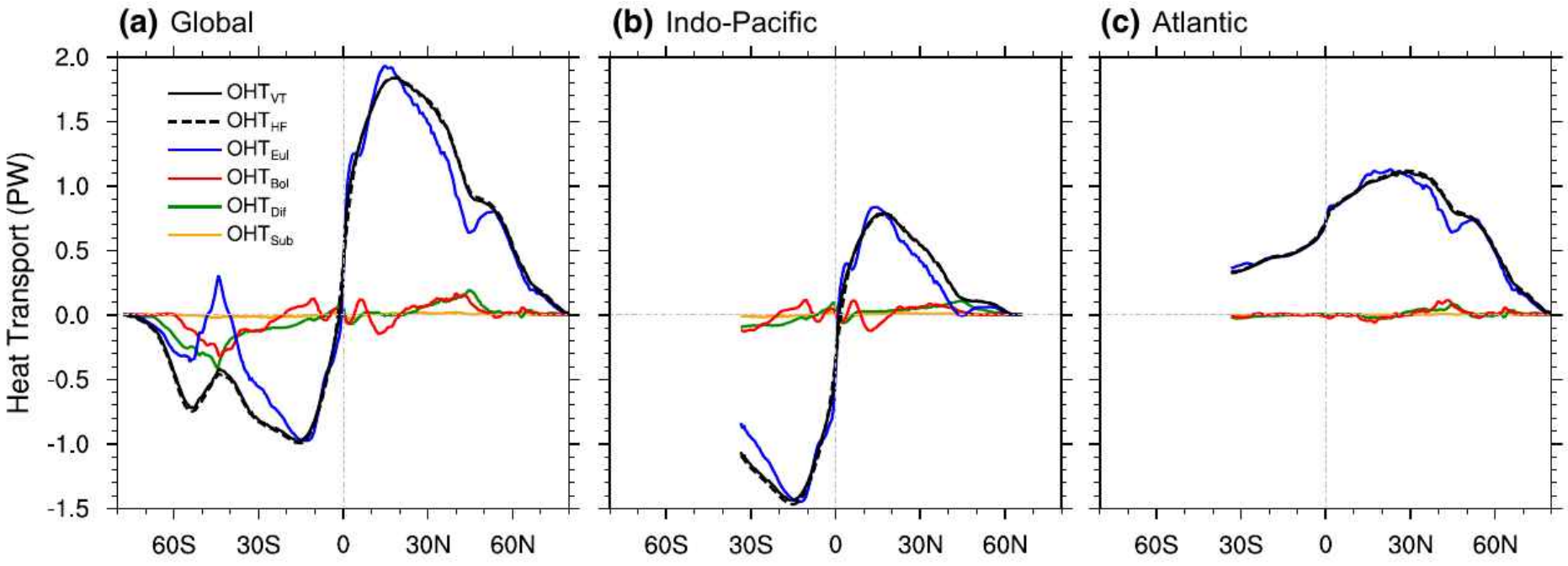


Surface Ocean Currents



Latitudinal Transport

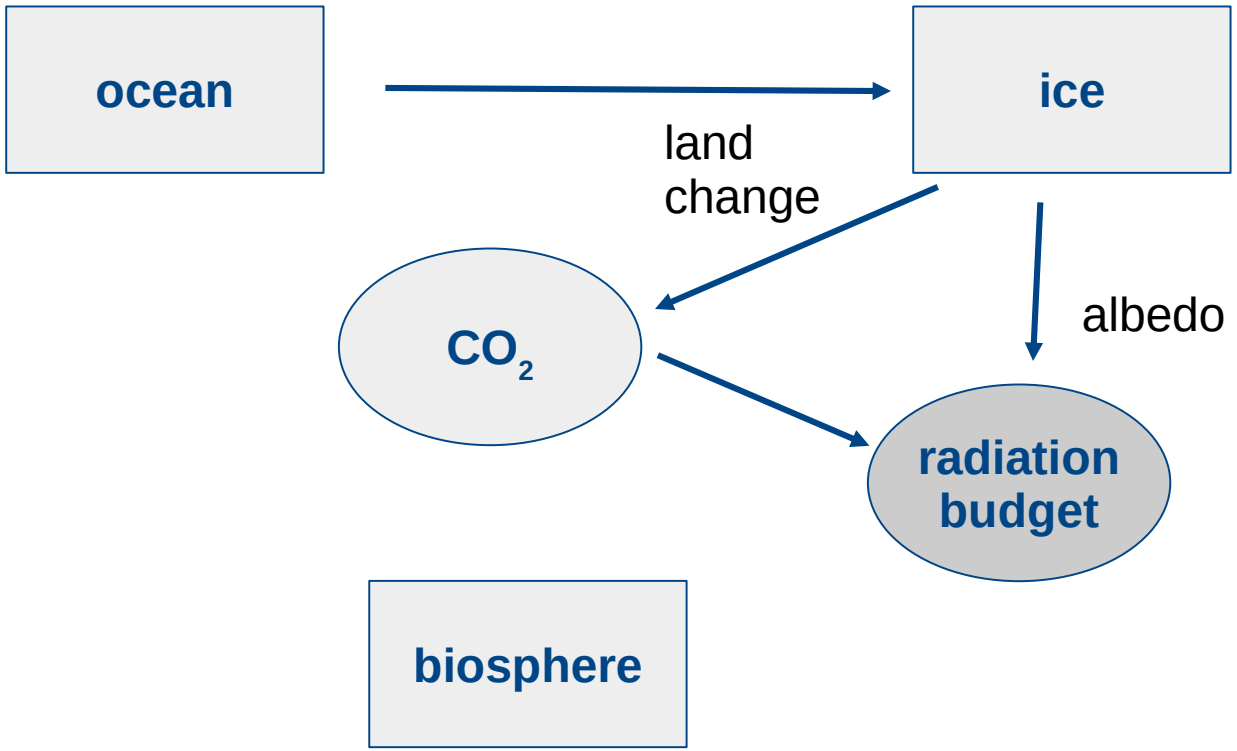
northward ocean heat transport



Yang et al. (2015)
Climate Dynamics

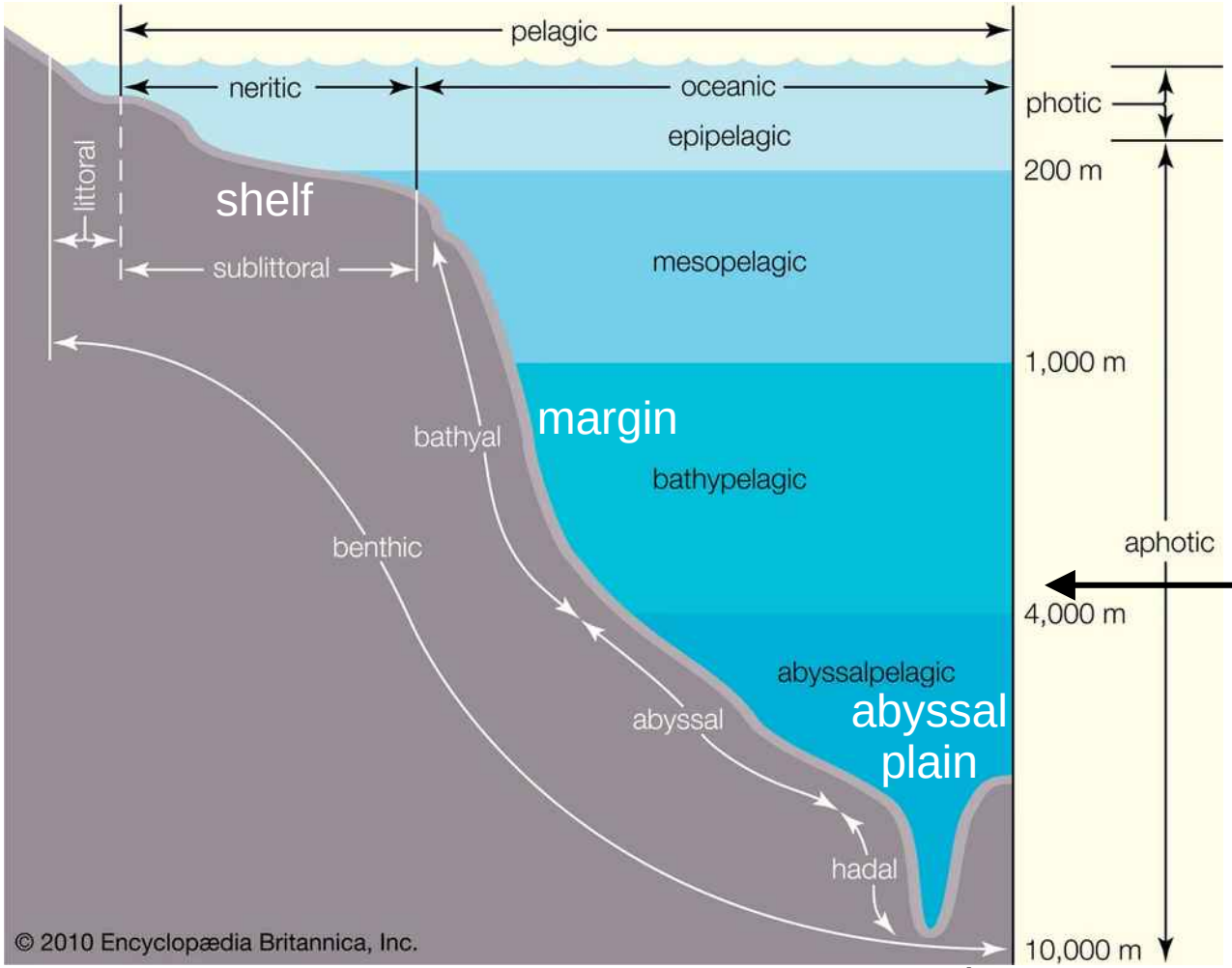
Last Glacial Cycle

most relevant climate players

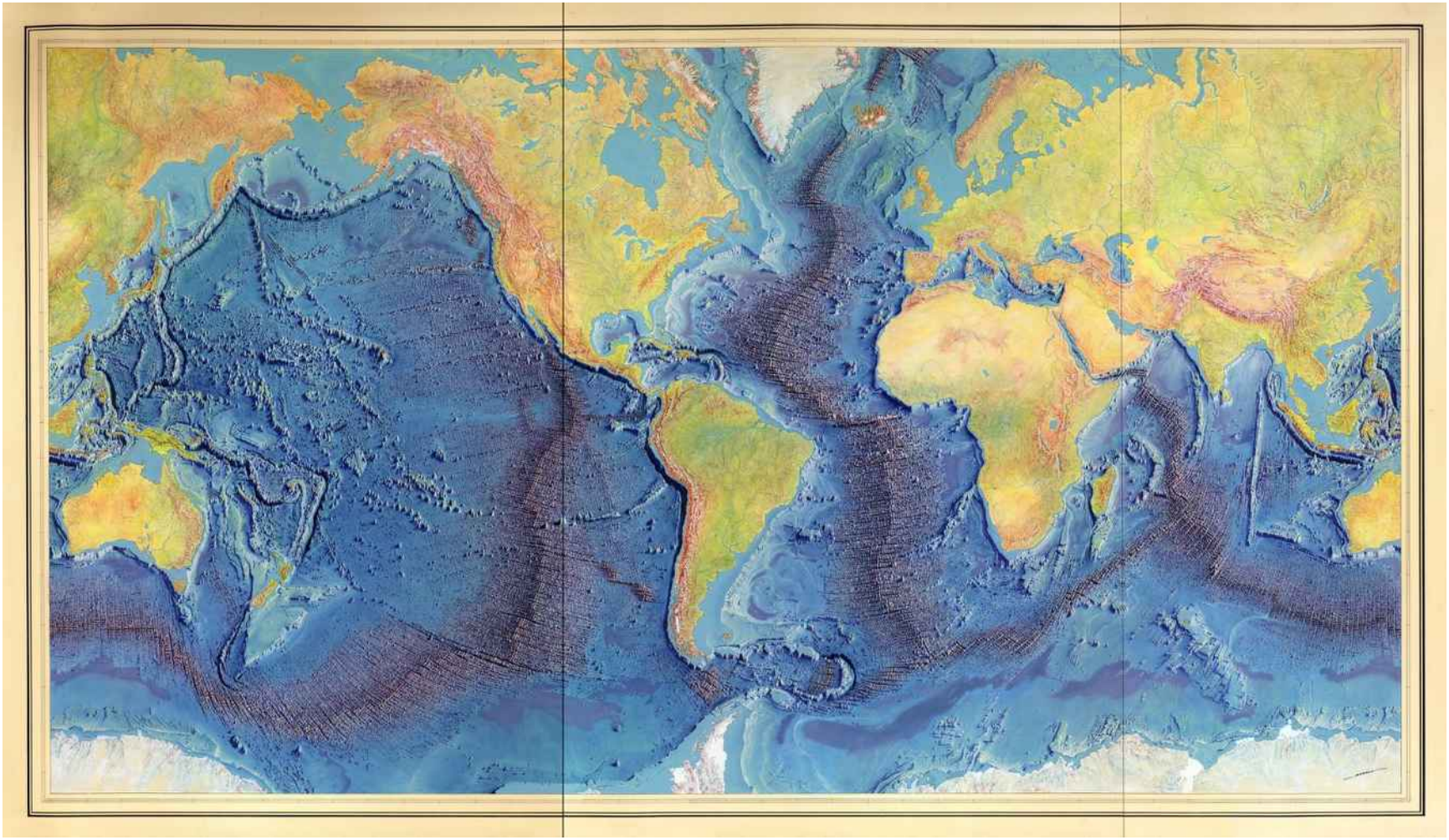


The Deep Ocean

Ocean Basins

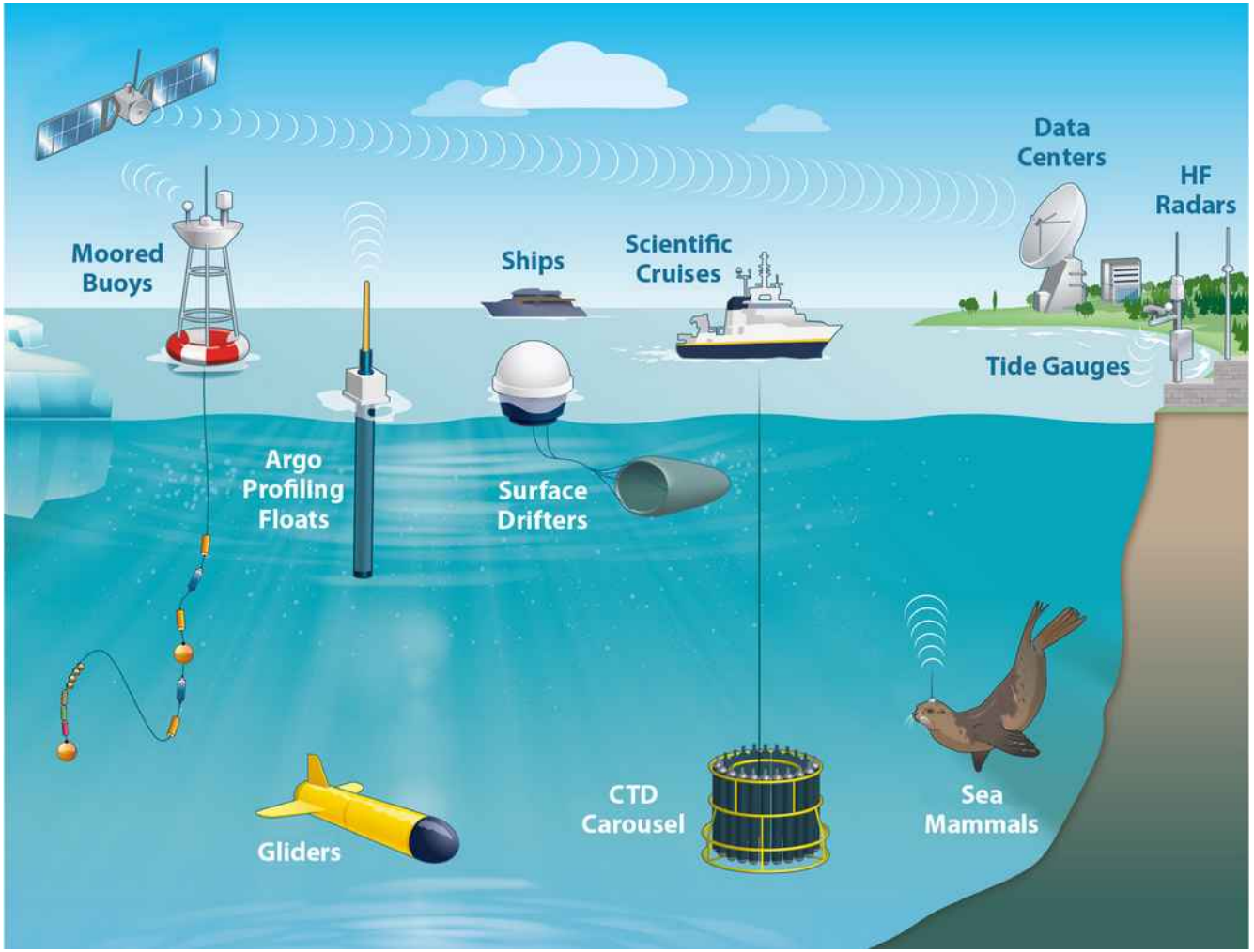


Ocean Basins



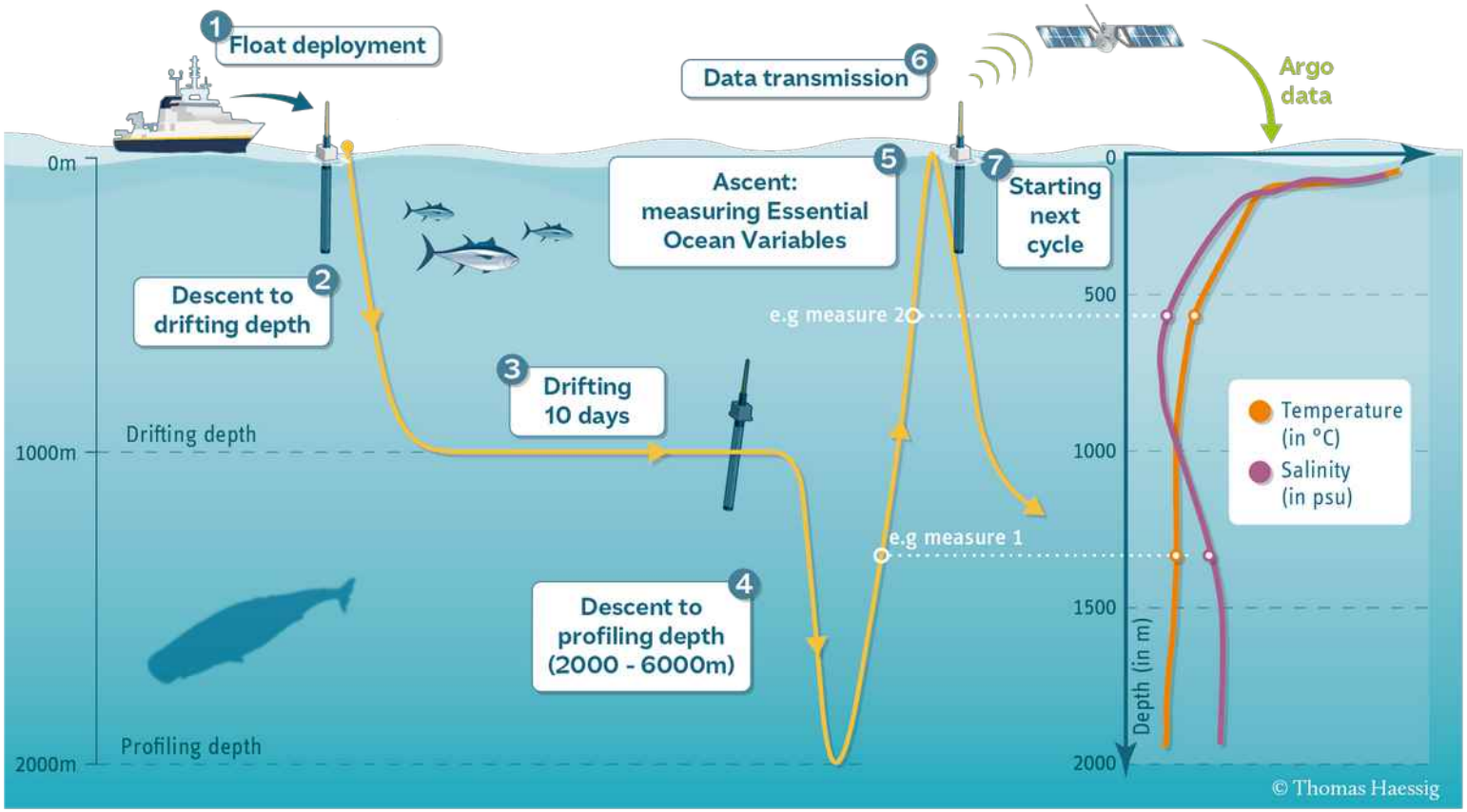
World Ocean Floor, Marie Tharp and Bruce Heezen (1977), Columbia University

The Deep Ocean - Observations



The Deep Ocean - Observations

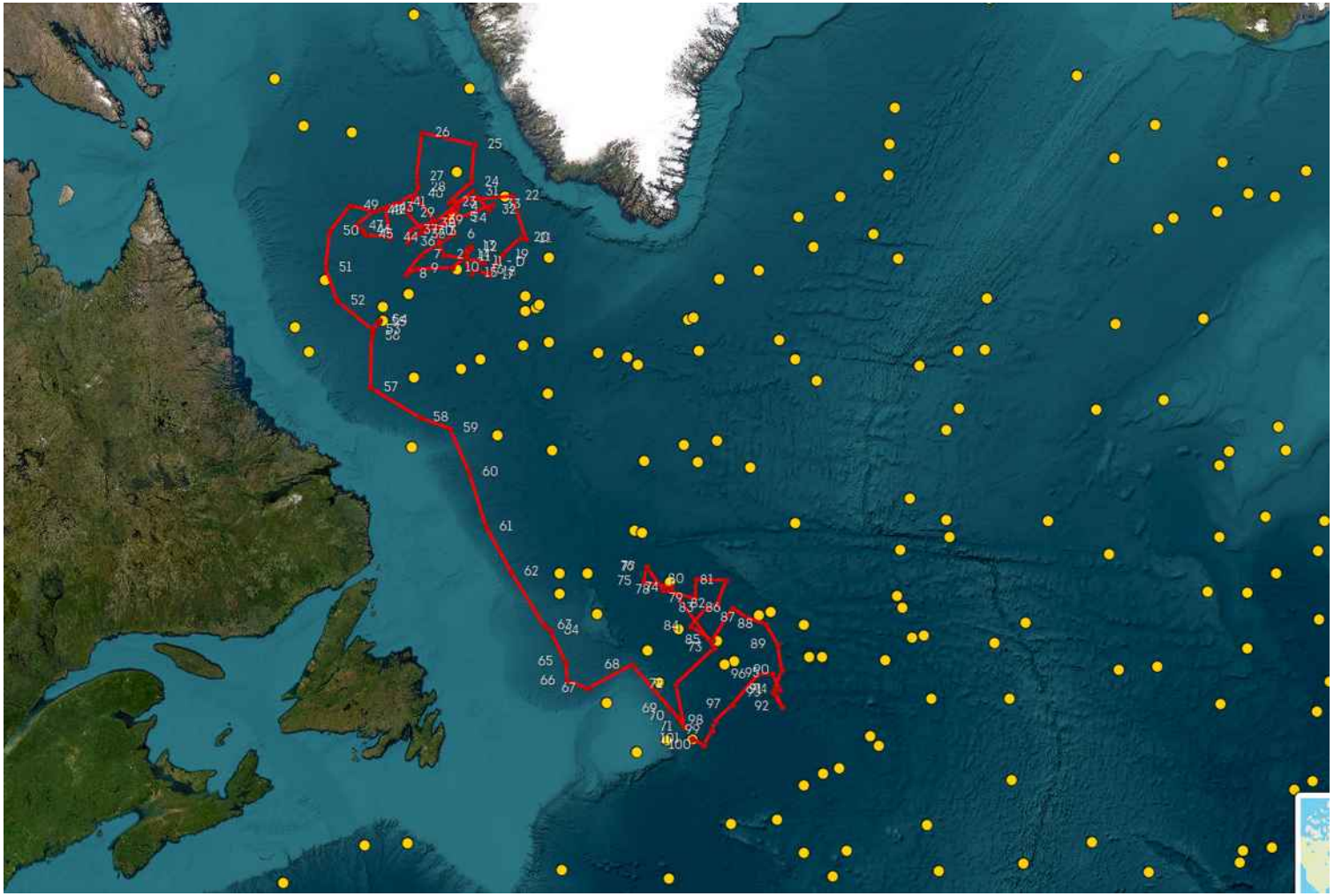
The Argo drifter array



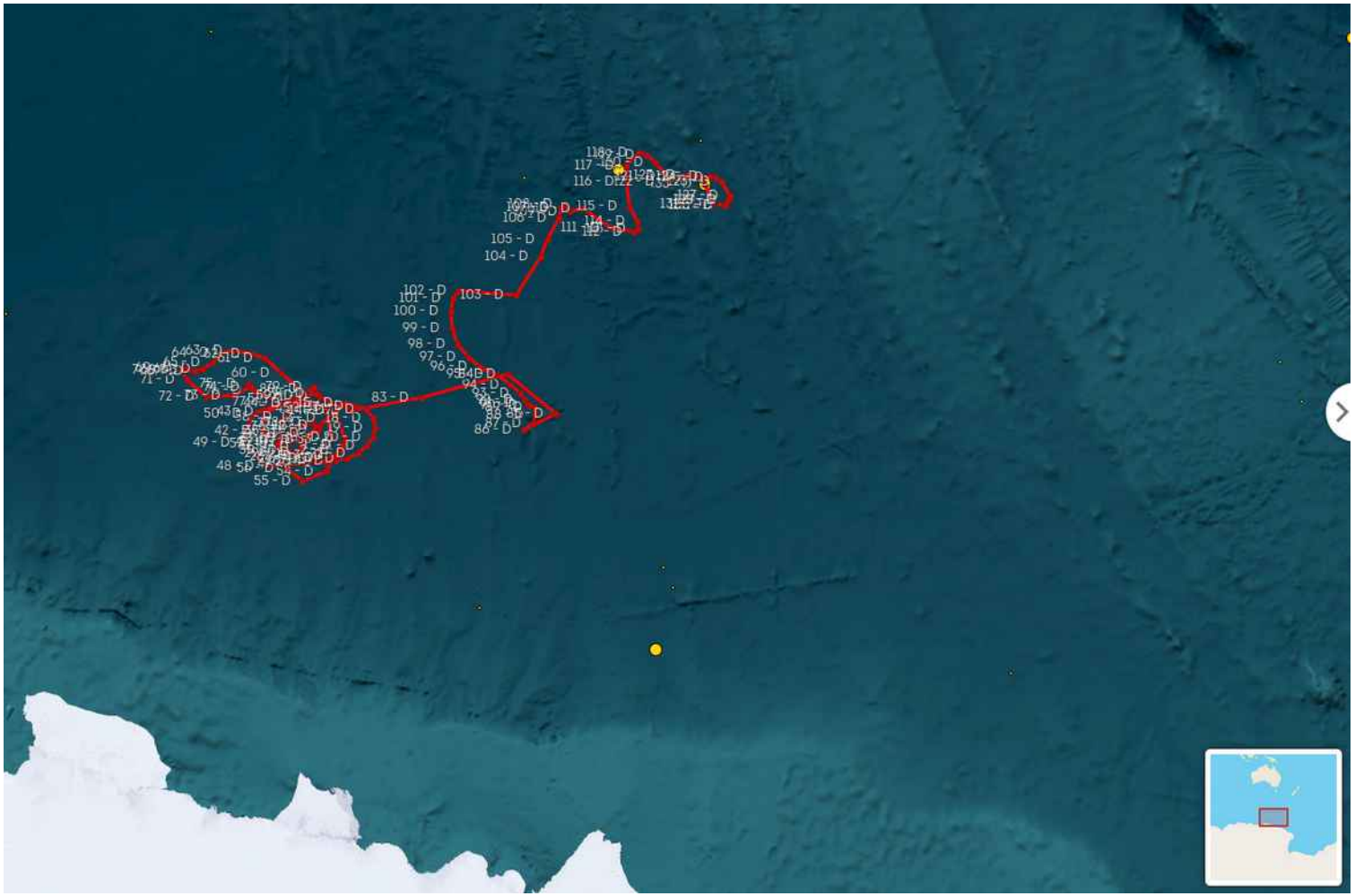
The Deep Ocean - Observations

all active Argo floats

The Deep Ocean - Observations



The Deep Ocean - Observations



The Deep Ocean - Observations

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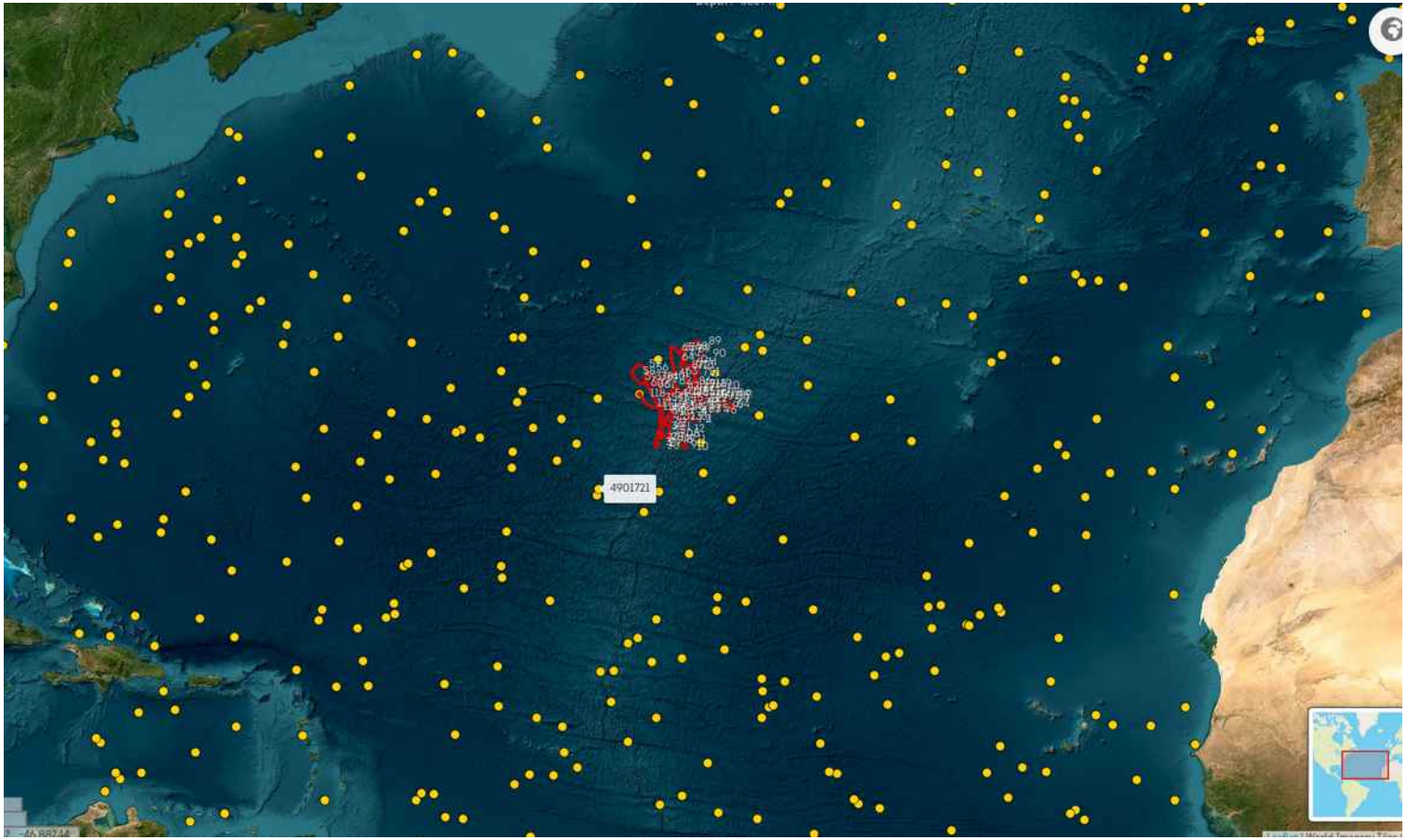
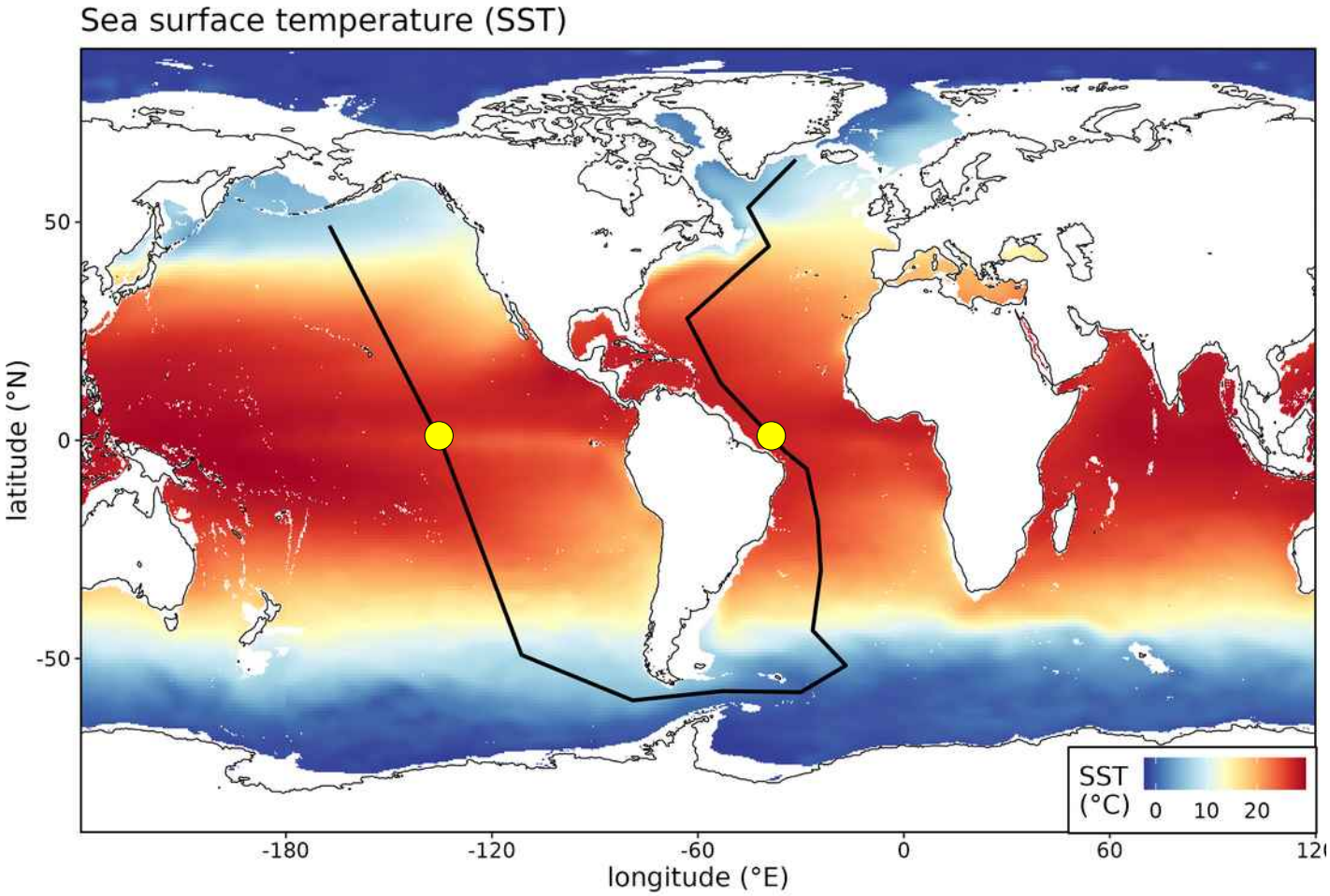
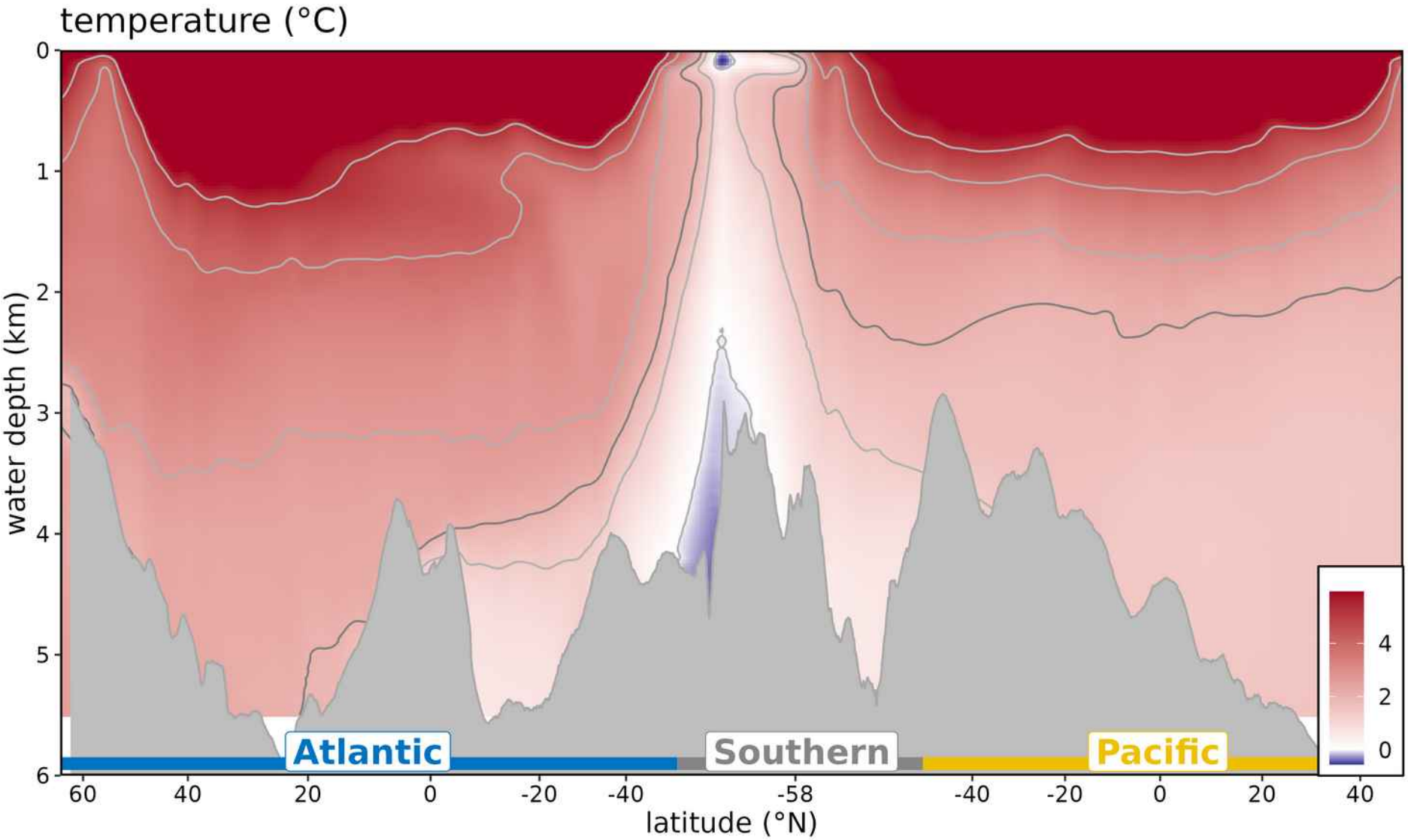


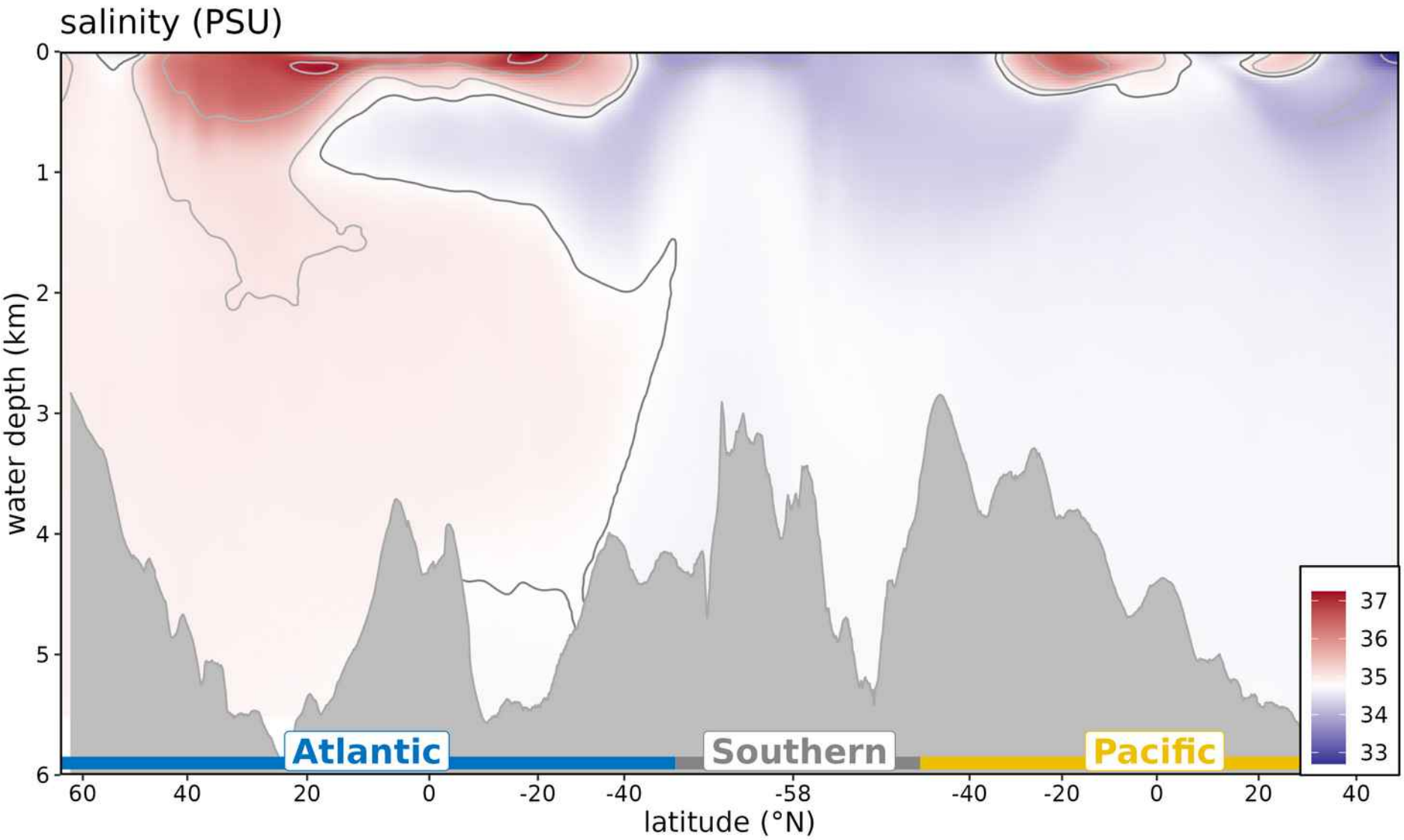
The Deep Ocean



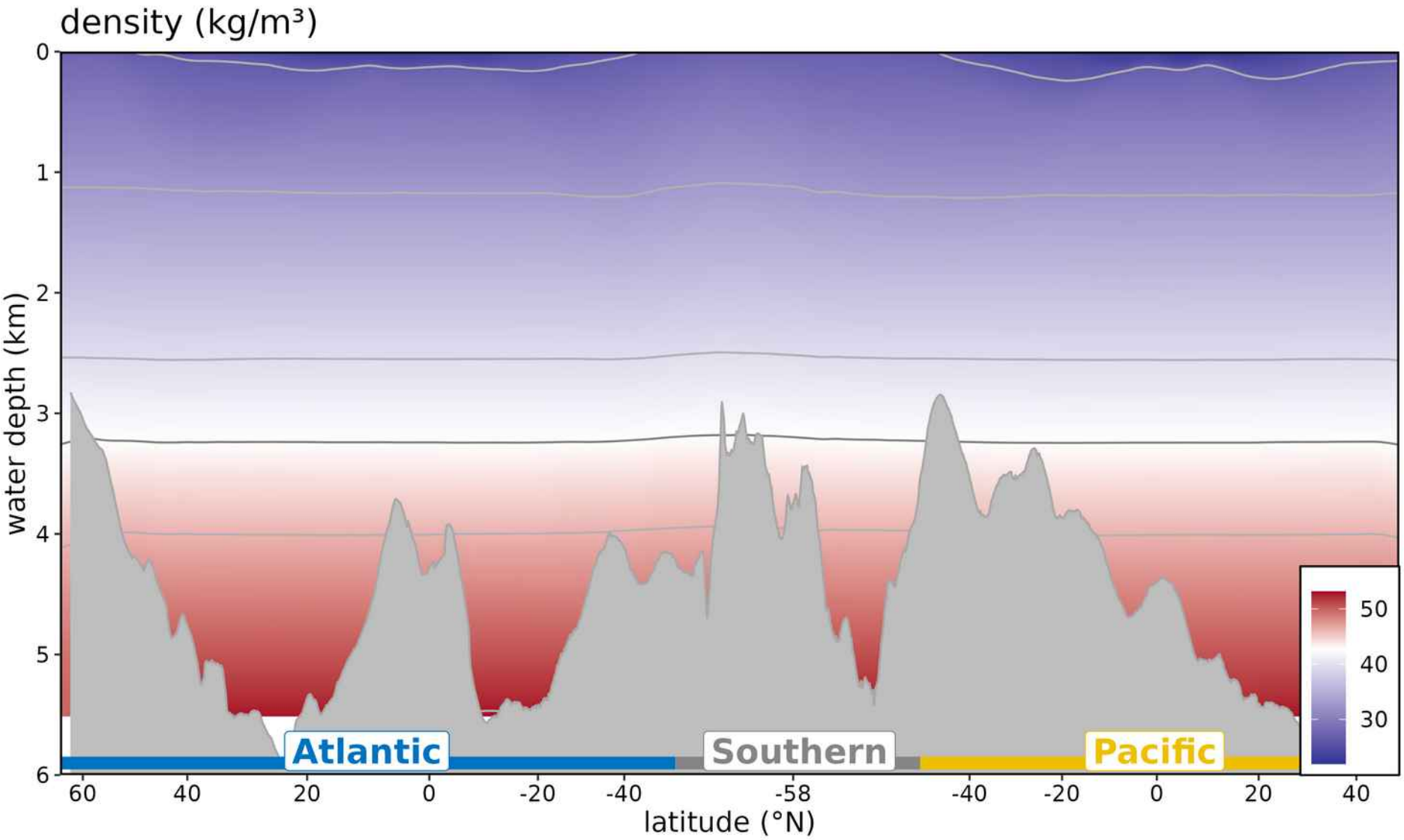
The Deep Ocean



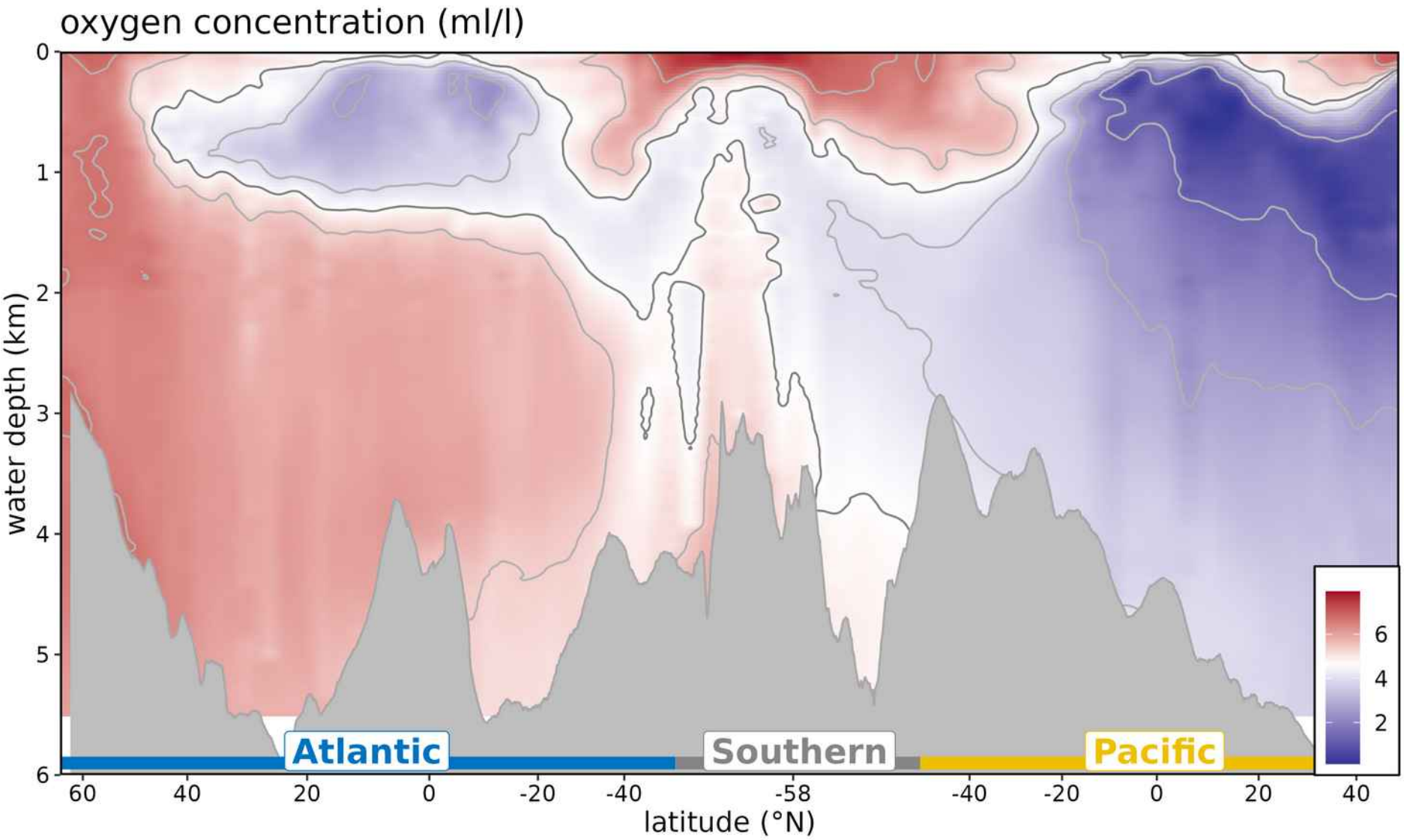
The Deep Ocean



The Deep Ocean



The Deep Ocean



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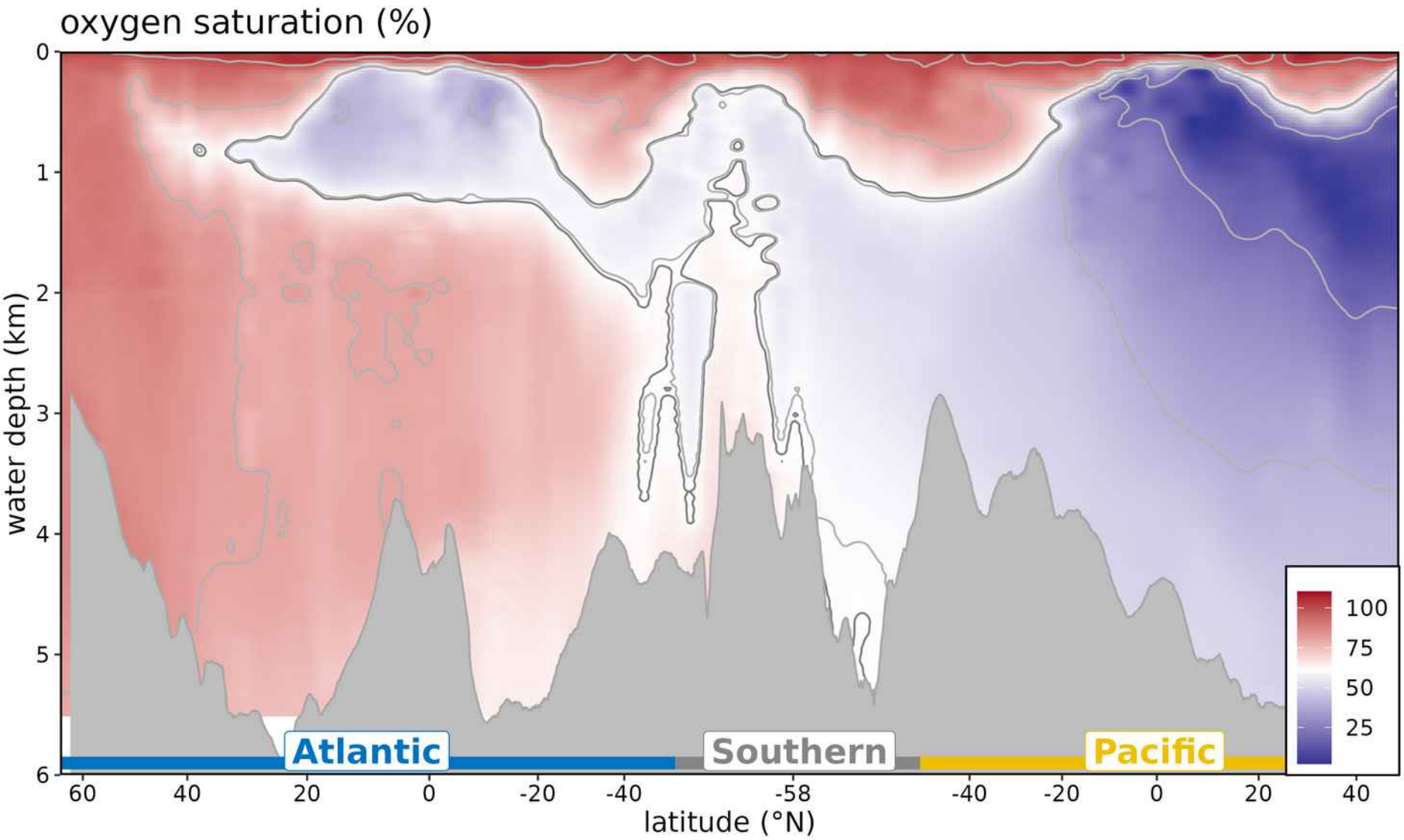
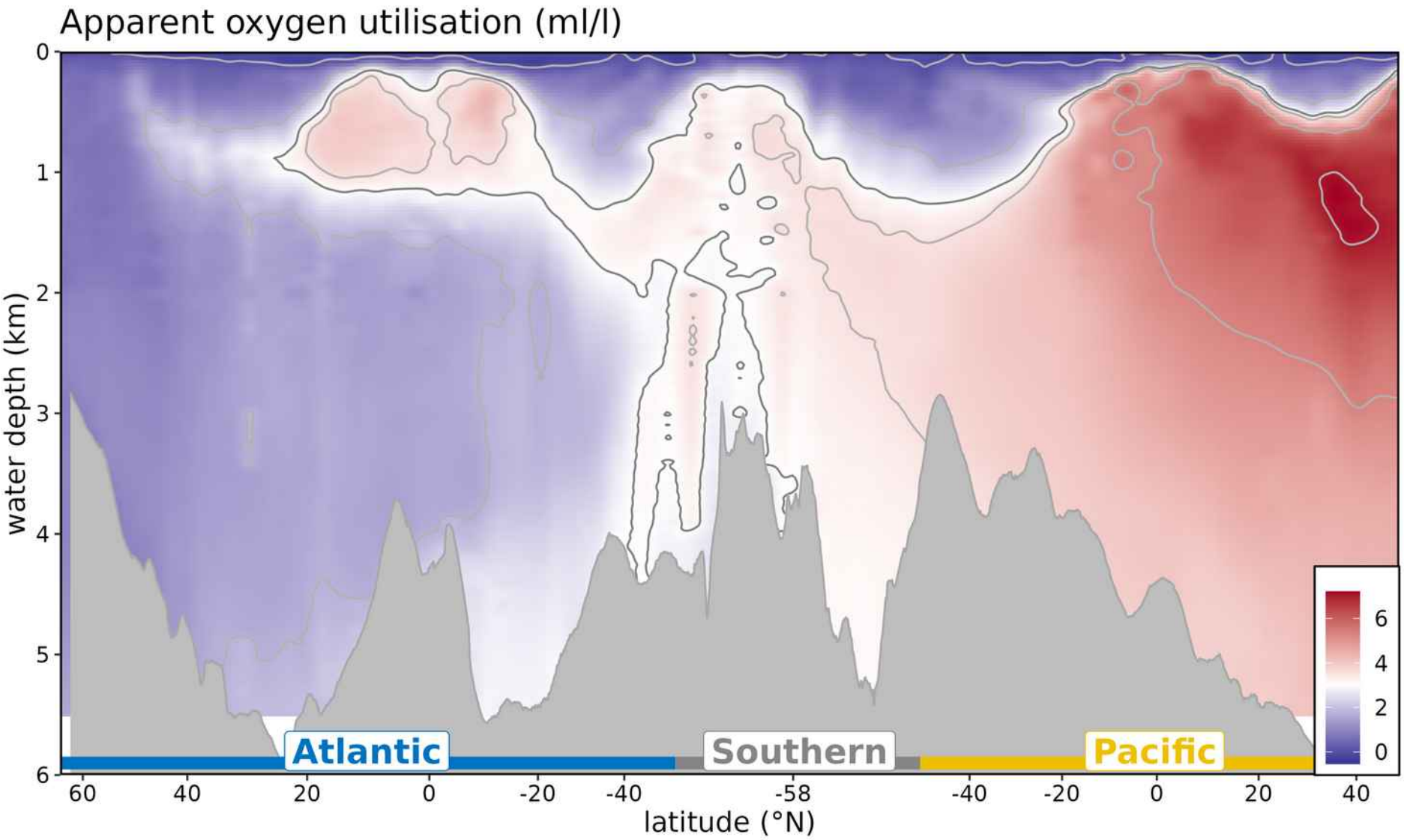
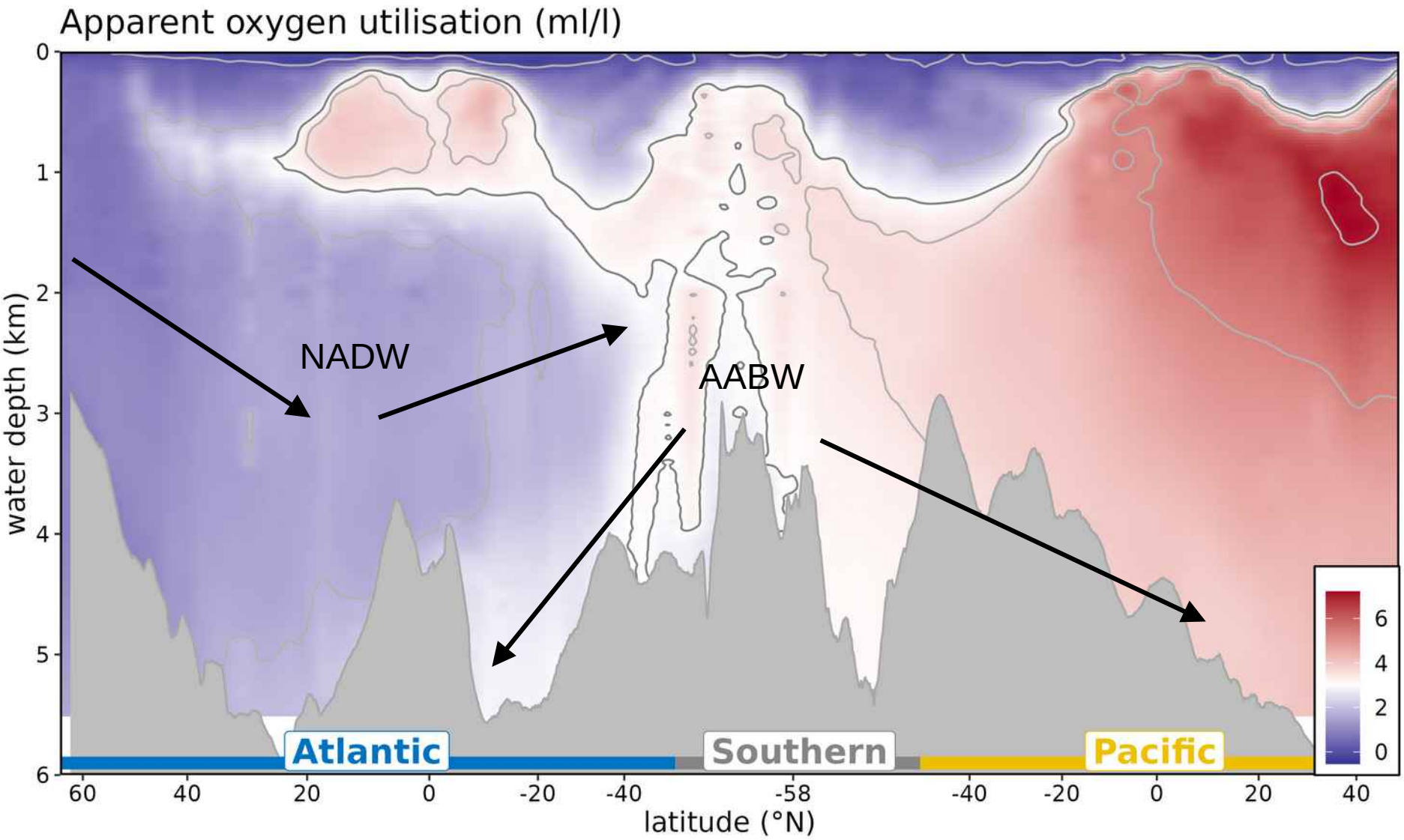


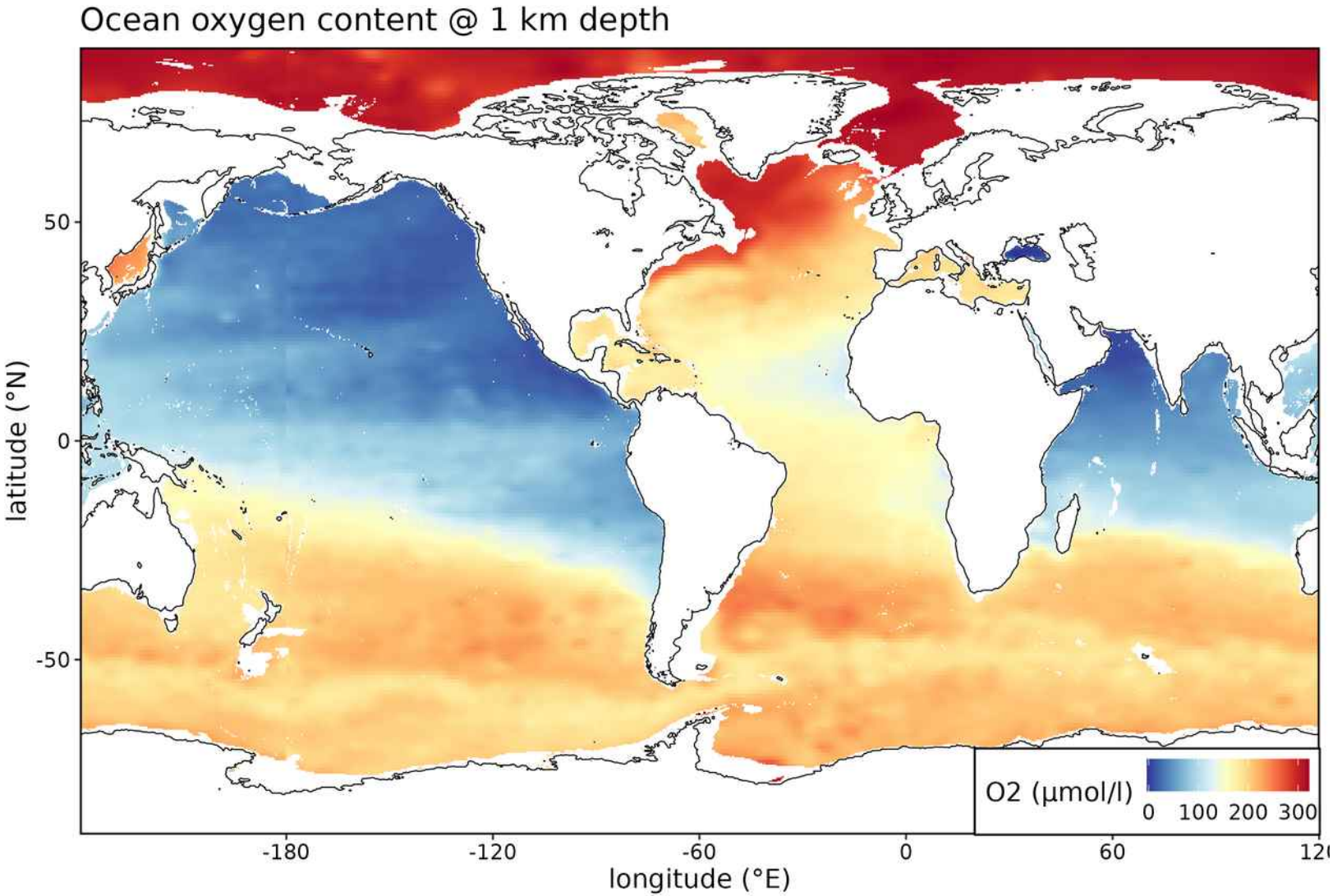
The Deep Ocean



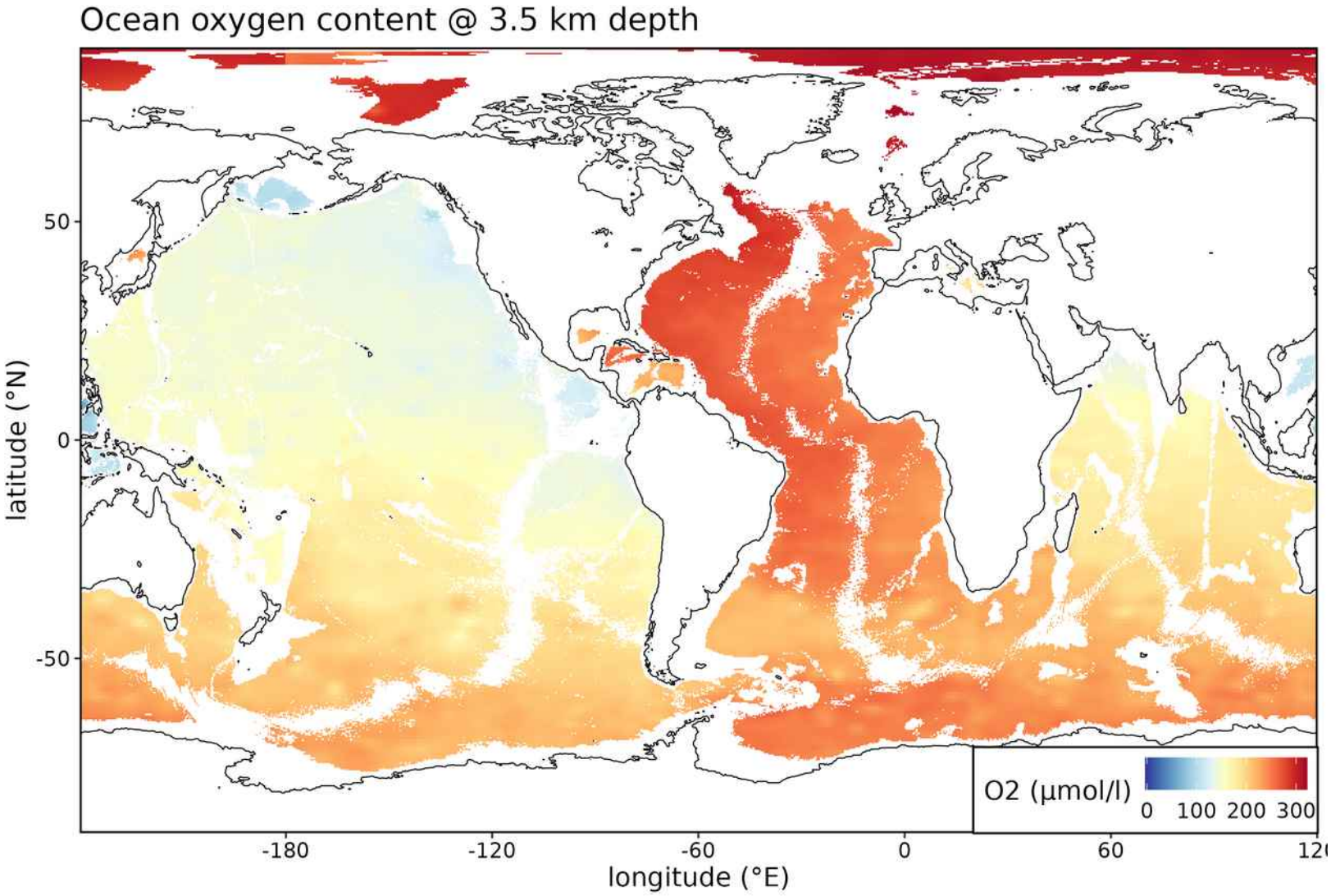
The Deep Ocean



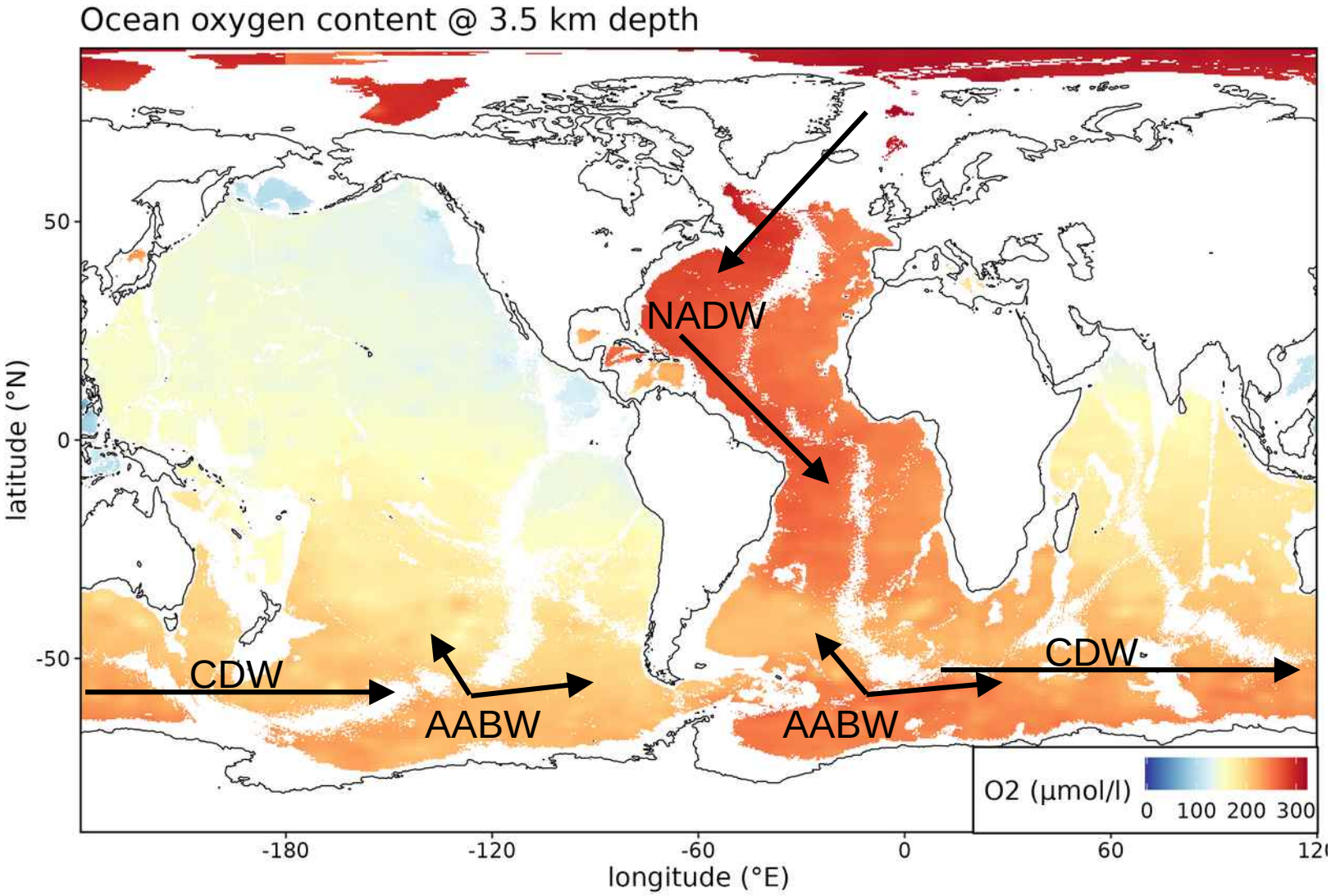
The Deep Ocean



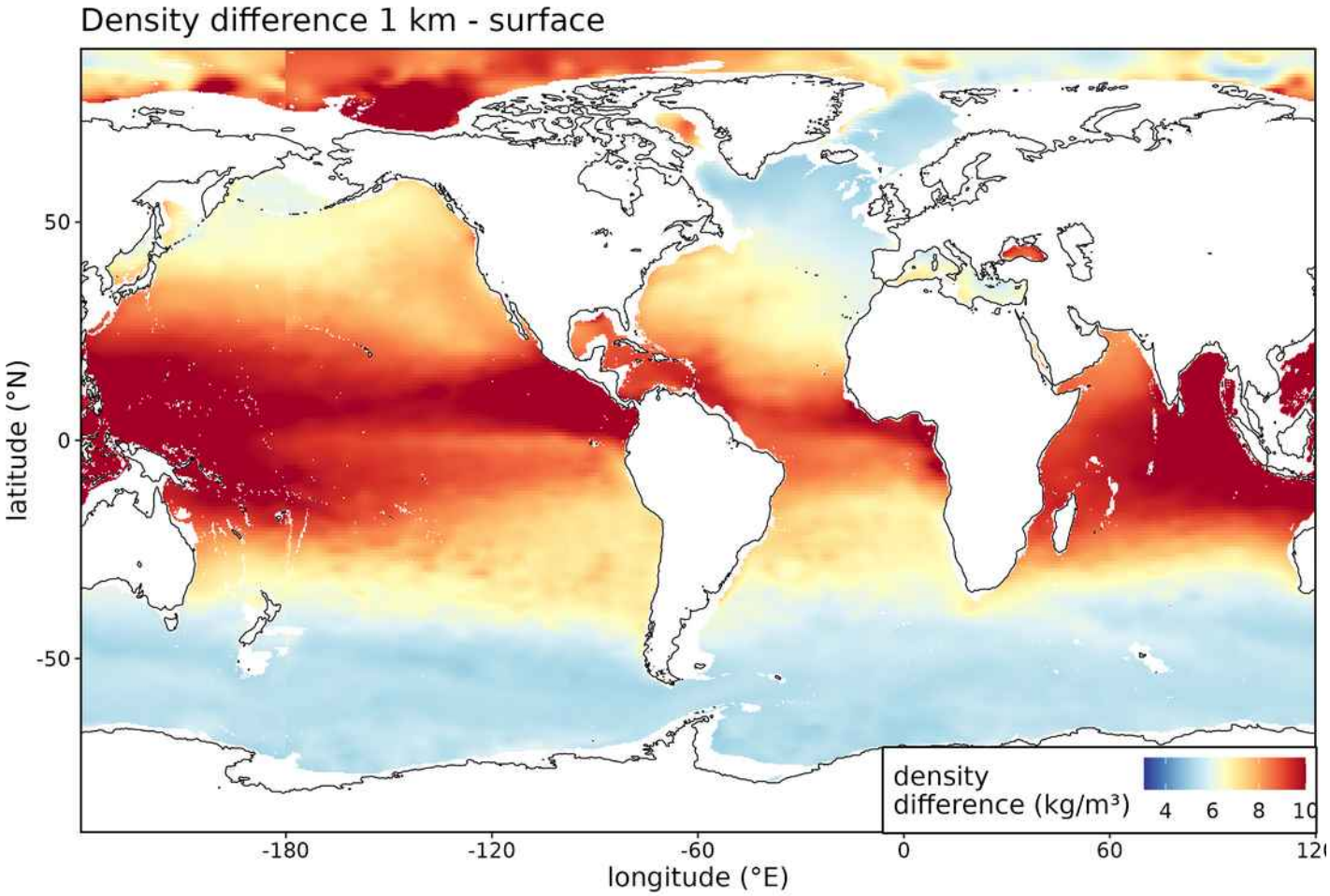
The Deep Ocean



The Deep Ocean

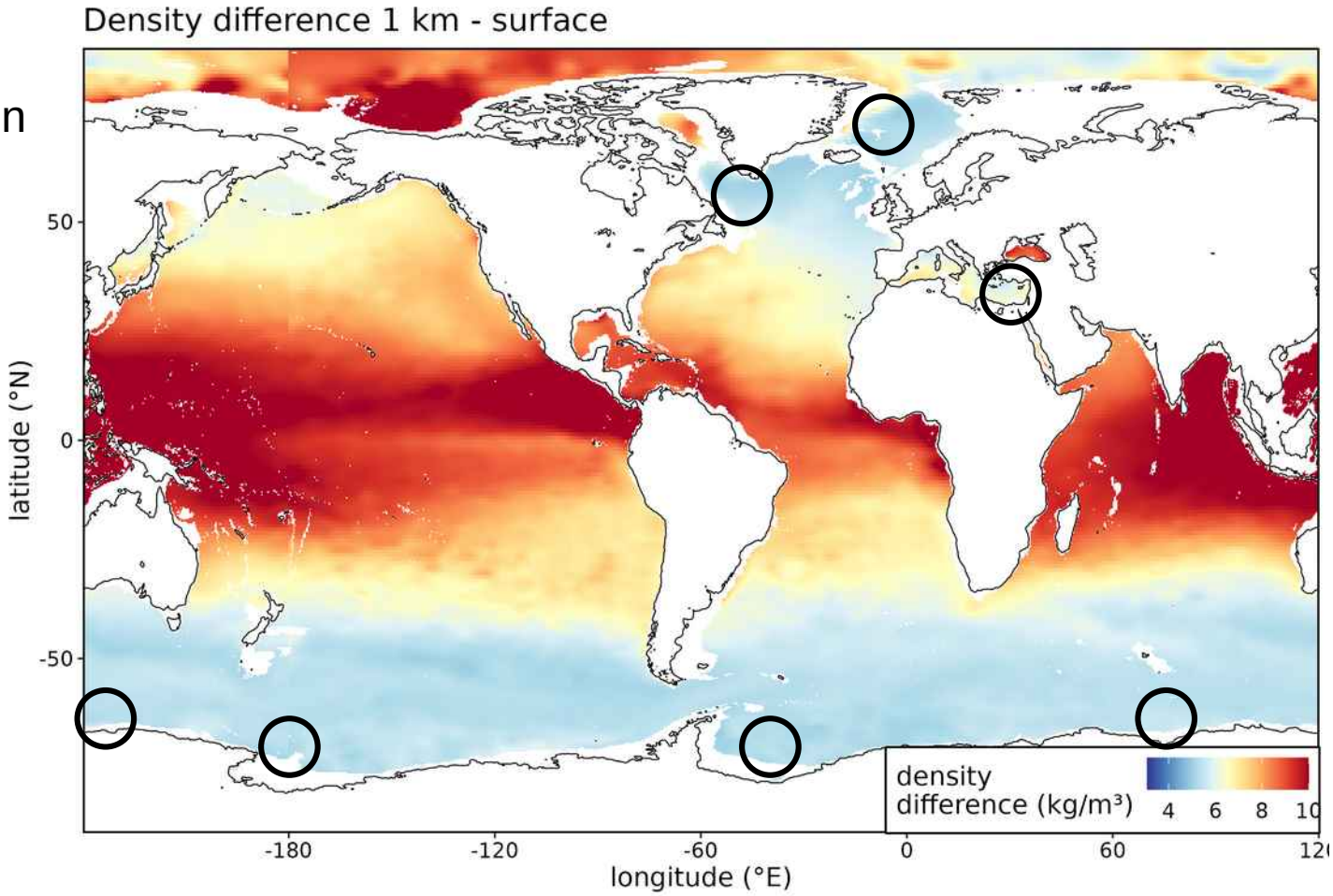


The Deep Ocean



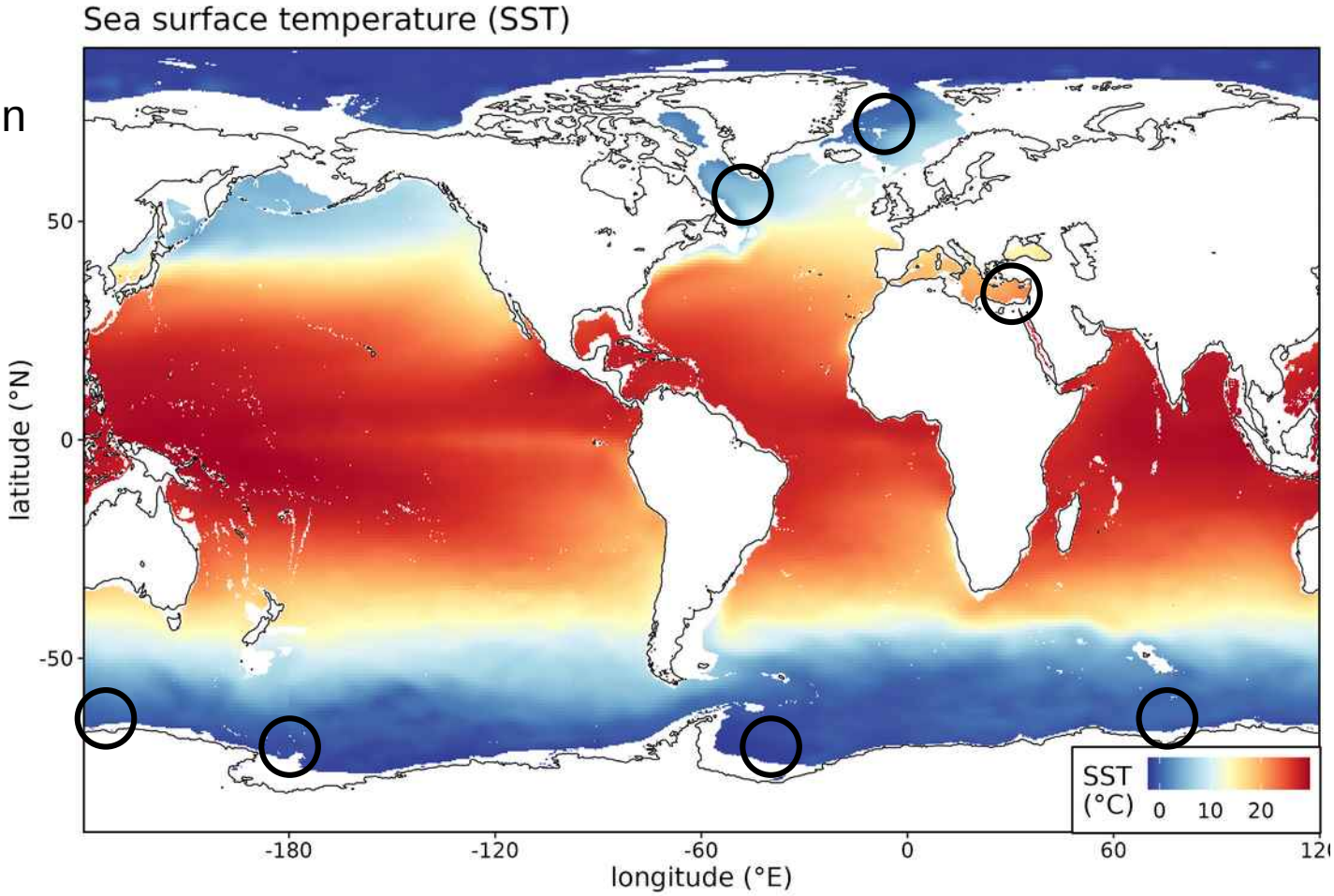
The Deep Ocean

Deep convection



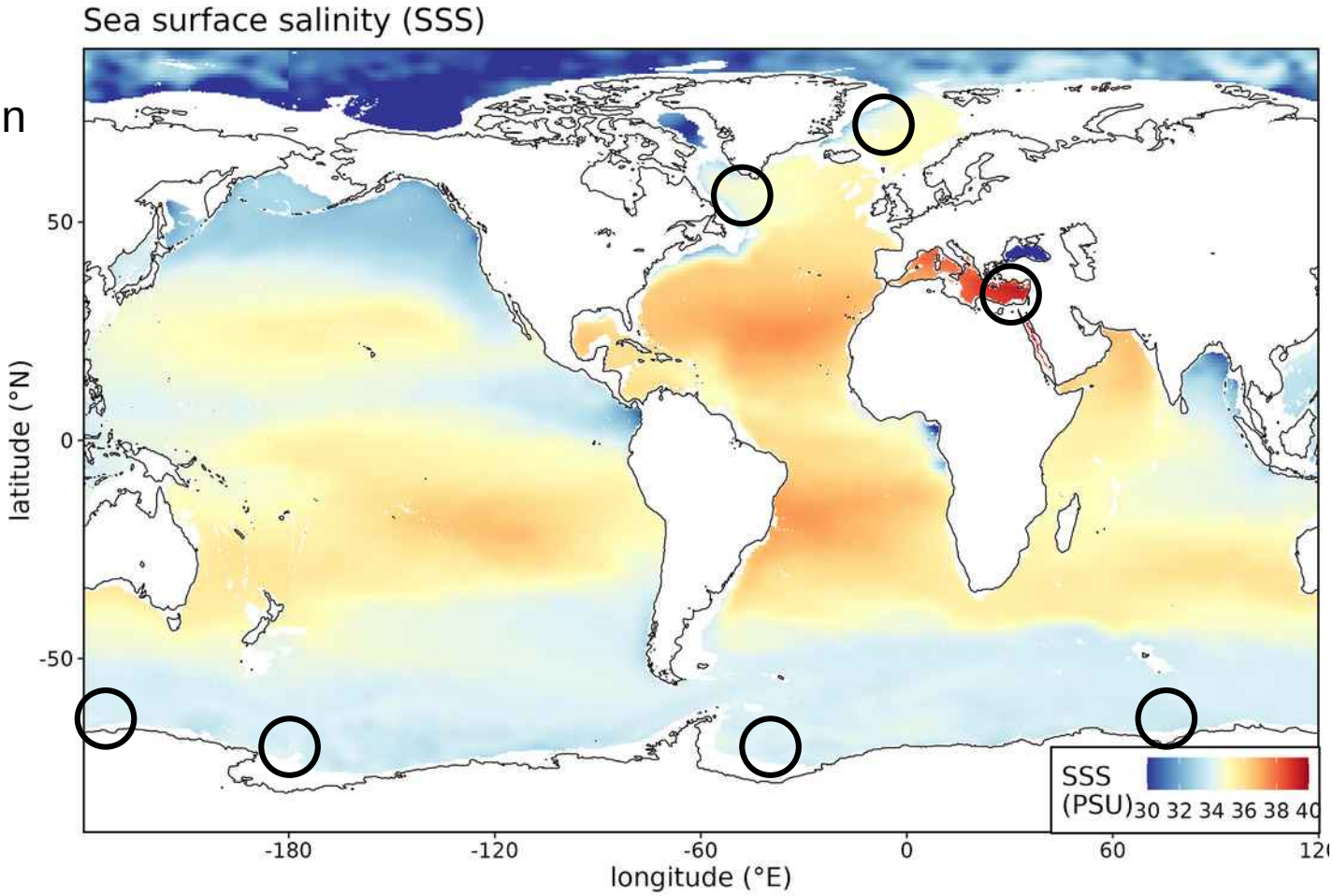
The Deep Ocean

Deep convection

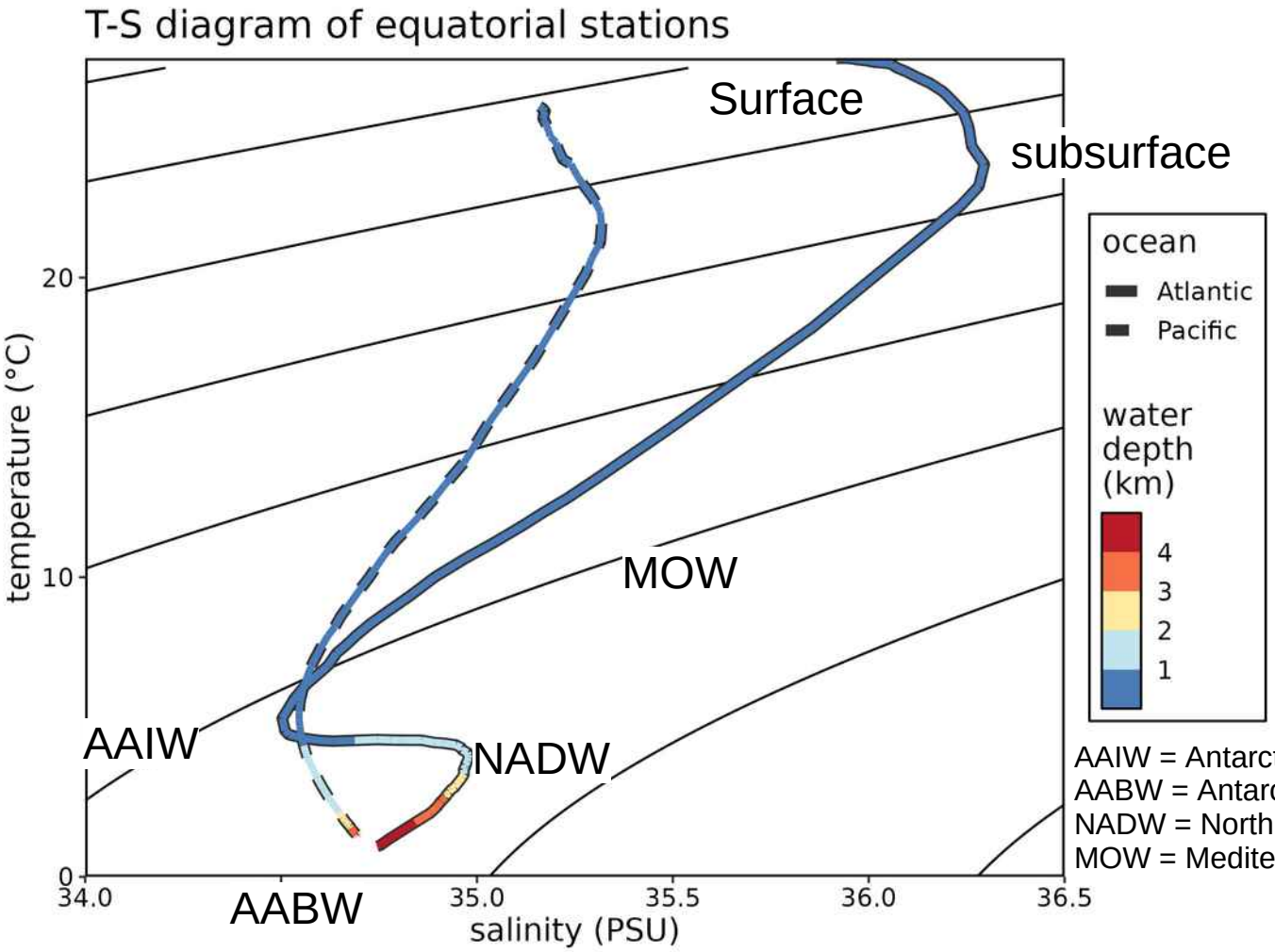


The Deep Ocean

Deep convection



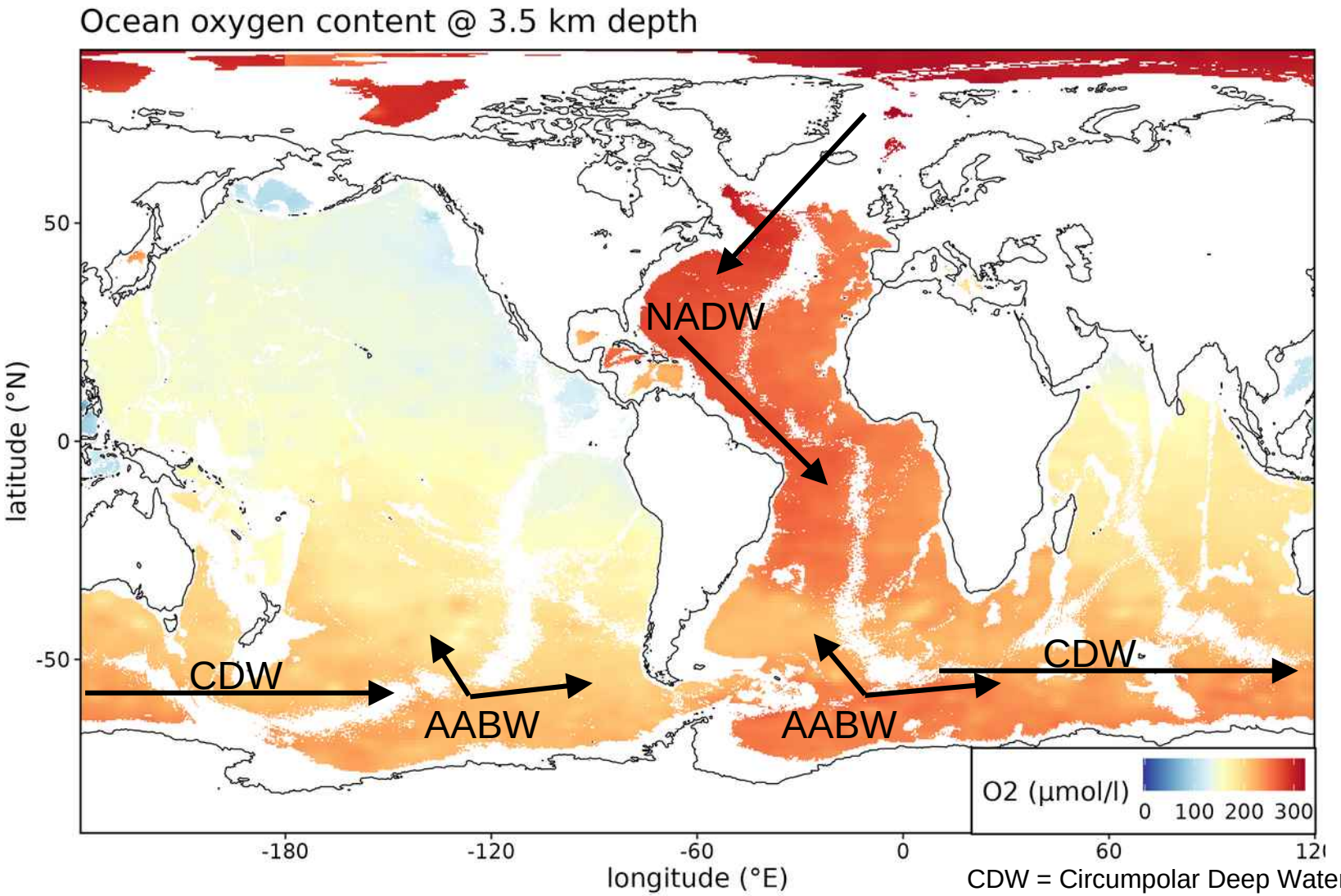
The Deep Ocean



AAIW = Antarctic Intermediate W.
AABW = Antarctic Bottom W.
NADW = North Atlantic Deep W.
MOW = Mediterranean Outflow W.

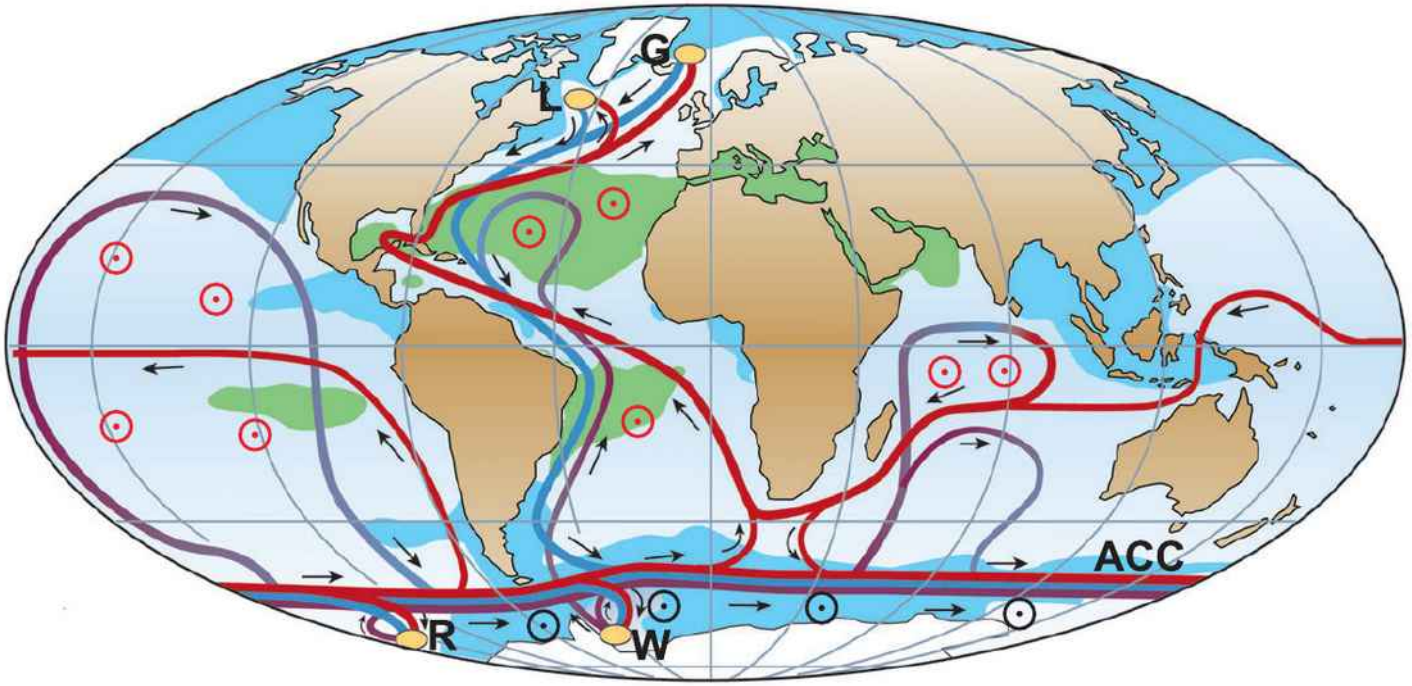
UNIL | Université de Lausanne

The Deep Ocean



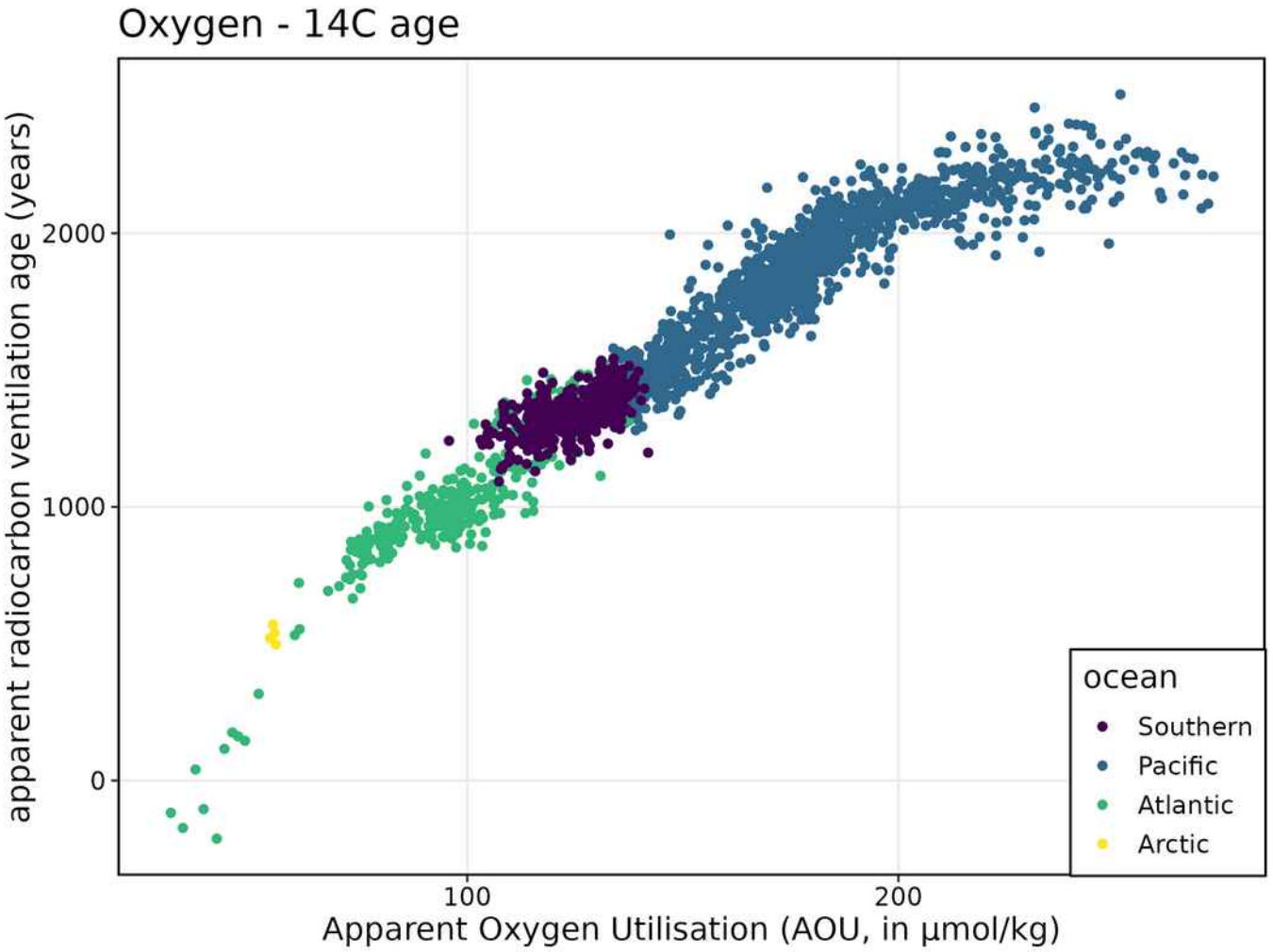
CDW = Circumpolar Deep Water

The Deep Ocean



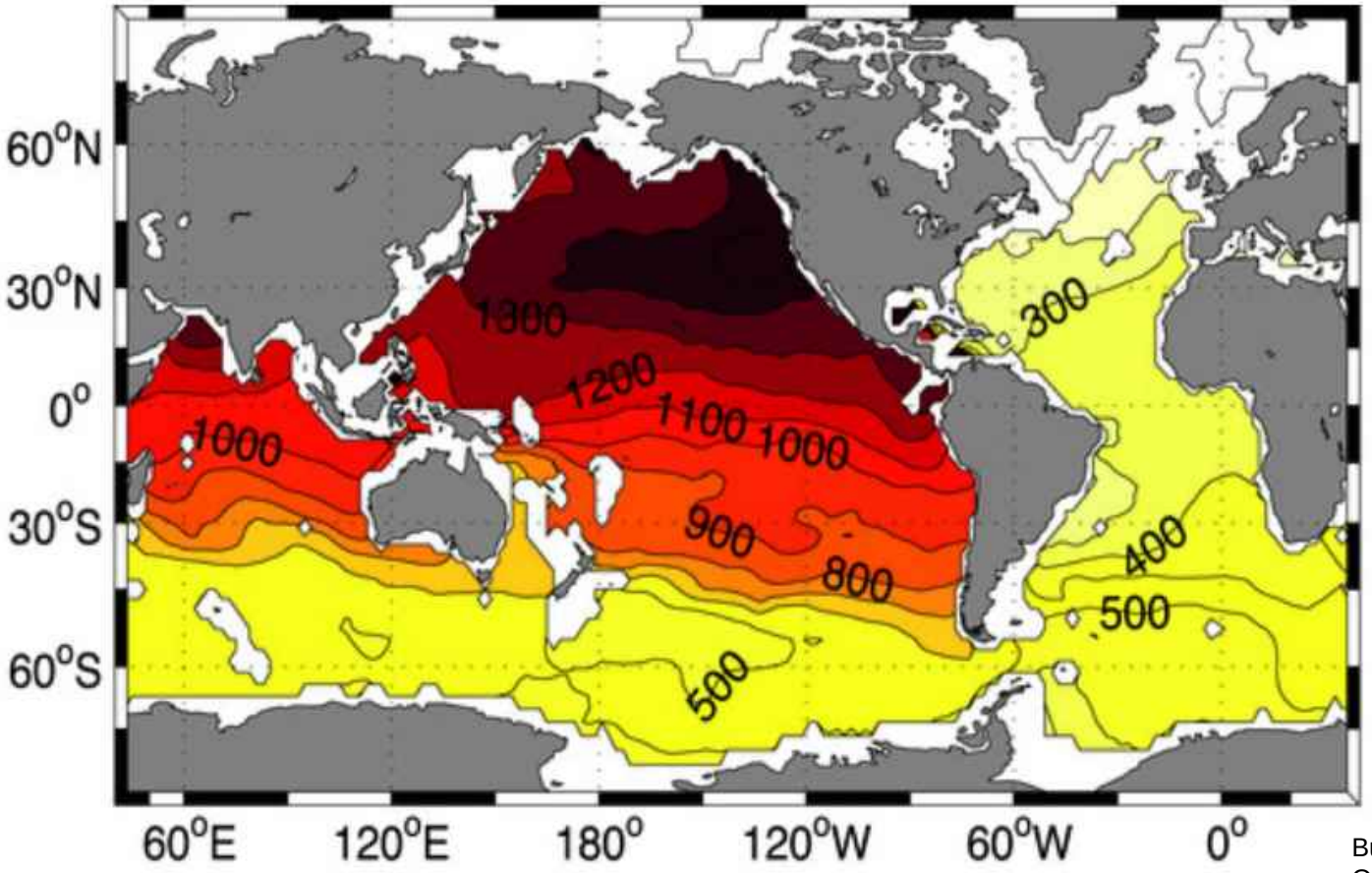
Rahmstorf (2006)
Enciclopedia of Quaternary Sciences

Thermohaline Overturning



Thermohaline Overturning

deep water “age”

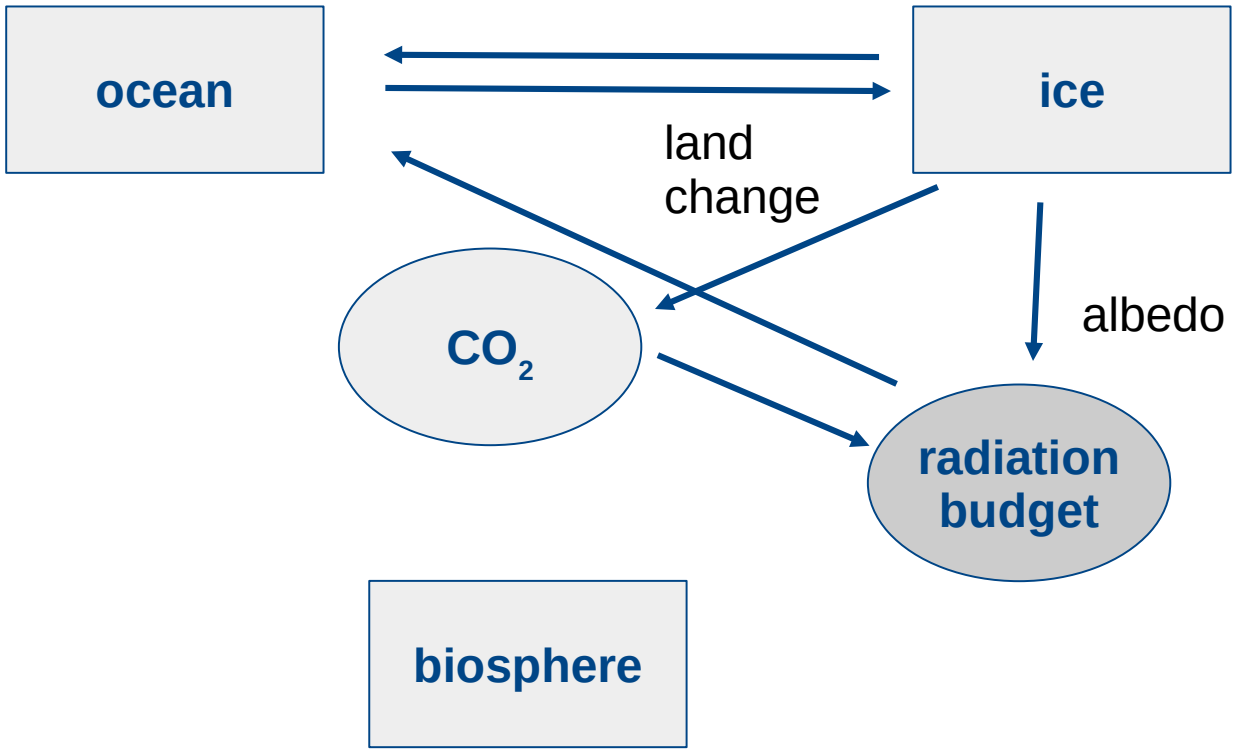


Bullister et al. (2013), Ocean Circulation and Climate

old water = low O_2 = high nutrient / DIC

Last Glacial Cycle

most relevant climate players



Ocean Biochemistry

Marine Primary Production

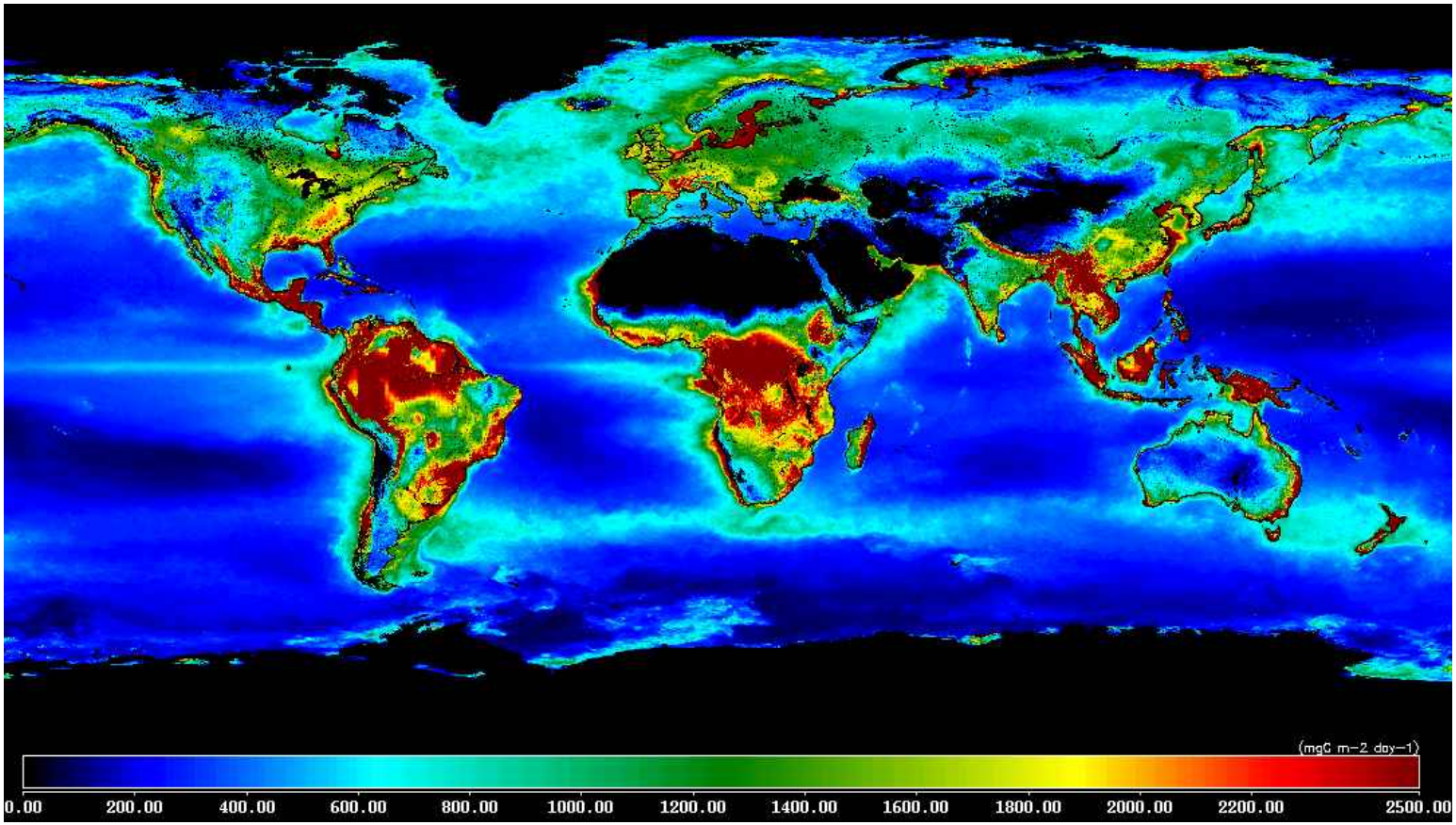
Marine Primary Production

silicate shell
(~ biogenic opal)

carbonate shell

Marine Primary Production

Primary productivity



Roughly 1/3 – ½ in the oceans

http://orca.science.oregonstate.edu

Marine Primary Production

silicate shell
(~ biogenic opal)

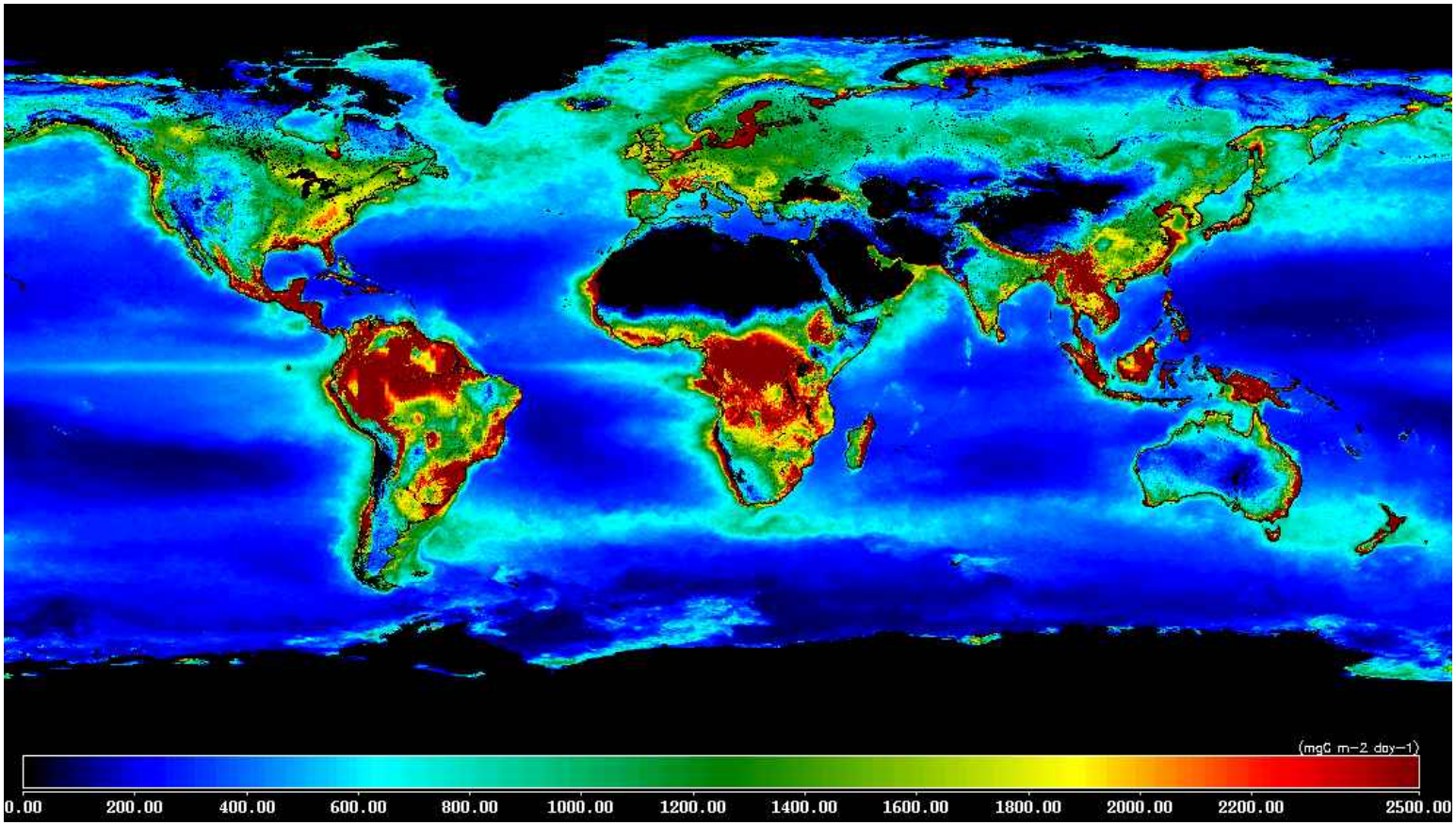
carbonate shell

require:

- light
- CO_2
- other major nutrients (N, P, Si, Ca)
- other micro nutrients (Fe,...)

Marine Primary Production

Primary productivity



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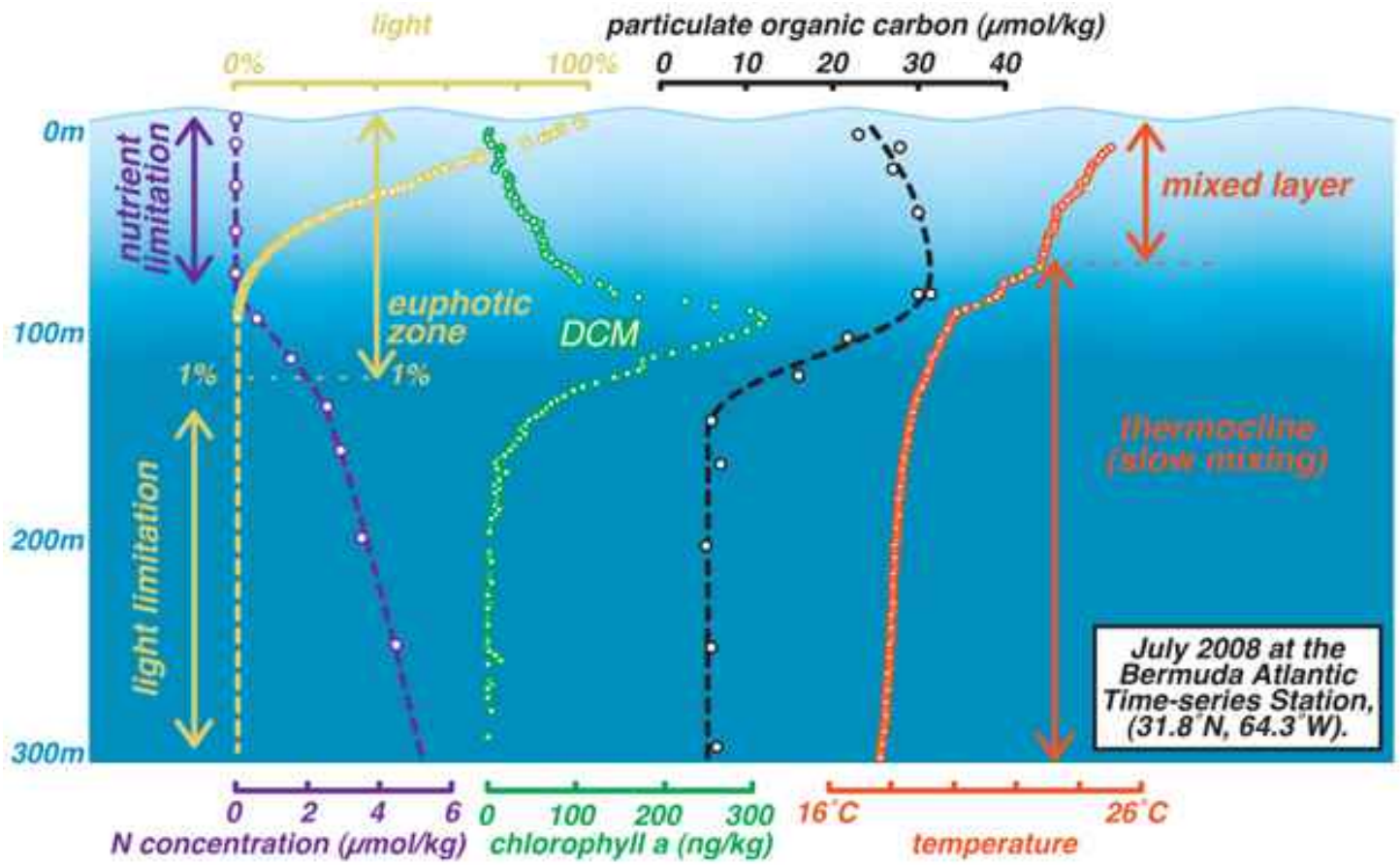
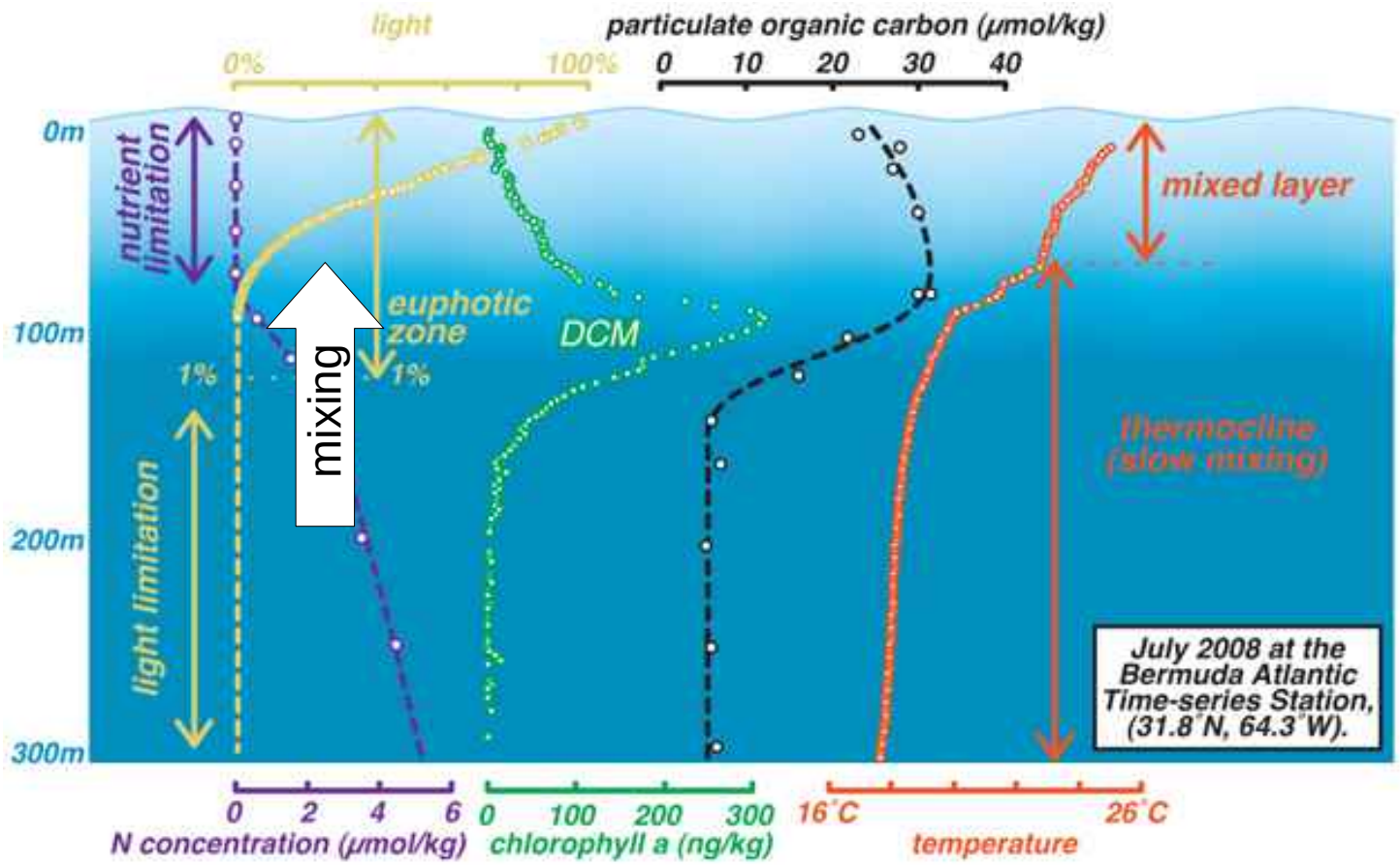


Nature education (2012)

Marine Primary Production



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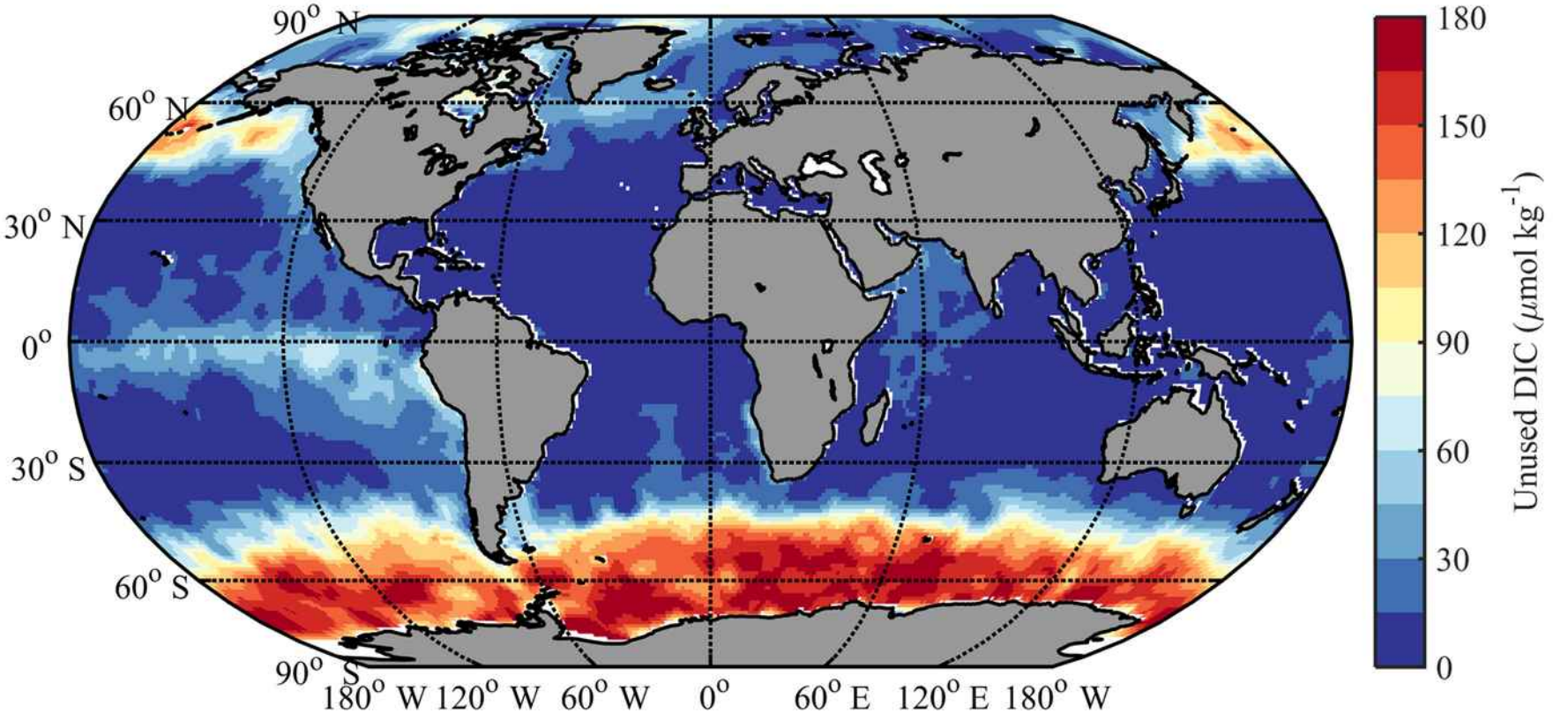
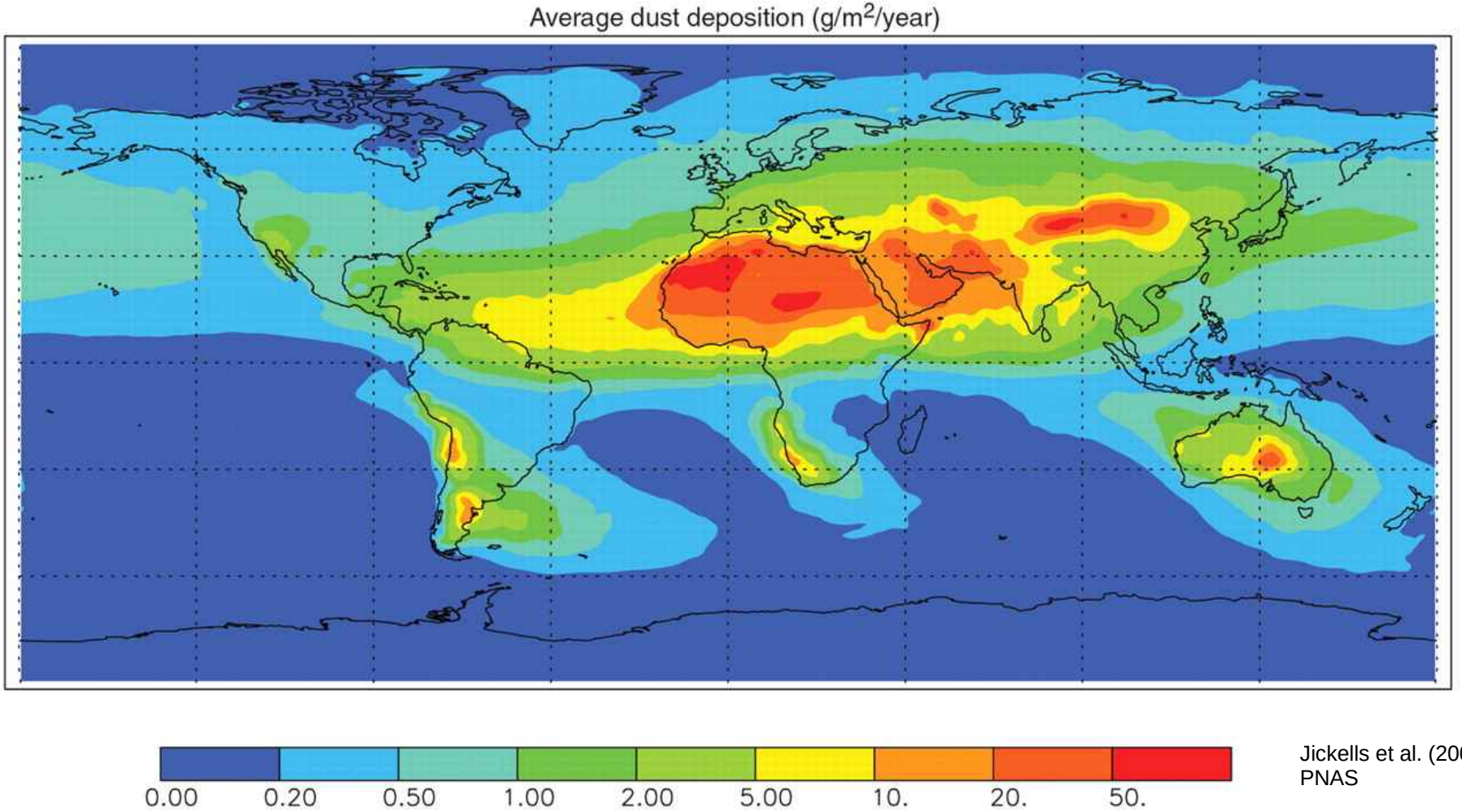
Marine Primary Production



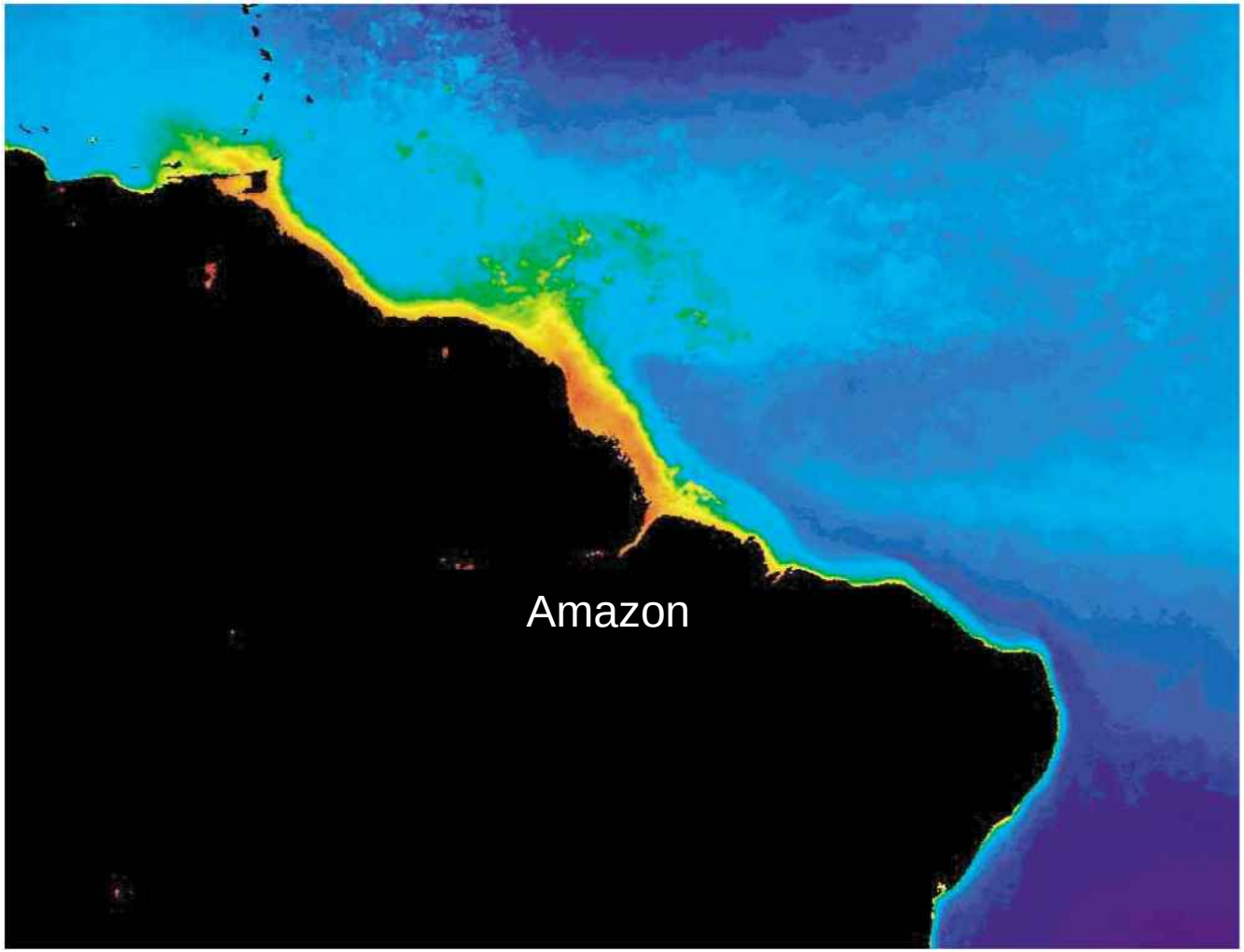
Wu et al. (2019), Biogeosciences

Marine Primary Production



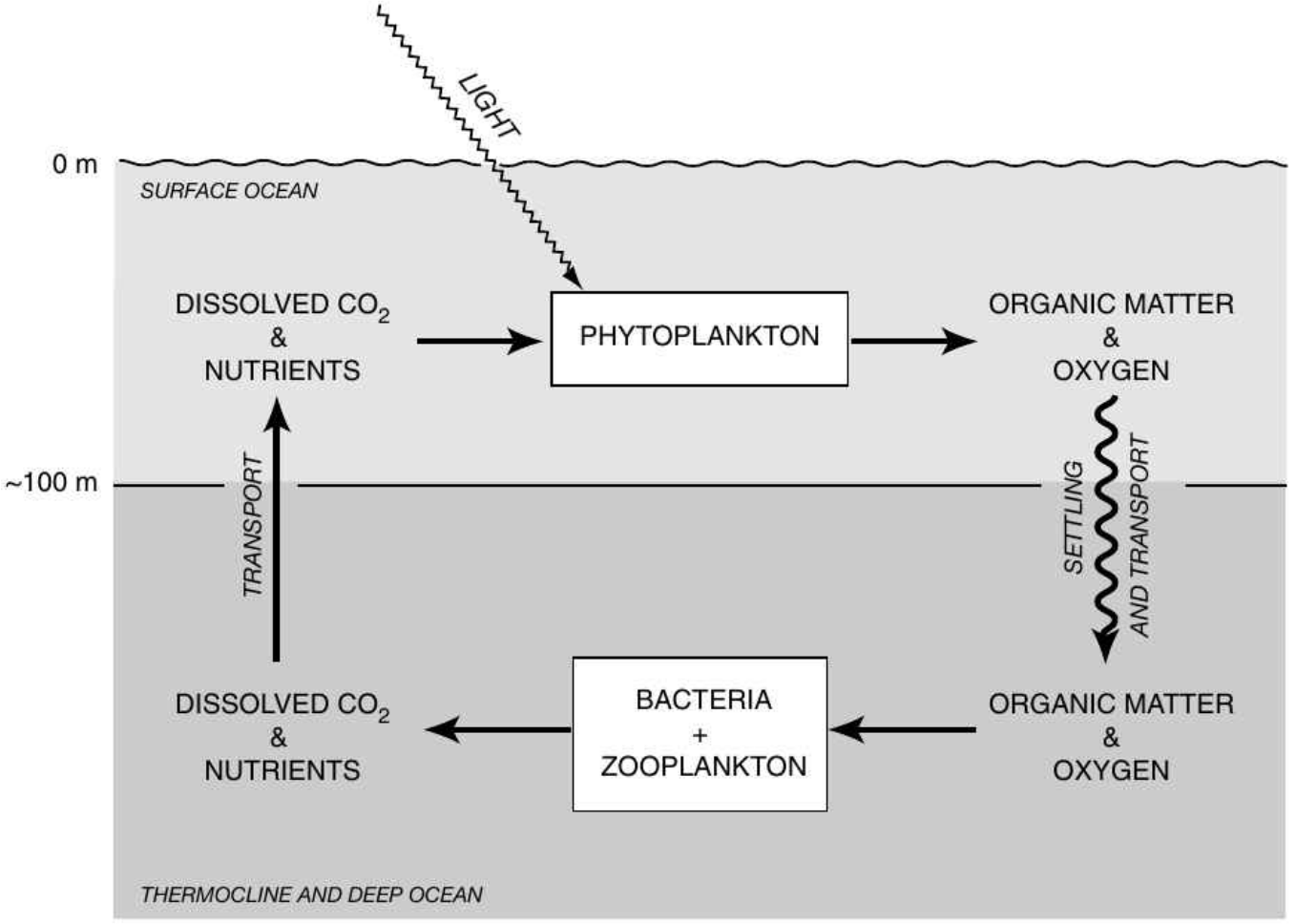
Jickells et al. (2005), PNAS

Marine Primary Production



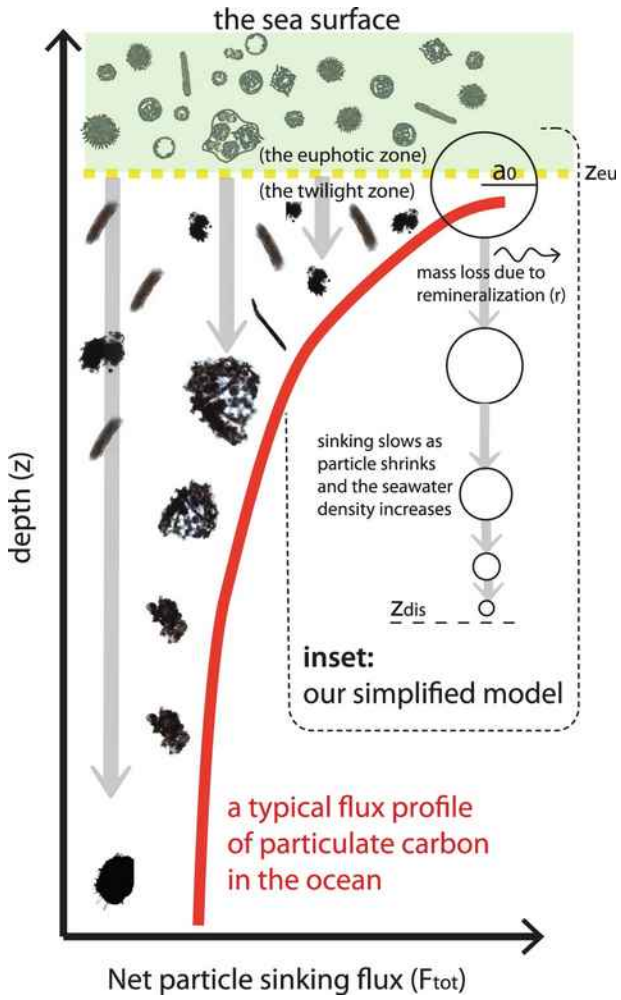
chlorophyll concentration

The Biological Pump



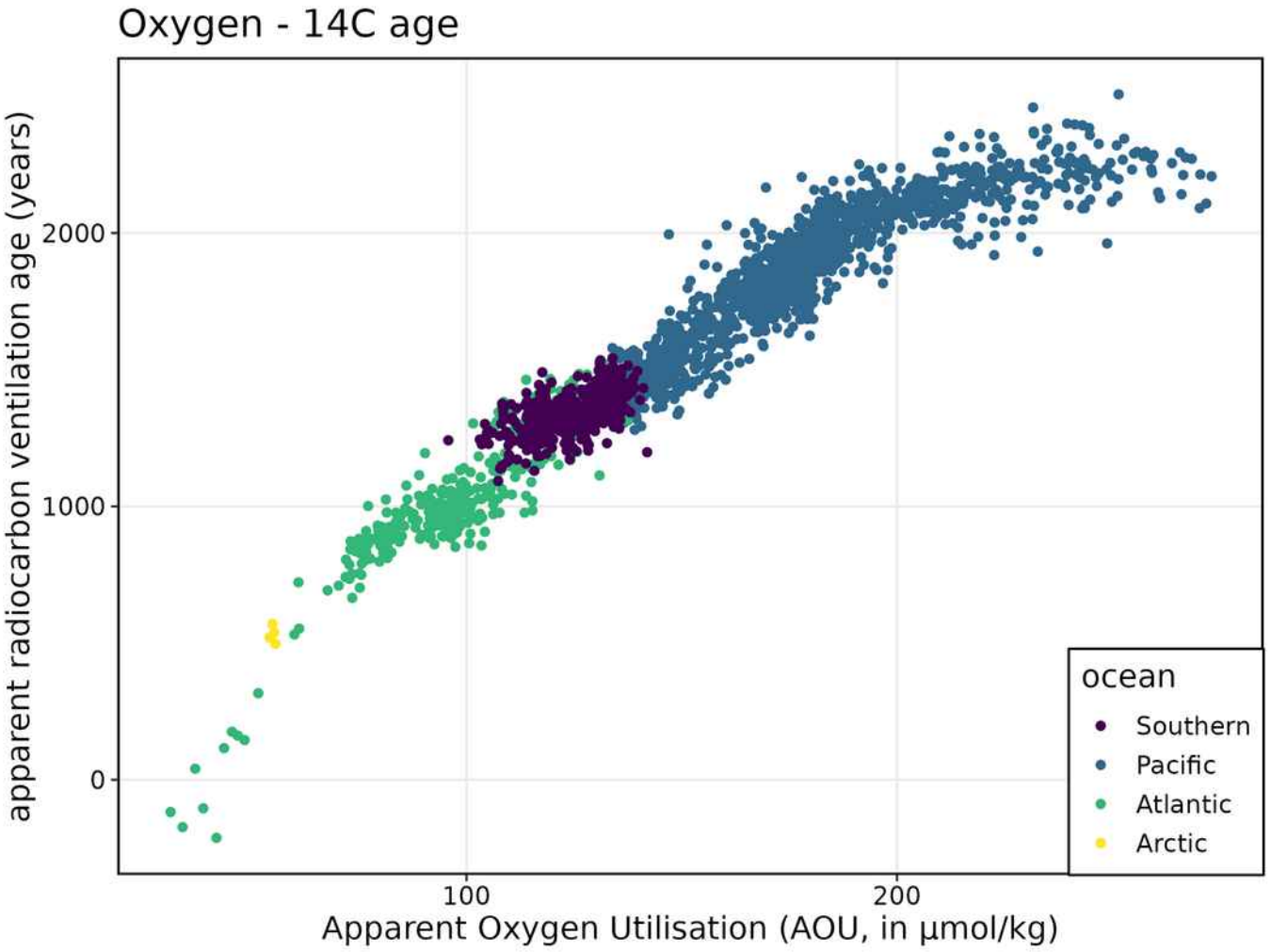
Sarmiento & Gruber (2006),
Ocean Biogeochemical Dynamics

The Biological Pump

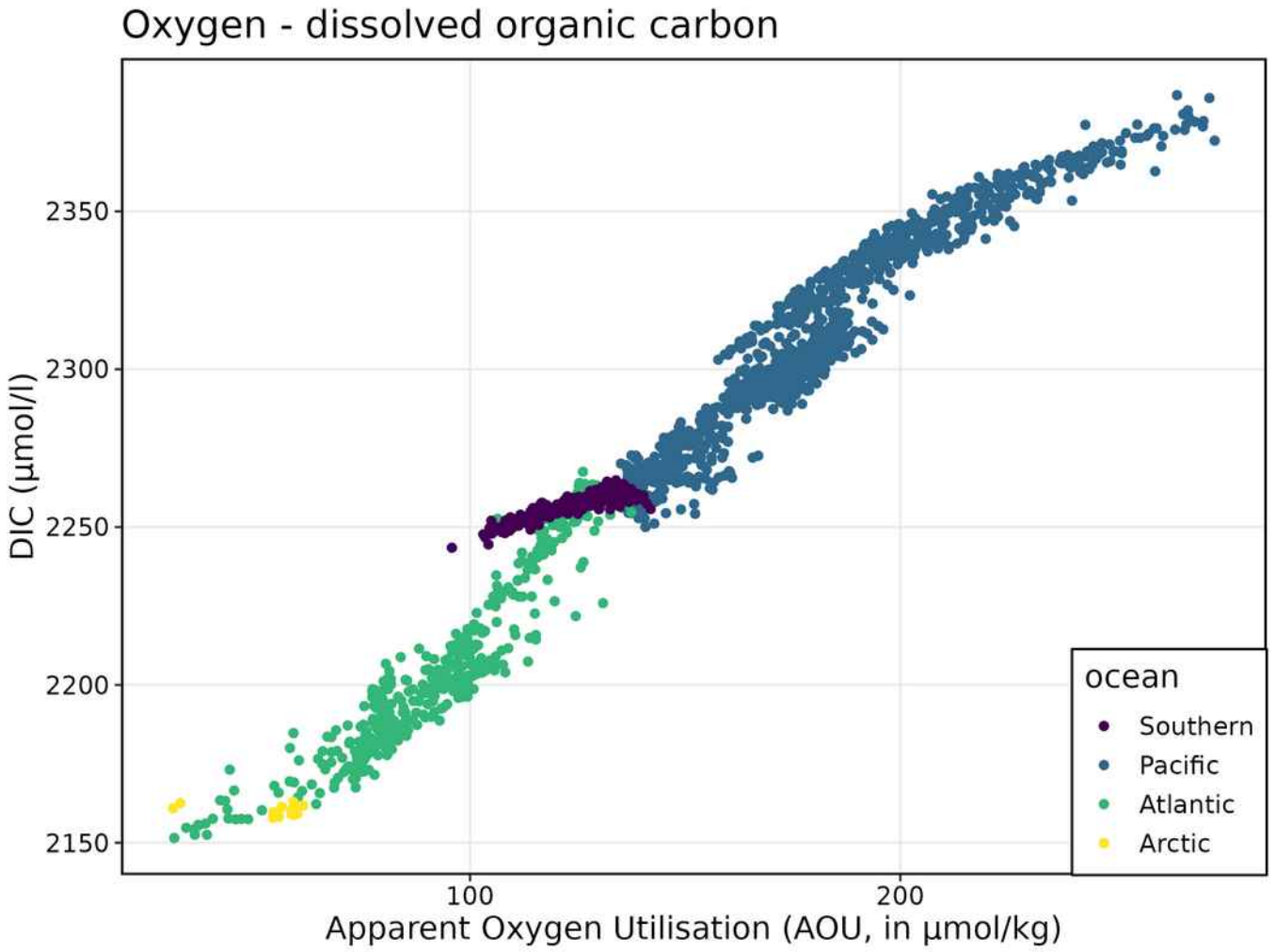


Omand et al. (2020), Nature Scientific Reports

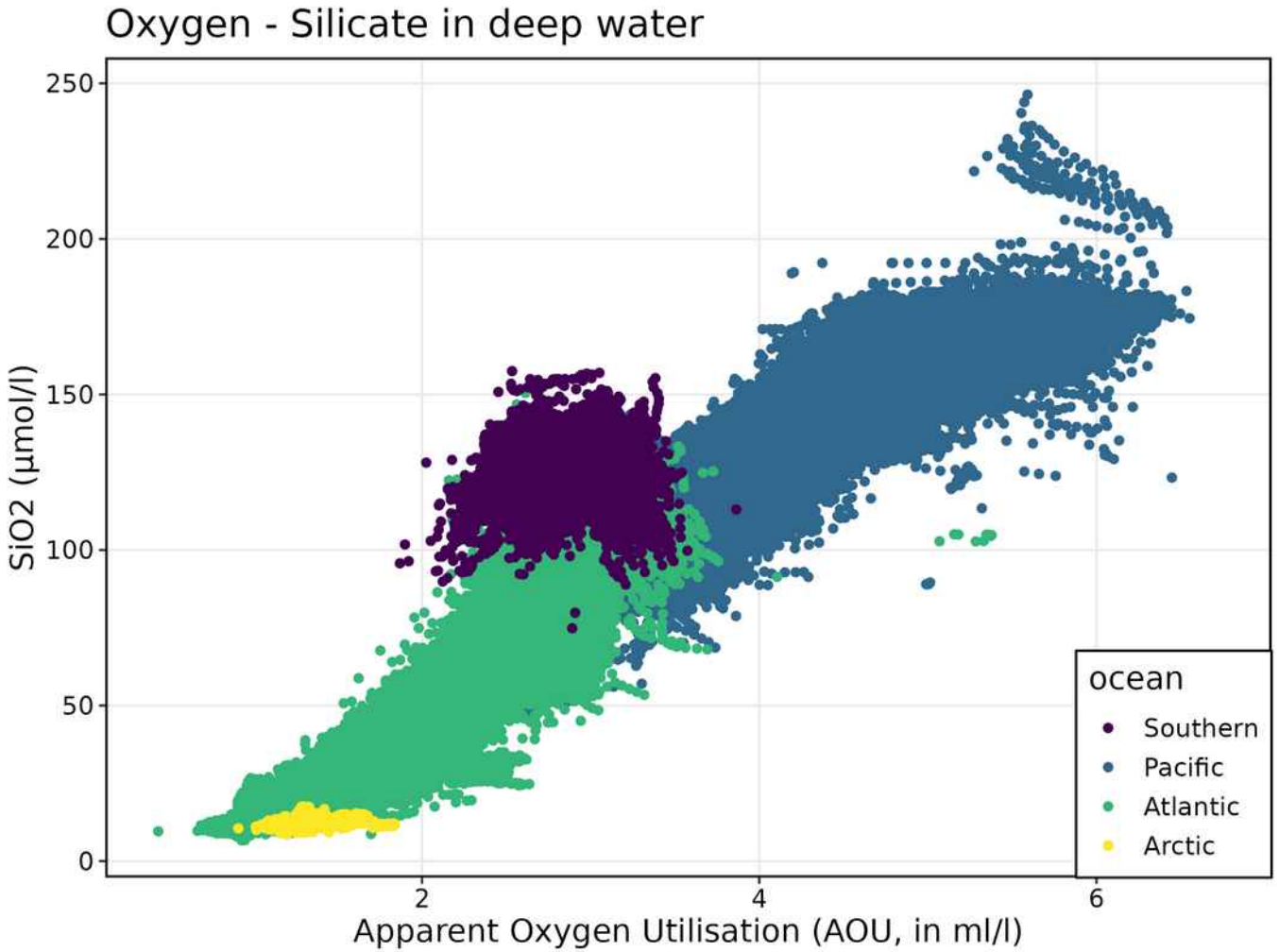
The Biological Pump



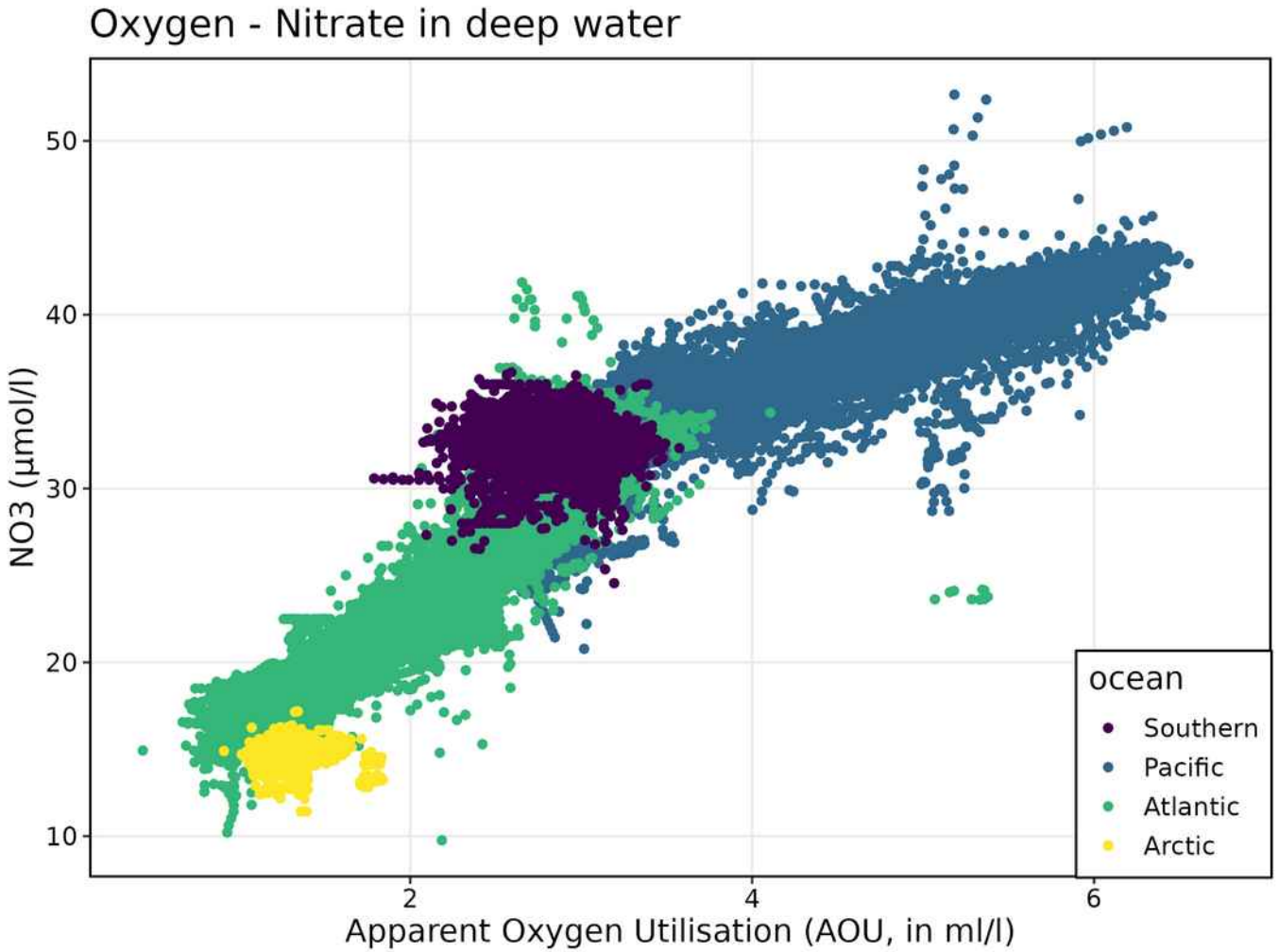
The Biological Pump



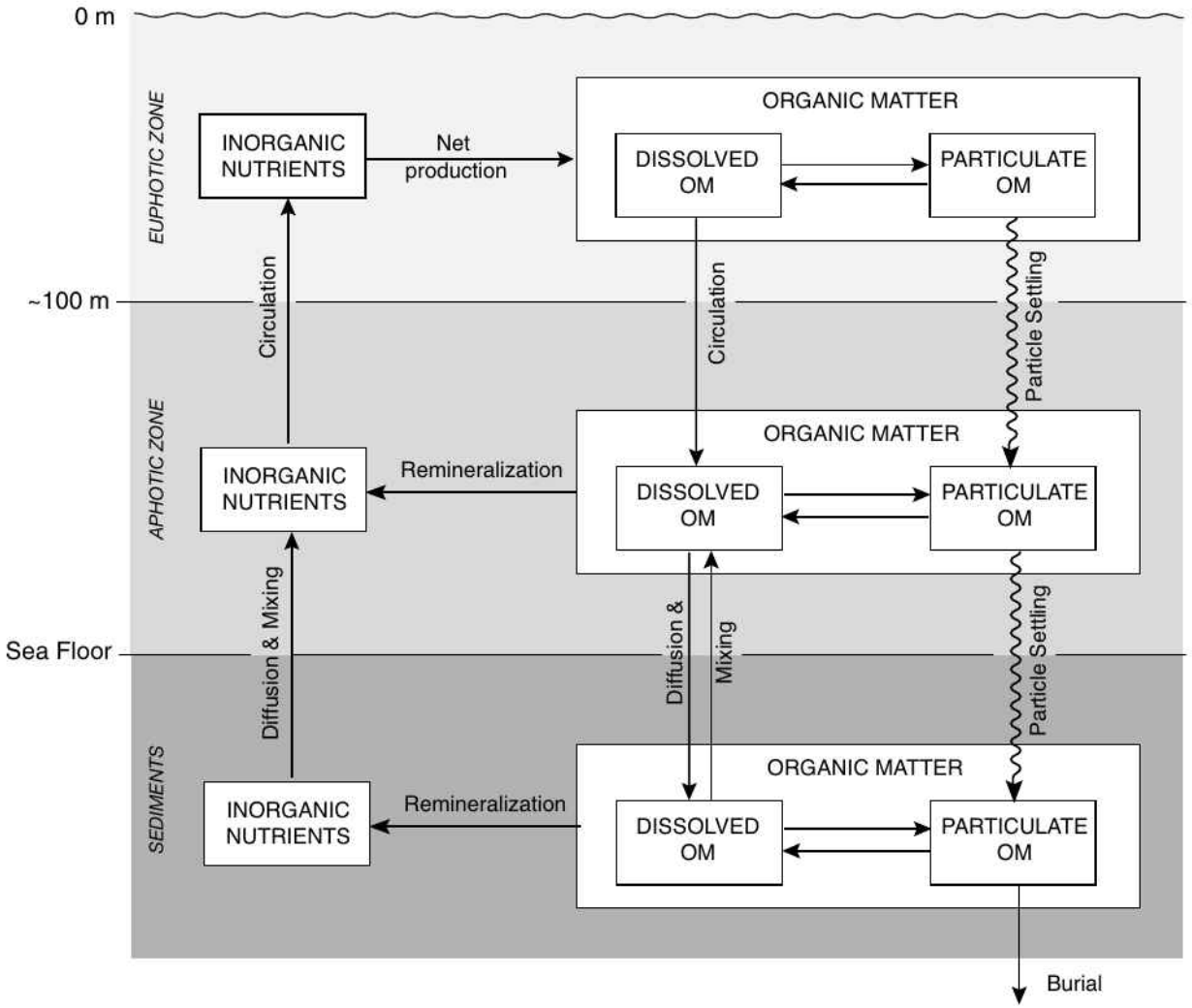
The Biological Pump



The Biological Pump

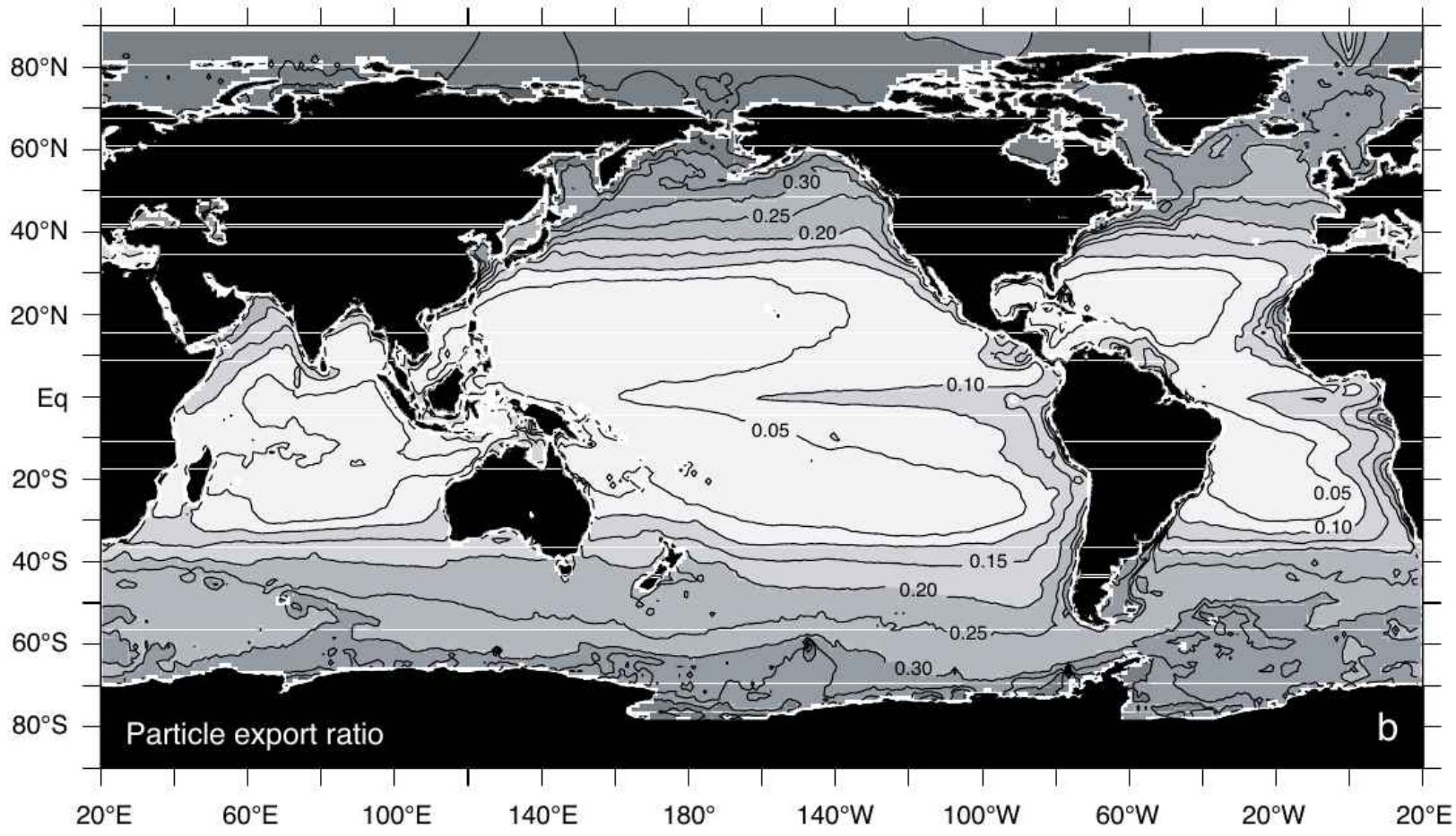


The Biological Pump



Sarmiento & Gruber (2006), Ocean Biogeochemical Dynamics

The Biological Pump



Sarmiento & Gruber (2006),
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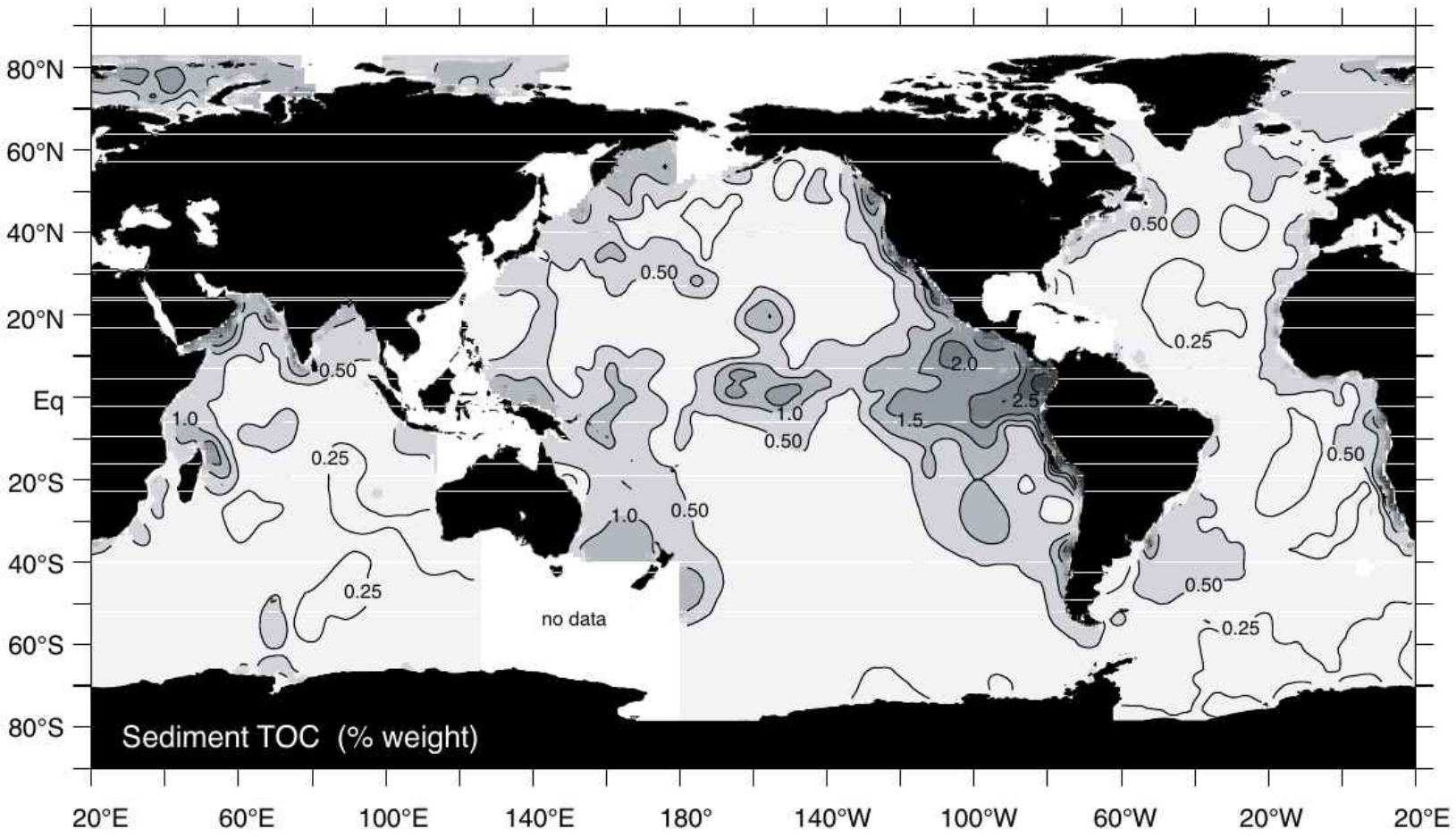
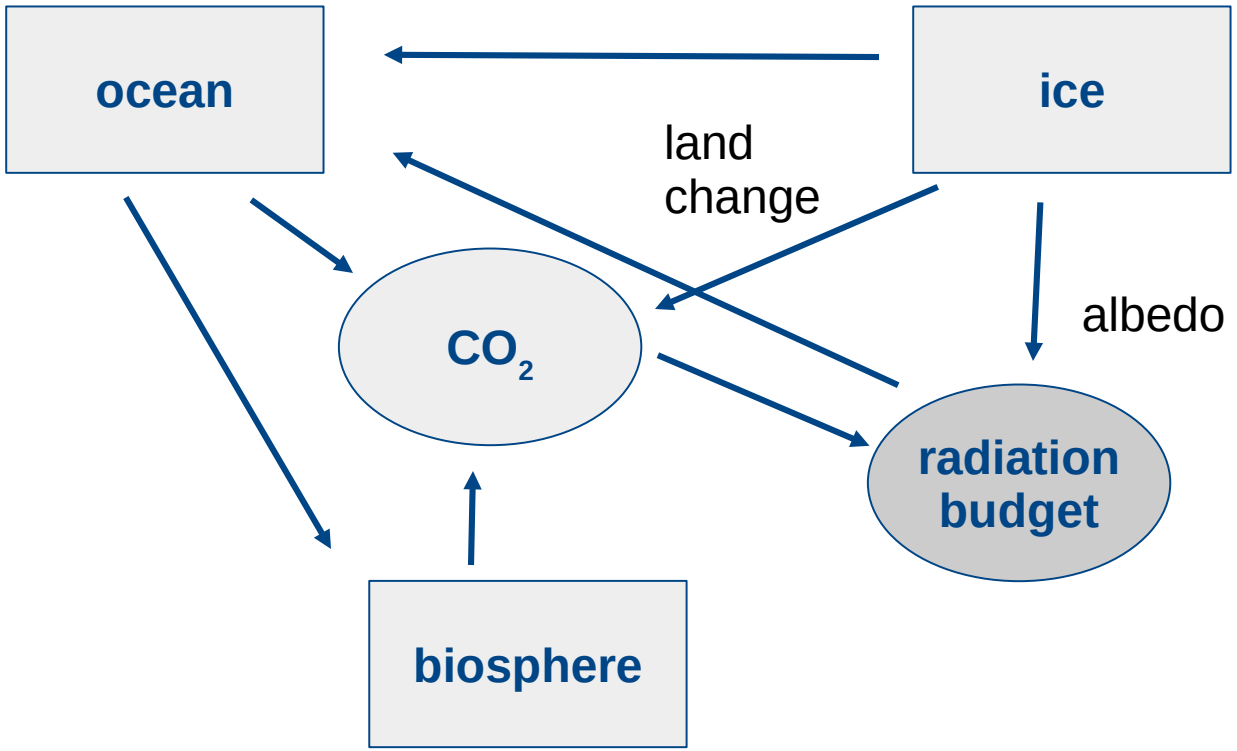
The Biological Pump



Sarmiento & Gruber (2006),
Ocean Biogeochemical Dynamics

Last Glacial Cycle

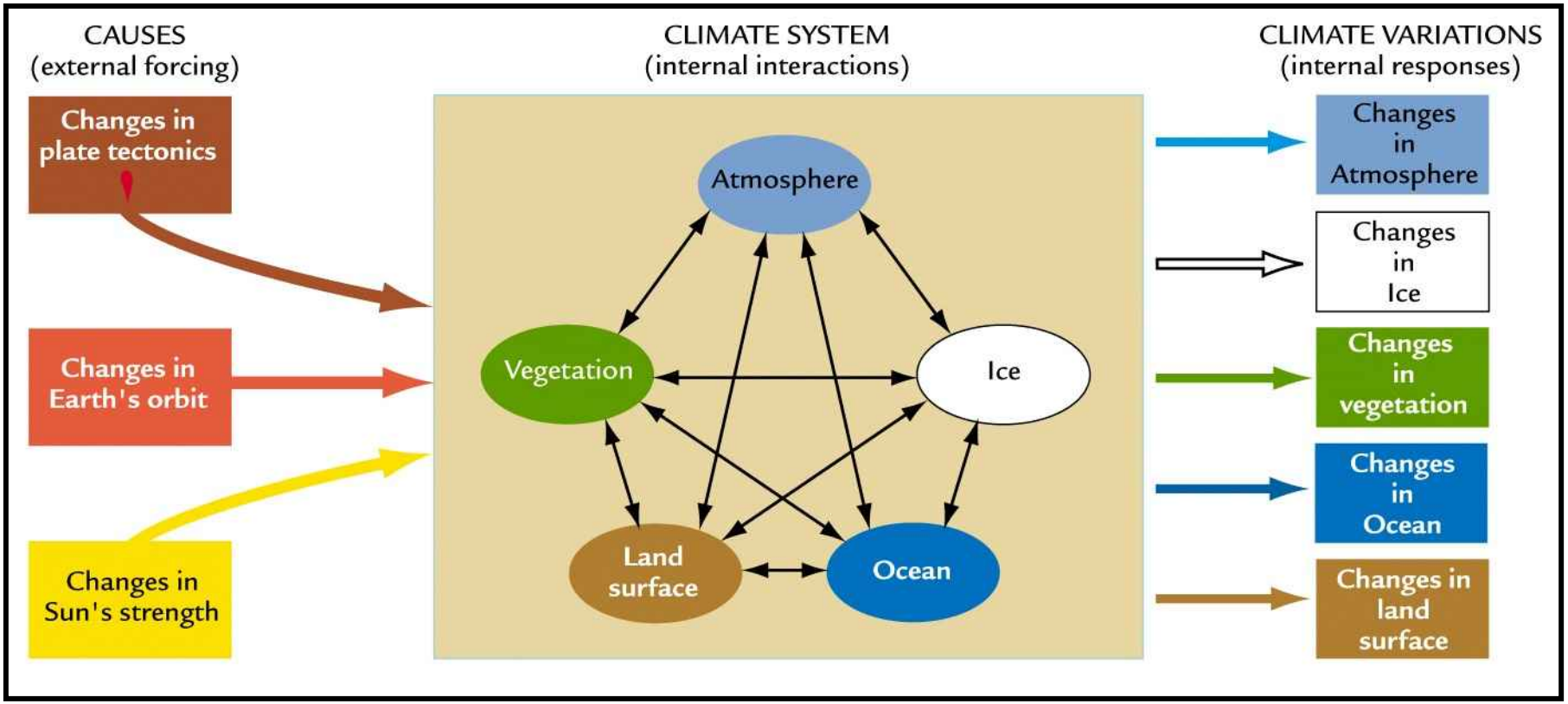
most relevant climate players



The Biological Pump

OceanX: The Miracle of Marine Snow
https://www.youtube.com/watch?v=Lt8rDz0vx2o

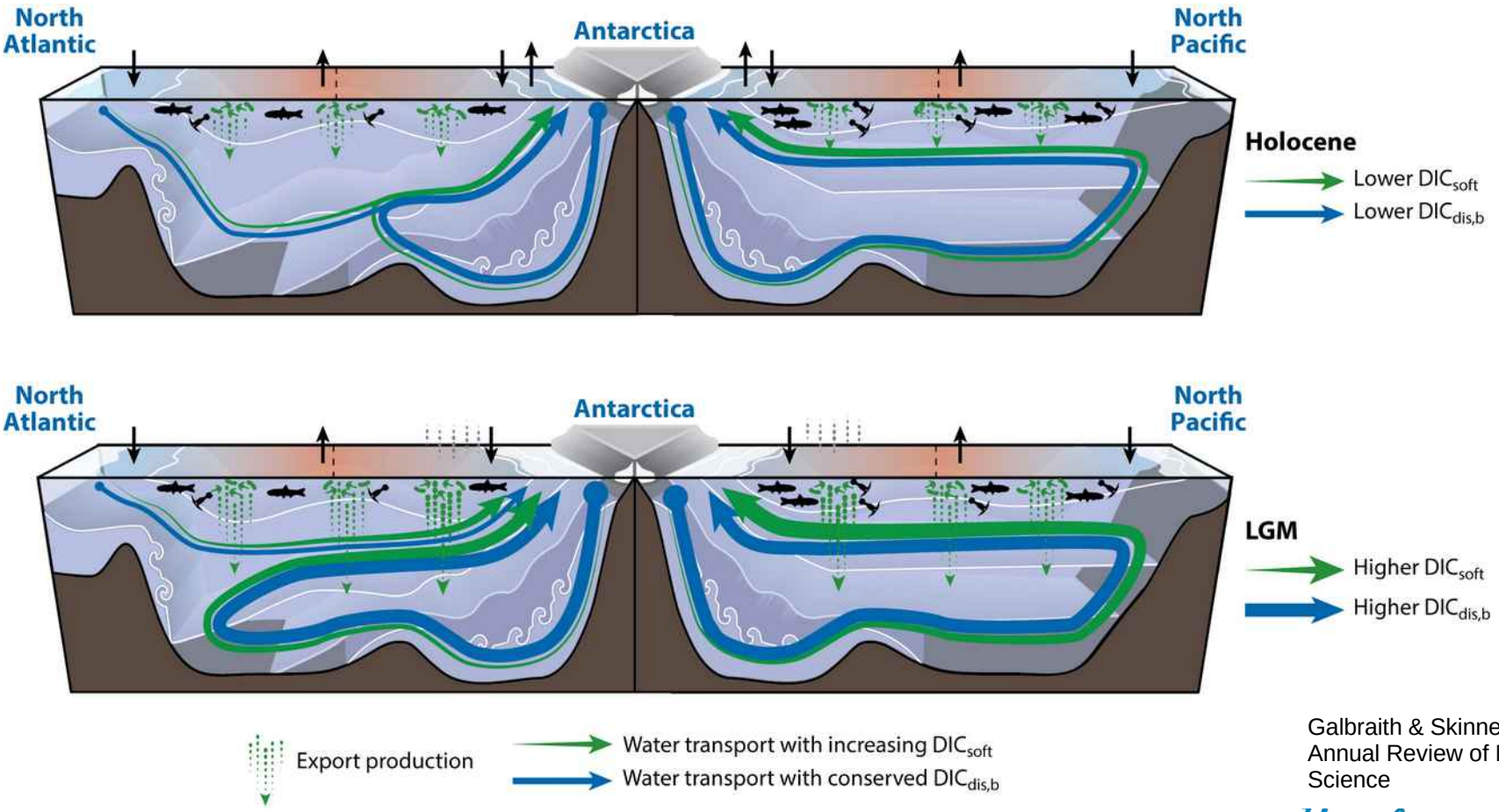
The Oceans in the Climate System



NOAA

The Oceans in G-IG cycles

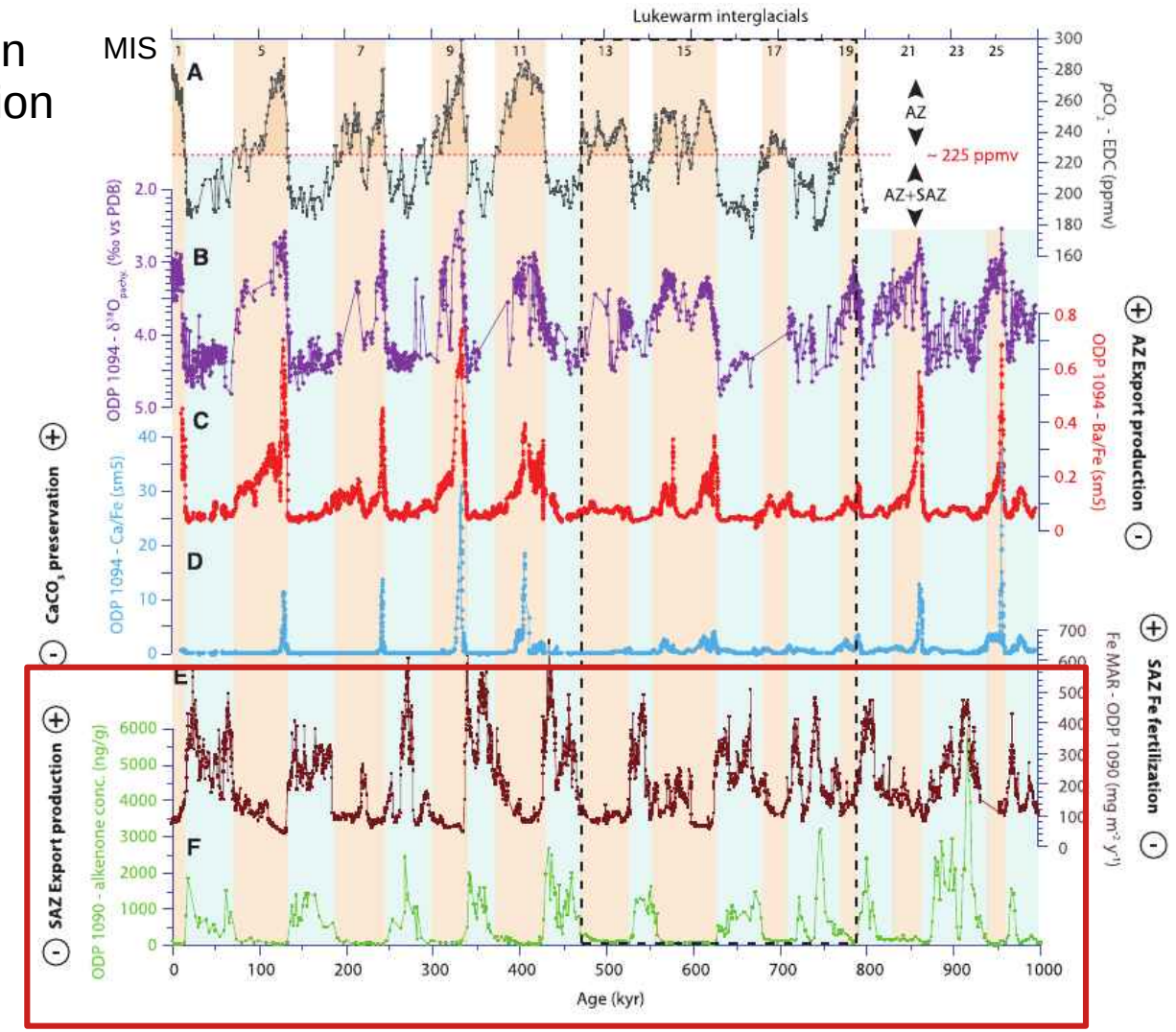
G-IG overturning and productivity



Galbraith & Skinner (2020), Annual Review of Marine Science

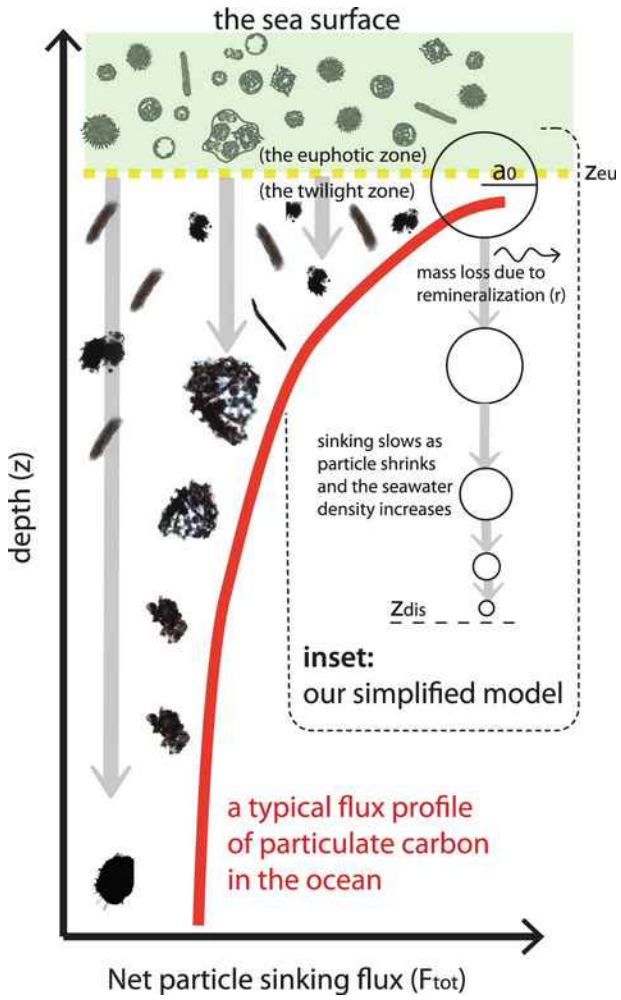
The Oceans in G-IG cycles

G-IG southern dust fertilisation



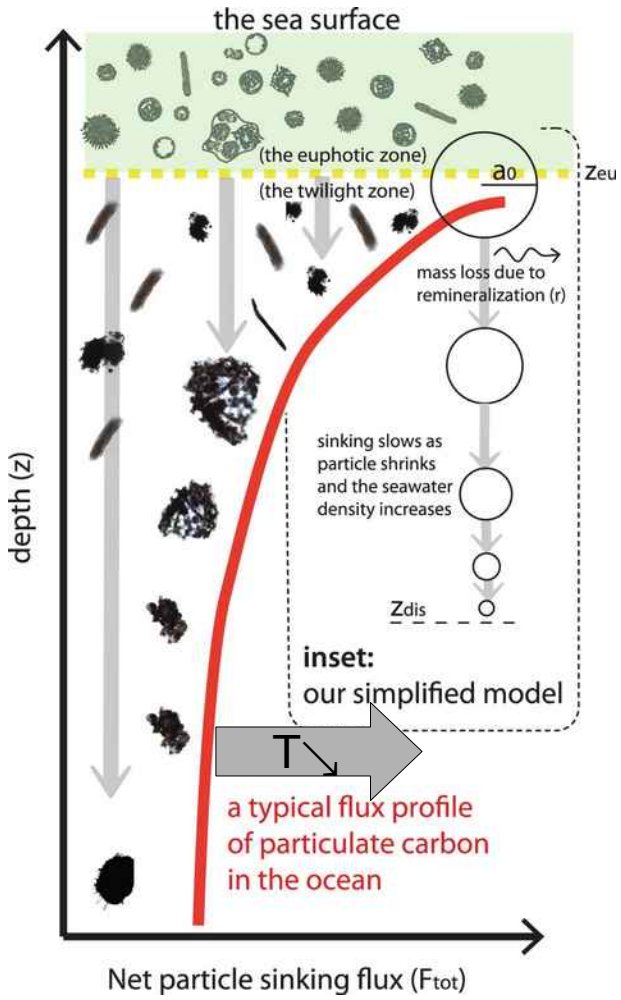
Jaccard et al. (2013), Science

The Oceans in G-IG cycles



Omand et al. (2020), Nature Scientific Reports

The Oceans in G-IG cycles



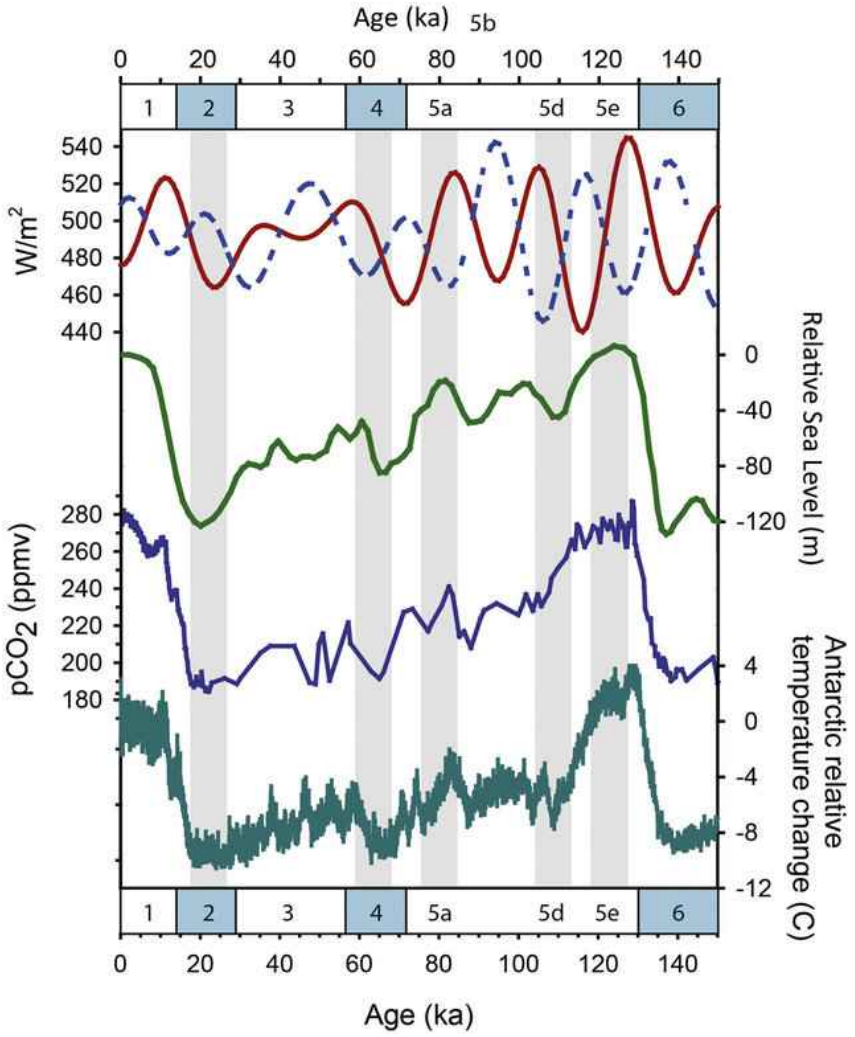
Omand et al. (2020), Nature Scientific Reports

Last Glacial Cycle

~ 120 m SLE

~ 80 ppm

~ 8°C



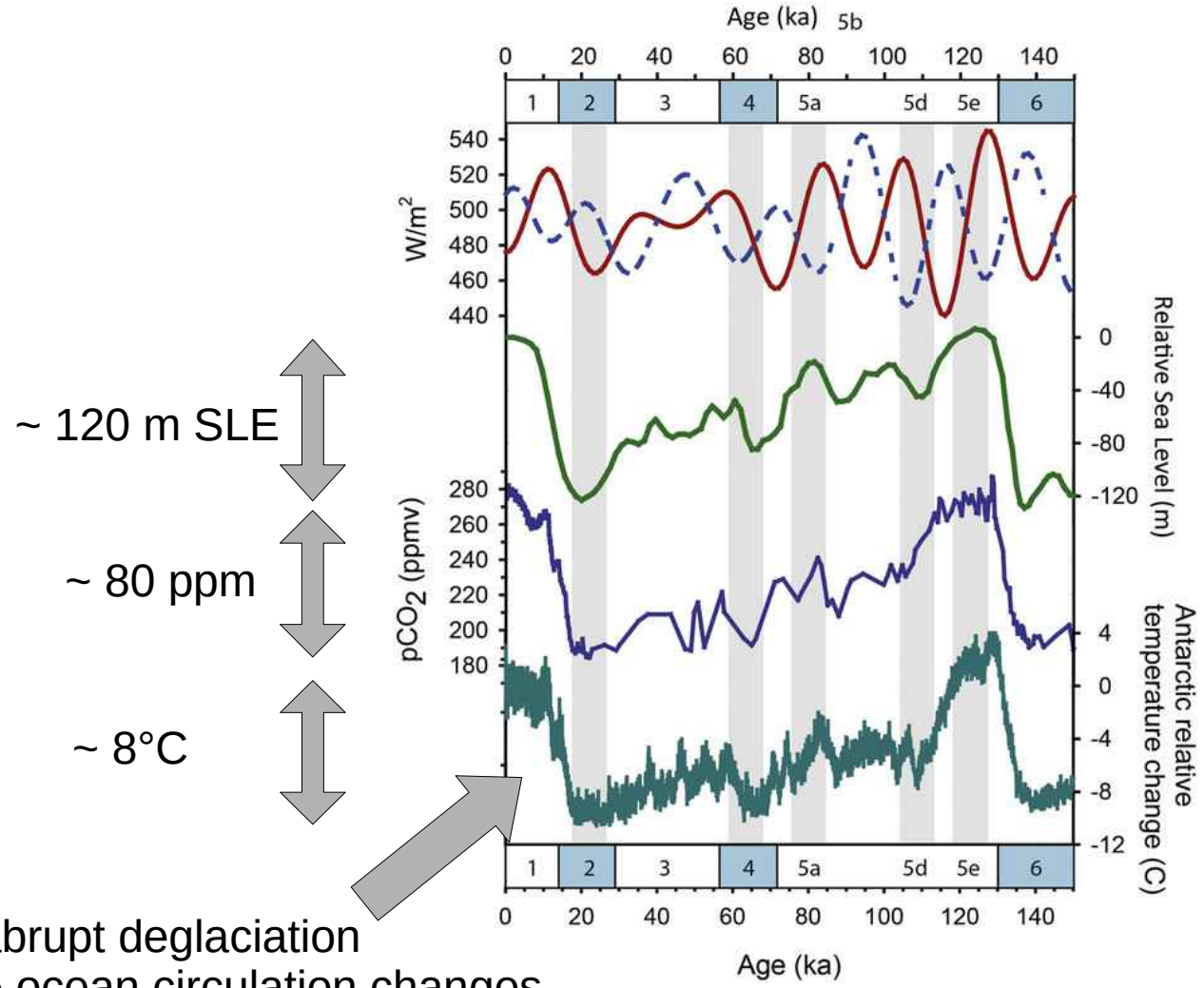
ice sheets & land:
albedo ↗
CO_2 ↘ ~ 7 – 12 ppm

oceans:
T ↗ CO_2 ↘ ~ 30 ppm
S ↗ CO_2 ↗ ~ 20 ppm

most of the rest:
deep ocean storage

Kohfeld & Chase (2017)
Earth and Planetary Science Letters

Last Glacial Cycle



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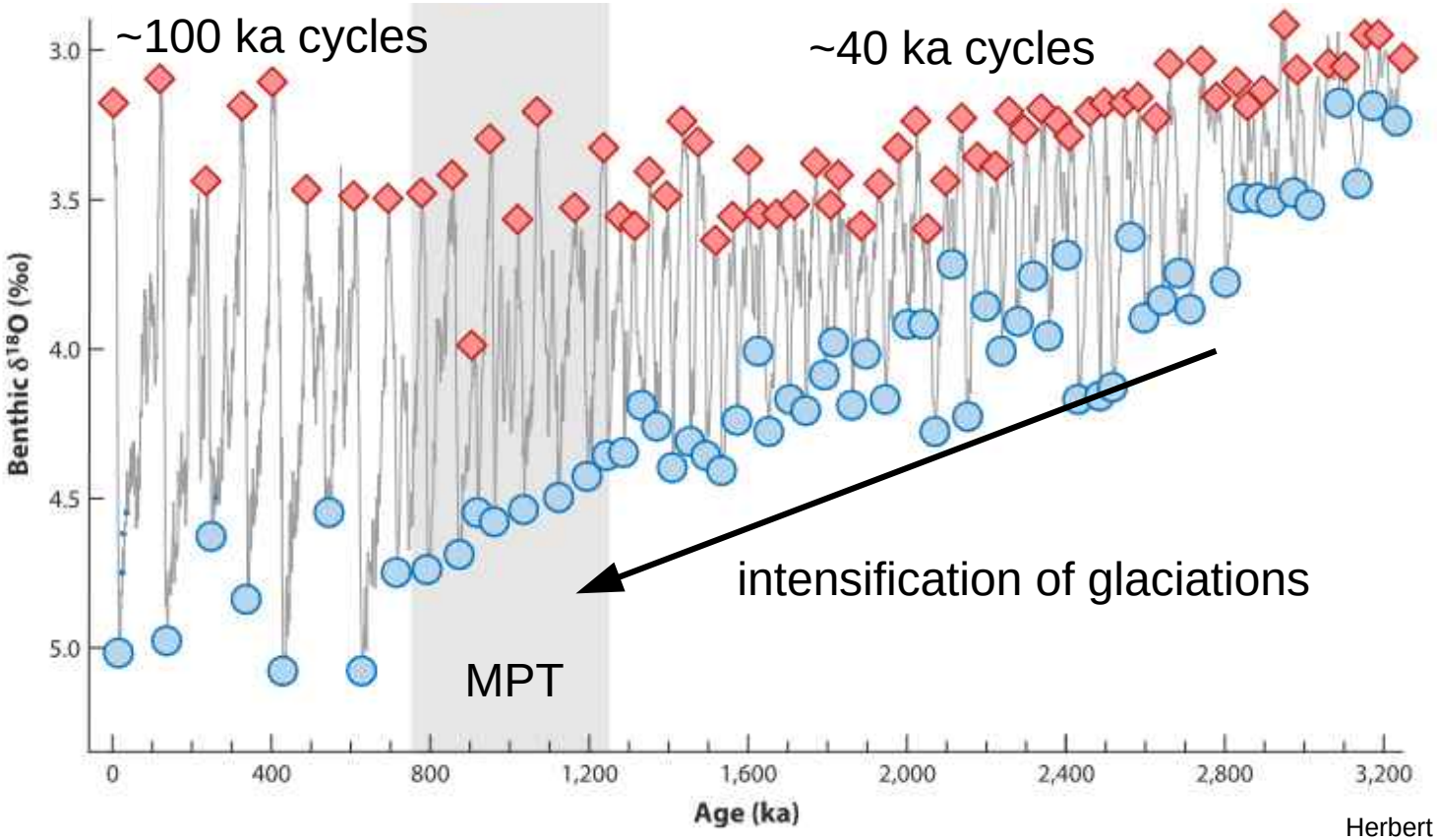
Kohfeld & Chase (2017)
Earth and Planetary Science Letters

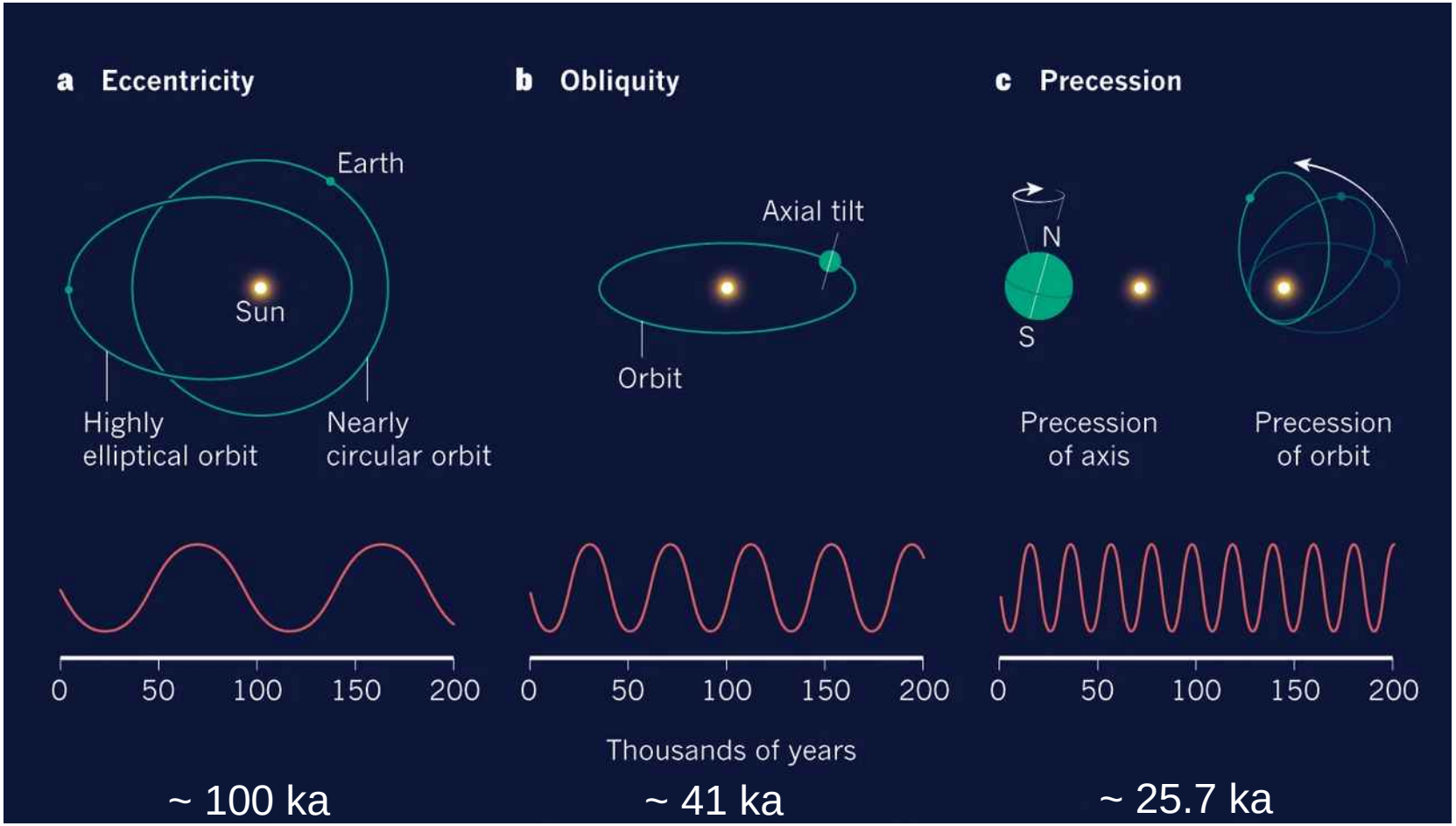
Pleistocene Climate

^{18}O in peak glacials vs. interglacials



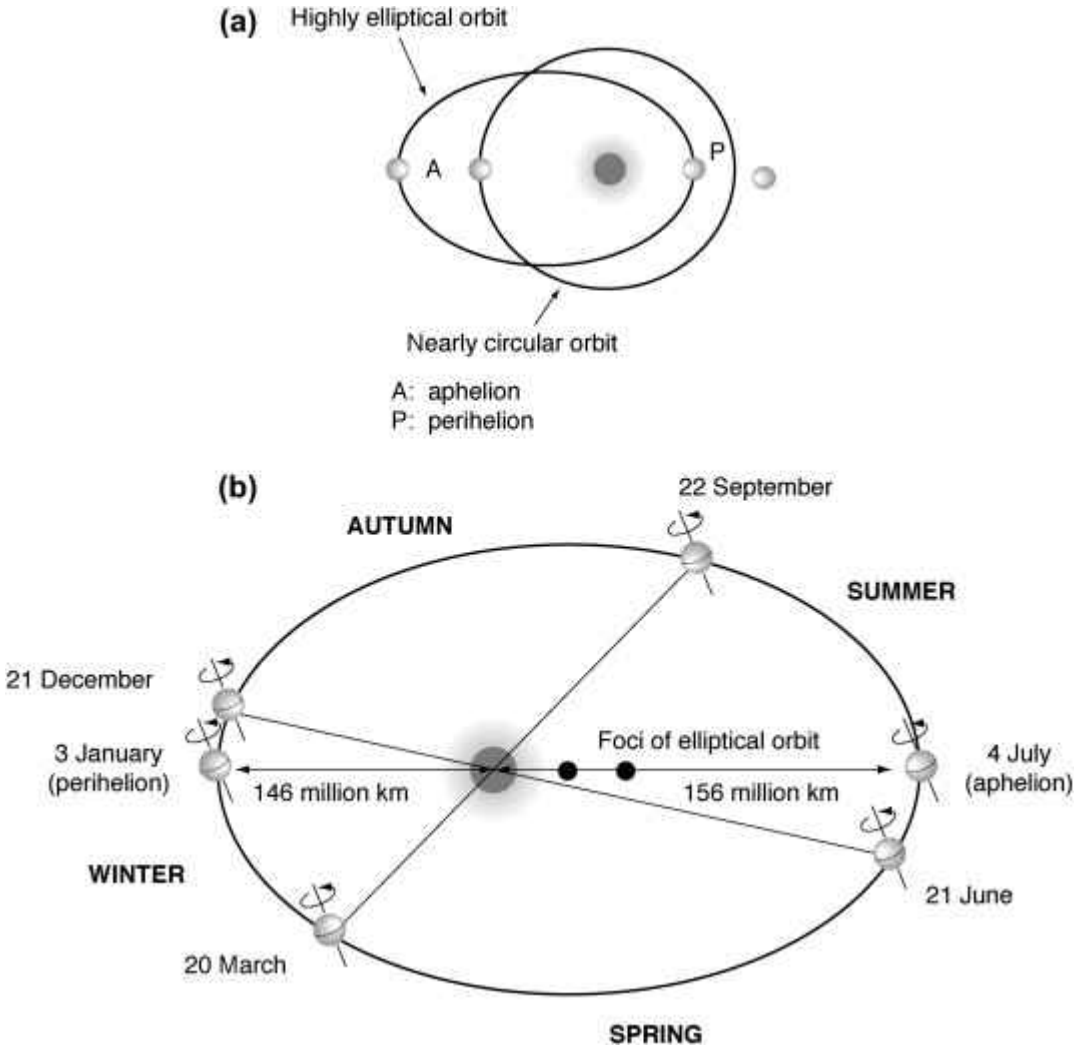
Herbert 2015

Orbital Forcing



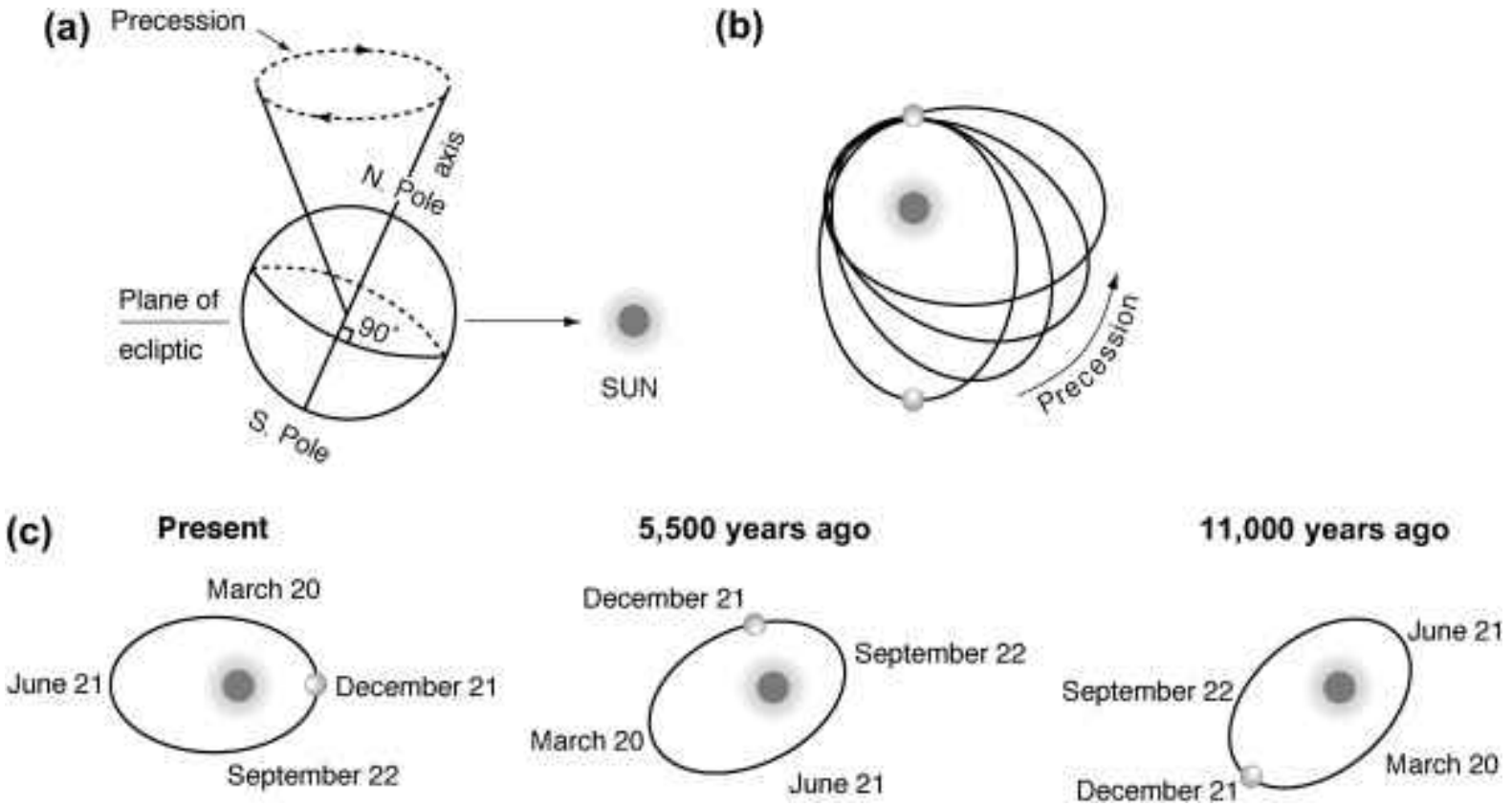
Maslin 2016

Orbital Forcing



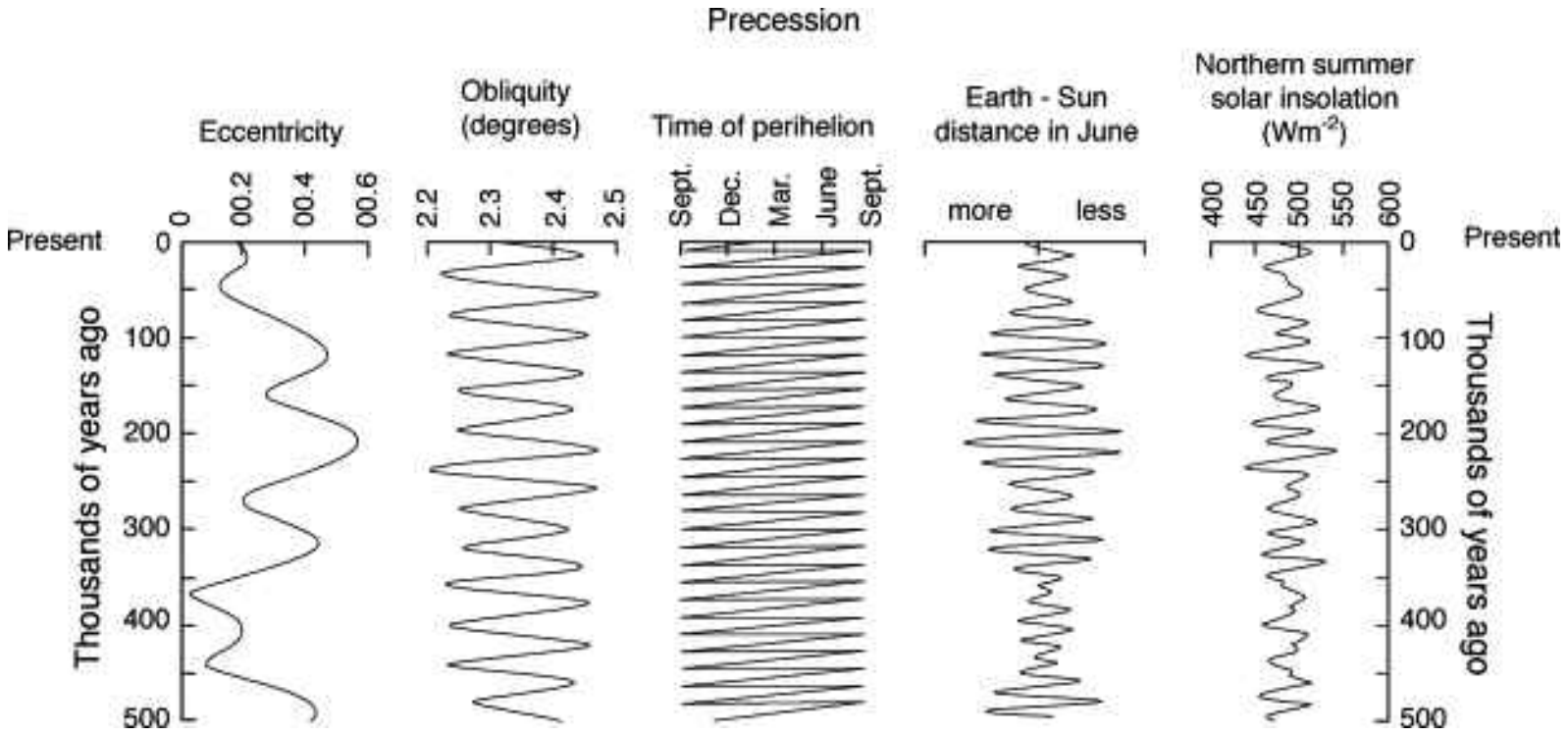
Maslin and Christensen (2007), Journal of Human Evolution

Orbital Forcing



Maslin and Christensen (2007), Journal of Human Evolution

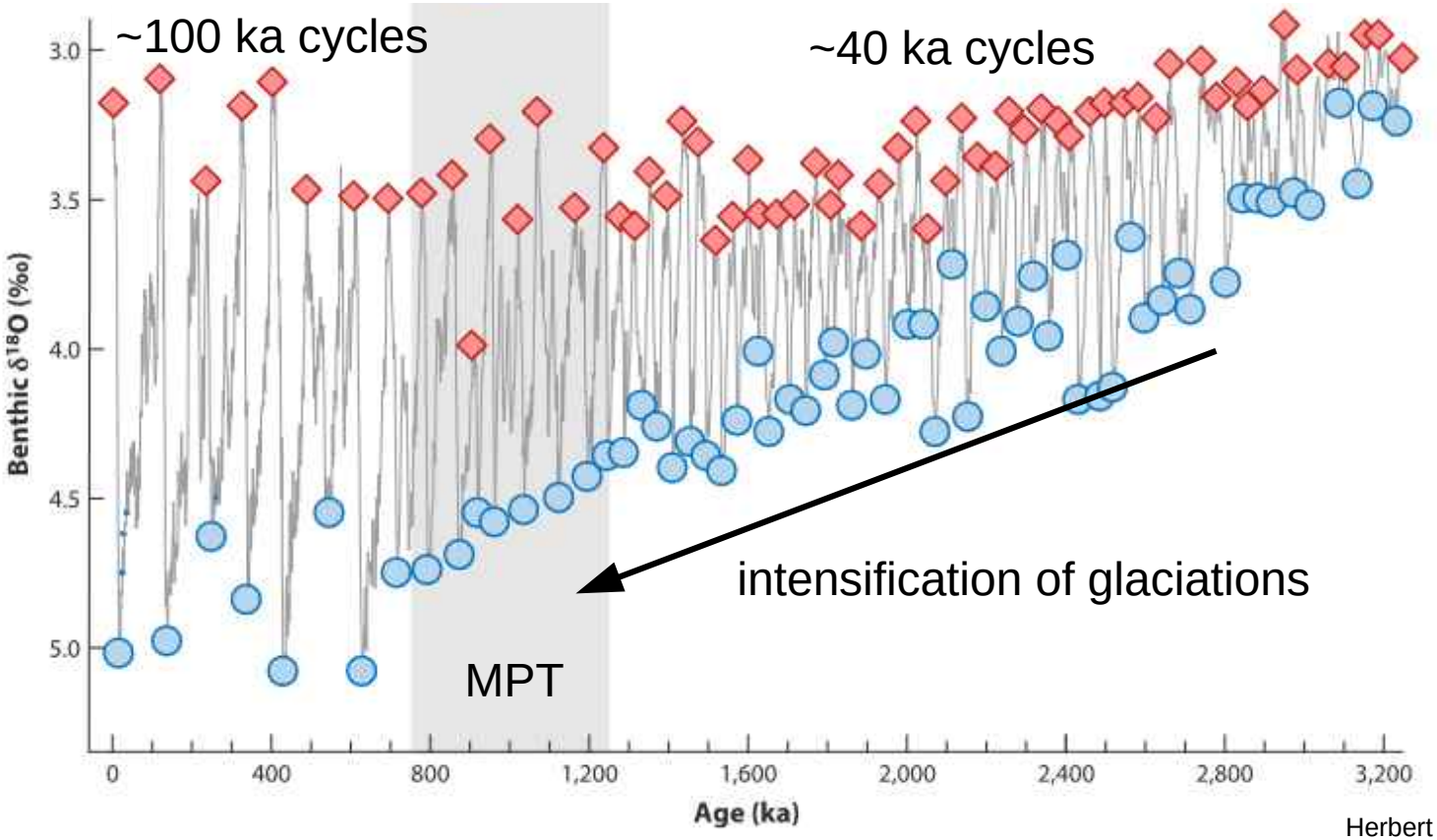
Orbital Forcing



Maslin and Christensen (2007), Journal of Human Evolution

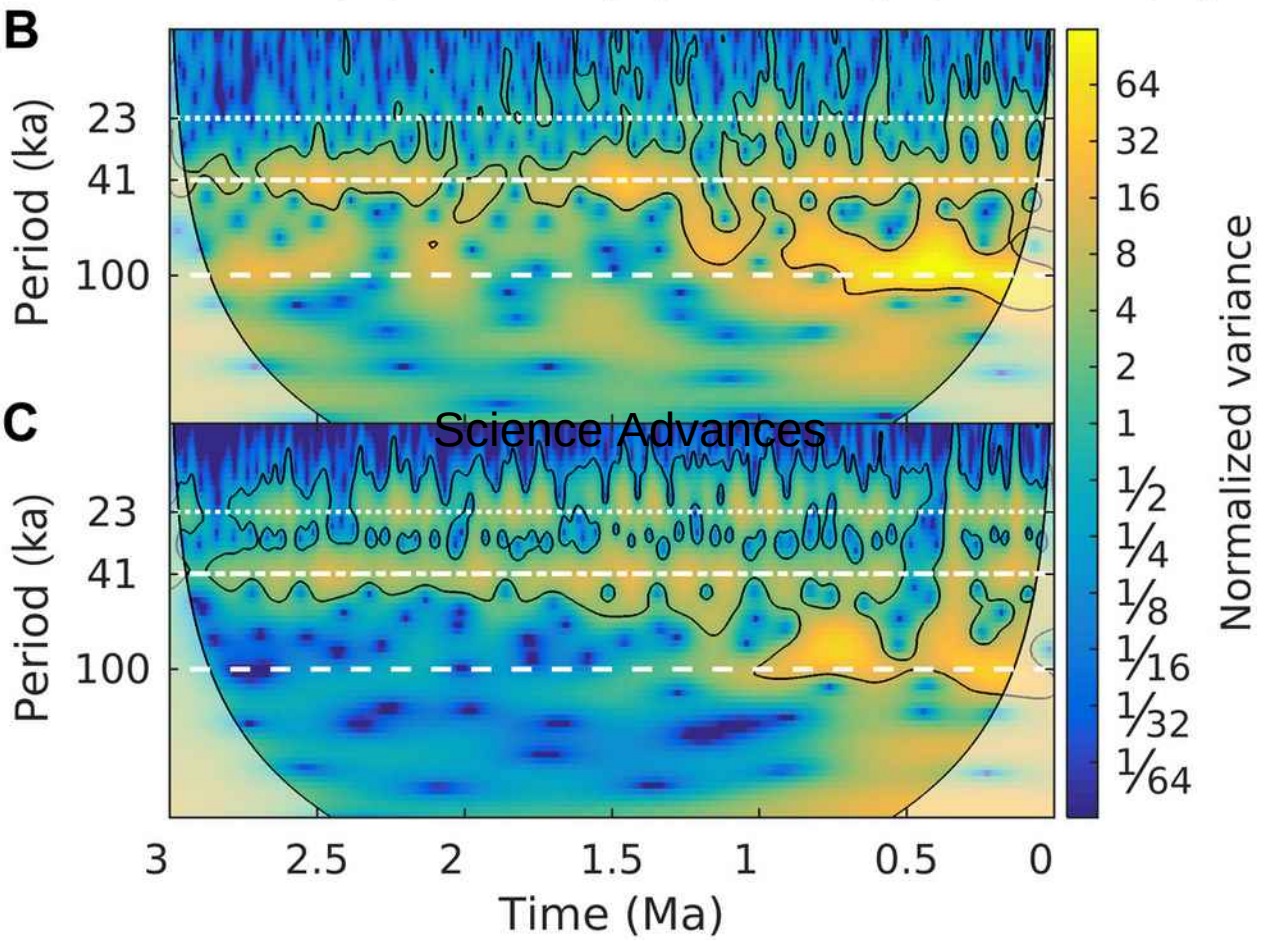
Pleistocene Climate

^{18}O in peak glacials vs. interglacials



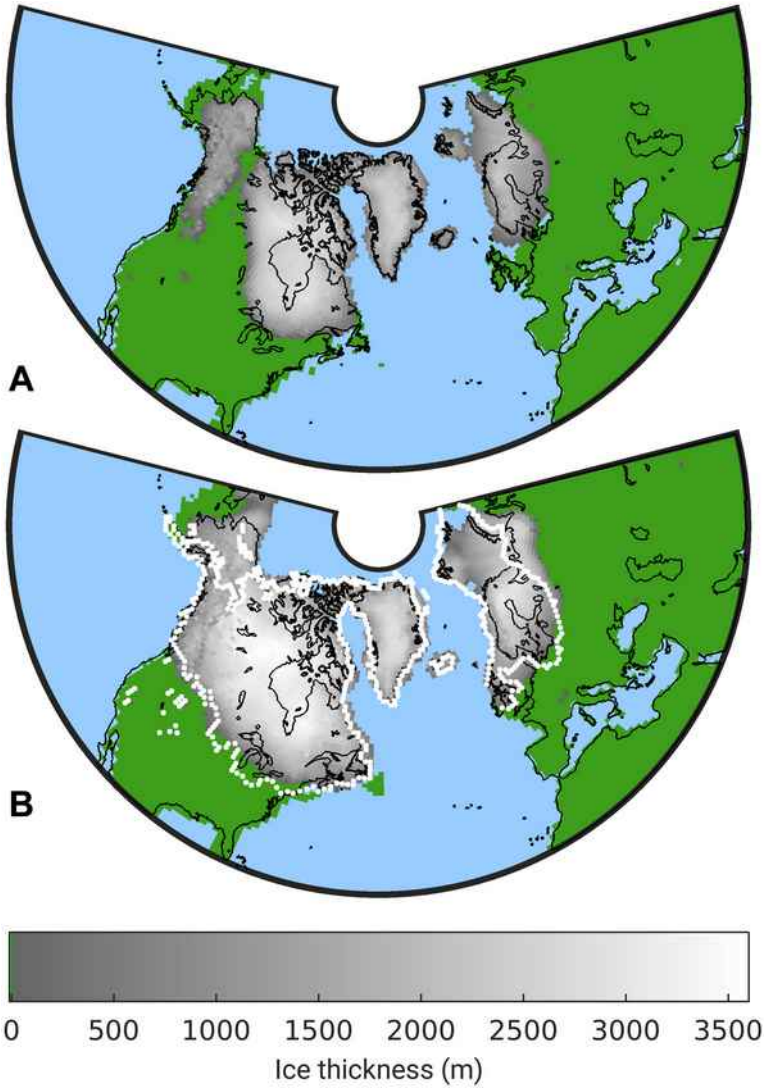
Herbert 2015

Mid-Pleistocene-Transition



Willeit et al. (2019)
Science Advances

Mid-Pleistocene-Transition

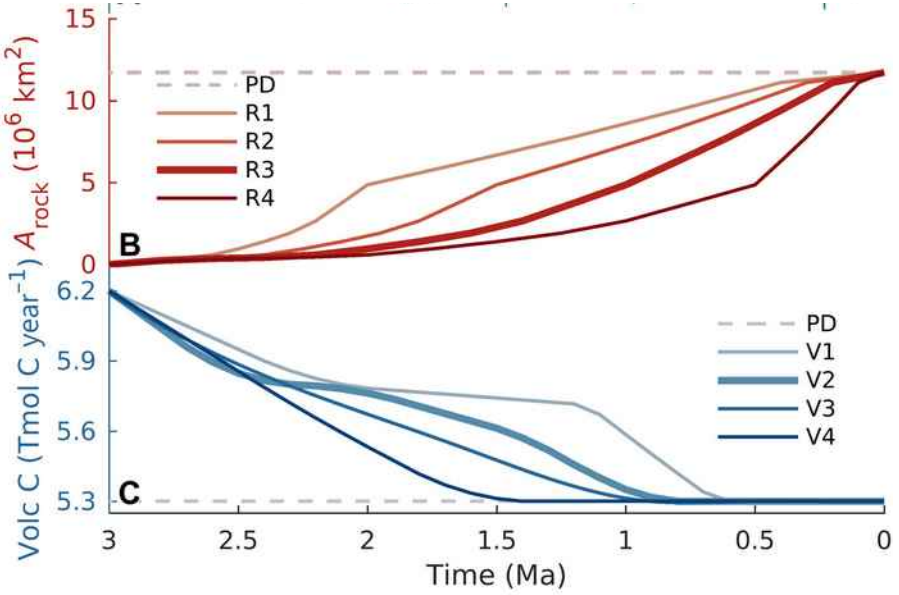


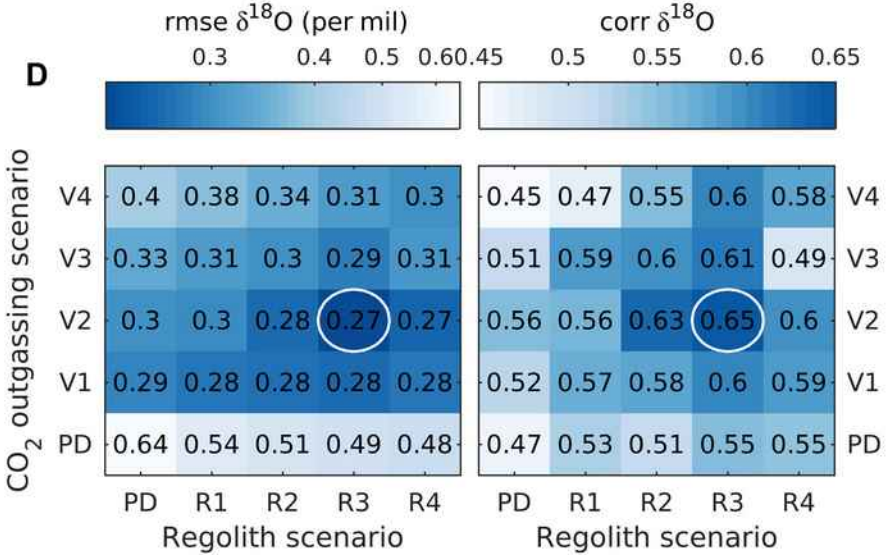
pre-MPT

post-MPT

Willeit et al. (2019)
Science Advances

Mid-Pleistocene-Transition





Willeit et al. (2019)
Science Advances

source: NASA Earth Observatory

Today's Summary

- Pleistocene Climate
- Glacial-Interglacial Cycles
- Glacial Ice Sheets
- The oceans in the climate system
  - ocean surface
  - deep ocean
  - ocean biochemistry
- Orbital Forcing
- The Mid-Pleistocene Transition

Outlook

Today we finish 15 min early!

Monday	Introduction	Earth History
Tuesday	Proxies I	Cenozoic Hot & Warm House
Wednesday	Specific Climate System components	Pleistocene G-IG climate
Thursday	Proxies II & Climate System Interactions	Abrupt Climate Change
Friday	Current Climate Change	Future & Synthesis