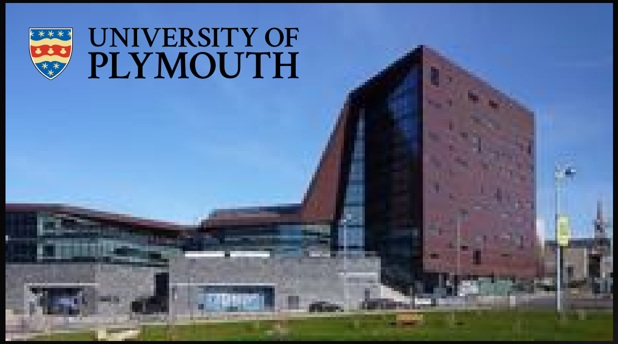
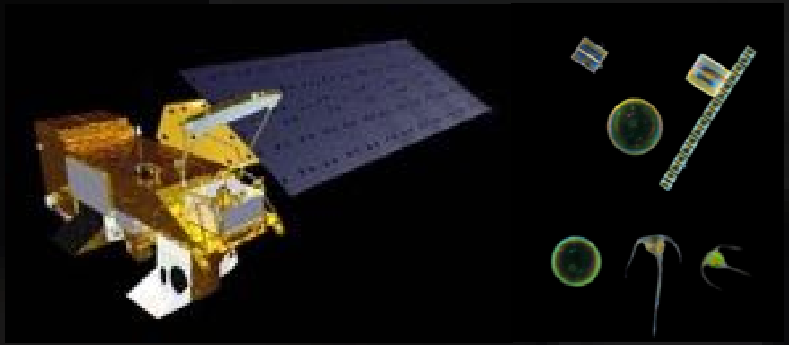
Ocean Biogeochemical Cycles

Bob Brewin

2003-2010



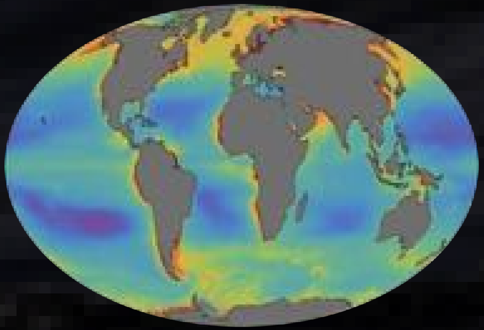


2010-2019

Atlantic Meridional Transect

esa

2019-present



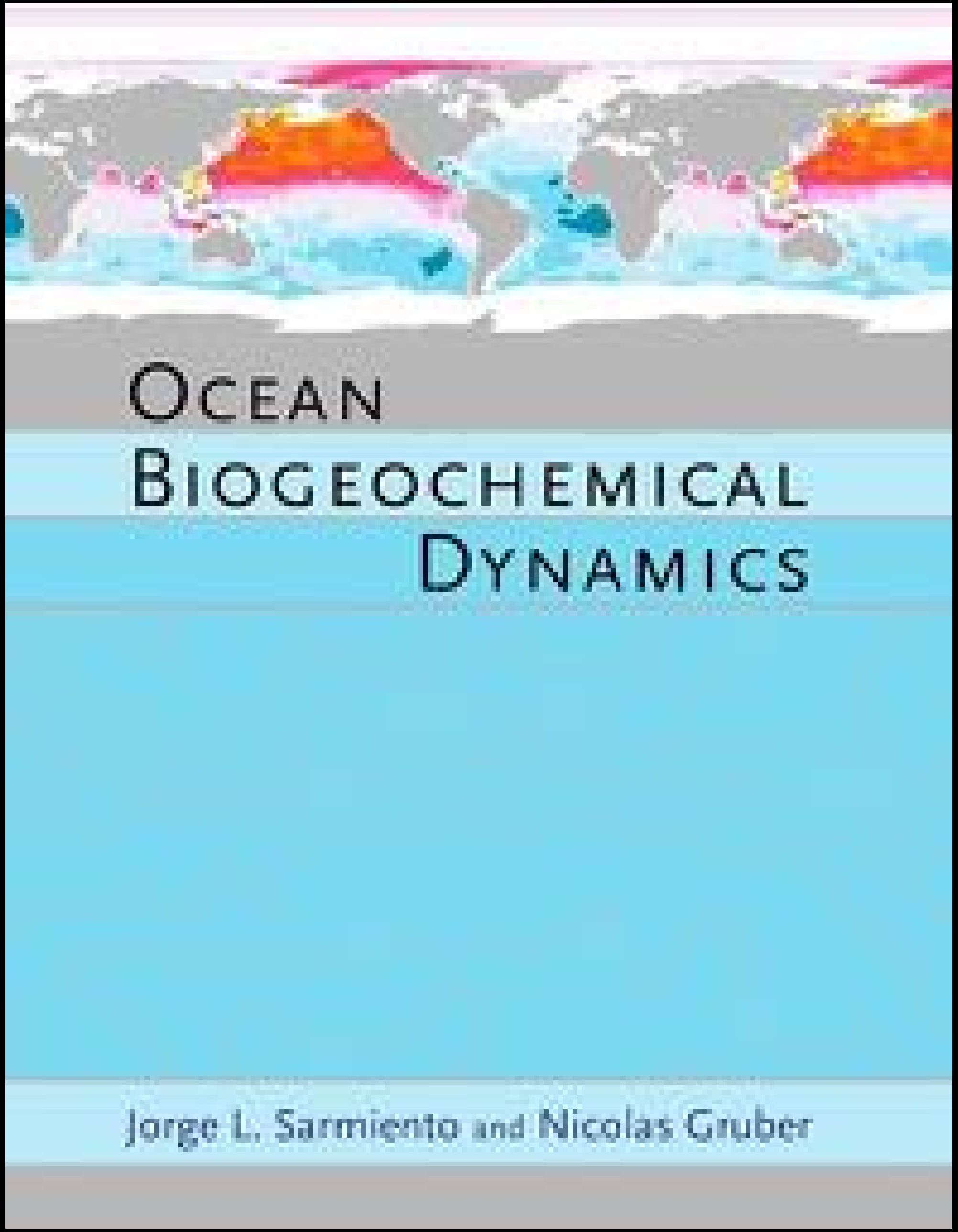
Lecture outline

1. Introduction to marine biogeochemical cycles
2. The Water cycle
3. The Redfield Ratio
4. The Carbon cycle
5. The Ocean Biological Carbon Pump
6. The Nitrogen cycle
7. The Iron cycle

Biogeochemical cycles are the pathways in which chemical substances (including elements and compounds) move through and within the environment.

Chemical substances can be combined and broken apart. But chemical elements can not be created or destroyed. Therefore, elements are recycled or stored (sequestered) somewhere on the planet.

The chemical substances can move between the marine environment and other components of the Earth System, such as atmosphere, ocean floor, terrestrial realms and polar regions.



Biogeochemical cycles are driven by a range of forces, including metabolic processes in organisms (bio); geological processes, e.g. the movement of the Earth (geo); and chemical reactions among the substances (chemical).

Hence the name biogeochemical cycles (BGC cycle).

Marine organisms (microorganisms in particular) are critical to the functioning of many BGC cycles.

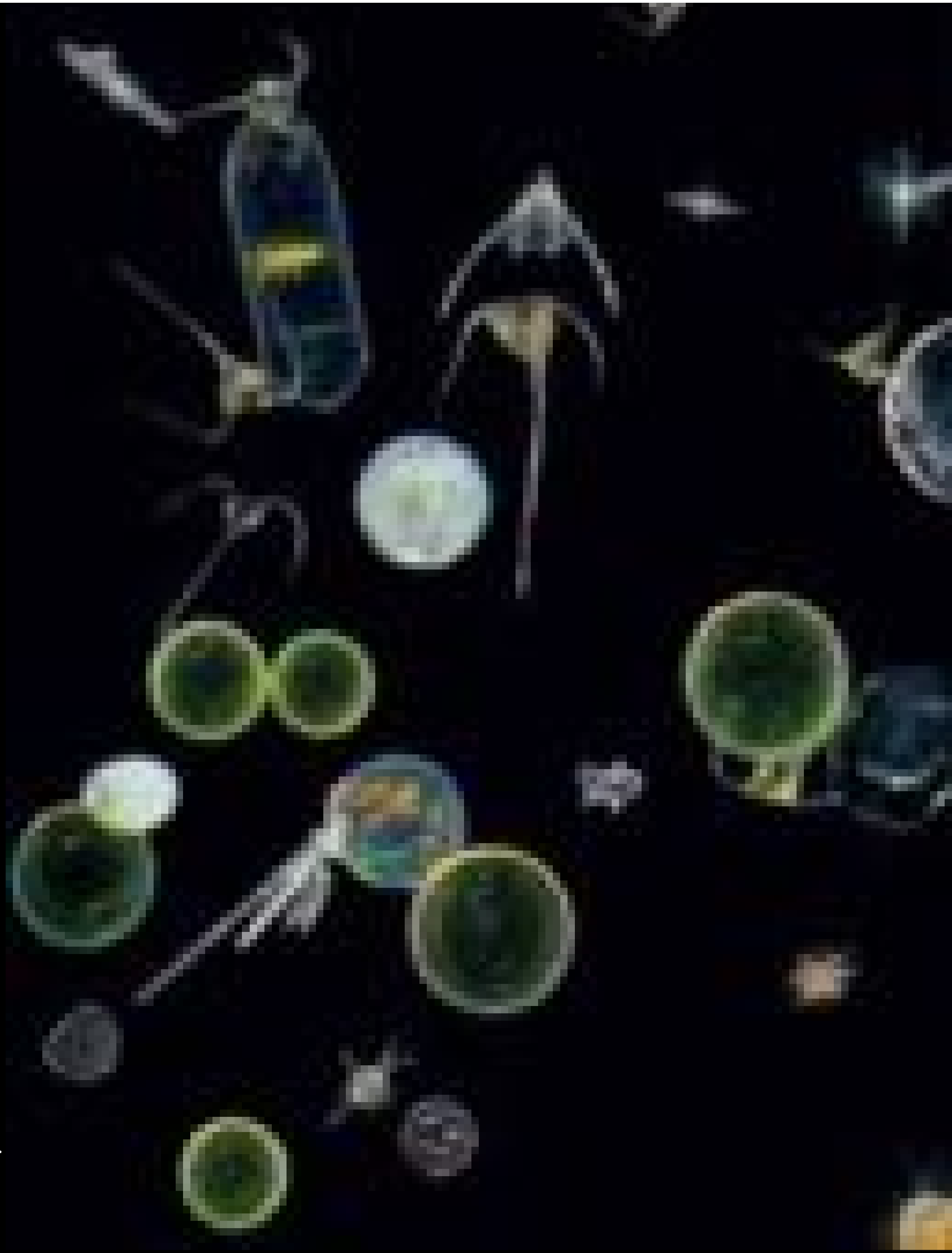
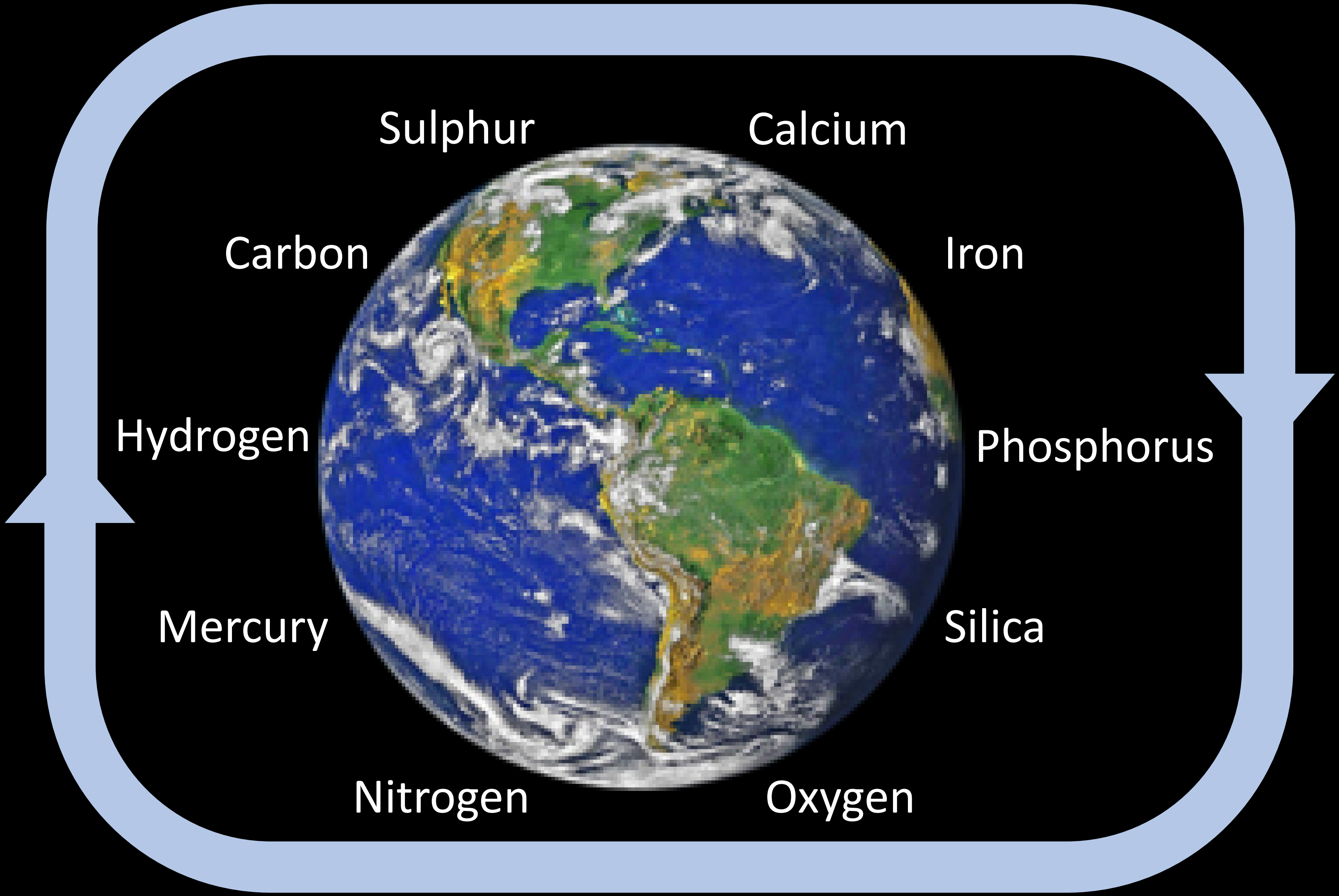
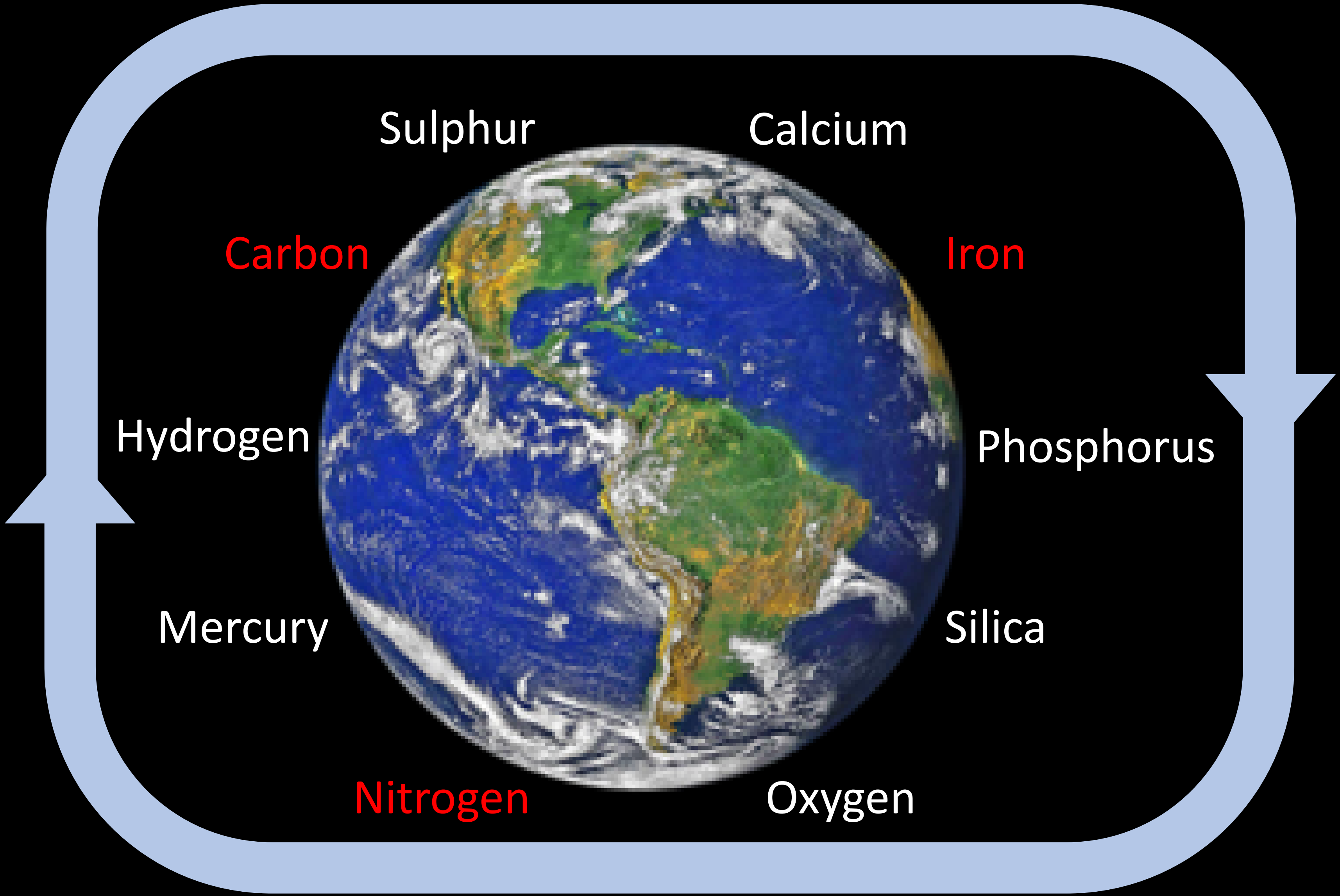


Image: Sardet (2015) Plankton wonders of drifting world. Univ. Chicago Press

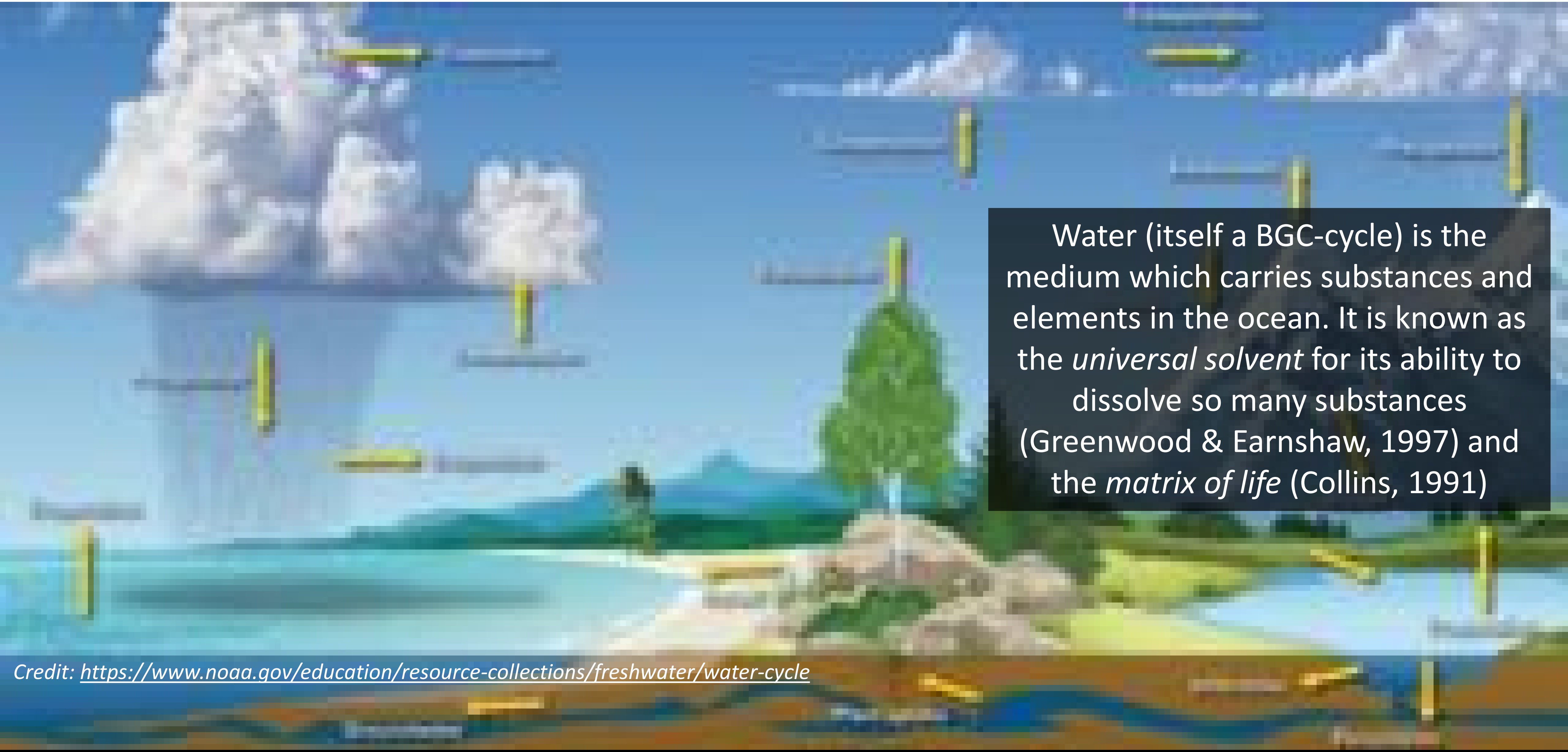


Many of these elemental cycles are intimately linked

Focus of the lecture



Many of these elemental cycles are intimately linked



Water (itself a BGC-cycle) is the medium which carries substances and elements in the ocean. It is known as the *universal solvent* for its ability to dissolve so many substances (Greenwood & Earnshaw, 1997) and the *matrix of life* (Collins, 1991)

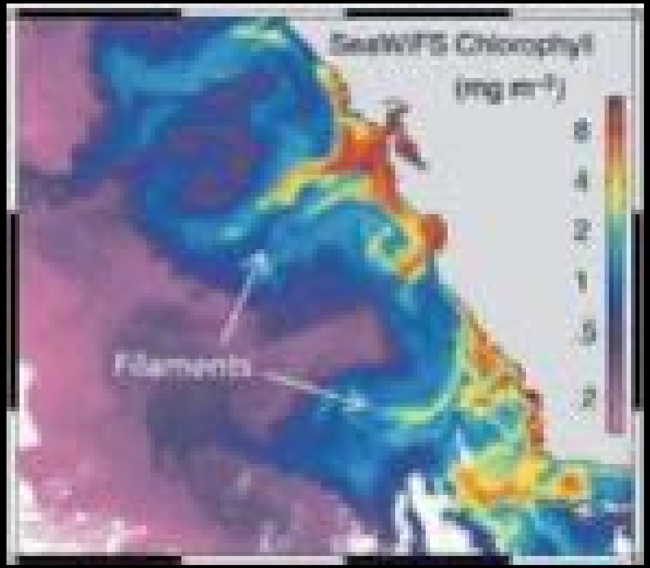
Credit: https://www.noaa.gov/education/resource-collections/freshwater/water-cycle

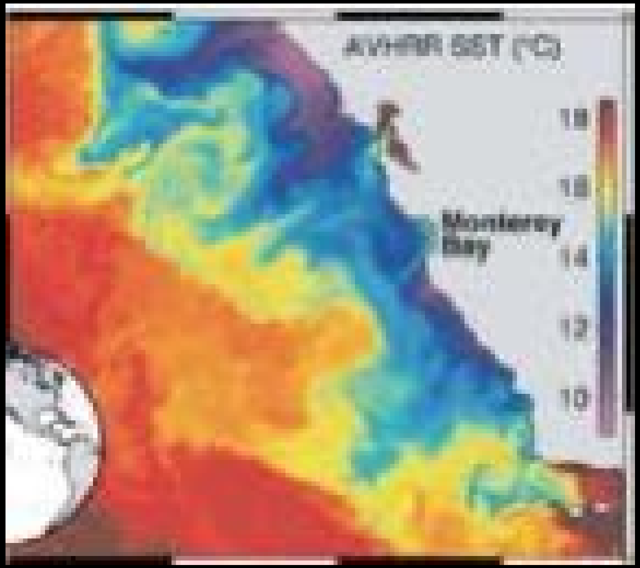
Greenwood, Norman N. Earnshaw, Alan (1997). Chemistry of the Elements (2nd ed.). Butterworth-Heinemann. p. 620.
Collins J. C. (1991) The Matrix of Life: A View of Natural Molecules from the Perspective of Environmental Water Molecular Presentations. ISBN 9780962971907.

Ocean circulation is driven by the uneven distribution of heat (solar radiation) at the equator. It is controlled by the density of the water. Residence time of a water molecule in the ocean is estimated at around 3,200 years

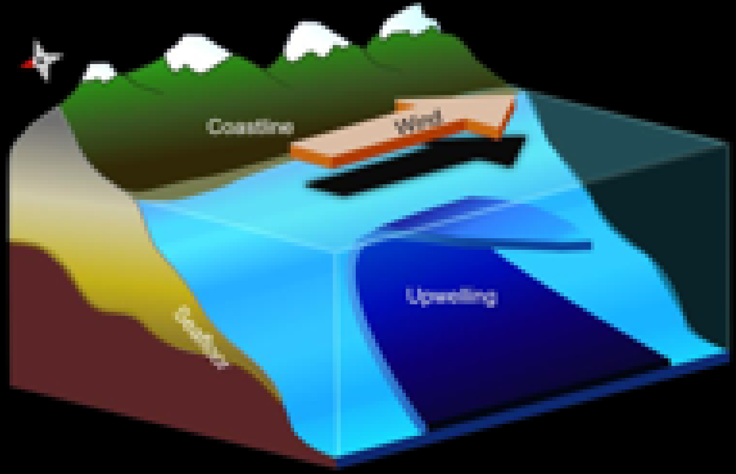
Credit: Brisbane https://commons.wikimedia.org/wiki/File:Thermohaline_circulation.png

Coastal upwelling



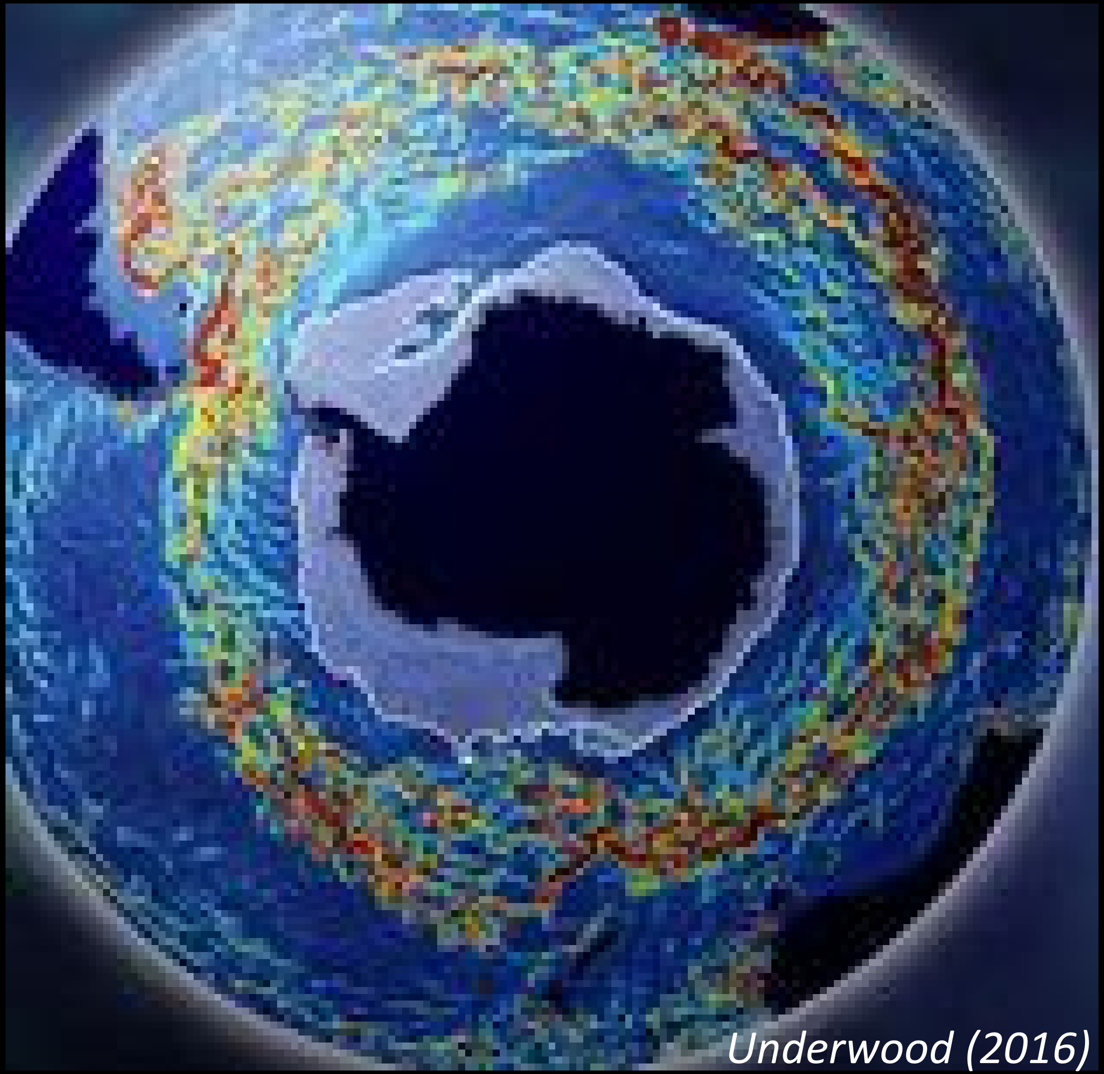


Kämpf & Chapman (2016)



Credit: CNX OpenStax
https://en.wikipedia.org/wiki/Marine_biogeochemical_cycles#/media/File:Figure_44_02_04.png

Wind-driven open ocean upwelling



Underwood (2016)

Kämpf & Chapman, P. 2016. The functioning of coastal upwelling systems. In Upwelling systems of the world (pp. 31-65). Springer, Cham.
Underwood (2016) https://doi.org/10.1029/2016EO064319

In 1934, Alfred C. Redfield reported a suite of dissolved nitrate, phosphate and oxygen measurements from various depths in the Atlantic, Pacific and Indian oceans. These data showed a remarkable consistency.

With nitrate and phosphate occurring in a ratio 16:1, and expanded to include a ratio of carbon to phosphate of 106:1, this Redfield ratio, consistent for dissolved and particulate matter, has come to define our understanding of ocean biogeochemical cycling.

Deviations from this ratio are now providing insights into the nutrient dynamics of oceans modern and ancient.

Alfred Redfield

C:N:P

106:16:1

A diagnostic for understanding how these elements move through the ocean!

Eighty years of Redfield. Nature Geosci ***7****, 849 (2014)* https://doi.org/10.1038/ngeo2319

Carbon cycling from nutrients

Carbon is harder to measure than nitrate or phosphate. Because of Redfield, scientists can estimate from nutrient observations: biological carbon uptake, respiration & organic matter export.

C:N:P

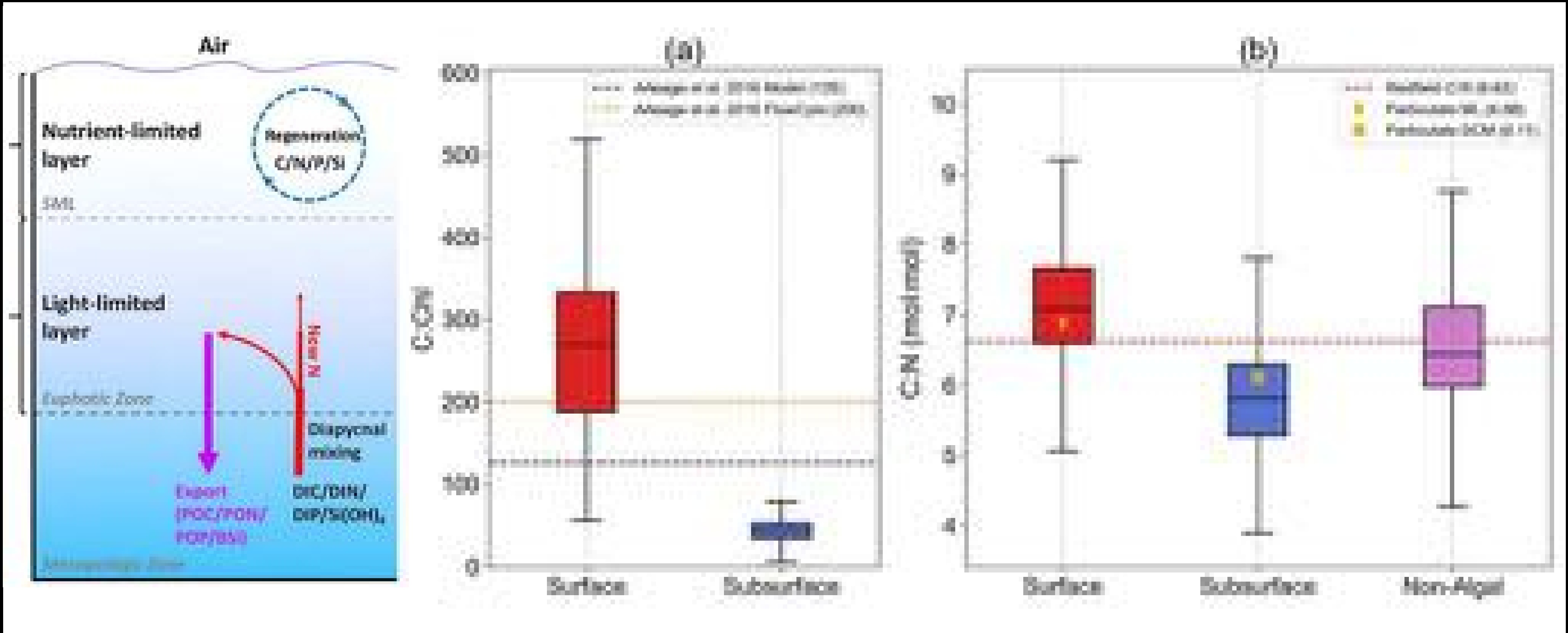
106:16:1

Ecosystem state

Fast-growing phytoplankton lower C:P ratios.
Nutrient-stressed cells may accumulate excess carbon, increasing C:N and C:P.
Cyanobacteria that fix atmospheric nitrogen can alter local N:P ratios.
Iron limitation in parts of the ocean changes nutrient utilization.

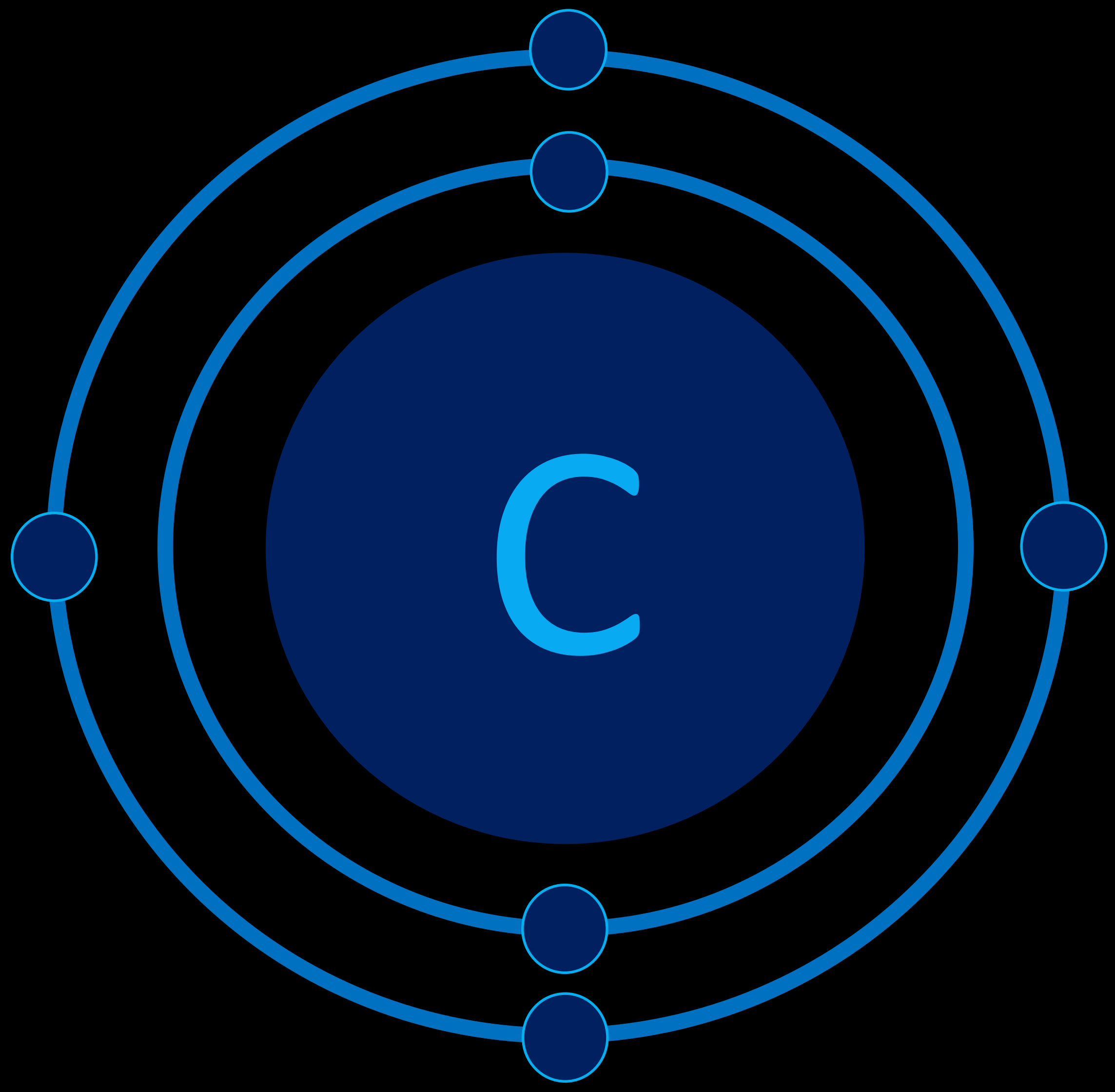
Identify nutrient limitation

Phytoplankton typically require nutrients in a 16:1 nitrogen-to-phosphorus ratio.
N:P < 16 → nitrogen be limiting
N:P > 16 → phosphorus may be limiting.



Dugdale (1967)
https://doi.org/10.4319/lo.1967.12.4.0685
Dai et al. (2023)
https://doi.org/10.1029/2022RG000800

Viljoen et al. (Under Review)
preprint https://doi.org/10.5194/essd-2025-659

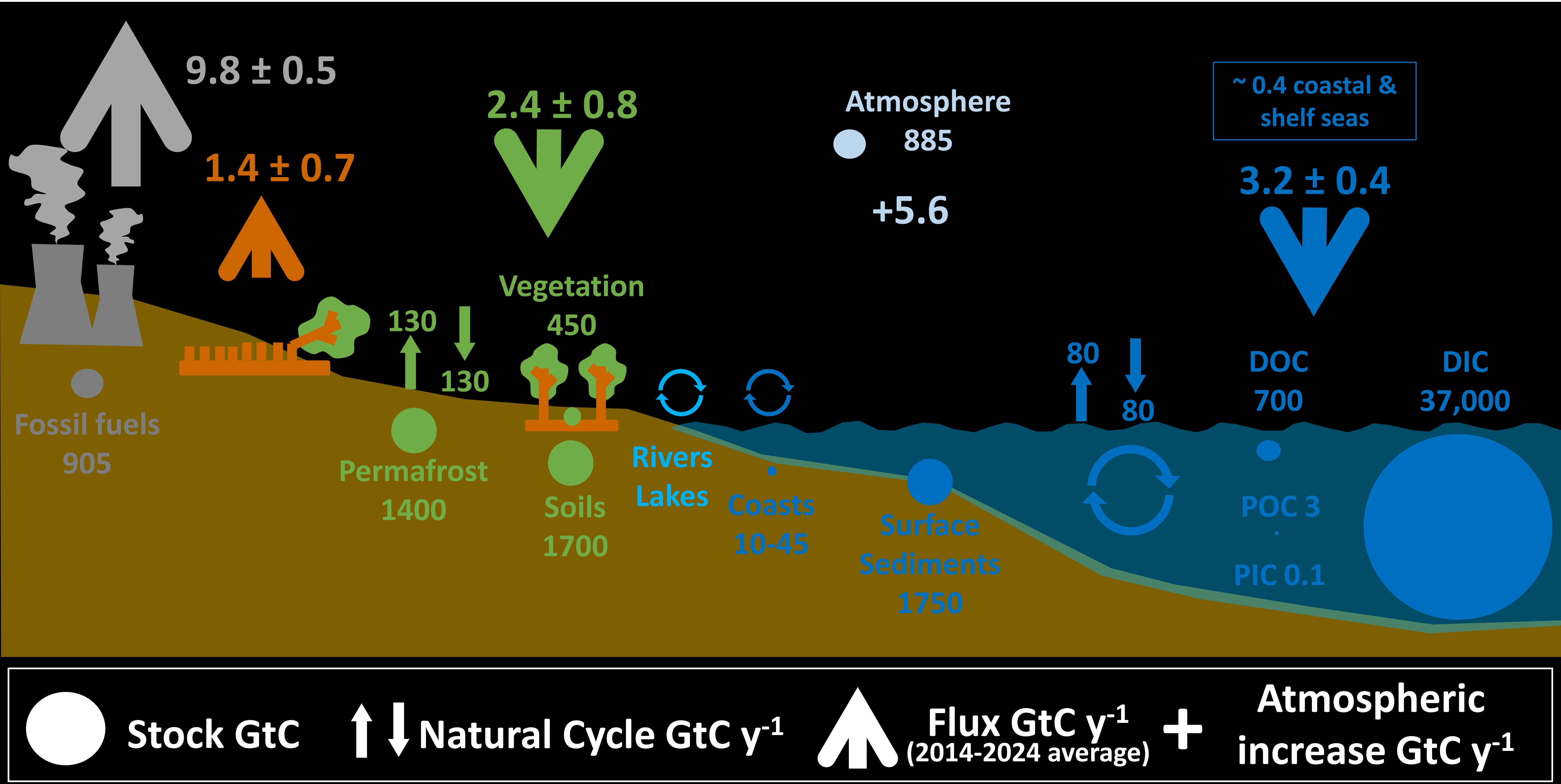


The most versatile element on Earth

Basis of all life

Fuels human civilization

Earth's carbon cycle controls climate



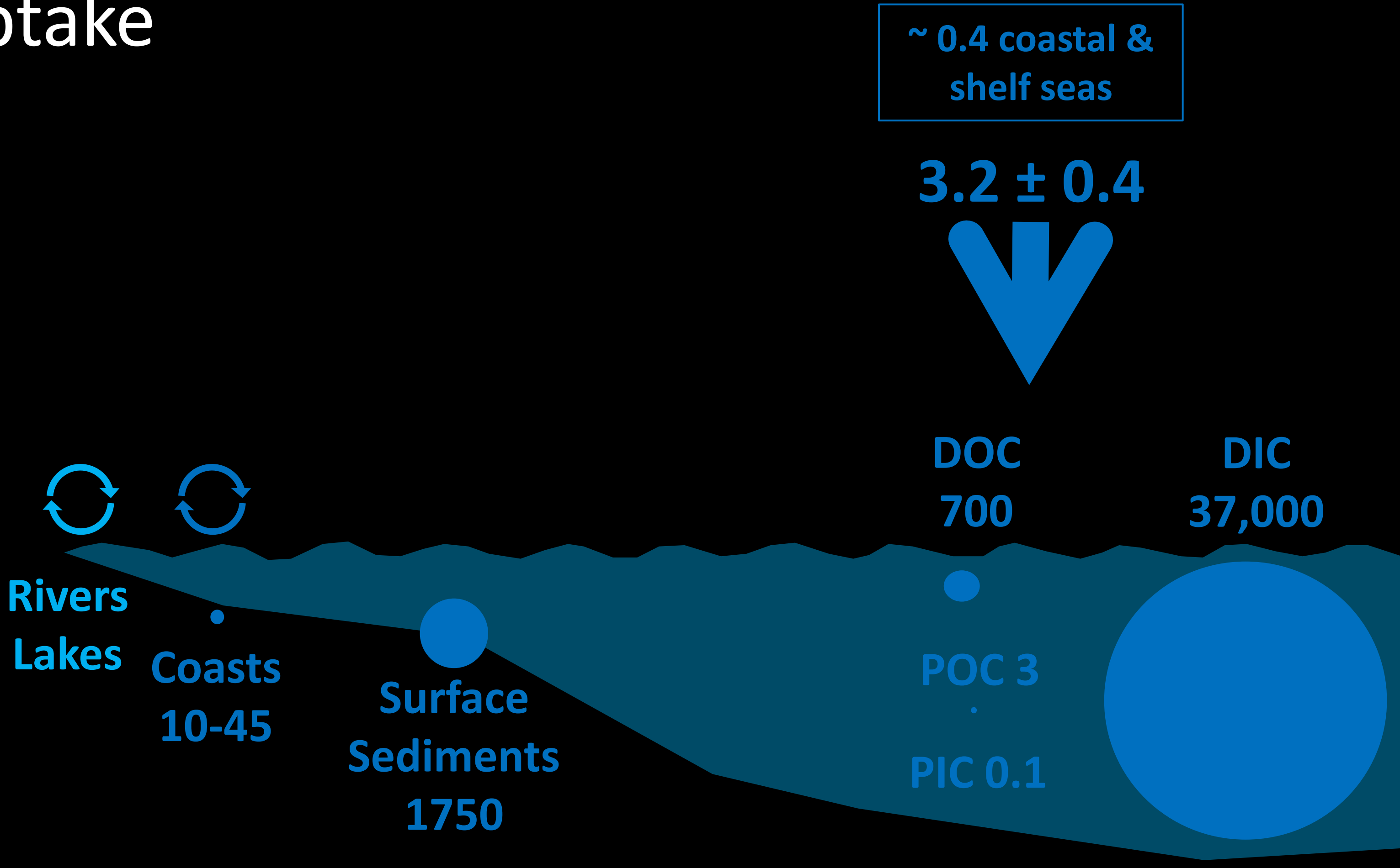
Friedlingstein et al. (2025) Global Carbon Budget 2025 https://doi.org/10.5194/essd-2025-659

30% anthropogenic CO_2 uptake

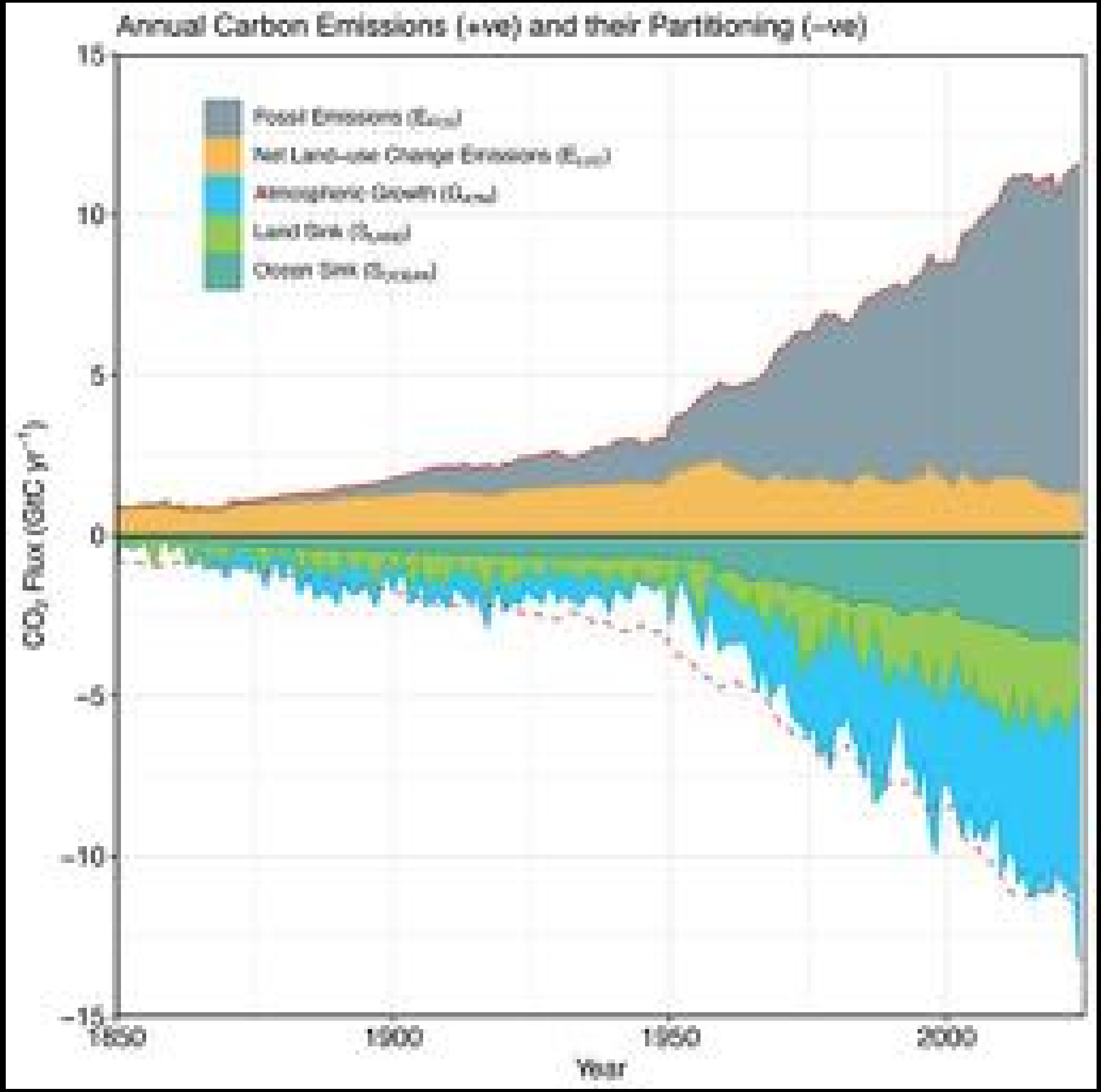
Largest reservoir of active carbon of Earth

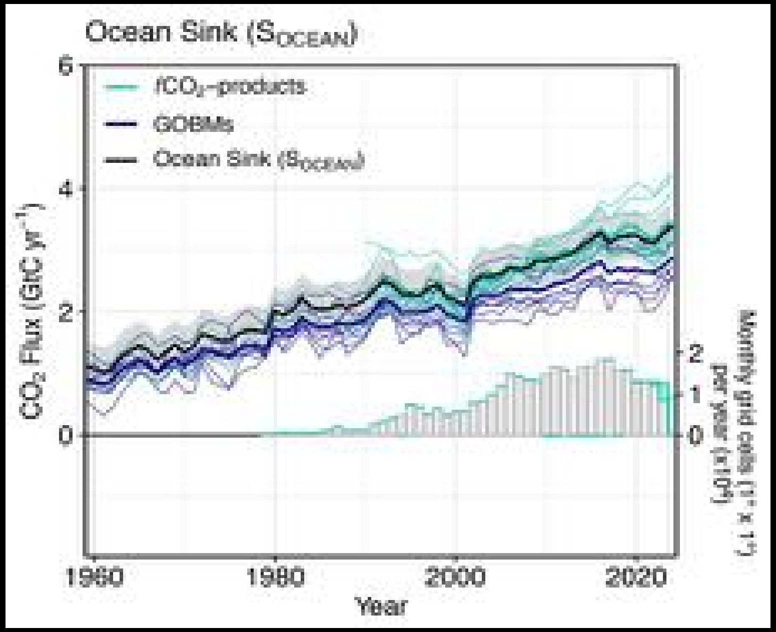
50% of planetary photosynthesis

One of the two main observational constraints on budget calculations



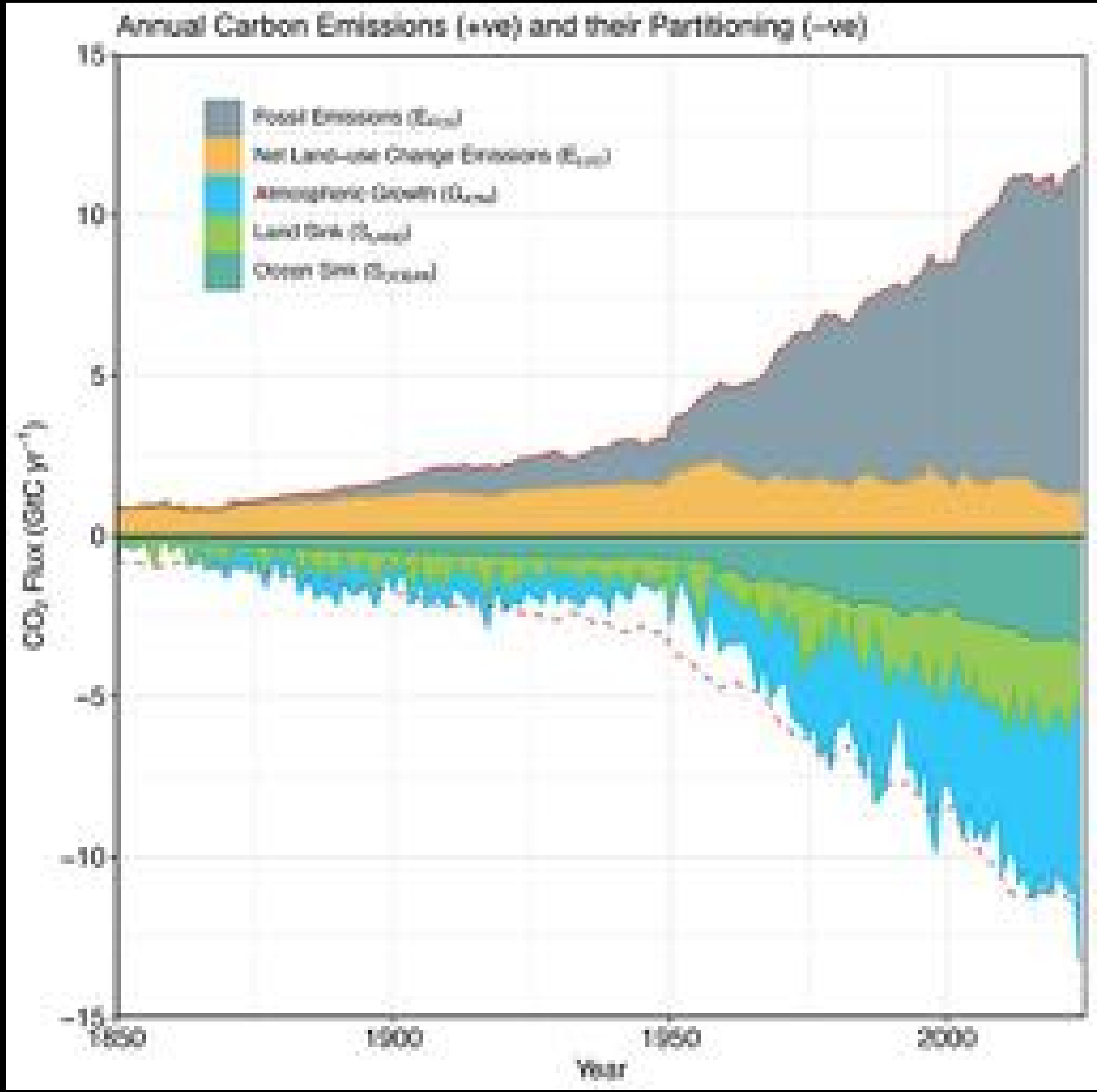
Friedlingstein et al. (2025) Global Carbon Budget 2025 https://doi.org/10.5194/essd-2025-659





Over the period (2014-2024) the ocean CO_2 sink appears to have intensified. This emphasises the importance of the oceans in the global carbon cycle. Yet, large uncertainties remain in how the oceans will respond to increased CO_2 emissions in the future.

Friedlingstein et al. (2025) Global Carbon Budget 2025 https://doi.org/10.5194/essd-2025-659



The solubility pump delivers cold, dense, DIC-rich waters to depth mostly at high latitudes

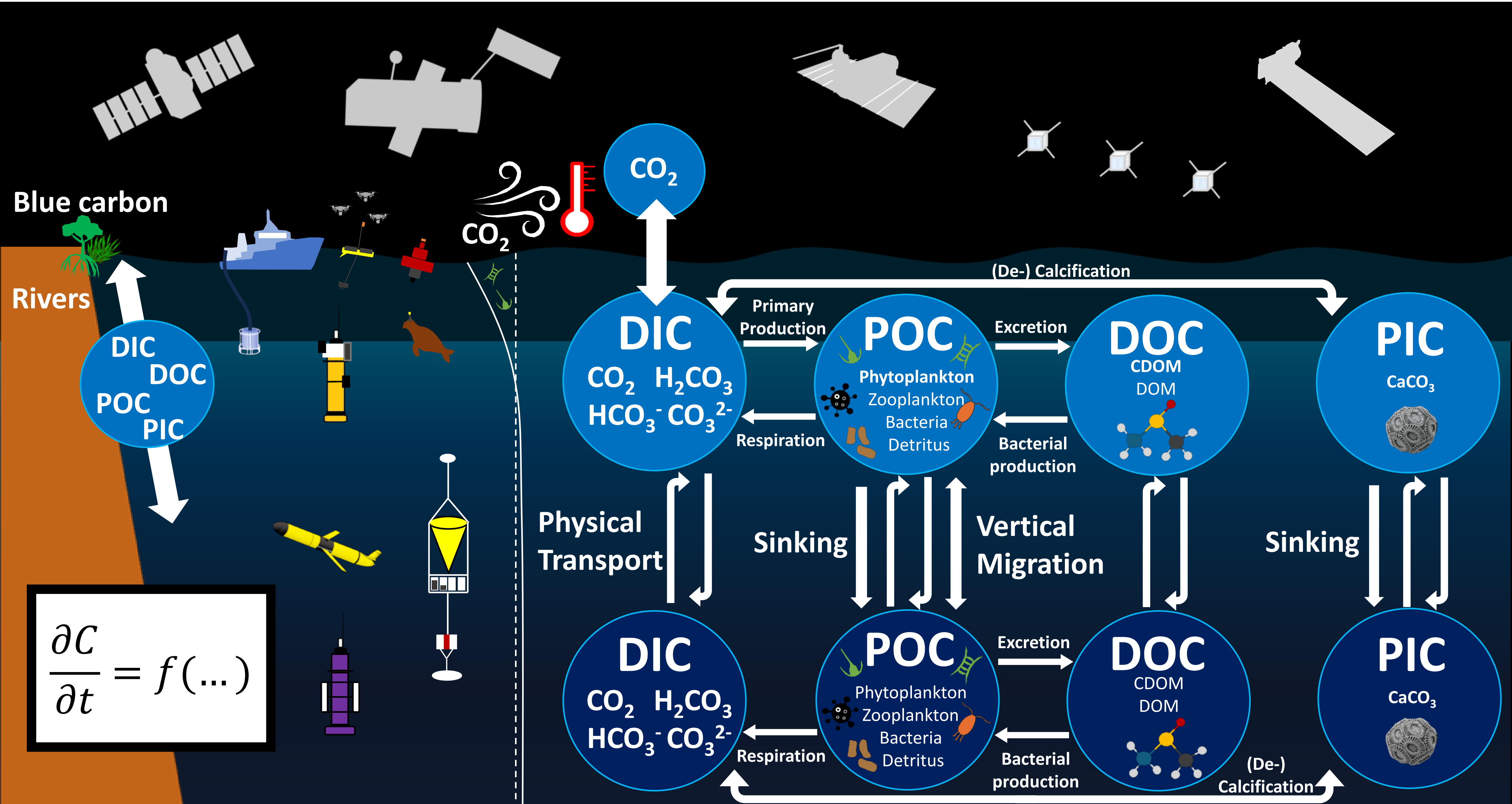
Intrinsically linked

The biological pump globally exports organic carbon from surface waters

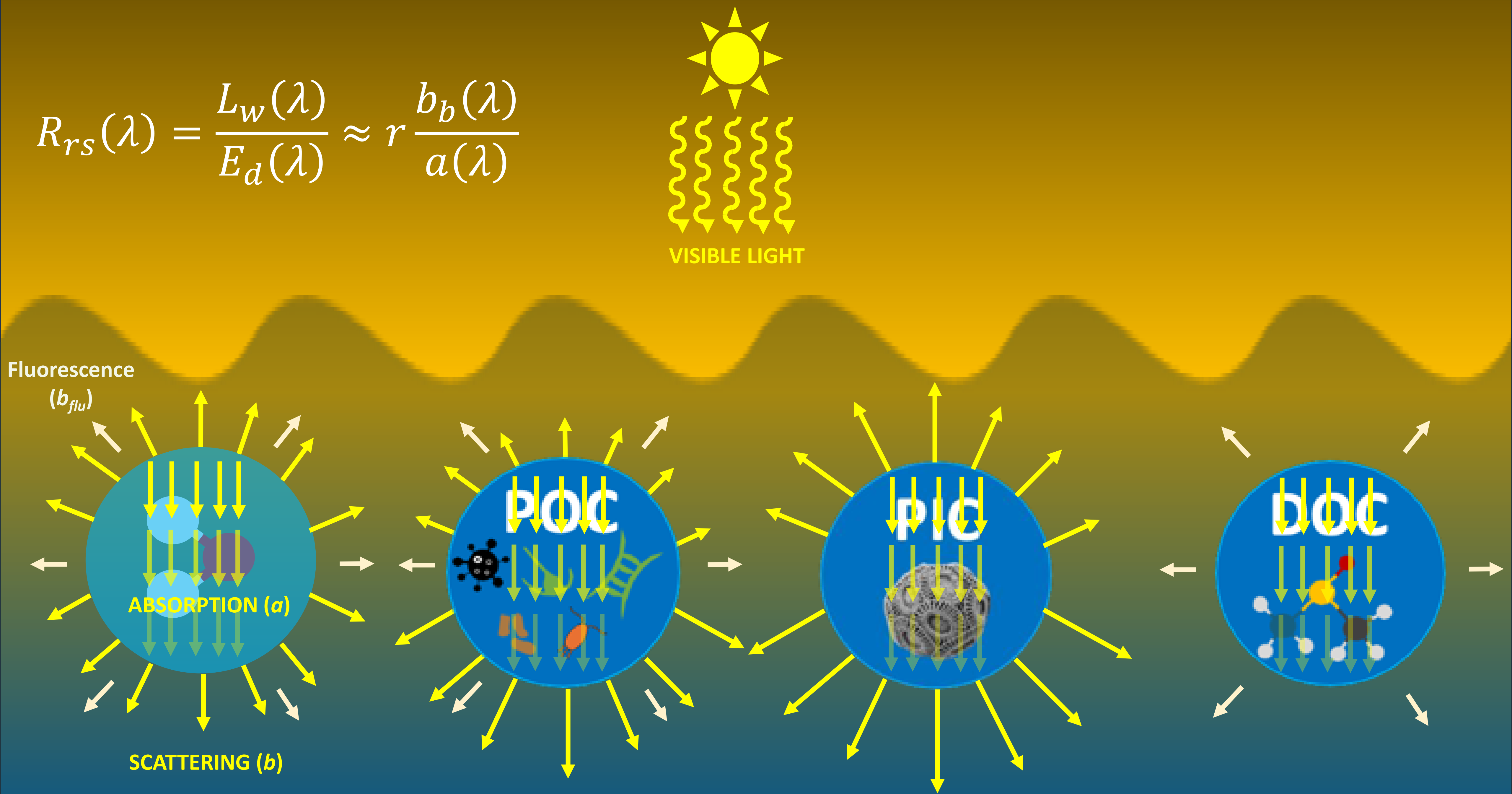
SHORTER TERM
Thought to be responsible for update of majority of anthropogenic CO_2

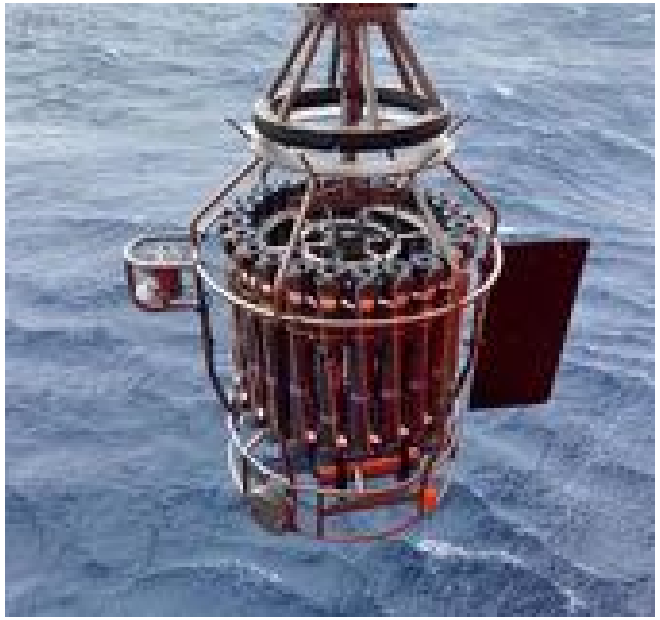
LONGER TERM
Thought to be responsible fluctuations in atmospheric CO_2 over long timescales

Friedlingstein et al. (2025) Global Carbon Budget 2025 https://doi.org/10.5194/essd-2025-659

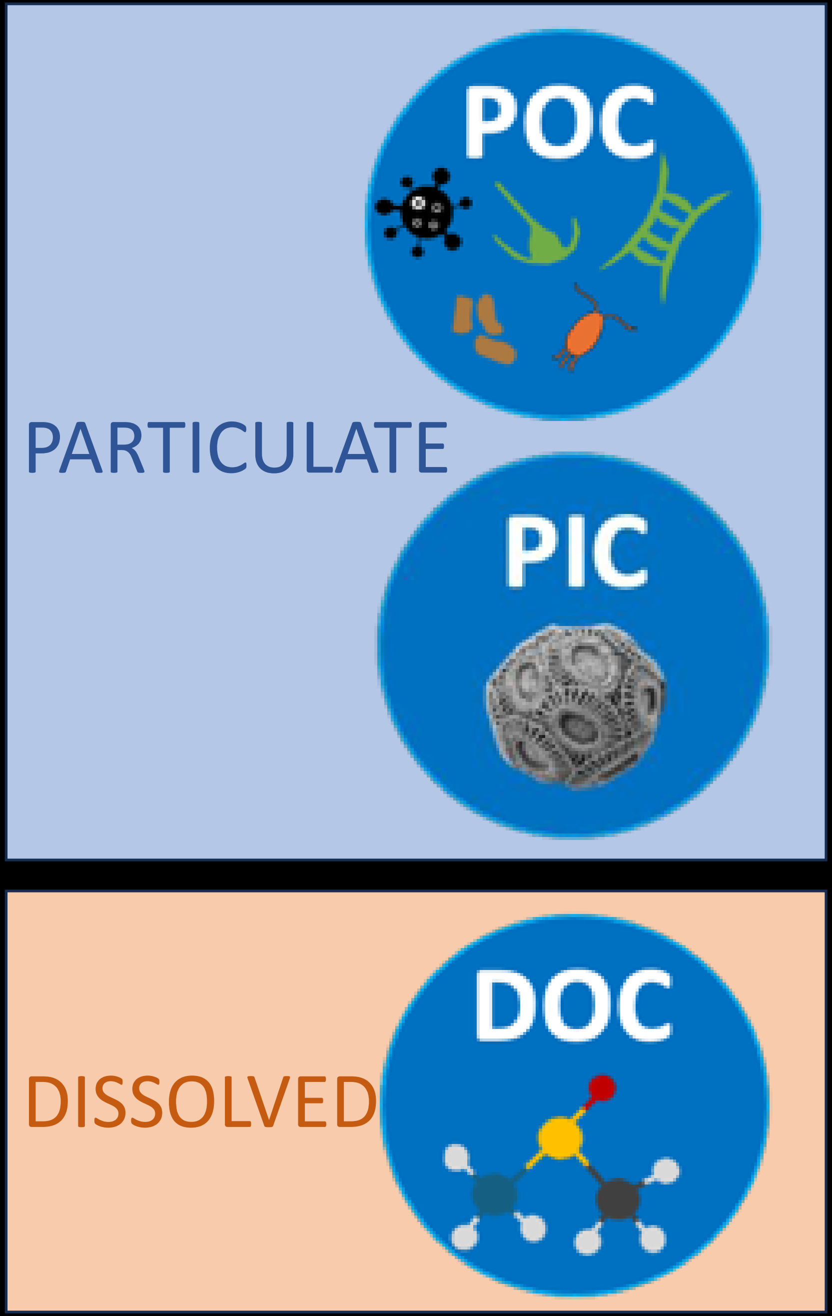

Blue carbon
Rivers
DIC
DOC
POC
PIC
CO_2
CO_2
(De-) Calcification
DIC
CO_2 H_2CO_3
HCO_3^- CO_3^{2-}
Primary Production
Respiration
POC
Phytoplankton
Zooplankton
Bacteria
Detritus
Excretion
Bacterial production
DOC
CDOM
DOM
PIC
$CaCO_3$
Physical Transport
Sinking
Vertical Migration
Sinking
DIC
CO_2 H_2CO_3
HCO_3^- CO_3^{2-}
Respiration
POC
Phytoplankton
Zooplankton
Bacteria
Detritus
Excretion
Bacterial production
DOC
CDOM
DOM
(De-) Calcification
PIC
$CaCO_3$
$\frac{\partial C}{\partial t} = f(\ldots)$

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda)} \approx r\frac{b_b(\lambda)}{a(\lambda)}$$





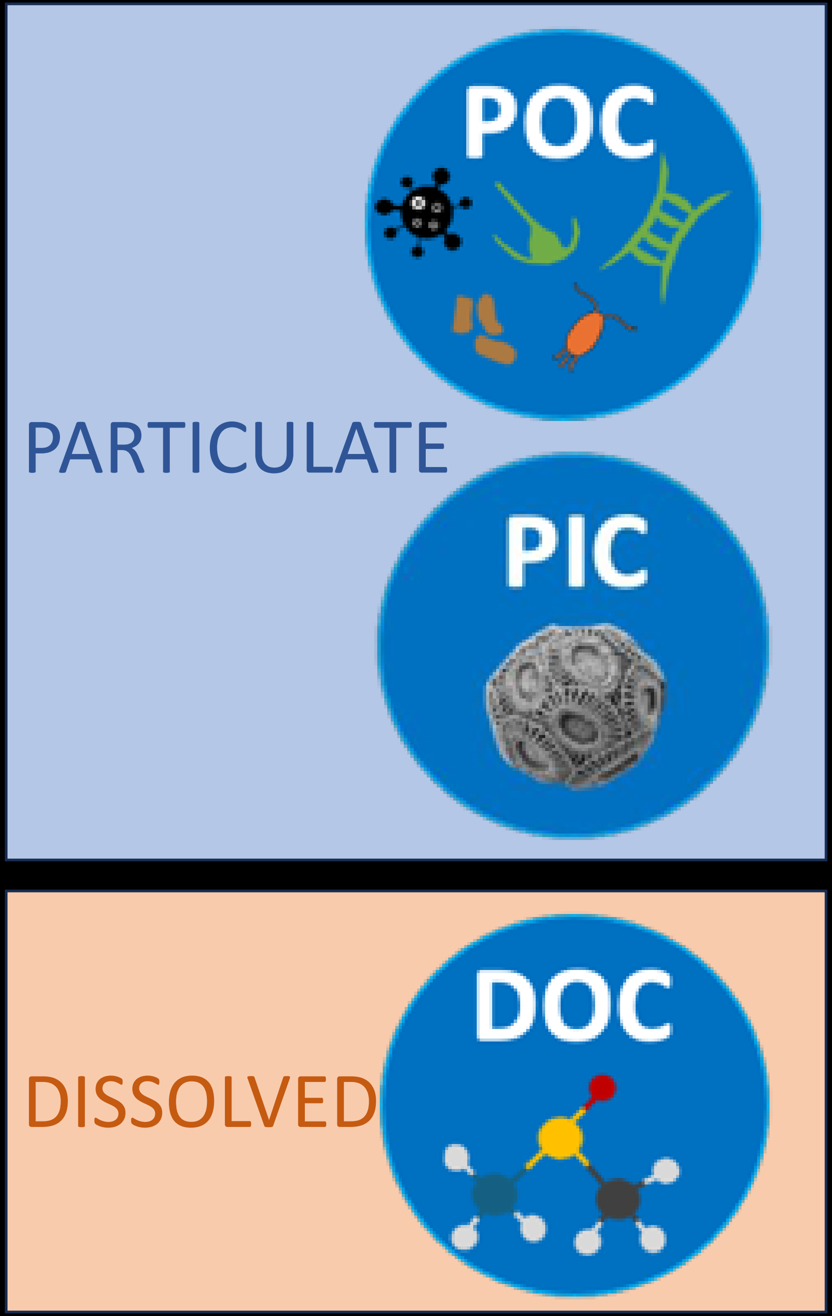
Credit https://www.seabird.com/ https://www.sequoiasci.com/ http://otronix.com/en/index.php/product/etc/?board_name=ect08&order_by=fn_pid&order_type=desc&vid=10 https://rbr-global.com/rbrtridente-a-closer-look/



Some Broad Challenges

- Challenges to measuring pools of carbon analytically (e.g. see IOCCG Protocols https://ioccg.org/what-we-do/ioccg-publications/ioccg-protocols/, measuring phytoplankton carbon (C_{phyto}) very difficult)
- Partitioning of optical signals into contributions of POC and PIC.
- Partitioning of optical signals related to POC into its components (phytoplankton (C_{phyto}) and non-algal organic particles, particle sizes and types)
- Relationship between DOC and CDOM highly variable and often not well correlated (CDOM and DOC are largely decoupled in the open ocean)

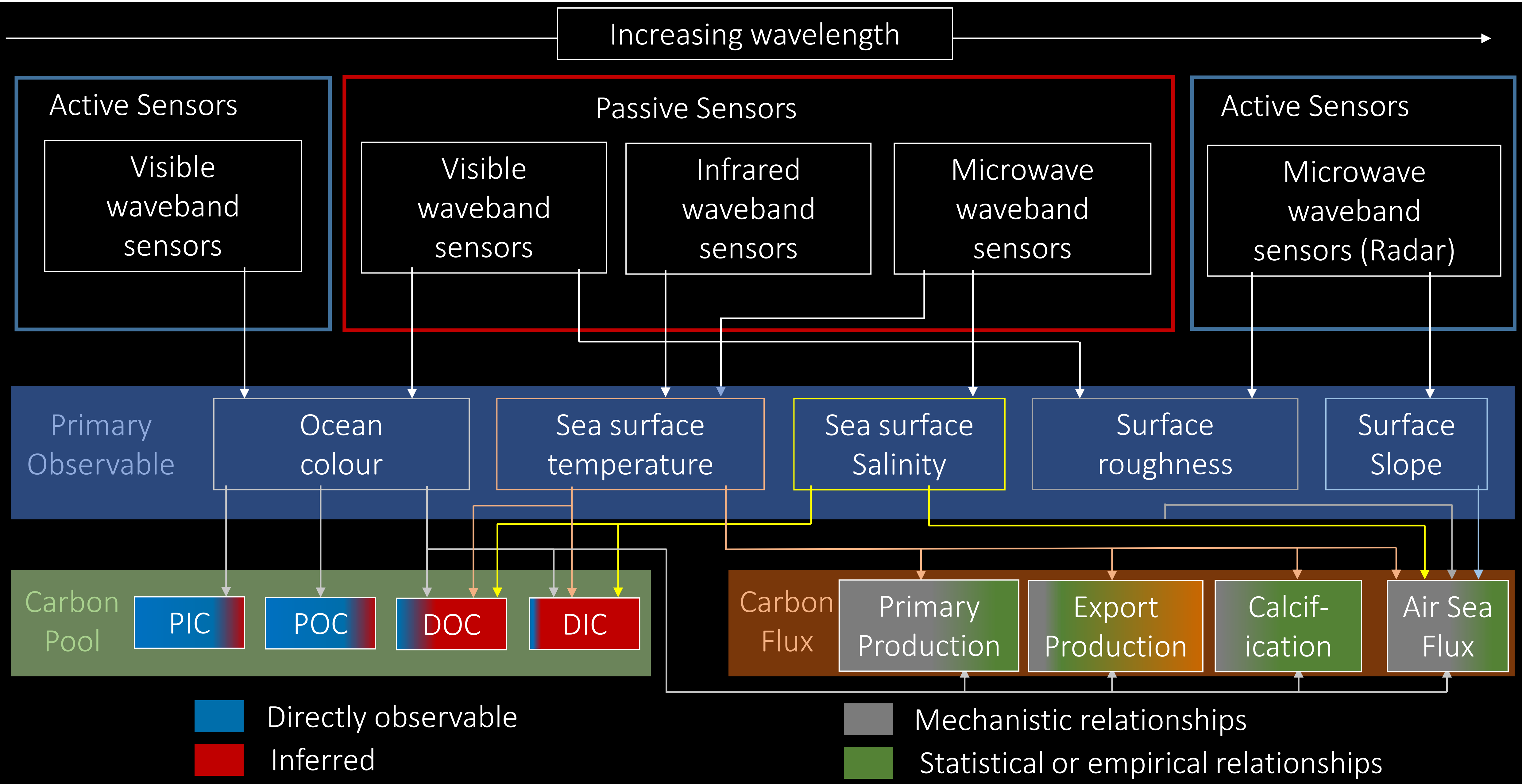
Brewin et al. (2023) https://doi.org/10.1016/j.earscirev.2023.104386



Some Opportunities

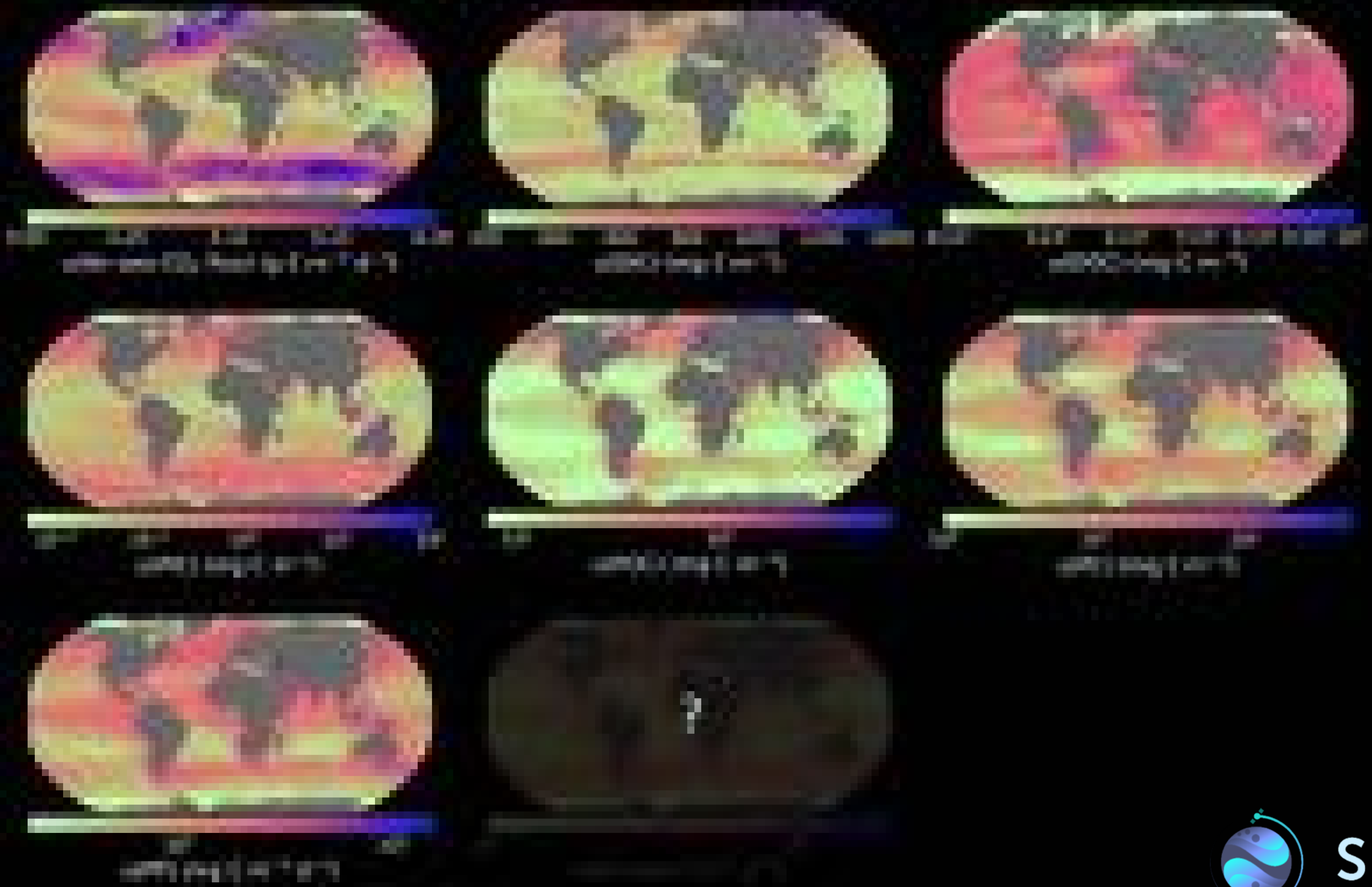
- Advance and standardise analytical methods for improved measurement of total POC, PIC and DO,and techniques to separate living and non-living POC. (https://ioccg.org/what-we-do/ioccg-publications/ioccg-protocols/)
- Development of optical sensors (e.g. light-scattering polarisation, hyperspectral backscattering)
- Expanding network of autonomous platforms
- Advancements in mechanistic and statistical approaches (e.g. machine learning) for relating optical signals to pools of carbon

Brewin et al. (2023) https://doi.org/10.1016/j.earscirev.2023.104386

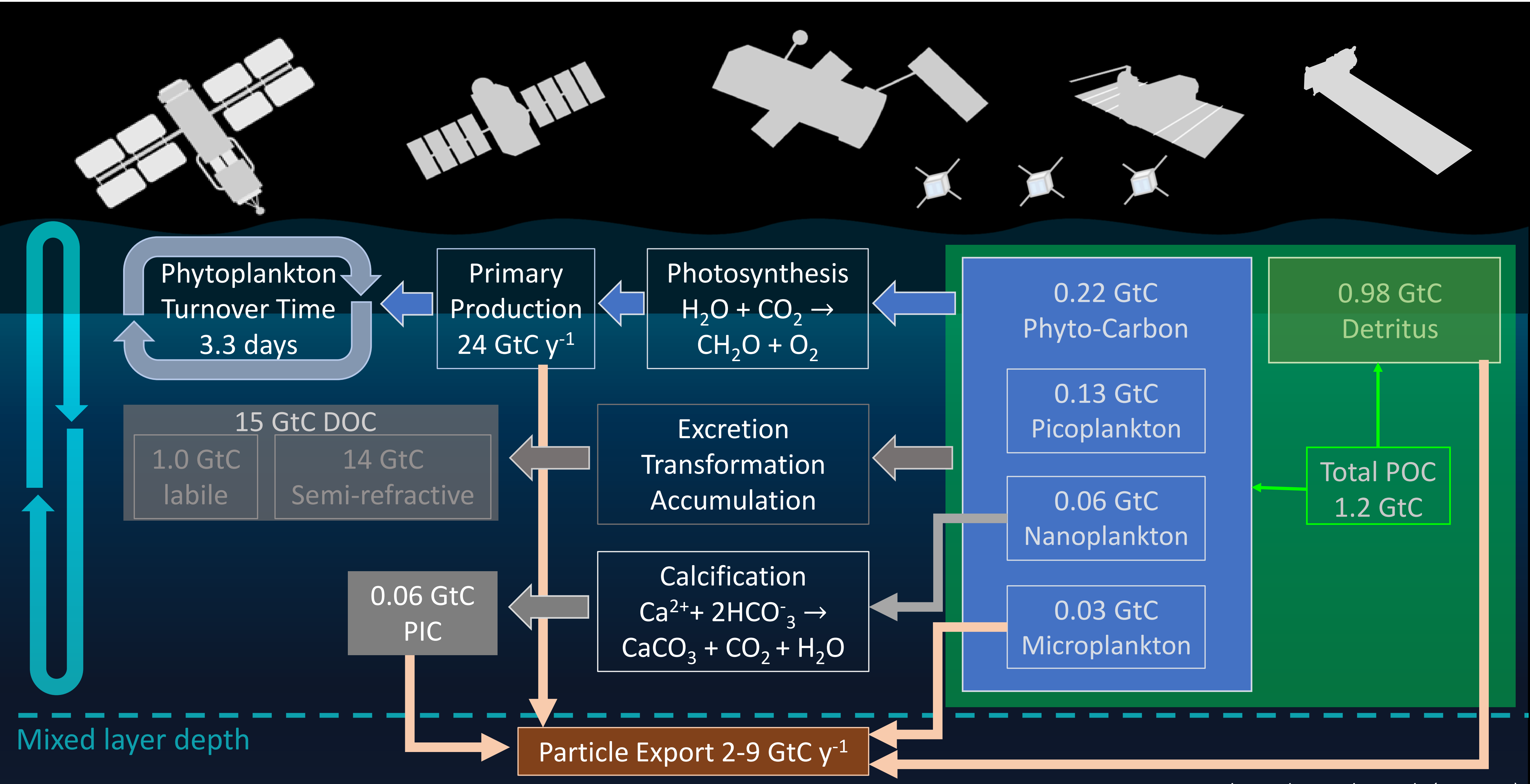


Inspired by Robinson (2004) Measuring the Oceans from Space

Kulk et al. (2025) Ocean Carbon from Space 2nd Workshop

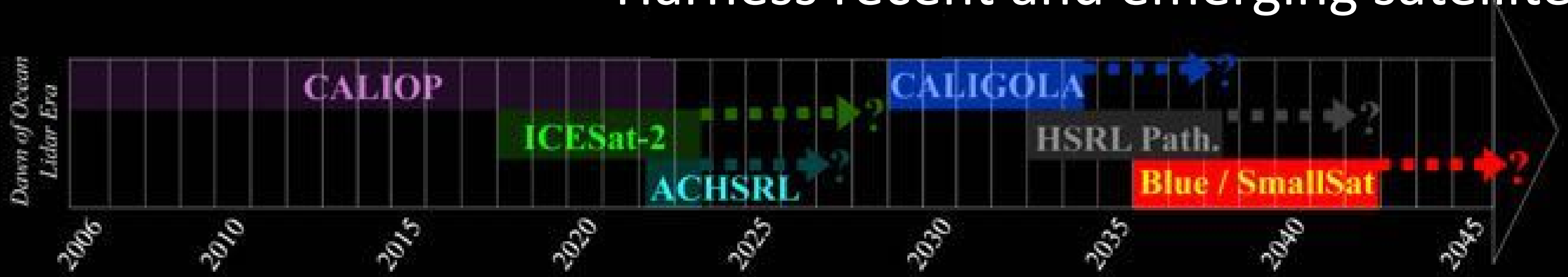


Kulk et al. (2025) Ocean Carbon from Space 2nd Workshop



Sathyendranath et al. (In Prep)

Harness recent and emerging satellites



Behrenfeld et al. (2023) https://doi.org/10.3390/rs15235567

PACE

GLIMR

EnMAP

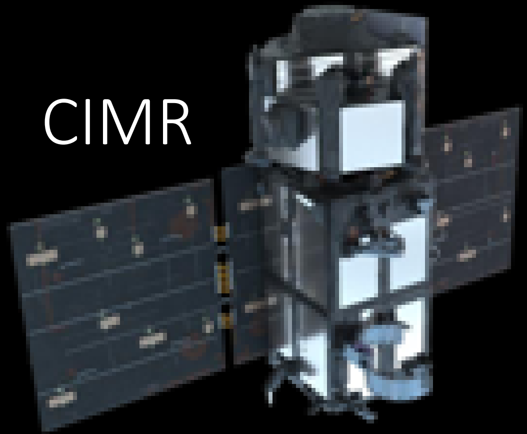
EU | ESA chime COPERNICUS

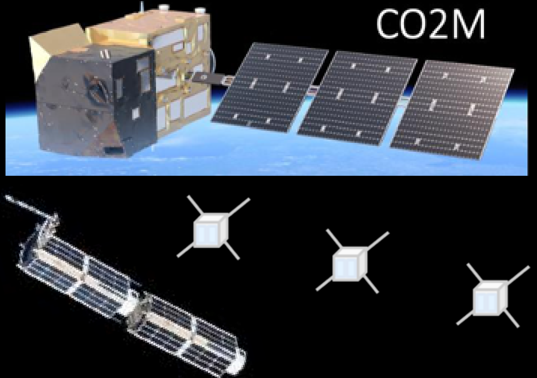
ESA | JAXA earthcare

SABIA-Mar

SWOT

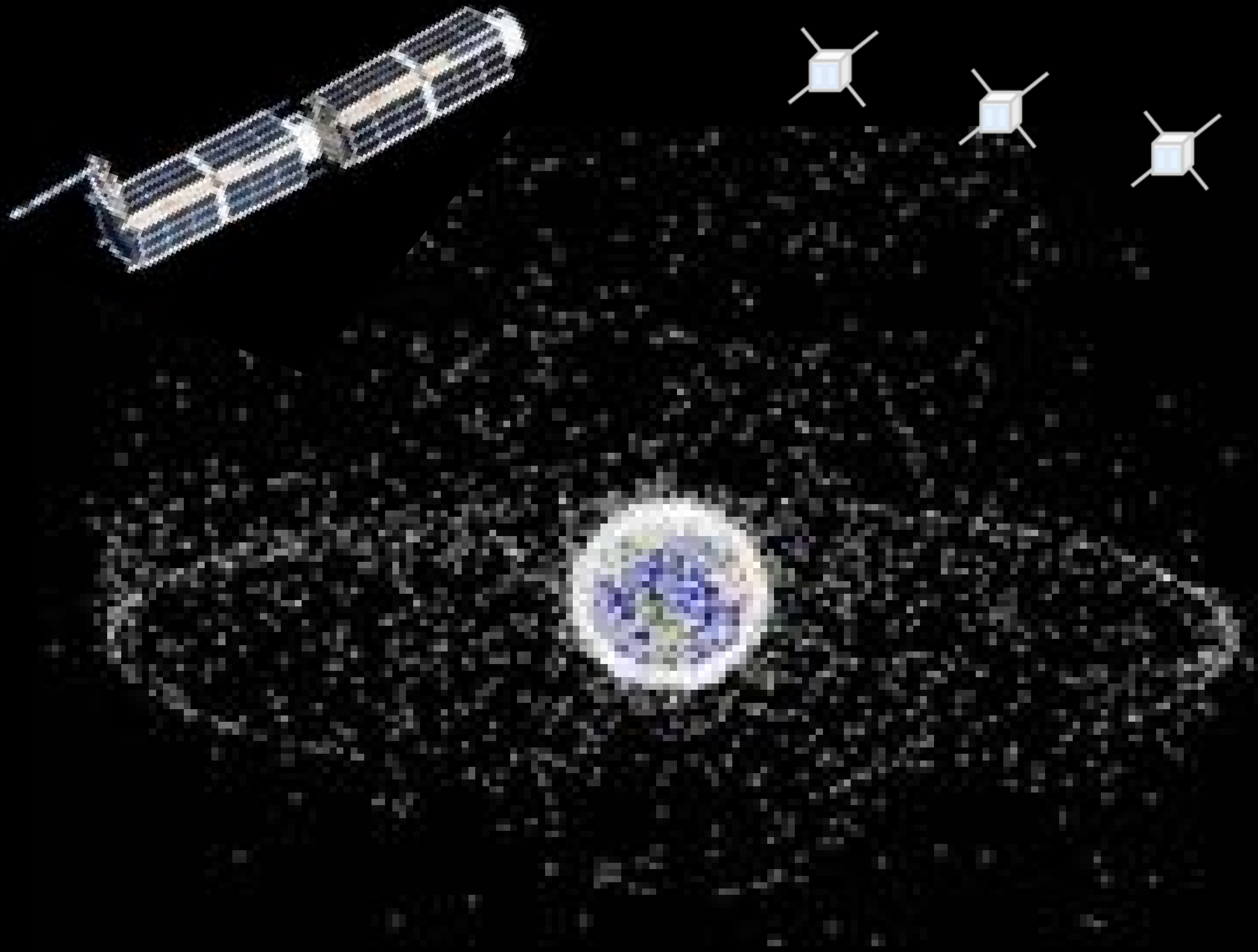
CIMR





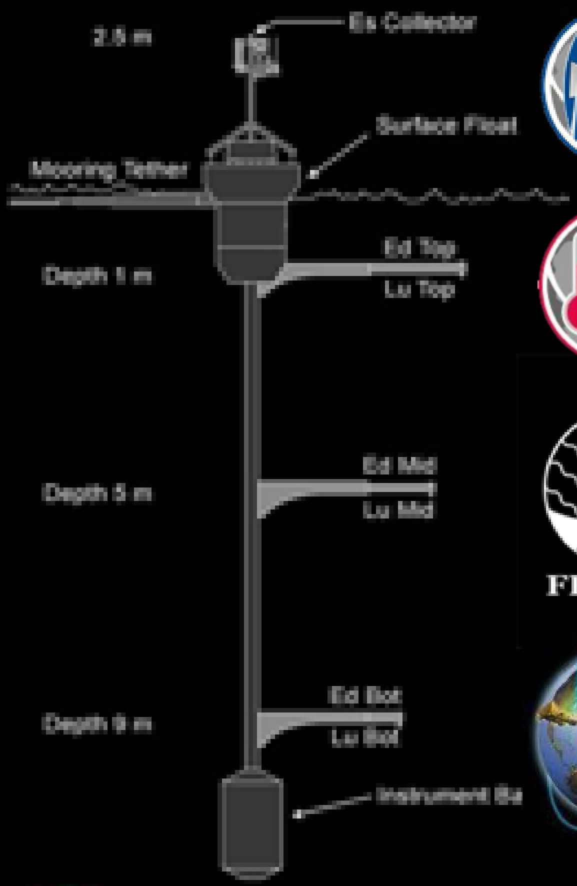
Small and commercial satellites

Bresnahan et al. (2024)
https://doi.org/10.1038/s41597-024-04076-4



Martellato et al. (2022)
https://doi.org/10.3390/rs14092066

Cal/Val of primary observables



fiducial reference measurements for satellite ocean colour

FRM4STS

FRM4ALT

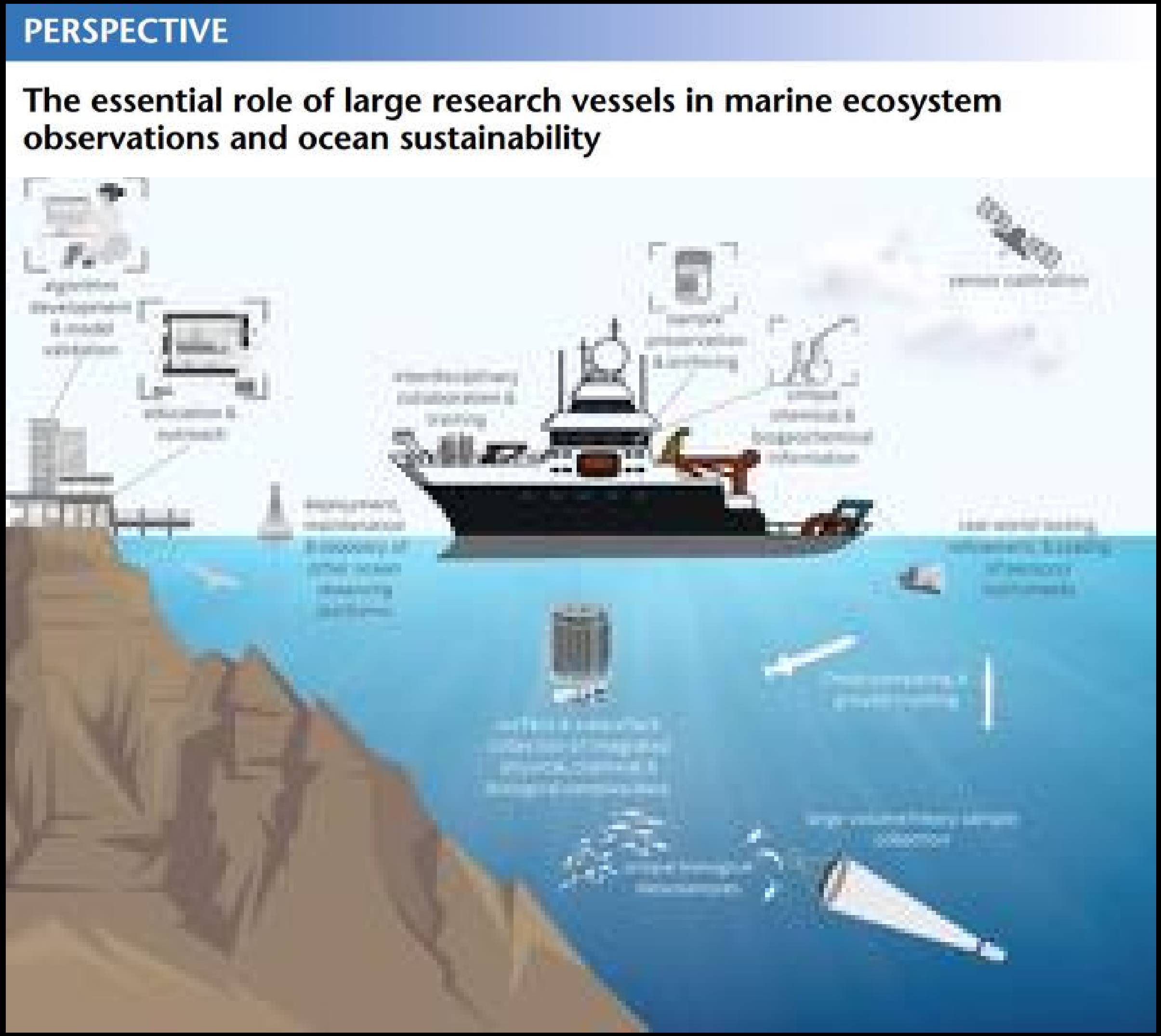
CEOS Committee on Earth Observation Satellites

IOCCG International Ocean Colour Coordinating Group

OCR-VC

Zibordi et al. (2025) *https://doi.org/10.1175/BAMS-D-24-0085.1*

Essential role of ships



Satterthwaite et al. (2025) https://doi.org/10.1002/lno.70110

REVIEWS 27

Satellites will address critical science priorities for quantifying ocean carbon

Jamie D Shutler[1*], Rik Wanninkhof[2], Philip D Nightingale[3], David K Woolf[4], Dorothee CE Bakker[5], Andy Watson[6], Ian Ashton[1], Thomas Holding[1], Bertrand Chapron[7], Yves Quilfen[7], Chris Fairall[8], Ute Schuster[6], Masakatsu Nakajima[9], and Craig J Donlon[10]

Shutler et al. (2020) *https://doi.org/10.1002/fee.2129*

Sensing the ocean biological carbon pump from space: A review of capabilities, concepts, research gaps and future developments

Robert J.W. Brewin[a,b,*], Shubha Sathyendranath[b,c], Trevor Platt[b], Heather Bouman[d], Stefano Ciavatta[b,c], Giorgio Dall'Olmo[b,c], James Dingle[b], Steve Groom[b], Bror Jönsson[b], Tihomir S. Kostadinov[e], Gemma Kulk[b], Marko Laine[f], Victor Martínez-Vicente[b], Stella Psarra[g], Dionysios E. Raitsos[h], Katherine Richardson[i], Marie-Hélène Rio[j], Cécile S. Rousseaux[k,l], Joe Salisbury[m], Jamie D. Shutler[a], Peter Walker[b]

Brewin et al. (2021)
https://doi.org/10.1016/j.earscirev.2021.103604

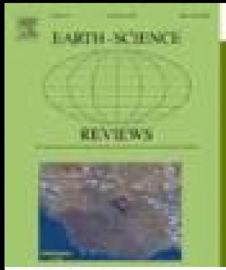
ANNUAL REVIEWS

Annual Review of Marine Science

Quantifying the Ocean's Biological Pump and Its Carbon Cycle Impacts on Global Scales

David A. Siegel,[1] Timothy DeVries,[1] Ivona Cetinić,[2,3] and Kelsey M. Bisson[4]

Siegel et al. (2023) *https://doi.org/10.1146/annurev-marine-040722-115226*



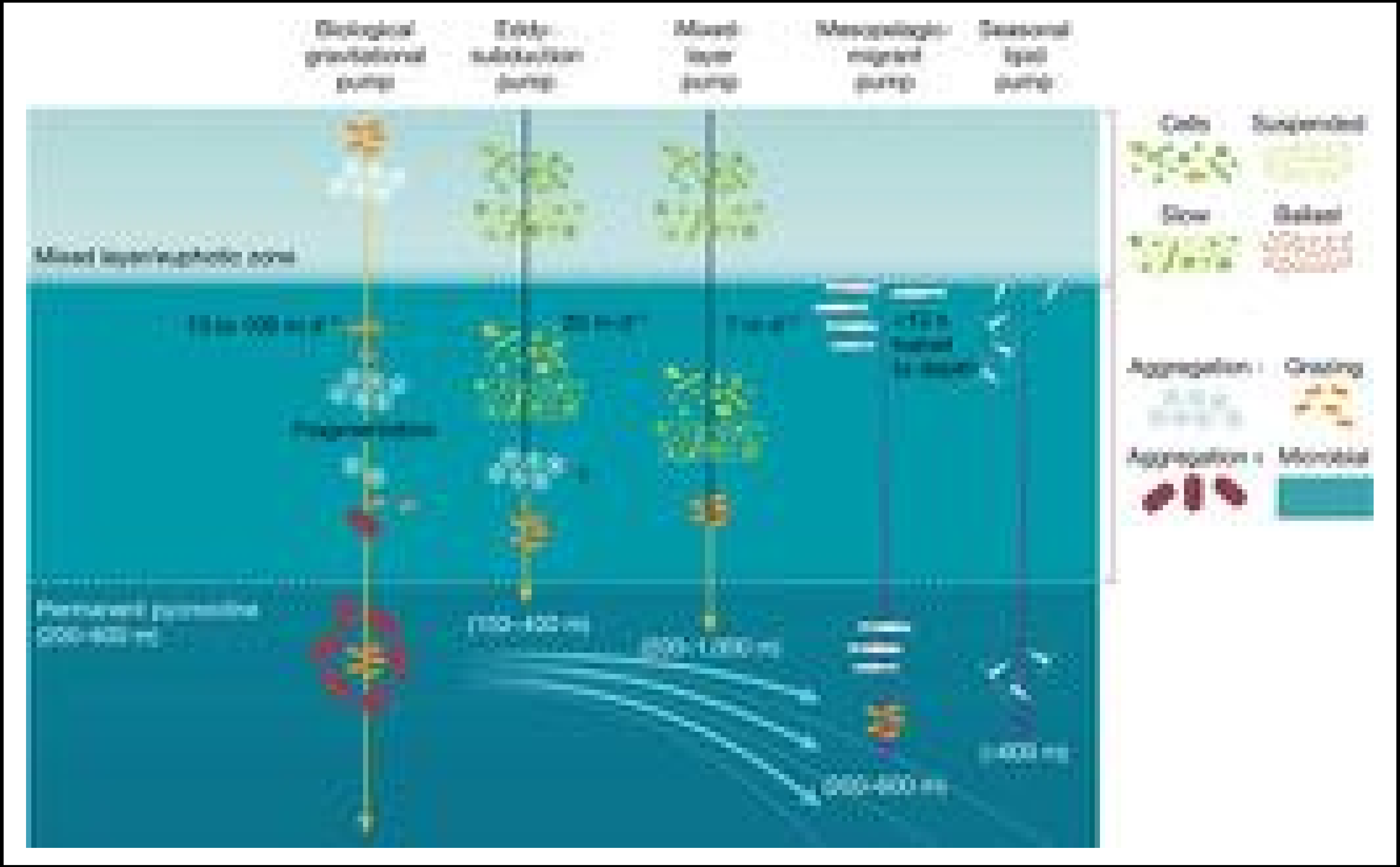
Earth-Science Reviews

Supports open access

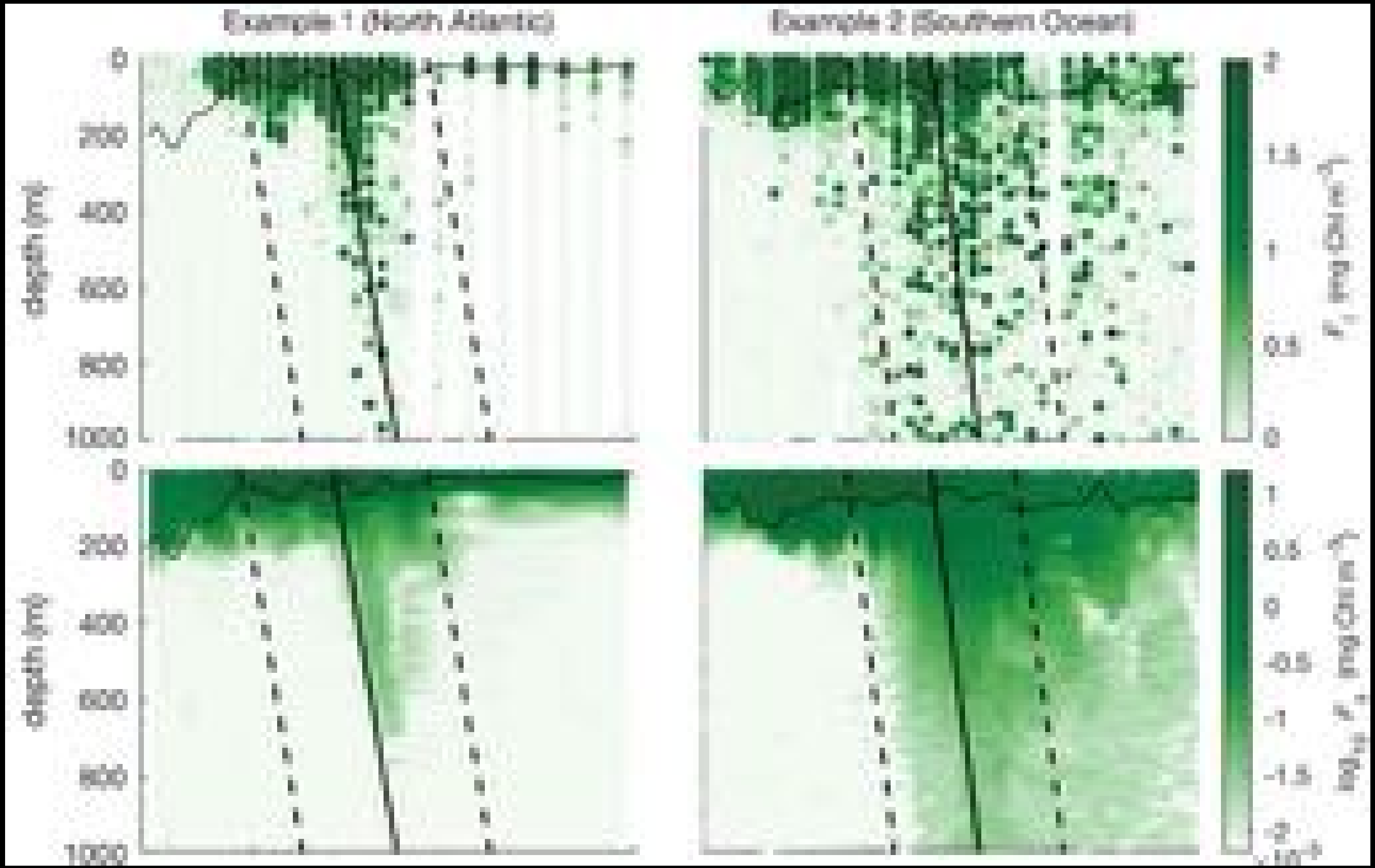
Special issue

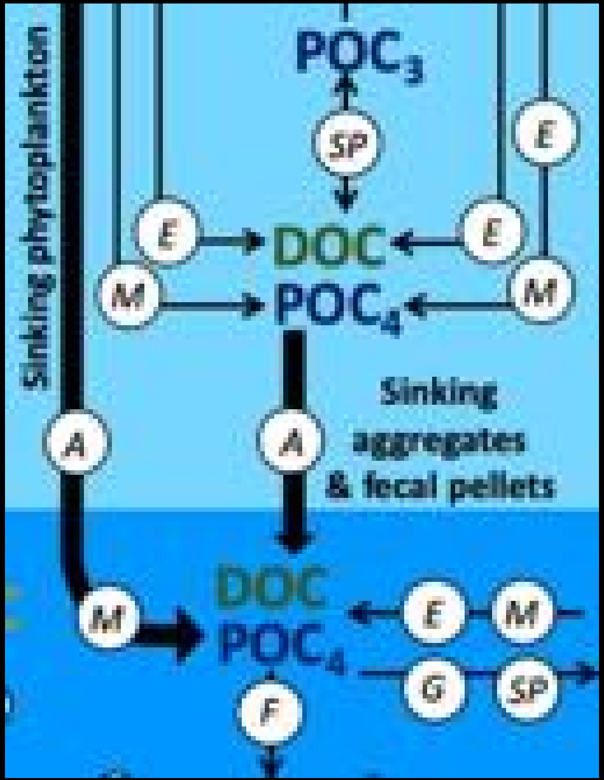
Aquatic carbon stocks and fluxes: The big picture from remote sensing

https://www.sciencedirect.com/special-issue/10JHBMJVSNW



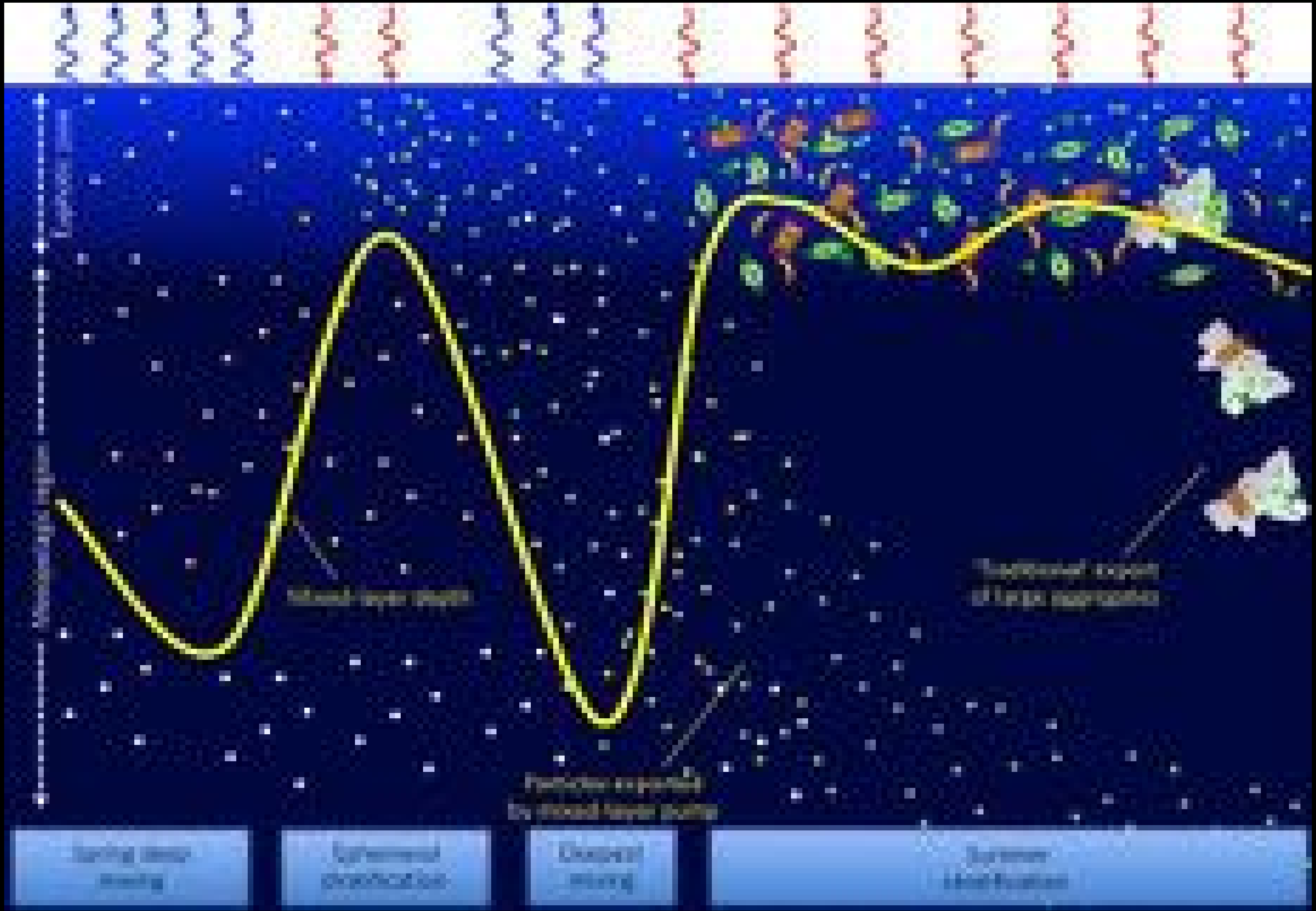
Boyd et al. (2019)
https://doi.org/10.1038/s41586-019-1098-2

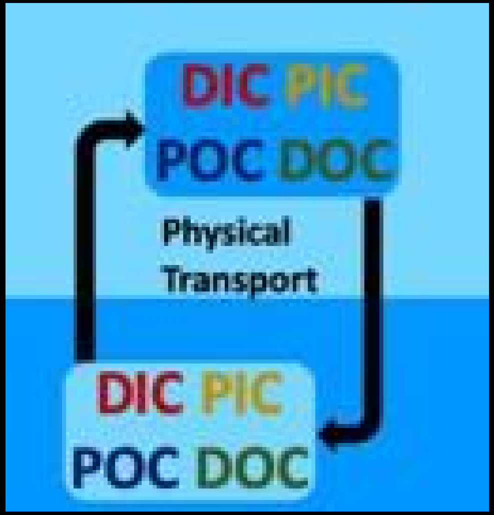




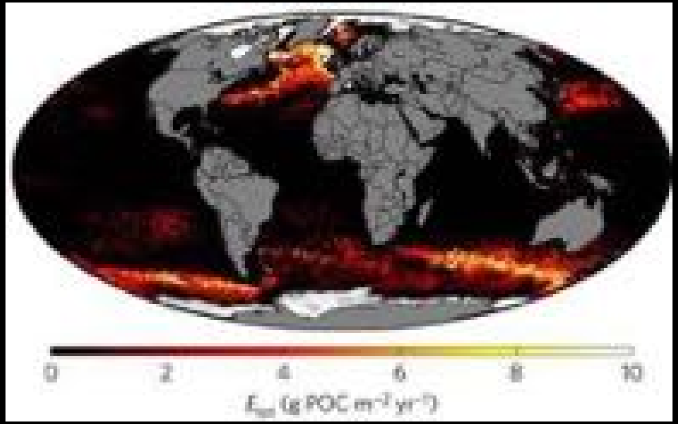
Briggs et al. (2020) http://doi.org/10.1126/science.aay1790

Briggs et al. (2026) GLOBESINK: Global Climatology of Particle Backscattering, Size, and Carbon Flux from BGC-Argo https://doi.org/10.5281/zenodo.19558504

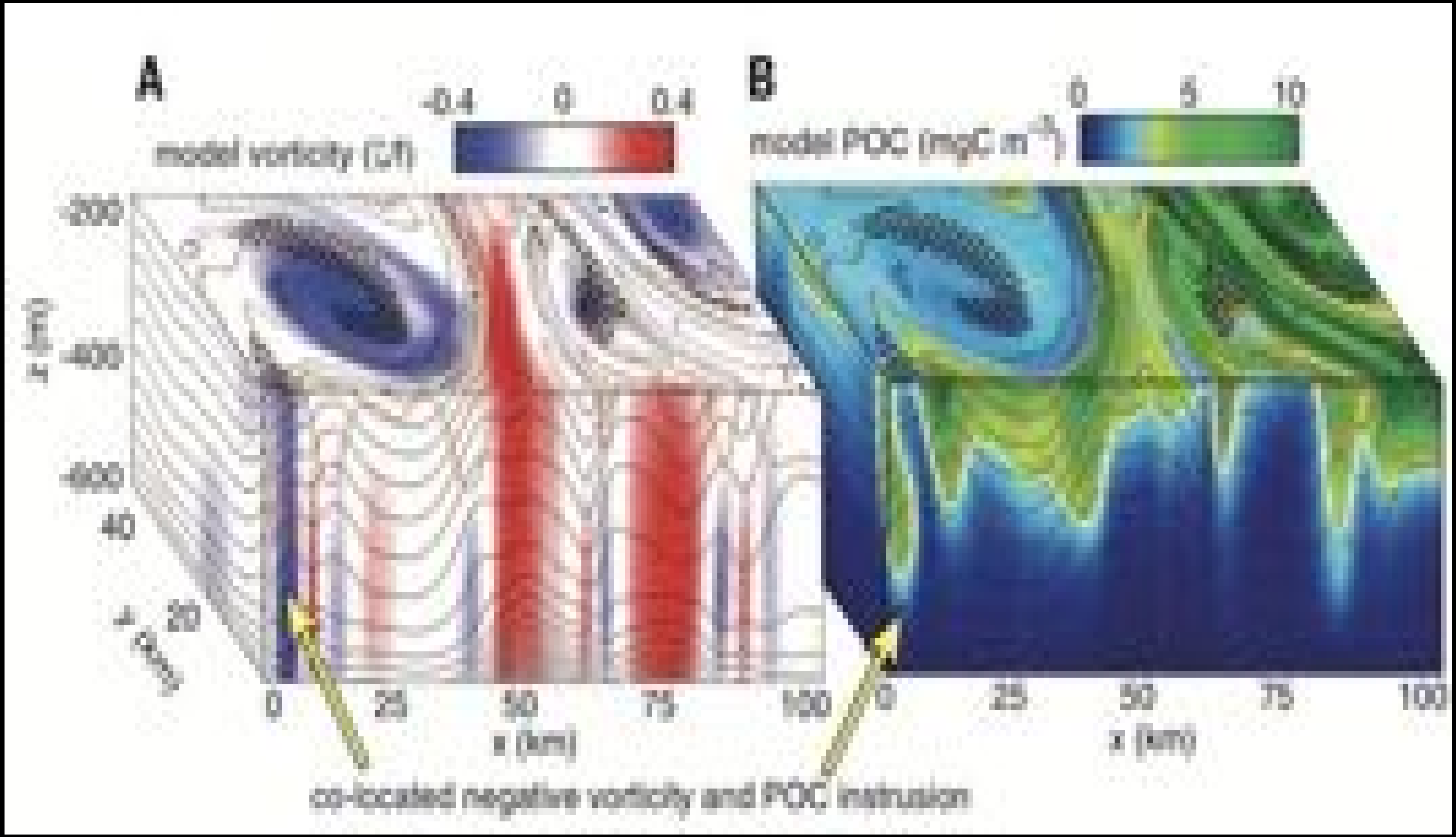


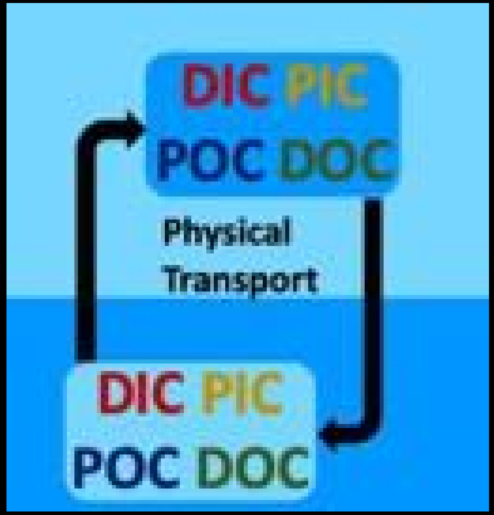


Mixed-layer pump is responsible for a global flux of 0.1 - 0.5 Pg C yr^{-1}



Dall'Olmo et al. (2016) [*https://doi.org/10.1038/ngeo2818*](https://doi.org/10.1038/ngeo2818)





Export of POC through subduction can contribute as much as ½ the total springtime export of POC from the highly productive subpolar oceans

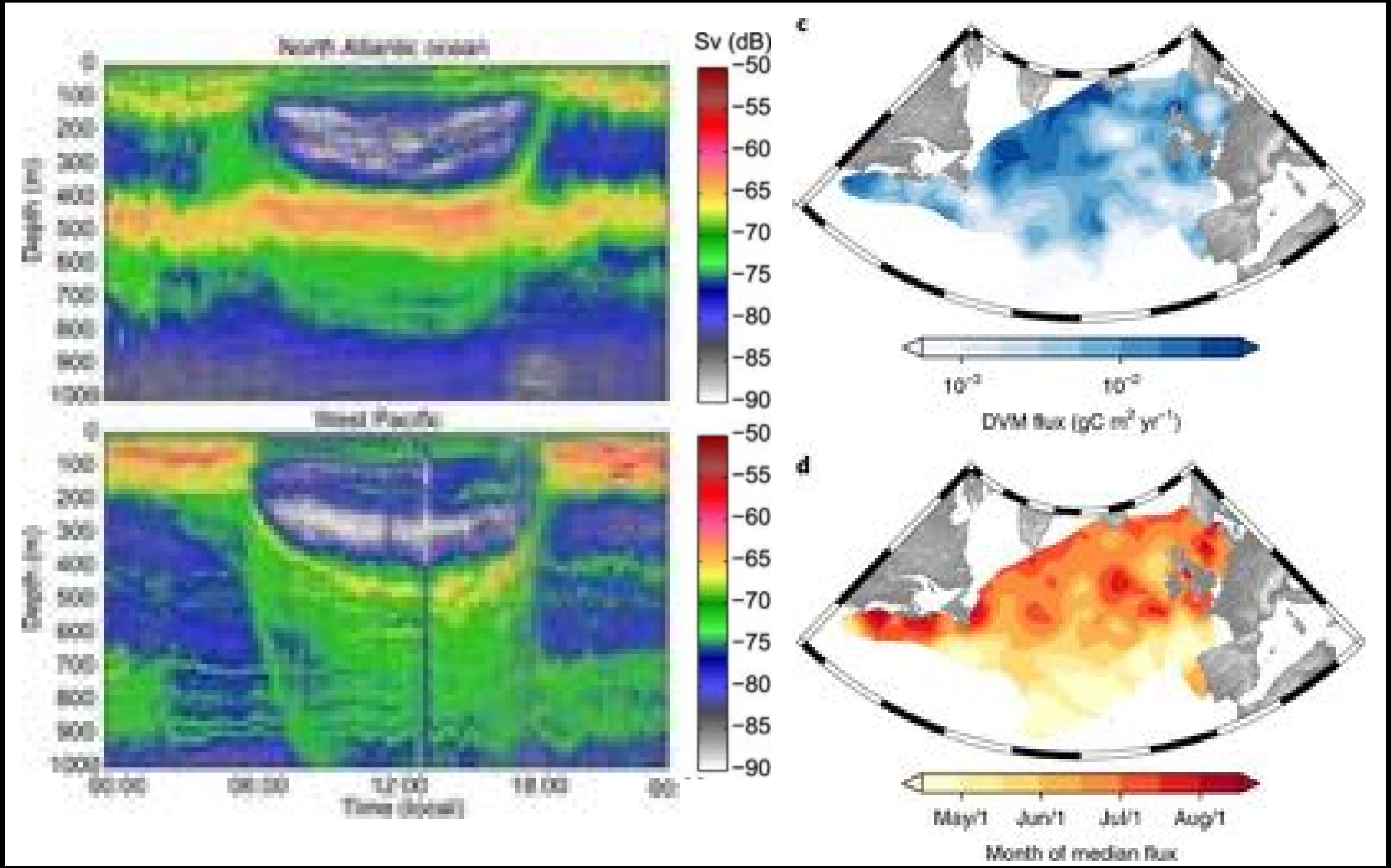

RESEARCH | REPORTS

OCEANOGRAPHY

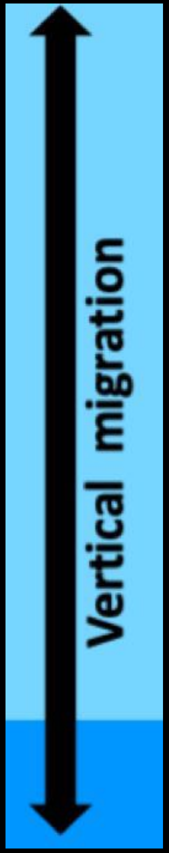
Eddy-driven subduction exports particulate organic carbon from the spring bloom

Melissa M. Omand, Eric A. D'Asaro, Craig M. Lee, Mary Jane Perry, Nathan Briggs, Ivona Cetinić, Amala Mahadevan

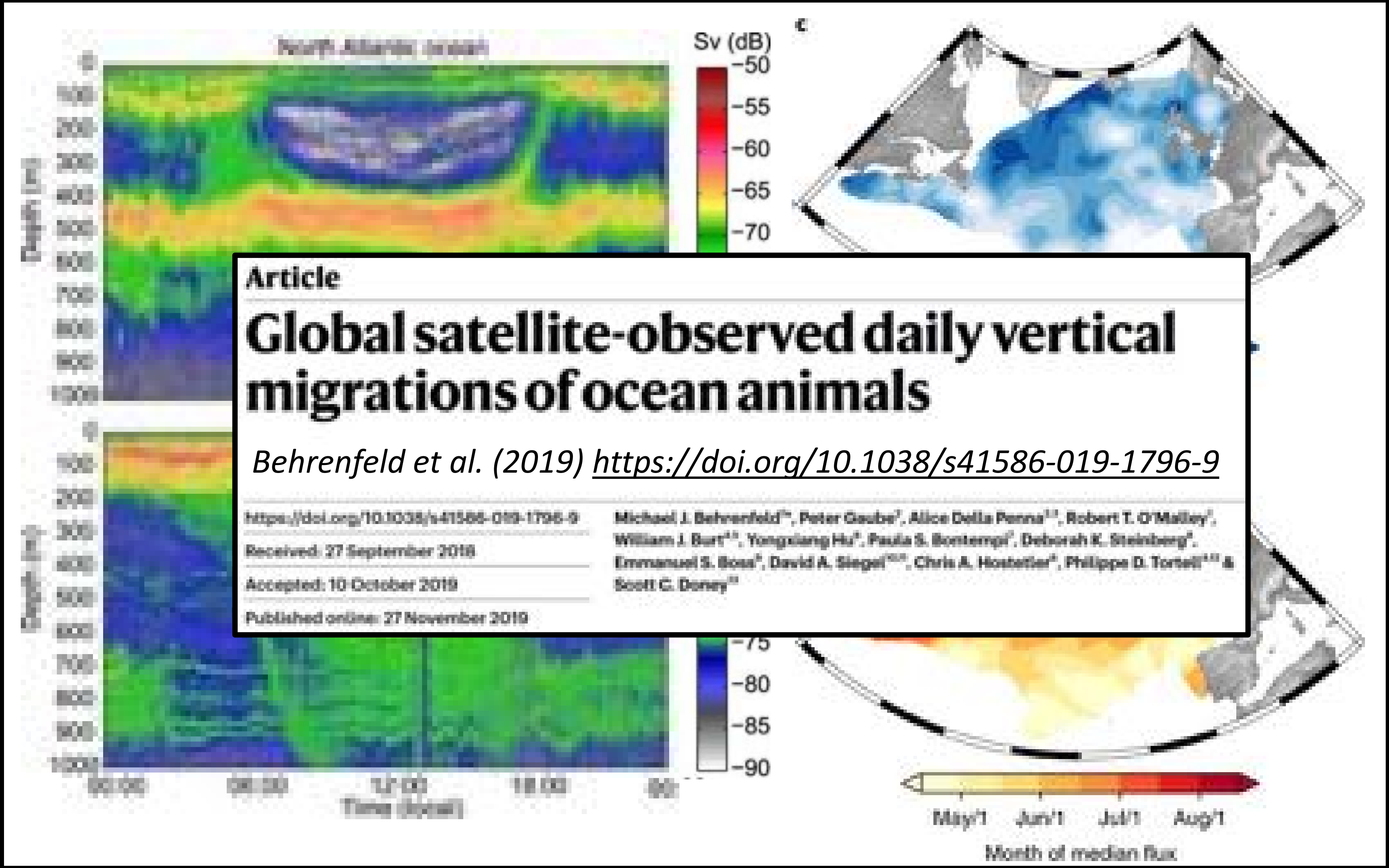
Omand et al. (2015) [*http://doi.org/10.1126/science.1218740*](http://doi.org/10.1126/science.1218740)



Mesopelagic-migrant pump injecting particles (fast sinking zooplankton faecal pellet) to greater depth



Klevjer et al. (2016) https://doi.org/10.1038/srep19873
Brun et al. (2019) https://doi.org/10.1038/s41559-018-0780-3



Article

Global satellite-observed daily vertical migrations of ocean animals

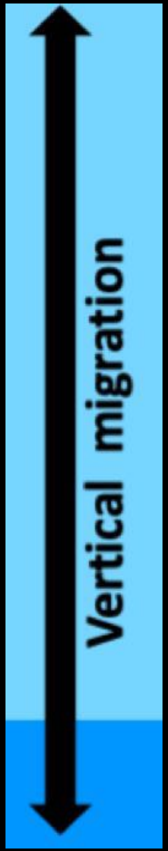
Behrenfeld et al. (2019) https://doi.org/10.1038/s41586-019-1796-9

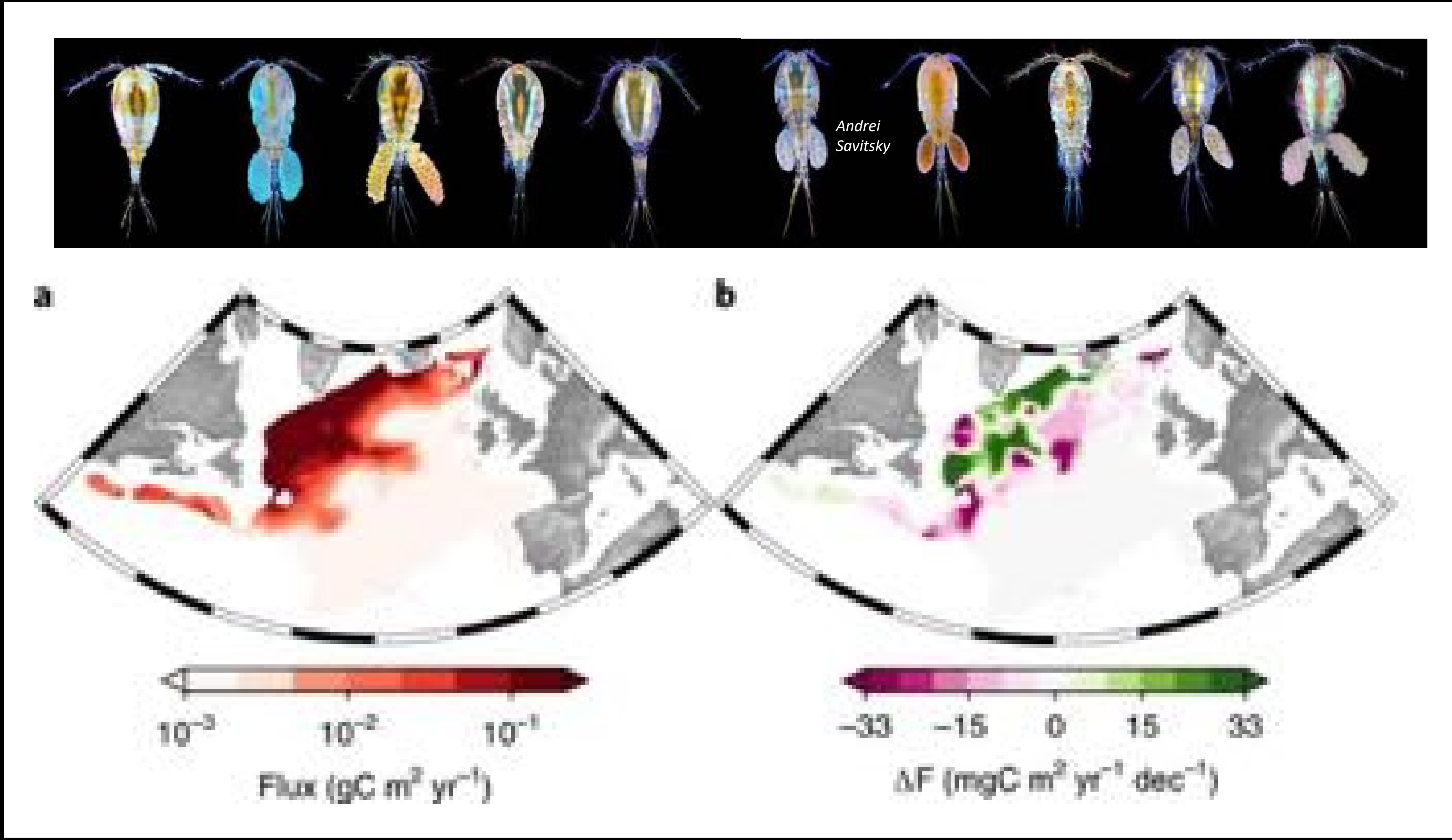
https://doi.org/10.1038/s41586-019-1796-9
Received: 27 September 2018
Accepted: 10 October 2019
Published online: 27 November 2019

Michael J. Behrenfeld, Peter Gaube, Alice Della Penna, Robert T. O'Malley, William J. Burt, Yongxiang Hu, Paula S. Bontempi, Deborah K. Steinberg, Emmanuel S. Boss, David A. Siegel, Chris A. Hostetler, Philippe D. Tortell & Scott C. Doney

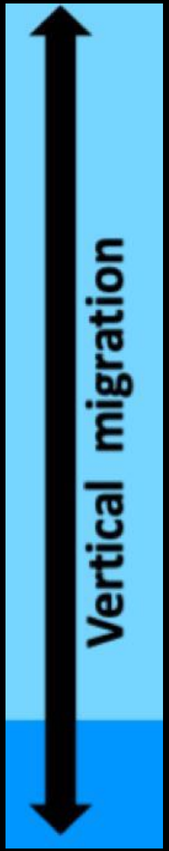
Klevjer et al. (2016) https://doi.org/10.1038/srep19873
Brun et al. (2019) https://doi.org/10.1038/s41559-018-0780-3

Mesopelagic-migrant pump injecting particles (fast sinking zooplankton faecal pellet) to greater depth

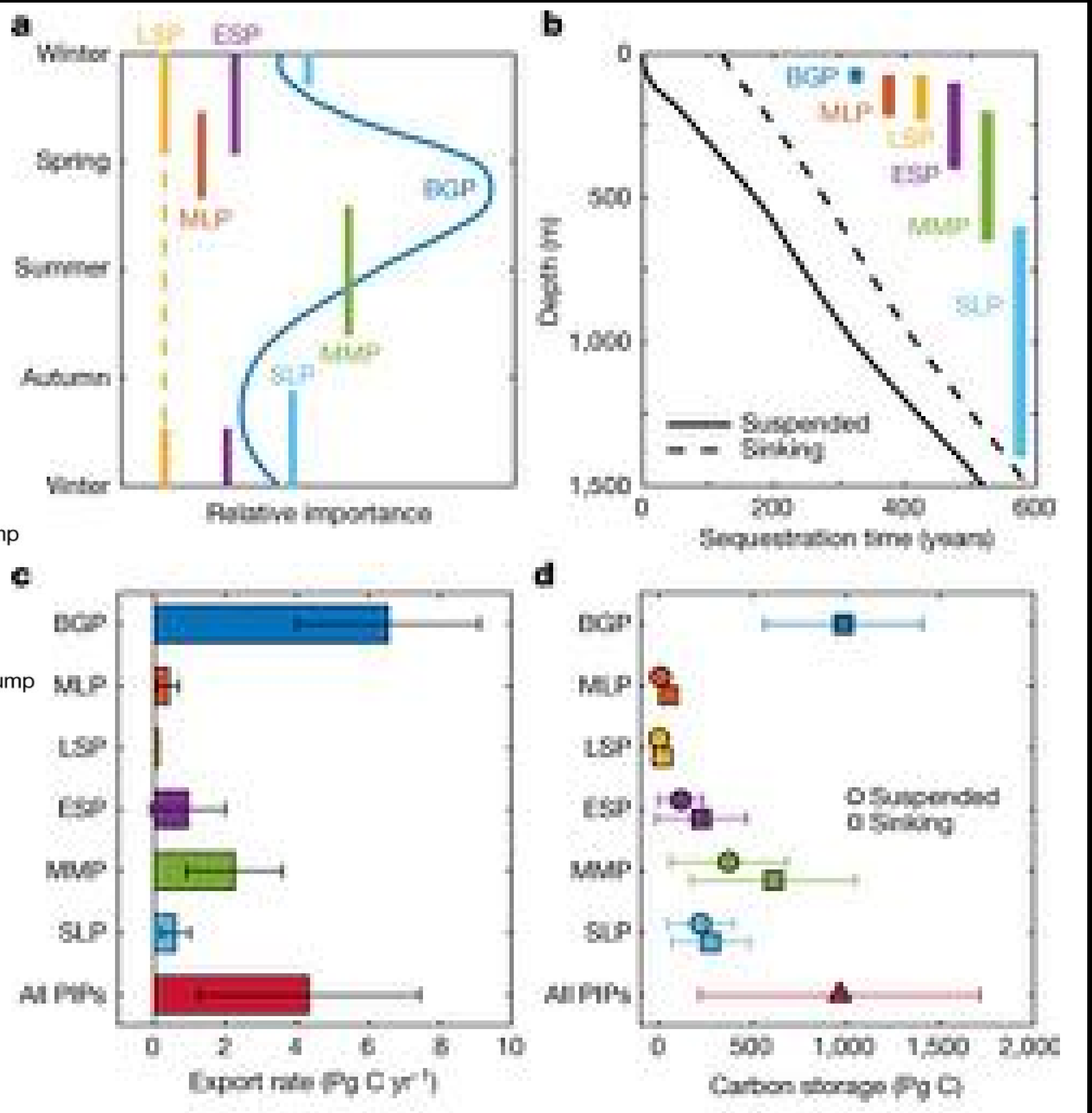




Hibernation of copepods at depths between 600 m and 1,400 m gives rise to a ‘seasonal lipid pump’, where copepods catabolize carbon-rich lipids that they accumulated in the upper layers during summer; shunting carbon to depth.



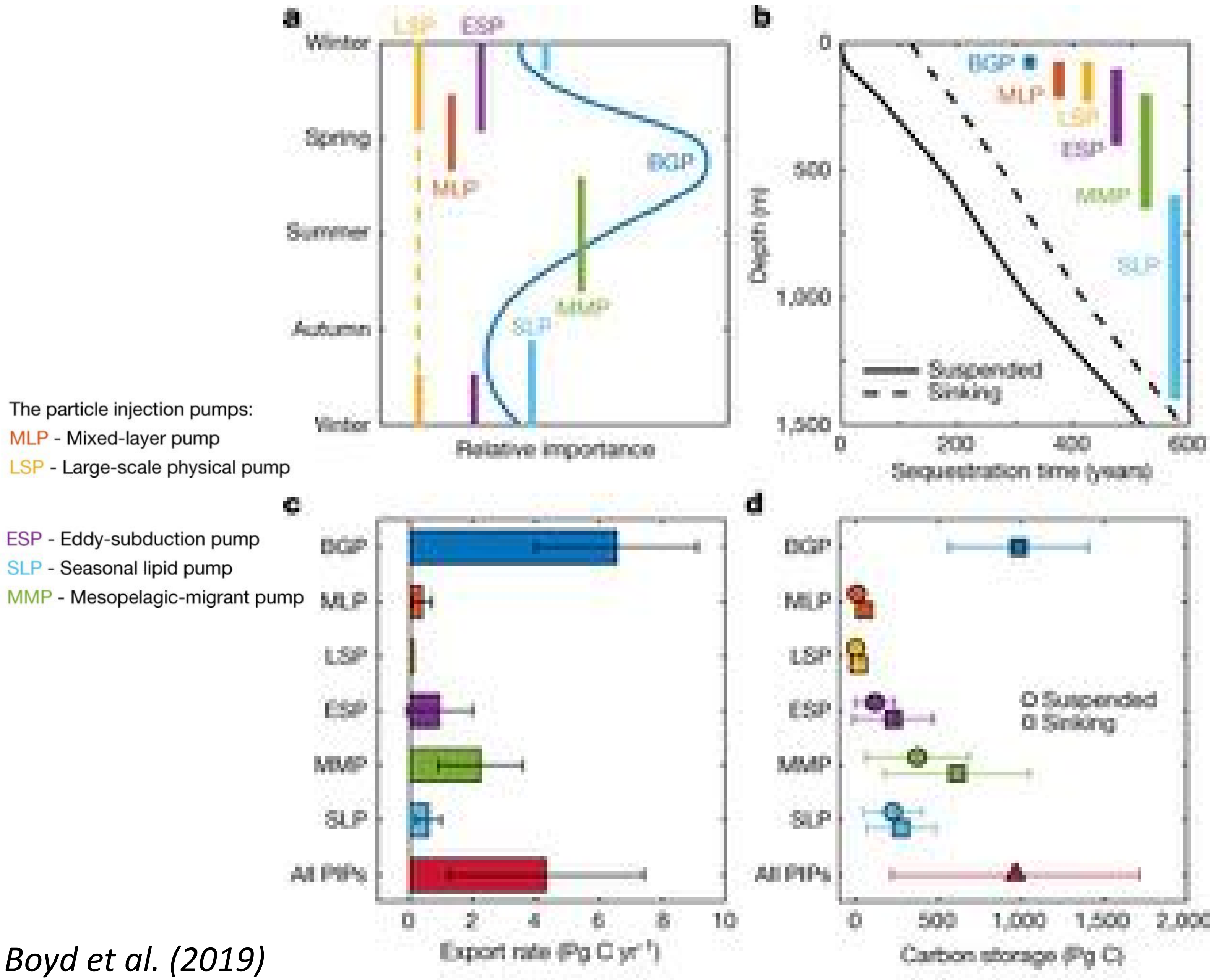
Jónasdóttir et al. (2015) *https://doi.org/10.1073/pnas.1512110112*



Boyd et al. (2019)

These 'particle injection pumps' probably sequester as much carbon as the gravitational pump, helping to close the carbon budget and motivating further investigation into their environmental control

Boyd et al. (2019)
https://doi.org/10.1038/s41586-019-1098-2



Boyd et al. (2019)

Ocean Biological Carbon pump exports between 9-13 Gt C y^{-1}

Laws et al. (2011)
https://doi.org/10.4319/lom.2011.9.593

If the OBCP were to be switched off, it has been estimated that atmospheric CO_2 concentrations would be 50% higher than they are today.

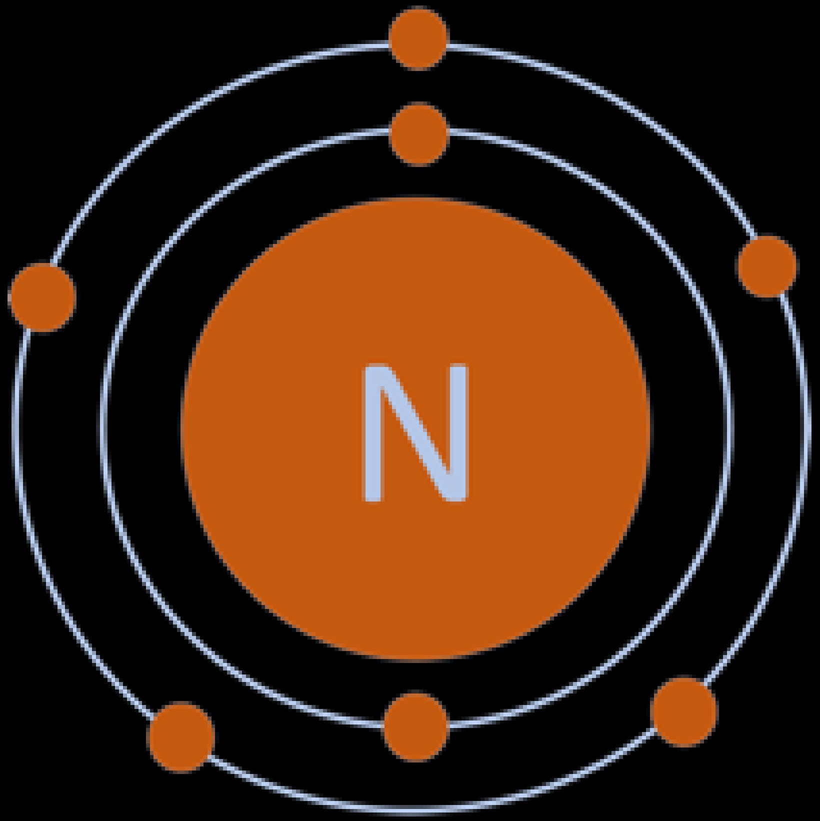
Parekh et al. (2006)
https://doi.org/10.1029/2005GL025098

Nitrogen (though incredibly abundant) is often a limiting nutrient for the growth for photosynthetic organisms. This is because the particular form of nitrogen found in air and that dissolves in water —nitrogen gas (N_2)—cannot be assimilated by most organisms.

Most algae and microbes require biologically available, or "fixed" forms of nitrogen, such as ammonia (NH_3^-) or ammonium (NH_4^+).

Fixed nitrogen is one of the most important growth-limiting nutrients for photosynthetic organisms (primary producers) such as algae. Nitrogen can also serve as an energy source or as an oxidant for marine bacteria and archaea.

The ocean absorbs nitrogen gas (N_2) from the atmosphere. It is the most abundant form of nitrogen in the ocean



Credit https://hahana.soest.hawaii.edu/cmoreserver/cruises/biolincs/nitrogen.htm

Nitrogen fixation is a process by which nitrogen in the water is converted into ammonium

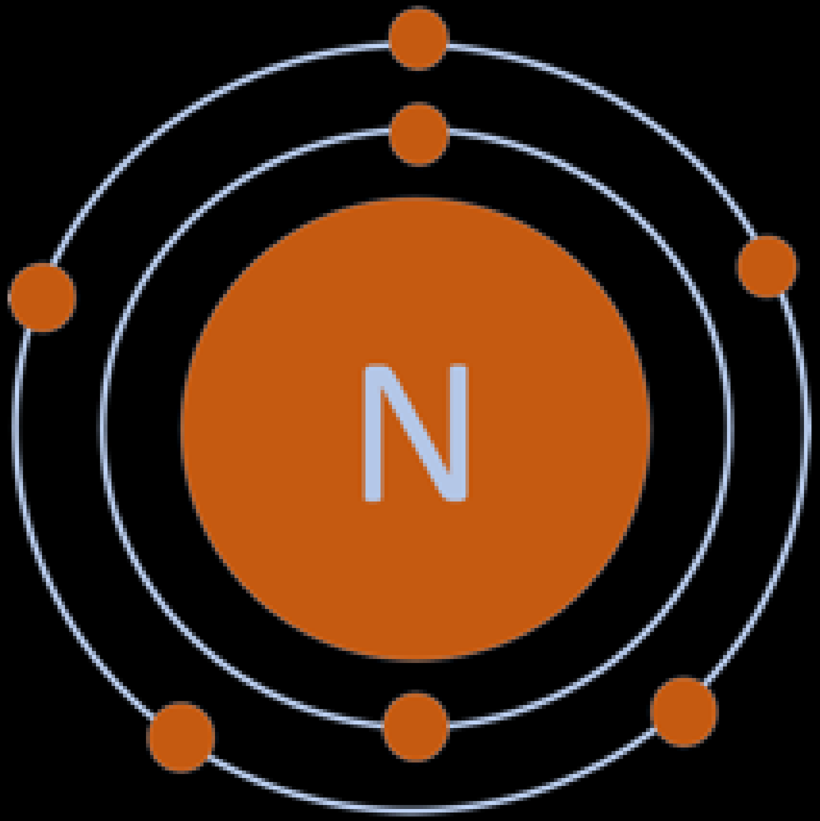
$N_2 \rightarrow NH_4^+$

Nitrification is the biological oxidation of ammonium to nitrite (NO_2^-) and nitrate (NO_3^-)

$NH_4^+ \rightarrow NO_3^-$

Denitrification is the microbial conversion of nitrate or nitrite into nitrogen gas (N_2).

$NO_2^- \rightarrow N_2$
$NO_3^- \rightarrow N_2$

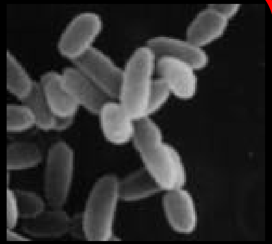


Credit https://hahana.soest.hawaii.edu/cmoreserver/cruises/biolincs/nitrogen.htm

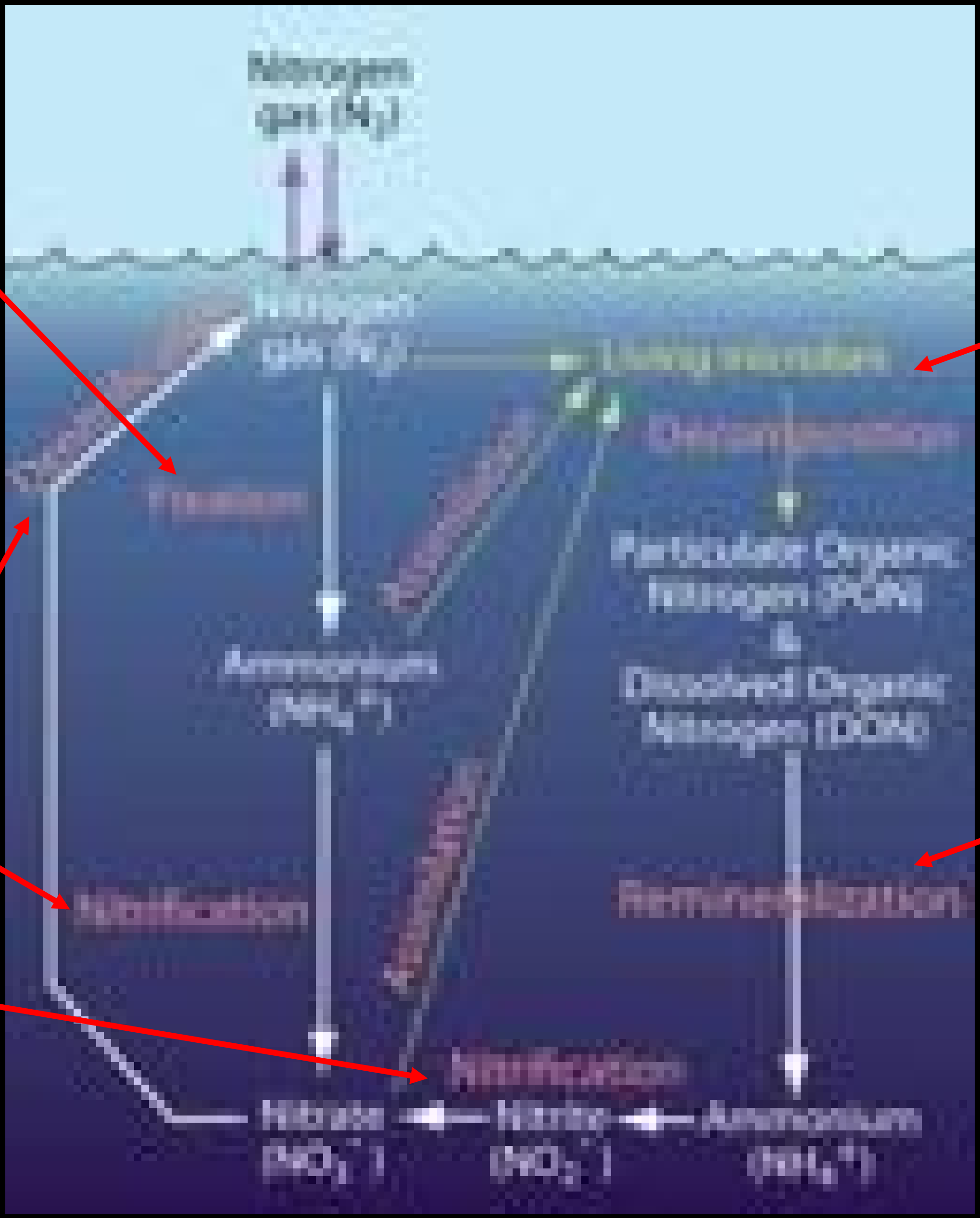
Trichodesmium

(Abby Helthoff, WHOI, IOCCG Report 15)

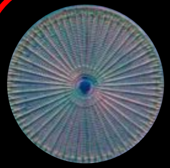
Bacteria



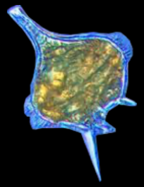
Credit:Kaden11a



Other Phytoplankton



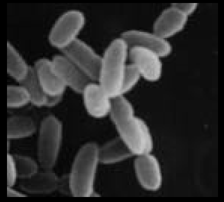
Diatoms (Carolina Biological Supply Company)



Dinoflagellates (Tintinnidguy)

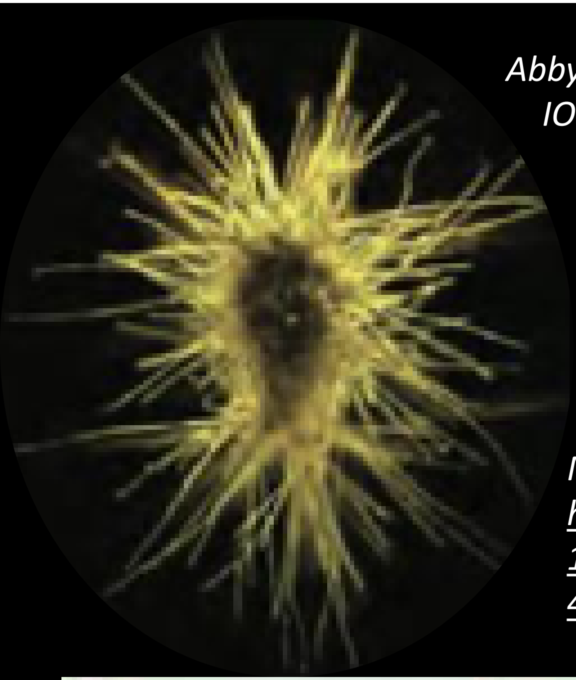
Zooplankton & Bacteria

Credit: Plymouth Marine Laboratory



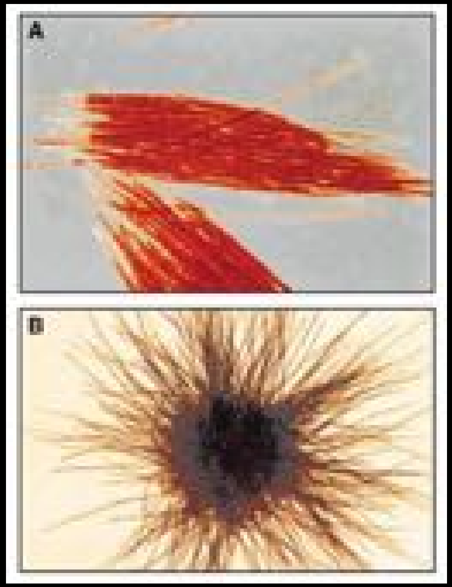
Credit: Kaden11a

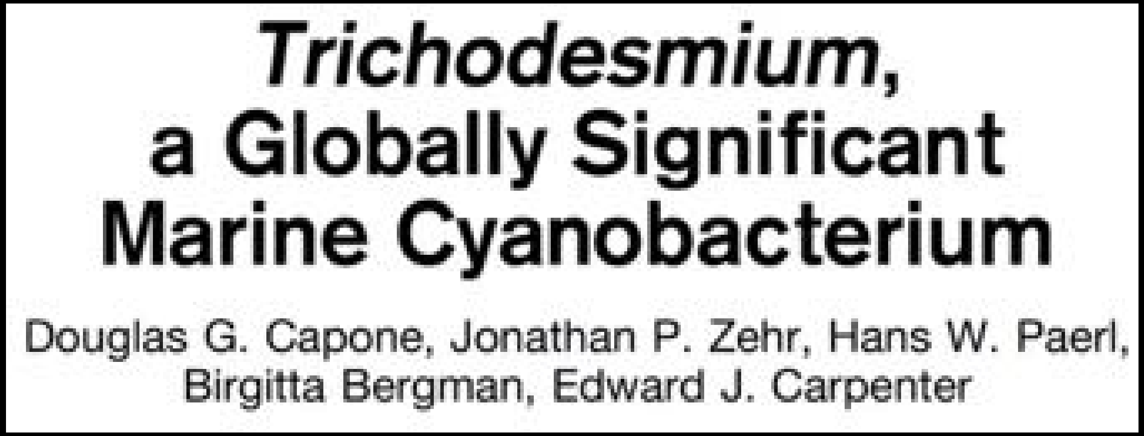
Credit https://hahana.soest.hawaii.edu/cmoreserver/cruises/biolincs/nitrogen.htm



Abby Helthoff, WHOI, IOCCG Report 15

McKinna (2015) https://doi.org/10.1016/j.pocean.2014.12.013

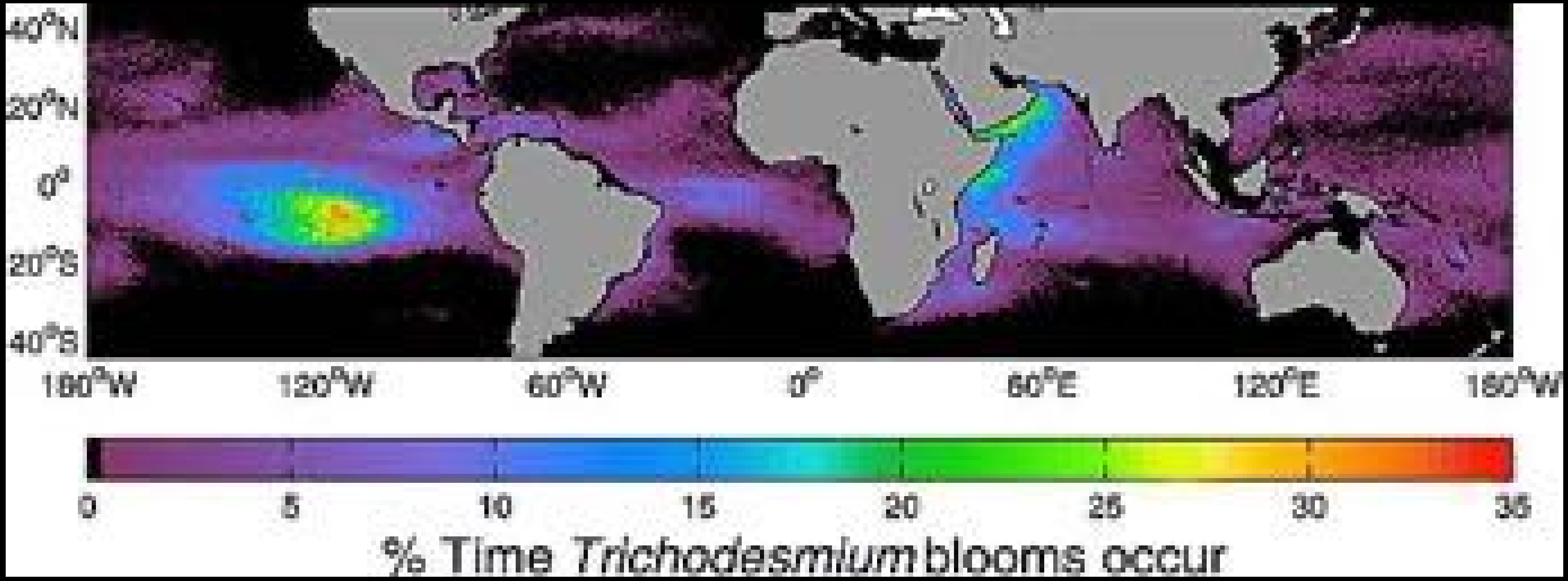




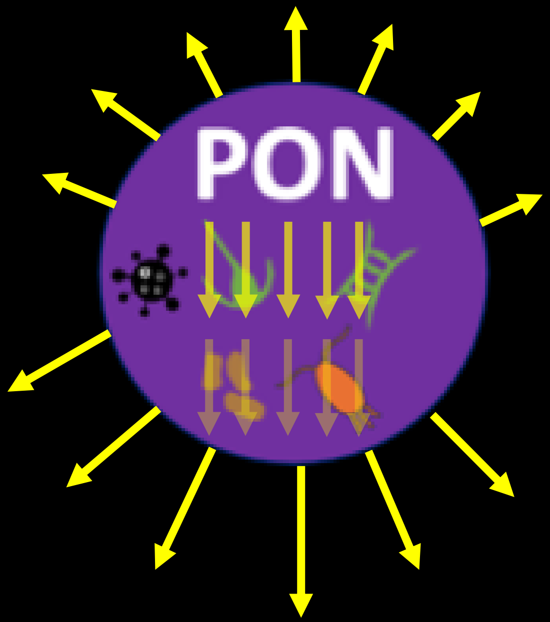
Trichodesmium, a Globally Significant Marine Cyanobacterium

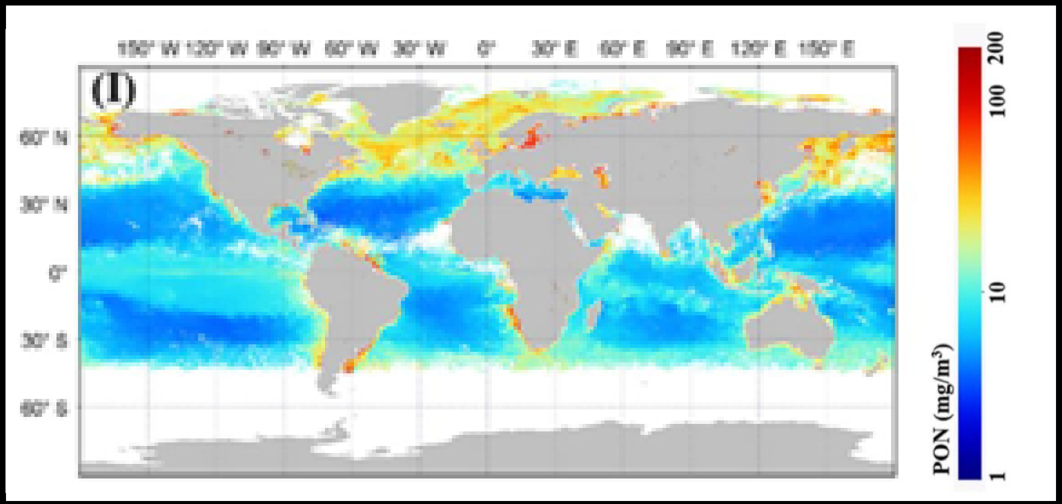
Douglas G. Capone, Jonathan P. Zehr, Hans W. Paerl, Birgitta Bergman, Edward J. Carpenter

Capone et al. (1997) https://doi.org10.1126/science.276.5316.1221

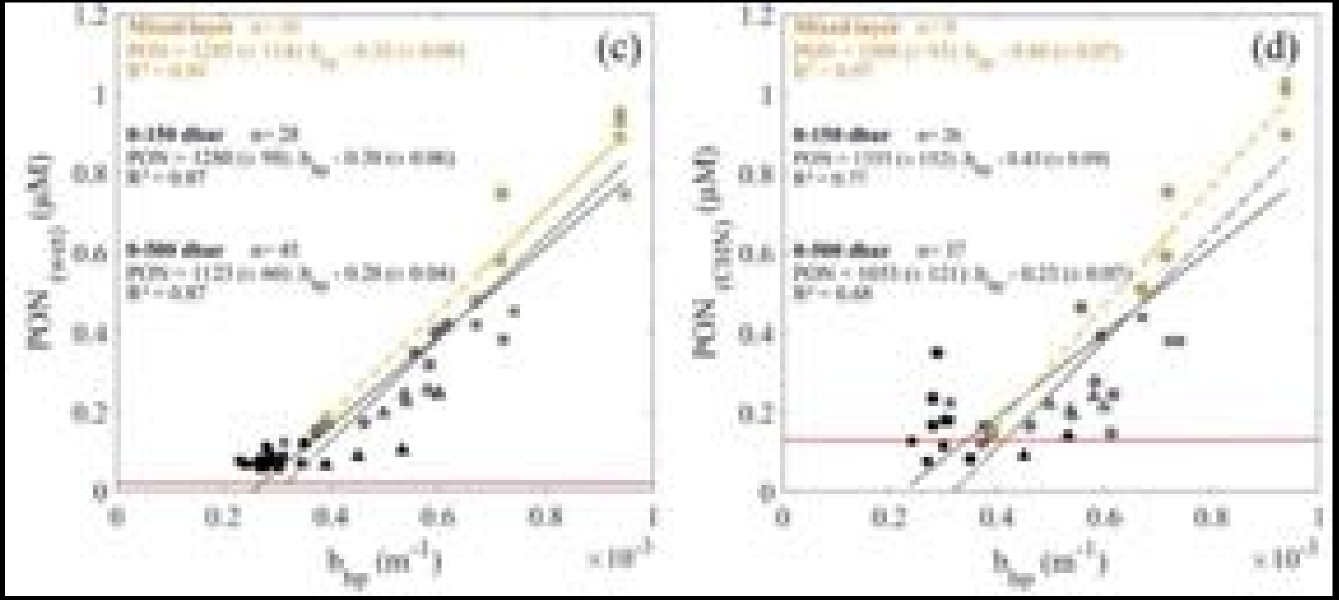


Subramaniam et al. (2001) https://doi.org/10.1016/S0967-0645(01)00096-0
Westberry and Siegel (2006). https://doi.org/10.1029/2005GB002673

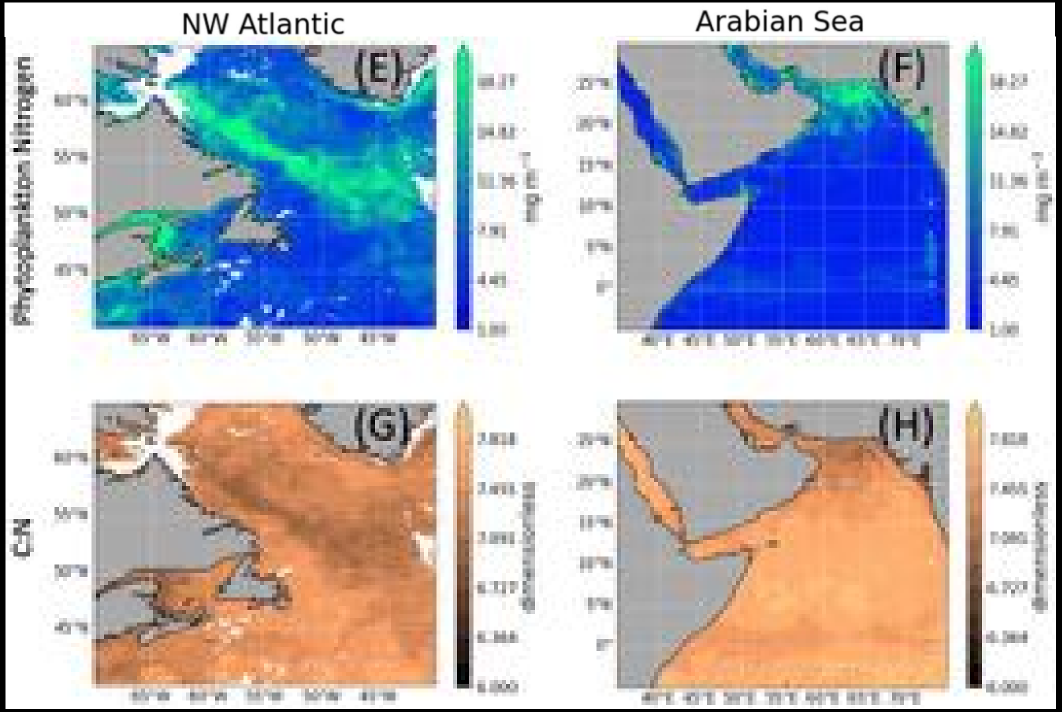




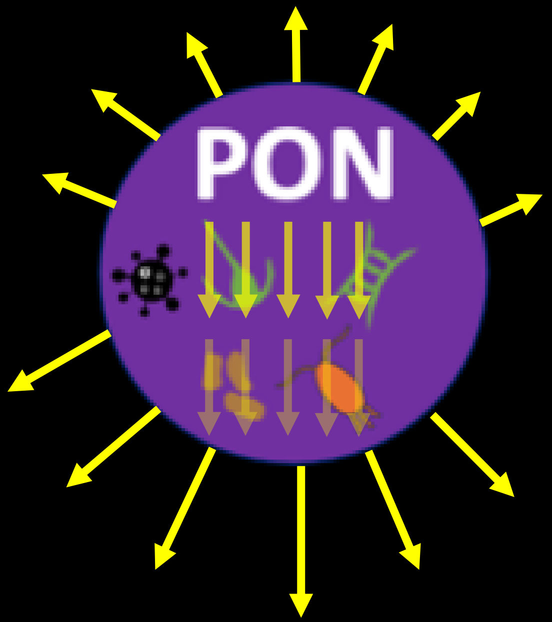
Wang et al. (2022) https://doi.org/10.3389/fmars.2022.943867



Fumenia et al. (2020) https://doi.org/10.1364/OE.395648



Manici et al. (2022) https://doi.org/10.3389/fmars.2022.1035399




communications earth & environment

Article

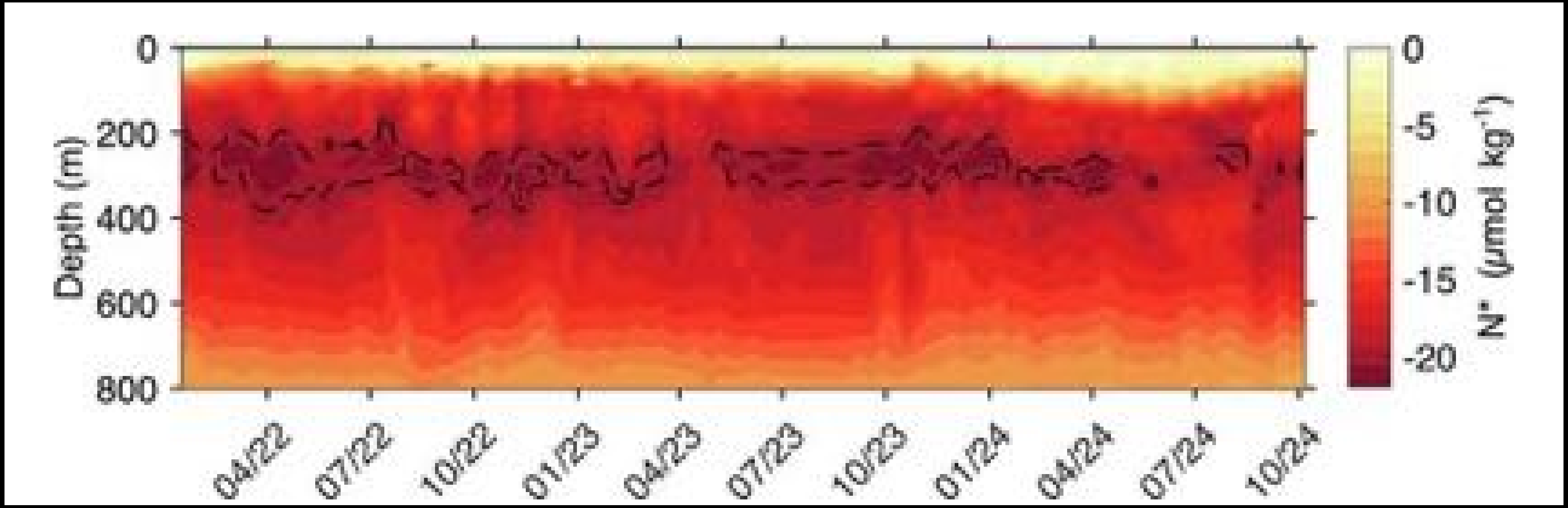
A Nature Portfolio journal

https://doi.org/10.1038/s43247-026-03410-5

BGC-Argo float reveals shifts in nitrogen-carbon cycling in an oxygen-deficient zone

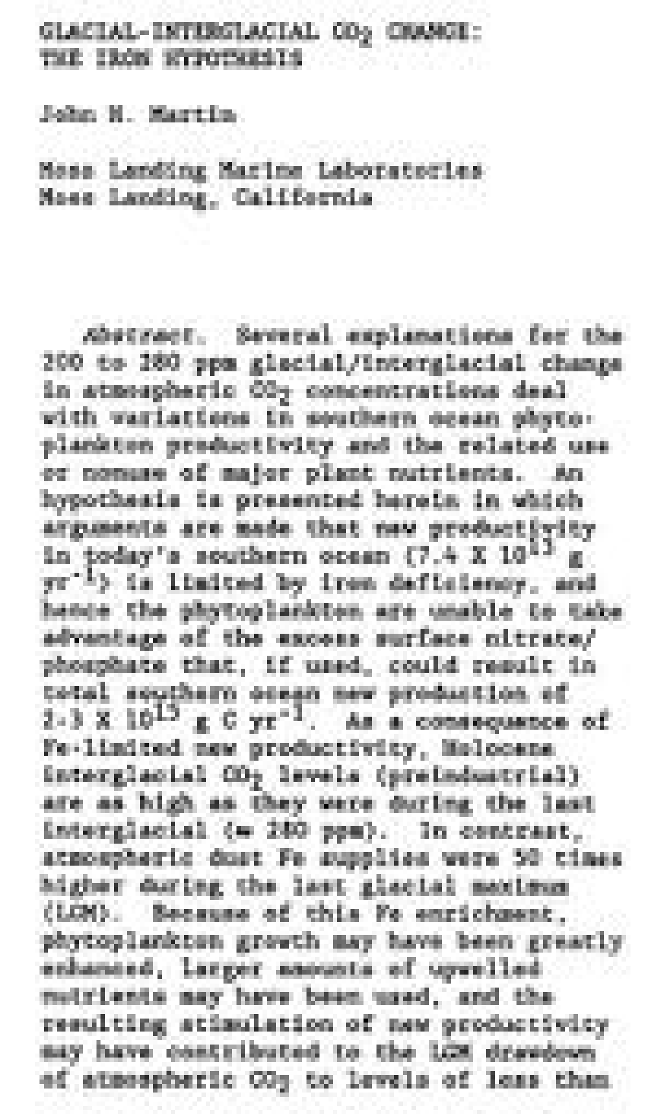
Check for updates

Mariana B. Bif, Colette Kelly, Mark A. Altabet, Annie Bourbonnais, Claire Elbon, Edgart Flores, Alanna Mnich, Josh Plant & Kenneth S. Johnson



*N** indicates the deviation from Redfield stoichiometry, with more negative values reflecting progressive fixed nitrogen loss. Black dashed contour marks the *N** = −20 μmol kg−¹ threshold.

Bif et al.(2026) https://doi.org/10.1038/s43247-026-03410-5



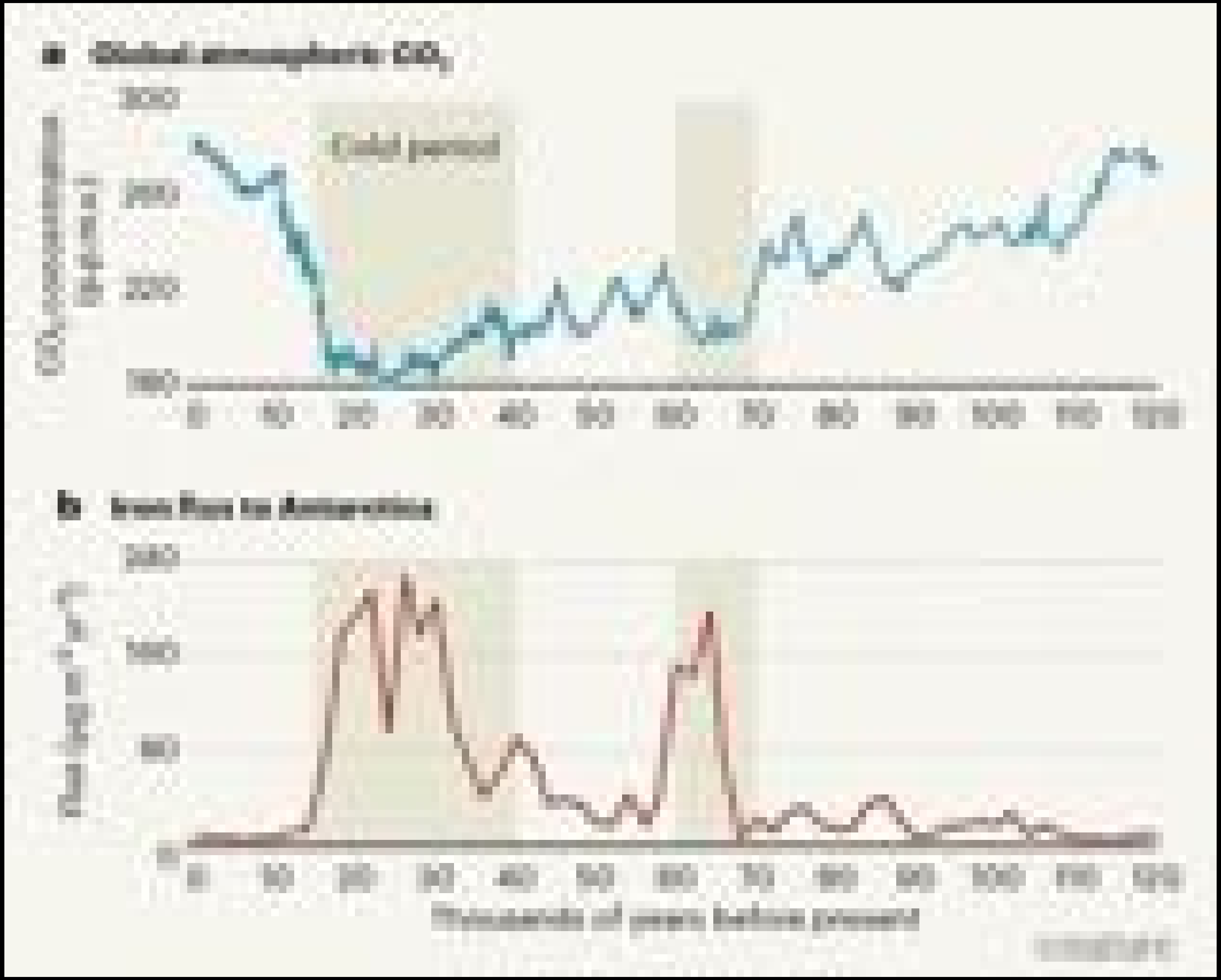
GLACIAL-INTERGLACIAL CO_2 CHANGE:
THE IRON HYPOTHESIS

John H. Martin

Moss Landing Marine Laboratories
Moss Landing, California

Abstract. Several explanations for the 200 to 280 ppm glacial/interglacial change in atmospheric CO_2 concentrations deal with variations in southern ocean phytoplankton productivity and the related use or nonuse of major plant nutrients. An hypothesis is presented herein in which arguments are made that new productivity in today's southern ocean (7.4×10^{13} g yr^{-1}) is limited by iron deficiency, and hence the phytoplankton are unable to take advantage of the excess surface nitrate/phosphate that, if used, could result in total southern ocean new production of $2\text{-}3 \times 10^{15}$ g C yr^{-1}. As a consequence of Fe-limited new productivity, Holocene interglacial CO_2 levels (preindustrial) are as high as they were during the last interglacial (≈ 280 ppm). In contrast, atmospheric dust Fe supplies were 50 times higher during the last glacial maximum (LGM). Because of this Fe enrichment, phytoplankton growth may have been greatly enhanced, larger amounts of upwelled nutrients may have been used, and the resulting stimulation of new productivity may have contributed to the LGM drawdown of atmospheric CO_2 to levels of less than

Martin et al. (1990) https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/PA005i001p00001



Stoll et al.(2020) https://doi.org/10.1038/d41586-020-00393-x

"Give me half a tanker of iron and I'll give you the next ice age"

John Martin

Considered among the biggest achievements in biological oceanography in the 20th century (Barber & Hilting 2000)

Iron Hypothesis

The iron issue is an example of classic science progress:

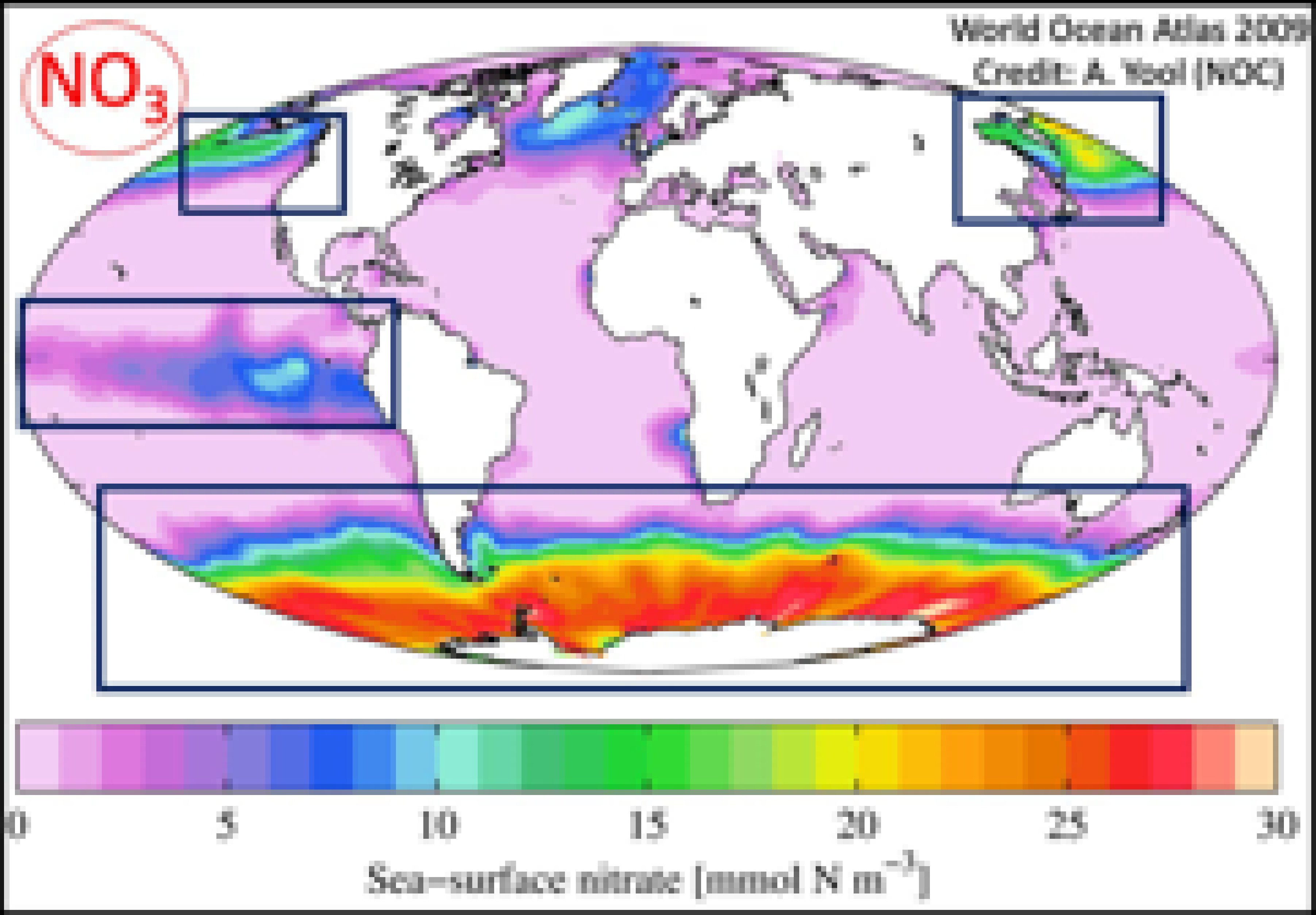
a. There was a nagging question.
b. A tentative explanation was advanced.
c. Available data did not support the explanation.
d. The data, however, were suspect.
e. A technical (analytical) breakthrough was made.
f. The new data suggested an hypothesis.
g. The hypothesis was tested and confirmed.
h. Textbooks had to be revised.

For the iron issue the nagging question was: Why do excess plant nutrients persist in the surface ocean in certain regions such as the Antarctic, equatorial Pacific, and Northeast Pacific? For 50 years there had been speculation that iron limitation might be a factor, but measurements showed there was abundant iron in seawater.

John Martin set out to improve the analytical chemistry of iron, and when he had done so, he found that iron was much less abundant in the ocean than previously thought.

Alongside discovery of hydrothermal vents and seeing the ocean for the first time though satellite ocean colour!

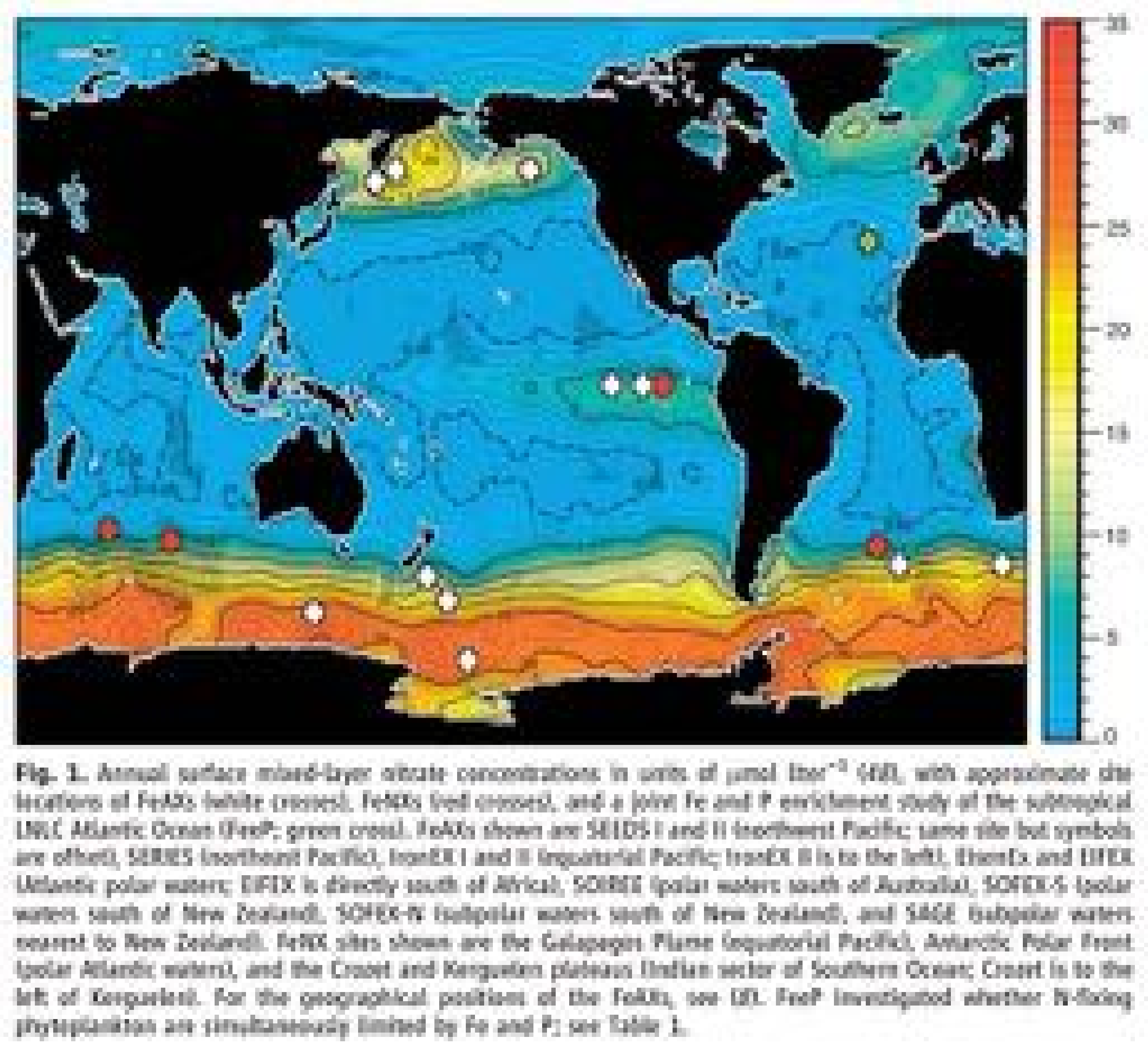
Barber & Hilting (2000)
https://www.ncbi.nlm.nih.gov/books/NBK208814/pdf/Bookshelf_NBK208814.pdf



Micro-nutrients

Fe

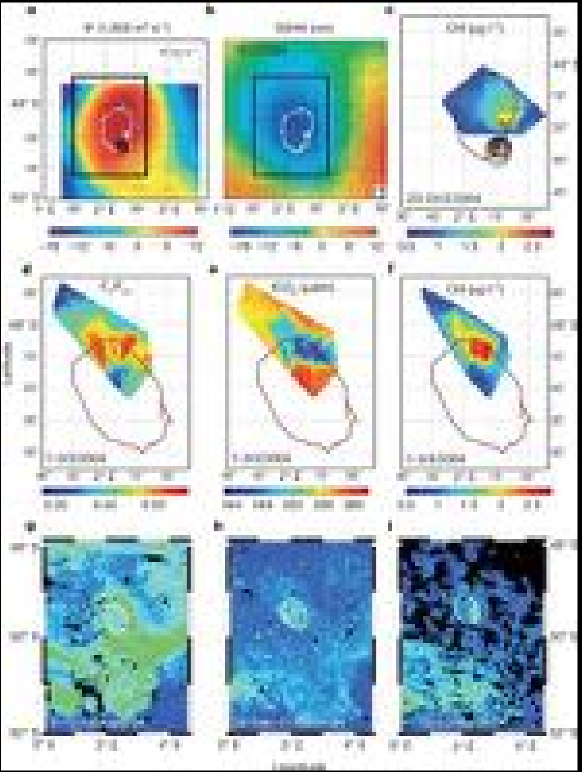
Martin et al . (1990) https://doi.org/10.1029/GB004i001p00005




ARTICLE

doi:10.1038/nature11229

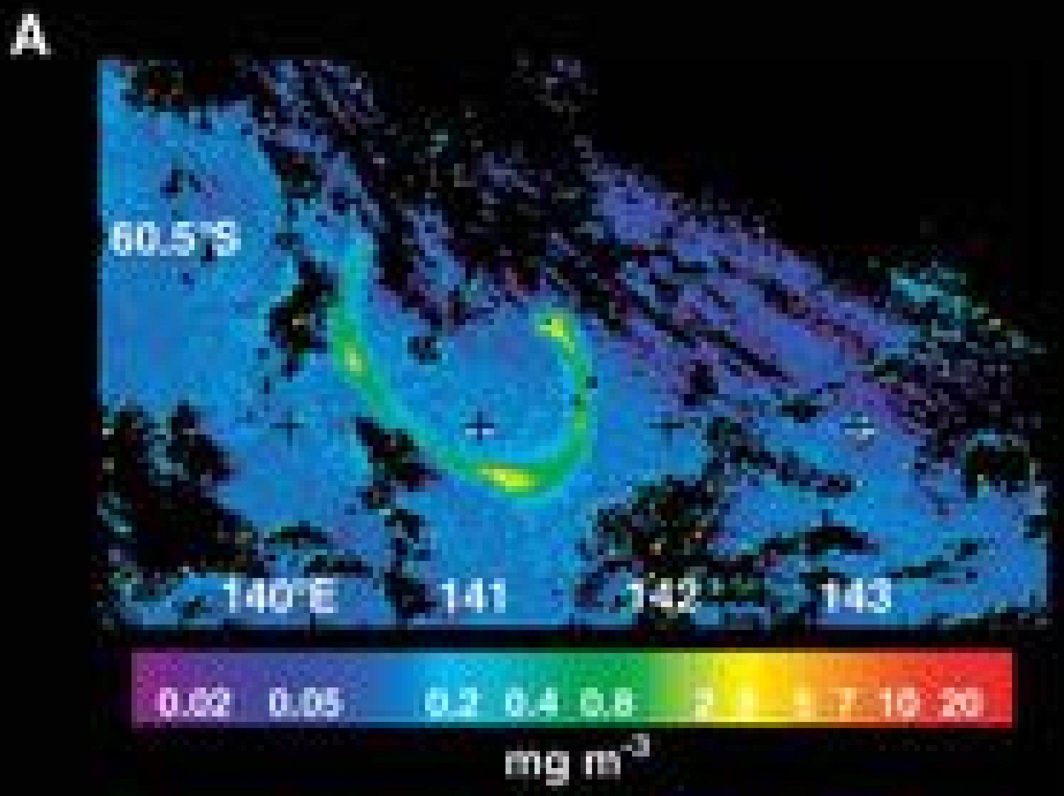
Deep carbon export from a Southern Ocean iron-fertilized diatom bloom

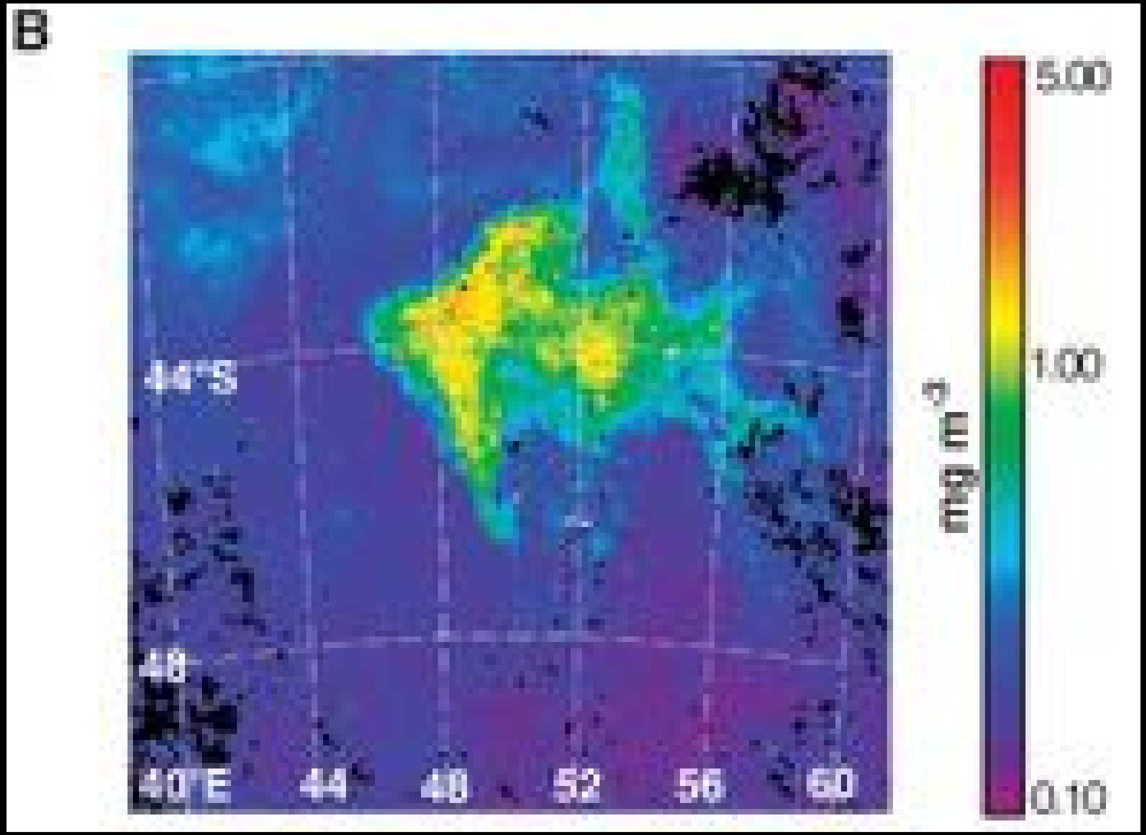


"at least half the bloom biomass sank far below a depth of 1,000 metres and that a substantial portion is likely to have reached the sea floor"

Boyd et al. (2007) [*https://doi.org/10.1126/science.1131669*](https://doi.org/10.1126/science.1131669)

Smetacek et al. (2012) [*https://doi.org/10.1038/nature11229*](https://doi.org/10.1038/nature11229)



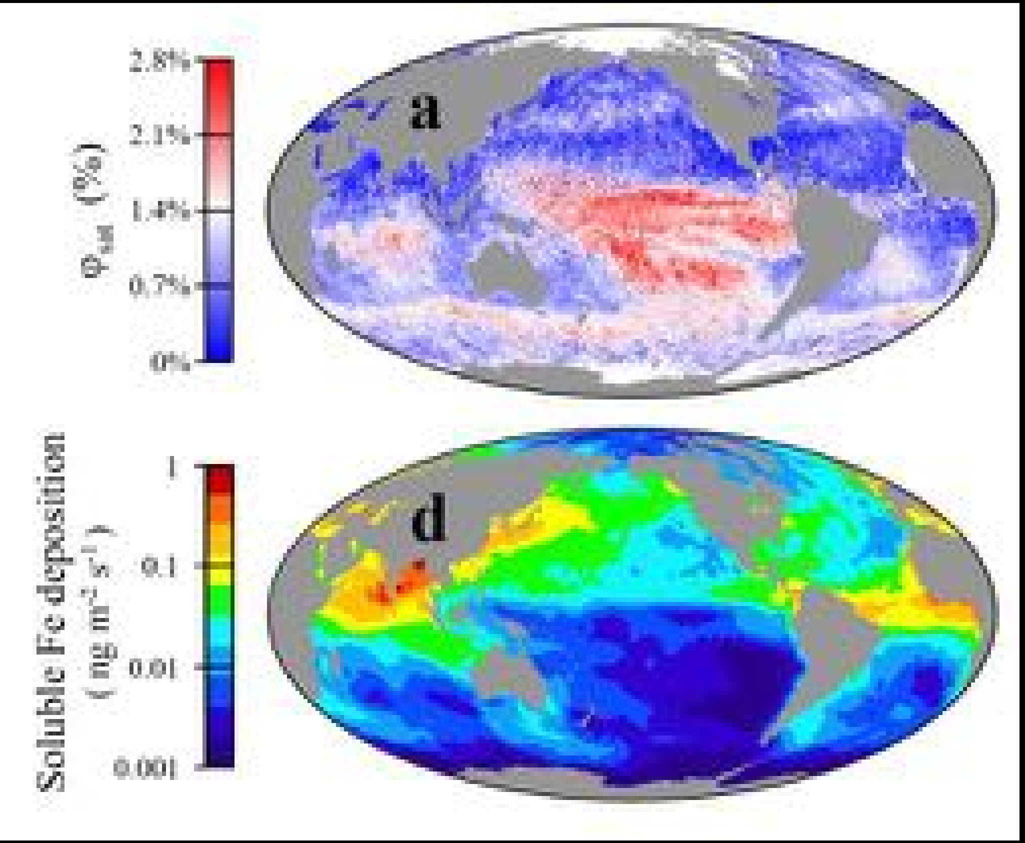


(A) Satellite image of a purposeful in situ Southern Ocean FeAX (SOIREE)

(B) An FeNX near Crozet within the HNLC Southern Ocean, where naturally occurring blooms are evident from remote sensing

Boyd et al. (2007) https://doi.org/10.1126/science.1131669

Passive and active fluorescence used as an optical measure of iron stress in phytoplankton



Behrenfeld et al. (2009)
https://doi.org/10.5194/bg-6-779-2009


Article

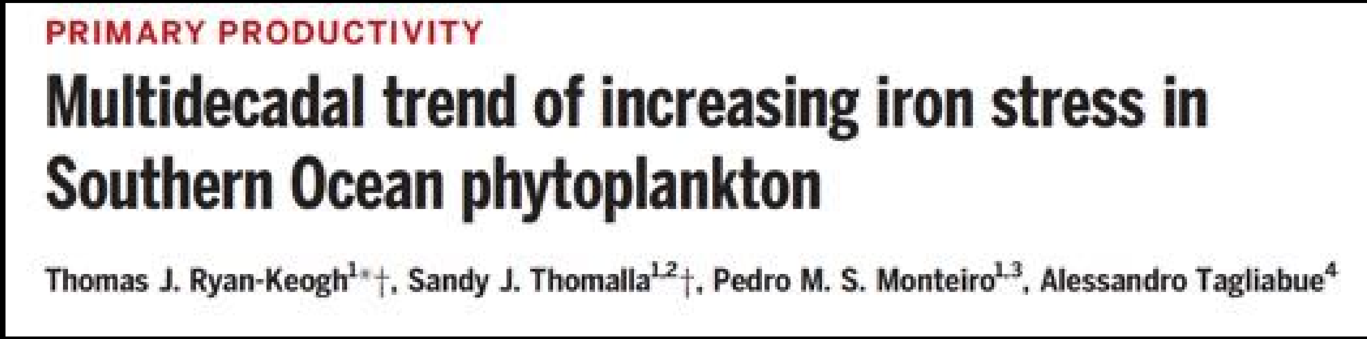
Persistent equatorial Pacific iron limitation under ENSO forcing

https://doi.org/10.1038/s41586-023-06439-0

Received: 13 January 2022

Accepted: 14 July 2023

Thomas J. Browning, Mak A. Saito, Shungudzemwoyo P. Garaba, Xuechao Wang, Eric P. Achterberg, C. Mark Moore, Anja Engel, Matthew R. McIlvin, Dawn Moran, Daniela Voss, Oliver Zielinski & Alessandro Tagliabue

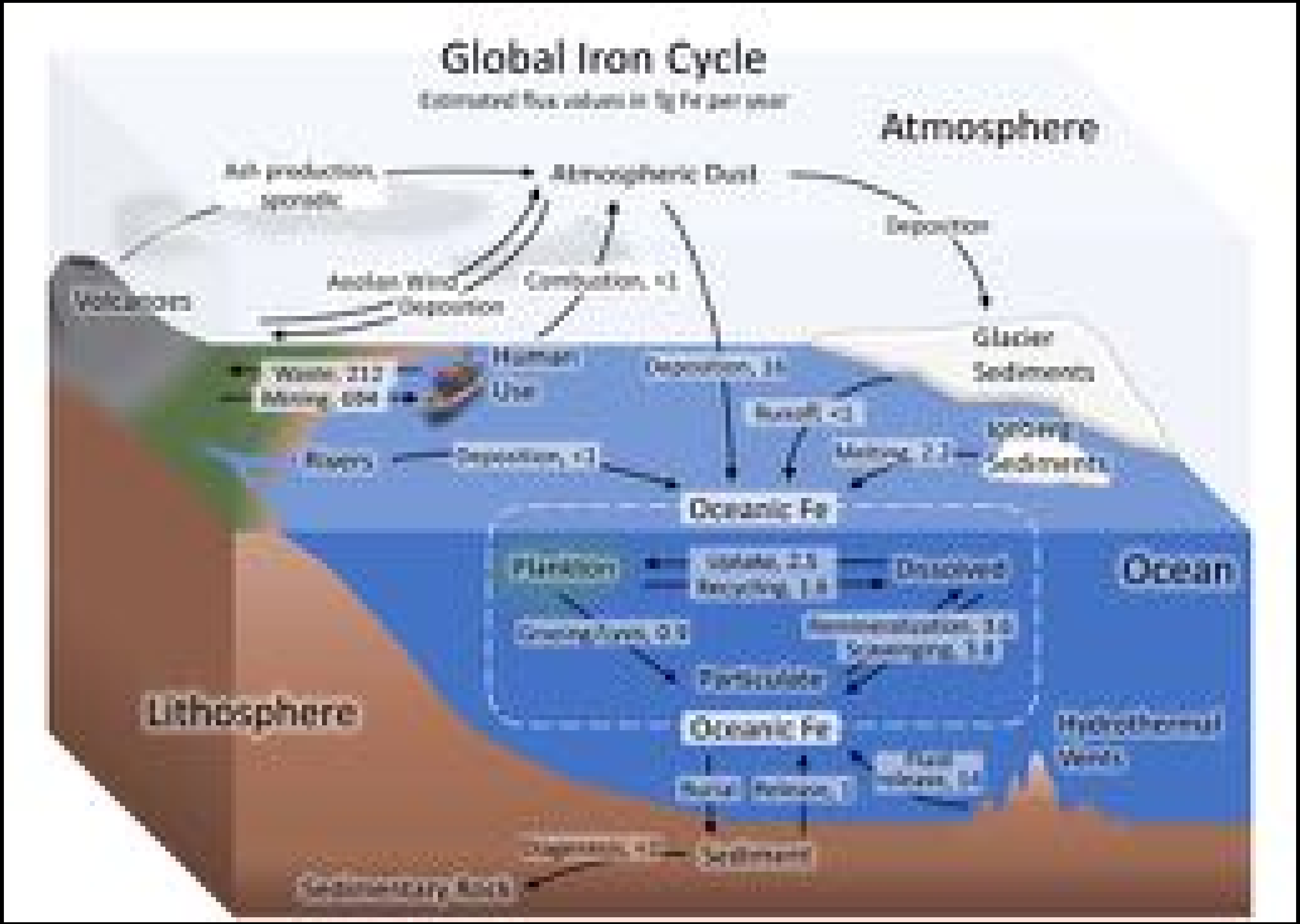

PRIMARY PRODUCTIVITY

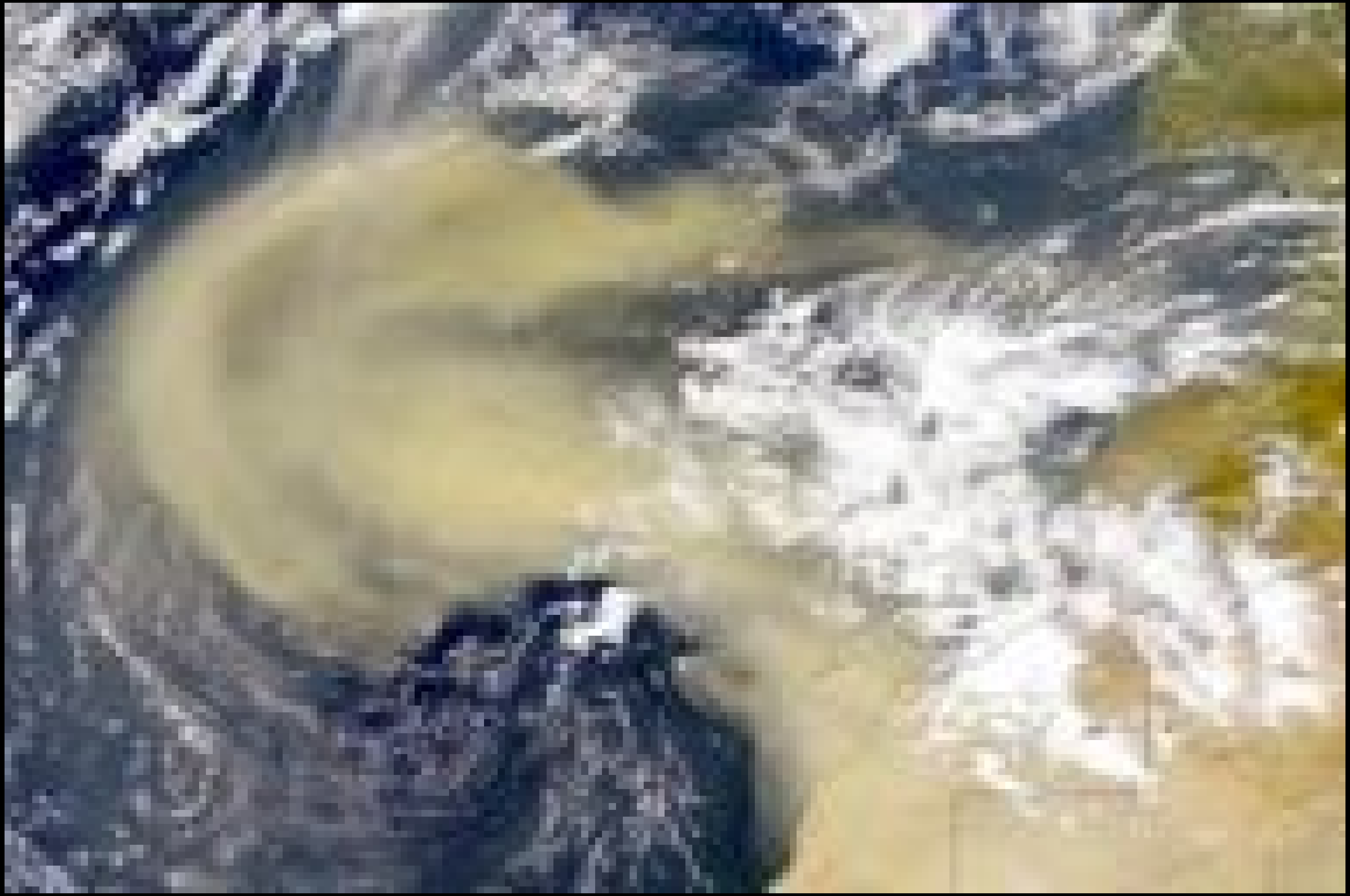
Multidecadal trend of increasing iron stress in Southern Ocean phytoplankton

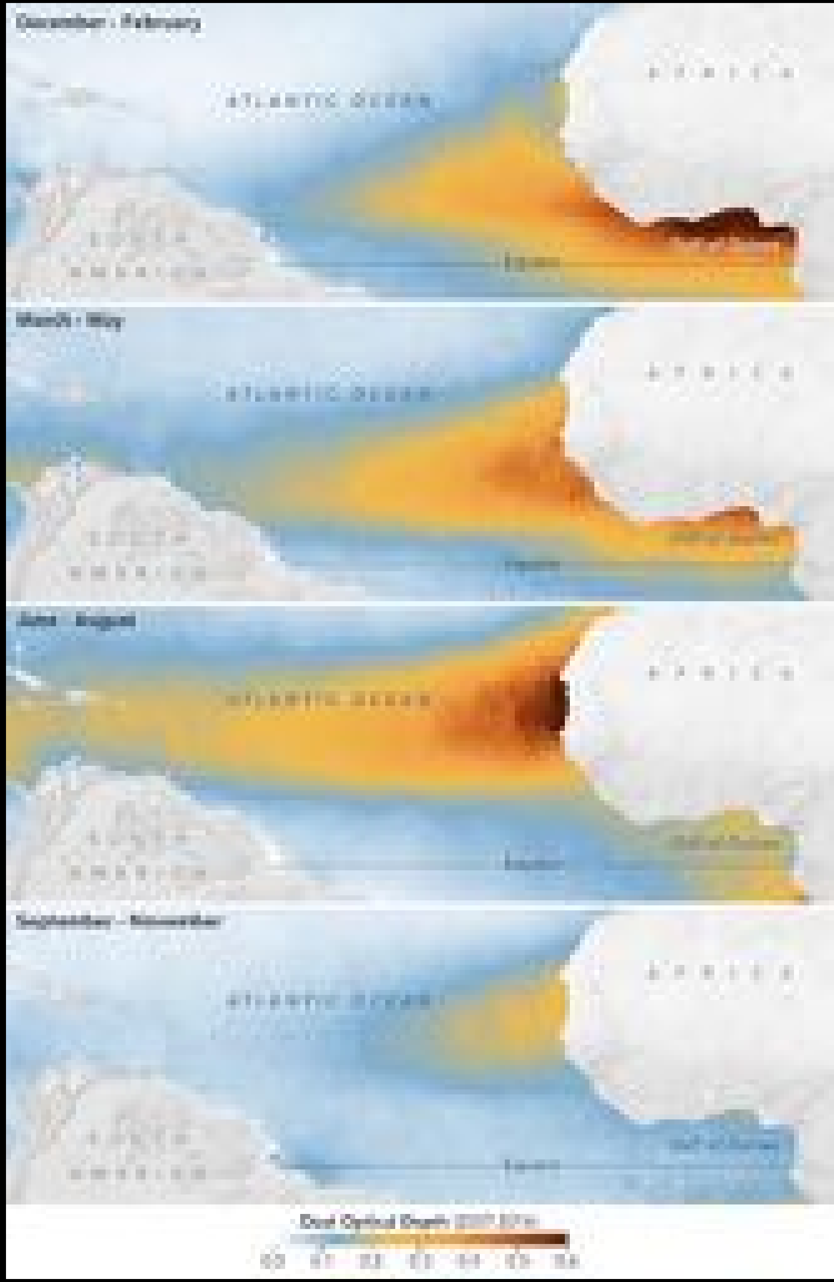
Thomas J. Ryan-Keogh[1*]†, Sandy J. Thomalla[1,2]†, Pedro M. S. Monteiro[1,3], Alessandro Tagliabue[4]

Browning et al. (2023) https://doi.org/10.1038/s41586-023-06439-0
Ryan-Keogh et al. (2023) https://doi.org/10.1126/science.abl5237

Credit BeccaMGM https://en.wikipedia.org/wiki/Iron_cycle#/media/File:Iron_cycle7.png

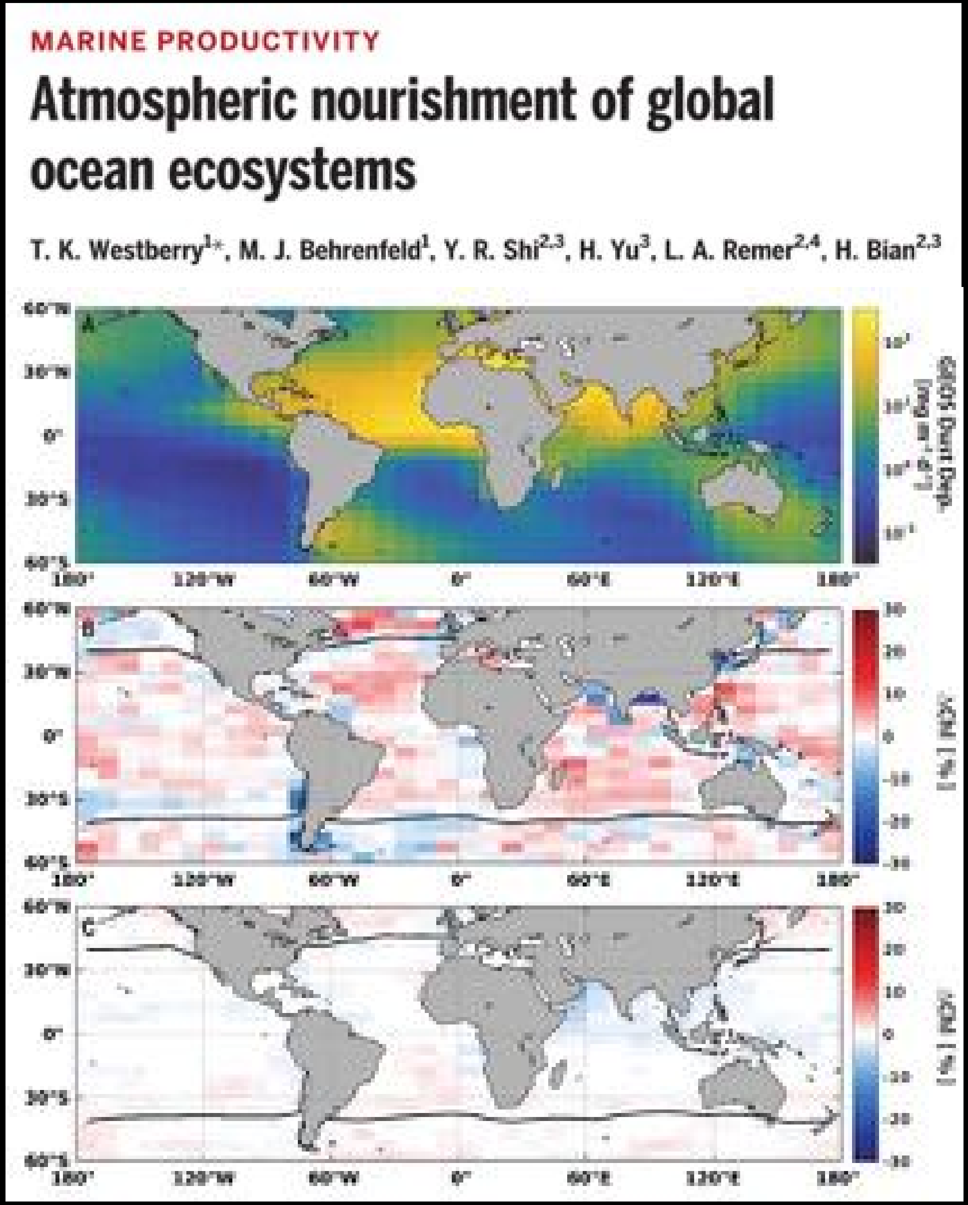




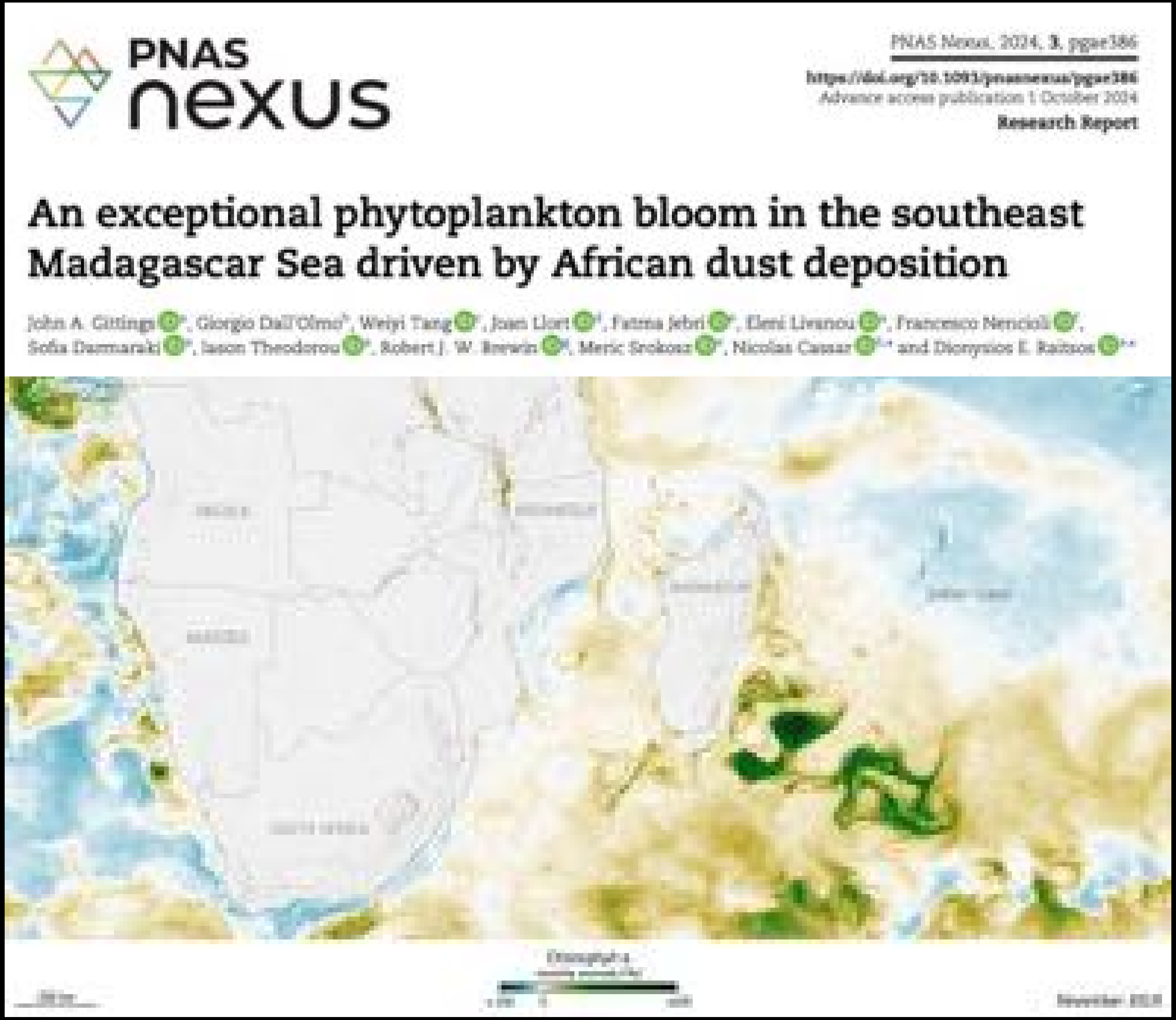


When winds lift particles up, they can spread across thousands of miles, circling the planet and fertilizing key parts of oceans with critical nutrients like iron.

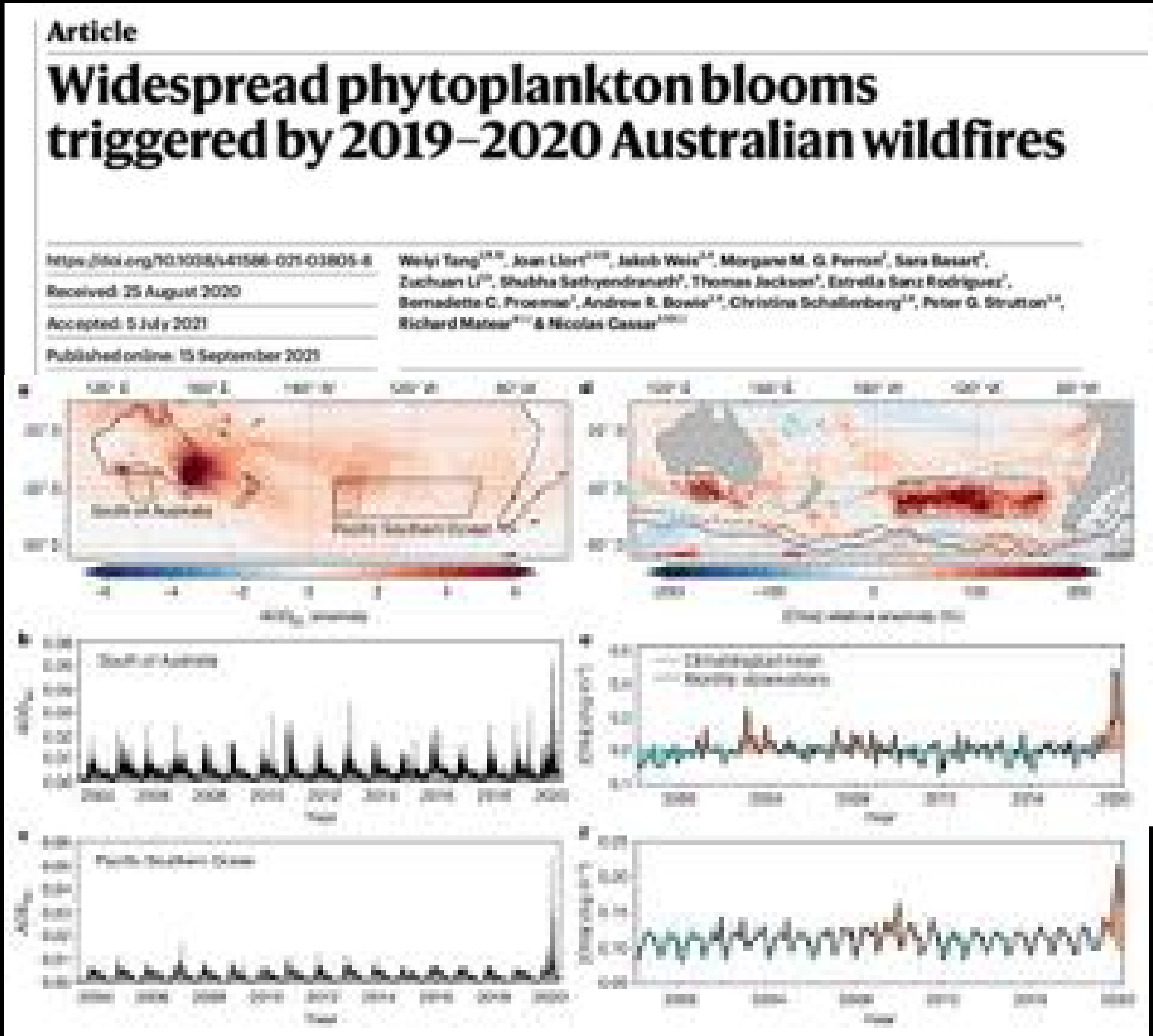
Credit https://www.nesdis.noaa.gov/content/dirt-atmospheric-dust
https://earthobservatory.nasa.gov/images/146122/a-dusty-journey



Westberry et al. (2023)
https://doi.org/10.1126/science.abq5252



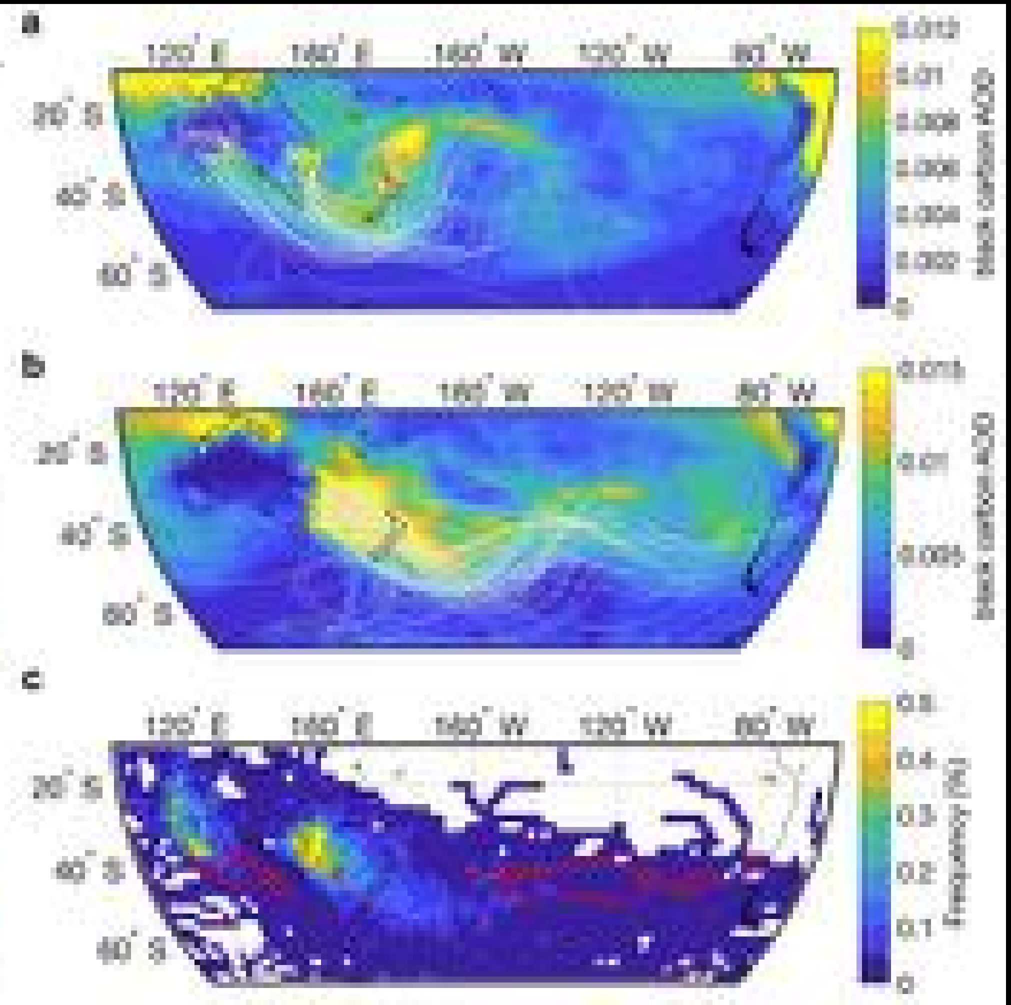
Gittings et al (2024)
https://doi.org/10.1093/pnasnexus/pgae386


Article

Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires

https://doi.org/10.1038/s41586-021-03805-8
Received: 25 August 2020
Accepted: 5 July 2021
Published online: 15 September 2021

Weiyi Tang, Joan Llort, Jakob Weis, Morgane M. G. Perron, Sara Basart, Zuchuan Li, Shubha Sathyendranath, Thomas Jackson, Estrella Sanz Rodríguez, Bernadette C. Proemse, Andrew R. Bowie, Christina Schallenberg, Peter G. Strutton, Richard Matear & Nicolas Cassar

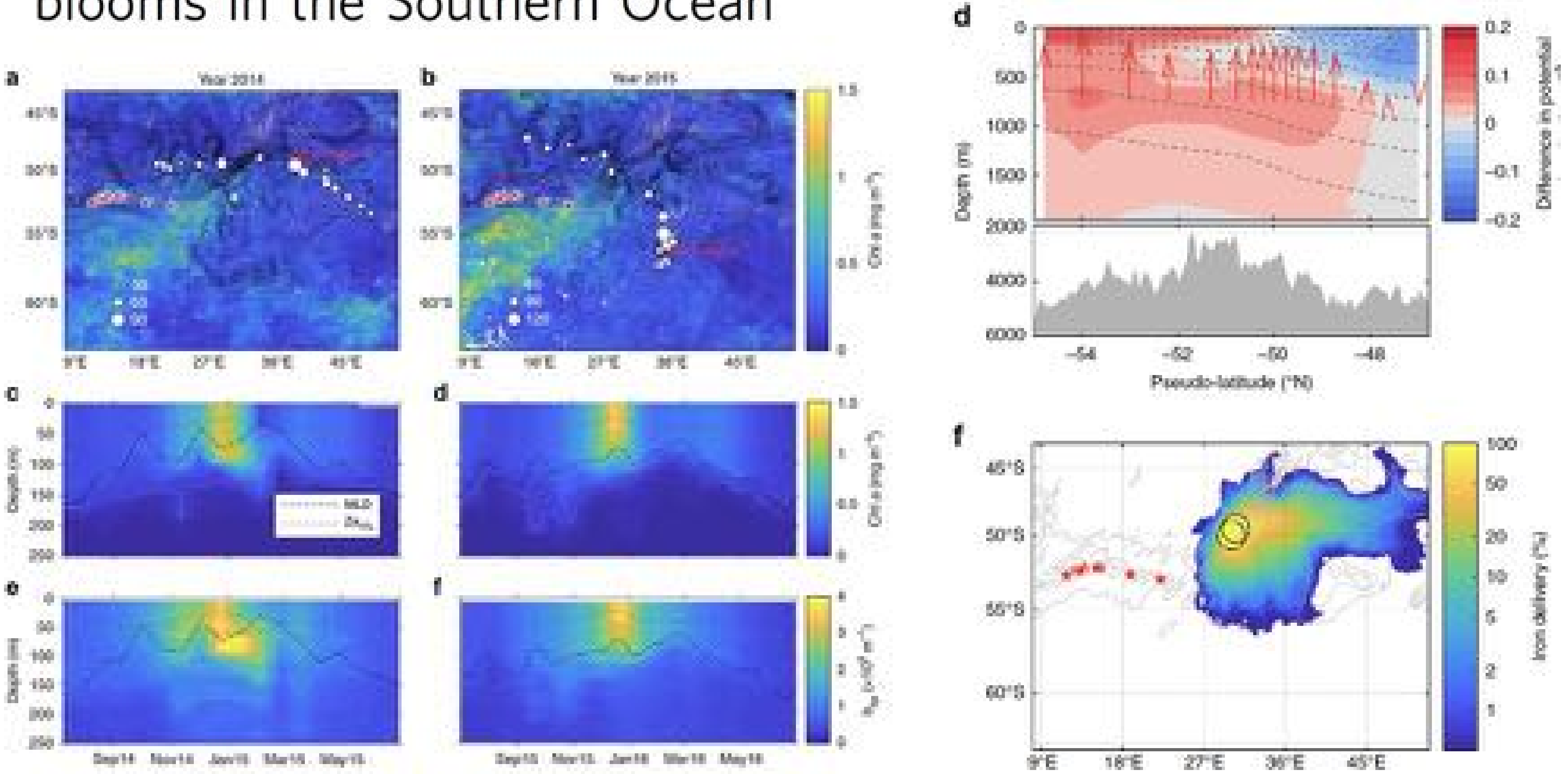


Tang et al. (2021)
https://doi.org/10.1038/s41586-021-03805-8

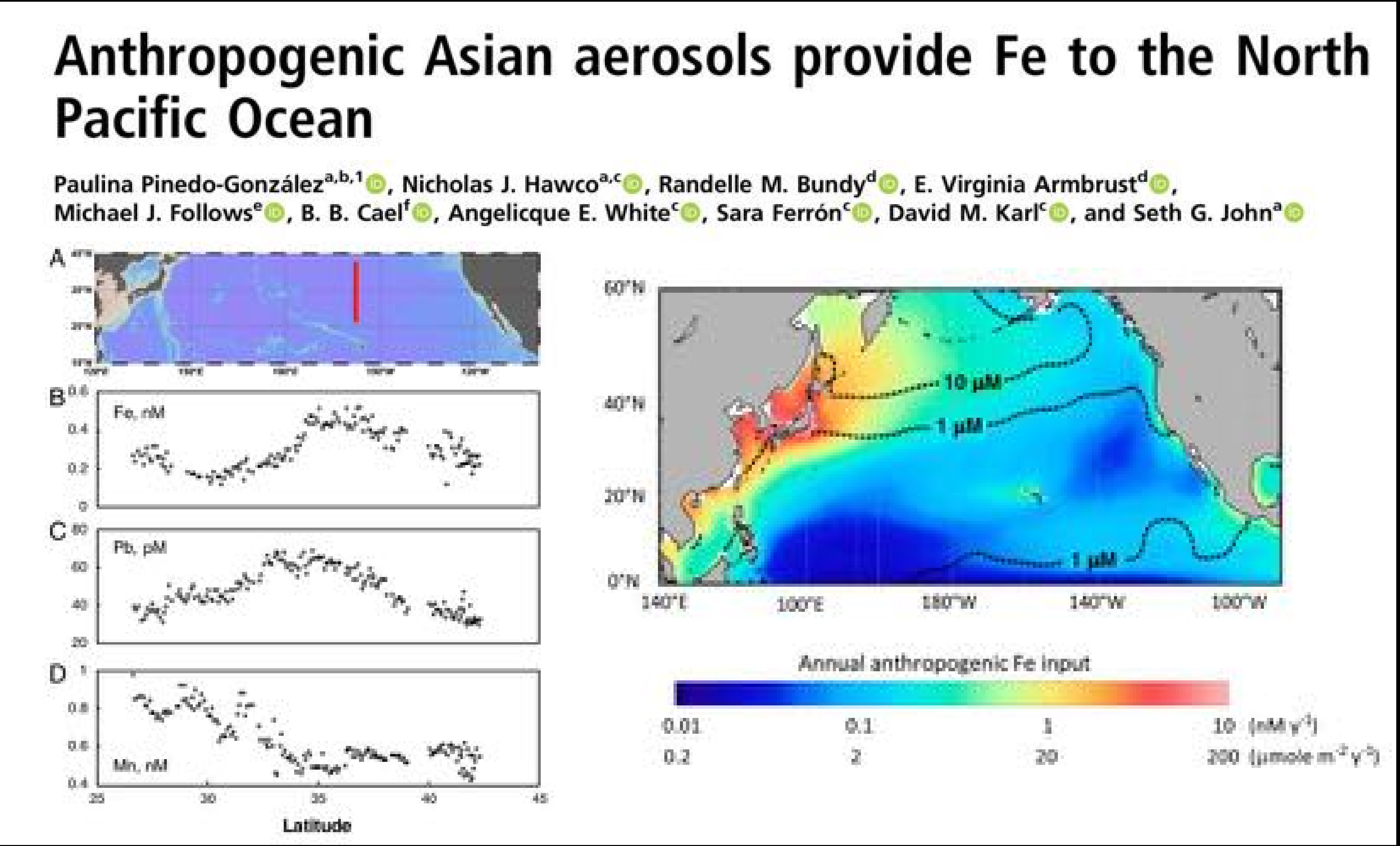
ARTICLE

https://doi.org/10.1038/s41467-019-09973-6 OPEN

Hydrothermal vents trigger massive phytoplankton blooms in the Southern Ocean



Ardyna et al. (2019) https://doi.org/10.1038/s41467-019-09973-6



Anthropogenic Asian aerosols provide Fe to the North Pacific Ocean

Paulina Pinedo-González[a,b,1], Nicholas J. Hawco[a,c], Randelle M. Bundy[d], E. Virginia Armbrust[d], Michael J. Follows[e], B. B. Cael[f], Angelicque E. White[c], Sara Ferrón[c], David M. Karl[c], and Seth G. John[a]

Anthropogenic Fe contributes 21-59% of dissolved Fe measured between 35° and 40°N

Pinedo-González et al. (2020) <u>*https://doi.org/10.1073/pnas.2010315117*</u>

Lecture outline

1. Introduction to marine biogeochemical cycles
2. The Water cycle
3. The Redfield Ratio
4. The Carbon cycle
5. The Ocean Biological Carbon Pump
6. The Nitrogen cycle
7. The Iron cycle