Primary production, export production and climate-driven changes

Bob Brewin

Lecture outline

1. Definition of phytoplankton biomass
2. Measuring phytoplankton biomass at sea
3. Estimating phytoplankton biomass from space
4. Definition of production
5. Importance of primary production
6. Measuring production at sea
7. Estimating primary production from space
8. Estimating export production from space
9. Climate-driven changes

Biomass of phytoplankton is the total mass of living phytoplankton present in a given volume or area of water at a specific time. For phytoplankton, the metric of biomass typically used is carbon, though others metric are used (e.g., nitrogen, and chlorophyll-a).

Phytoplankton
0.2 - 1 Gt C

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

Terrestrial plants
450 Gt C

Le Quéré et al. (2005) *https://doi.org/10.1111/j.1365-2486.2005.1004.x*
Kostadinov et al. (2016) *https://doi.org/10.5194/os-12-561-2016*

Barr-On et al. (2018)
https://doi.org/10.1073/pnas.1711842115

Table 2 Comparison of chlorophyll-a and carbon as the state variable in computations of primary production

Chlorophyll-a	Carbon
Has distinctive optical and chemical signatures that cannot be mistaken for anything else (direct methods)	Phytoplankton carbon has no distinctive signal that allows separation from other types of particulate carbon at sea (indirect methods)
There is a wealth of data on chlorophyll from a variety of sources (both in situ and satellite)	Phytoplankton carbon is difficult to measure, not just from satellites, but also in situ
There is a large body of photosynthesis-rate parameters that are available from in situ observations that can underpin chlorophyll-based models	Carbon-based growth parameters from the field are difficult to measure, and hence hard to find in literature and data repositories
Chlorophyll-a is at the heart of the photosynthetic reaction (but note: not all chlorophyll-a is in the photosystems)	Not all carbon in the cell is linked to primary production
Chlorophyll-a is the transducer that acts to connect the supply of energy from the sun to the plant-based ecosystems on our planet	Phytoplankton carbon without chlorophyll-a in photosystems cannot produce organic material
There is perhaps less recognition of the central role played by chlorophyll-a and associated pigments in maintaining life as we know it on this planet	In the climate context, and in ecosystem models, the importance of biologically mediated carbon pools and fluxes is now well-recognised

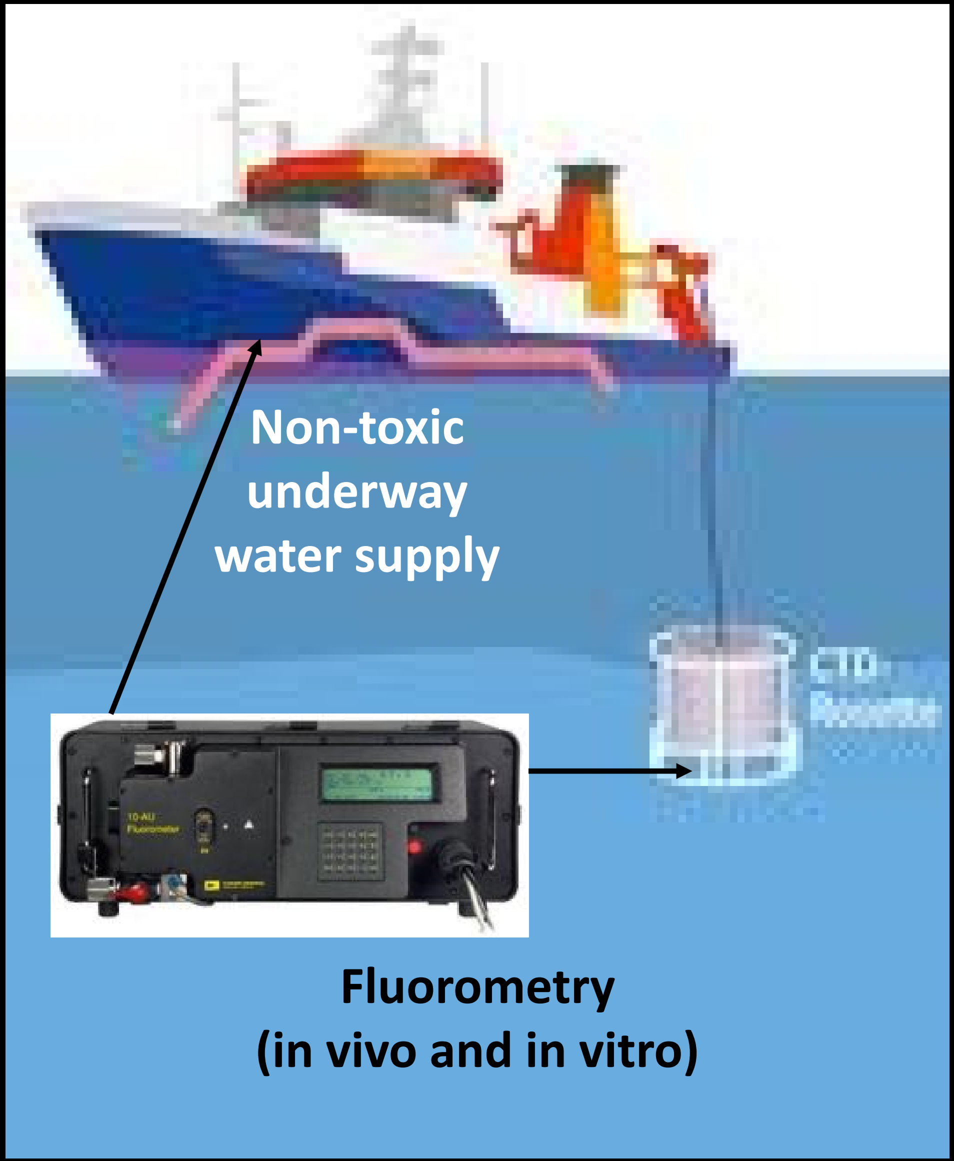
Sathyendranath et al. (2023) https://doi.org/10.1007/s10712-023-09805-9

Skákala et al. (2026) https://doi.org/10.5194/os-22-1457-2026

a_{ph}

Lee et al. (1996) https://doi.org/10.1364/AO.35.000463

Chlorophyll-a: Fluorometric Methods

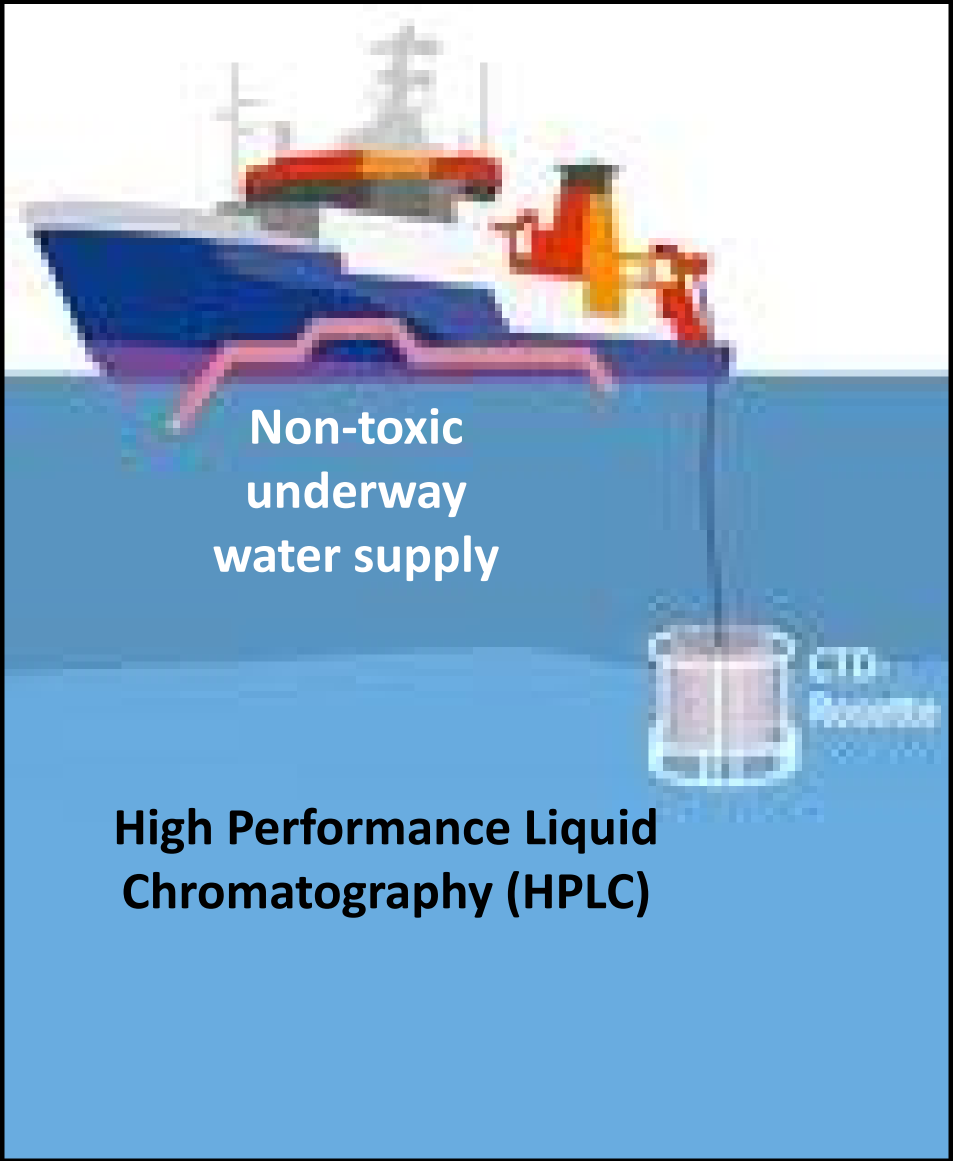


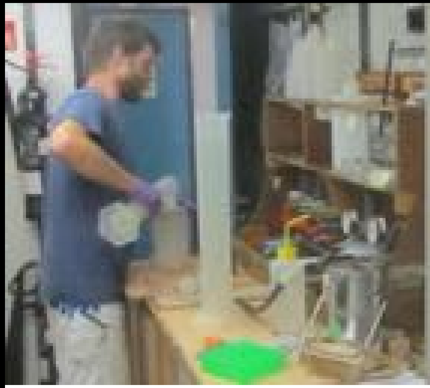
https://www.turnerdesigns.com/trilogy-laboratory-fluorometer

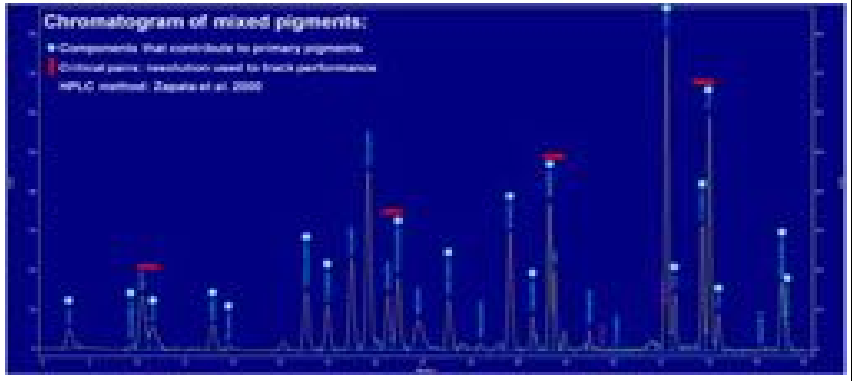
https://www.jove.com/

https://www.turnerdesigns.com/c3-submersible-fluorometer

Chlorophyll-a: High Performance Liquid Chromatography



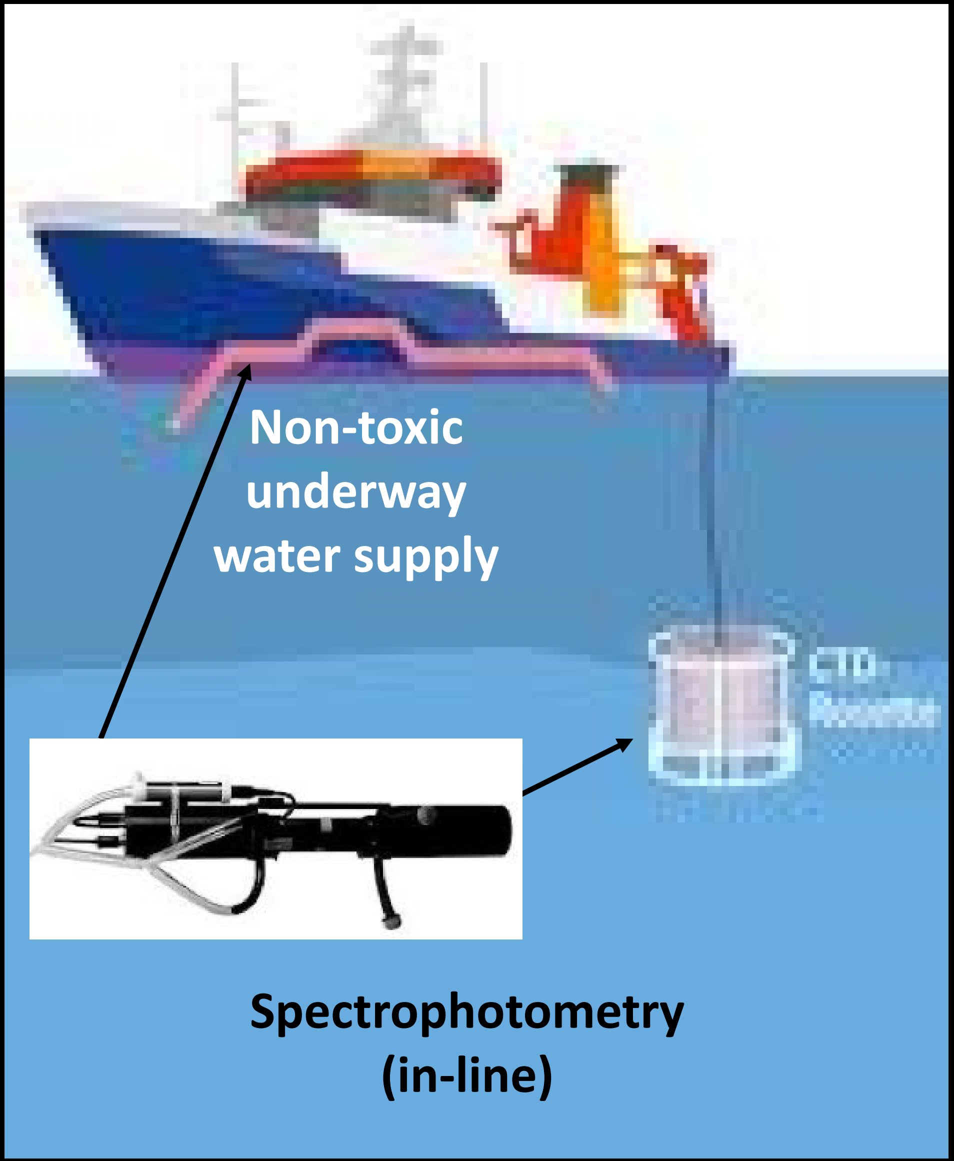


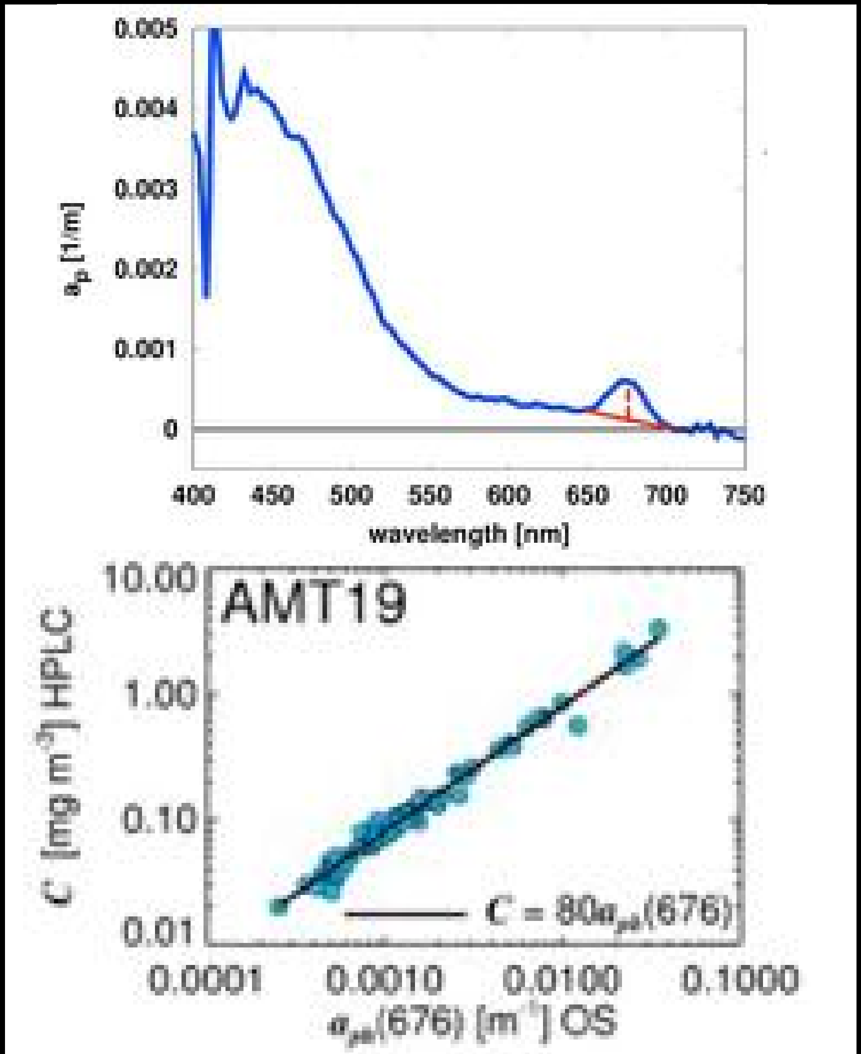


"Gold standard for calibrating and validating satellite-derived Chlorophyll-*a* concentration"

Canuti et al. (2025)
https://doi.org/10.1016/j.marchem.2025.104516

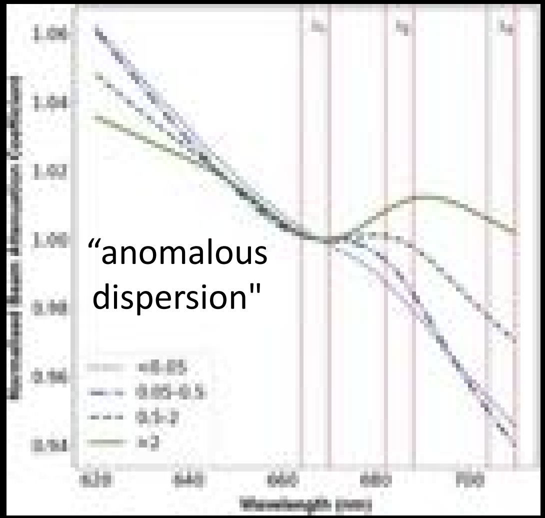
Chlorophyll-a: Absorption line-height





Brewin et al. (2016)
https://doi.org/10.1016/j.rse.2016.05.005

Davis et al. (1997)
https://doi.org/10.1029/96JC02430
Boss et al. (2007)
https://doi.org/10.1007/s10750-006-2609-3
Dall'Olmo et al. (2012)
https://doi.org/10.1364/OE.20.021532



Graban et al. (2020)
https://doi.org/10.1364/OE.397863
Houskeeper et al. (2020)
https://doi.org/10.1364/AO.396832

IOCCG PROTOCOLS https://ioccg.org/what-we-do/ioccg-publications/ioccg-protocols/

X-ray microanalysis transmission electron microscope (TEM)
Heldal et al., (2003)
https://doi.org/10.4319/lo.2003.48.5.1732

Elemental analysis of flow cytometrically-sorted samples
Graff et al. (2012, 2015)
https://doi.org/10.4319/lom.2012.10.910
https://doi.org/10.1016/j.dsr.2015.04.006

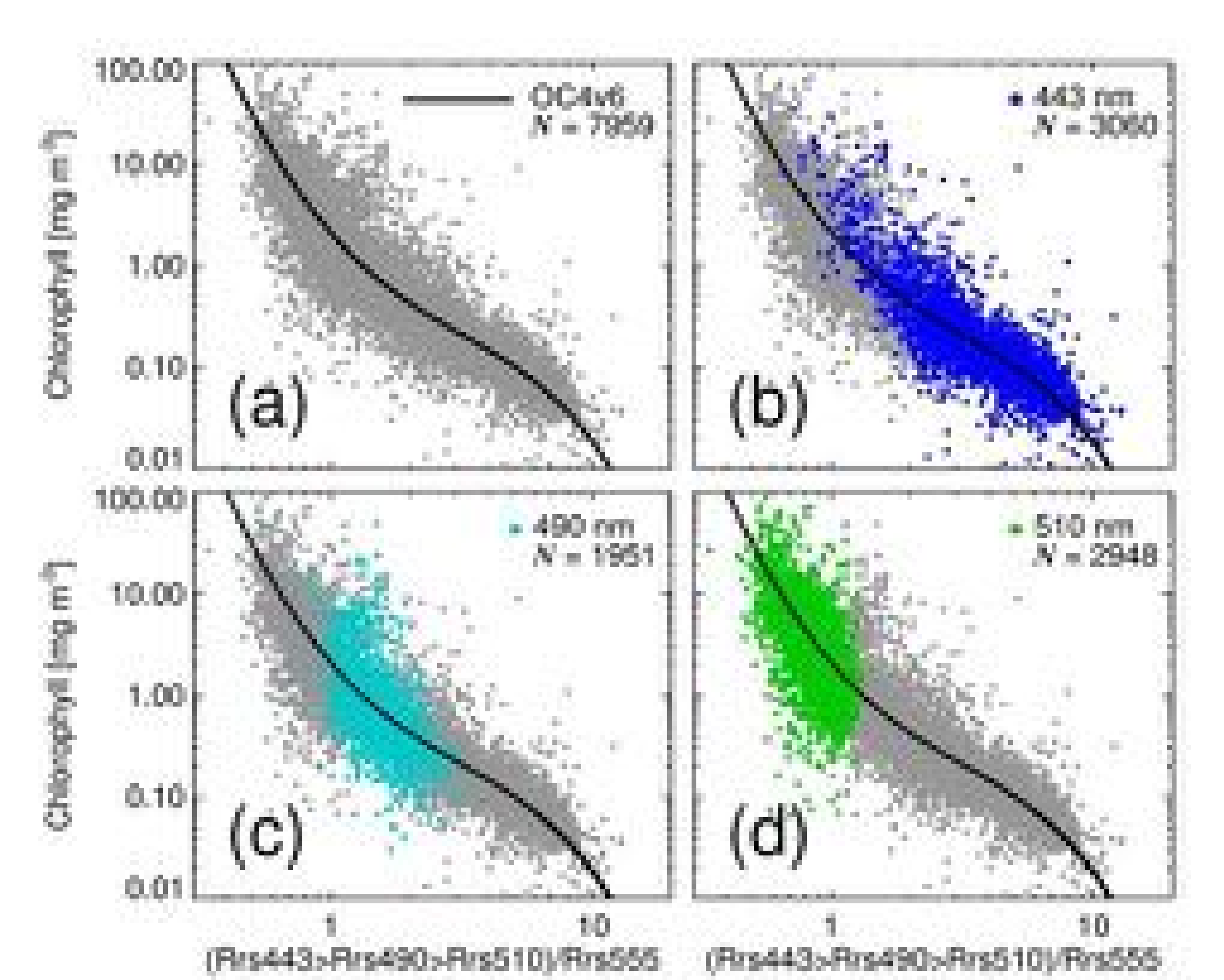
Simultaneous analysis of POC and Chl-a data
Sathyendranath et al. (2009)
https://doi.org/10.3354/meps07998

Measuring phytoplankton carbon *in situ*

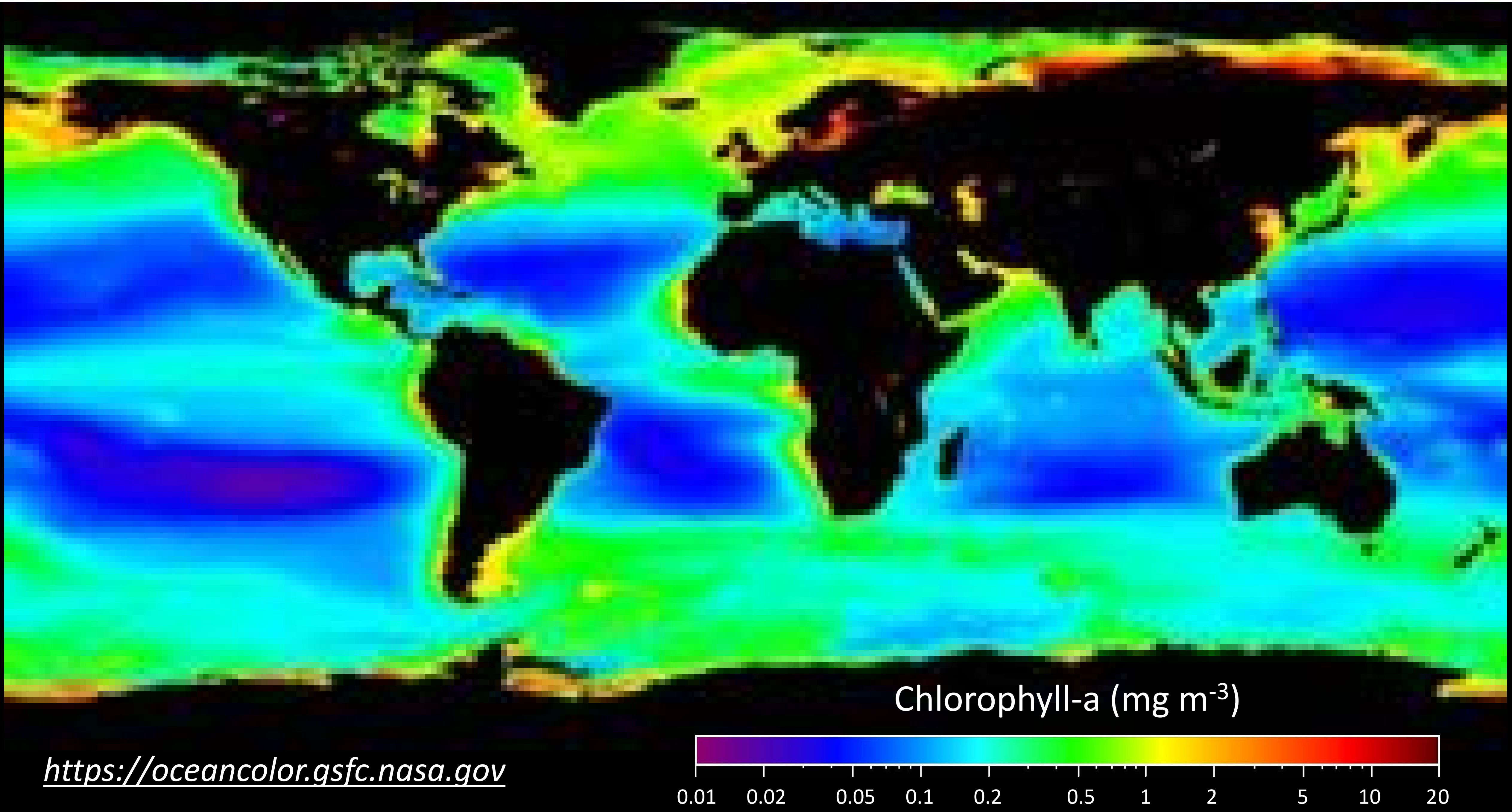
Cell counts (e.g. from light microscopy and flow cytometry) assumptions on per-cell biovolume and carbon
e.g. Menden-Deuer and Lessard, (2000)
https://doi.org/10.4319/lo.2000.45.3.0569

Optical backscattering
e.g. Behrenfeld et al. (2005)
https://doi.org/10.1029/2004GB002299
Martinez-Vicente et al. (2013)
https://doi.org/10.1002/grl.50252

Calibrating flow cytometer forward and side scattering (for small phytoplankton) and video-based analysis (for large phytoplankton)
e.g. Casey et al. (2013) https://doi.org/10.1016/j.dsr2.2013.02.002

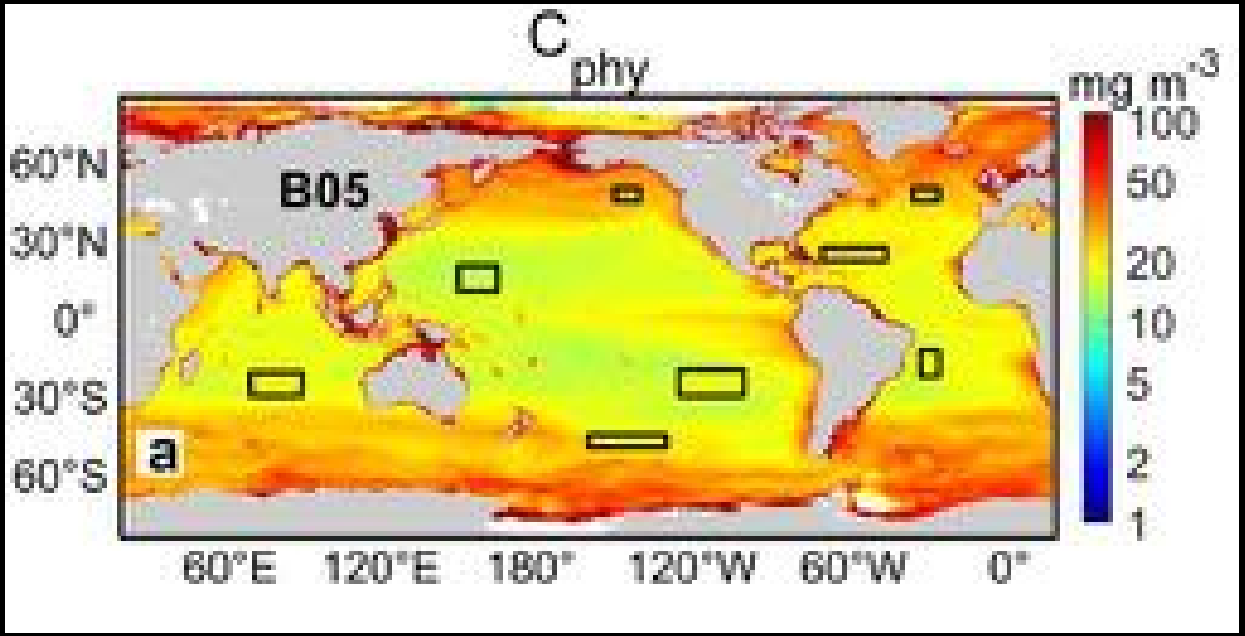


O'Reilly & Werdell (2019) https://doi.org/10.1016/j.rse.2019.04.021
Sathyendranath et al. (2017) https://doi.org/10.1016/j.rse.2017.04.017



https://oceancolor.gsfc.nasa.gov

Phytoplankton carbon from space



Yang et al. (2024) https://doi.org/10.1029/2023JC019922

Phytoplankton biomass and diversity Climate Change Initiative (PHYTO-CCI)

SCOPE

BICEP Biological Pump and Carbon Exchange Processes

Backscattering based

Behrenfeld et al. (2005)
https://doi.org/10.1029/2004GB002299
Bellacicco et al. (2018)
https://doi.org/10.1029/2018GL078185
Yang et al. (2024) https://doi.org/10.1029/2023JC019922
Kostadinov et al. (2016)
https://doi.org/10.5194/os-12-561-2016

Chlorophyll-a based (C:Chl ratio)

Sathyendranath et al. (2009)
https://doi.org/10.3354/meps07998
Marañón et al. (2014)
https://doi.org/10.1371/journal.pone.0099312
Sathyendranath et al. (2020)
https://doi.org/10.1364/AO.386252

Absorption based

Roy et al. (2016) https://doi.org/10.1016/j.rse.2017.02.015

Challenges in clear waters at surface

Antoine et al. (2026) https://doi.org/10.5194/bg-23-2641-2026

Primary production in the ocean is the process by which photosynthetic organisms convert inorganic carbon into organic matter using sunlight as an energy source. It is expressed in terms of mass of carbon converted (fixed) per unit volume of water per unit time. If biomass is like money in the bank, primary production is like the interest earned by the capital.

Phytoplankton
45-50 Gt C

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

Longhurst et al. (1995) https://doi.org/10.1093/plankt/17.6.1245
Field et al. (1998) https://doi.org/10.1126/science.281.5374.237

Terrestrial plants
50 Gt C

Field et al. (1995) https://doi.org/10.1016/0034-4257(94)00066-V
Field et al. (1998) https://doi.org/10.1126/science.281.5374.237

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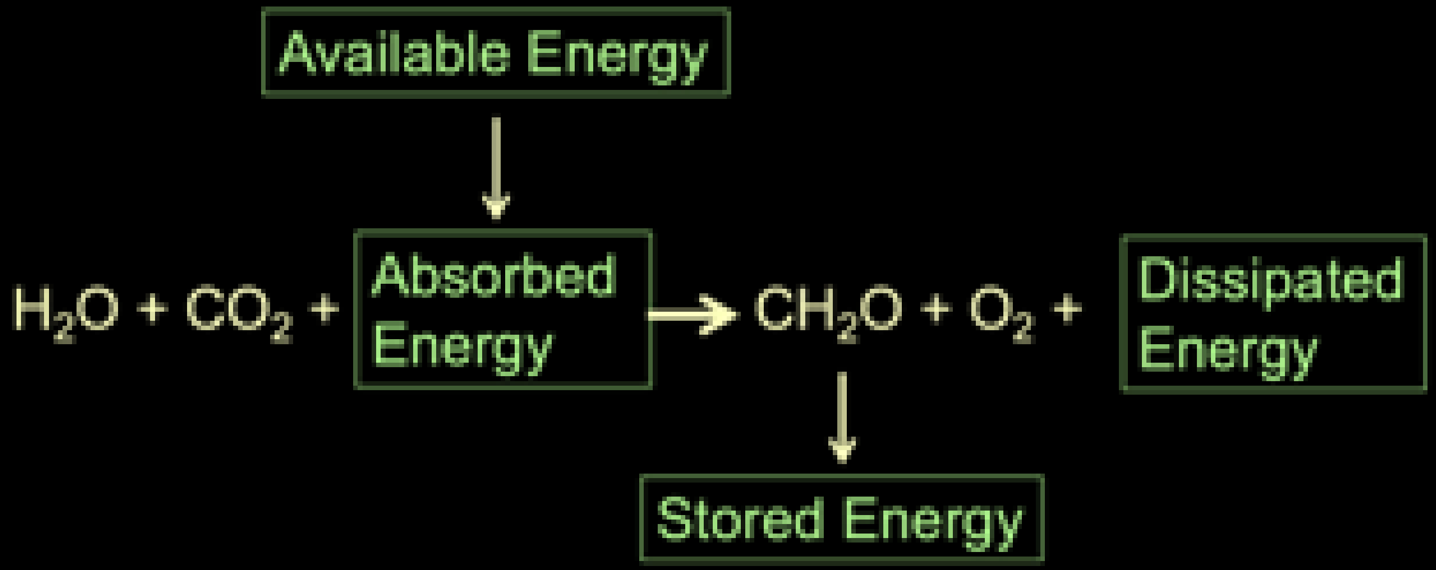
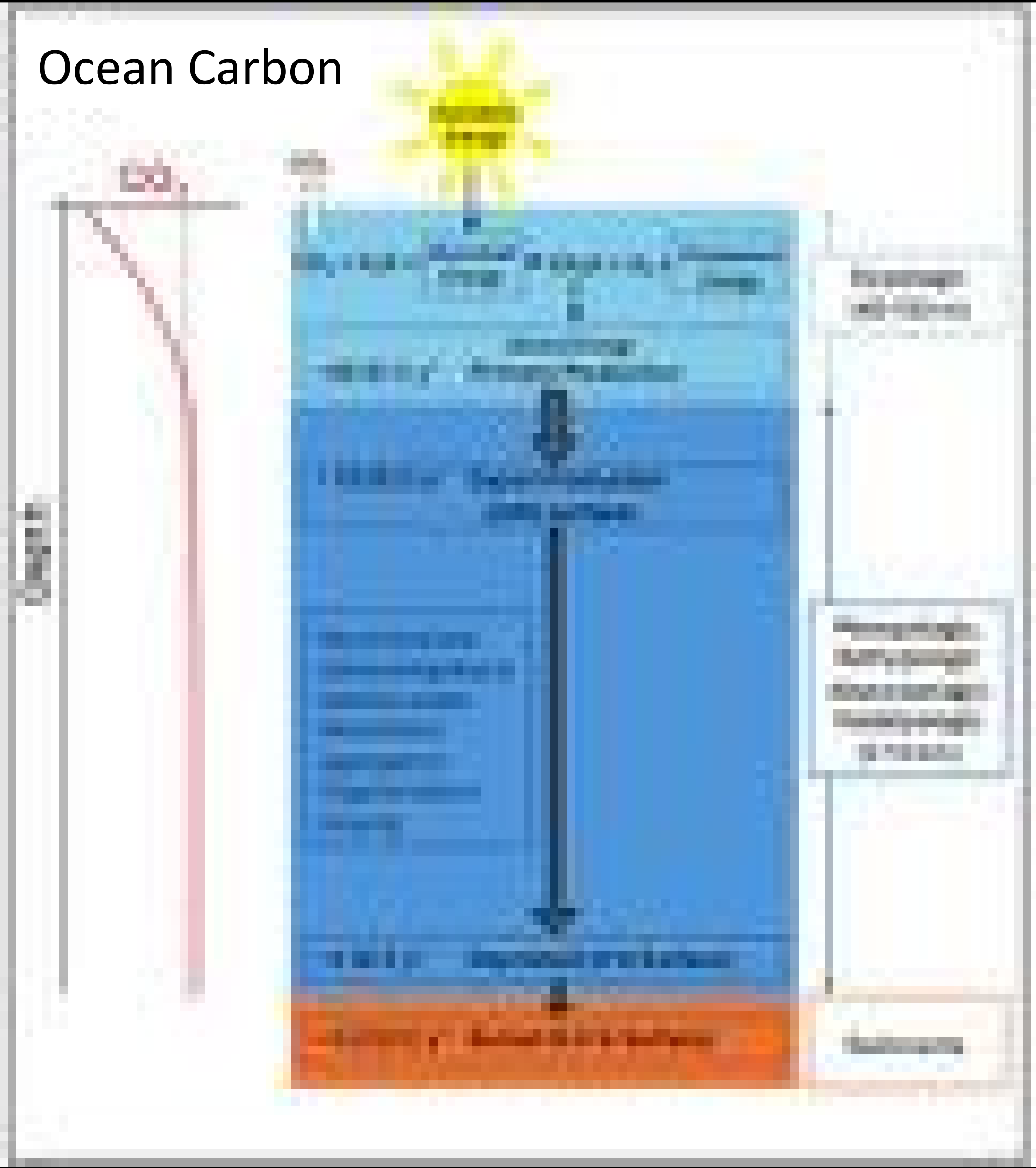


Image courtesy of Shubha Sathyendranath

The growth requirements of phytoplankton are like those of any green plant:

- Water
- Carbon dioxide
- Visible light
- Macronutrients
- Micronutrients

Type of Production	Definition
Gross Primary Production (GPP)	the total rate of organic carbon production by autotrophs
Net primary Production (NPP)	the total rate of organic carbon production by autotrophs minus respiration by phytoplankton
Net community production (NCP)	the total rate of organic carbon production by autotrophs minus respiration all organisms in the ecosystem
New production	New production is the portion of NPP supported by nutrients entering the euphotic zone from outside it
Regenerated production	Regenerated production is the portion of NPP supported by nutrients recycled within the euphotic zone
Export production	is the amount of NPP that is lost from the surface ocean


Ocean Carbon

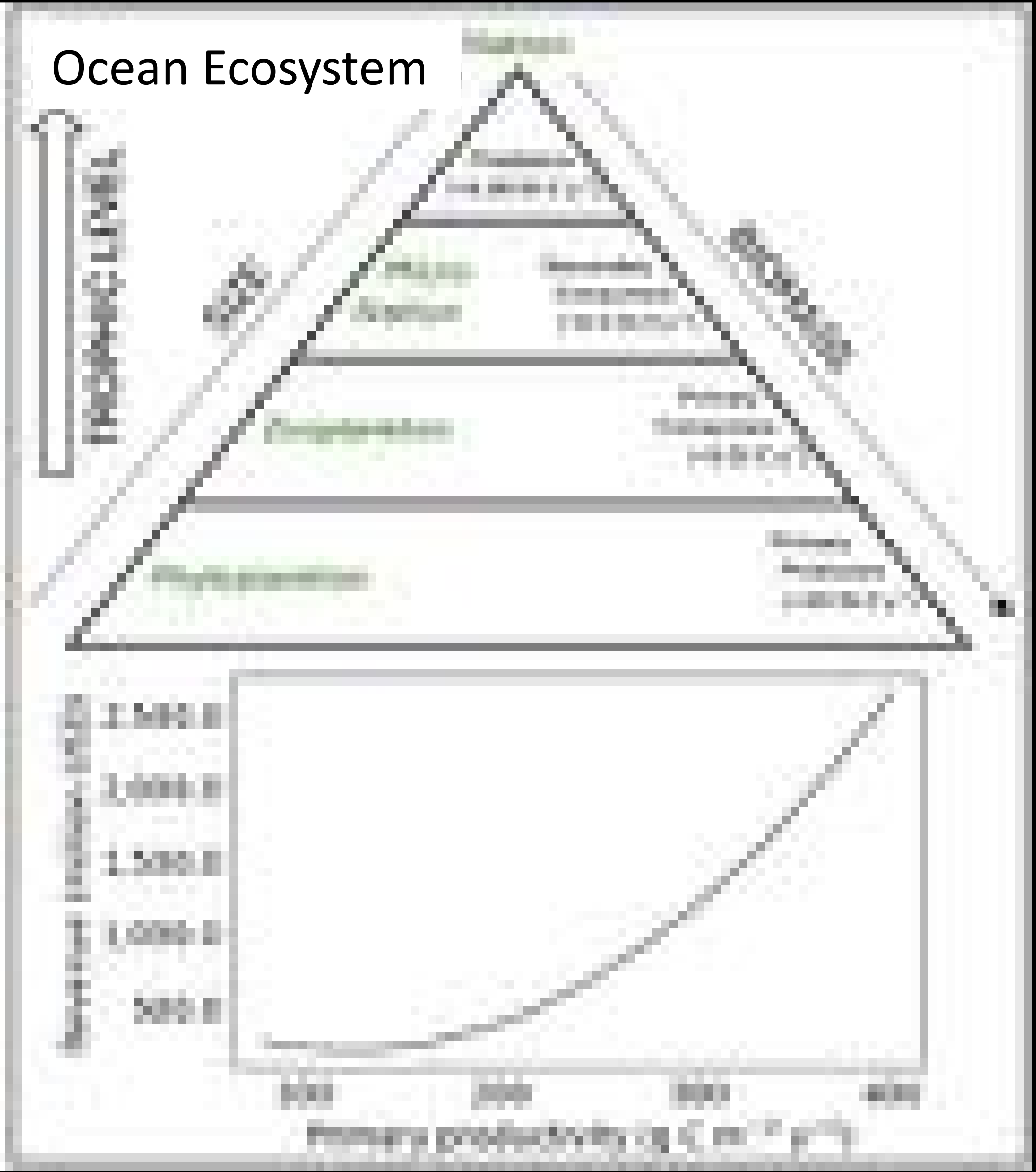

Ocean Ecosystem
Primary productivity (g C m⁻² y⁻¹)

Table 1 Various methods for estimating primary production in the ocean. The nominal timescales applicable to the results are also given. The components of primary production P_G (gross primary production), P_N (net primary production), and P_C (net community production) are based on rates of carbon uptake. P_T (total primary production), P_r (regenerated production) and P_{new} (new production) refer to nitrogen uptake rates. Sedimentation rate refers to the flux of organic particles from the photic zone

Method	Nominal component of production	Nominal timescale
In vitro		
^{14}C assimilation	P_N (> P_G)	Hours to 1 day (duration of incubation)
O_2 evolution	P_G	Hours to 1 day (duration of incubation)
$^{15}NH_4$ assimilation	P_r	Hours to 1 day (duration of incubation)
$^{15}NO_3$ assimilation	P_{new}	Hours to 1 day (duration of incubation)
In situ property		
NO_3 flux to photic zone	P_{new}	Hours to days
O_2 utilization rate (OUR) below photic zone	P_{new}	Seasonal to annual
Net O_2 accumulation in photic zone	P_{new}	Seasonal to annual
$^{234}Th/^{238}U$	P_{new}	1–100 days
$^{3}He/^{3}H$	P_{new}	Seasonal and longer
Optical		
Double-flash fluorescence	P_G	<1 s
Passive fluorescence	P_G	<1 s
Remote sensing	P_G, P_{new}	Days to weighted annual
Upper and lower limits		
Sedimentation rate below photic zone	P_{new} (= P_N) (lower limit)	Days to months (duration of trap deployment)
Optimal energy conversion of photons absorbed	P_G (upper limit)	Instantaneous to annual
Depletion of winter accumulation of NO_3	P_{new} (lower limit)	Seasonal

Sathyendranath et al. (2019) Primary Production Distribution. In Cochran et al. (Eds.) Encyclopedia of Ocean Sciences, ISBN: 978-0-12-813081-0

See also Regaudie-de-Gioux et al. (2014) https://doi.org/10.3389/fmars.2014.00019

Table 2 Summary of methodologies for measuring marine primary production, including the type of production and time scales over which methods estimate production

Method	Form of production measured	Integration scale	Notes
In vitro light/dark O_2	GPP, NCP	Daily	Incubation-dependent; GPP derived from measurements of NCP and inferred respiration (R)
$^{18}O_2$	GPP	Daily	Incubation-dependent; requires gas-tight incubation bottles and efforts to simulate in situ temperature and light conditions
$\Delta^{17}O$	GPP	Weekly-monthly	Incubation-independent; requires knowledge of time history of physical processes influencing mixed layer O_2 concentrations
^{14}C-assimilation	GPP to NPP	Daily	Incubation-dependent; requires consideration of incubation vessel (e.g., glass vs plastic), efforts to simulate in situ temperature and light conditions, and decision on filter- vs. whole-water processing of samples. Over short incubation periods the method estimates GPP
Beam attenuation, c_p	NCP and GPP	Daily	Incubation-independent; assumes diel changes in c_p attributable to daytime accumulation of particles and nighttime loss due to respiration, grazing, and export. Daytime changes in c_p yield estimates approaching NCP, which when combined with nighttime rates of consumption yields estimates of GPP
O_2/Ar	NCP	Weekly-monthly	Incubation-independent; separates physical from biological processes influencing O_2 concentrations; applicable to mixed layer estimates of NCP, assuming O_2 and Ar are not modified by vertical mixing or diffusion
Mixed layer in situ O_2	GPP, NCP	Weekly	Incubation-independent; in the mixed layer diel variability in O_2 can be used to estimate GPP and NCP; requires quantifying physical processes that influence mixed layer O_2 concentrations
Subsurface O_2 maximum	NCP	Seasonal to annual	Incubation-independent; in the sub-surface O_2 maximum seasonal-scale accumulation of O_2 can be used to estimate annual NCP
Mixed layer DIC and $\delta^{13}C$ measurements	NCP	Annual	Incubation-independent; requires quantifying physical and biological processes determining mixed layer DIC concentrations

Church, M., Cullen, J. & Karl, D..(2019) Approaches to Measuring Primary Production. In Cochran et al. (Eds.) Encyclopedia of Ocean Sciences, ISBN: 978-0-12-813081-0


IOCCG Protocol Series

Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation

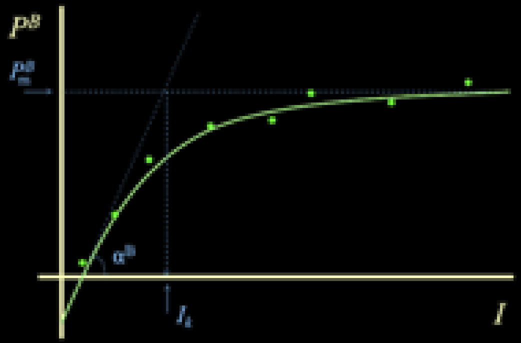
Volume 7: Aquatic Primary Productivity Field Protocols for Satellite Validation and Model Synthesis (v7.0)

September 2022

IOCCG Protocol Series (2022)
http://dx.doi.org/10.25607/OBP-1835

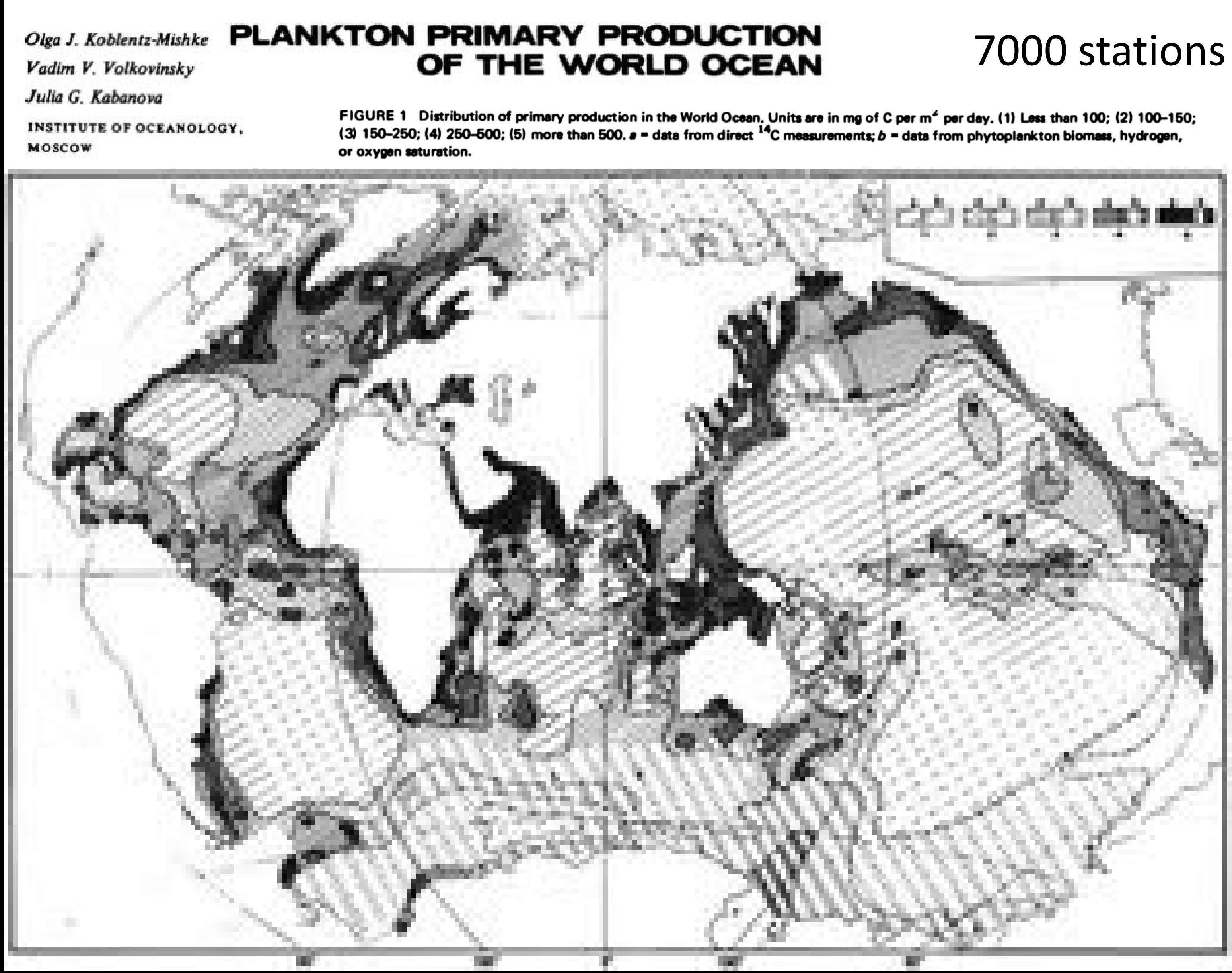
Two common approaches

Daily incubations (in water, on-deck) at a range of irradiances.



1-2 hr photosynthesis-irradiance experiments run in photosynthetrons illuminated by tungsten halogen lamps or LEDs

Spike ^{14}C, incubate, filter to remove inorganic ^{14}C , then determine how much ^{14}C has been taken up using a liquid scintillation counter, convert to carbon.



~23 Gt C y^{-1}

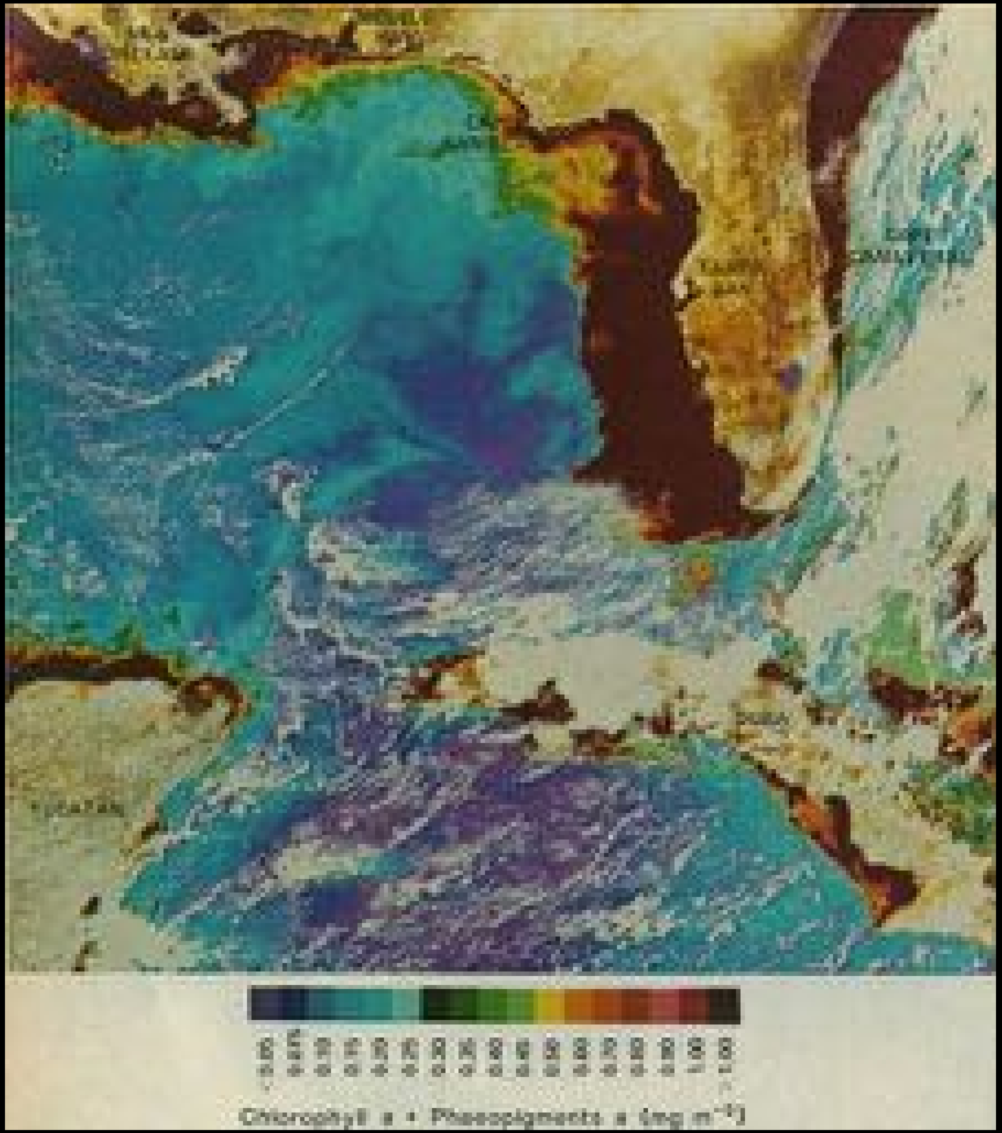
"..total primary production of the World Ocean amounts to 23 x 10^9 tons of carbon …during the year"

Koblentz-Mishke et al. (1970)

National Research Council. 1970. Scientific Exploration of the South Pacific. https://doi.org/10.17226/20491

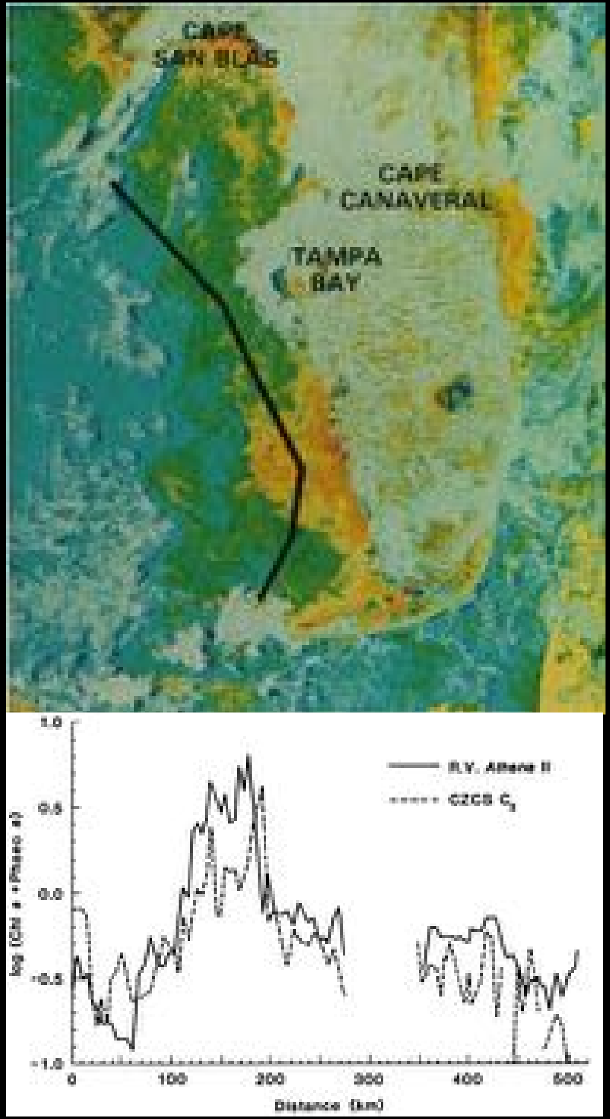
Primary production from satellite ocean colour ranked as among the biggest achievements in biological oceanography!

Barber & Hilting (2000)



Hovis et al. (1980) Science

http://doi.org/10.1126/science.210.4465.60



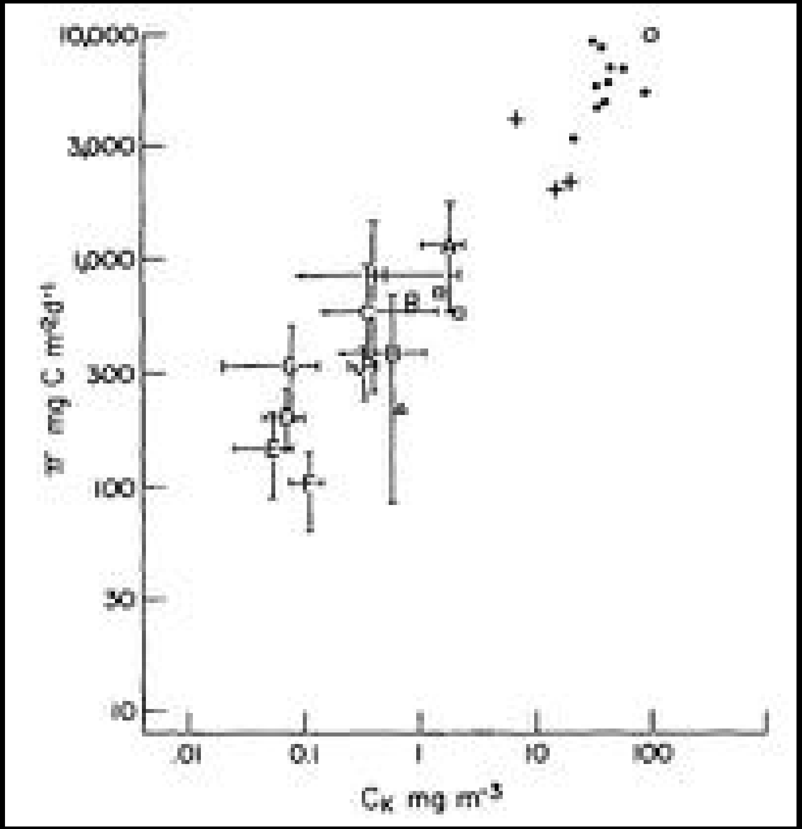
Gordon et al. (1980) Science

http://doi.org/10.1126/science.210.4465.63

Journal of Plankton Research Vol.7 no.1 pp.57 – 70, 1985

Estimating ocean primary production from satellite chlorophyll. Introduction to regional differences and statistics for the Southern California Bight

R.W. Eppley[1], E. Stewart[1], M.R. Abbott[2] and U. Heyman[1,3]



Epply et al. (1985)
https://doi.org/10.1093/plankt/7.1.57

Correlation of Primary Production as Measured Aboard Ship in Southern California Coastal Waters and as Estimated from Satellite Chlorophyll Images

R.C. Smith[1,*], R.W. Eppley[2] and K.S. Baker[1,**]

[1] Visibility Laboratory, Scripps Institution of Oceanography; La Jolla, California 92093, USA
[2] Institute of Marine Resources, Scripps Institution of Oceanography; La Jolla, California 92093, USA

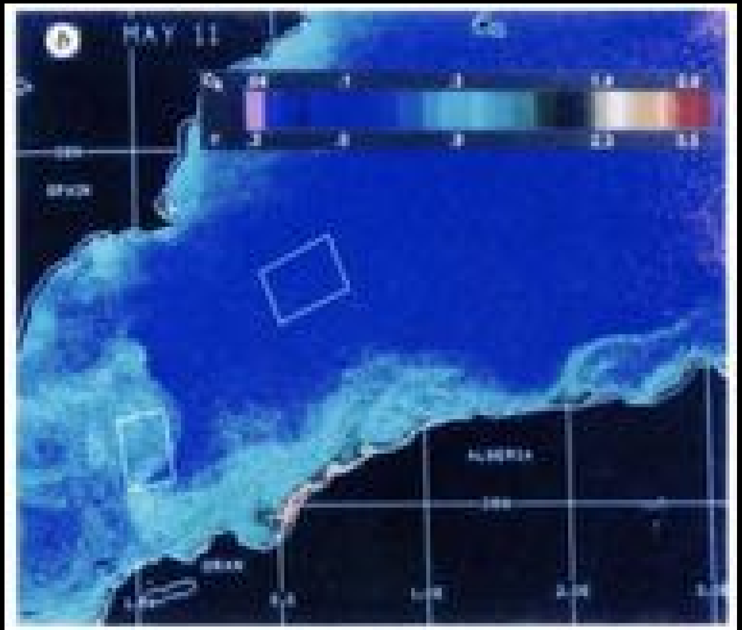
Smith et al. (1982) https://doi.org/10.1007/BF00397033

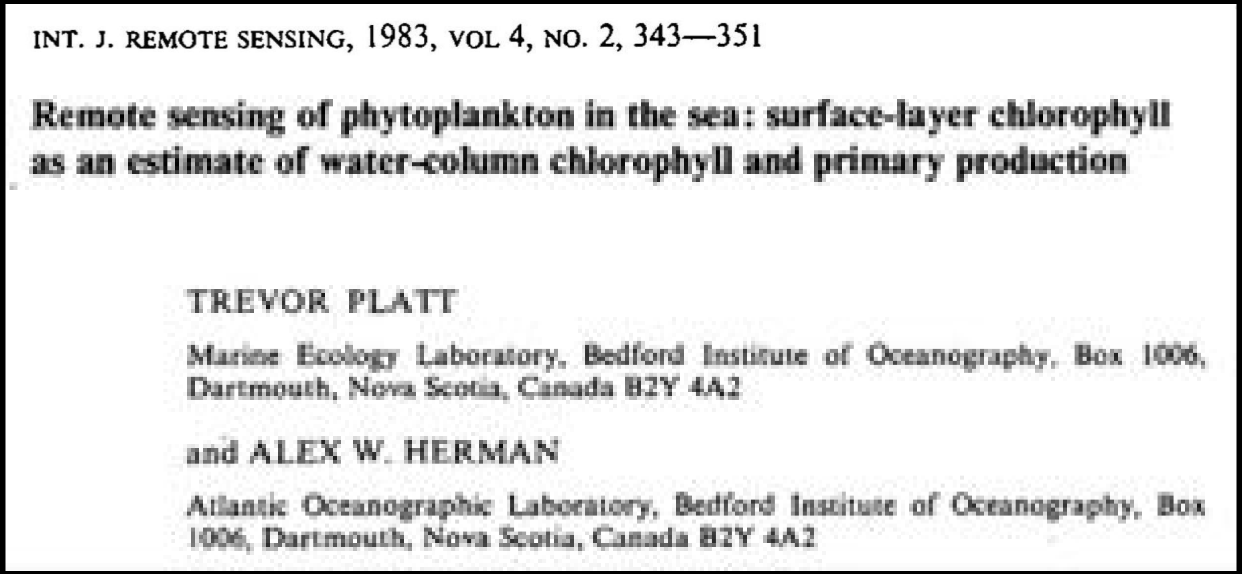
Satellite detection of transient enhanced primary production in the western Mediterranean Sea

Steven E. Lohrenz*, Robert A. Arnone, Denis A. Wiesenburg* & Irene P. DePalma

Oceanography Division, Naval Ocean Research and Development Activity, Stennis Space Center, Mississippi 39529, USA

Lohrenz et al. (1988)
https://doi.org/10.1038/335245a0





INT. J. REMOTE SENSING, 1983, VOL 4, NO. 2, 343—351

Remote sensing of phytoplankton in the sea: surface-layer chlorophyll as an estimate of water-column chlorophyll and primary production

TREVOR PLATT

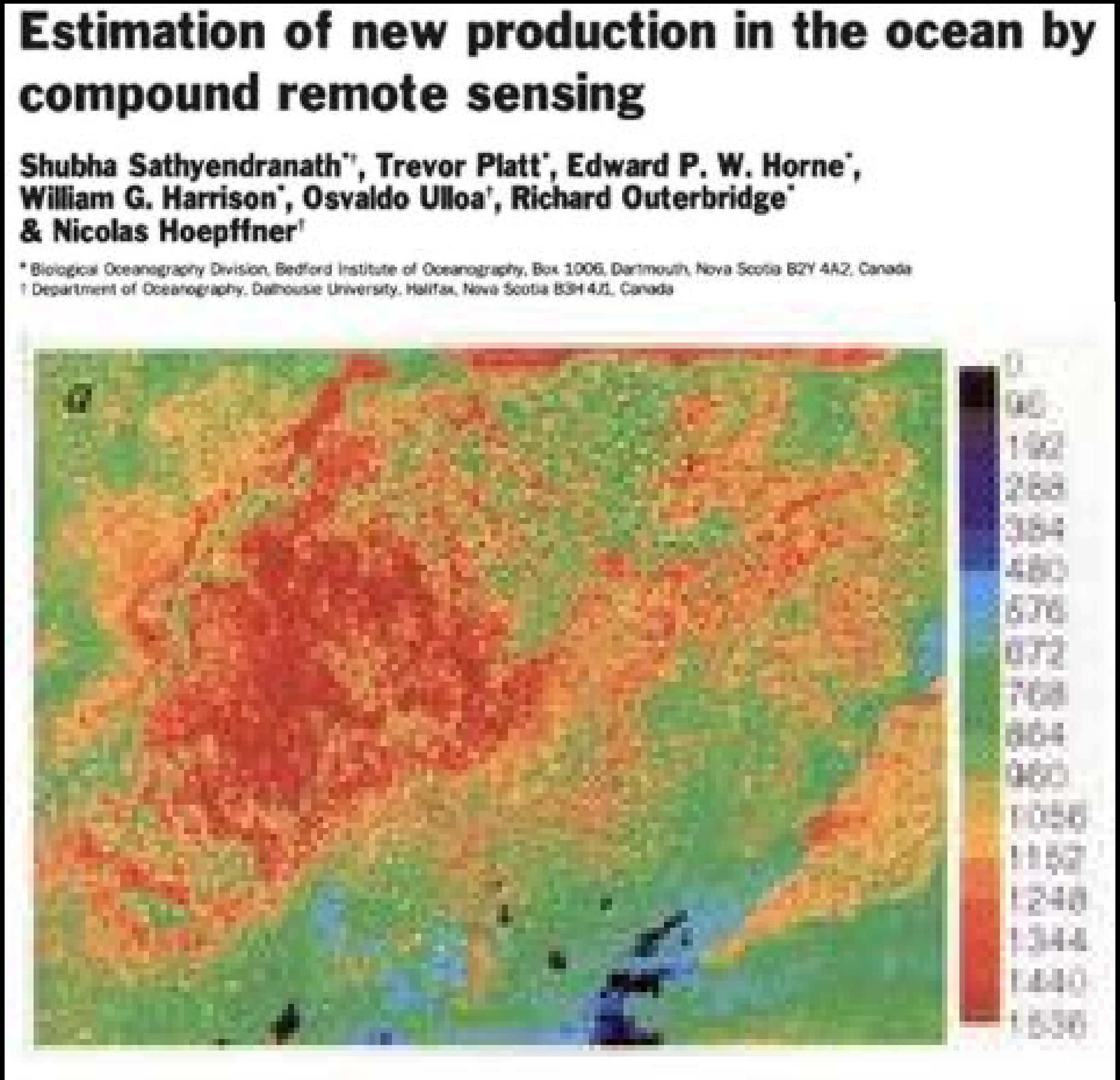
Marine Ecology Laboratory, Bedford Institute of Oceanography, Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2

and ALEX W. HERMAN

Atlantic Oceanographic Laboratory, Bedford Institute of Oceanography, Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2

Platt and Herman et al (1983)
https://doi.org/10.1080/01431168308948552
See also Morel (1991)
https://doi.org/10.1016/0079-6611(91)90004-6

In the 1980s, approaches began to be implemented that captured the fundamental relationships between light and chlorophyll-a, to map primary production at regional scales



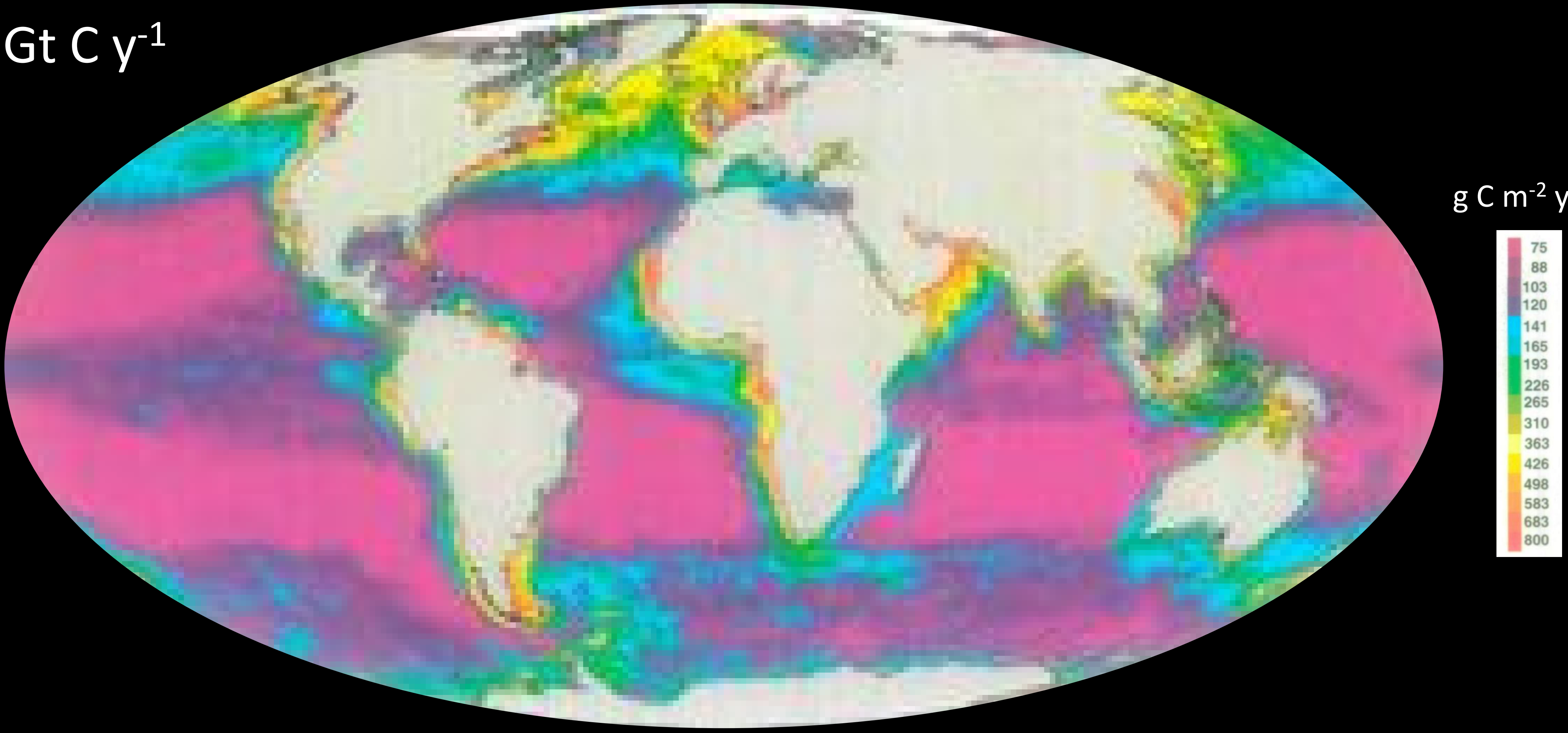
Estimation of new production in the ocean by compound remote sensing

Shubha Sathyendranath*†, Trevor Platt*, Edward P. W. Horne*, William G. Harrison*, Osvaldo Ulloa†, Richard Outerbridge* & Nicolas Hoepffner†

* Biological Oceanography Division, Bedford Institute of Oceanography, Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada
† Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4J1, Canada

Sathyendranath et al. (1991)
https://doi.org/10.1038/353129a0

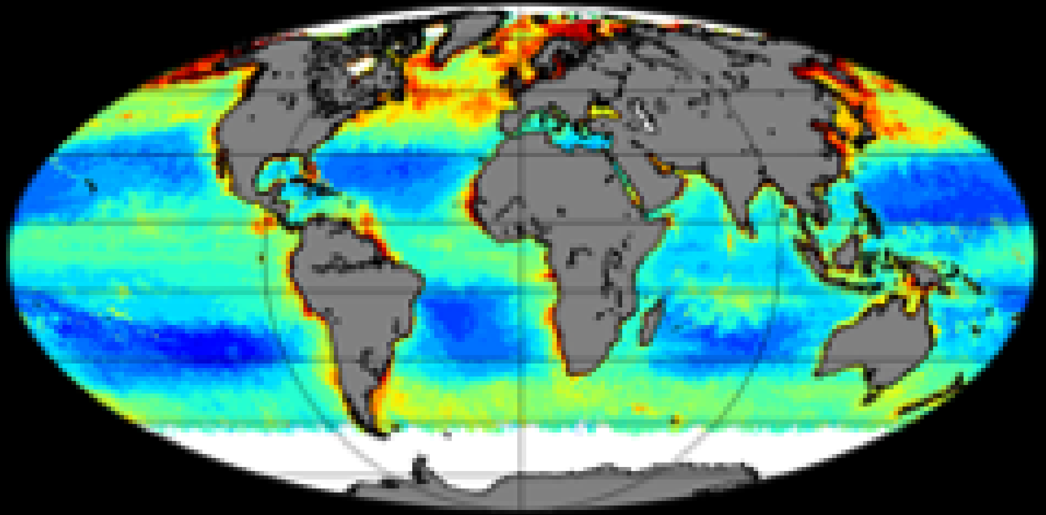
~50 Gt C y^{-1}



Longhurst et al. (1995) https://doi.org/10.1093/plankt/17.6.1245
(see also Antoine et al. (1996) https://doi.org/10.1029/95GB02832;
Behrenfeld and Falkowski, (1997) https://doi.org/10.4319/lo.1997.42.1.0001)

Chlorophyll models

In computing primary production (P) from remote sensing it is common to work with the chlorophyll-normalised variable (P^B), where *B* is chlorophyll. If we know P^B the absolute production P can be recovered through multiplication by *B*



Chlorophyll-a (B)

$$P^B = \frac{P}{[Chl]} \qquad P = P^B[Chl]$$

Chlorophyll models

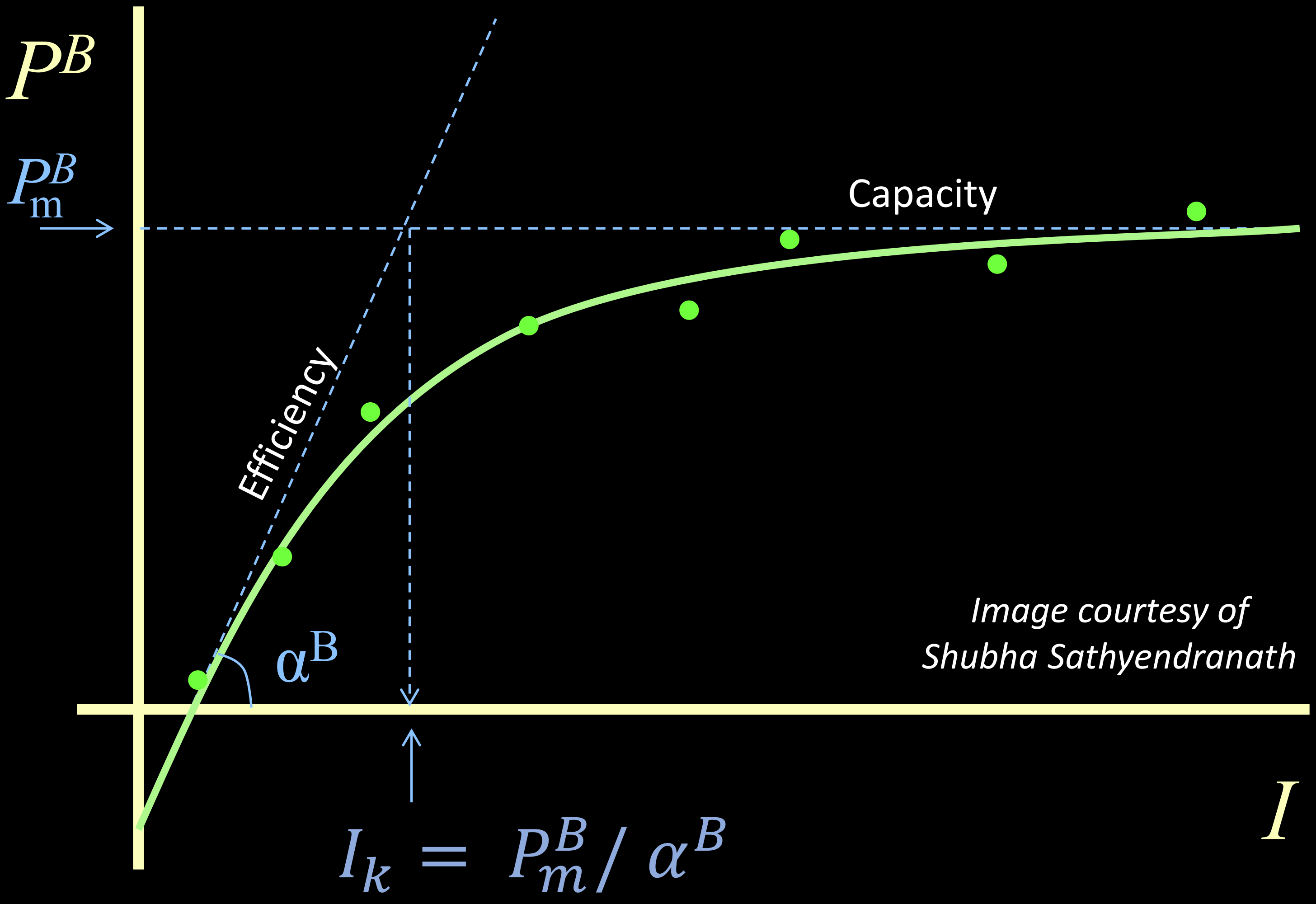
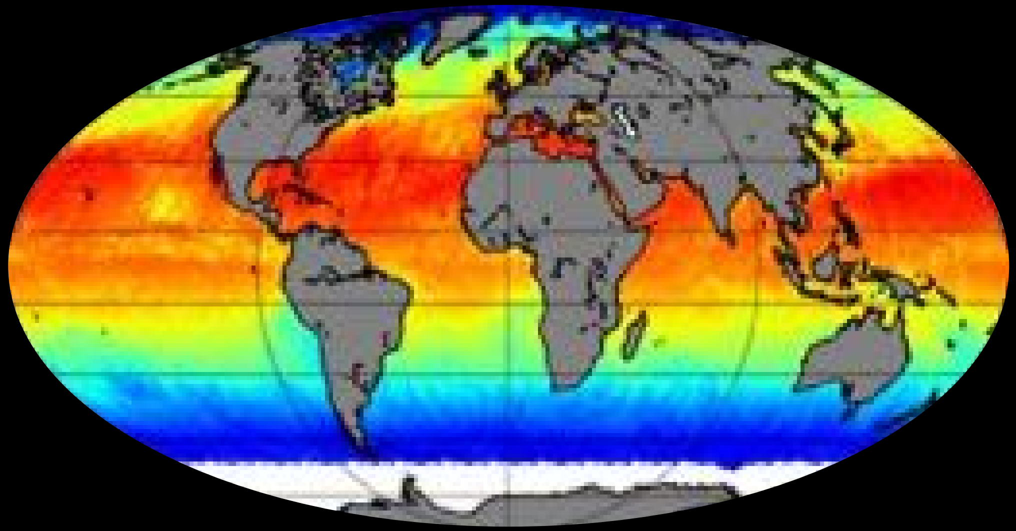


Image courtesy of Shubha Sathyendranath



I (Photosynthetically- Available Radiation, PAR, mol quanta m^{-2} d^{-1})

Platt et al. (1980) J. Mar. Res.
https://images.peabody.yale.edu/publications/jmr/jmr38-04-06.pdf

Chlorophyll models

$$P = P_m^B \left(1 - \exp\left(-\frac{\alpha^B I}{P_m^B}\right)\right)[Chl]$$

$$I_k = \frac{P_m^B}{\alpha^B}$$

$$I_* = \frac{I}{I_k}$$

P_m^B Assimilation number of the light saturation curve

α^B Initial slope of the light saturation curve

I Light

$[Chl]$ Chlorophyll-a concentration

Sathyendranath & Platt (2007)
Oceanologia, 49, 5–39

Chlorophyll models

$$P = P_m^B\left(1 - \exp(-I_*)\right)[Chl]$$

$$I_k = \frac{P_m^B}{\alpha^B}$$

$$I_* = \frac{I}{I_k}$$

P_m^B Assimilation number of the light saturation curve

α^B Initial slope of the light saturation curve

I Light

$[Chl]$ Chlorophyll-a concentration

Sathyendranath & Platt (2007)
Oceanologia, 49, 5–39

Absorption models

$$P = \phi I a_{ph}$$

ϕ	Realised quantum yield
a_{ph}	Spectral average absorption coefficient for phyto
I	Light

Sathyendranath & Platt (2007)
Oceanologia, 49, 5–39

Absorption models

$$P = \phi_m I_k \big(1 - \exp(-I_*)\big) a_{ph}$$

ϕ_m	Realised maximum quantum yield
a_{ph}	Spectral average absorption coefficient for phyto
I	Light

Can transform between chlorophyll and absorption models

$$a_{ph}^* = \frac{a_{ph}}{[Chl]}$$

$$\alpha^B = \phi_m \, a_{ph}^*$$

$$I_k = \frac{P_m^B}{\phi_m a_{ph}^*}$$

Sathyendranath & Platt (2007) Oceanologia, 49, 5–39

Carbon-based models

$$P = \frac{dC}{dt}$$

C Carbon (subscript *i* = initial carbon)

t Time

Sathyendranath & Platt (2007)
Oceanologia, 49, 5–39

Carbon-based models

$$P = gC_i \qquad g = \frac{1}{C_i}\frac{dC}{dt}$$

$$C_i = \chi[Chl]$$

C	Carbon (subscript *i* = initial carbon)
t	Time
g	growth
χ	Carbon to Chlorophyll ratio

Sathyendranath & Platt (2007)
Oceanologia, 49, 5–39

Carbon-based models

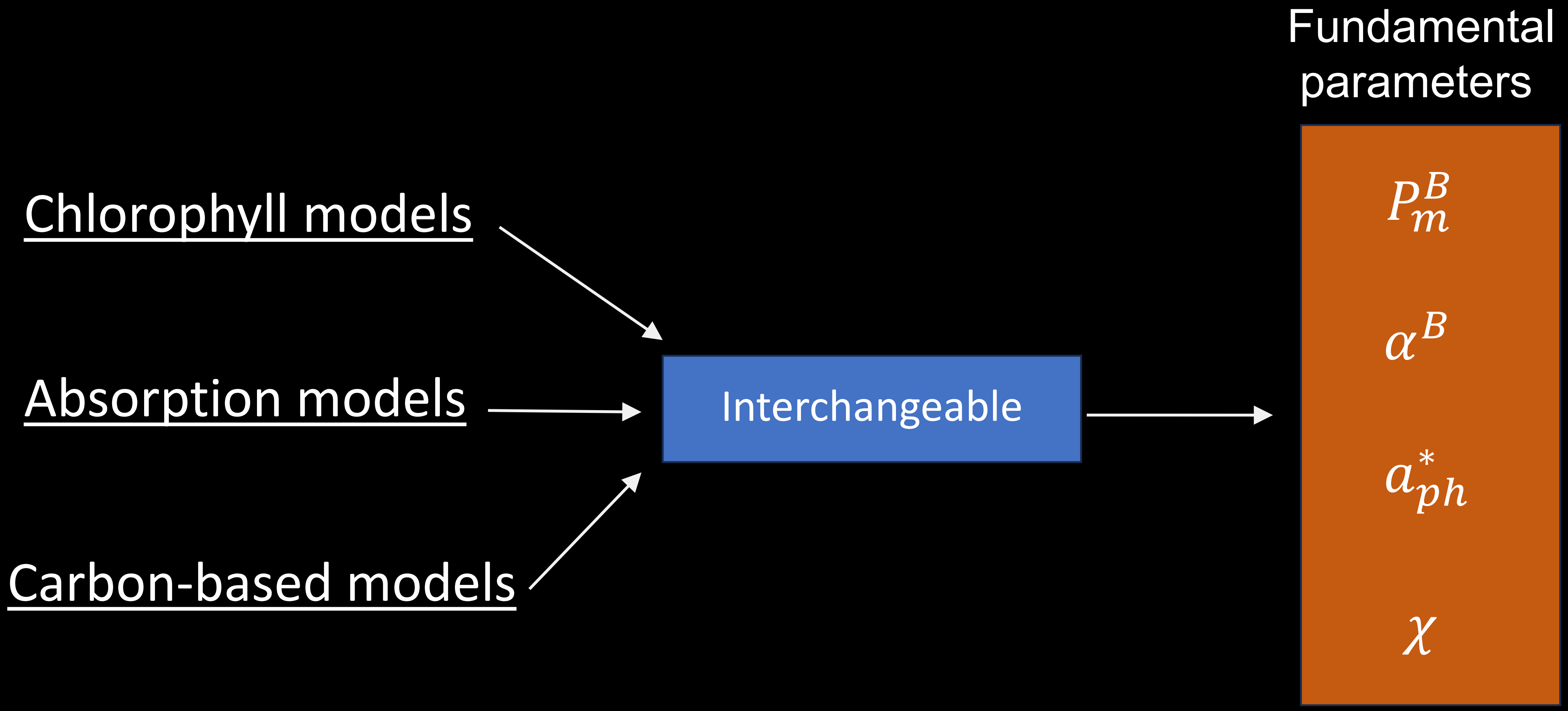
$$P = gC_i \qquad g = \frac{1}{C_i}\frac{dC}{dt} \qquad g = \frac{1}{\chi[Chl]}\frac{dC}{dt}$$

Can transform between chlorophyll and carbon models

$$C_i = \chi[Chl]$$

C	Carbon (subscript *i* = initial carbon)
t	Time
g	growth
χ	Carbon to Chlorophyll ([*Chl*]) ratio

Sathyendranath & Platt (2007) Oceanologia, 49, 5–39



Sathyendranath & Platt (2007) Oceanologia, 49, 5–39

Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z)\left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right)[Chl](z)\ dtdz$$

D	Daylength (h)
Z_p	Euphotic Depth (m)

This simplification does not account directly for spectral variations in light-driven photosynthesis, and assumes photosynthetic parameters and biomass do not change over the day (in reality they can!)

Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z) \left(1 - \exp\left(- \frac{\alpha^B(z) I(z,t)}{P_m^B(z)} \right) \right) [Chl](z) \; dt dz$$

D Day length (D) can be estimated as a simple function of latitude and day of year (e.g. Schoolfield model)

Forsythe et al. (1995) https://doi.org/10.1016/0304-3800(94)00034-F

Chlorophyll model implementation

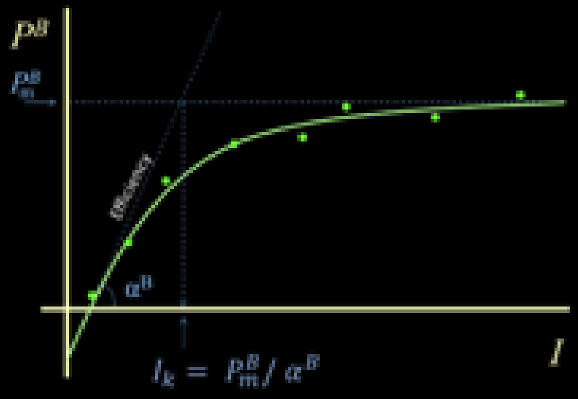
$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z) \left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right) [Chl](z) \; dtdz$$

Z_p Euphotic Depth can be estimated from satellite ocean-colour data

Lee et al. (2007) https://doi.org/10.1029/2006JC003802

Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z) \left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right) [Chl](z)\ dtdz$$



P_m^B

α^B

Satellite derived estimates using SST and *I*

Saux-Picart et al. (2014) https://doi.org/10.1016/j.rse.2013.10.032

Nearest neighbour

Platt et al. (2008) https://doi.org/10.1016/j.rse.2007.11.018

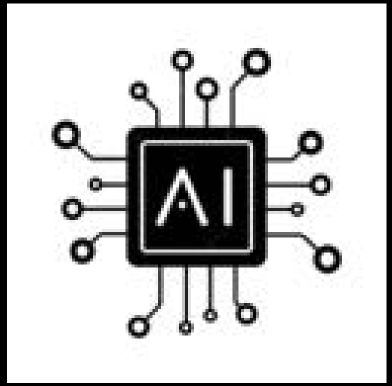
Phytoplankton community structure

Uitz et al. (2008) https://doi.org/10.4319/lo.2008.53.2.0614

Brewin et al. (2017) https://doi.org/10.1016/j.pocean.2017.02.002

Biogeochemical provinces

Kulk et al. (2020) https://doi.org/10.3390/rs12050826



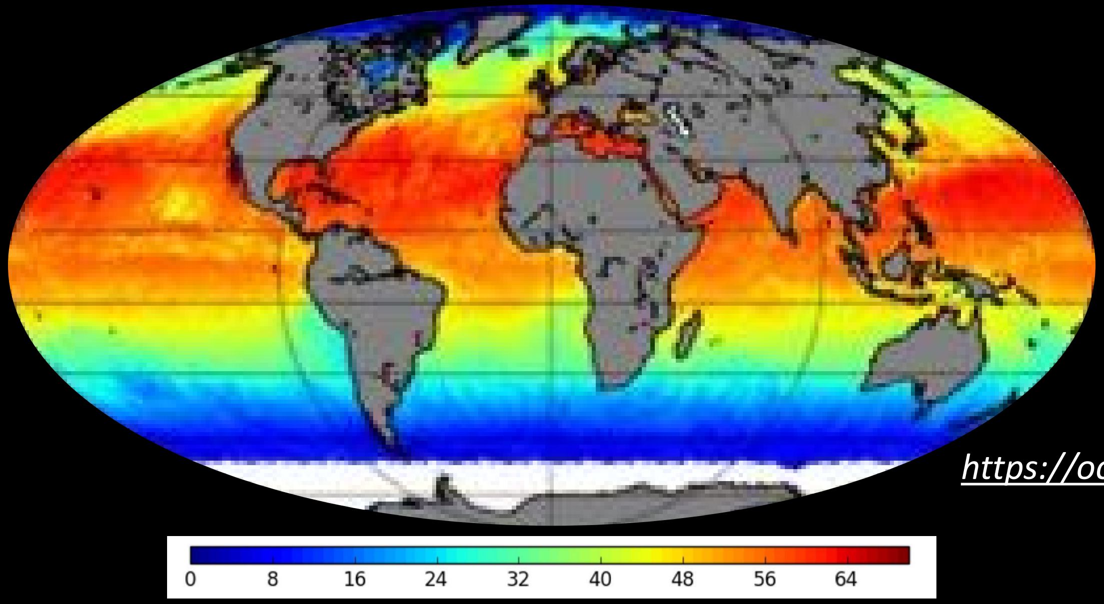
Britten et al. (2025) https://doi.org/10.1002/lol2.70062

Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z)\left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right)[Chl](z)\ dtdz$$

Photosynthetically- Available Radiation
(PAR, mol quanta m^{-2} d^{-1})

I

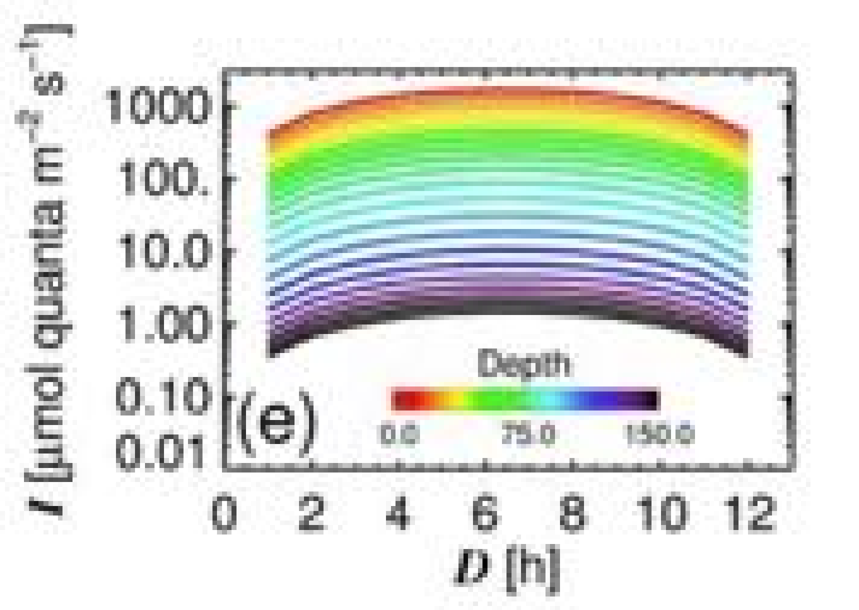


https://oceancolor.gsfc.nasa.gov

Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z)\left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right)[Chl](z)\; dtdz$$

I



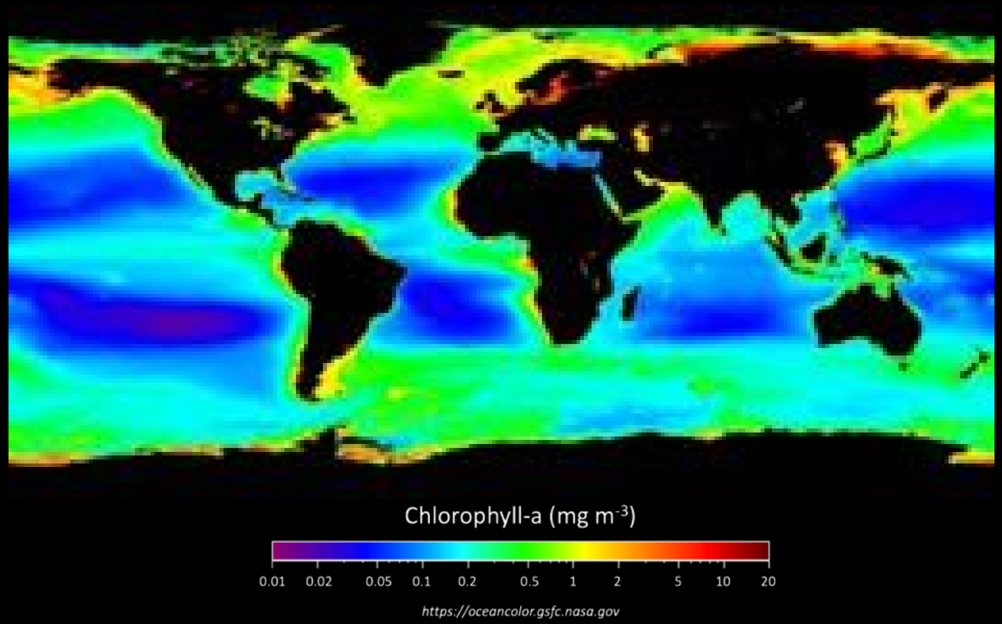
Needs to be broken down into time of day and propagate with depth using vertical profiles of the diffuse attenuation coefficient (K_d)

Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z) \left(1 - \exp\left(- \frac{\alpha^B(z) I(z,t)}{P_m^B(z)} \right) \right) [Chl](z) \; dtdz$$

$[Chl]$

Chlorophyll Biomass (mg m^{-3})

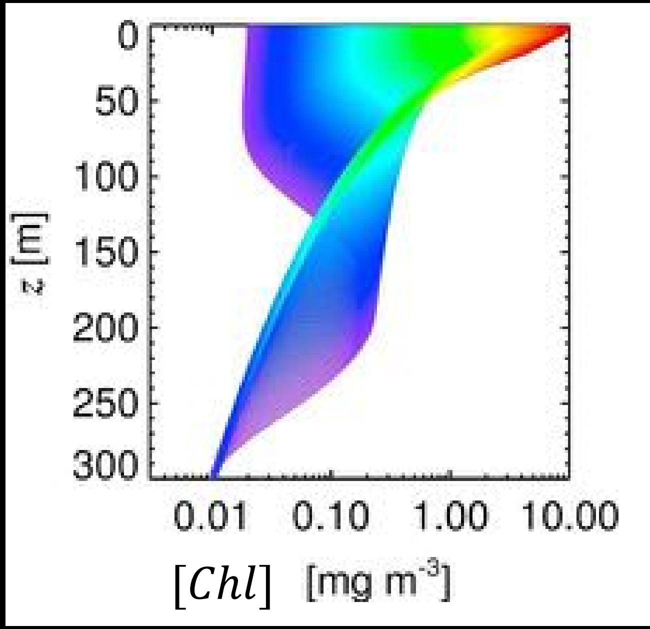


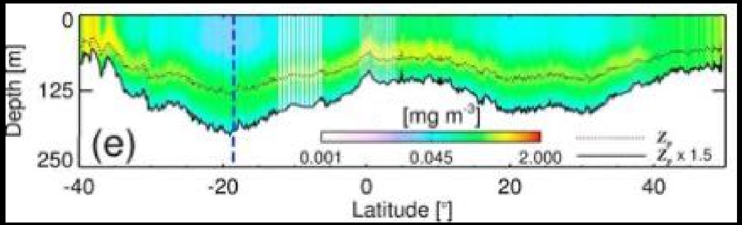
Chlorophyll model implementation

$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z) \left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right) [Chl](z) \; dtdz$$

Chlorophyll Biomass (B, mg m^{-3})

$[Chl]$



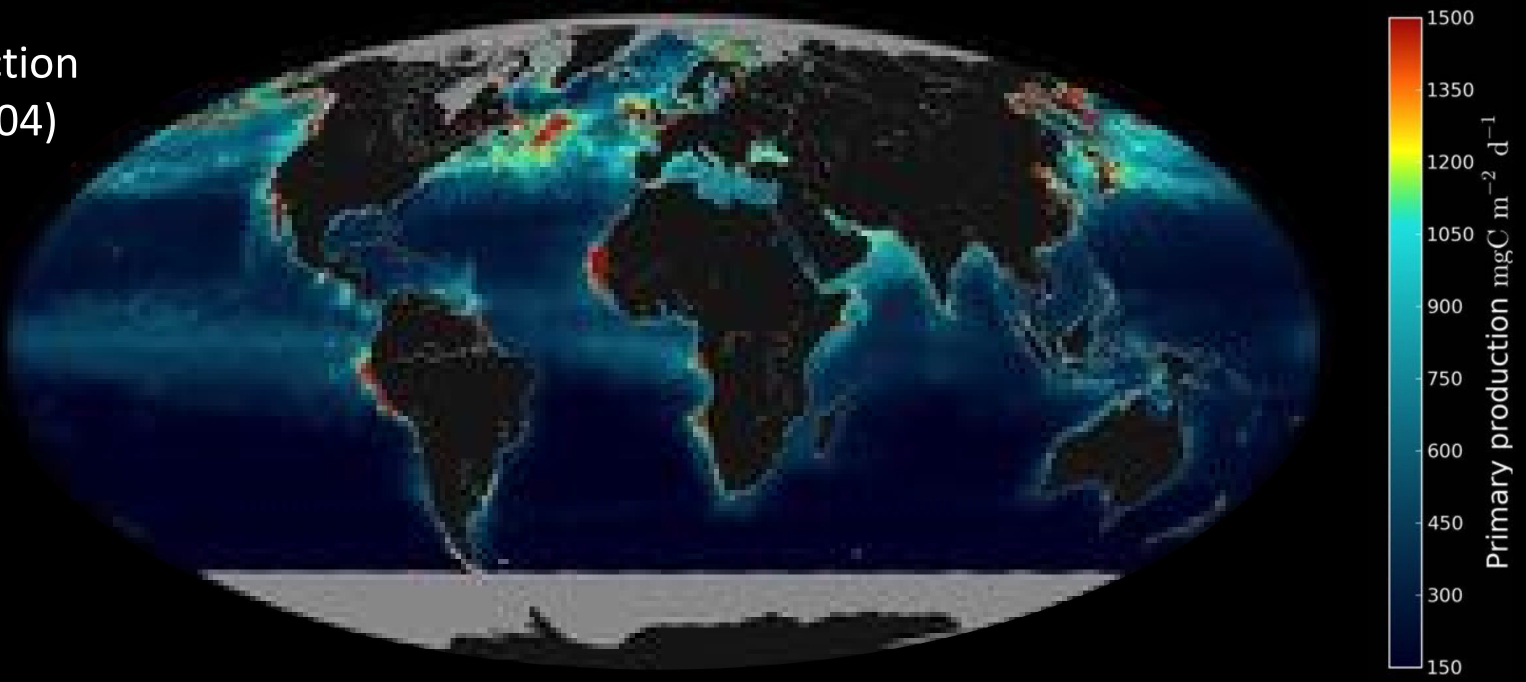


Uitz et al. (2006)
https://doi.org/10.1029/2005JC003207
Brewin et al. (2017)
https://doi.org/10.1016/j.pocean.2017.02.002

Chlorophyll model implementation

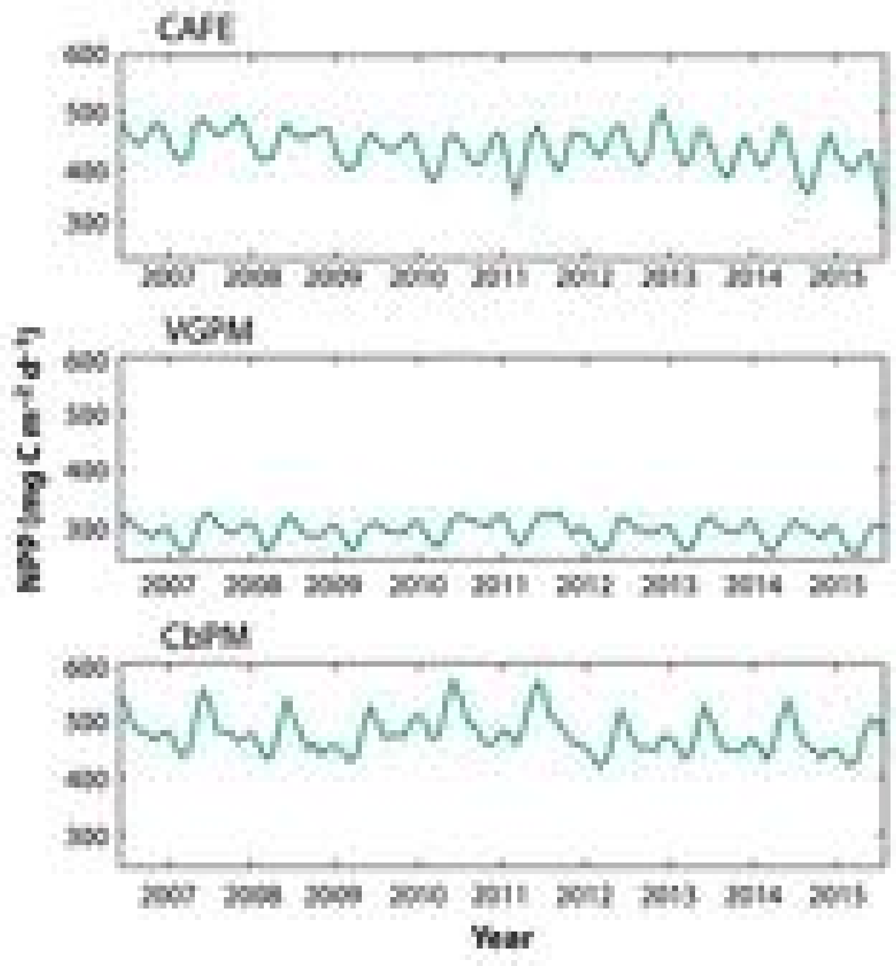
$$P = \int_{t=0}^{D} \int_{z=0}^{Z_p} P_m^B(z)\left(1 - \exp\left(-\frac{\alpha^B(z) I(z,t)}{P_m^B(z)}\right)\right)[Chl](z)\ dtdz$$

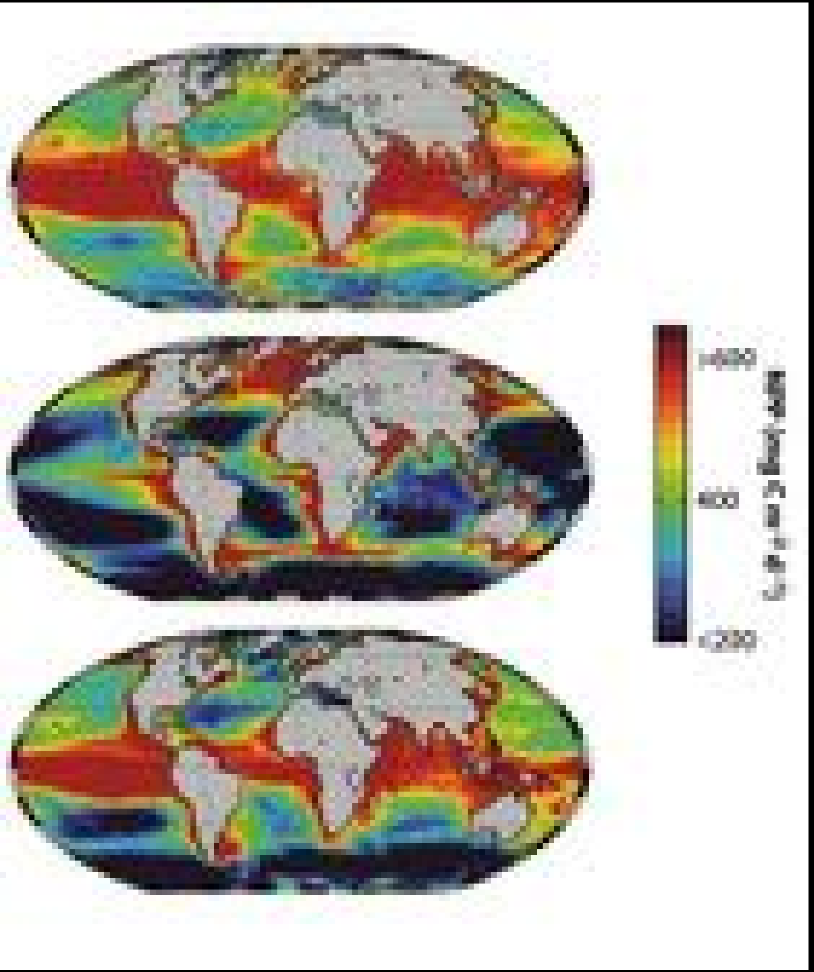
Primary Production
(Global May 2004)

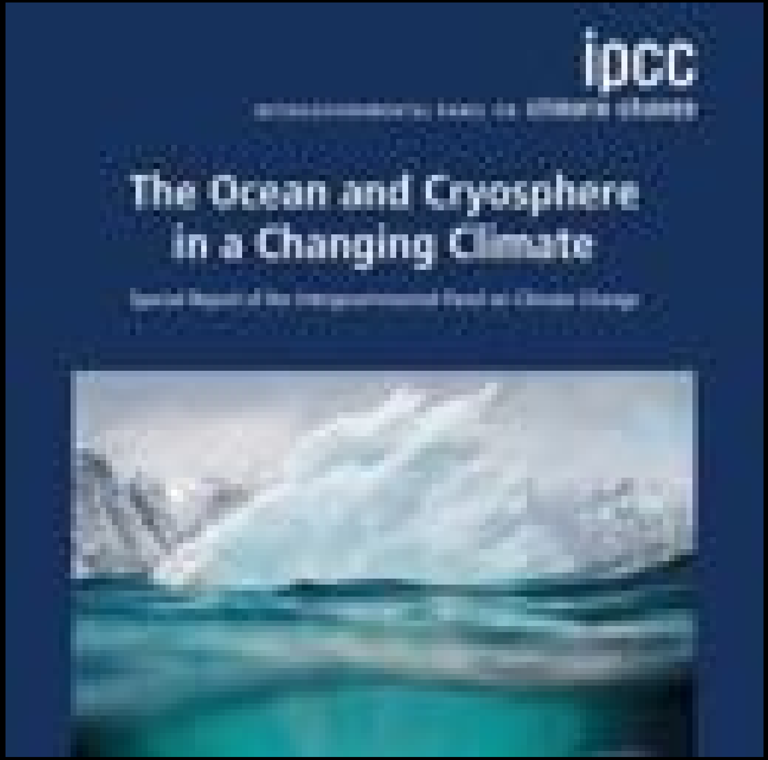


Satellite forcing and model parameters matter!

CHALLENGE







In response to ocean warming and increased stratification, open ocean nutrient cycles are being perturbed and there is *high confidence* that this is having a regionally variable impact on primary producers. There is currently *low confidence* in appraising past open ocean productivity trends, including those determined by satellites, due to newly identified region-specific drivers of microbial growth and the lack of corroborating *in situ* time series datasets. {5.2.2.5, 5.2.2.6}

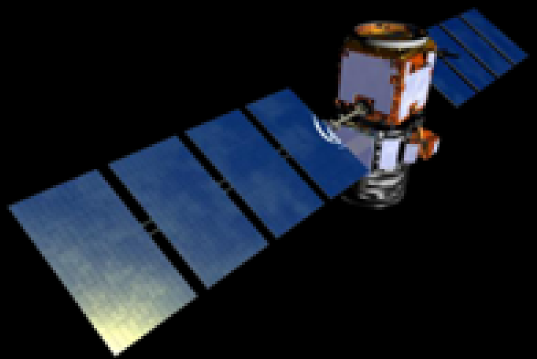
Siegel et al. (2023) https://doi.org/10.1146/annurev-marine-040722-115226
see also Westberry et al. (2023) https://doi.org/10.1016/j.earscirev.2023.104322

New observations (space and *in situ*)

OPPORTUNITY

PACE

earthcare



GLIMR

IOCCG Working Group on Primary Production (Report in progress)

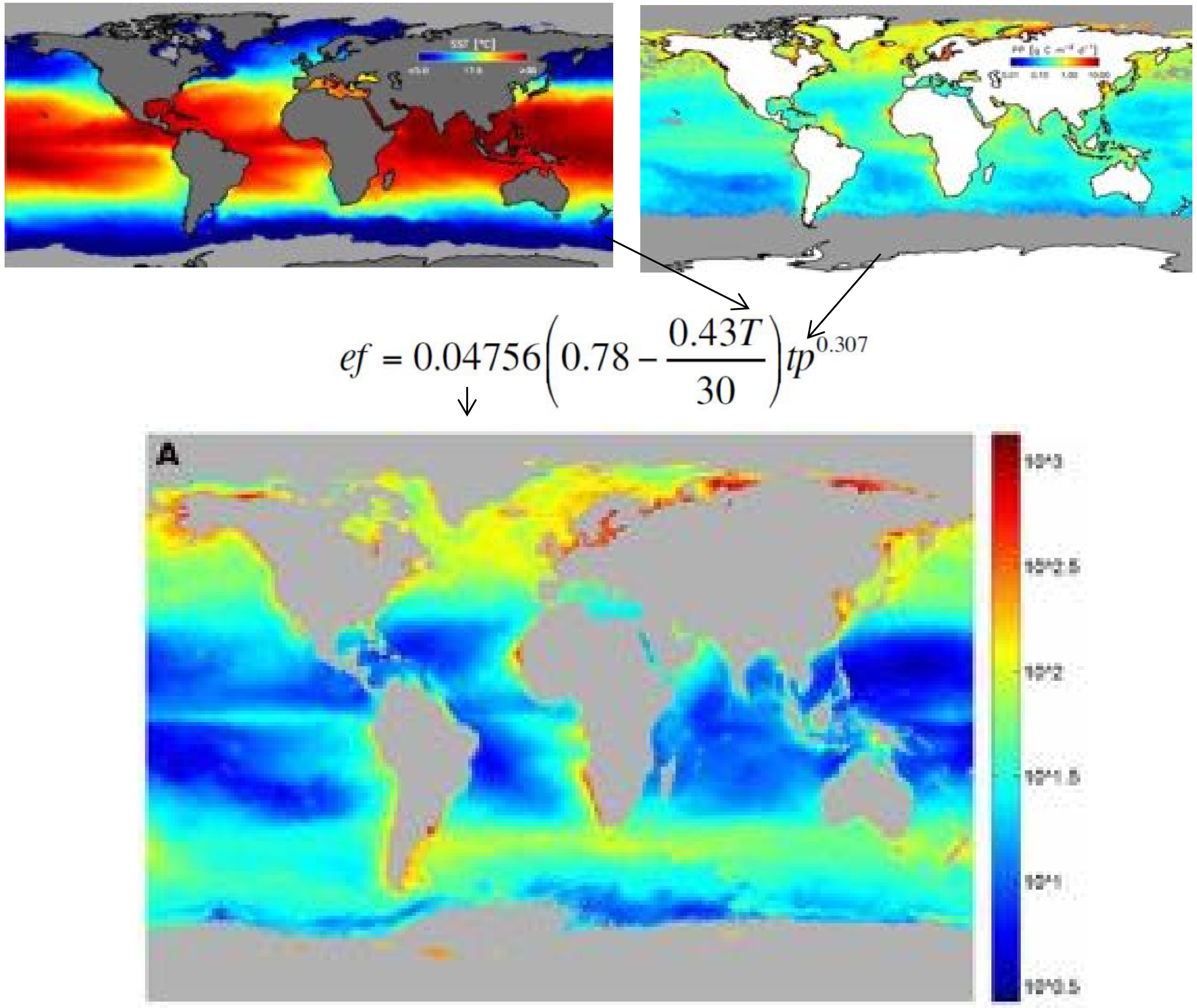
Export production in the ocean is net primary production transported out of the sunlit surface layer (the euphotic zone) into the deeper ocean.

Empirical methods

Methods can be traced back to early work where proxies of export (e.g. the ratio of new production to total production, defined as the f-ratio, or particle fluxes from sediment traps) were empirically related to primary production, chlorophyll-a concentration and depth, or to nutrient concentrations.

Eppley and Peterson (1979) https://doi.org/10.1038/282677a0; Suess (1980 https://doi.org/10.1038/288260a0 ; Betzer et al. (1984) https://doi.org/10.1016/0198-0149(84)90068-2; Pace et al. (1987) https://doi.org/10.1038/325803a0 ; Wassman (1990) https://doi.org/10.4319/lo.1990.35.2.0464; Platt and Harrison, (1985) https://doi.org/10.1038/318055a0 Harrison et al. (1987) https://doi.org/10.1093/plankt/9.1.235

One of the first techniques, that directly used satellite data, was proposed by Laws et al. (2000, 2011) *Laws et al. (2000) https://doi.org/10.1029/1999GB001229 Laws et al. (2011) https://doi.org/10.4319/lom.2011.9.593*



$$ef = 0.04756\left(0.78 - \frac{0.43T}{30}\right)tp^{0.307}$$

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

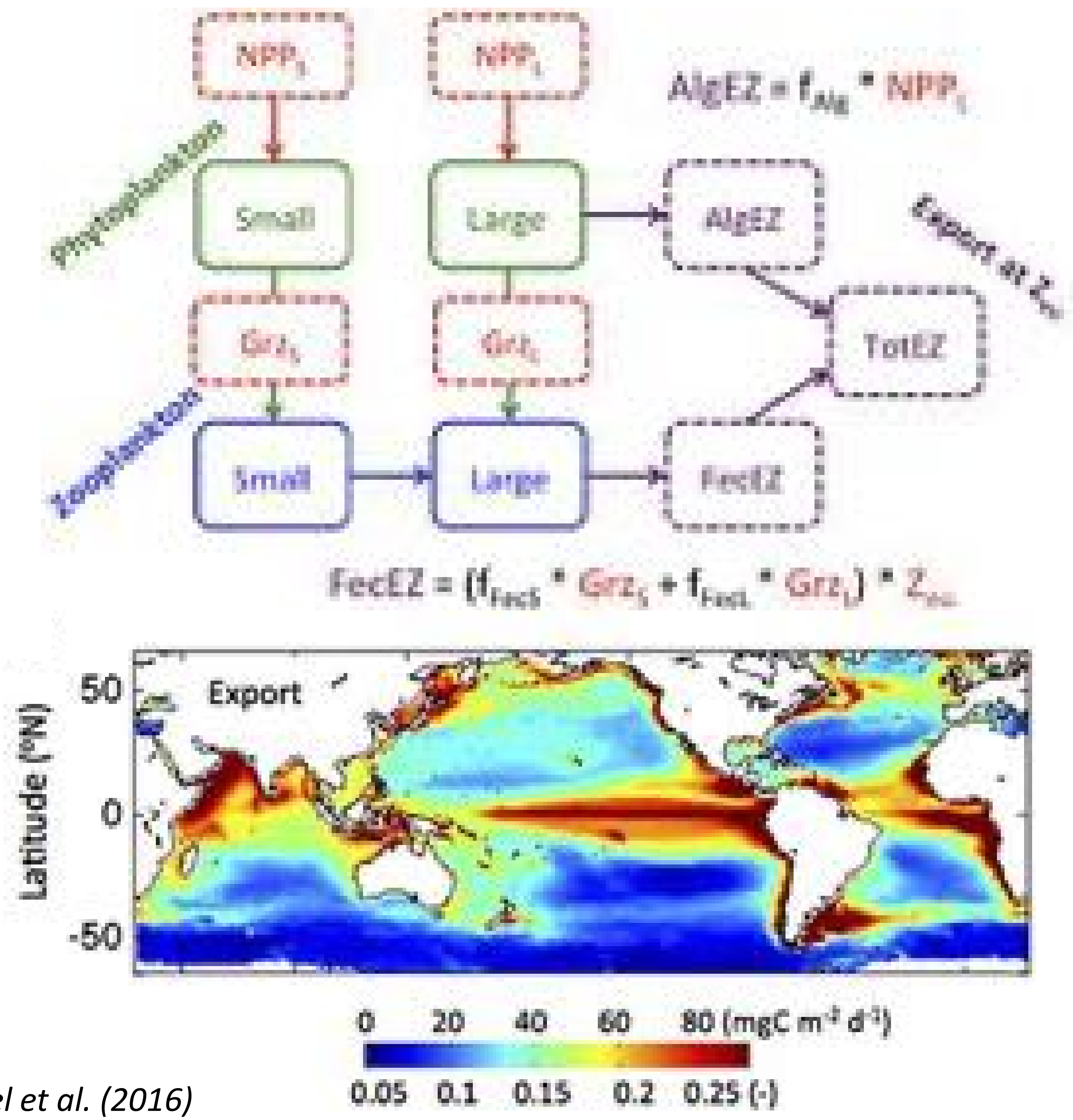
Other satellite-based empirical algorithms have been presented, for example:

Dunne et al. (2005) modelled as an empirical function of SST, chlorophyll-a and primary production
https://doi.org/10.1029/2004GB002390

Henson et al. (2011) as an empirical function of SST and primary production
https://doi.org/10.1029/2011GL046735

Empirical approaches are, by their very nature

Stukel et al., 2015 https://doi.org/10.1002/2015jc011264
Palevsky et al., 2016 https://doi.org/10.1002/2016gl070226



Siegel et al. (2016)
https://doi.org/10.3389/fmars.2016.00022

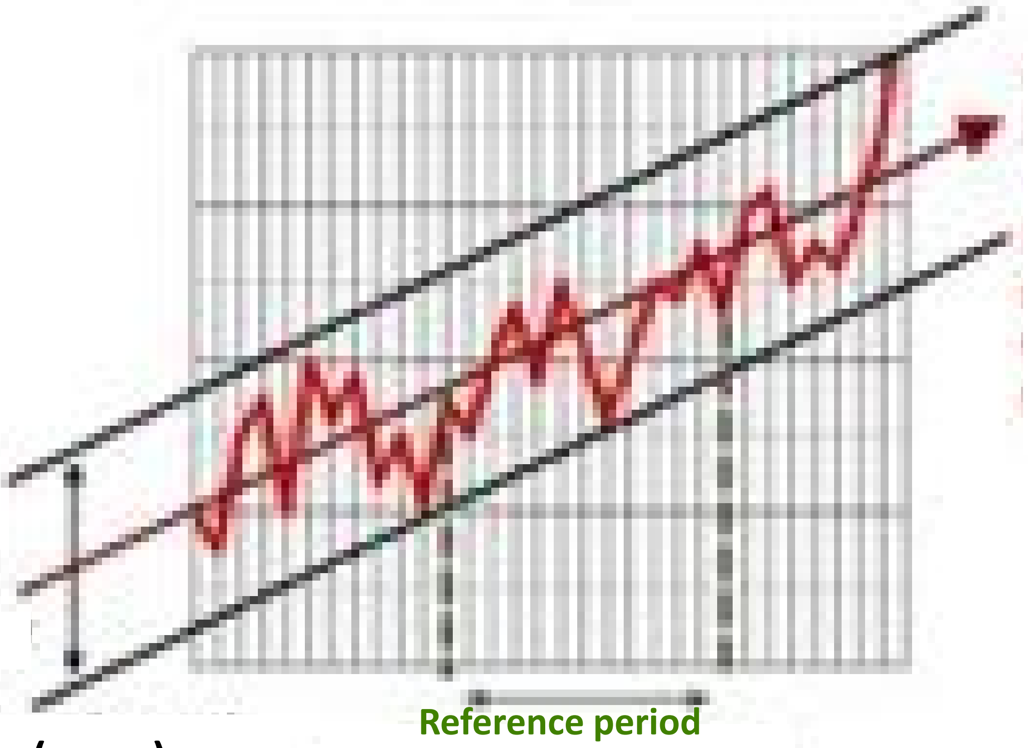
Simple food-web based models, driven by satellite observations, that are more mechanistic in nature than the empirical approaches, have also been proposed as a means for estimating EP from space.

See review by Jönsson et al. (2023)
https://doi.org/10.3389/fmars.2023.1149938

ML

BIO CARBON

EXPORTS
EXport Processes in the Ocean from RemoTe Sensing



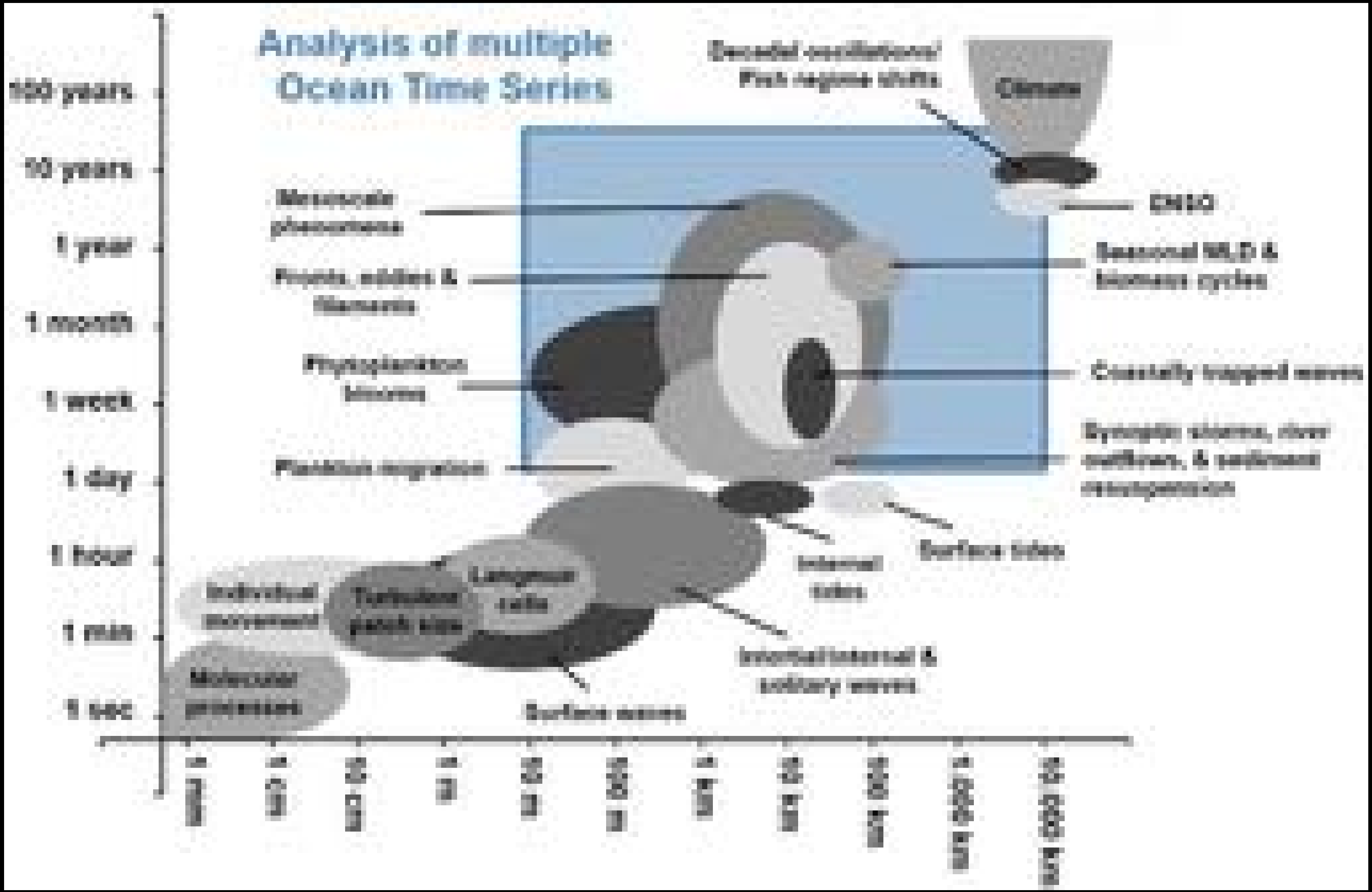
Climate change

Long-term: (multi-decadal to century)
Persistent rise or fall in either the mean state of the climate or in its variability for an extended period

Climate variability

Short-term: (years)
rises and falls about the mean state of the climate

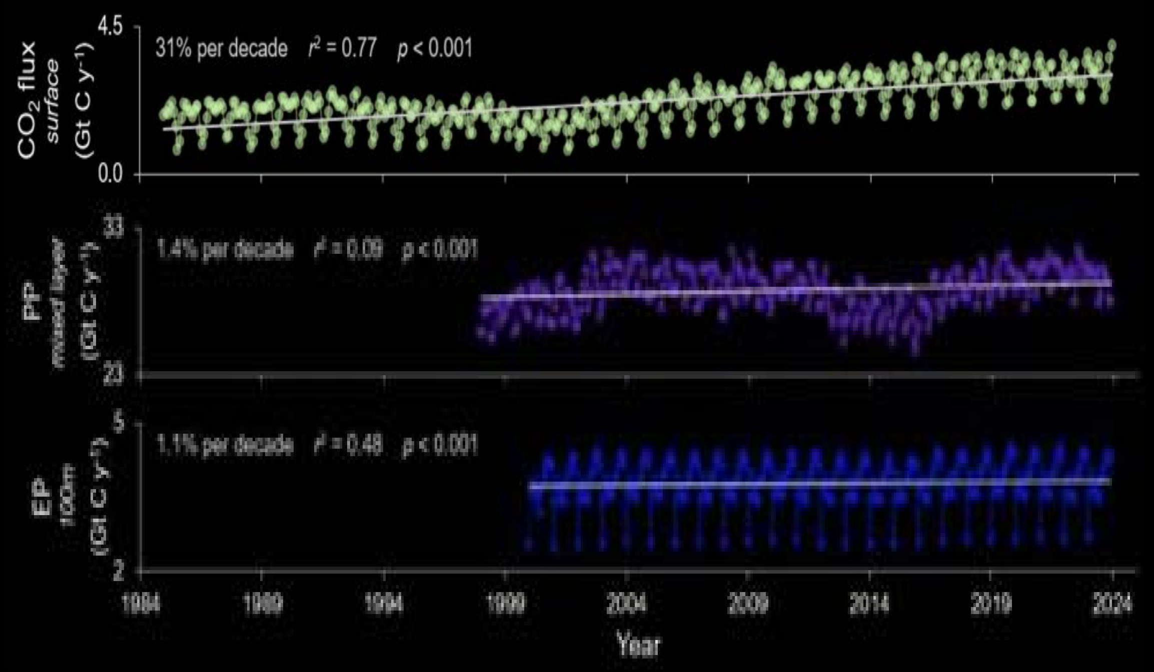
Adapted from E. Barrow, http://www.cccsn.ec.gc.ca
With help from Marie-Fanny Racault (PML, UEA)



Benway et al. (2019) https://doi.org/10.3389/fmars.2019.00393

Continued investment in climate data records

SCOPE



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

Journal of Remote Sensing
A SCIENCE PARTNER JOURNAL

RESEARCH ARTICLE

Cross-Satellite Atmospheric Correction for Consistent Remote Sensing Reflectance from Multiple Ocean Color Satellites: Concept and Demonstrations

Zhongping Lee[1*†], Tianhao Wang[1†], Longteng Zhao[1], Daosheng Wang[1], Xiaomin Ye[2], Shaoling Shang[1], and Xiaolong Yu[1*]

IOCCG International Ocean Colour Coordinating Group

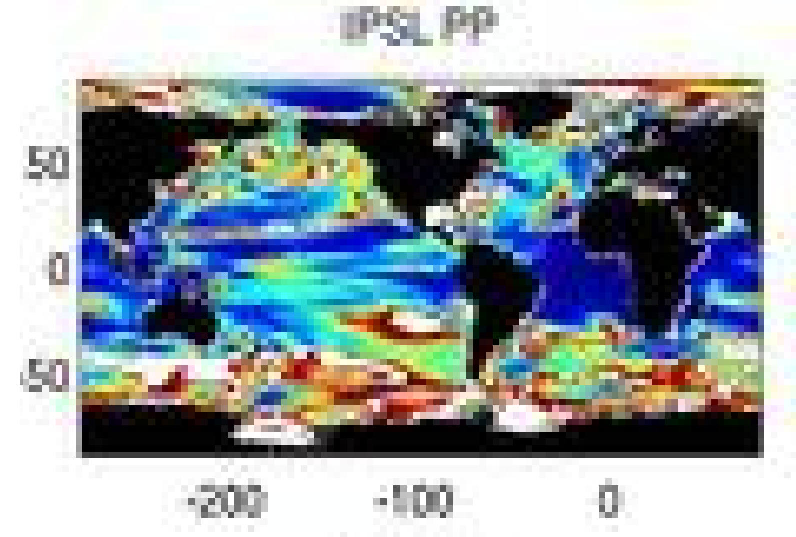
New Task force – Harmonizing Global Ocean Colour for Long-Term Climate and Ecosystem monitoring

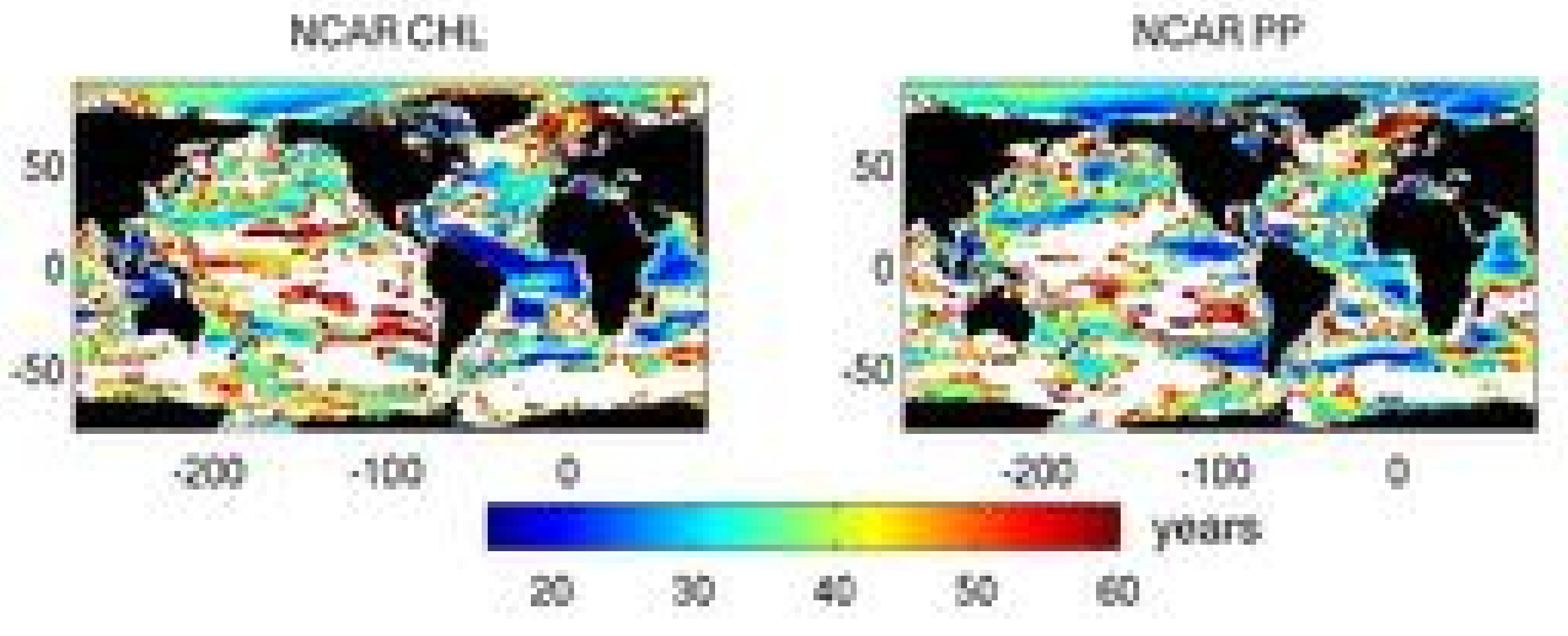
Biogeosciences, 7, 621–640, 2010
www.biogeosciences.net/7/621/2010/

Biogeosciences

Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity

S. A. Henson[1,*], J. L. Sarmiento[1], J. P. Dunne[2], L. Bopp[3], I. Lima[4], S. C. Doney[4], J. John[2], and C. Beaulieu[1]





Our analyses suggest that a time series of ~ 40 years length is needed to distinguish a global warming trend from natural variability

Henson et al .(2010)
https://doi.org/10.5194/bg-7-621-2010

Responses of the marine ecosystem to a changing climate focused on phytoplankton

- The total amount of phytoplankton might change
- The community structure of phytoplankton might change
- The physiology of phytoplankton might change
- The phenology of phytoplankton might change
- The geographical distribution of phytoplankton might change
- The vertical distribution of phytoplankton might change

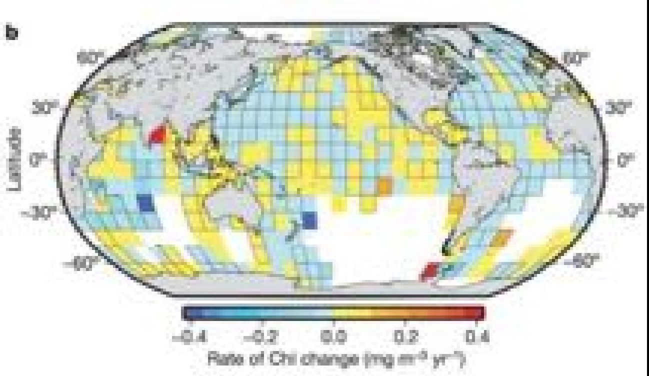
Sathyendranth et al. (2017) https://doi.org/10.1016/j.rse.2017.04.017

Vol 466 | 29 July 2010 | doi:10.1038/nature09268 — nature

ARTICLES

Global phytoplankton decline over the past century

Daniel G. Boyce[1], Marlon R. Lewis[2] & Boris Worm[1]



OCEANOGRAPHY

Century of phytoplankton change

David A. Siegel and Bryan A. Franz

Phytoplankton biomass is a crucial measure of the health of ocean ecosystems. An impressive synthesis of the relevant data, stretching back to more than 100 years ago, provides a connection with climate change.

nature

Does blending of chlorophyll data bias temporal trend?

Abstract

nature

A measured look at ocean chlorophyll trends

Abstract

nature

Is there a decline in marine phytoplankton?

Abstract

LIMNOLOGY and OCEANOGRAPHY: METHODS

Integrating global chlorophyll data from 1890 to 2010

Daniel G. Boyce, Marlon Lewis, and Boris Worm*

Abstract

Contents lists available at ScienceDirect

Progress in Oceanography

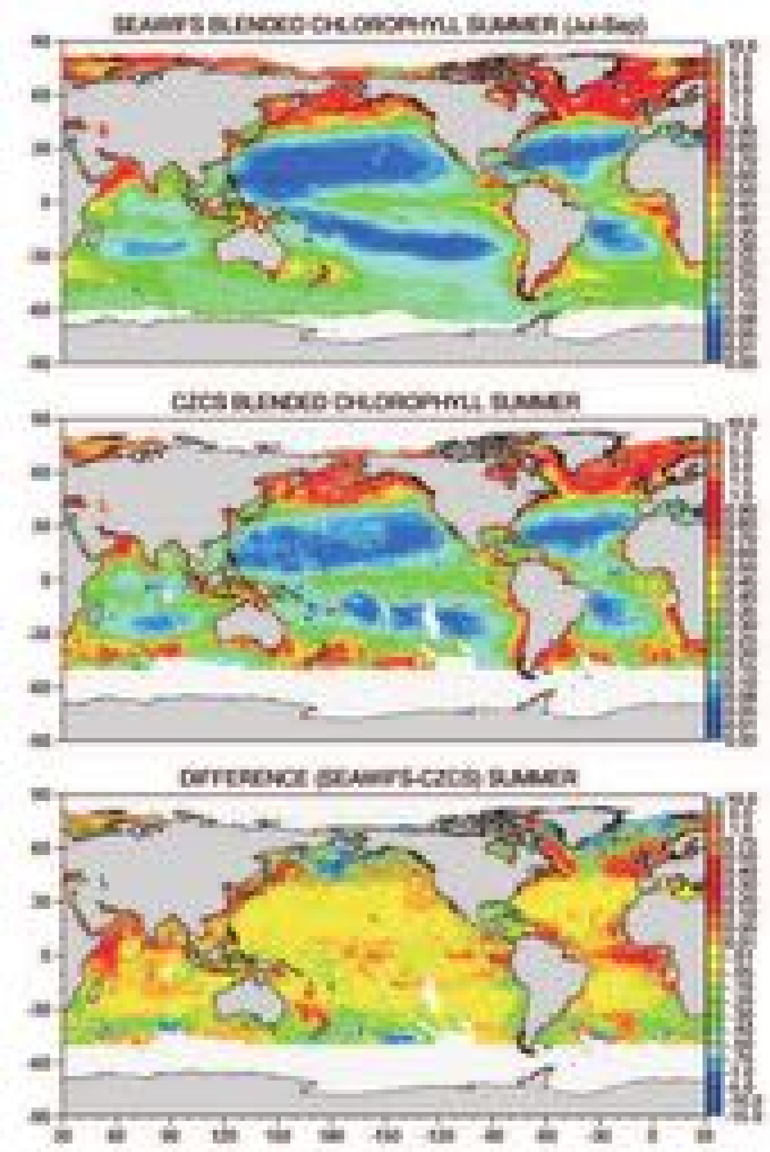
journal homepage: www.elsevier.com/locate/pocean

ELSEVIER

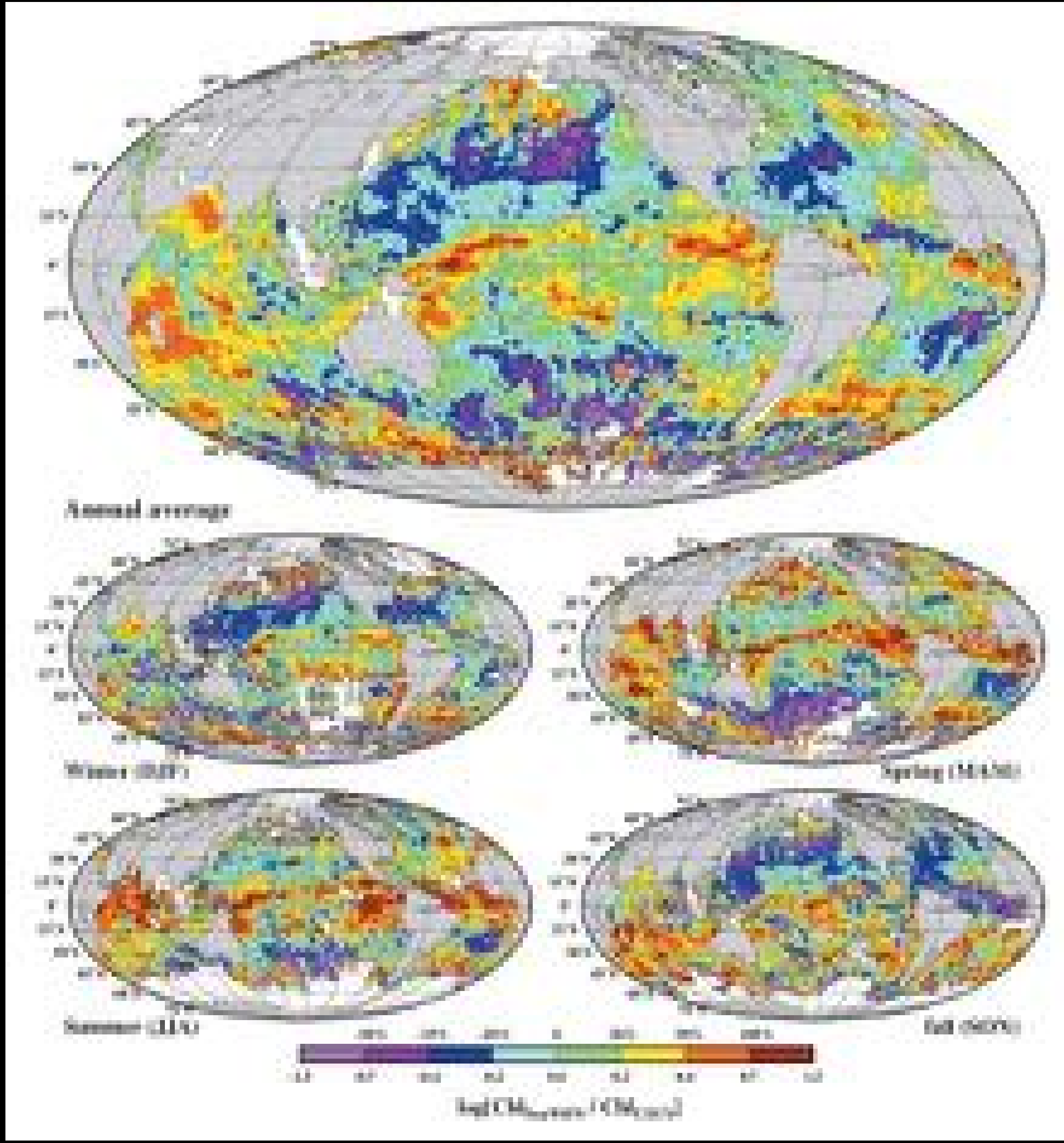
Estimating global chlorophyll changes over the past century

Daniel G. Boyce[a,b,c,*], Michael Dowd[d], Marlon R. Lewis[c], Boris Worm[a]

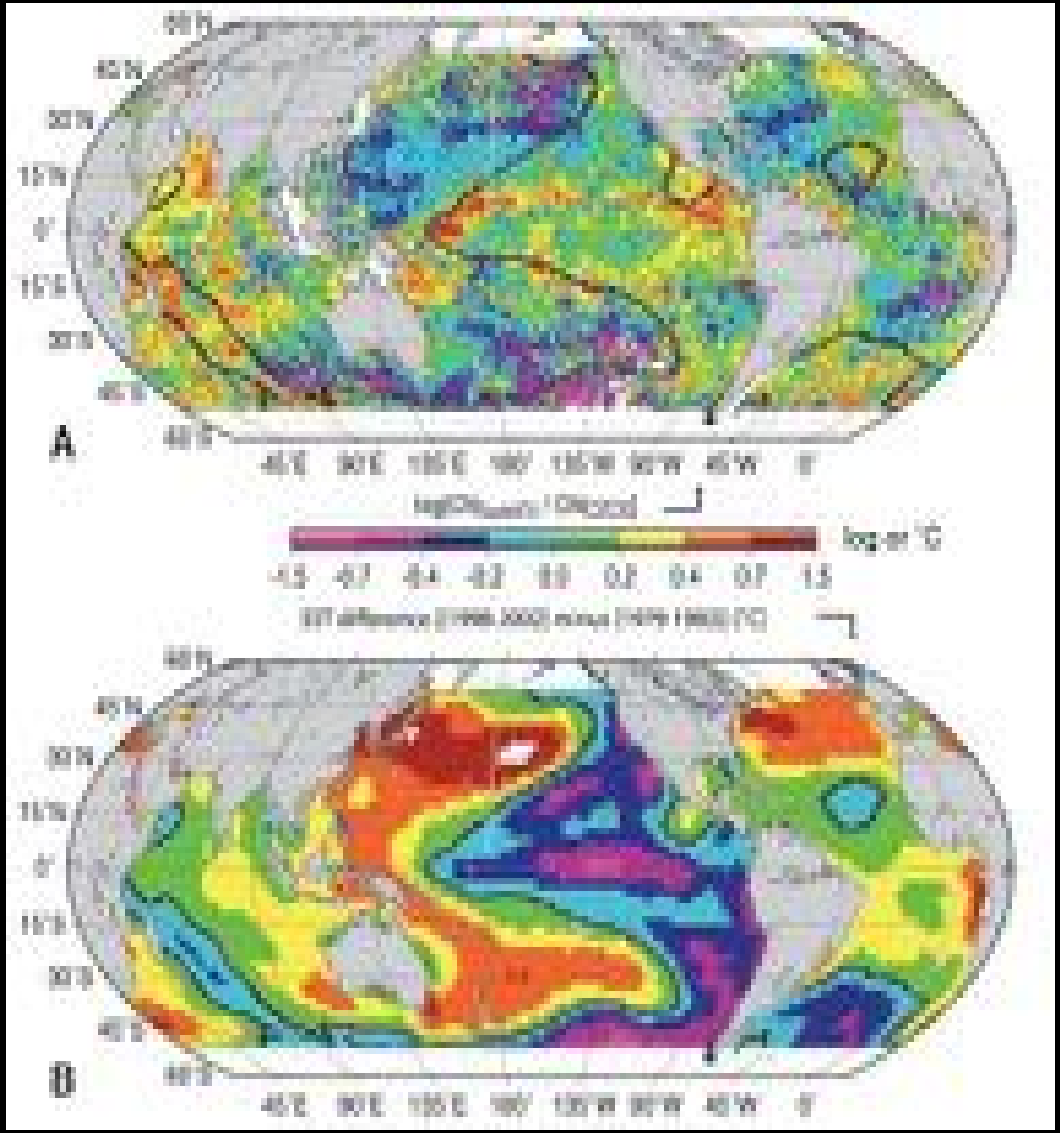
"The analyses of Boyce *et al.* document the historical record. Looking into the future, however, satellite measurements will be the main source of data for assessing change in pelagic ecosystems."



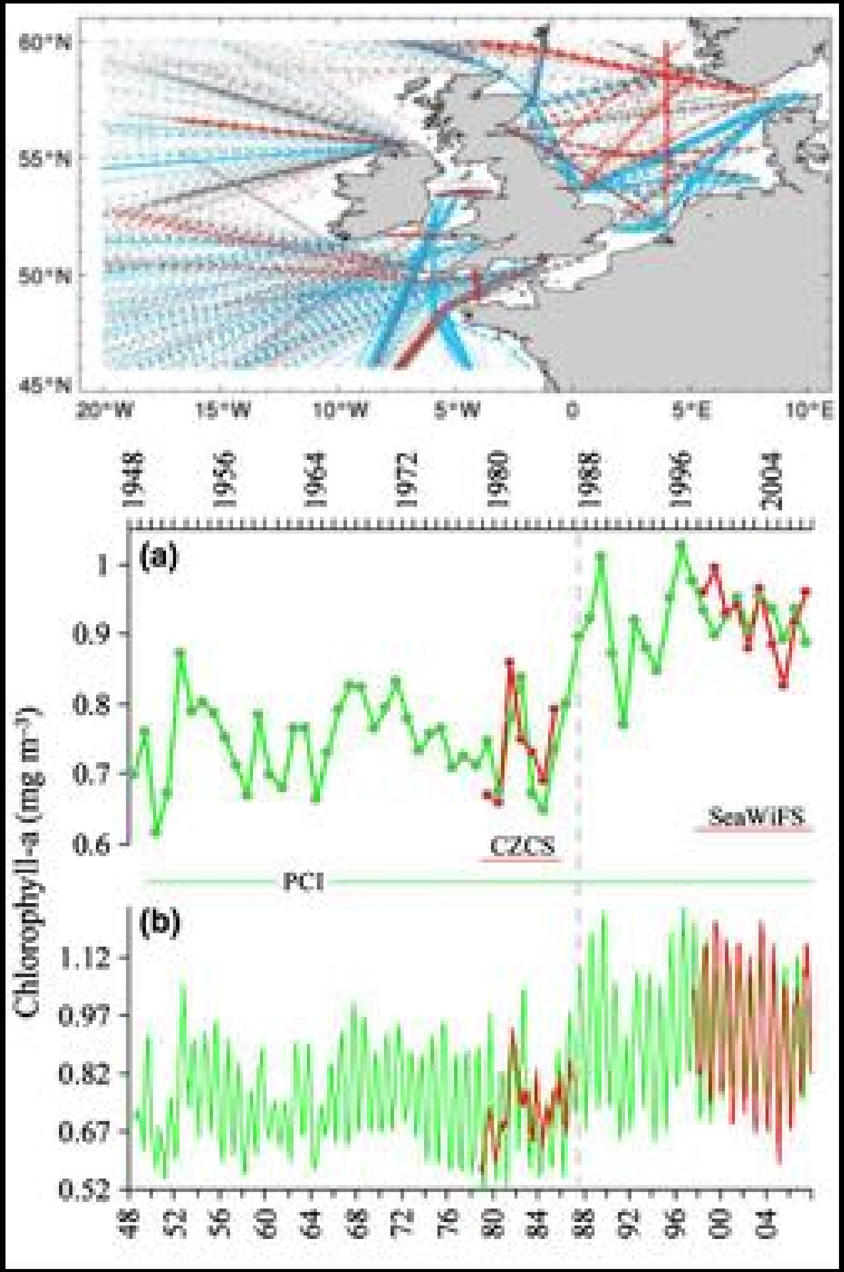
Gregg & Conkright (2002)
https://doi.org/10.1029/2002GL014689



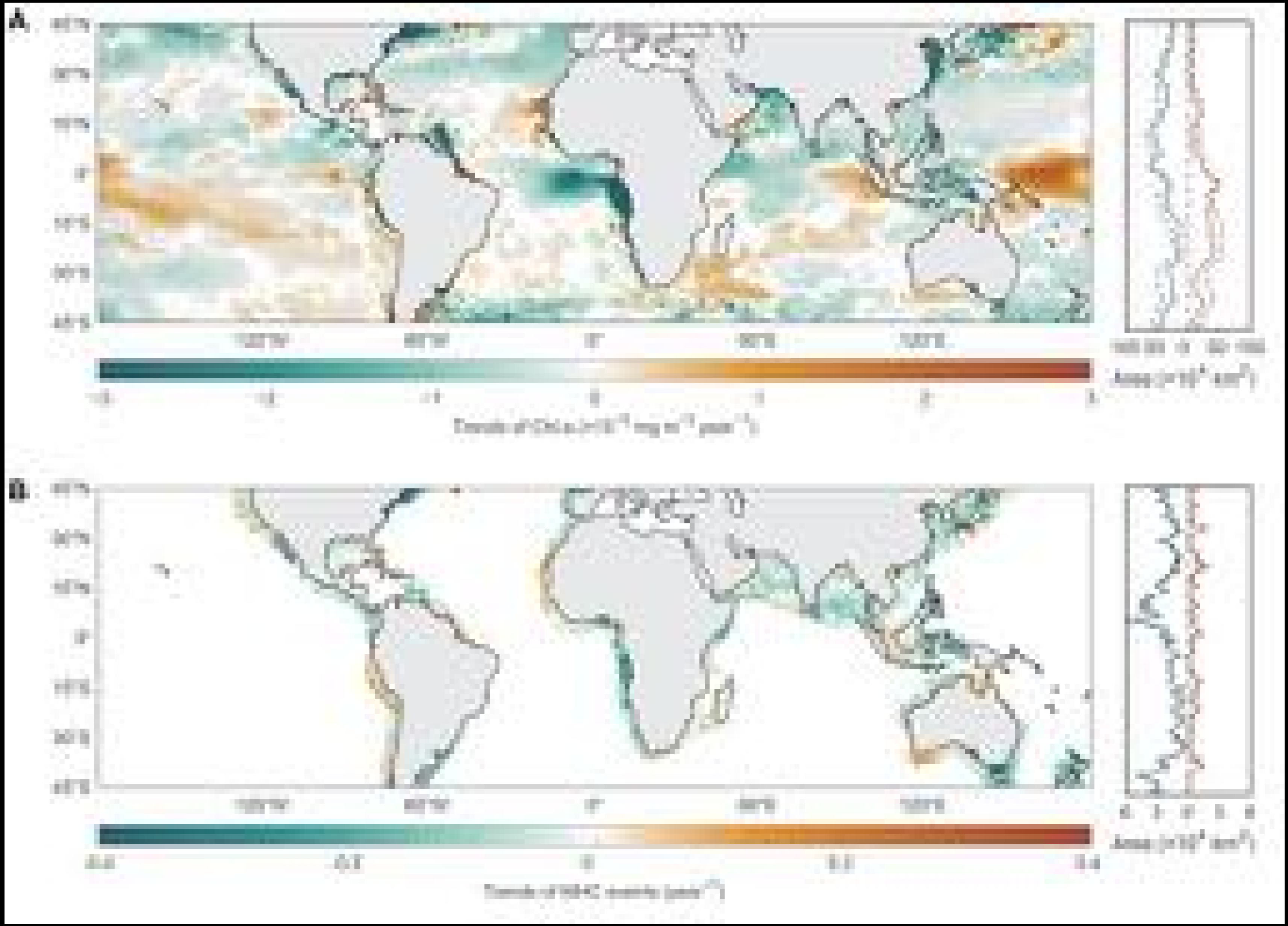
Antoine et al. (2005)
https://doi.org/10.1029/2004JC002620



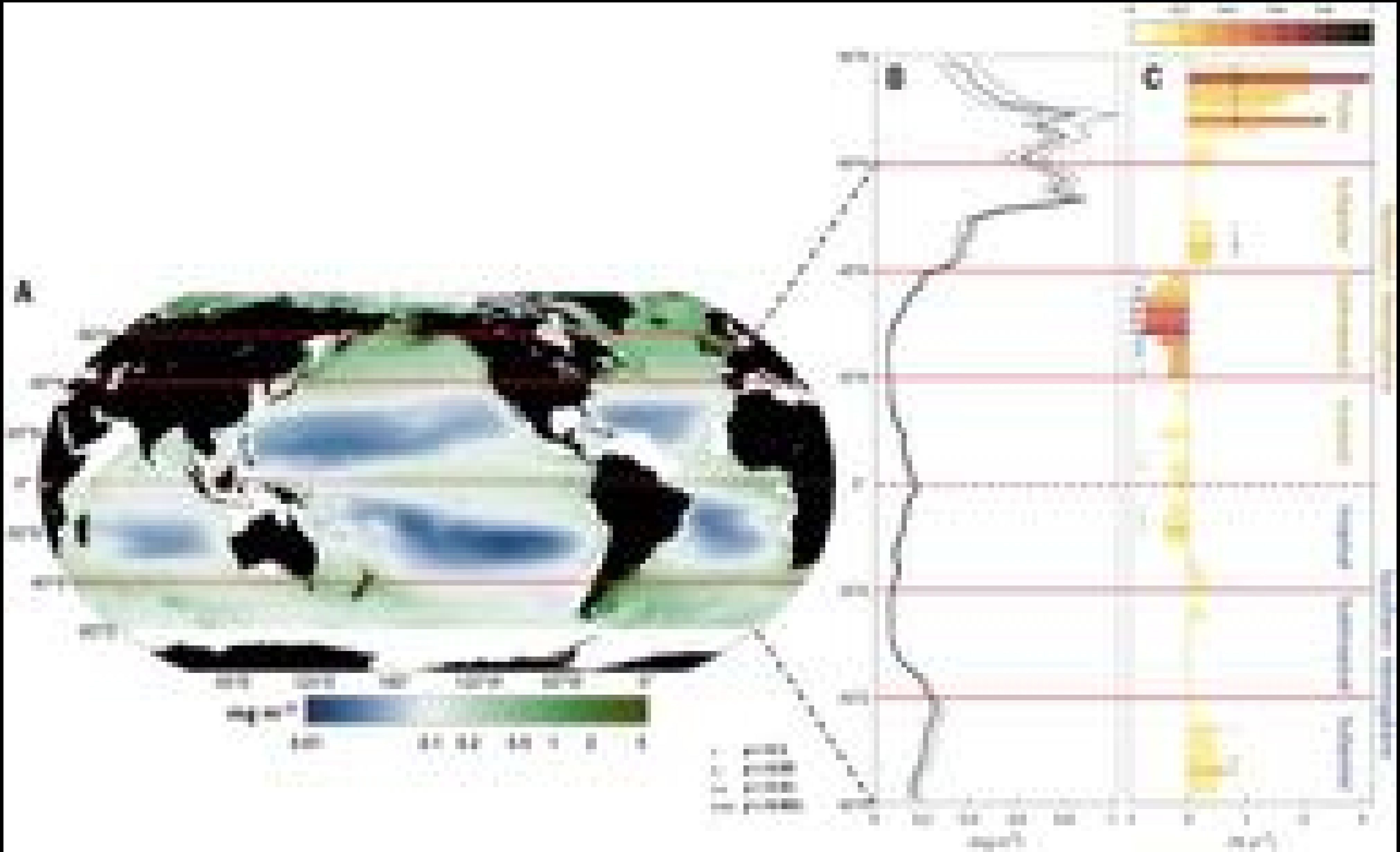
Martinez et al. (2009)
https://doi.org/10.1126/science.1177012



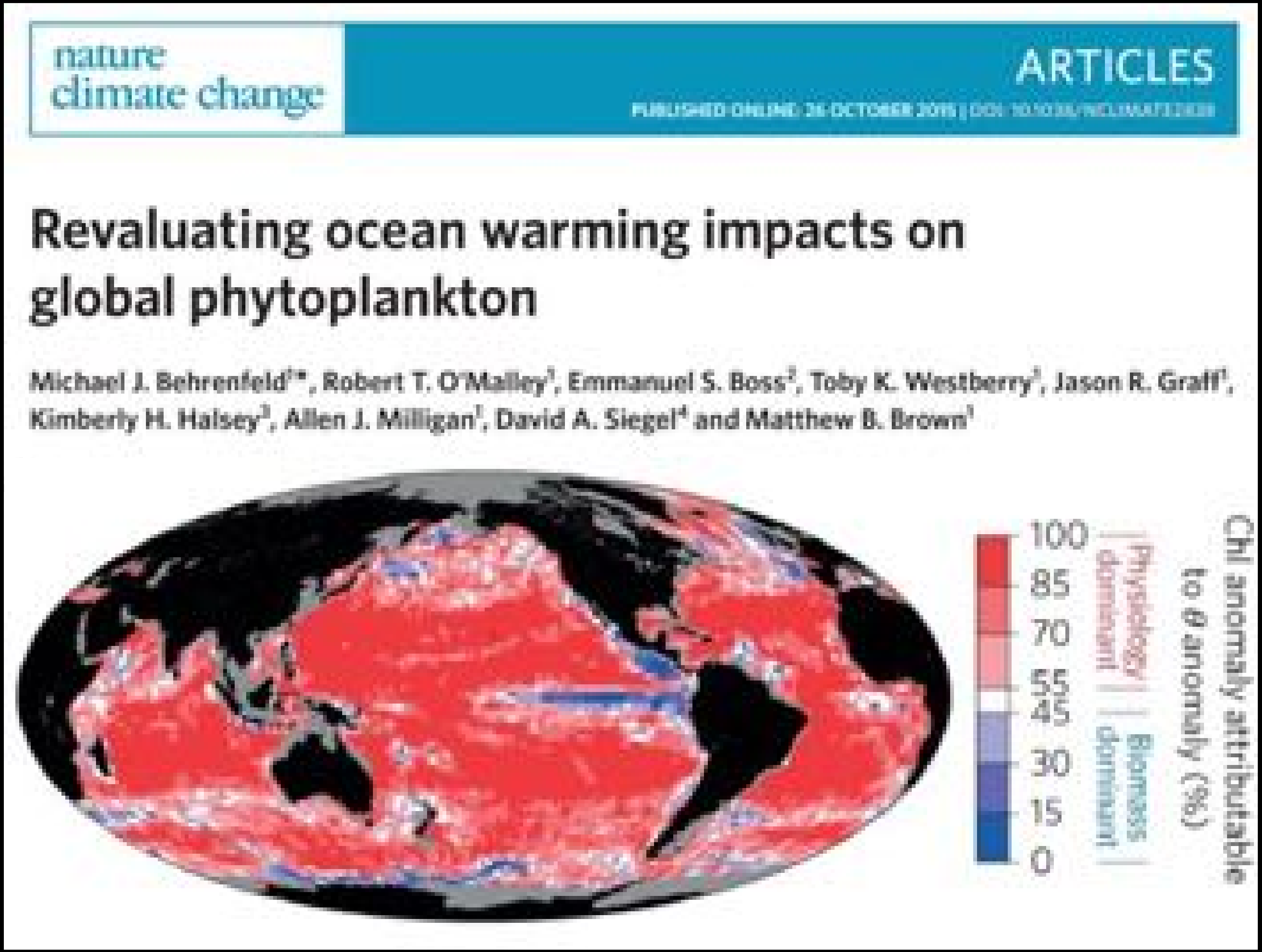
Raitsos et al. (2013)
https://doi.org/10.1111/gcb.12457



Hong et al. (2025) https://doi.org/10.1126/sciadv.adx4857

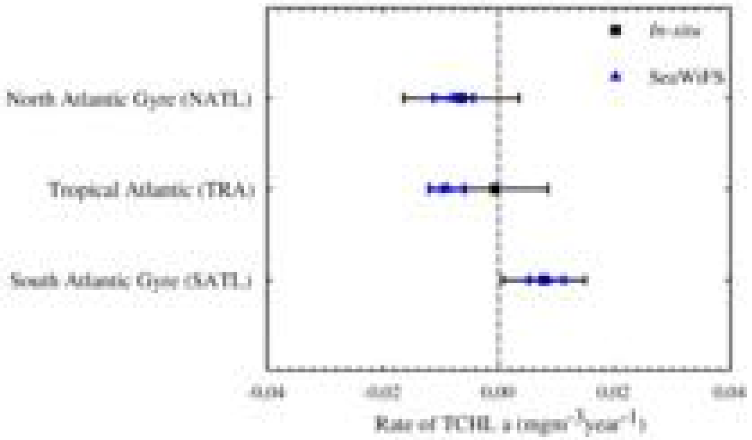


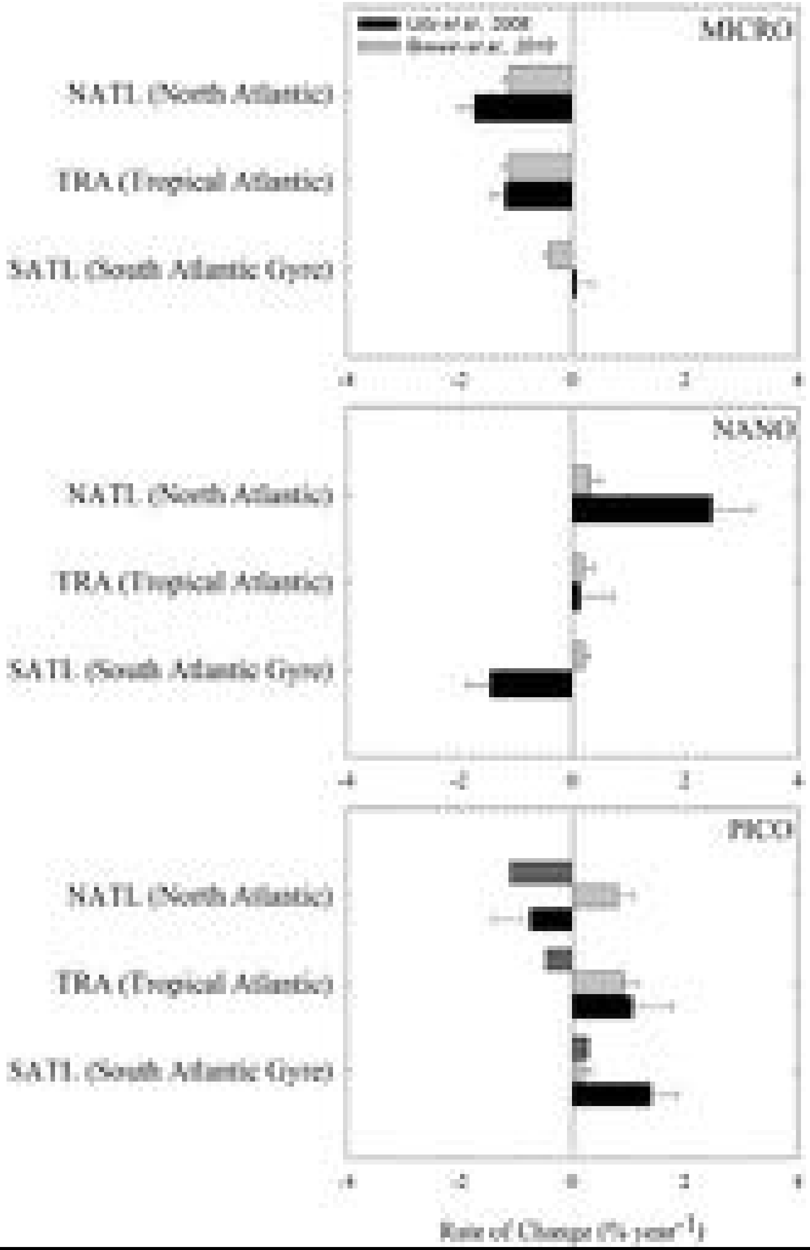
Zhao et al. (2025) https://doi.org/10.1126/science.adr9715



Photoacclimation response is an important component of temporal chlorophyll variability across the global ocean

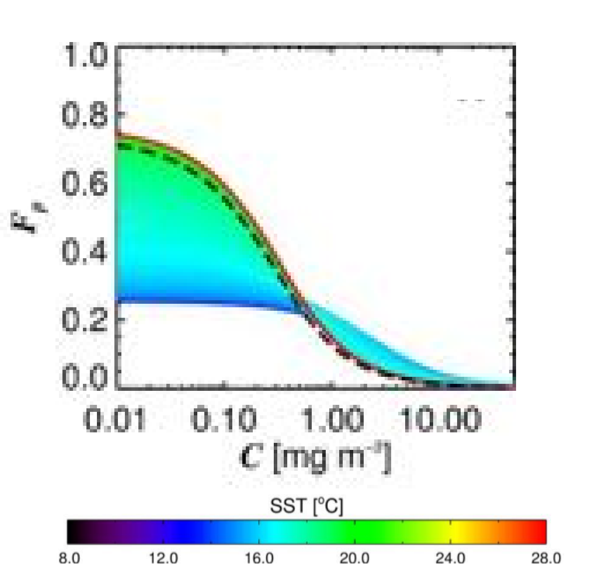
Behrenfeld et al. (2015)
https://doi.org/10.1038/nclimate2838





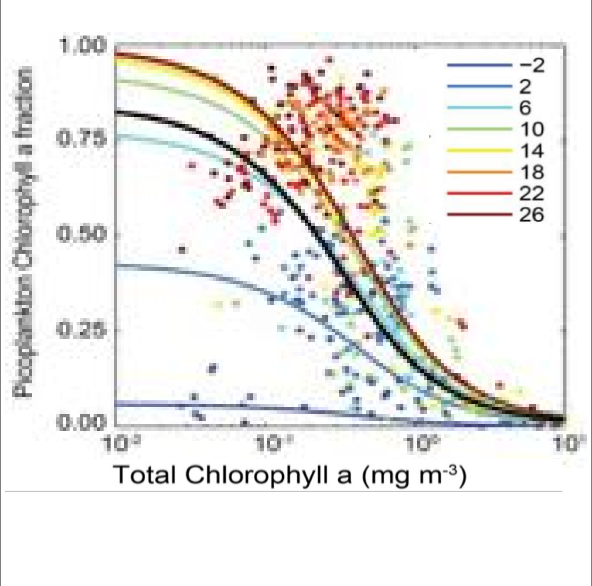
No significant changes in Chl-a in northern and equatorial provinces of the Atlantic, but significant changes in size-structure over a 7-year period

Agirbas et al. (2014)
https://doi.org/10.1016/j.jmarsys.2015.05.008



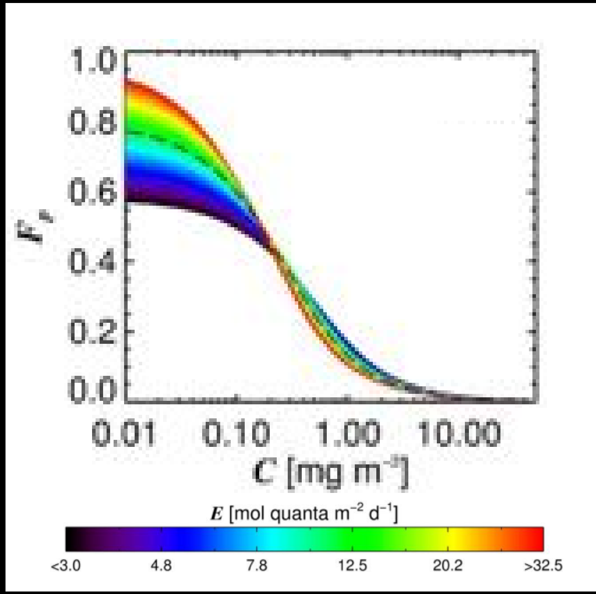
Fraction of picoplankton to total chl-a in the North Atlantic as a function of SST

Brewin et al. (2017)
https://doi.org/10.3389/fmars.2017.00104



Fraction of picoplankton to total chl-a in the Global Ocean as a function of SST

Ward et al. (2015)
https://doi.org/10.1371/journal.pone.0135581



Fraction of picoplankton to total chl-a in the Global Ocean as a function of light

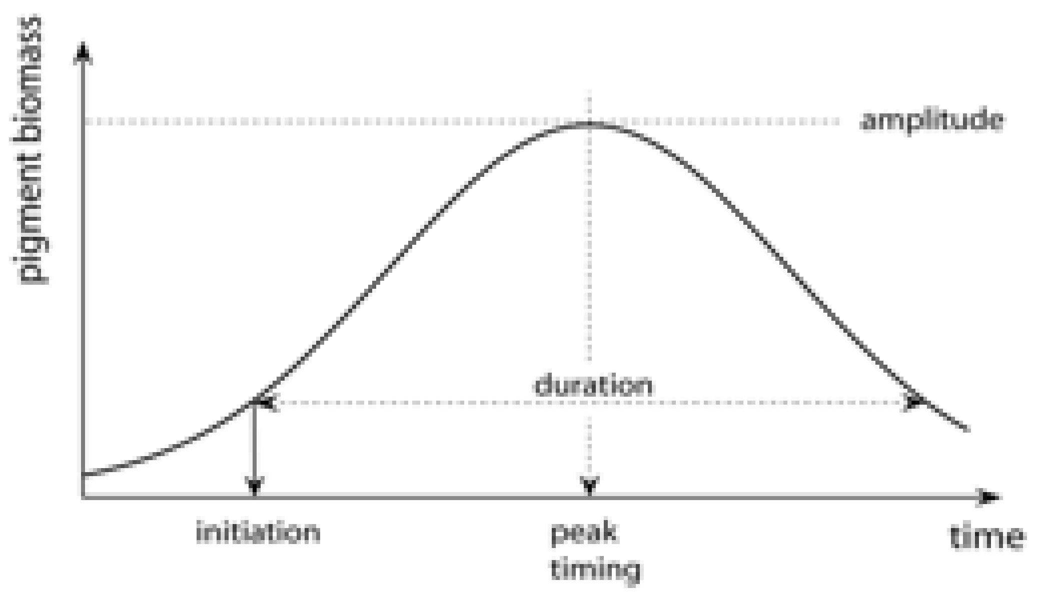
Brewin et al. (2015)
https://doi.org/10.1016/j.rse.2015.07.004

Implications for ocean colour algorithms (see Sun et al. (2023,2025,2026)

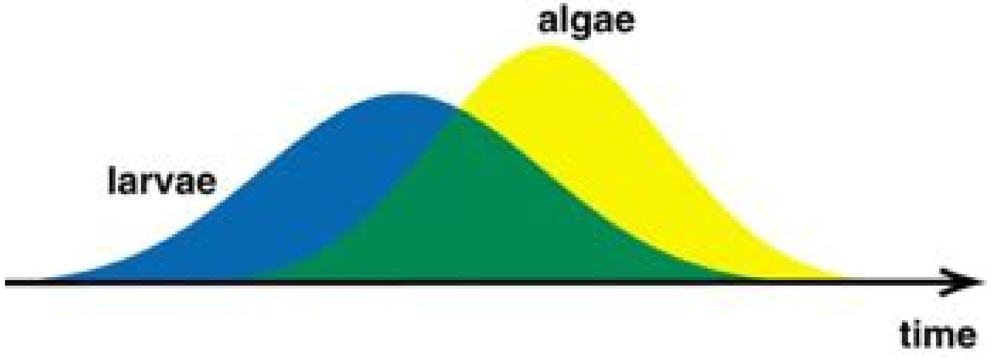
https://doi.org/10.1016/j.rse.2022.113415

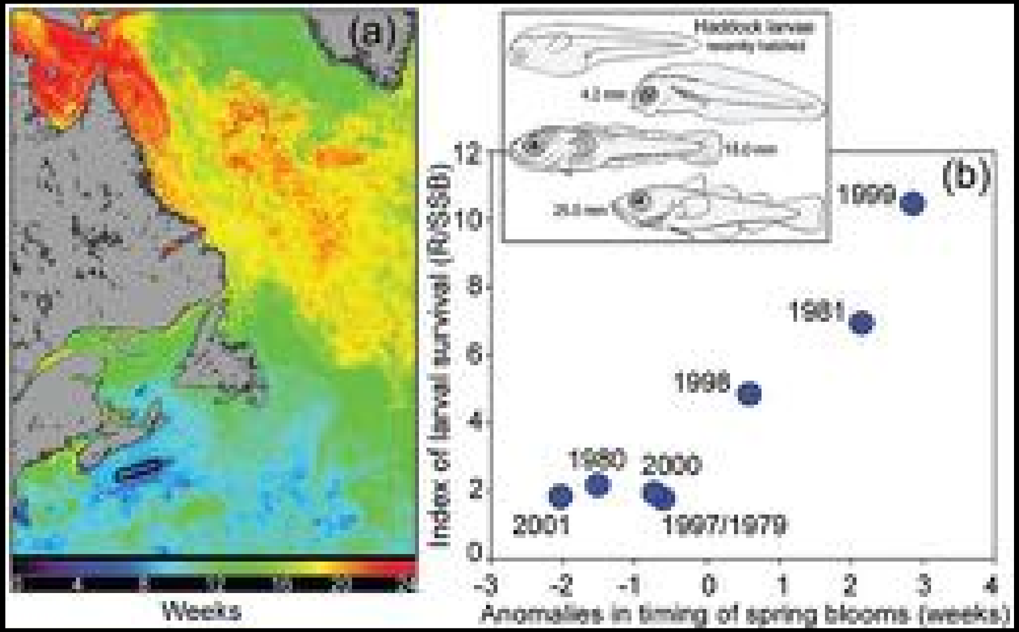
https://doi.org/10.1016/j.rse.2024.114487

https://doi.org/10.3389/frsen.2025.1692306



Platt et al. (2007) https://doi.org/10.1093/icesjms/fsm072

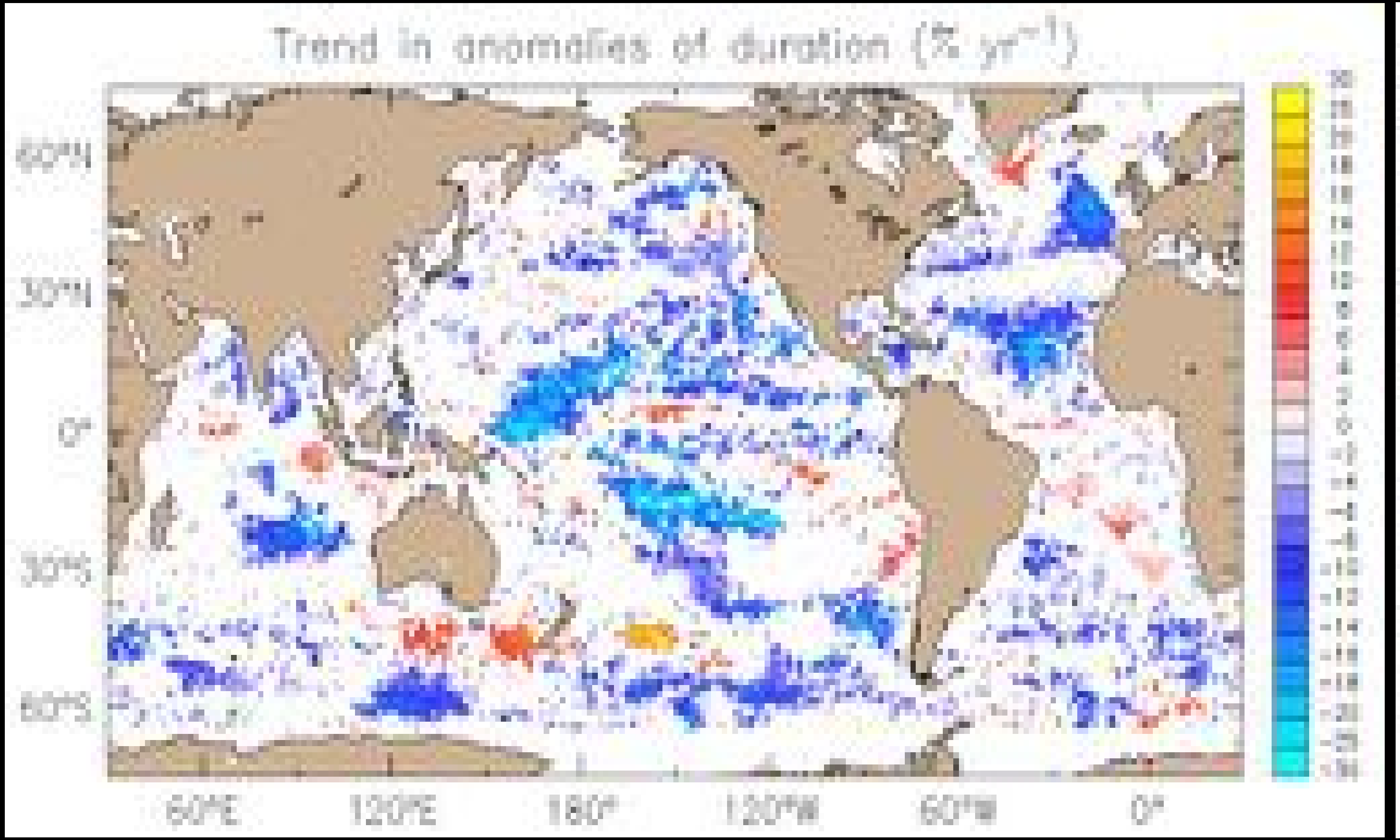




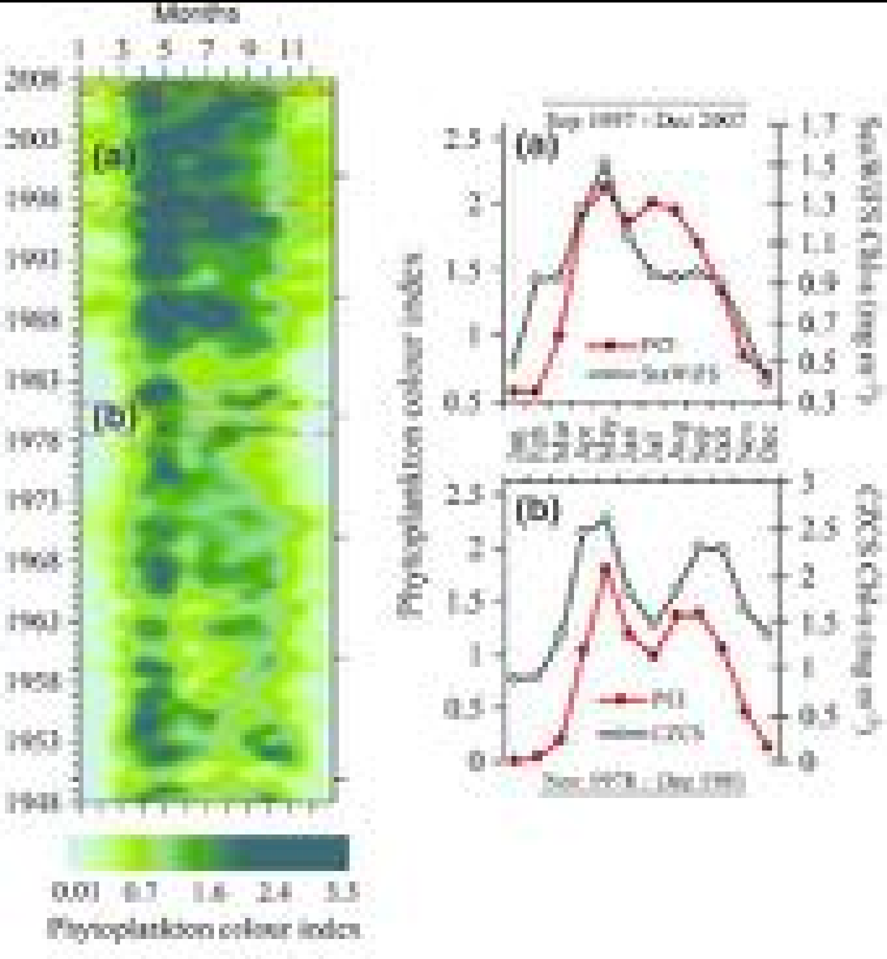
Inter-annual variations in the timing of the spring bloom impacts survival of larval fish

Platt et al. (2003) https://doi.org/10.1038/423398b

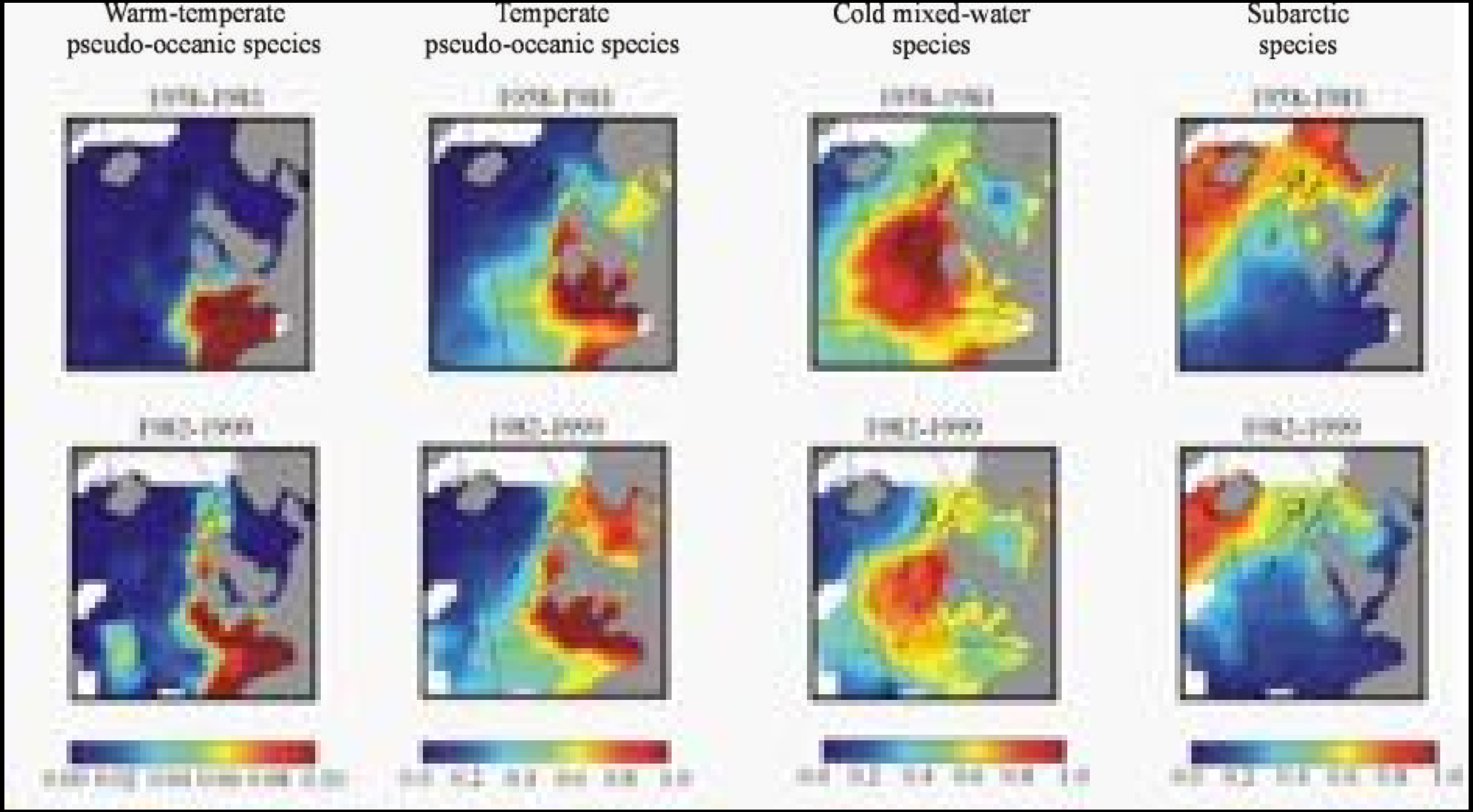
Koeller et al. (2009) http://doi.org/10.1126/science.1170987



Racault et al. (2012) https://doi.org/10.1016/j.ecolind.2011.07.010



Raitsos et al. (2013)
https://doi.org/10.1111/gcb.12457



Biogeographical changes in plankton assemblages spanning five decades. Warm water plankton are moving north, and cold-water plankton are moving out of the North Sea

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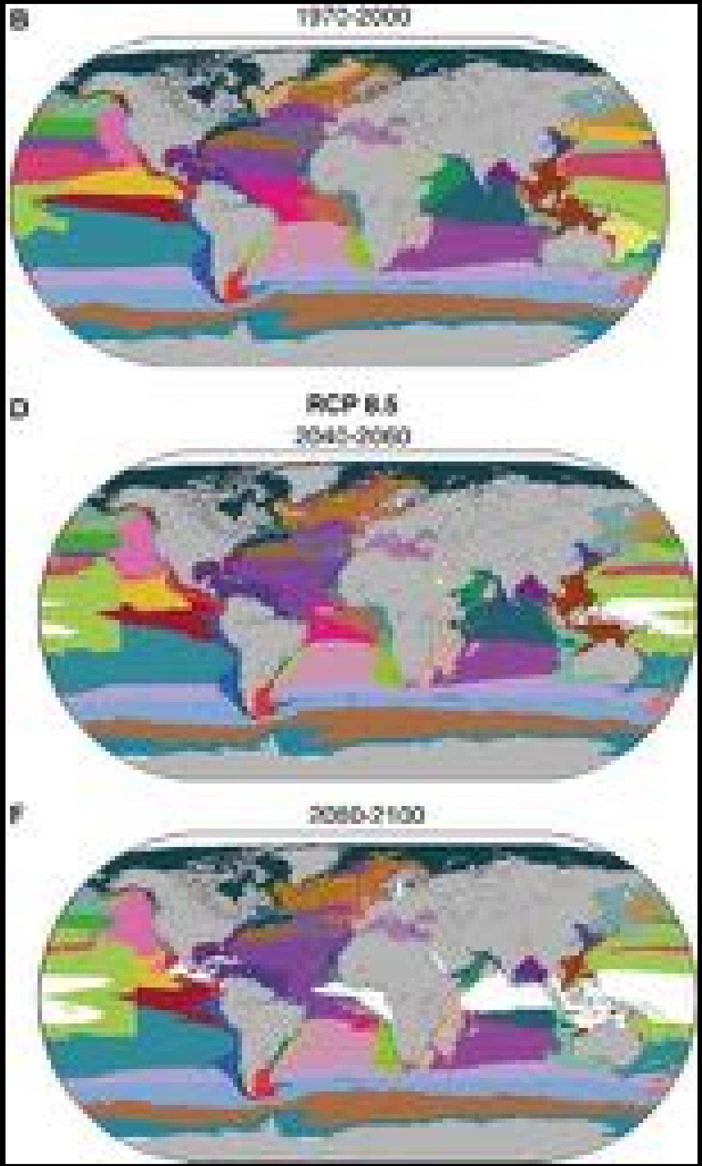

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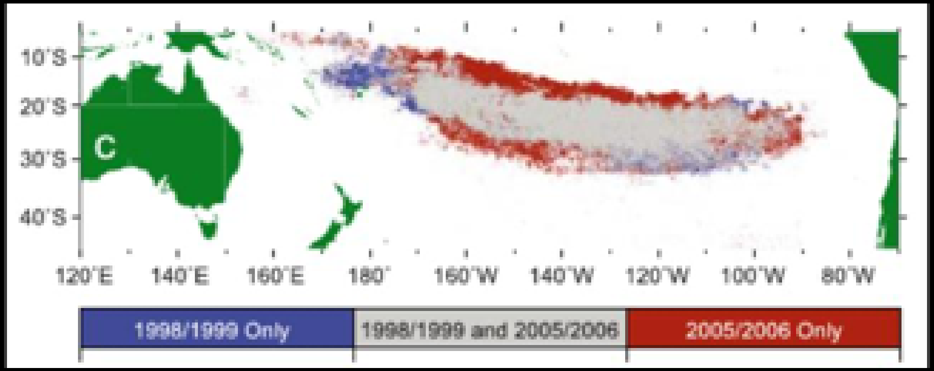

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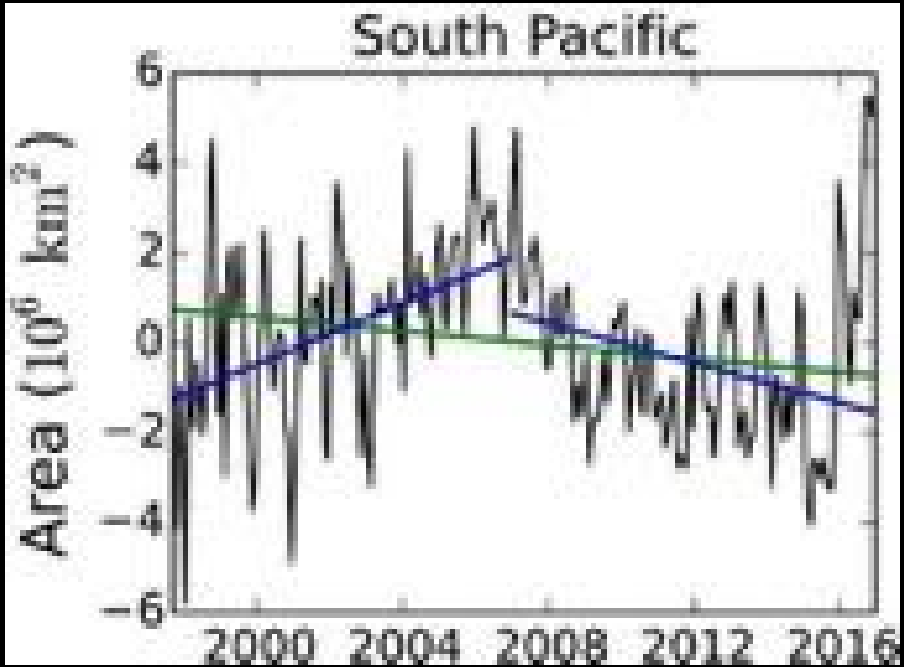

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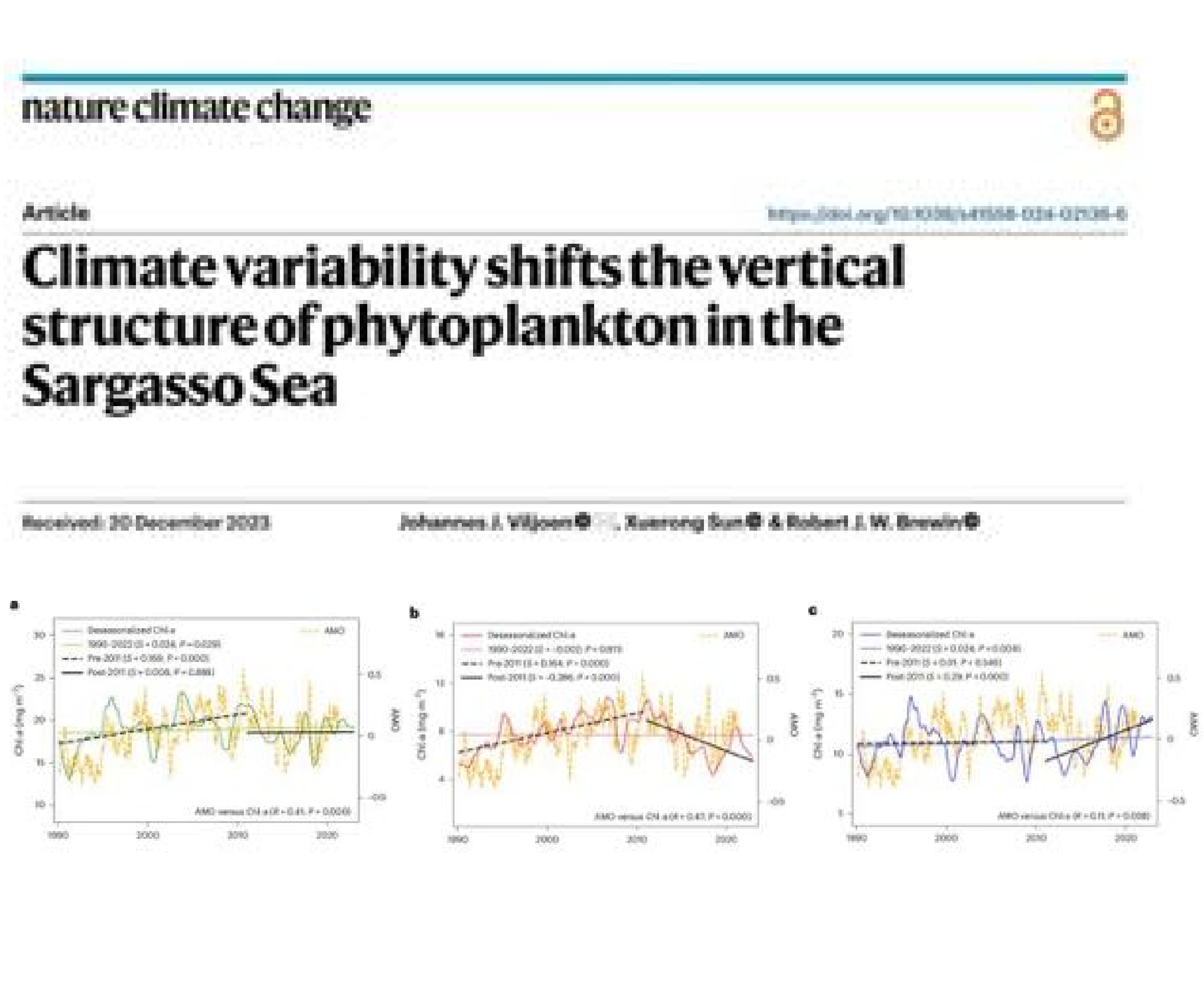
https://doi.org/10.1080/1755876X.2018.1489208


nature climate change

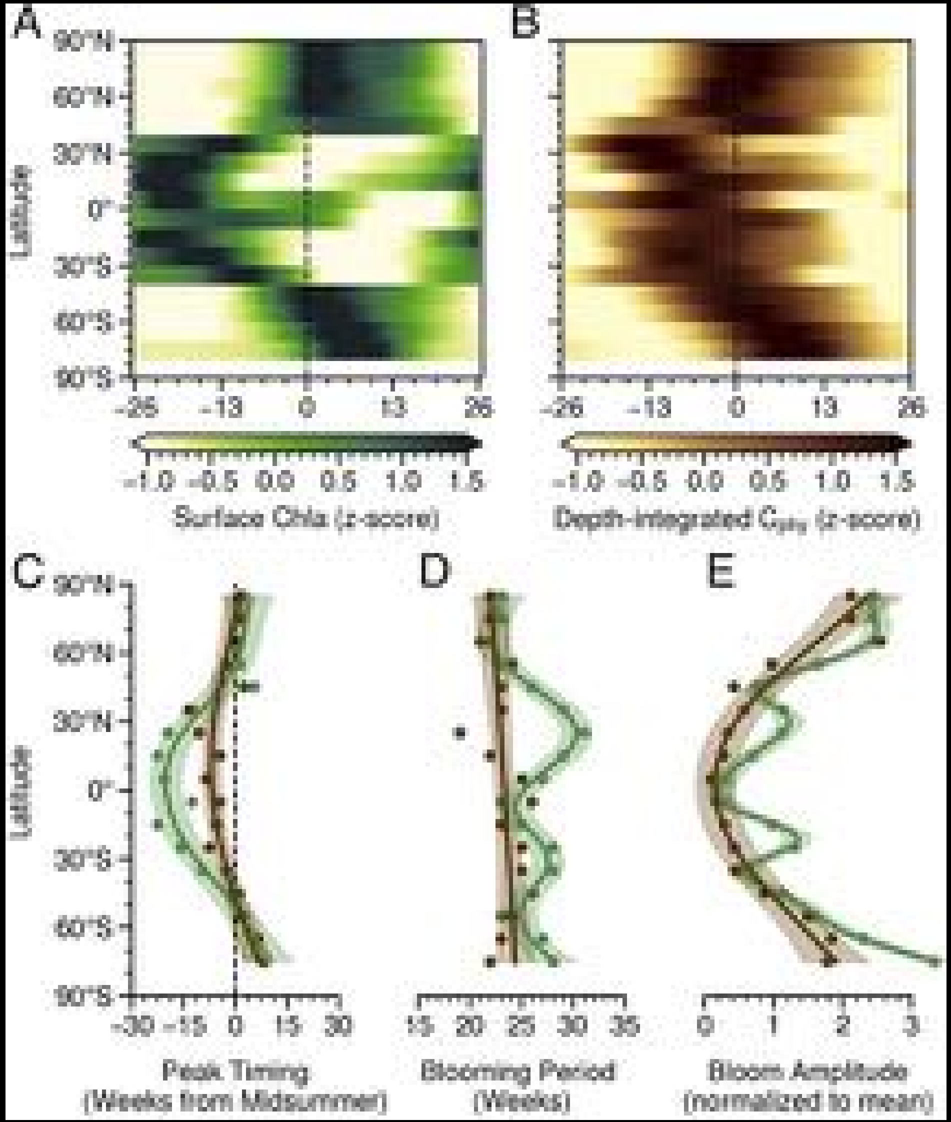
Article

https://doi.org/10.1038/s41558-024-02136-6

Climate variability shifts the vertical structure of phytoplankton in the Sargasso Sea

Received: 20 December 2023

Johannes J. Viljoen, Xuerong Sun & Robert J. W. Brewin



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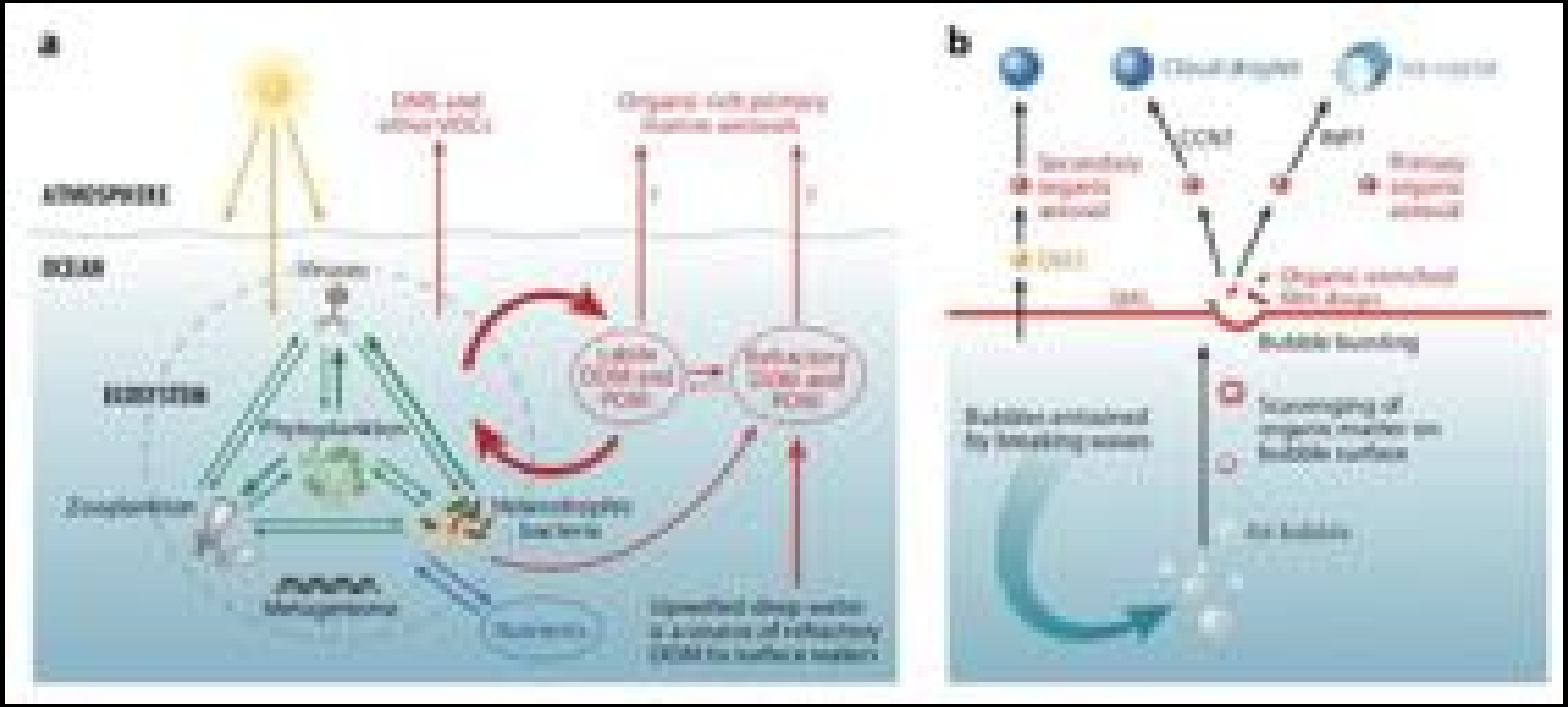

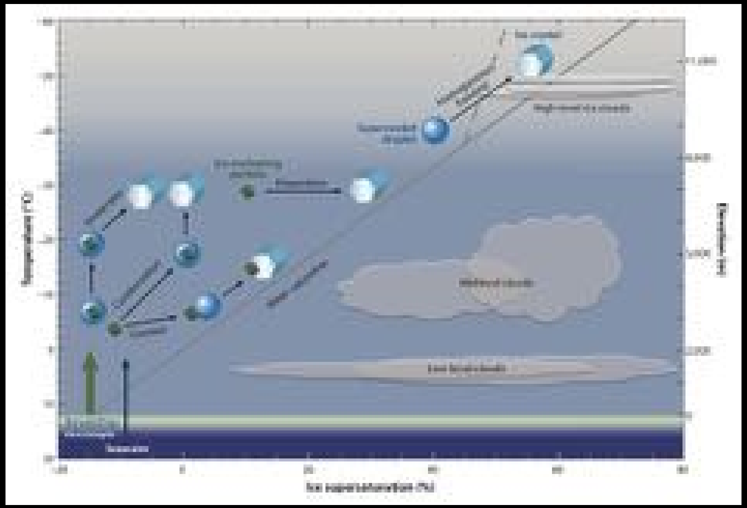

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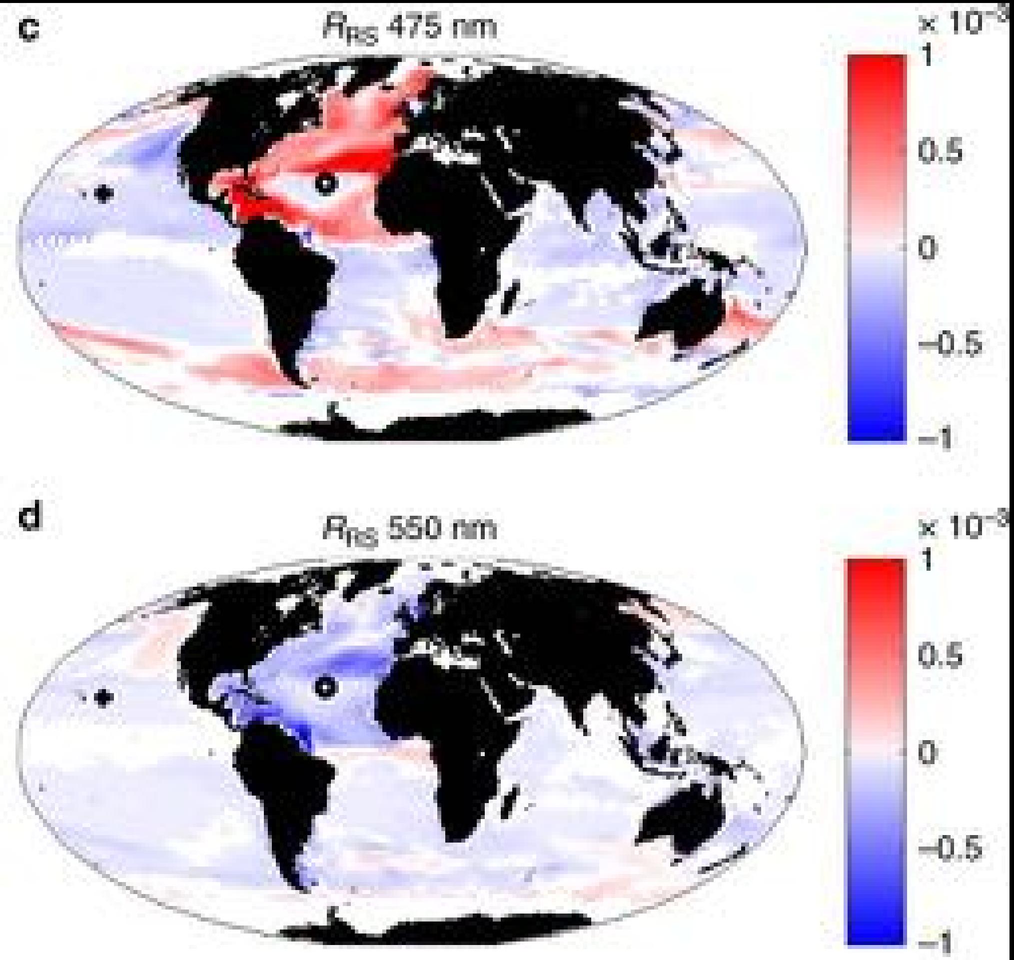
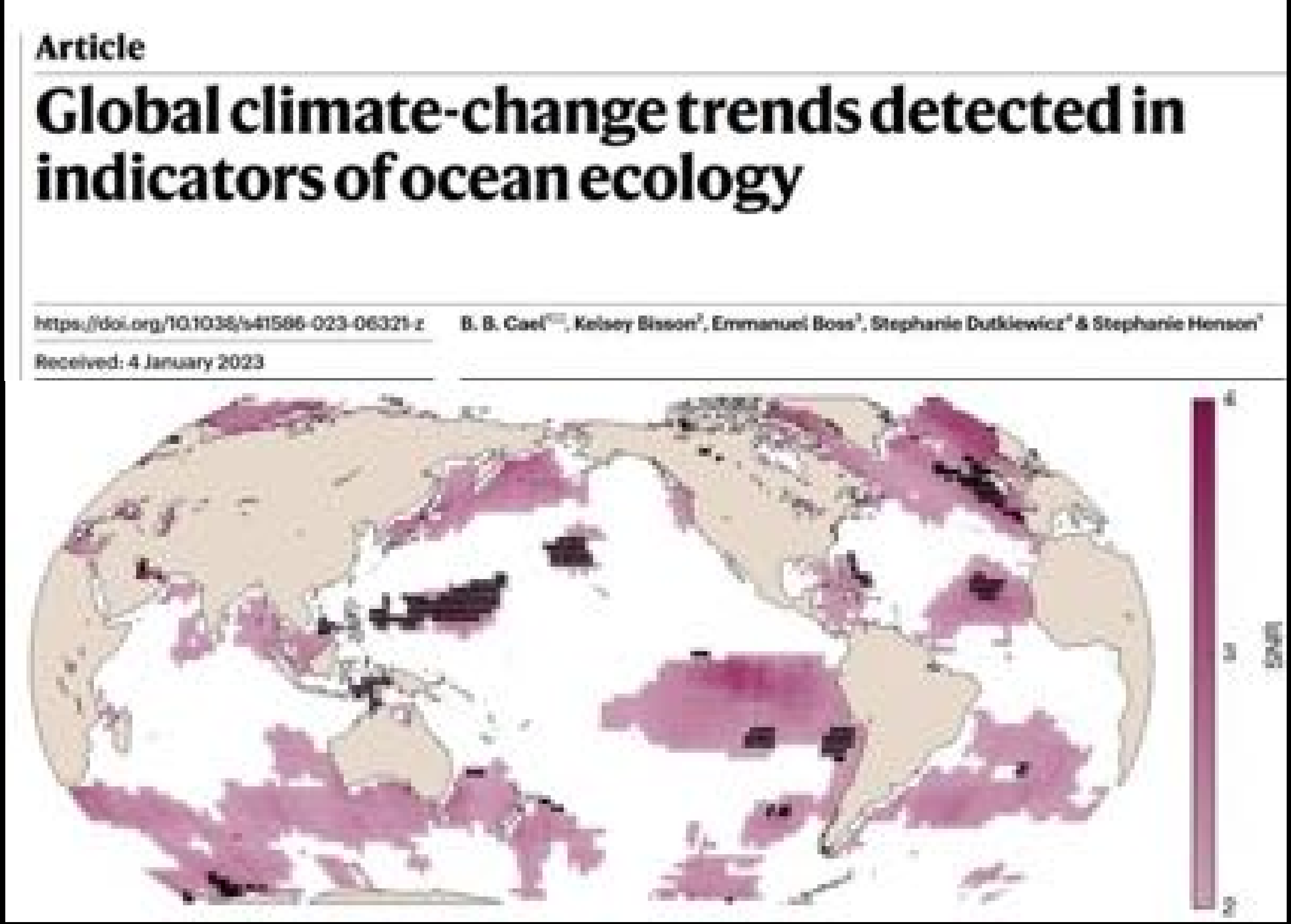
The CLAW hypothesis proposes that marine phytoplankton regulate climate by producing dimethyl sulfide (DMS), which forms atmospheric aerosols that increase cloud formation and reflect sunlight, creating a feedback that can cool the Earth.

Charlson, R. J., Lovelock, J. E., Andreae, M. O., & Warren, S. G. (1987). Nature, *https://doi.org/10.1038/326655a0*





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Lecture outline

1. Definition of phytoplankton biomass
2. Measuring phytoplankton biomass at sea
3. Estimating phytoplankton biomass from space
4. Definition of production
5. Importance of primary production
6. Measuring production at sea
7. Estimating primary production from space
8. Estimating export production from space
9. Climate-driven changes