Satellite ocean colour radiometry and carbon fluxes

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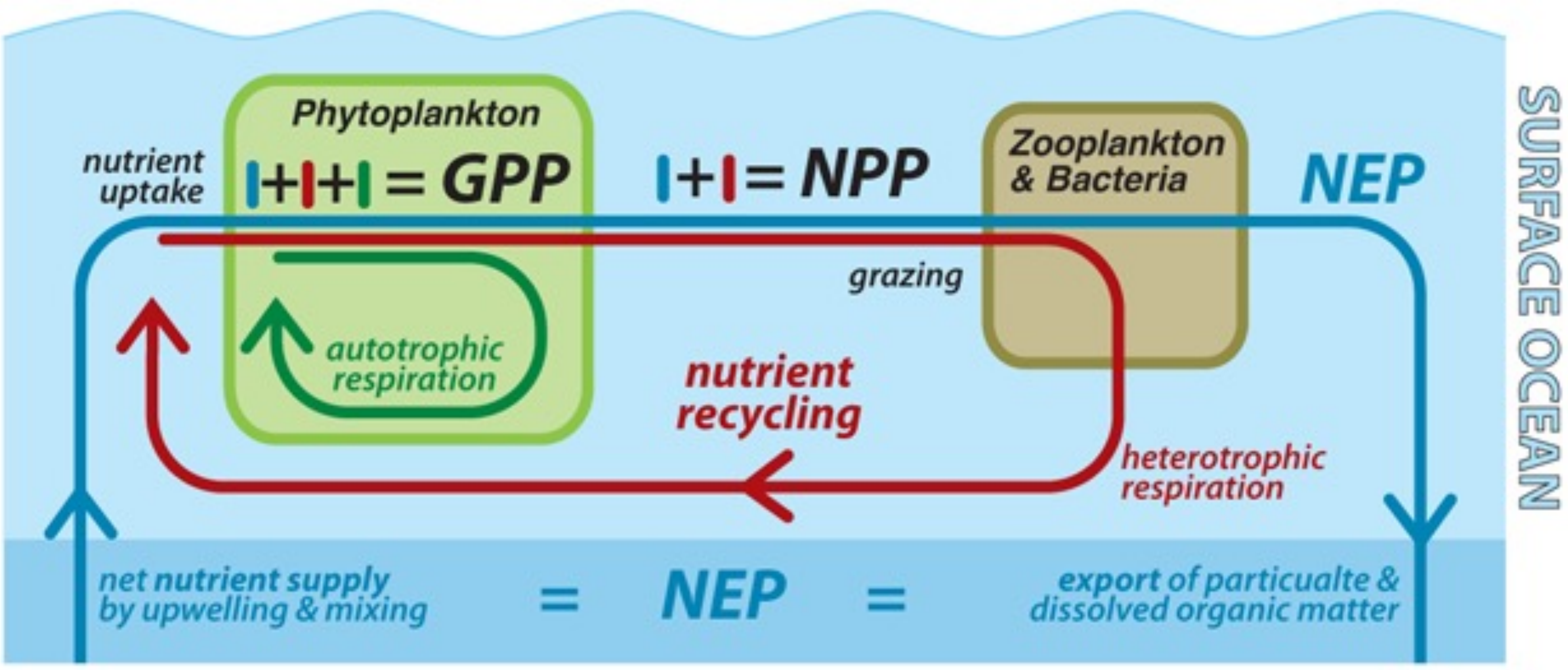
Primary production is a flux:
Carbon per unit volume and unit time

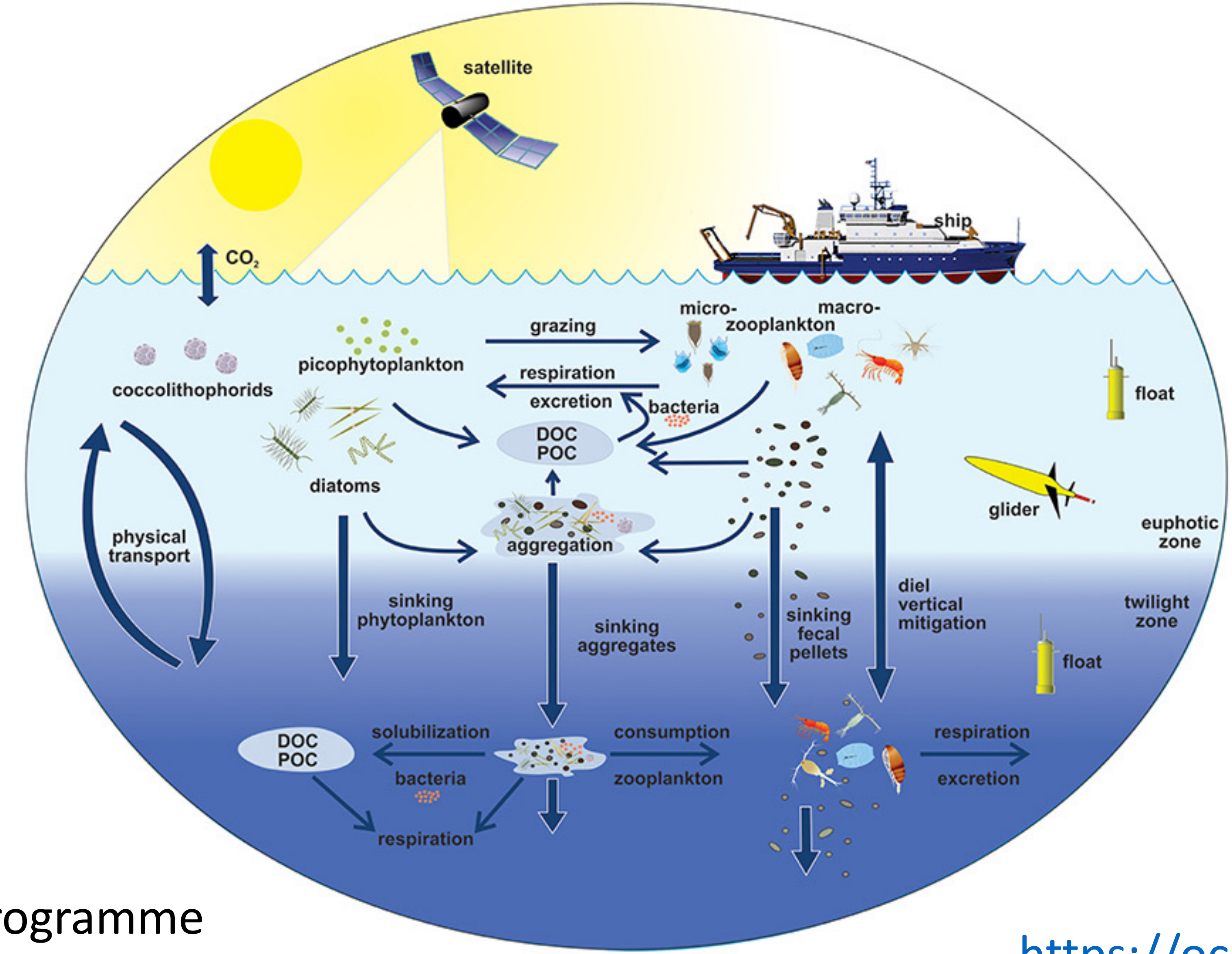


Gross PP, Net PP, and export are the quantities we try to derive from satellite OCR

From: Sigman, D. M. & Hain, M. P. (2012) The Biological Productivity of the Ocean. Nature Education Knowledge 3(10):21

https://www.nature.com/scitable/knowledge/library/the-biological-productivity-of-the-ocean-70631104/

Quantify NPP and export using a variety of tools

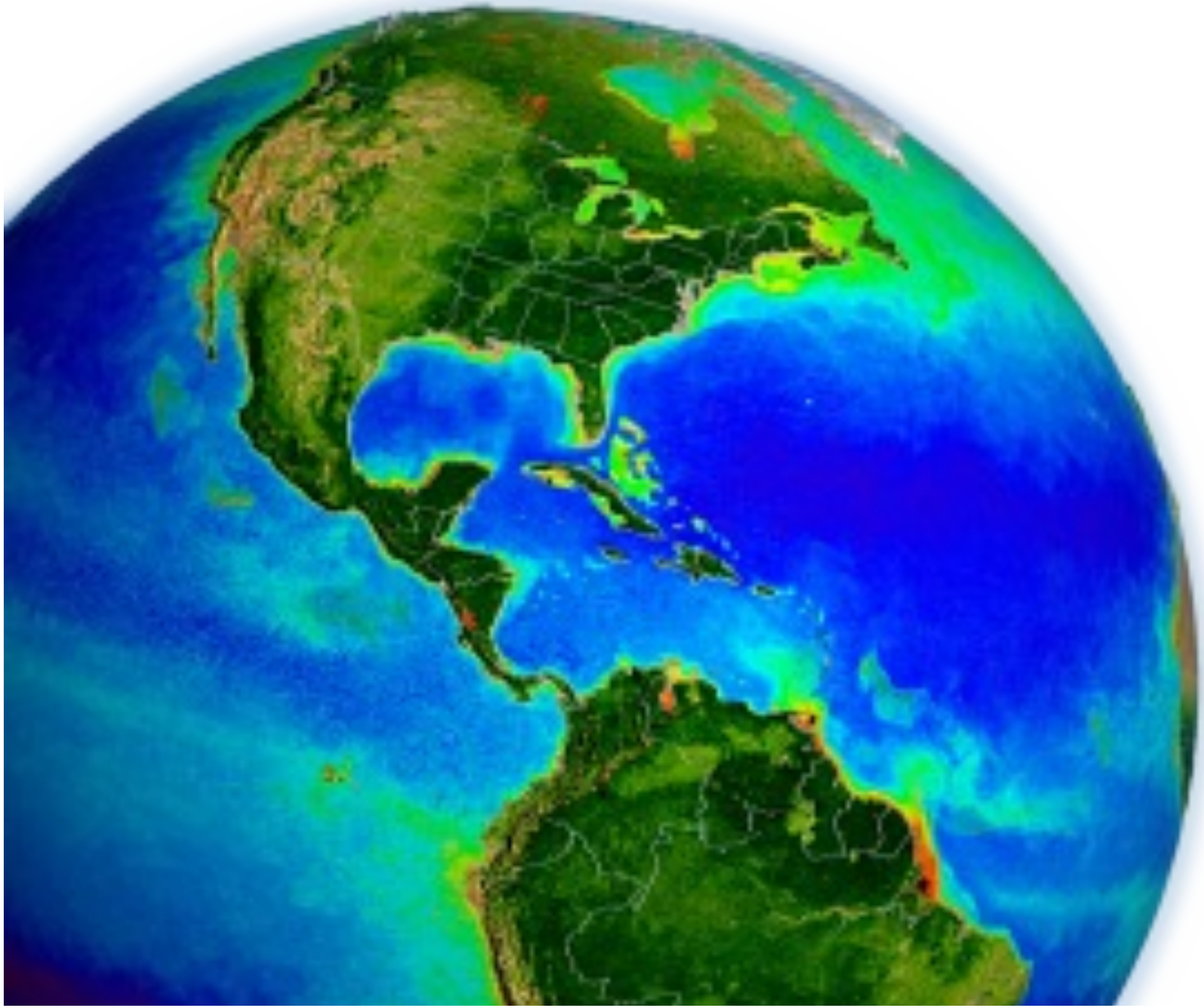


NASA EXPORTS programme
"EXport Processes in the Ocean from Remote Sensing"

https://oceanexports.org

Satellite ocean colour

Is a “snapshot” of chlorophyll (of biomass?) at a given time and at the surface of the oceans



https://oceancolor.gsfc.nasa.gov/gallery/search/?arg=chlorophyll#&gid=1&pid=8

Satellite ocean colour and carbon fluxes

What we start with:

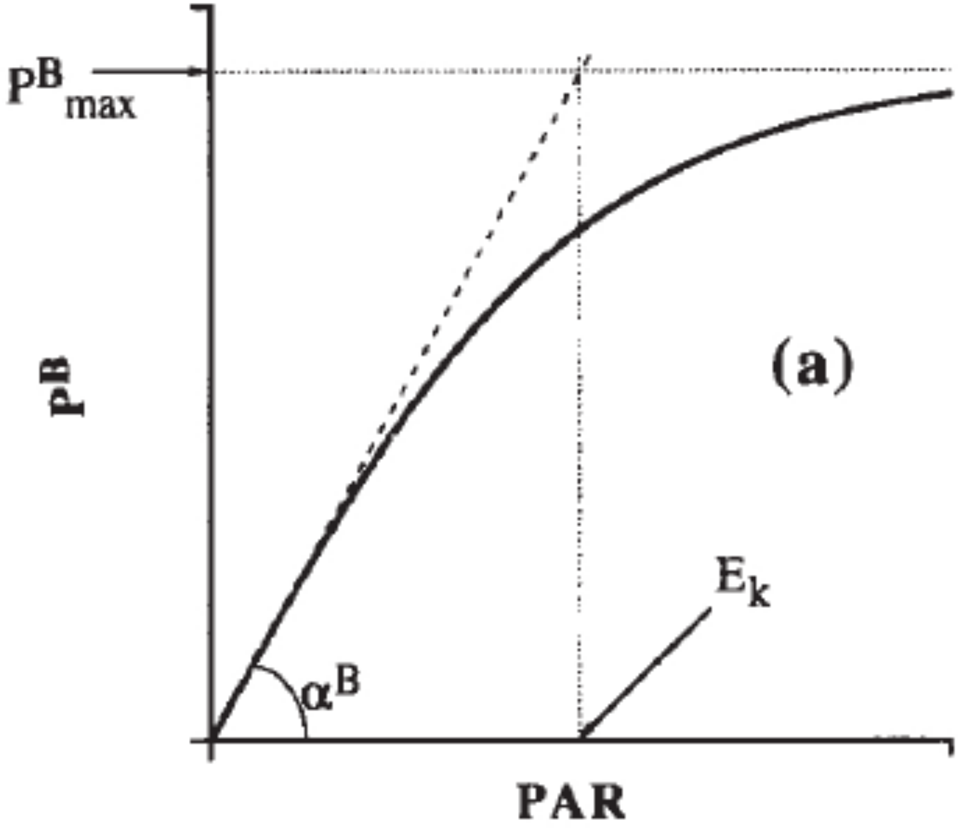
- After atmospheric correction of the satellite OCR measurement:
  - Remote sensing reflectances, R_{rs} (sr^{-1}), and various combinations of R_{rs} (ratios, differences, used as input data sets to training ML techniques etc.)
- Derived from the above:
  - Pigment (chlorophyll-a) concentrations (mg(Chl) m^{-3})
  - IOPs: Phytoplankton absorption (a_{ϕ}, m^{-1}) and particulate backscattering (b_{bp}, m^{-1})
  - From b_{bp}: Particulate Organic Carbon (gC m^{-3}) or phytoplankton carbon (gC m^{-3})

What we are aiming at:

- Phytoplankton net (or gross) productivity: mass of C per unit volume or surface area and per unit time: gC m^{-3} s^{-1} gC m^{-2} h^{-1}
- How much of this is exported to greater depths? (C export), e.g., yearly in gC m^{-2}

We start from a stock and want to derive a flux

Stock to flux: transfer function

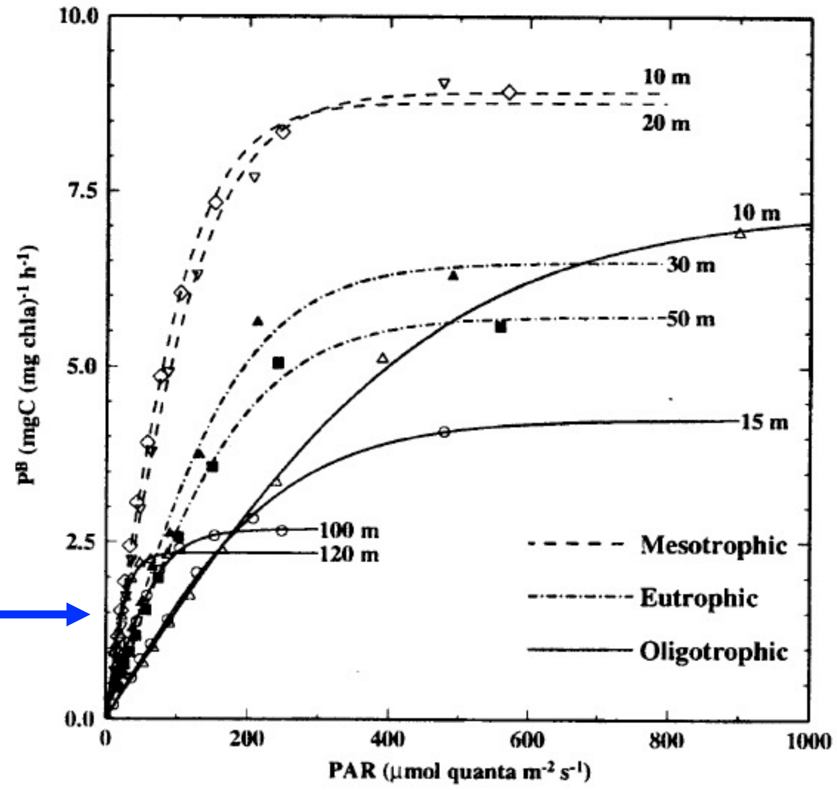


The "P vs E" curve

P^B_{max} : Chl-specific maximum photosynthesis rate (gC g(Chl)$^{-1}$ h^{-1}

α^B : Chl-specific initial slope of the P *vs*. E curve (gC g(Chl)$^{-1}$ (mol Quanta m^{-2})$^{-1}$

$$E_k = P^B_{max} / \alpha^B$$



Examples in the sub-tropical north Atlantic
From: Morel et al., Deep-Sea Res., 1996

Bouman et al., 2018. Earth Syst. Sci. Data, 10, 251–266, 2018
https://doi.org/10.5194/essd-10-251-2018

Example of a spectral light-photosynthesis model

(Morel, 1991, Progress in Oceanography, 26, 263-306)

Basic Equation for
- LOCAL (z)
- INSTANTANEOUS Photosynthesis (t)

Under
- MONOCHROMATIC Irradiance (λ)

$$P(\lambda,z,t) = \frac{dC(\lambda,z,t)}{dt} = E(\lambda,z,t) \quad Chl(z,t) \quad a^*(\lambda,z,t) \quad \Phi(\lambda,z,t)$$

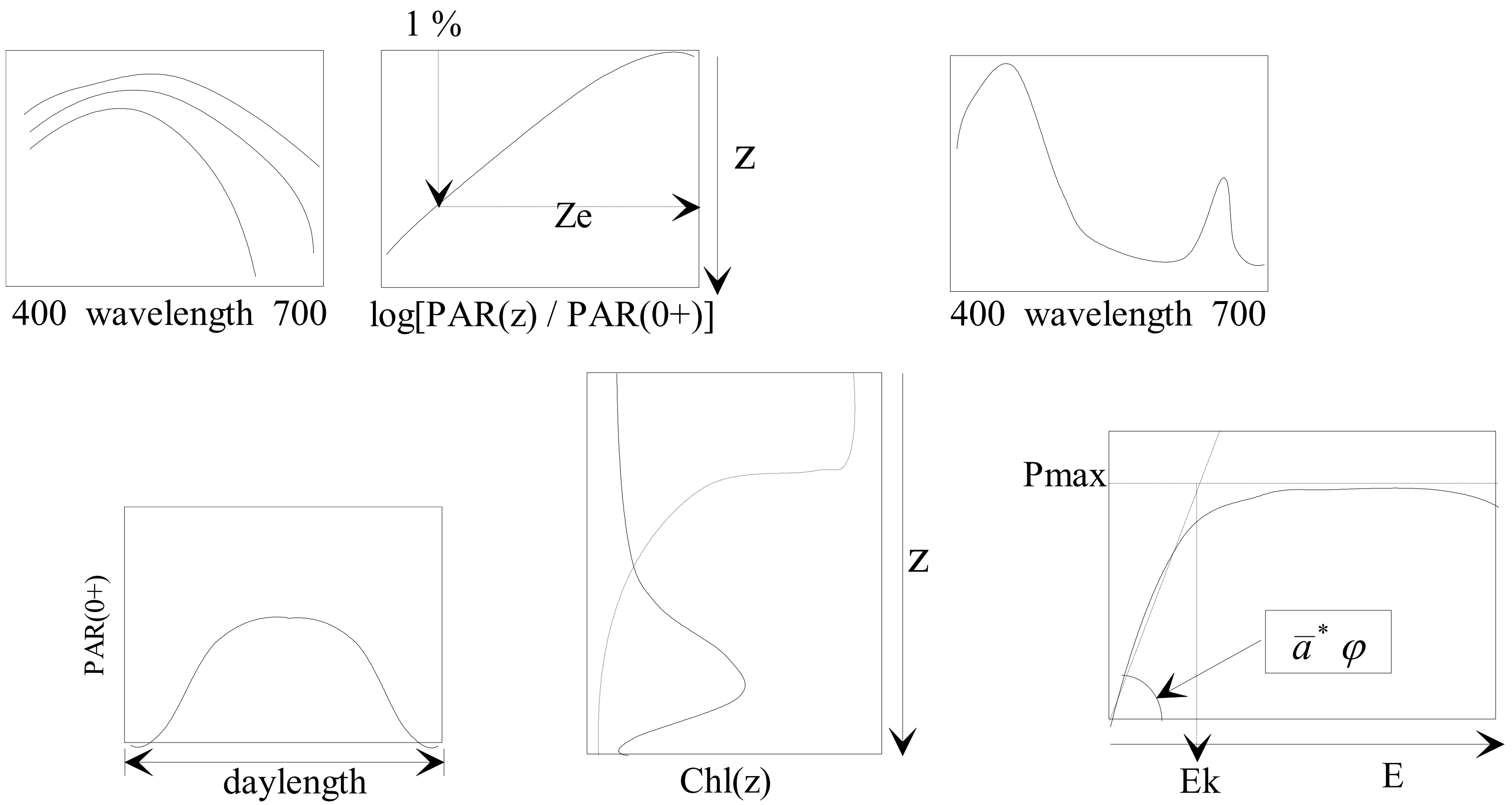
Daily, column-integrated production

$$P = \int^{D} \int_{0}^{Zp} \int_{400}^{700} P(\lambda,z,t)\, d\lambda\, dz\, dt$$

- 400 – 700 nm : Limits for PAR
- Z_p : Depth of the « productive » zone (e.g., 1.5 Z_e)
- D : Day length

Spectral & depth changes of the various parameters

$$P(\lambda,z,t) = \frac{dC(\lambda,z,t)}{dt} = E(\lambda,z,t) \quad Chl(z,t) \quad a^{*}(\lambda,z,t) \quad \Phi(\lambda,z,t)$$



LIMNOLOGY
AND
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A consumer's guide to phytoplankton primary productivity models

Michael J. Behrenfeld and Paul G. Falkowski
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I. Wavelength-resolved models (WRMs)

$$\sum PP = \int_{\lambda=400}^{700} \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \Phi(\lambda, t, z) \times \mathrm{PAR}(\lambda, t, z) \times a^*(\lambda, z) \times \mathrm{Chl}(z)\, d\lambda\, dt\, dz - R$$

II. Wavelength-integrated models (WIMs)

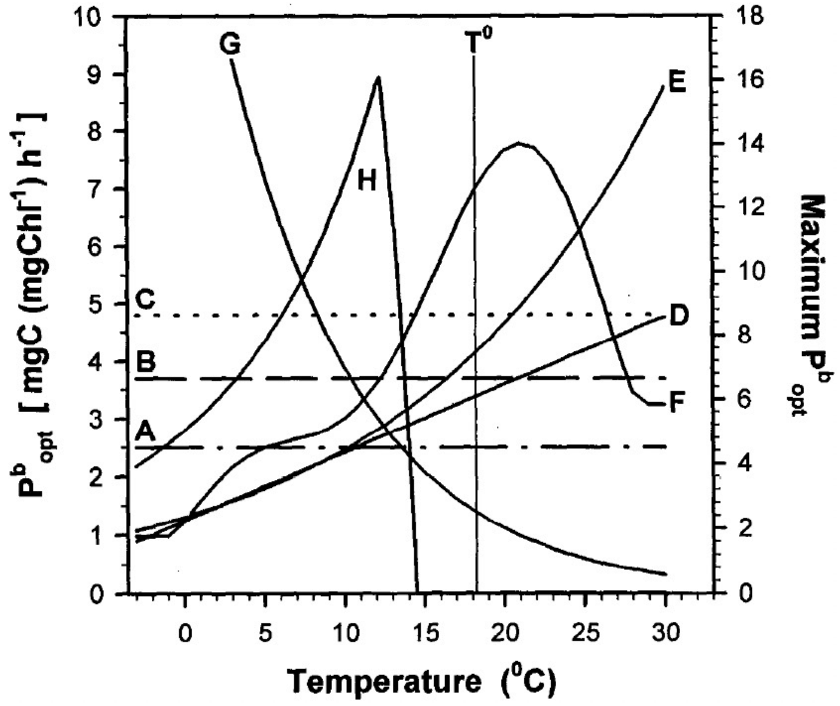
$$\sum PP = \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \varphi(t, z) \times \mathrm{PAR}(t, z) \times \mathrm{Chl}(z)\, dt\, dz - R$$

II. Time-integrated models (TIMs)

$$\sum PP = \int_{z=0}^{Z_{eu}} P^b(z) \times \mathrm{PAR}(z) \times DL \times \mathrm{Chl}(z)\, dz$$

IV. Depth-integrated models (DIMs)

$$\sum PP = P^b{}_{opt} \times f[\mathrm{PAR}(0)] \times DL \times \mathrm{Chl} \times Z_{eu}$$



Integrating over the three dimensions (wavelength, depth, time)

$$P = \iiint P(\lambda, z, t)\, d\lambda\, dz\, dt = \iiint \left[E(\lambda, z, t)\;\; Chl(z,t)\;\; a^*(\lambda, z, t)\;\; \Phi(\lambda, z, t)\right]$$

$$\int_{400}^{700} E(\lambda, 0^+, t)\, d\lambda = PAR(0^+, t)$$

$$\int_0^D PAR(0^+, t)\, dt = \overline{PAR}(0^+) \qquad \int_{z=0}^{z=Z_p} Chl(z)\, dz = \langle Chl \rangle_{tot} \qquad \text{(t is ignored)}$$

$$\boxed{\psi^* = \frac{P \propto PSR}{\overline{PAR}(0^+)\;\langle Chl \rangle_{tot}}}$$

ψ^* LUT (2 LUTs : uniform or non-uniform Chl distributions)

- Date
- Latitude
- Cloudiness
- Temperature
- Chl

ψ^* : $m^2\ (gChl)^{-1}$

Photosynthesis cross section per unit of areal chlorophyll

Berthon and Morel (1992), Limnology and Oceanography, 37, 781-796

Antoine and Morel (1996), Global Biogeochemical Cycles, 10, 43-55

The integral, “satellite version” of the model

$$\boxed{P \propto PSR = \langle Chl \rangle_{tot} \, \overline{PAR}(0^+) \, \psi^*}$$

For given $\overline{PAR}(0^+)$ and temperature distributions :

♦ $\langle Chl \rangle_{tot}$ is the first determinant, to the extent that

→ ψ^* is only weakly dependent on Chl ←

(mainly depends on T° and $\overline{PAR}(0^+)$)

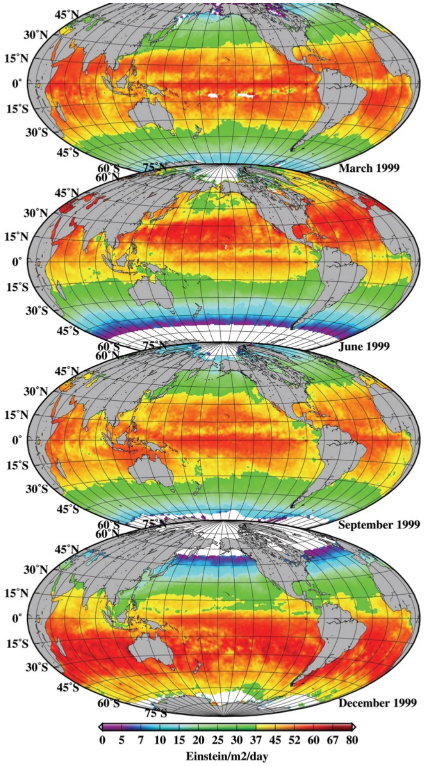
♦ $\langle Chl \rangle_{tot}$ roughly varies as $\sqrt{Chl_{sat}}$, so does P (approximately)

♦ While Chl_{sat} spans about 3 orders of magnitude,

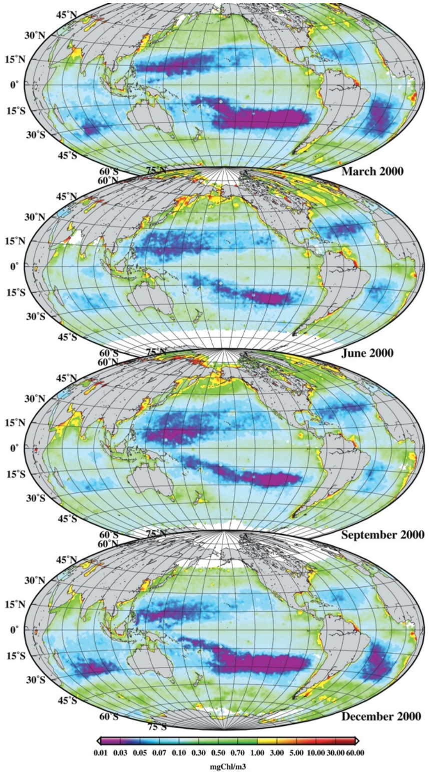
$\langle Chl \rangle_{tot}$ and P span about 1.5 orders of magnitude

From phytoplankton biomass to a carbon flux

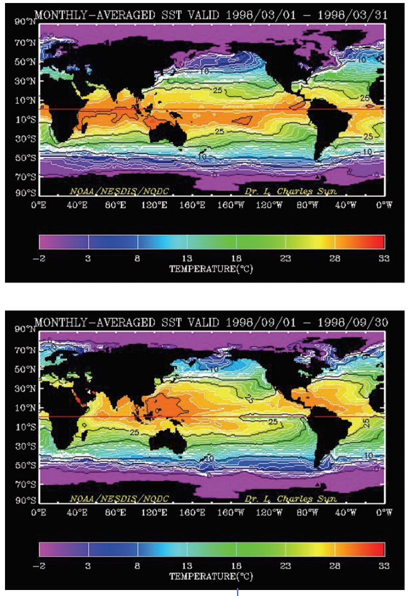
How much Light?



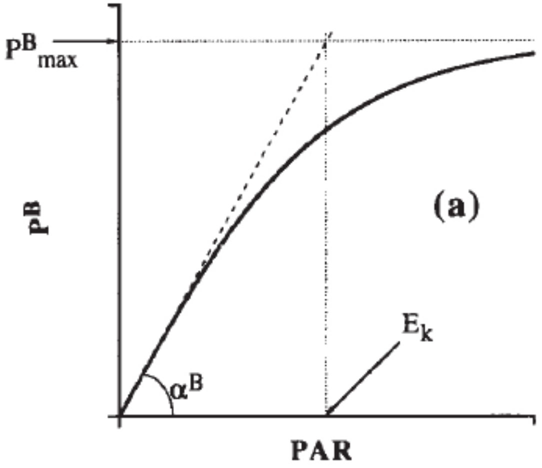
How much phytoplankton?
(chlorophyll)



How warm/cold?

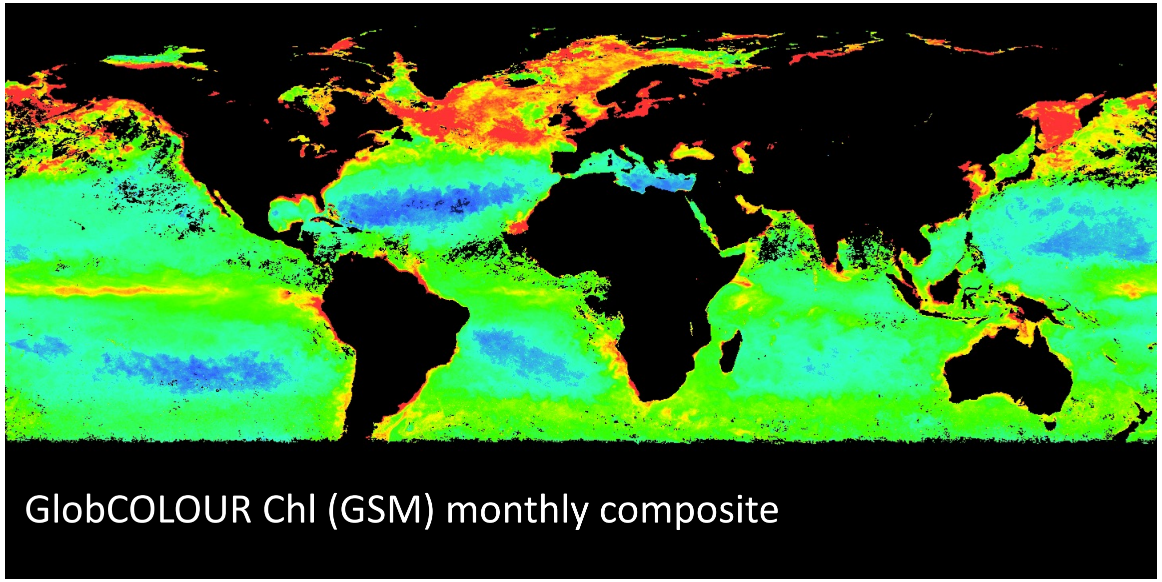


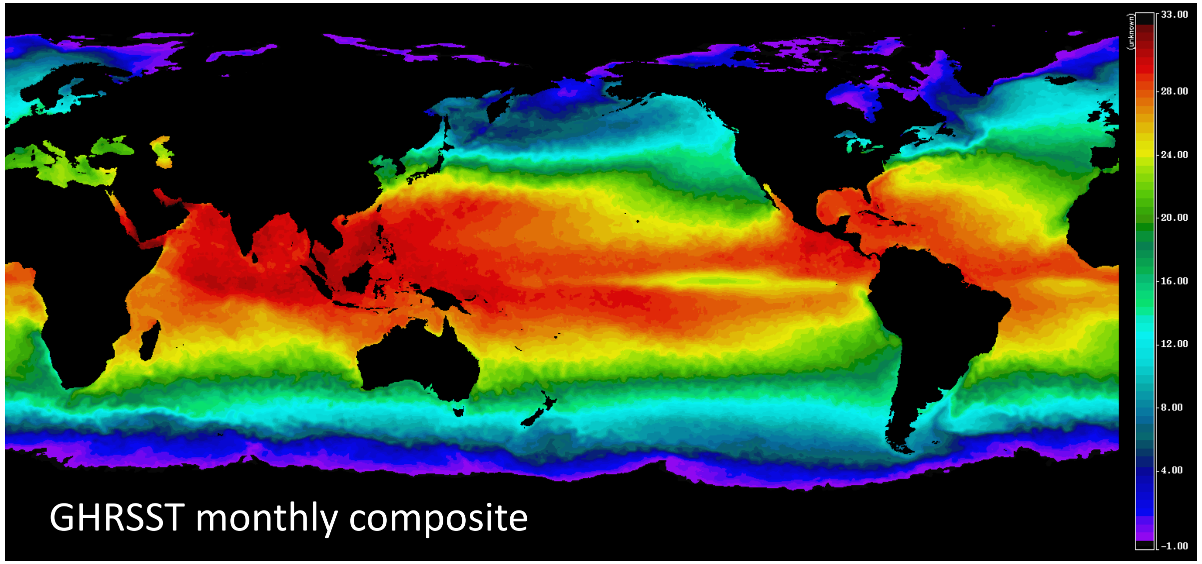
How photosynthesis works?



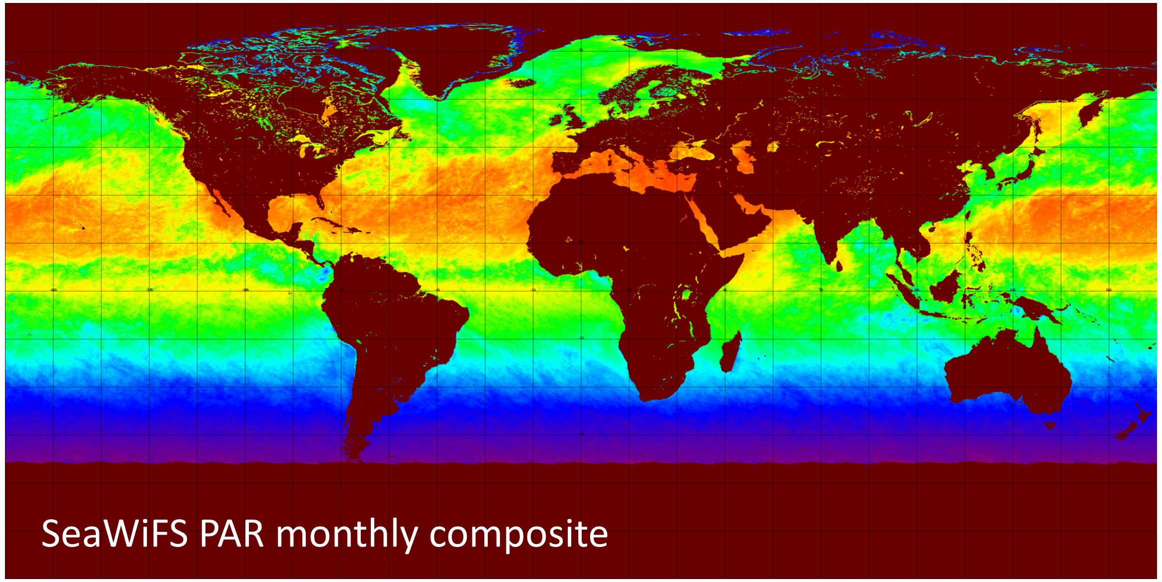
$$P(\lambda,z,t) = \frac{dC(\lambda,z,t)}{dt} = E(\lambda,z,t) \quad Chl(z,t) \quad a^*(\lambda,z,t) \quad \Phi(\lambda,z,t)$$

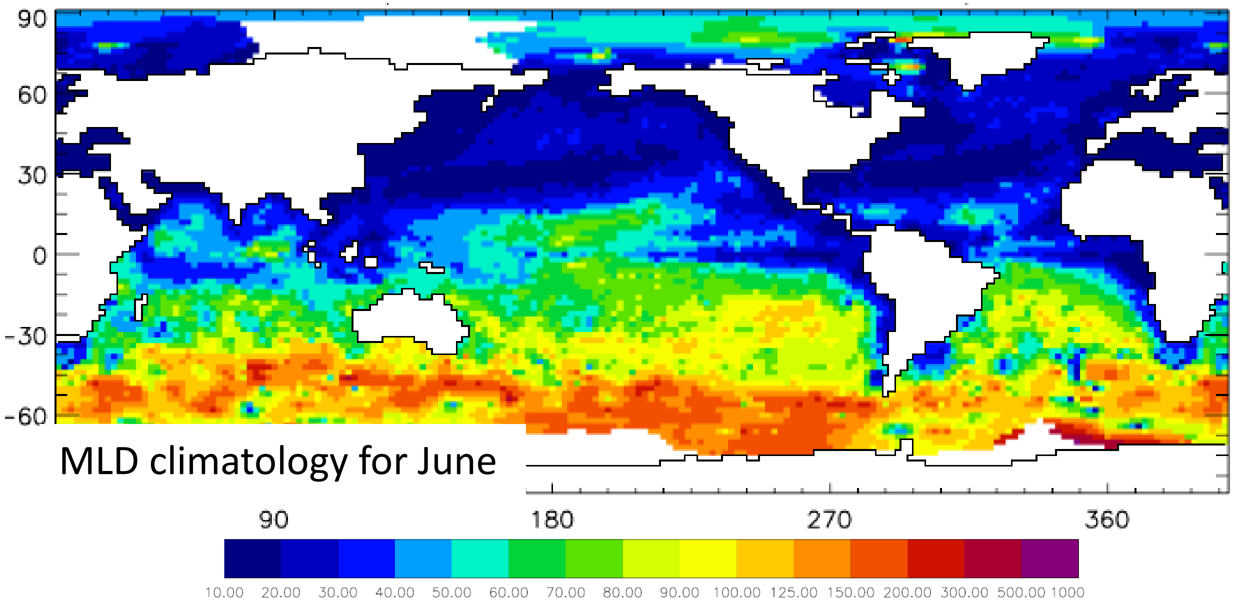
Input data sets: examples for June 1998


GlobCOLOUR Chl (GSM) monthly composite

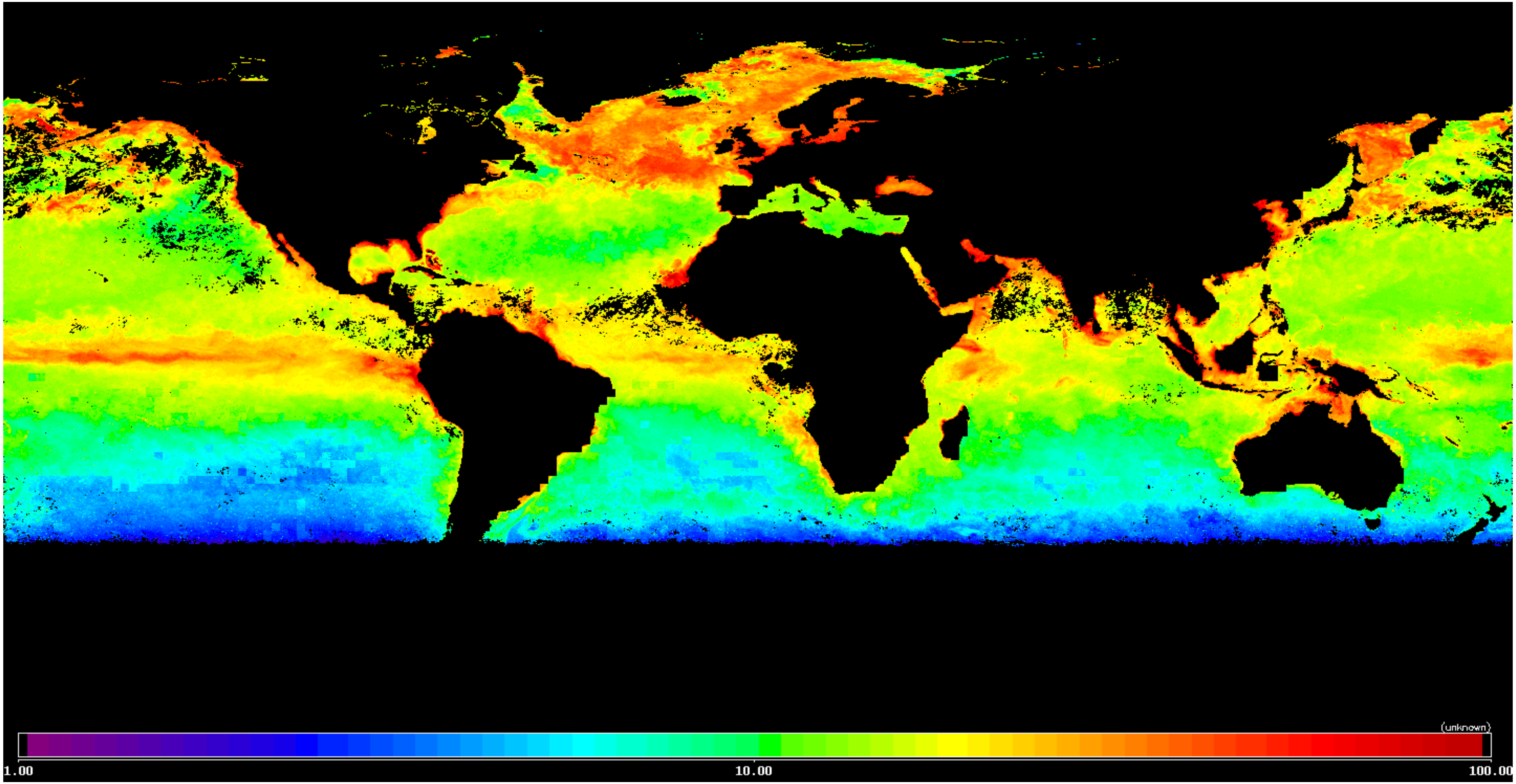


GHRSST monthly composite


SeaWiFS PAR monthly composite



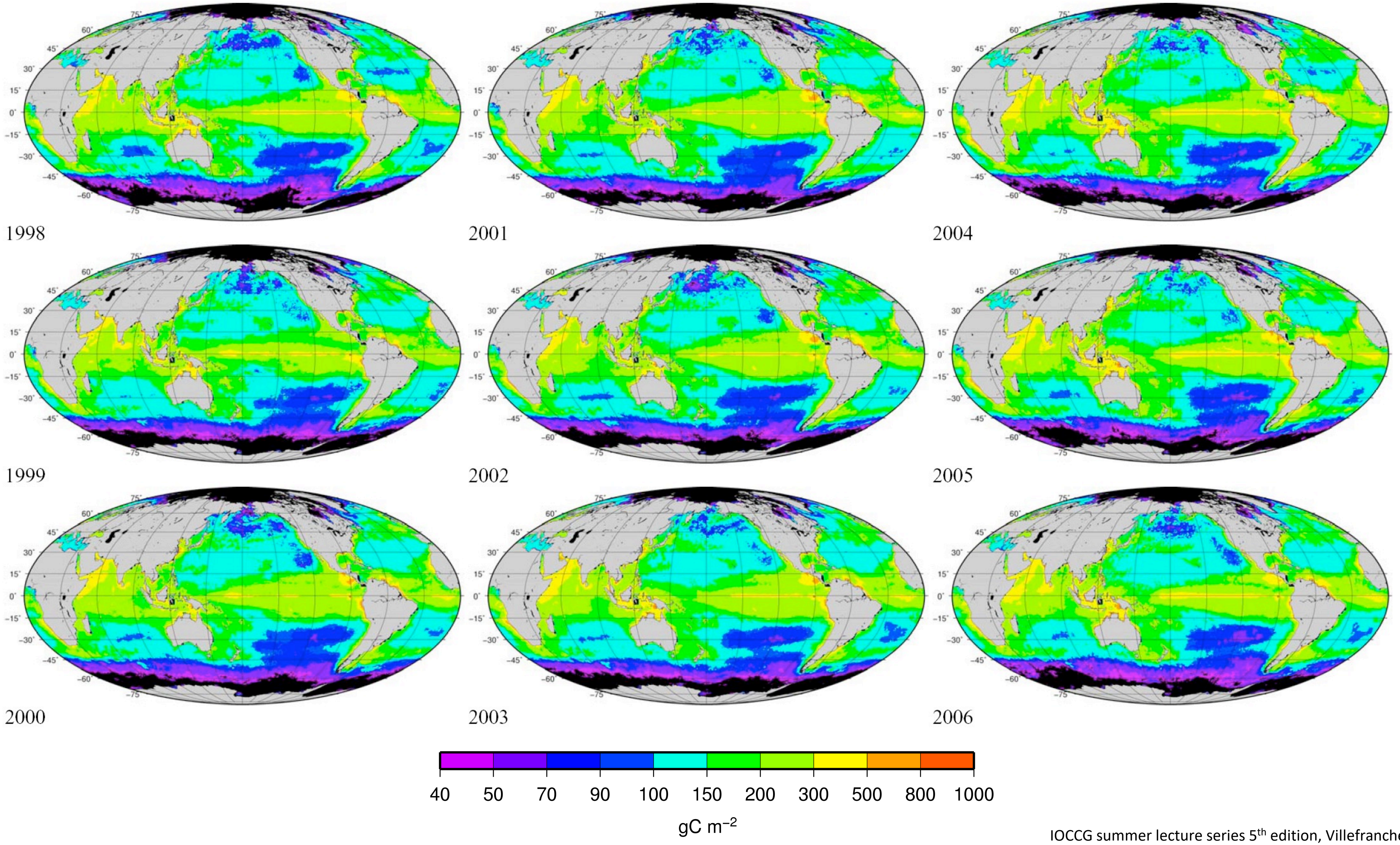
MLD climatology for June



Resulting global PP : 4.2 Gt C (54 for the year 1998)

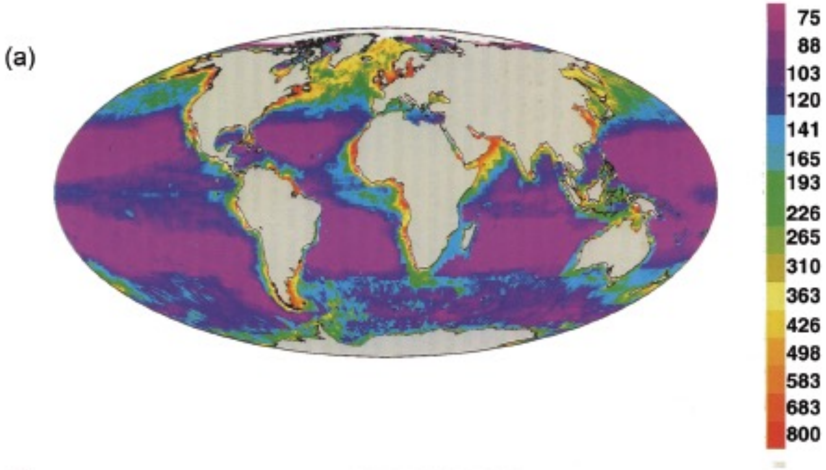
Results: interannual variability

Annual PP for a 9-year time series

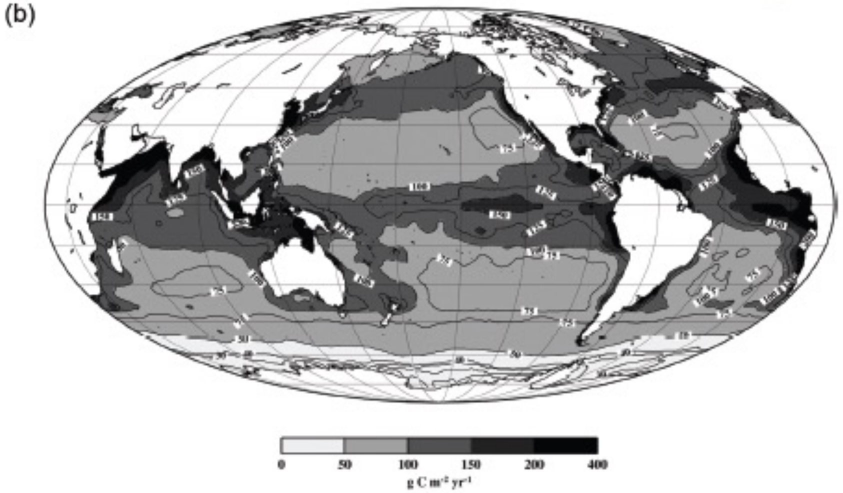


Global estimates

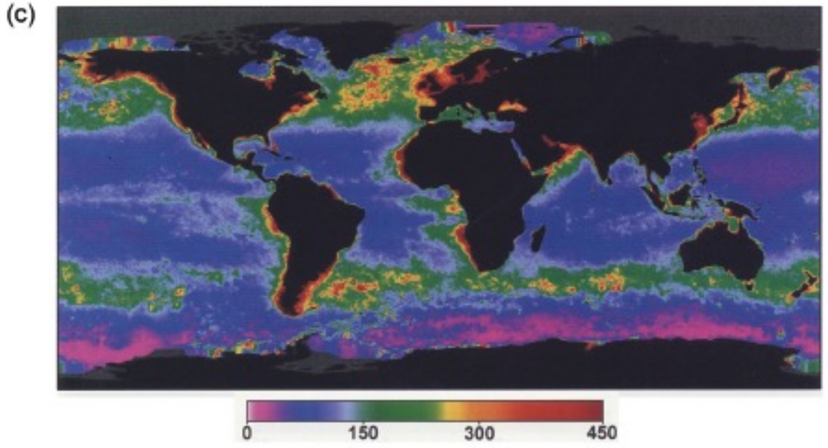
(Studies in the 1990's)



Longhurst et al., J. Plank. Res., 1995;
~50 Gt C per year

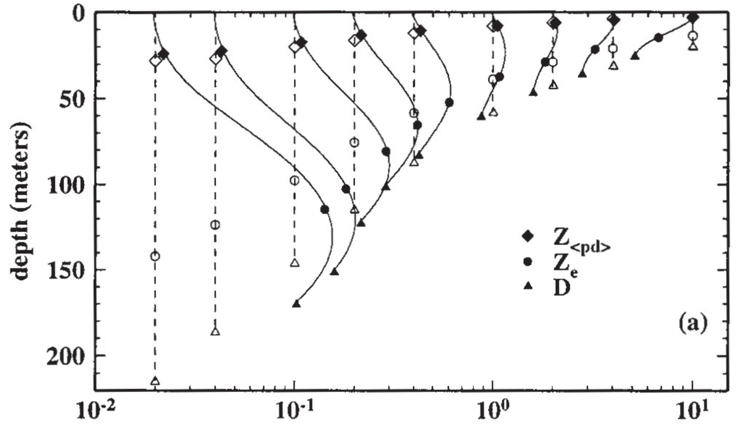


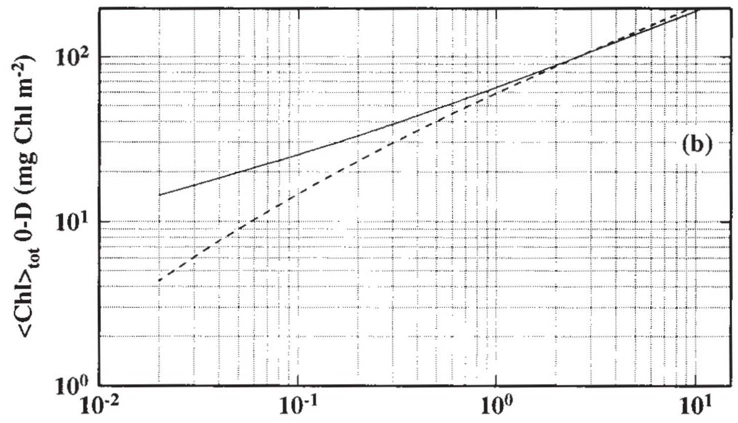
Antoine et al., Global Biogeochem. Cycles, 1996
~47 Gt C per year



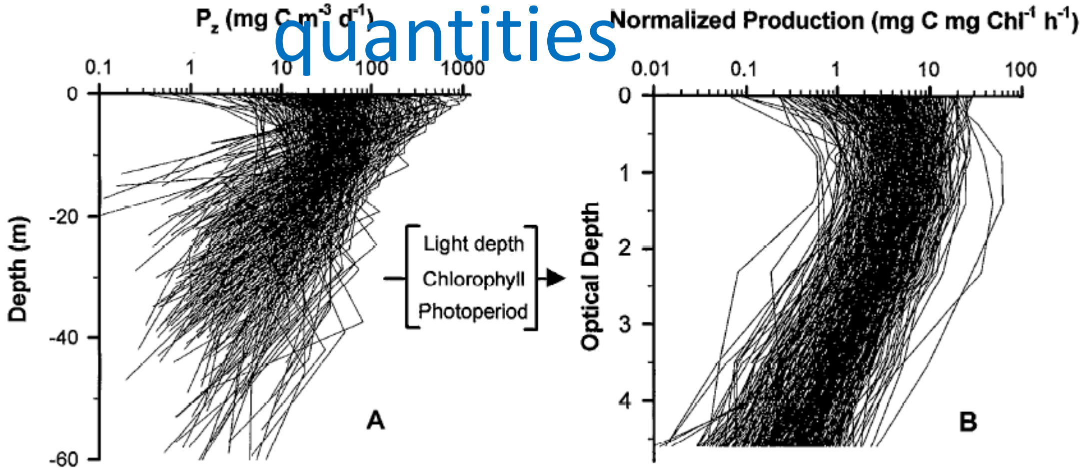
Behrenfeld and Falkowski, Limnol. Oceanogr., 1997
~43 Gt C per year

“Surface” to a vertical profile and to water-column integrated quantities

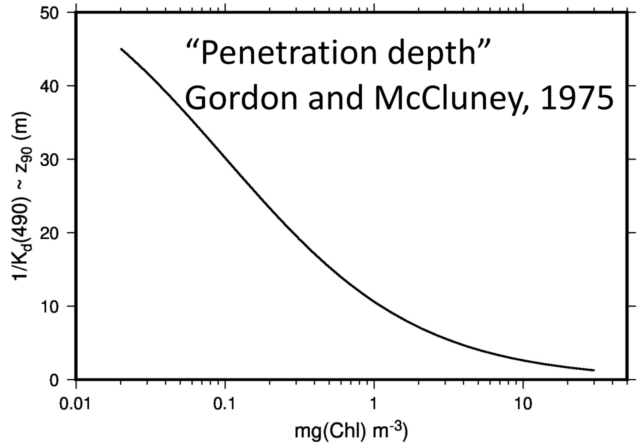


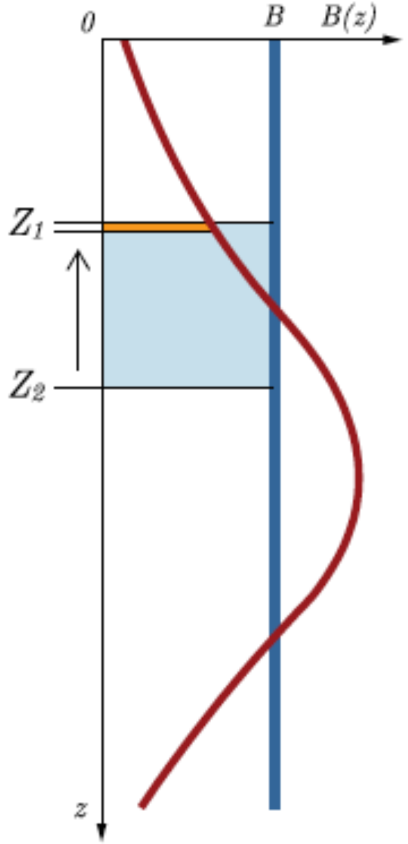


Antoine, D. and A. Morel, 1996. Oceanic primary production : I. Adaptation of a spectral light-photosynthesis model in view of application to satellite chlorophyll observations, Global Biogeochemical Cycles 10, 43-55.

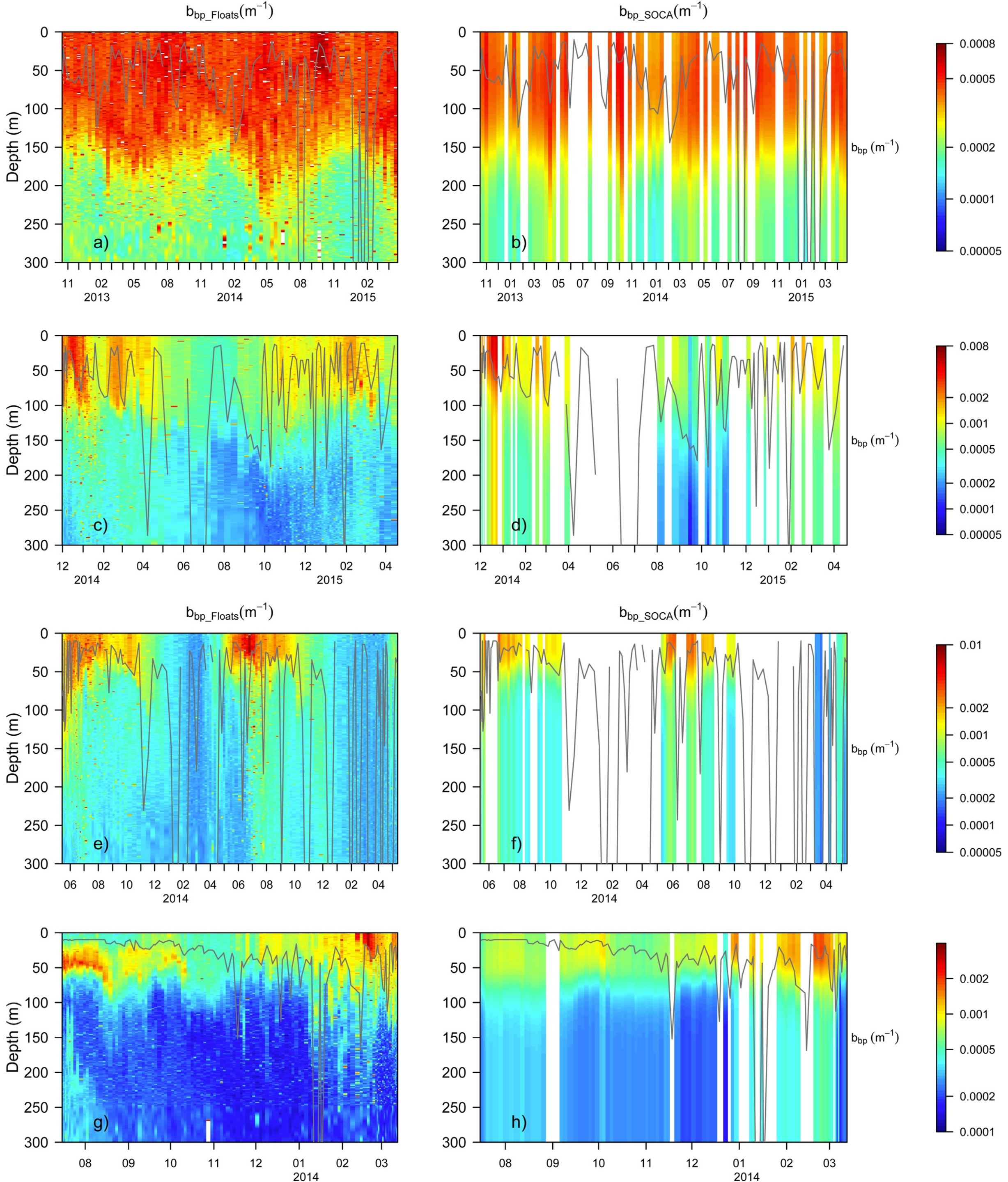


Behrenfeld, M. J., and P. G. Falkowski (1997), Photosynthetic rates derived from satellite-based chlorophyll concentration, Limnol. Oceanogr., 42(1), 1–20, doi:10.4319/lo.1997.42.1.0001.





Kovacˇ, Z., T. Platt, S. Sathyendranath, and M. Morovic´ (2016), Analytical solution for the vertical profile of daily production in the ocean, J. Geophys. Res. Oceans, 121, 3532–3548, doi:10.1002/2015JC011293.



"Surface" to a vertical profile and to water-column integrated quantities

Taking advantage of the measurements from the new networks of autonomous profiling floats BGC-Argo (https://biogeochemical-argo.org)

Sauzède, R., H. Claustre, J. Uitz, C. Jamet, G. Dall'Olmo, F. D'Ortenzio, B. Gentili, A. Poteau, and C. Schmechtig (2016), A neural network-based method for merging ocean color and Argo data to extend surface bio-optical properties to depth: Retrieval of the particulate backscattering coefficient, J. Geophys. Res. Oceans, 121, 2552–2571,doi:10.1002/2015JC011408.

Everything presented so far was chlorophyll-based
What about carbon?

Deep-Sea Research I 102 (2015) 16–25

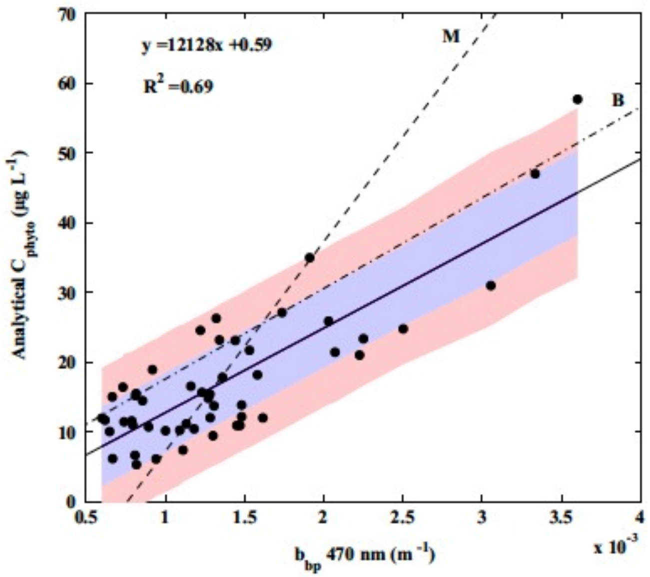
Contents lists available at ScienceDirect

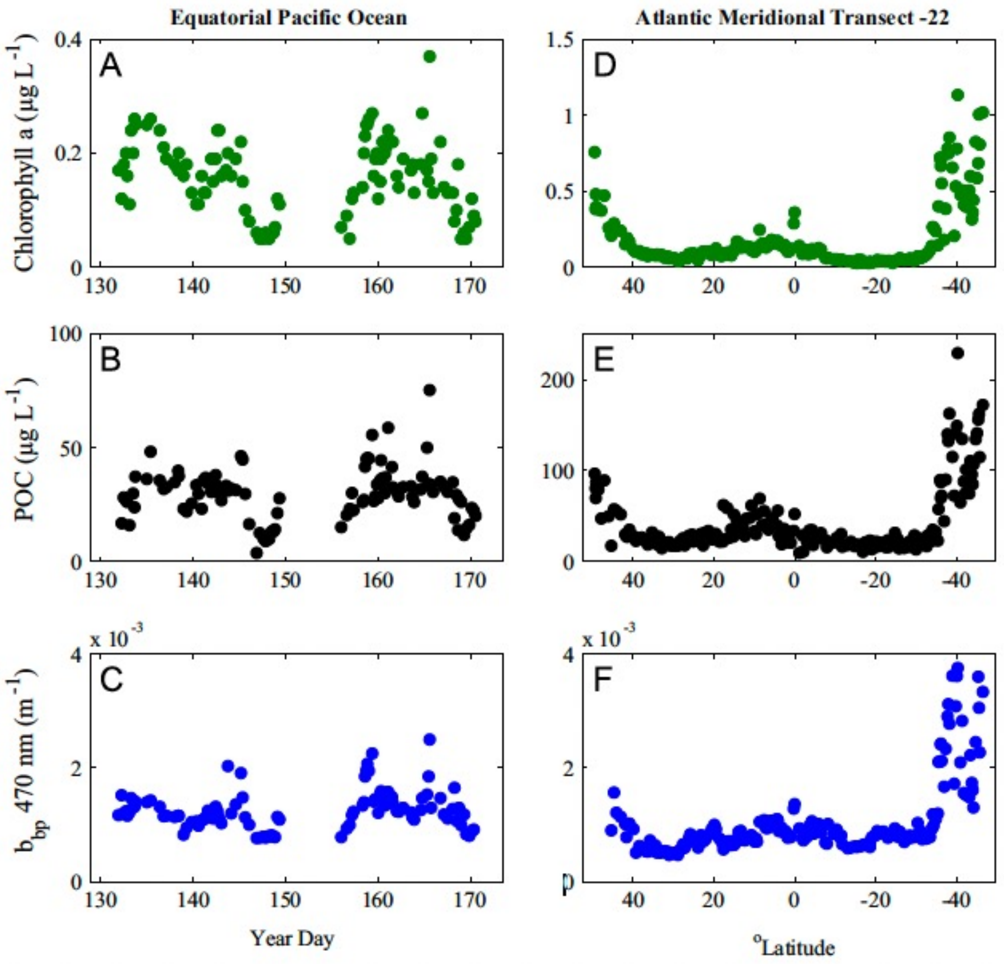
Deep-Sea Research I

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

Analytical phytoplankton carbon measurements spanning diverse ecosystems

Jason R. Graff [a,*], Toby K. Westberry [a], Allen J. Milligan [a], Matthew B. Brown [a], Giorgio Dall'Olmo [b], Virginie van Dongen-Vogels [a,1], Kristen M. Reifel [a], Michael J. Behrenfeld [a]



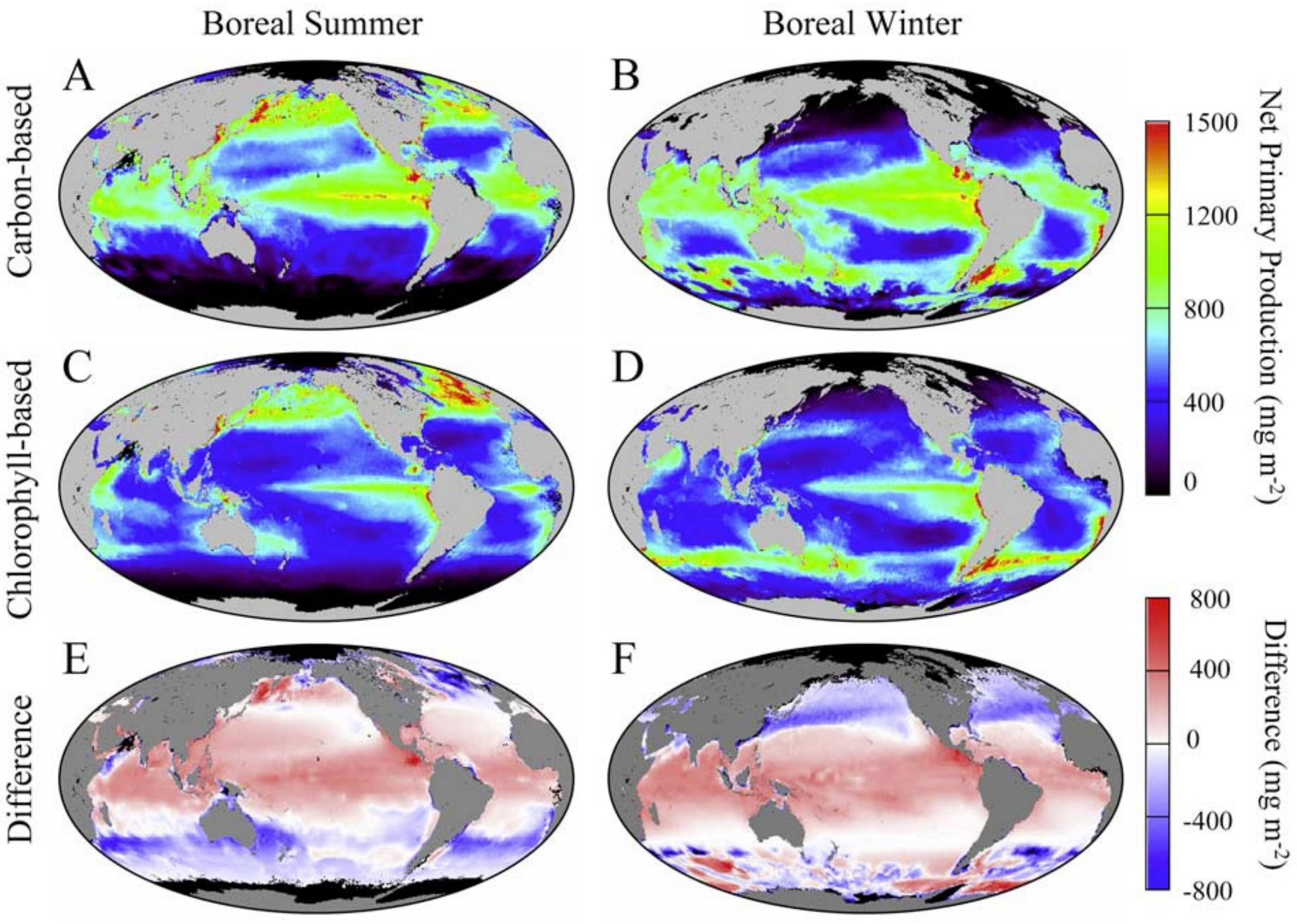


“Carbon-based” productivity

Photo-acclimation:

Phytoplankton can change their Chl levels in response to changes in available light, without the carbon biomass changing.

Therefore, changes in Chl and changes of biomass are not necessarily coupled.



M. J. Behrenfeld, E. Boss, D. A. Siegel, and D. M. Shea, “Carbon based ocean productivity and phytoplankton physiology from space,” Glob. Biogeochem. Cycles 19, 1–14 (2005).

More recent estimates

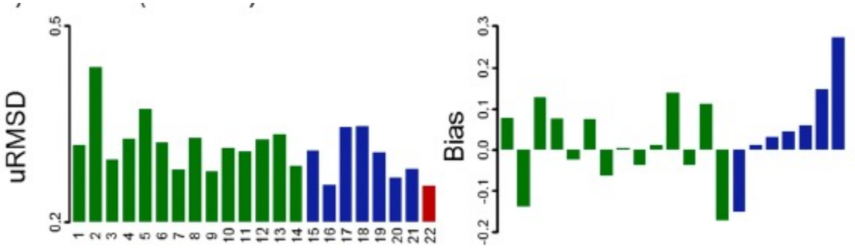
Global Biogeochemical Cycles

RESEARCH ARTICLE
10.1002/2016GB005521

The CAFE model: A net production model for global ocean phytoplankton

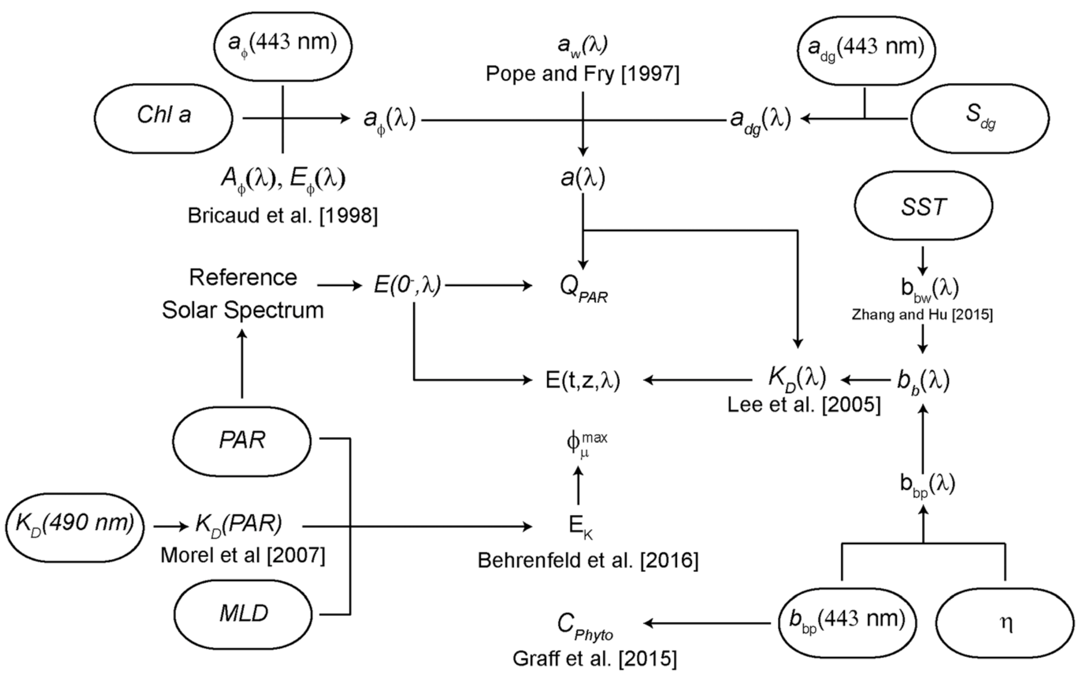
Greg M. Silsbe[1,2], Michael J. Behrenfeld[1], Kimberly H. Halsey[3], Allen J. Milligan[1], and Toby K. Westberry[1]

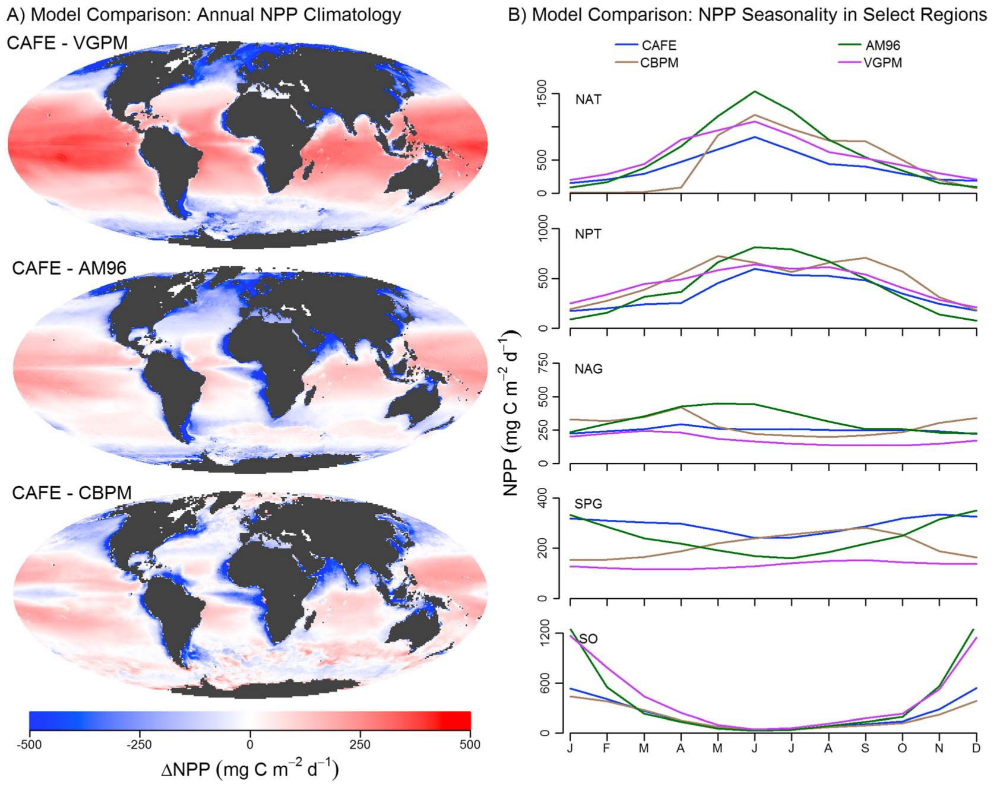
[1]Department of Botany and Plant Pathology, Oregon State University, Corvallis, Oregon, USA, [2]Now at Horn Point Laboratory, University of Maryland Center for Environmental Sciences, Cambridge, Maryland, USA, [3]Department of Microbiology, Oregon State University, Corvallis, Oregon, USA



$$NPP = Q_{PAR} \times \phi_{\mu}^{max} \times tanh(E_K \,/\, E(t,z,\lambda))$$

$$\mu = NPP \,/\, C_{Phyto}$$



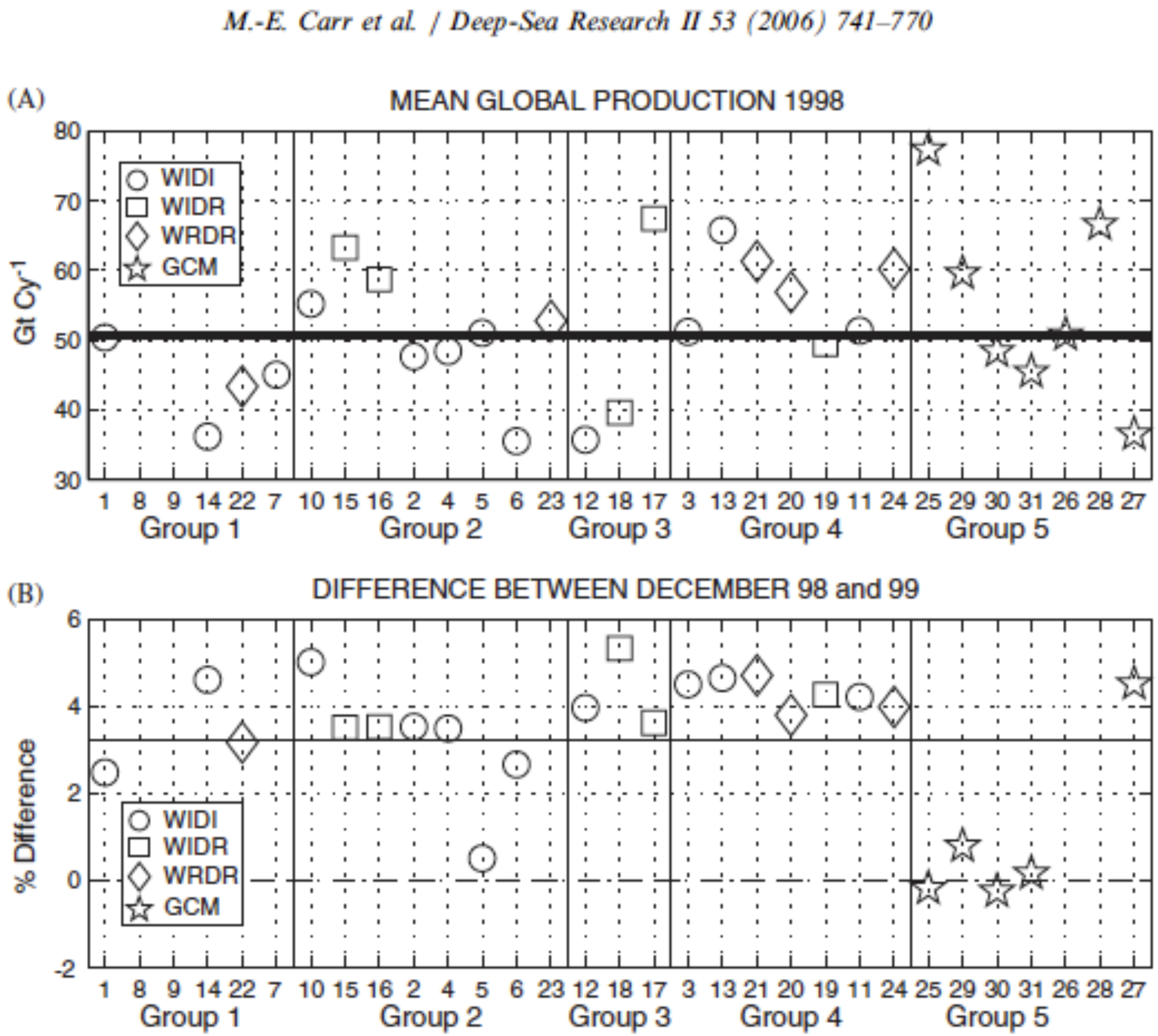


“Variations on this theme” (Chl-based)

NASA Primary Production Algorithms Round Robins (PPARR)

- Campbell J., D. Antoine, R. Armstrong, W. Balch, R. Barber, M. Behrenfeld, R. Bidigare, J Bishop, M-E Carr, W. Esaias, P. Falkowski, N. Hoepffner, R. Iverson, D. Kiefer, O. Kopelevich, S. Lohrenz, J. Marra, A. Morel, J. Ryan, V. Vedernikov, K. Waters, C. Yentsch, and J. Yoder, 2002. Comparison of algorithms for estimating primary productivity from surface chlorophyll, temperature and irradiance, Global Biogeochemical Cycles 16, 3, 10.10129, 2001, GB001444
- Carr M.-E., M.A.M. Friedrichs, M. Schmeltz, M.N. Aité, D. Antoine, K.R. Arrigo, I. Asanuma, O. Aumont, R. Barber, M. Behrenfeld, R. Bidigare, E. Buitenhuis, J. Campbell, A. Ciotti, H. Dierssen, M. Dowell, J. Dunne, W. Esaias, B. Gentili, S. Groom, N. Hoepffner, J. Hishisaka, T. Kameda, C. LeQuéré, S. Lohrenz, J. Marra, F. Mélin, K. Moore, A. Morel, T. Reddy, J. Ryan, M. Scardi, T. Smyth, K. Turpie, G. Tilstone, K. Waters, Y. Yamanaka, 2006. A comparison of global estimates of marine primary production from ocean color, Deep-Sea Research II, 53, 741-770.
- Friedrichs, M.A.M., M.-E. Carr, R. T. Barber, M. Scardi, D. Antoine, R. A. Armstrong, I. Asanuma, M. J. Behrenfeld, E. T. Buitenhuis, F. Chai, J. R. Christian, A. M. Ciotti, S. C. Doney, M. Dowell, J. Dunne, B. Gentili, W. Gregg, N. Hoepffner, J. Ishizaka, T. Kameda, I. Lima, J. Marra, F. Mélin, J. K. Moore, A. Morel, R. T. O’Malley, J. O’Reilly, V. S. Saba, M. Schmeltz, T. J. Smyth, J. Tjiputra, K. Waters, T. K. Westberry, A. Winguth, 2009. Assessing the uncertainties of model estimates of primary production in the tropical Pacific ocean, Journal of Marine Systems, doi:10.1016/j.jmarsys.2008.05.010.
- Saba V.S., M A. M. Friedrichs, M.E. Carr, D. Antoine , R. A. Armstrong, I. Asanuma, O. Aumont, N.R. Bates, M.J. Behrenfeld , V. Bennington, L.Bopp, J.Bruggeman, E.T. Buitenhuis, M.J. Church, A.M. Ciotti, S.C. Doney, M.Dowell, J.Dunne, S.Dutkiewicz , W.Gregg, N.Hoepffner, K.J. W. Hyde, J.Ishizaka , T. Kameda, D.M. Karl, I.Lima, M.W. Lomas, J.Marra , G.A. McKinley, F.Mélin, J. K.Moore, A.Morel, J.O’Reilly , B. Salihoglu, M. Scardi, T.J. Smyth, S.Tang, J.Tjiputra, J. Uitz , M.Vichi, K.Waters, T.K. Westberry, A.Yool, 2010. The challenges of modeling depth-integrated marine primary productivity over multiple decades: A case study at BATS and HOT, Global Biogeochemical Cycles, 24, GB3020, doi:10.1029/2009GB003655.
- Saba V.S., M.A. M. Friedrichs, D.Antoine, R.A. Armstrong, I.Asanuma, M.J. Behrenfeld, A.M. Ciotti, M.Dowell, N. Hoepffner, K.J. W. Hyde, J. Ishizaka, T. Kameda, J. Marra, F. Mélin, A. Morel, J.O’Reilly, M. Scardi, W.O. Smith Jr., T.J. Smyth, S. Tang, J. Uitz, K. Waters, T.K. Westberry, 2011. An evaluation of ocean color model estimates of marine primary productivity in coastal and pelagic regions across the globe, Biogeosciences, 8, 489–503.

What did we learn from the PPARR?



How can we improve this?

- With current approaches, the main sources of uncertainties are:

- Chl and b_{bp}: the uncertainties here are inherent to satellite OCR
- Phytoplankton carbon from b_{bp}
- Photosynthetic parameters (P^B_{max} and α^B)

- Improving understanding of how α_B and P^B_{max} vary with environment parameters accessible from space (SST, average light, nutrients)
- Improving determination of phytoplankton carbon from satellite OCR (C_{phy} *vs.* b_{bp})
- Collect more data (!)

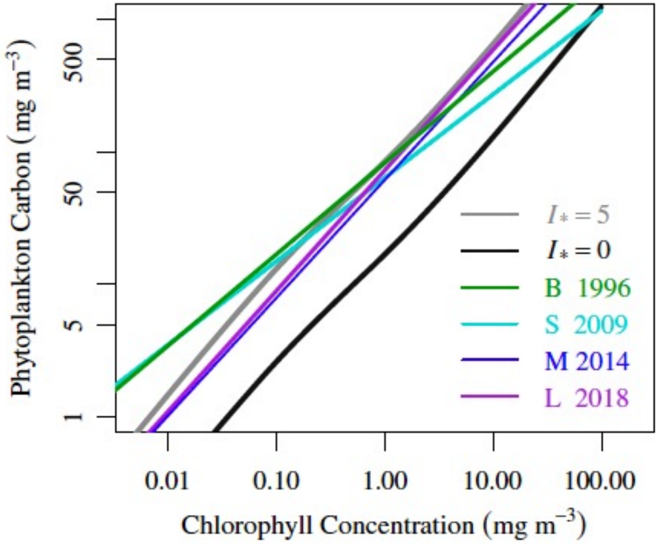
Reconciling approaches?
Ch-based *vs.* C-based

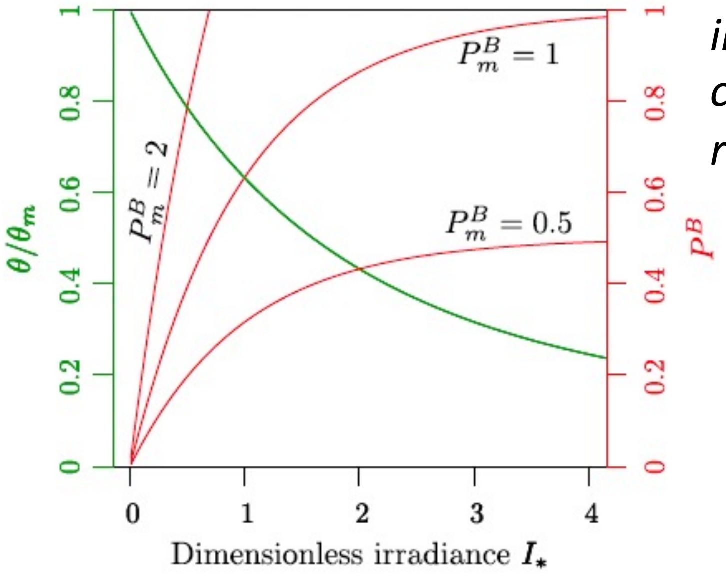
C100 Vol. 59, No. 10 / 1 April 2020 / *Applied Optics* **Research Article**

applied optics

Reconciling models of primary production and photoacclimation [Invited]

Shubha Sathyendranath,[1,*] Trevor Platt,[2] Žarko Kovač,[3] James Dingle,[2] Thomas Jackson,[2] Robert J. W. Brewin,[4] Peter Franks,[5] Emilio Marañón,[6] Gemma Kulk,[2] and Heather A. Bouman[7]





"The first ocean-color-based computations of primary production at the global scale emerged some 25 years ago [6]. Many others have followed in the intervening years [23,33,48–51], using one or another classes of models discussed in the previous section. Much effort has been expended comparing the products against each other, against in situ data, and against ecosystem models [11,13,14,52]. Yet, we have made little progress in reducing uncertainties in the products and the confidence of the climate community in these products remains low"

Oh, wait, could we do otherwise?

- With satellite OCR, we have repeated biomass observations.
- Therefore, we can assess the observed change in biomass from a time t to a time $t + \Delta t$
- The difference will indicate whether there is accumulation, stability or decline in biomass (this is still Chl, however. So you need a C:Chl ratio).

  The observed gains or losses are however caused by combined effects of:

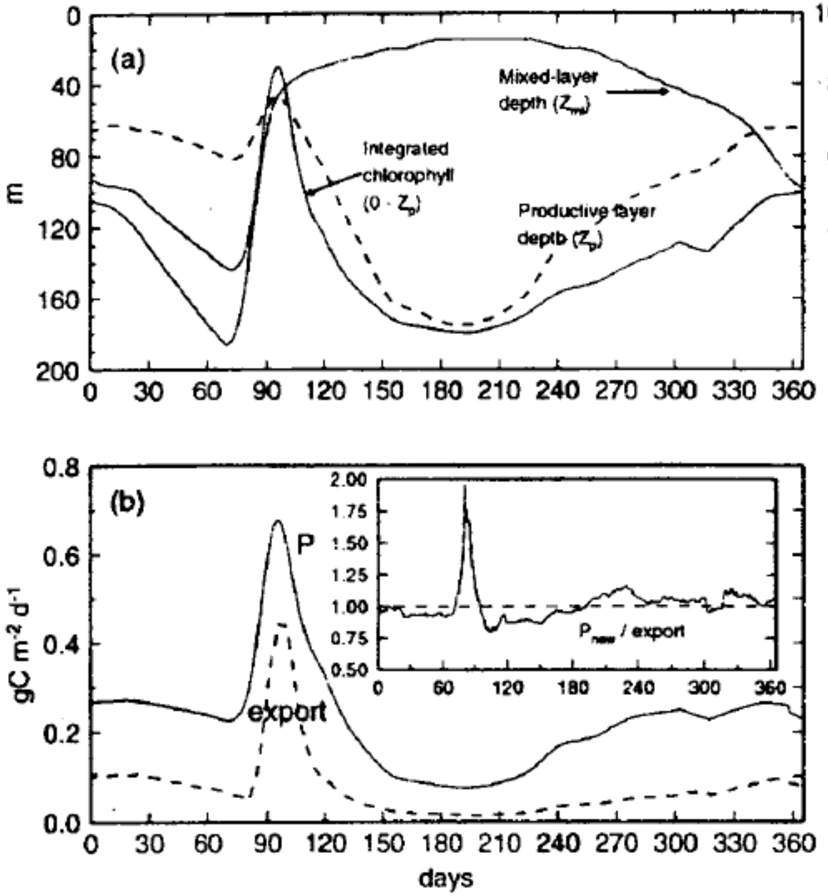
  1. Production of new biomass (+)
  2. Horizontal advection, vertical mixing (+/-)
  3. Local recycling of biomass (-)
  4. Export of biomass to deeper layers (-)

This means OCR observations alone are not enough to assess export (4).
You need to:

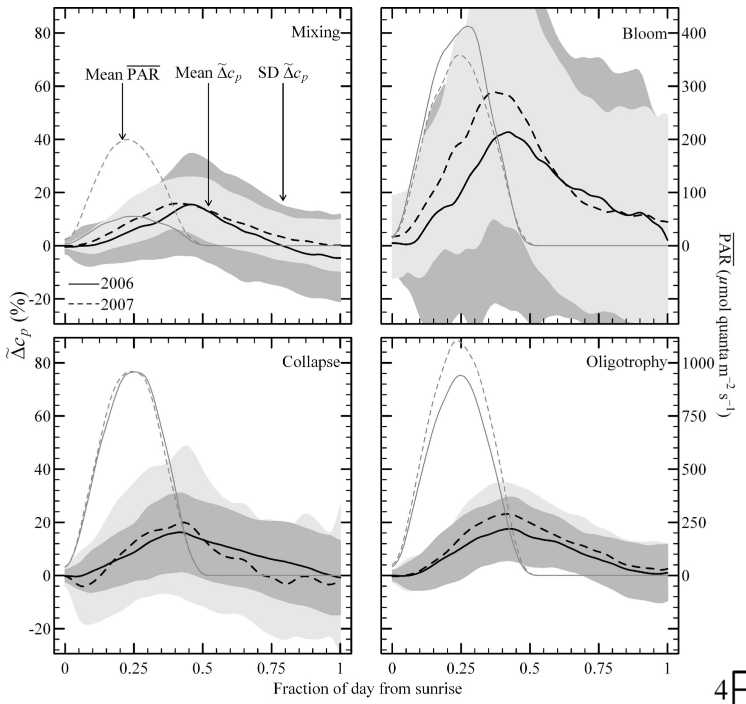
- Either neglect or model (2)
- Assess the gross production, so that you can compare the predicted increase of biomass to the observed increase or decrease
- If a loss, assess how much of it is export and how much is recycling

Examples

Daily scale

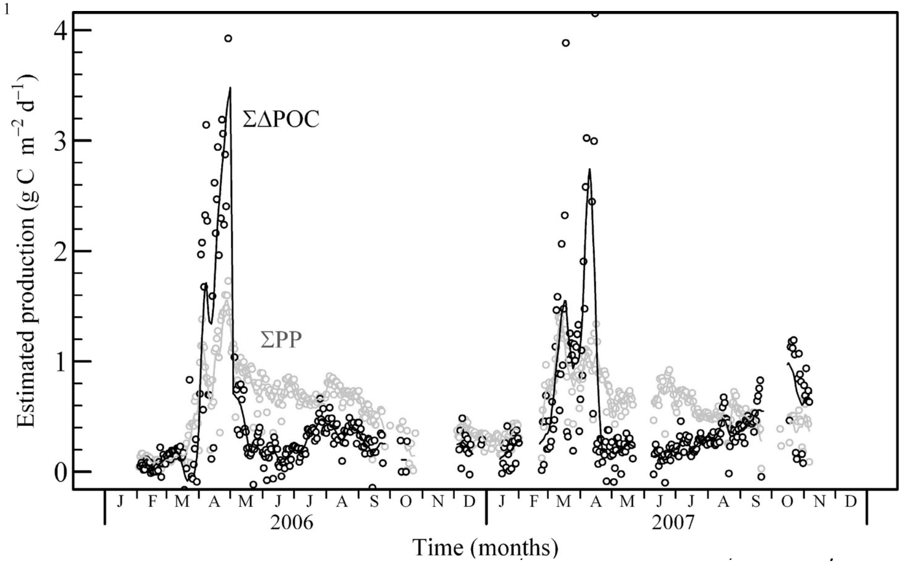


Antoine and Morel, Tellus 1995a,b



Gernez, Antoine and Huot, Limnol. Oceanogr., 56(1), 2011, 17–36

Hourly scale



Primary production derived from OCR observations from geostationary platforms

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095528

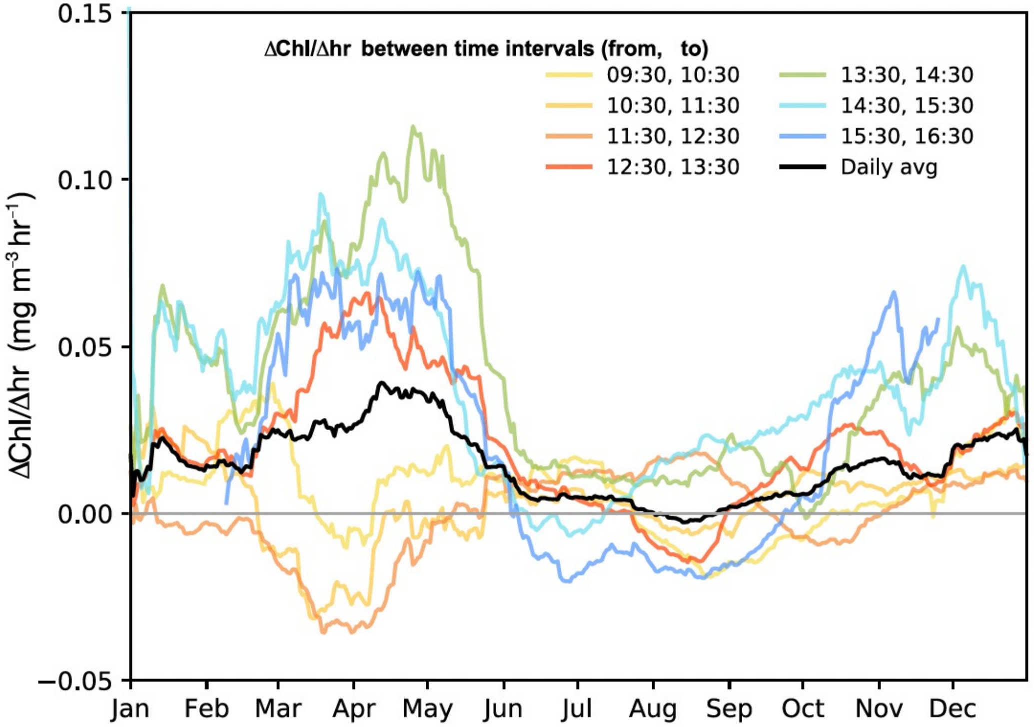
Key Points:

- The Geostationary Ocean Color Instrument tracks changes in net phytoplankton growth at hourly intervals

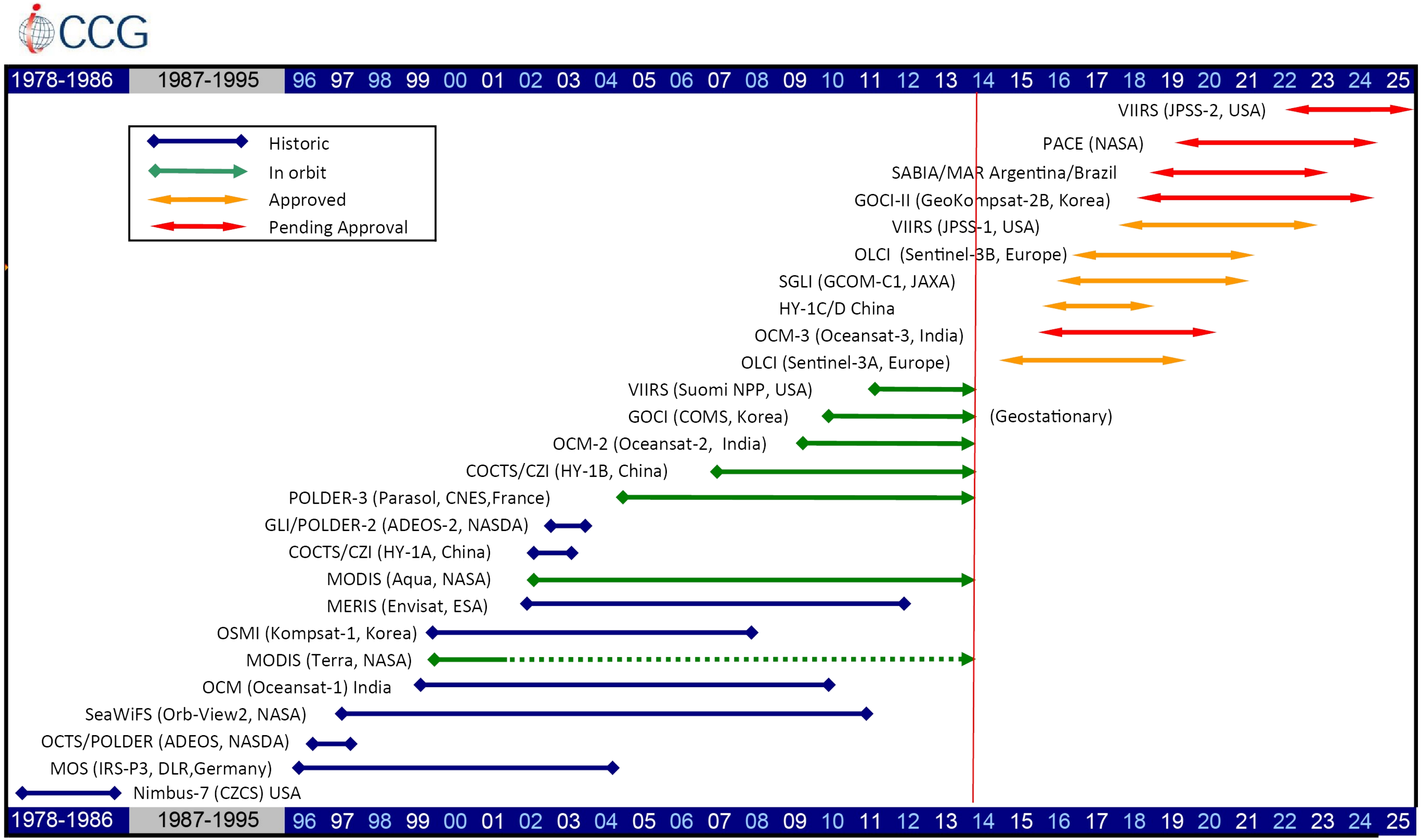
Assessing Net Growth of Phytoplankton Biomass on Hourly to Annual Time Scales Using the Geostationary Ocean Color Instrument

Joseph E. Salisbury[1], Bror F. Jönsson[2], Antonio Mannino[3], Wonkook Kim[4], Joaquim I. Goes[5], Jin-Yong Choi[6], and Javier A. Concha[7]

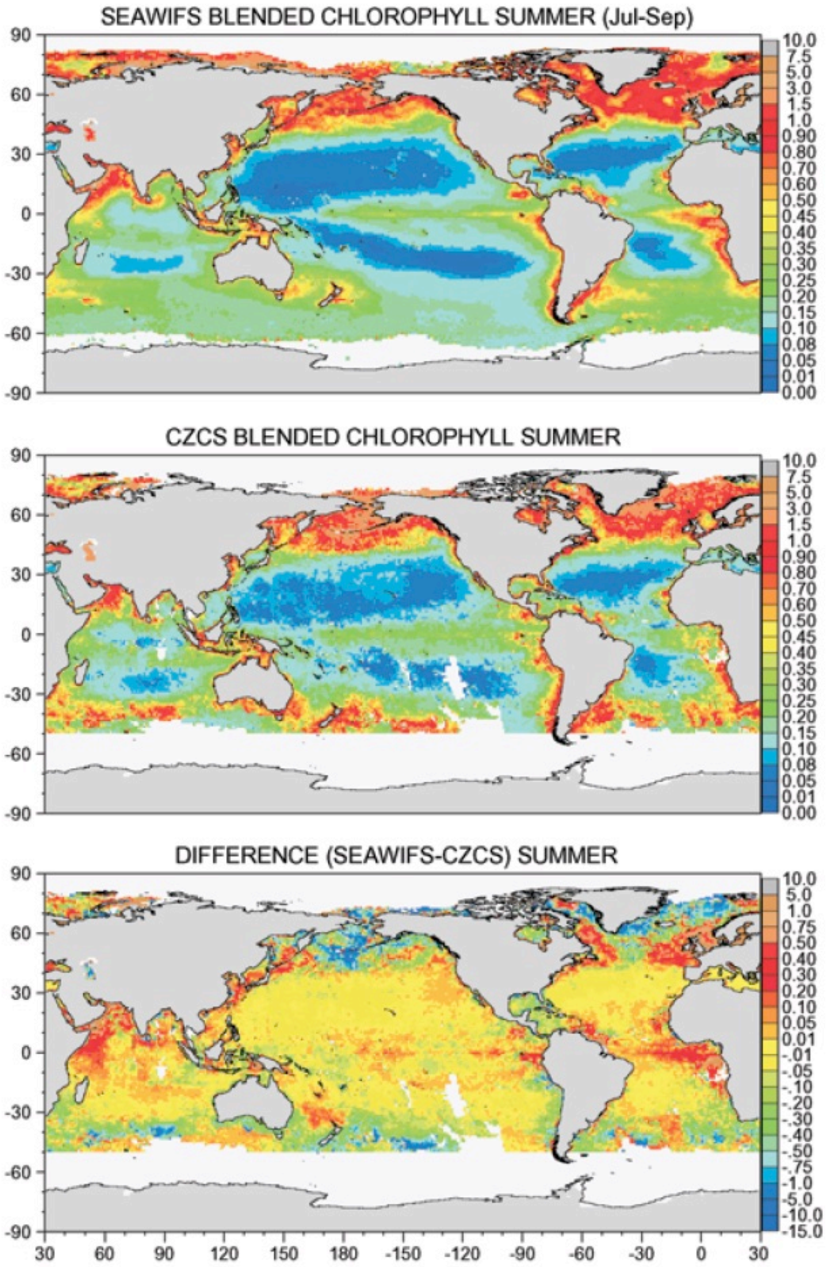
$$\mu_{Chl} = \ln\left(\frac{Chl_{t+1}}{Chl_t}\right)$$



The quest for quantifying long-term changes



The quest for quantifying long-term changes



Gregg and co-workers

(Gregg and Conkright, 2001, 2002; Gregg et al., 2002, 2003)

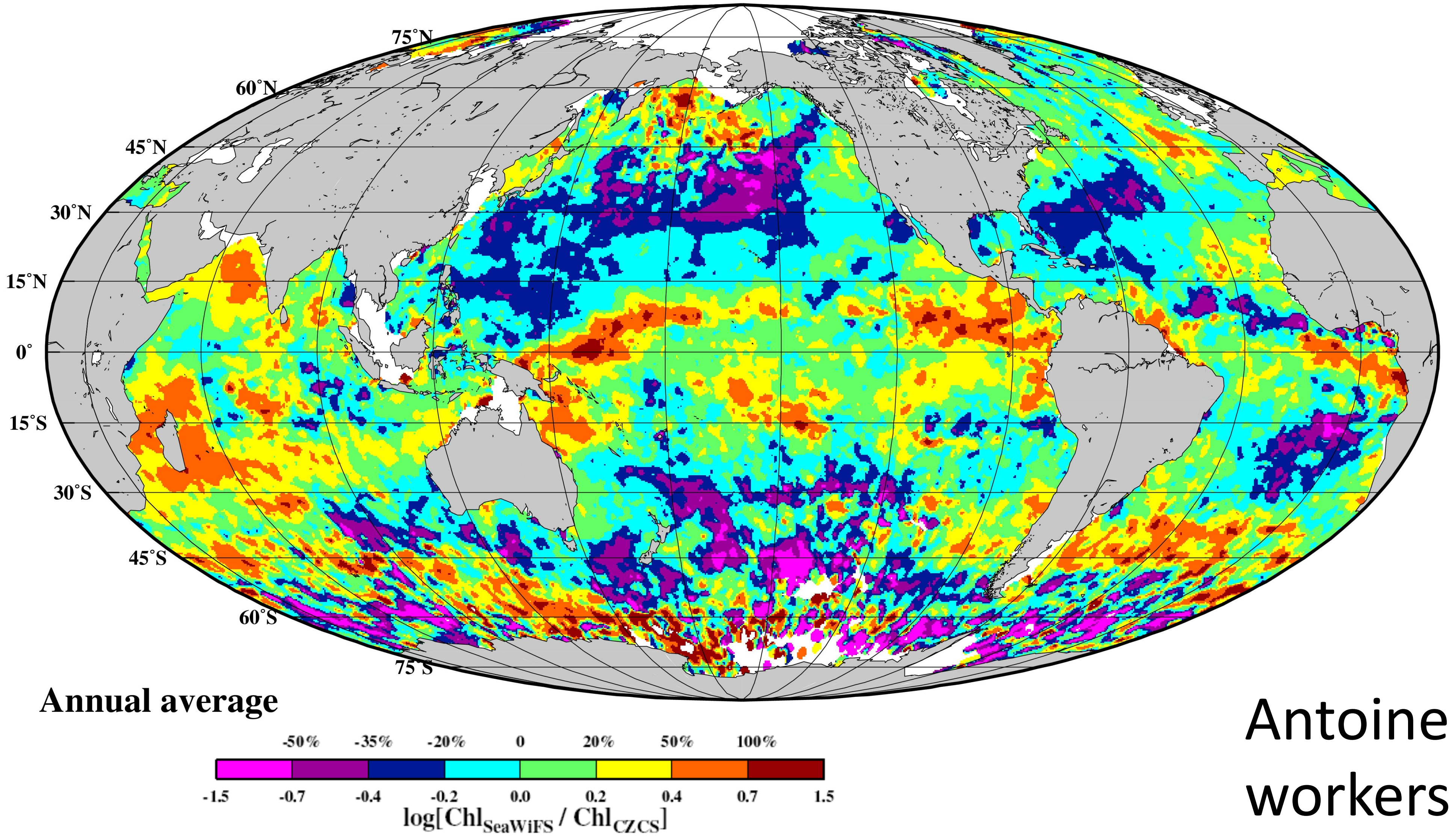
They performed a re-analysis of the CZCS record (1979-1985) and then a blending of this record with in situ chlorophyll.
The SeaWiFS record was similarly blended, and then compared to CZCS.

They claim a 6% decrease of global chlorophyll from the 1980’s (CZCS era) to the 2000’s (SeaWiFS era)

6% decrease on primary production as well

Figure 2 from Gregg and Conkright, Geophys. Res. Letters, vol 29, 2002

The quest for quantifying long-term changes



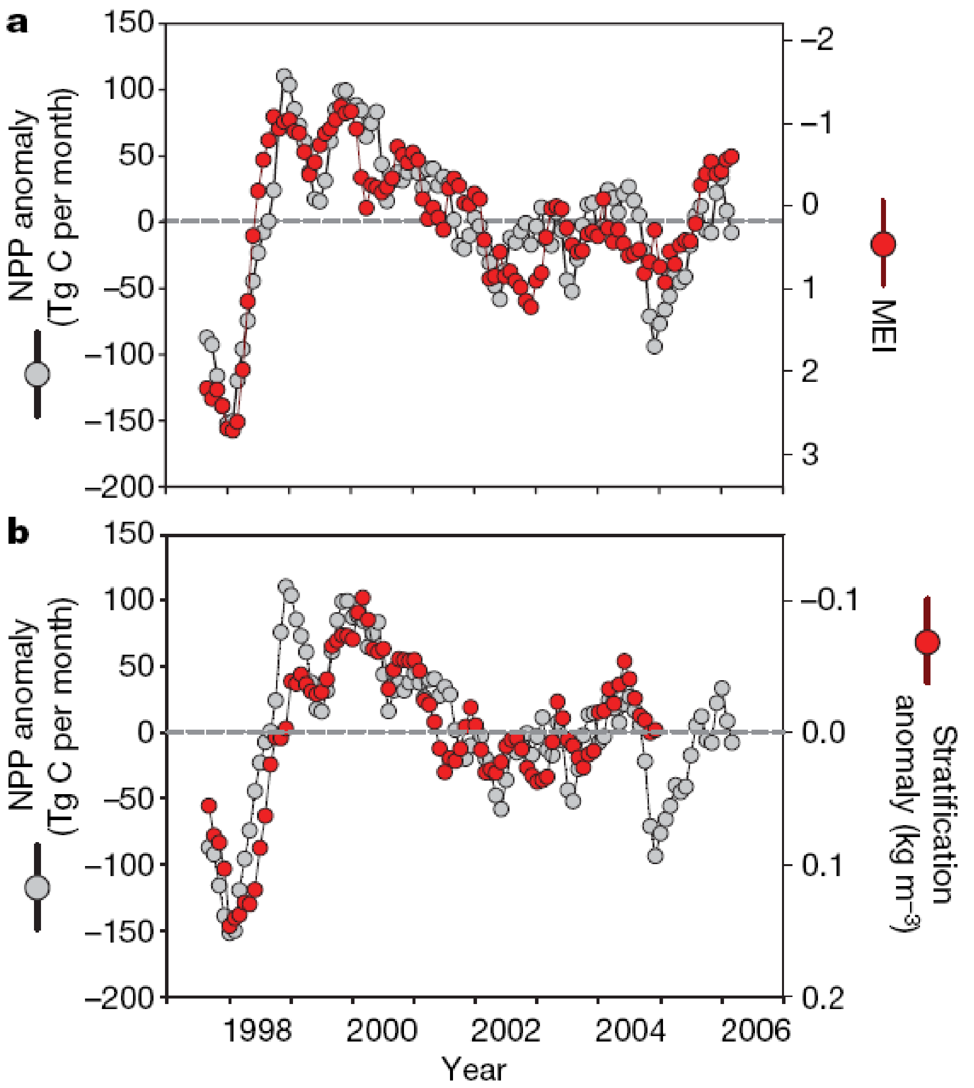
Antoine and co-workers, 2005

From Antoine, D., Morel, A., Gordon, H.R., Banzon, V.F. and R.H. Evans (2005) Bridging ocean color observations of the 1980's and 2000's in search of long-term trends. J. Geophys. Res., VOL. 110

The quest for quantifying long-term changes

Behrenfeld et al., Nature, vol 444, 2006

SeaWiFS 9-year global record coupled with indicators of the ocean physical state



Anomalies in Chl and net primary production (NPP; gray dots) correlate with the Multivariate ENSO index (MEI; red dots) or the stratification anomaly (red dots also; density difference between the surface and a depth of 200 m)

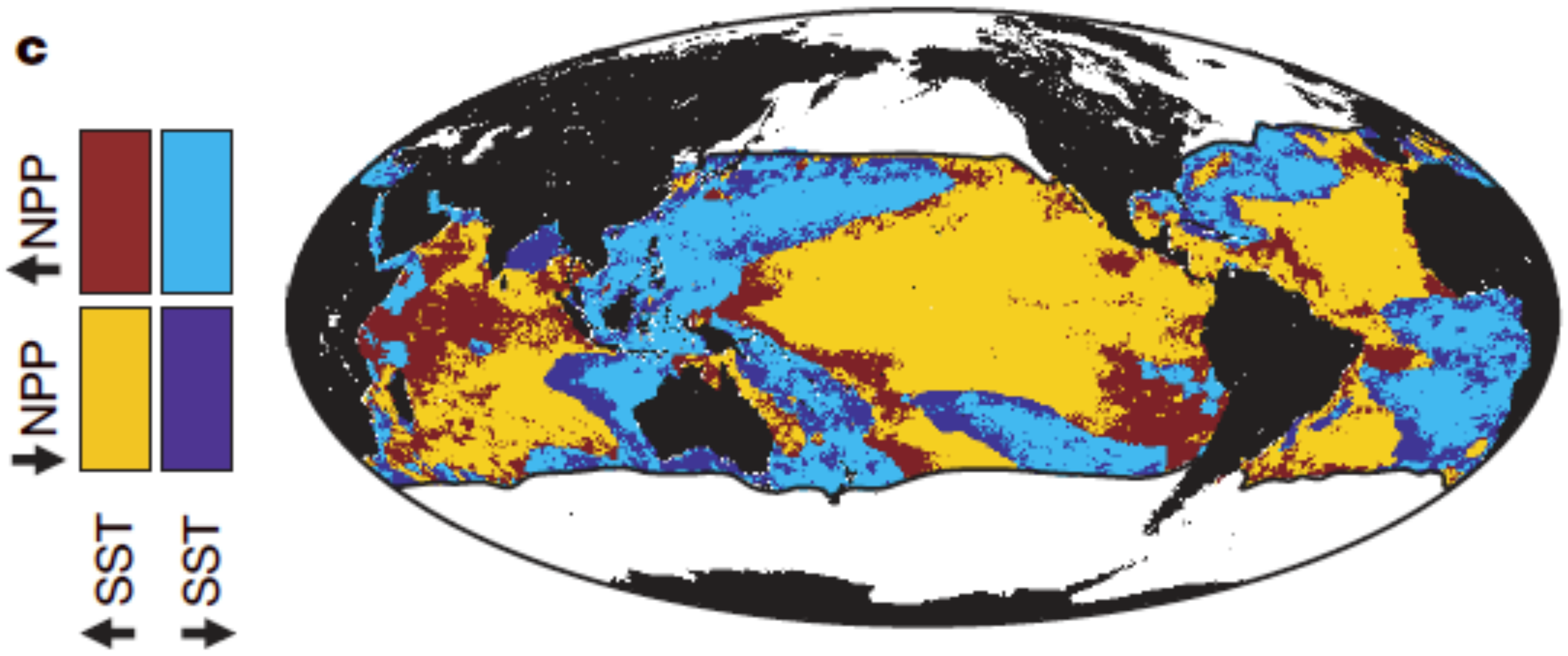
(MEI includes sea-level pressure, surface winds, SST, surface air temperature and cloudiness)

This is not a decadal or multi-decadal analysis, but it indicates how the system could respond; the MEI extends back to the 50's so it could be used as a proxy to reconstruct past changes in ocean NPP

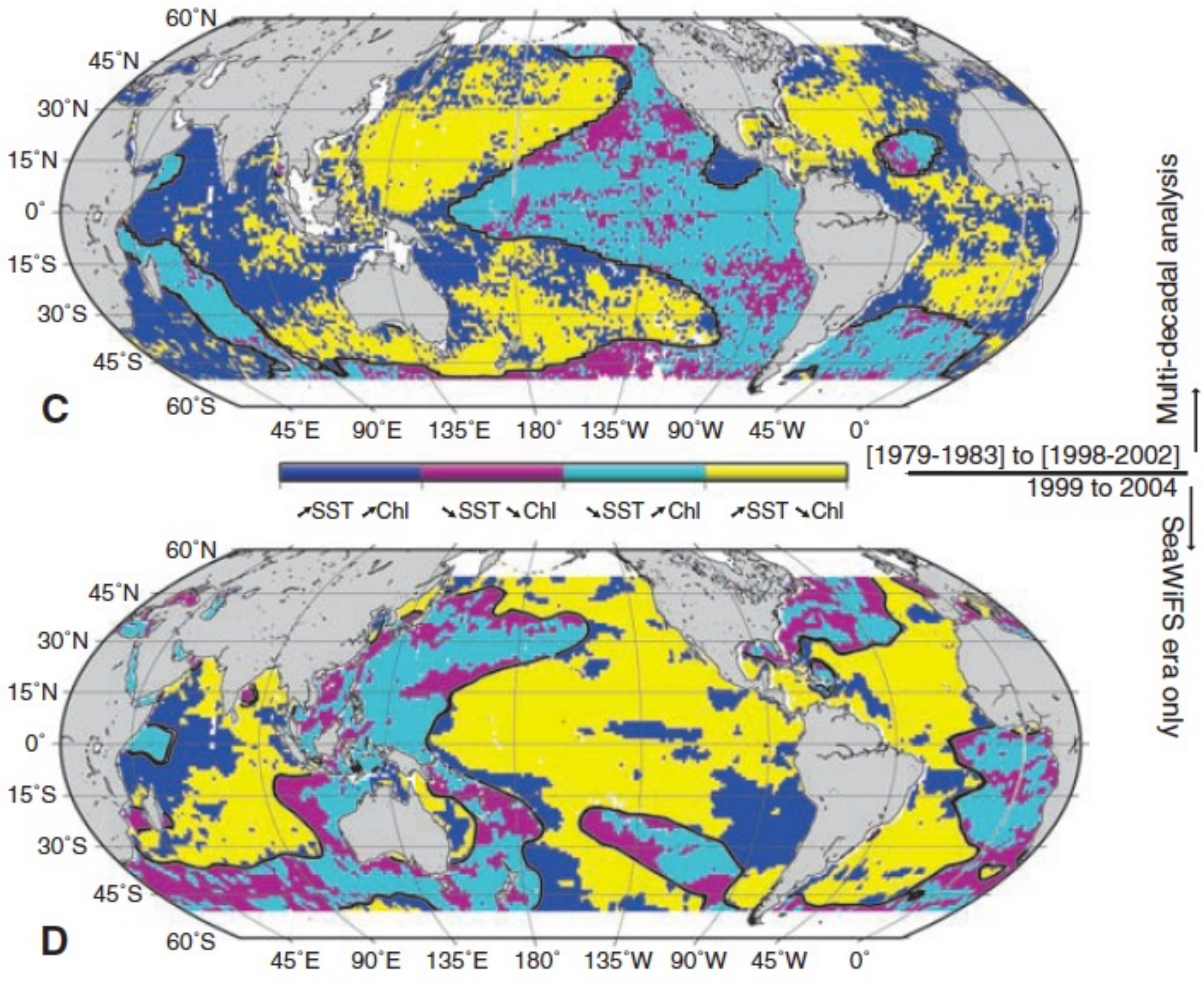
The quest for quantifying long-term changes

Behrenfeld et al., Nature, vol 444, 2006

SeaWiFS 9-year global record coupled with indicators of the ocean physical state

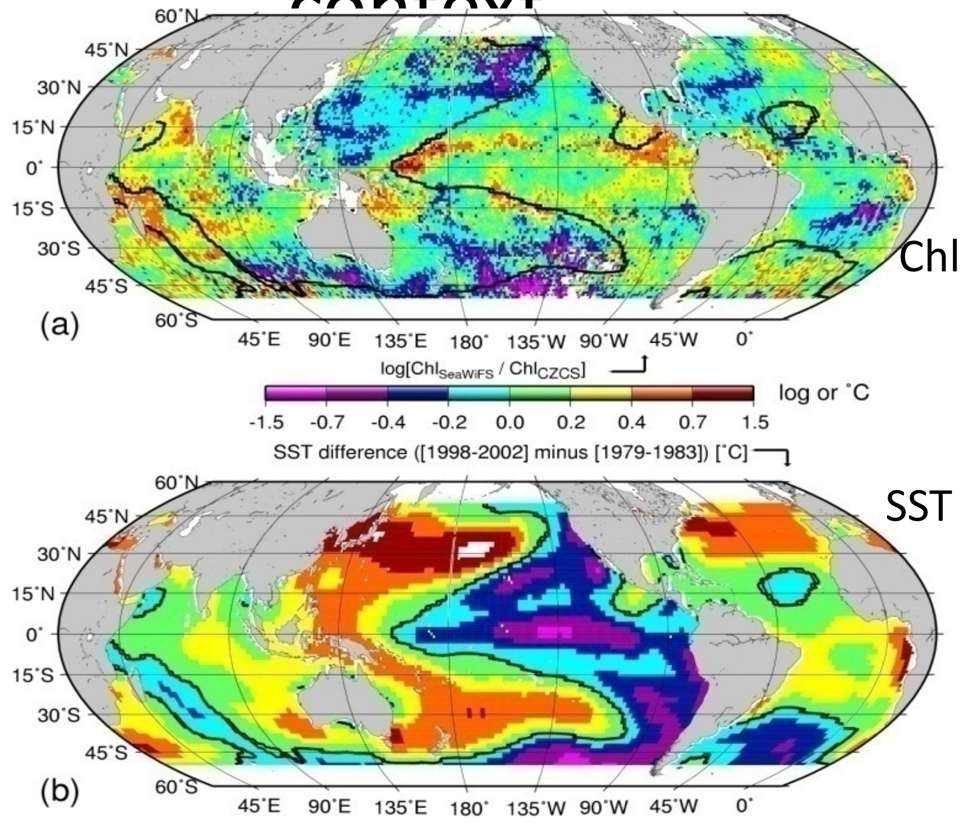


The quest for quantifying long-term changes



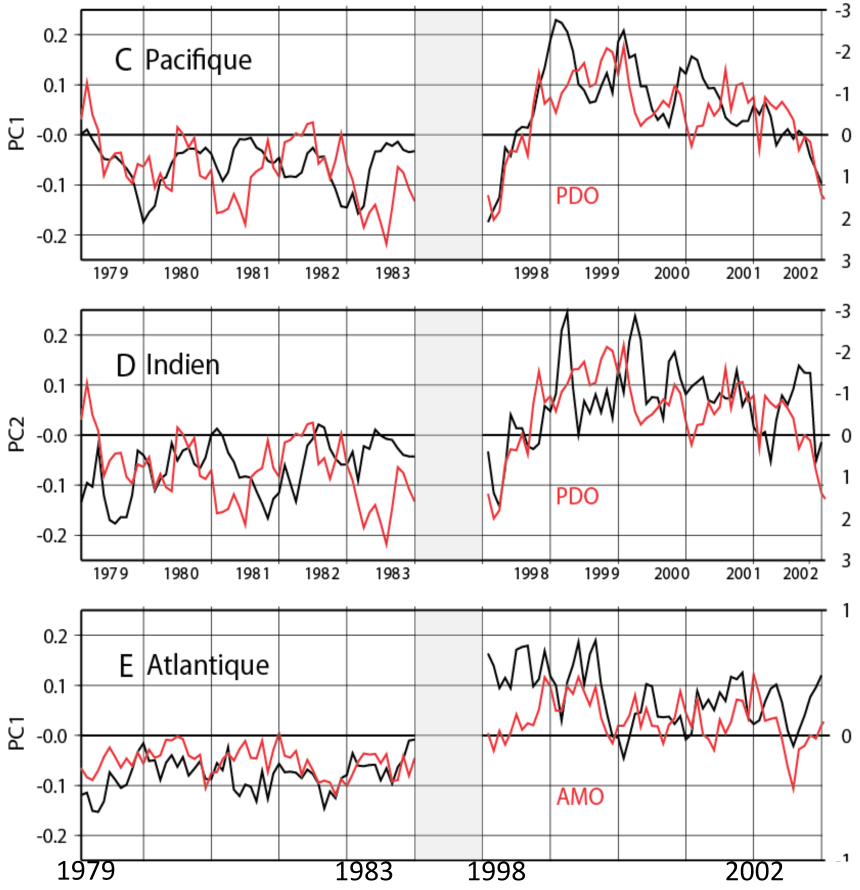
The quest for quantifying long-term changes

Natural decadal oscillations: the global context



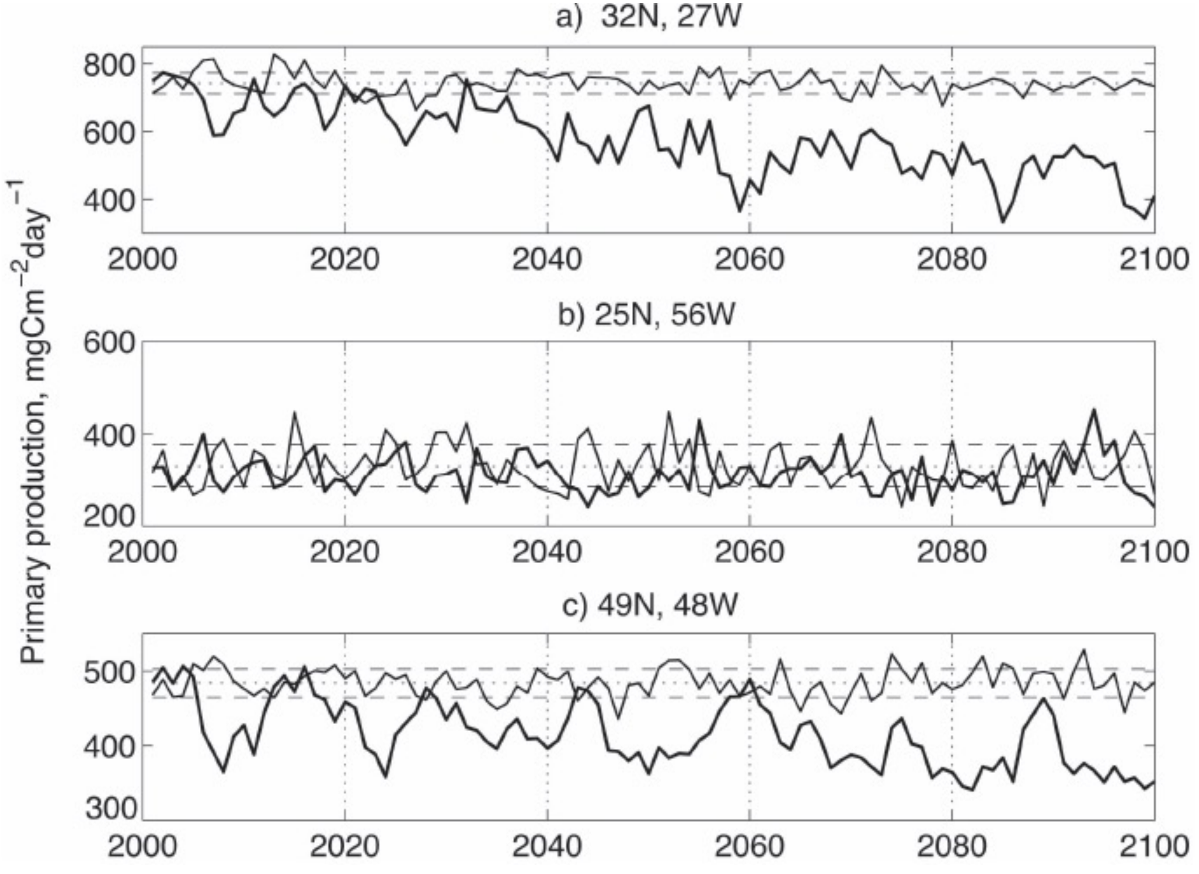
(Martinez et al., Science 2009)

1979-1983 (CZCS) 1998-2002 (SeaWiFS)



- Atlantic Multidecadal Oscillation regime shift (cold to warm phase)
- Pacific Decadal Oscillation regime shift (warm to cold phase)

"Climate Change detectability"
Henson et al., 2010, Biogeosciences, 7, 621–640



Their fig. 7 (example from the GFDL model)

Their work:

• Running 3 global coupled ocean-ecosystem models (GFDL MOM-4/TOPAZ, IPSL NEMO/PISCES, NCAR physical model/CCM-3) over 2001-2100.

• Comparing Chl and production in reference runs and "climate change runs" with the IPCC AR4 A2 scenario

Their conclusions:

•Detection of climate change-driven trends in the satellite data is confounded by the relatively short time series and large interannual and decadal variability.

•Thus, recent observed changes in chlorophyll, primary production and the size of the oligotrophic gyres cannot be unequivocally attributed to the impact of global climate change.

•Analysis of modeled chlorophyll and primary production from 2001–2100 suggests that, on average, the climate change-driven trend will not be unambiguously separable from decadal variability until 2055.

•Because the magnitude of natural variability in chlorophyll and primary production is larger than, or similar to, the global warming trend, a consistent, decades-long data record must be established if the impact of climate change on ocean productivity is to be definitively detected

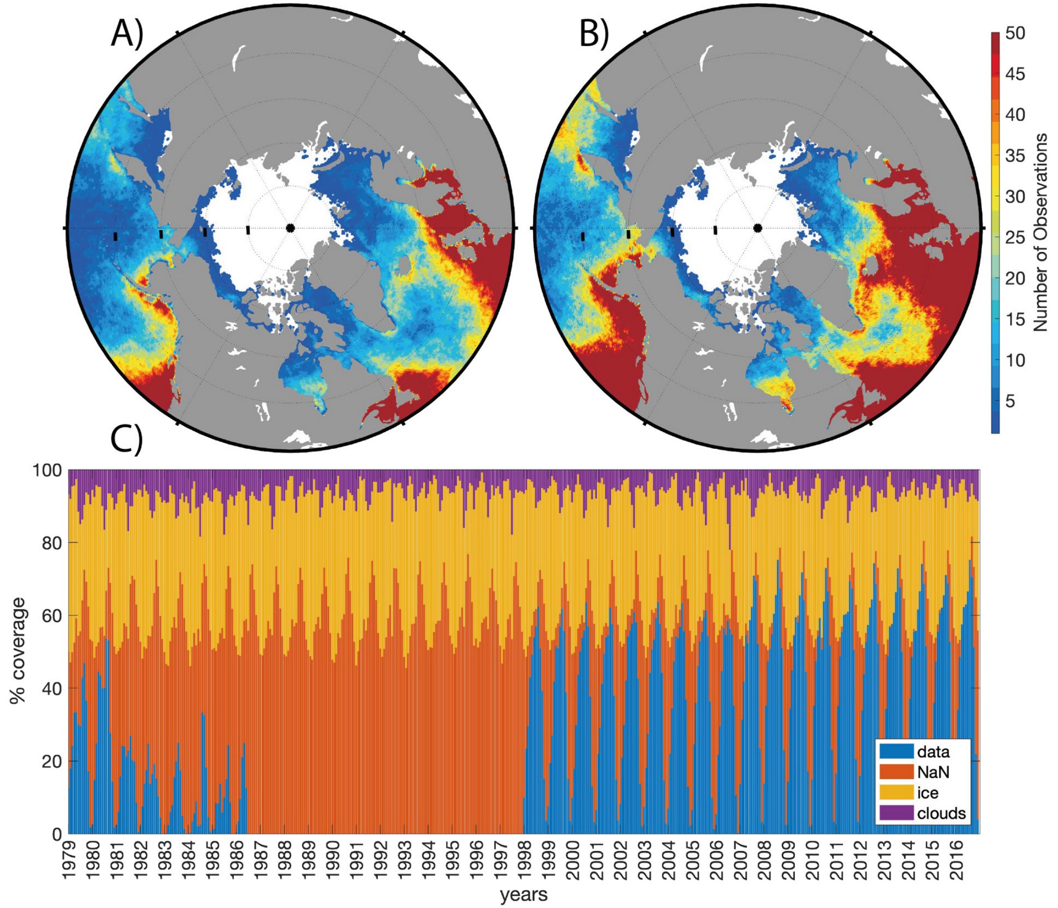
Contents lists available at ScienceDirect

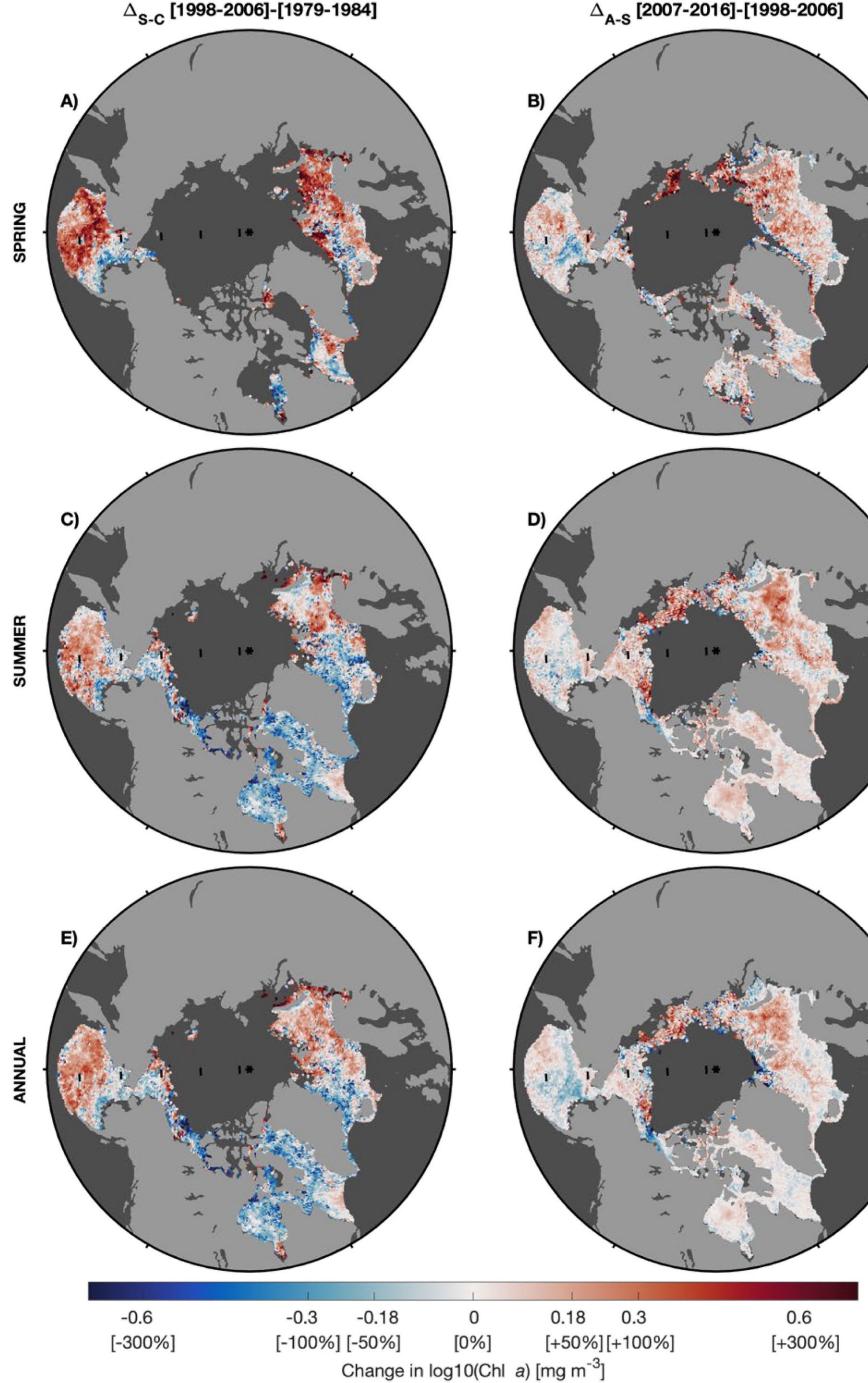
Remote Sensing of Environment

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

Decadal changes in Arctic Ocean Chlorophyll *a*: Bridging ocean color observations from the 1980s to present time

L. Oziel [a,b,c,*], P. Massicotte [b], M. Babin [b], E. Devred [a]





ıly 2022

Everything presented so far was "diagnostic"

- Means that NPP or GPP are estimated from what the input quantities are at a given point in time.
- Can perform retrospective analyses, but how do we predict the future?

- Statistics approach using satellite OCR and other data sources
- Satellite OCR assimilation into Mechanistic global coupled physical/BGC models

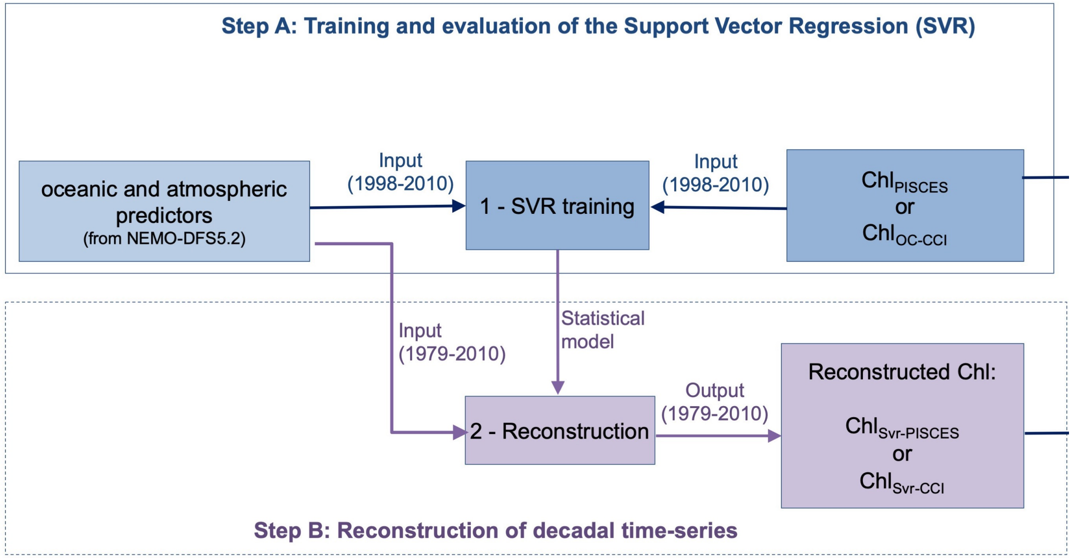
frontiers in Marine Science

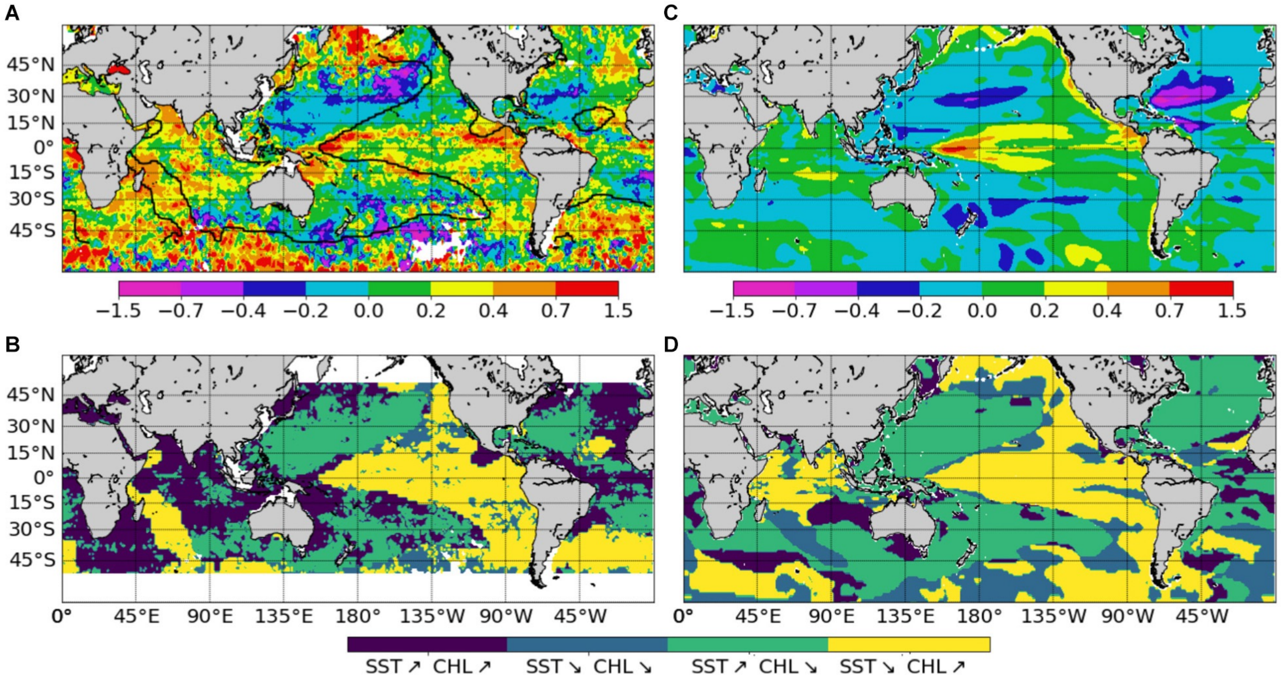
ORIGINAL RESEARCH
published: 30 June 2020
doi: 10.3389/fmars.2020.00464

Check for updates

Reconstructing Global Chlorophyll-a Variations Using a Non-linear Statistical Approach

Elodie Martinez[1,2], Thomas Gorgues[1], Matthieu Lengaigne[3†], Clement Fontana[2], Raphaëlle Sauzède[2†], Christophe Menkes[4], Julia Uitz[5], Emanuele Di Lorenzo[6] and Ronan Fablet[7]*





"Extracting" relationships between Chl and parameters of the physical environment
Then using predictions of this environment to infer future Chl changes

2022

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Journal of Marine Systems 69 (2008) 205–225
JOURNAL OF MARINE SYSTEMS
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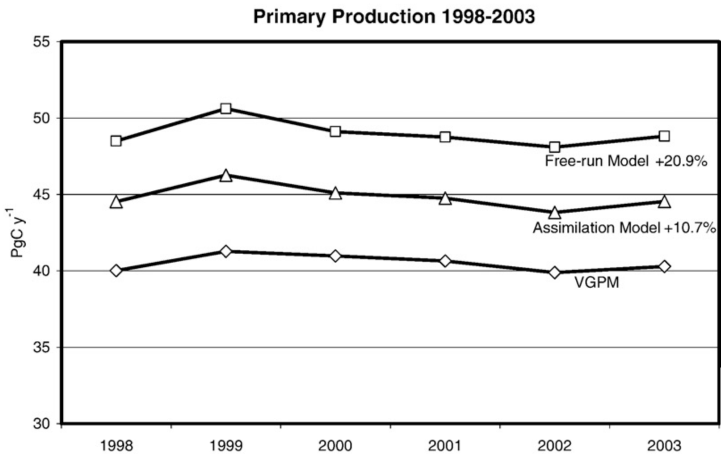
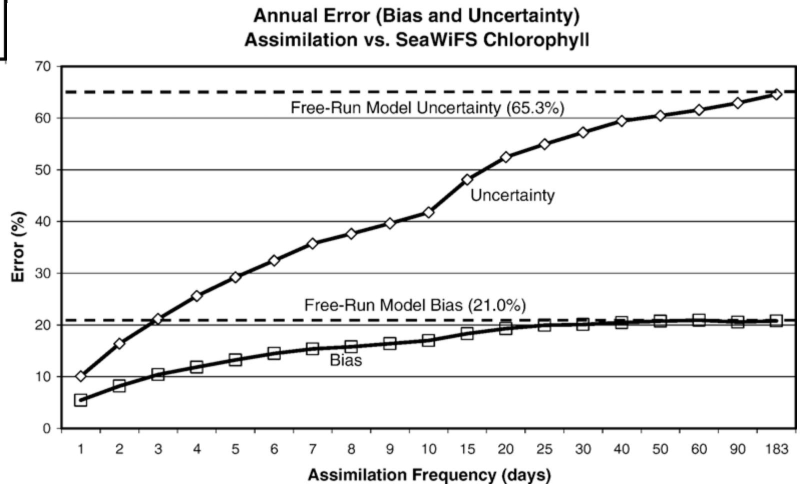
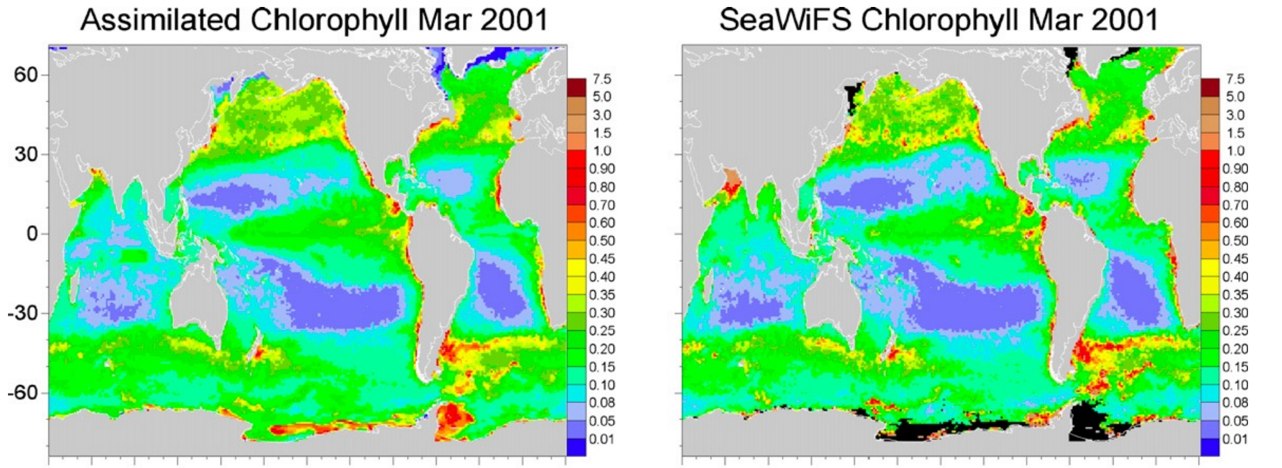
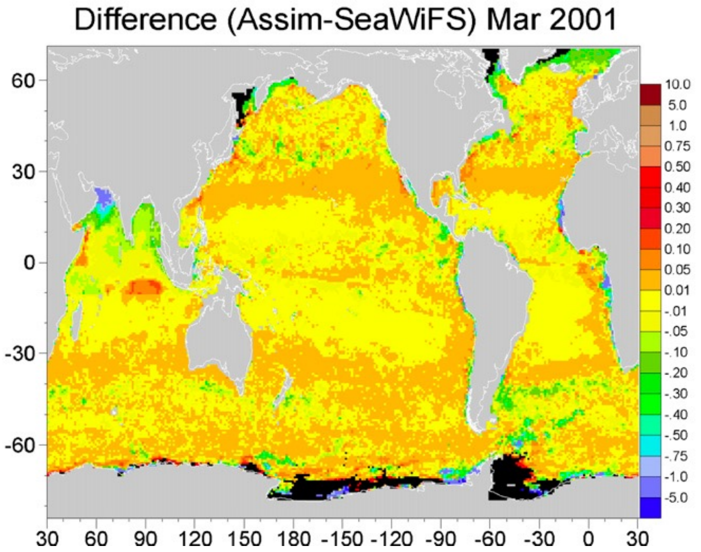
Assimilation of SeaWiFS ocean chlorophyll data into a three-dimensional global ocean model

Watson W. Gregg









Thank you
for your attention