UNIVERSITY OF EXETER

Centre for Geography
and Environmental Science

esa

Optical Remote Sensing for Marine applications

Dr Bob Brewin

Lecturer in Physical Geography,

University of Exeter,

Penryn Campus, Cornwall, TR10 9FE, UK

(r.brewin@exeter.ac.uk)

Additional contact information can also be found on my website https://geography.exeter.ac.uk/staff/index.php?web_id=Bob_Brewin .

A bit about myself: my path

2003-
2010

BSc Surf Science & Technology
MSc Applied Marine Science
PhD Marine Remote Sensing
Associate lecturer and demonstrator
Marine Remote Sensing

2010-
2019

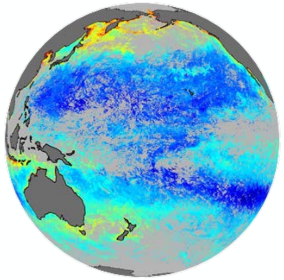
Research Scientist
ESA post-doc fellow
NCEO scientist

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL
esa

Atlantic Meridional Transect

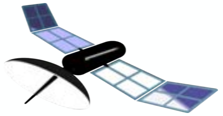
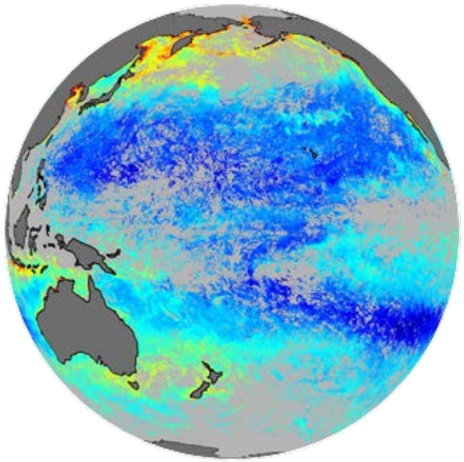
2019-
present

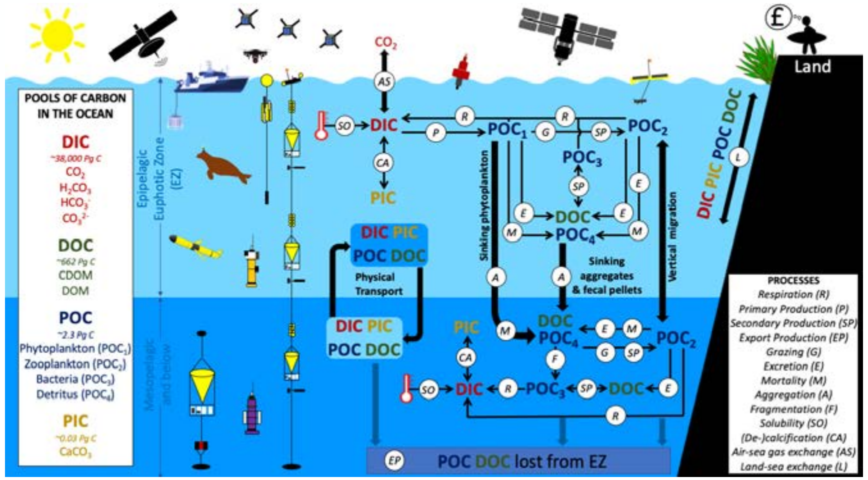
Lecturer in Physical Geography



A bit about myself: research interests

Remote sensing

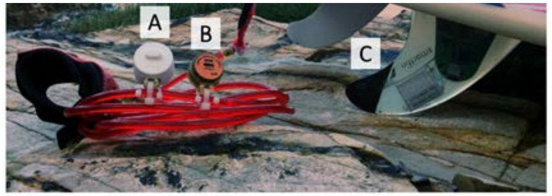



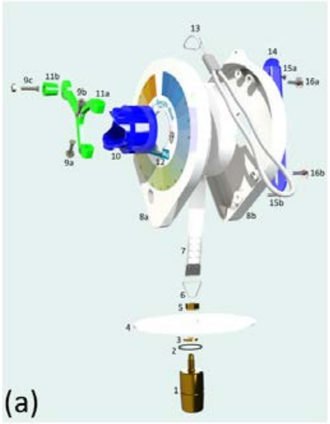


Sardet (2015) Plankton wonders of drifting world. Univ. Chicago Press

Field work

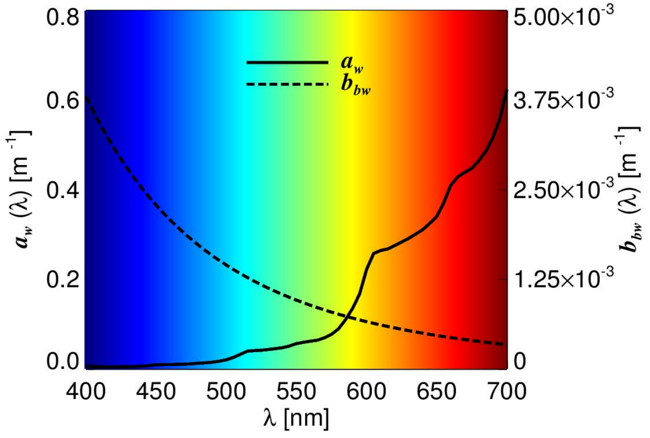

Citizen Science

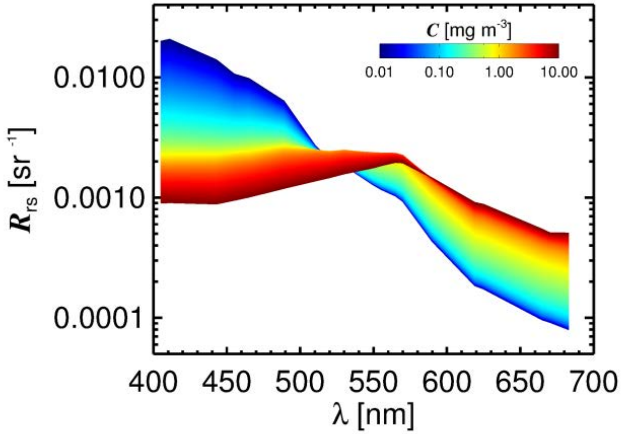




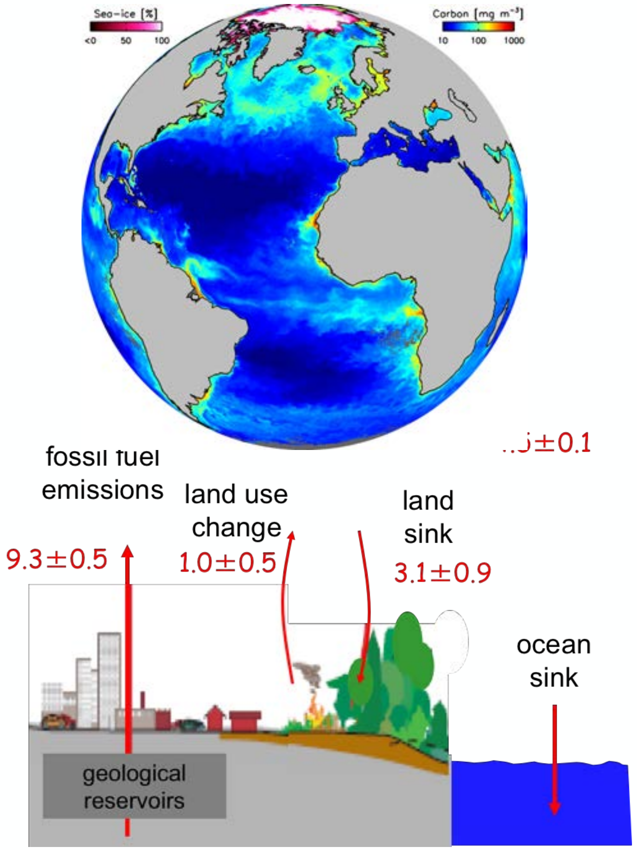
Lecture plan

Ocean Colour theory (Part 1)

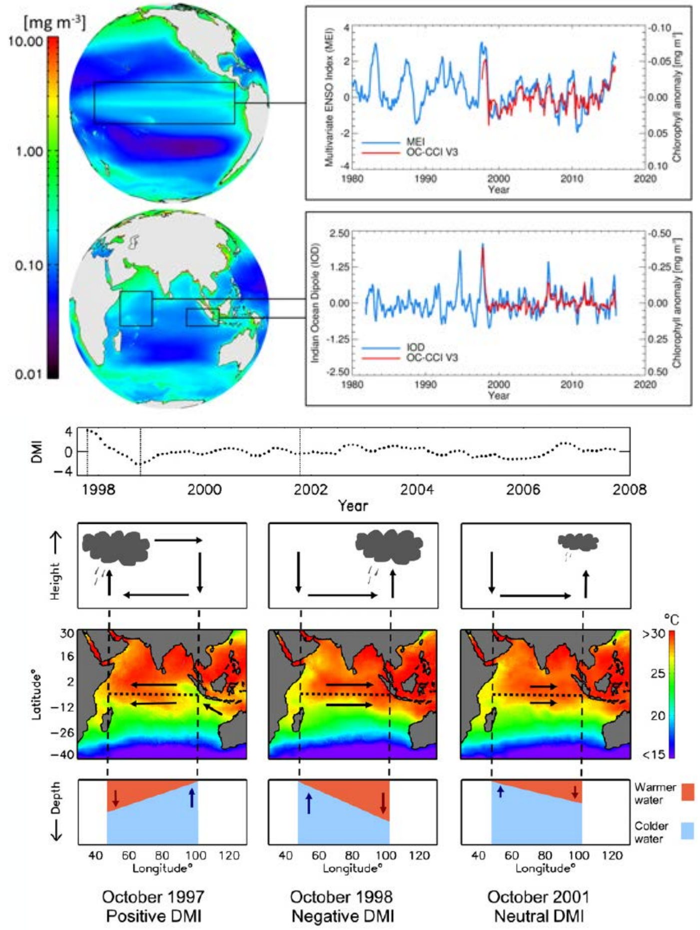




Ocean Colour applications: carbon cycle (Part 2)



Ocean Colour applications: climate (Part 3)



Part 1: Outline

1) What is ocean colour?

2) History of ocean colour

3) Optical properties of water and its constituents

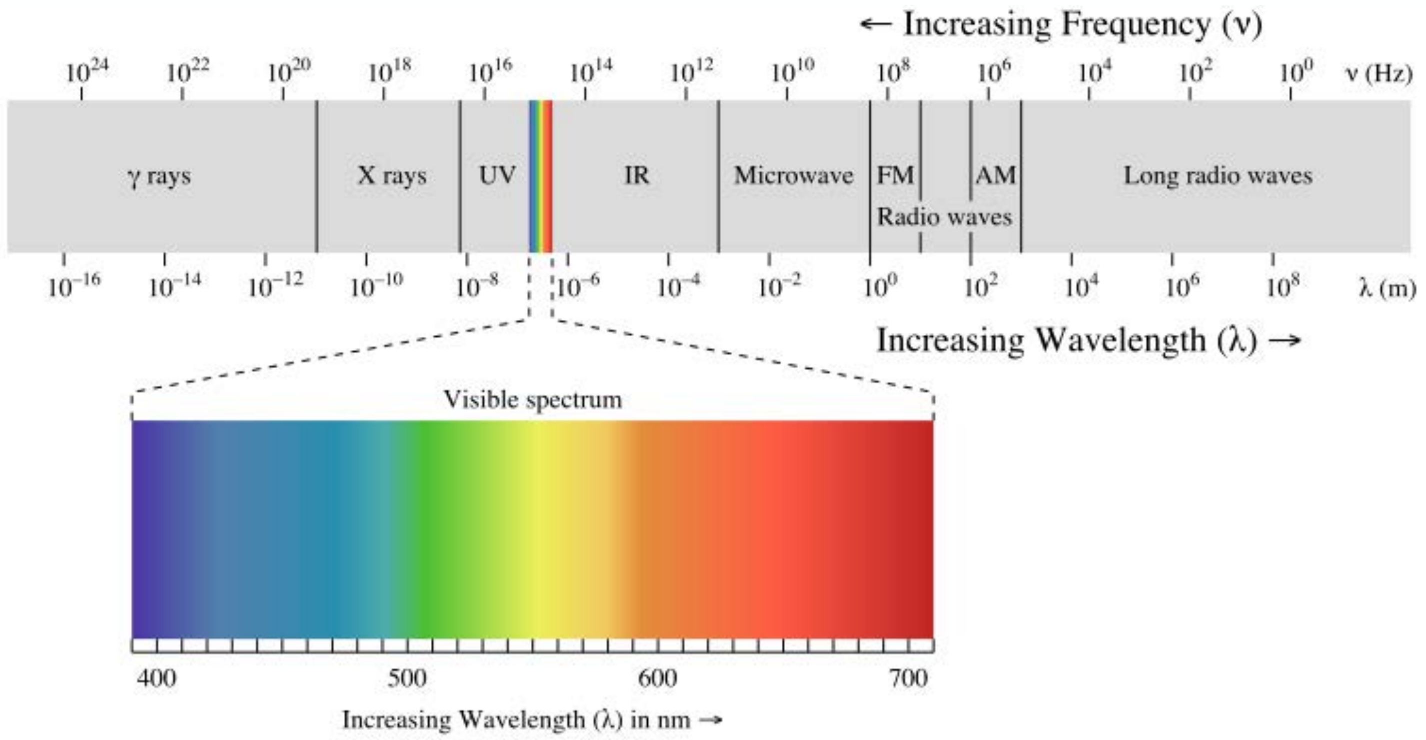
4) In situ measurements of ocean colour

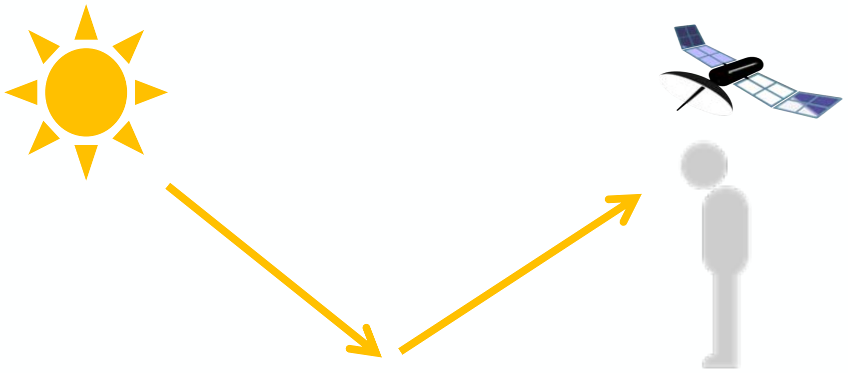
5) Satellite remote-sensing of ocean colour

1) What is ocean colour?

Spectral variations in visible light reflected from water

Sunlight that enters the water and is absorbed, scattered and reflected by water and the constituents that make up the water. These processes vary with wavelength of light

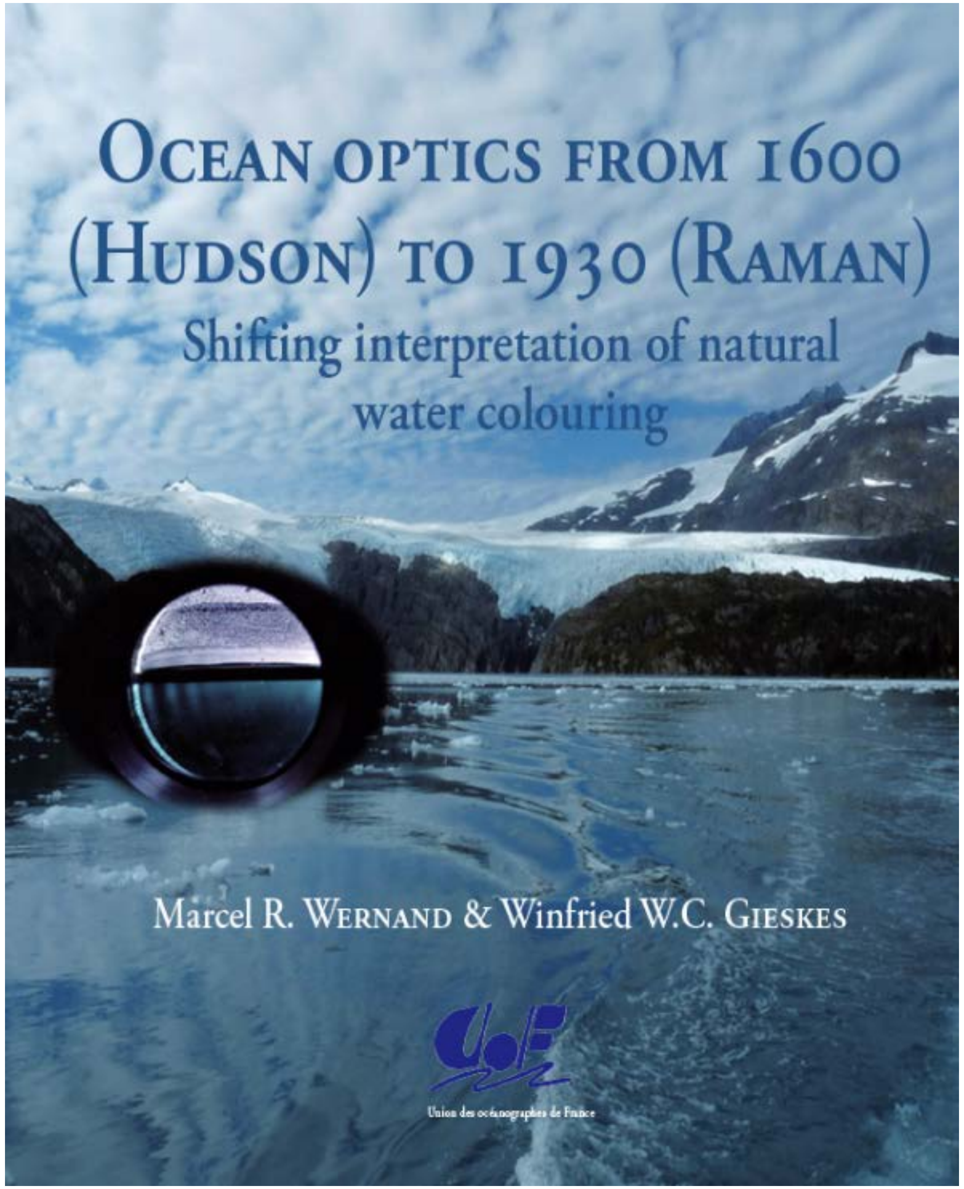




2) History of ocean colour

Paintings by Albert Bierstadt, Emil Nolde, Ivan Aivazovsky

Early navigation: bottom topography, presence of ice bergs, river discharge, occurrence of fish (e.g., H. Hudson, First voyage, 1607; W. Scoresby, 1820)



Wernand (2011) PhD Thesis
https://www.researchgate.net/publication/254886155_Poseidon%27s_paintbox_historical_archives_of_ocean_colour_in_global-change_perspective

2) History of ocean colour

From CEOS Report 2018, Images Courtesy CSIRO

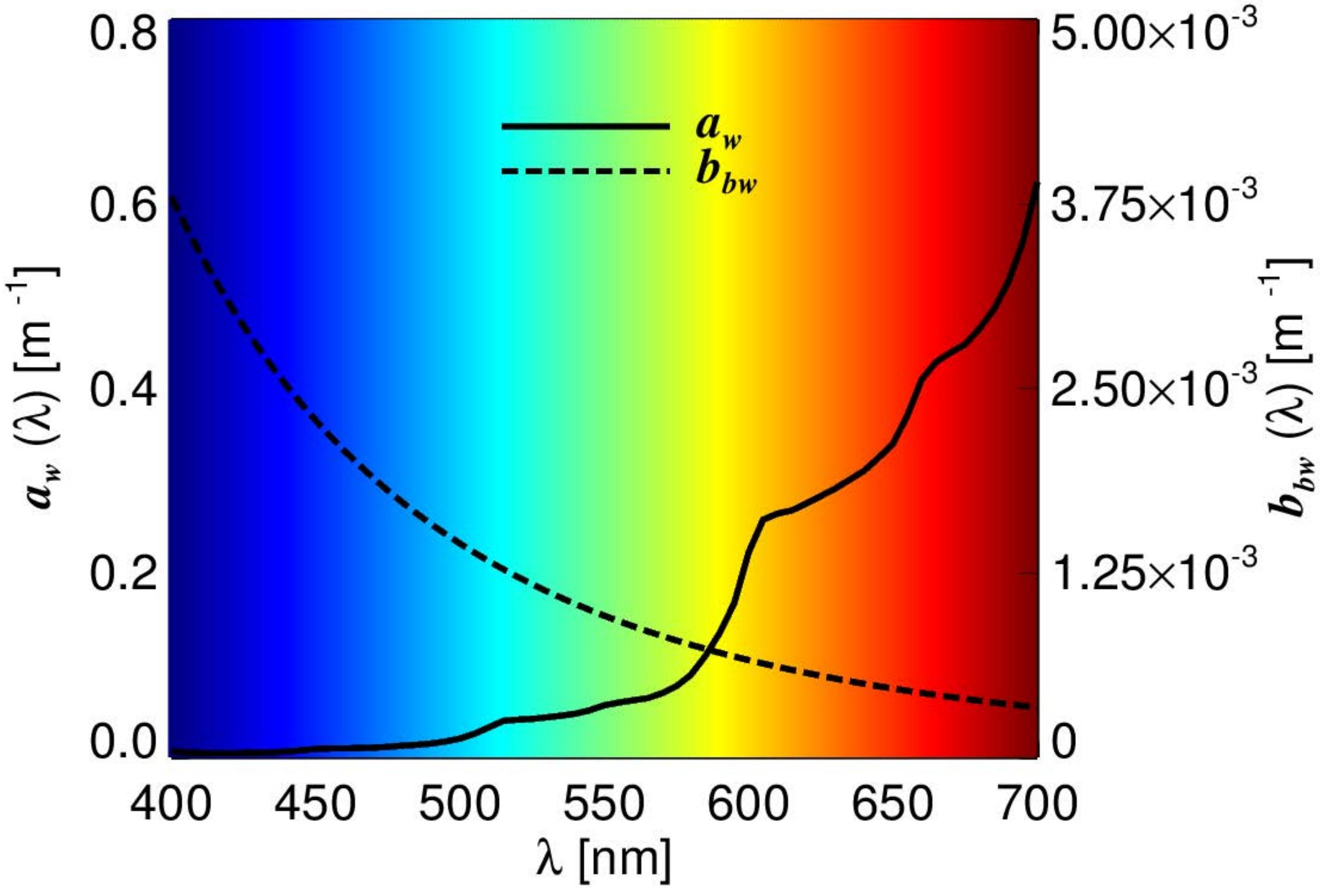
- Everyday observation: colour of water changes with time and place
- What is responsible for these changes?
- Can we quantify the responsible agents?
- Why should we care?

Slide kindly prepared by Shubha Sathyendranath

2) History of ocean colour

A sufficient deep layer of pure water exhibits by molecular scattering a deep blue colour more saturated than sky-light and of comparable intensity. The colour is primarily due to diffraction, the absorption only making it of a fuller hue. The theories hitherto advanced that the dark blue of the deep sea is reflected sky-light or that it is due to suspended matter are discussed and shown to be erroneous

C. Raman, 1922



$$R(\lambda) = \frac{E_u(\lambda)}{E_d(\lambda)} \approx r\,\frac{b_b(\lambda)}{a(\lambda)}$$

R = Reflectance

E = Irradiance (*u* = upwelling, *d* = downwelling)

$a(\lambda)$ = absorption $b_b(\lambda)$ = backscattering

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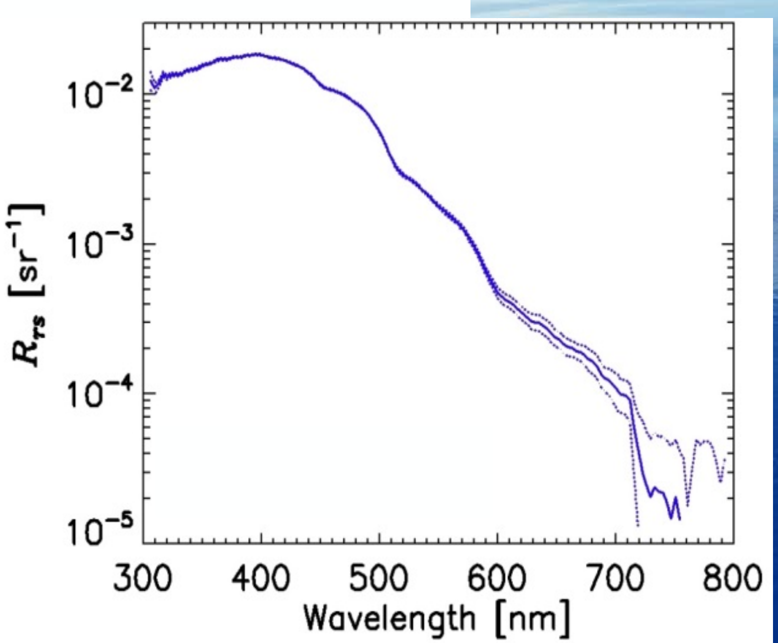

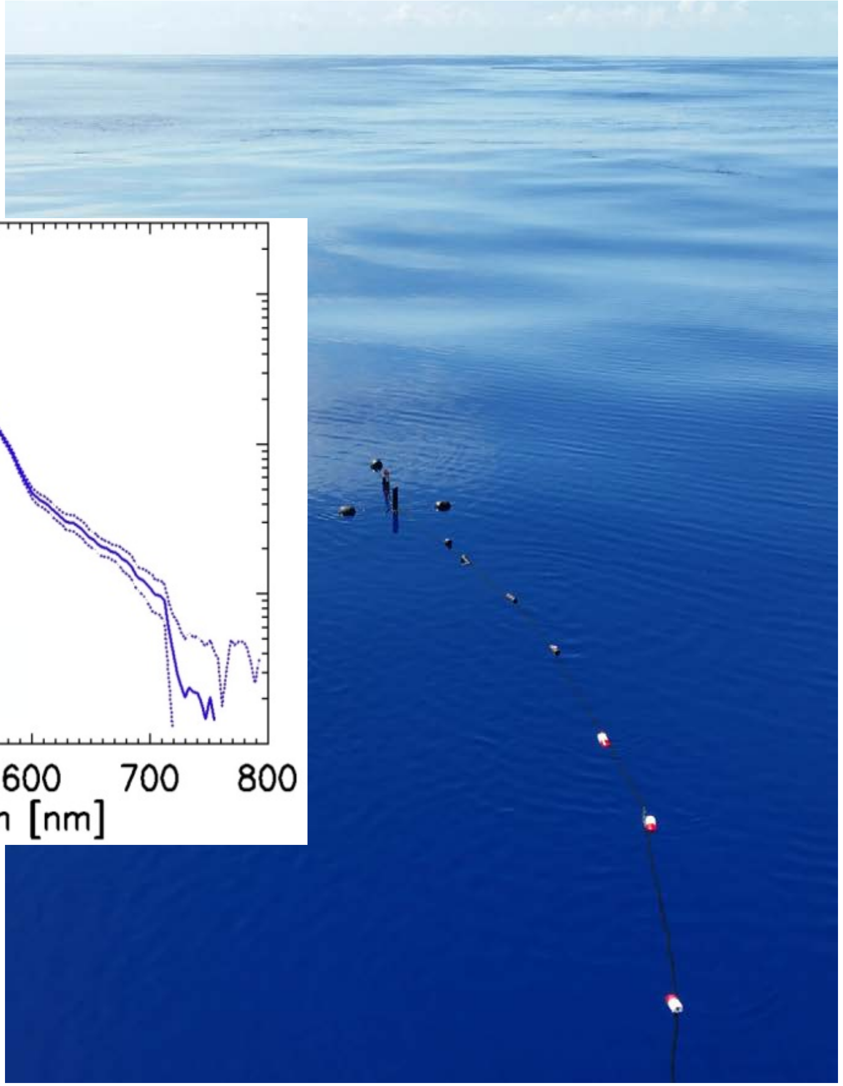

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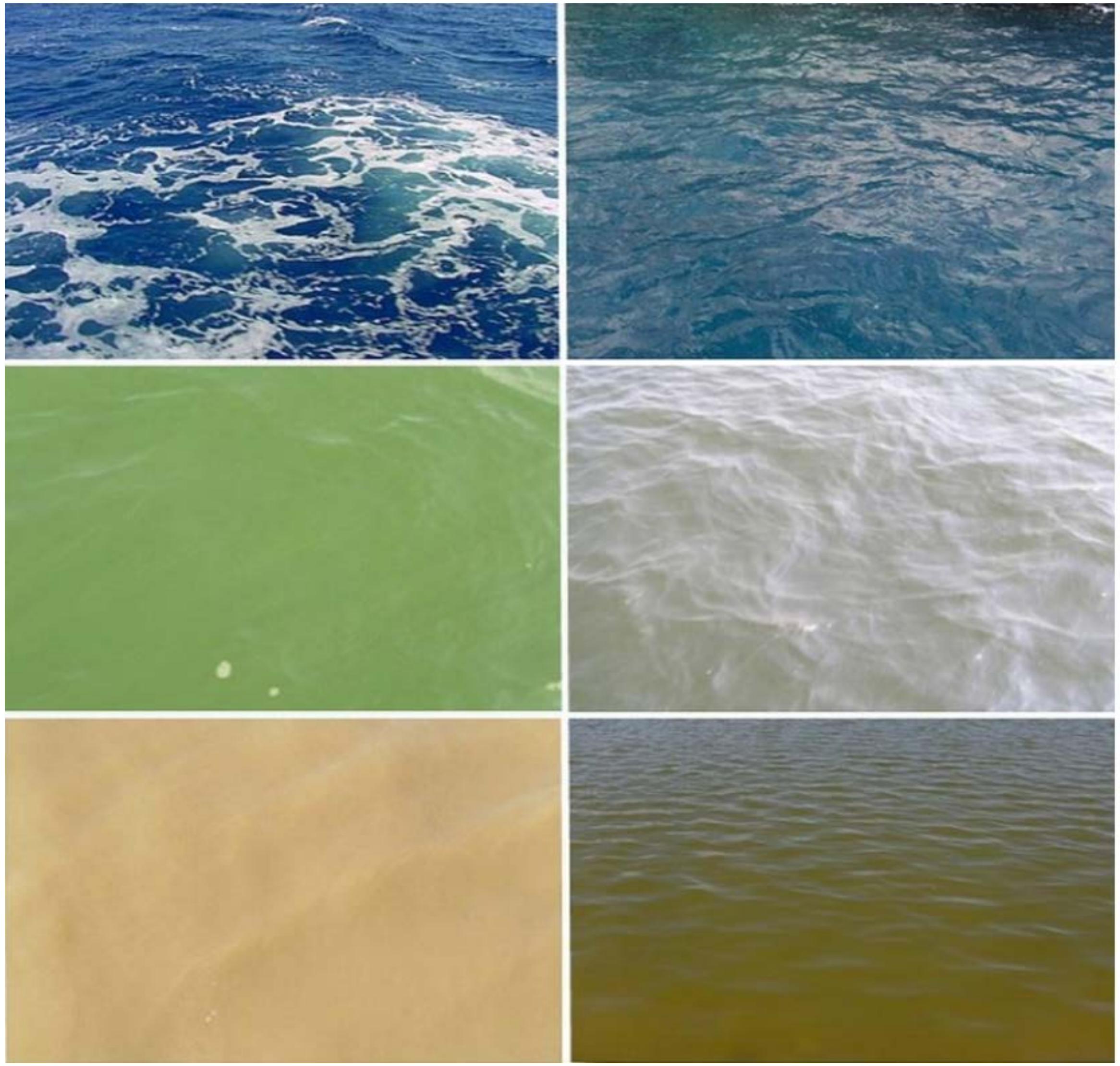

Taken from Wernand (2011, see link to reference on earlier slide)

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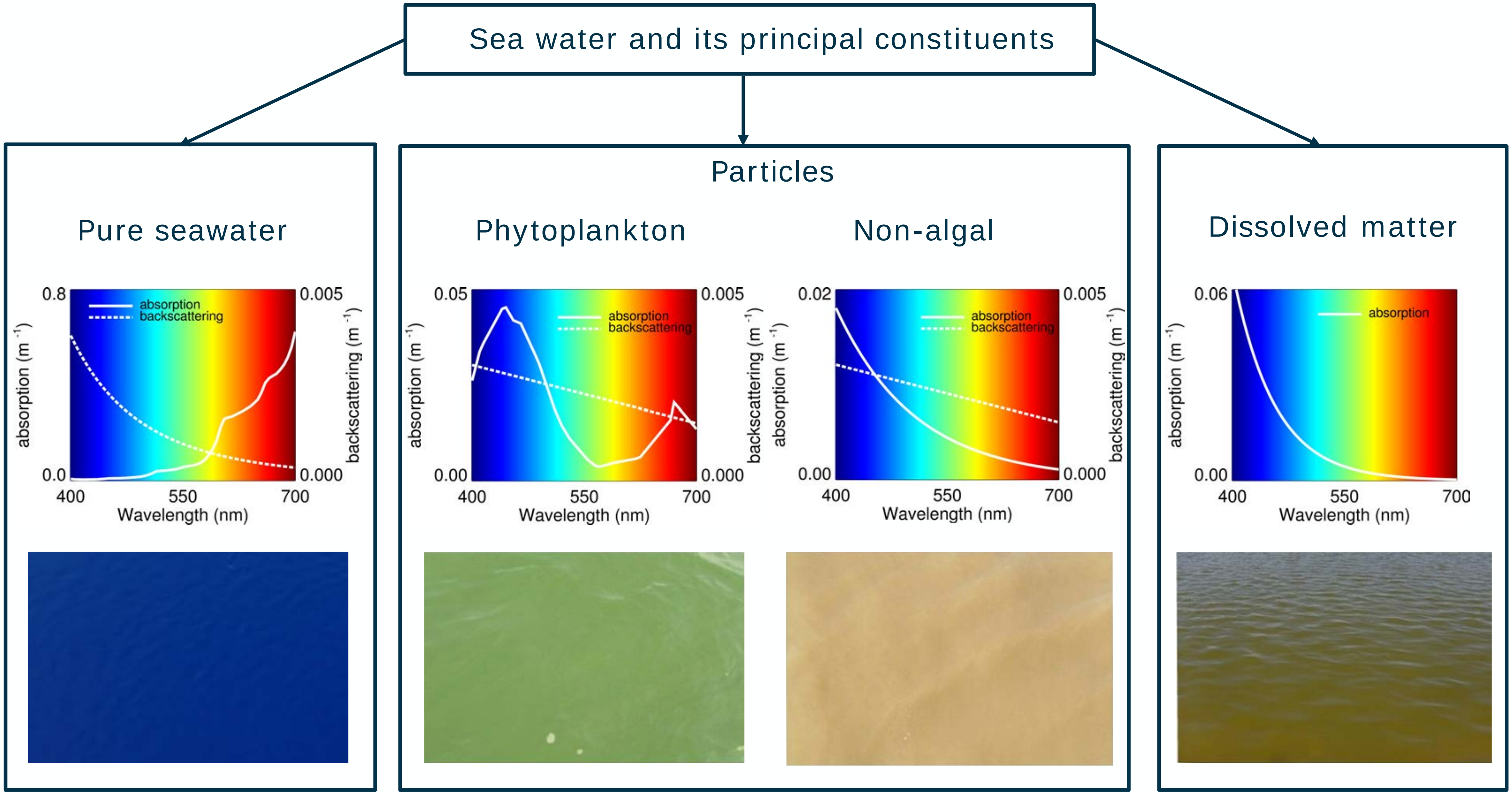
3) Optical properties of water and its constituents



3) Optical properties of water and its constituents

Apparent optical properties (AOPs)

Dependant on the inherent optical properties of the water, and the directional distribution of the light field in the sea (e.g., water leaving radiance, reflectance and diffuse attenuation coefficient of seawater)

Inherent optical properties (IOPs)

The optical properties of the water and its constituents independent of the directional distribution of the light field in the sea (e.g., absorption, backscattering, beam attenuation).

3) Optical properties of water and its constituents

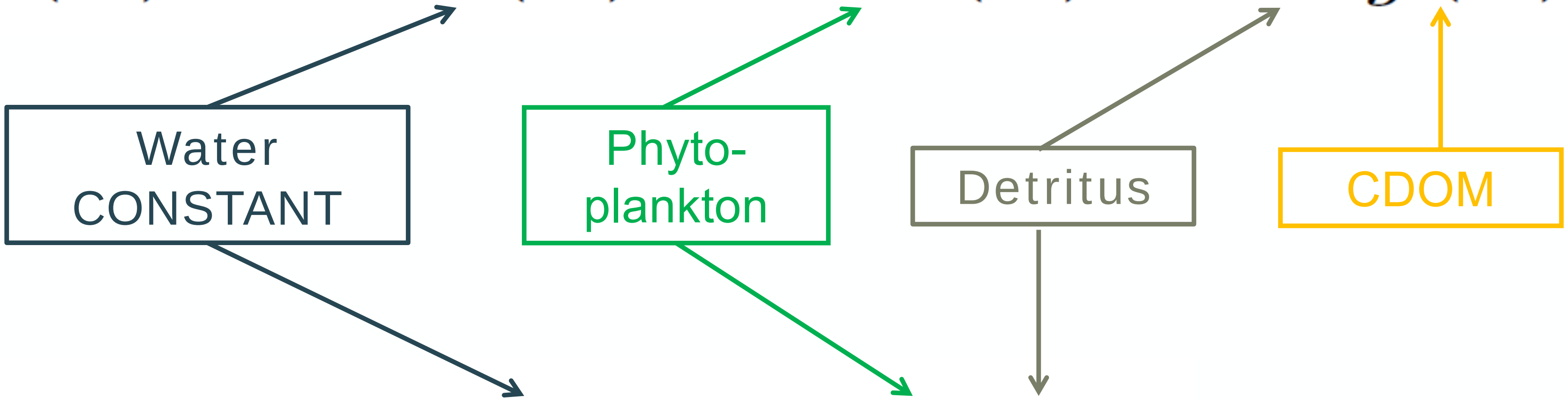
Inherent Optical Properties

Specific inherent optical properties: the individual scattering and absorption components per unit concentration ($a^*_B(\lambda) = a_B(\lambda)/B$)

Bulk inherent optical properties: the individual scattering and absorption components per unit concentration multiplied by concentration ($a_B(\lambda) = a^*_B(\lambda)B$). Will vary with variations in specific IOPs and concentration.

3) Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$



$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

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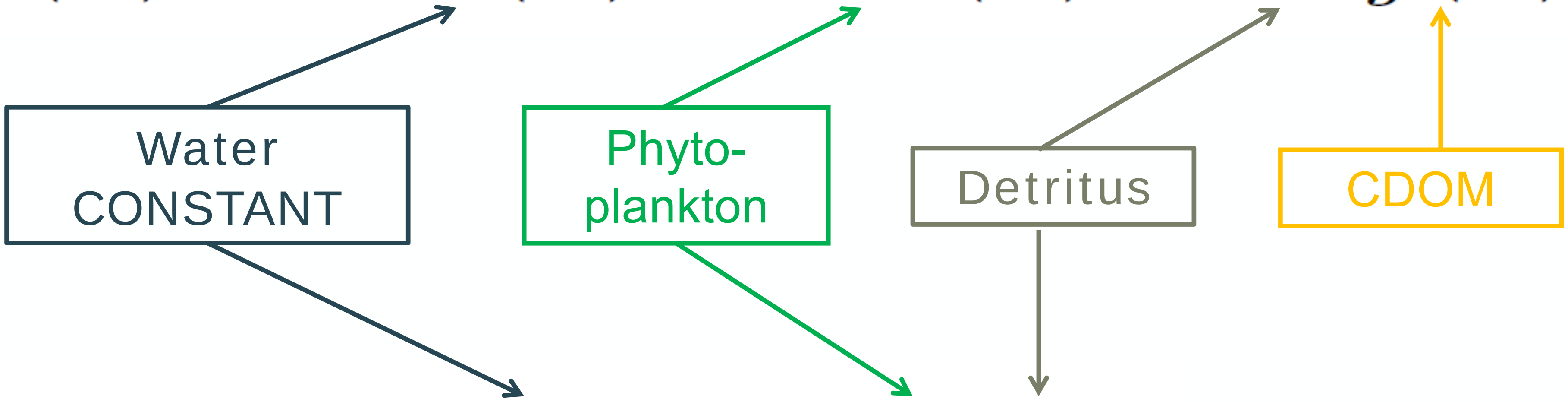

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

Case-2: Phytoplankton biomass does not covary with detritus and CDOM

Case-1: Phytoplankton biomass covaries with detritus and CDOM. IOPs can be tied with reasonable confidence to the chlorophyll concentration (*C*)

Morel and Prieur (1977) Limnol. Oceanogr.

3) Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$

Water CONSTANT

$\propto$ Chlorophyll (C)

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

Case-2: Phytoplankton biomass does not covary with detritus and CDOM

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Morel and Prieur (1977) Limnol. Oceanogr.

3) Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$

Phytoplankton

- Total Chlorophyll-a
- Phytoplankton pigment composition
- Phytoplankton size structure
- Phytoplankton Chl for different groups
- Phytoplankton Carbon for different groups
- Light attenuation (heating of ocean and primary production)

Detritus

- Sinking of material
- Coastal erosion of terrigenous sediments
- River deposition
- Dust / Volcanic / Cosmogenic deposition
- Recycling
- Light attenuation

CDOM

- Dissolved organic carbon cycle
- Proportions of humic and fulvic acids
- Semi-labile and refractory fractions
- Photodegradation status
- Water mass change
- Light attenuation

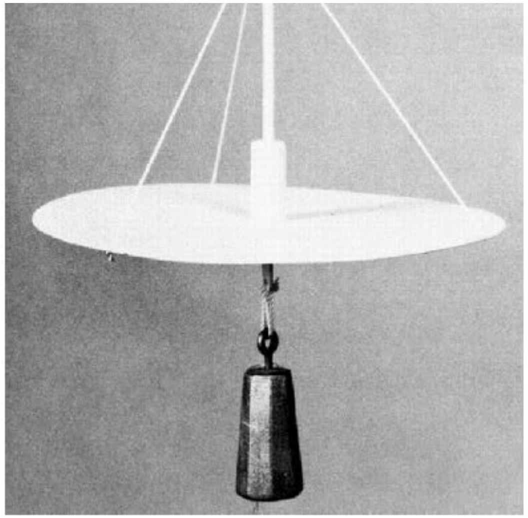
3) Optical properties of water and its constituents

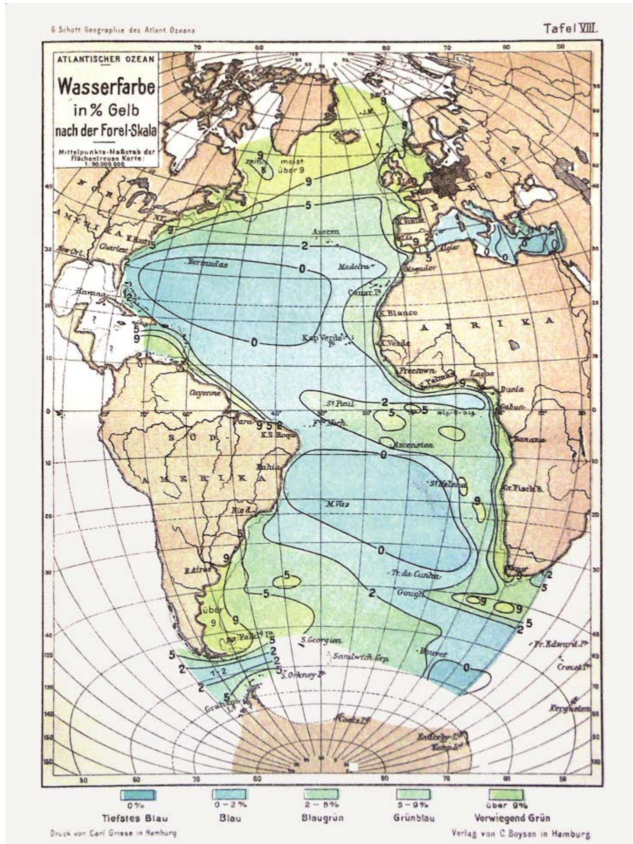
$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

Particles

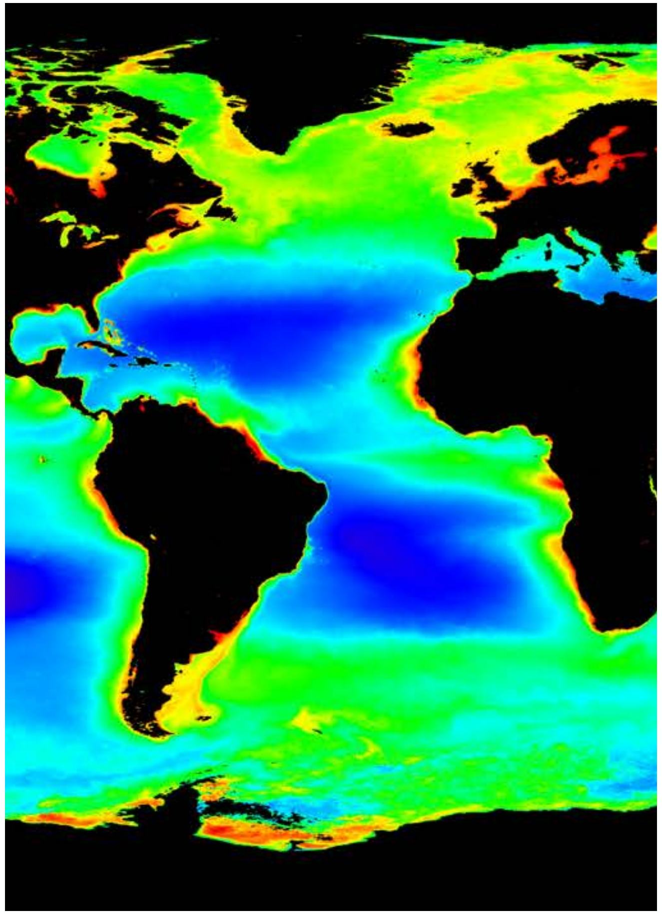
- Suspended particulate material
- Light attenuation
- Particle size structure
- Phytoplankton Carbon
- Phytoplankton Carbon for different groups
- Particulate Organic Carbon
- Particulate Inorganic Carbon

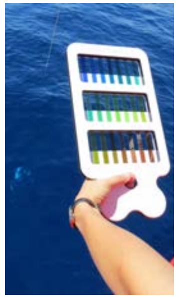
4) *In situ* measurements of ocean colour

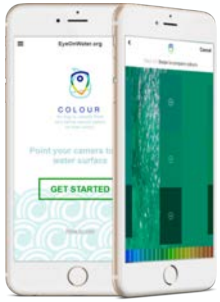




Wernand et al. (2011) PhD Thesis



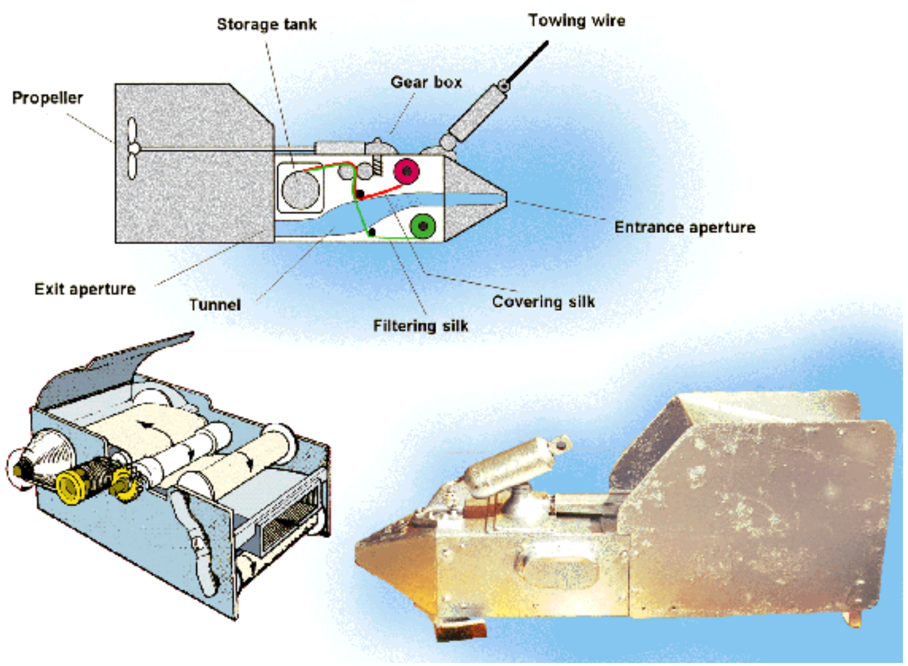




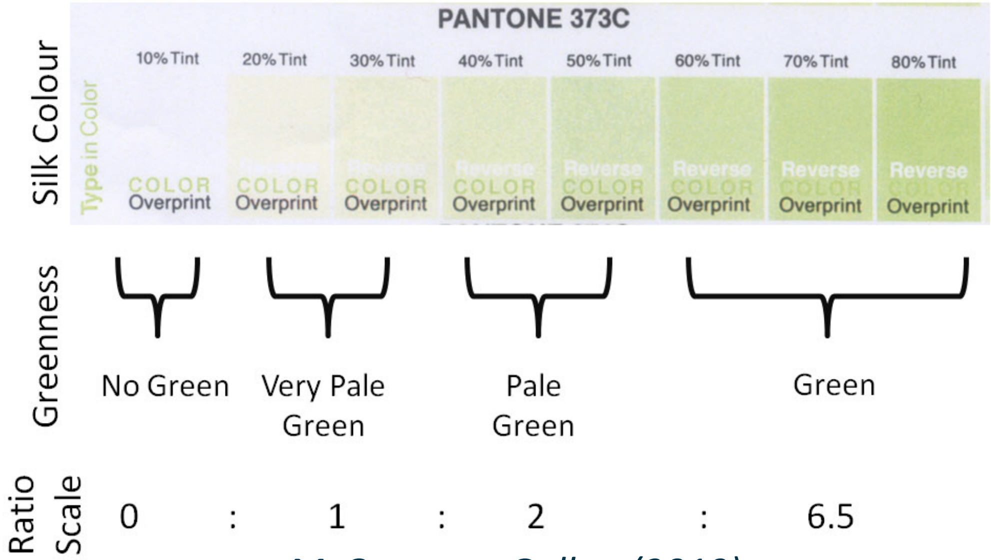
Siegel & Franz (2010) https://doi.org/10.1038/466569a
Seafarers et al. (2017) https://doi.org/10.1371/journal.pone.0186092
Brewin et al (2019) https://doi.org/10.3390/s19040936
Garaba et al (2015) https://doi.org/10.3390/ijerph121215044
Ceccaroni et al. (2020) https://doi.org/10.1371/journal.pone.0230084

4) *In situ* measurements of ocean colour

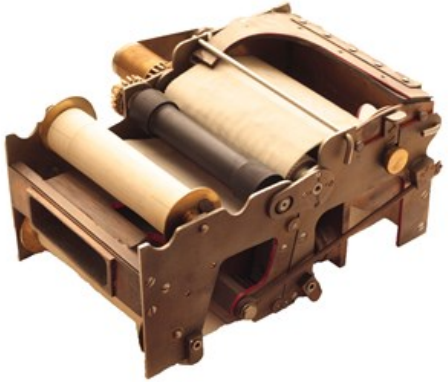
Sir Alister Clavering Hardy (1896- 1985)



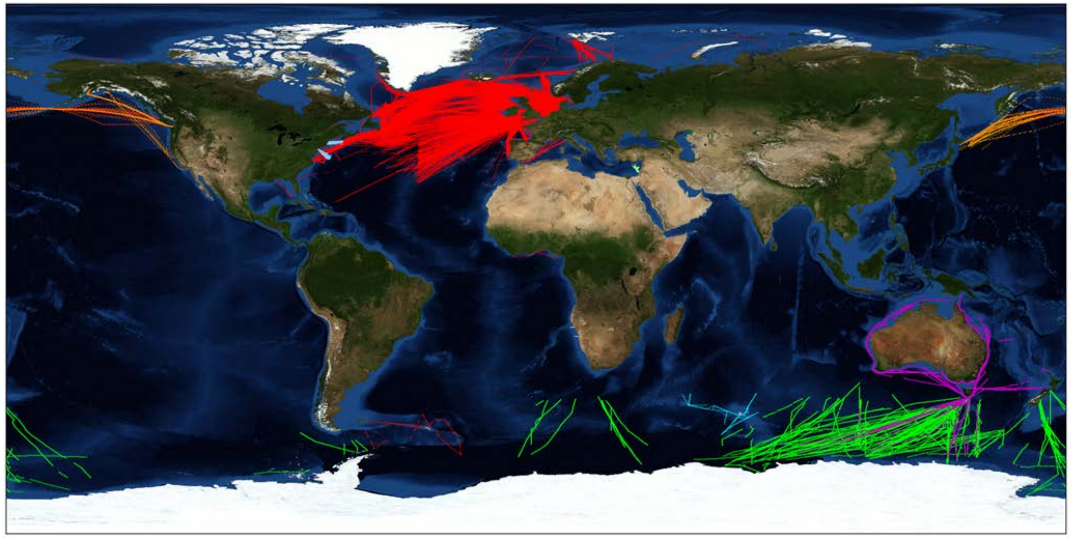
Richardson et al. (2006)
https://doi.org/10.1016/j.pocean.2005.09.011



McQuatters-Gollop (2019)
https://www.goesfoundation.com/references/posts/2019/january/are-marine-phytoplankton-in-decline/



https://www.cprsurvey.org/services/the-continuous-plankton-recorder/



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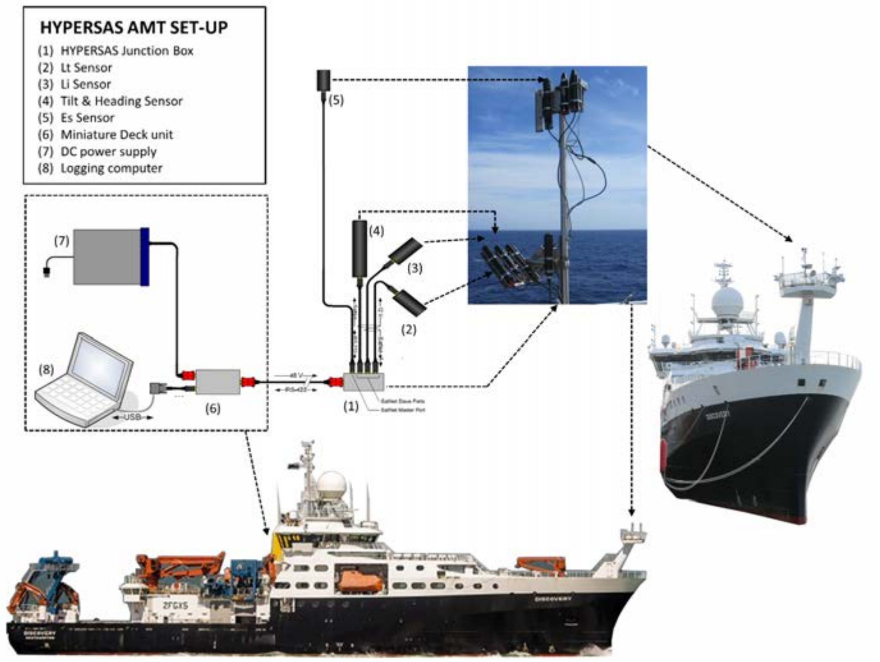
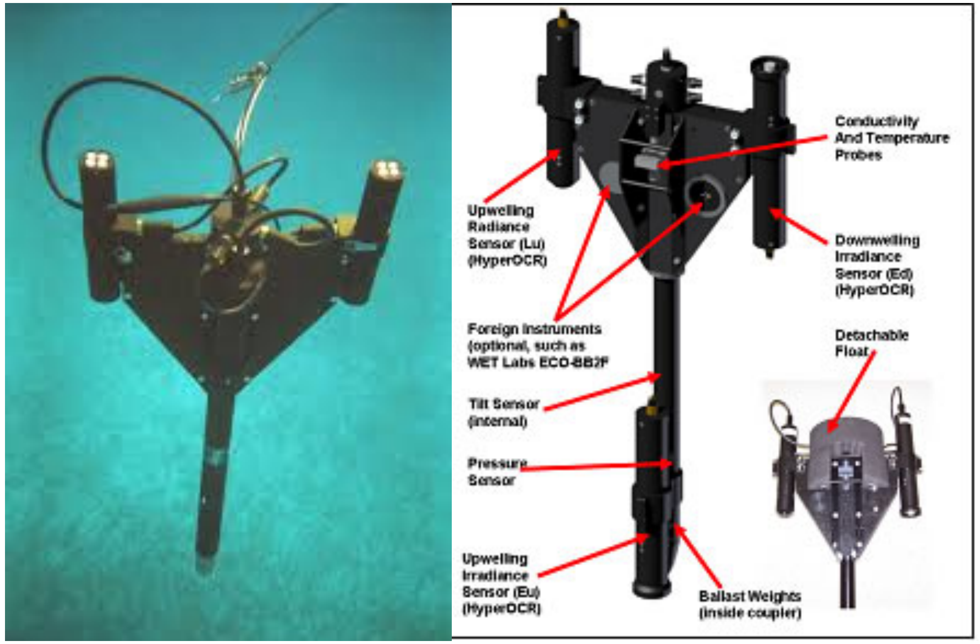
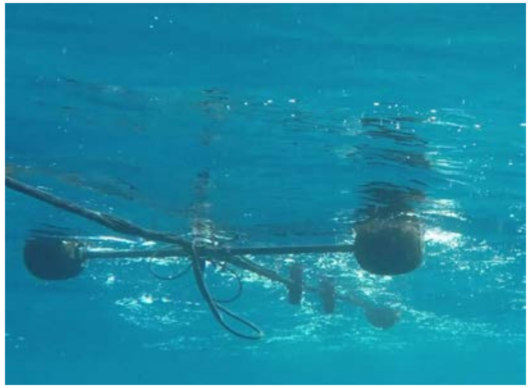
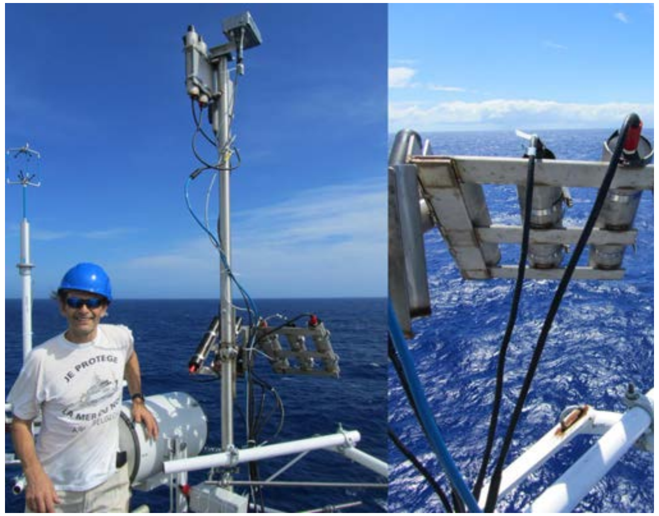






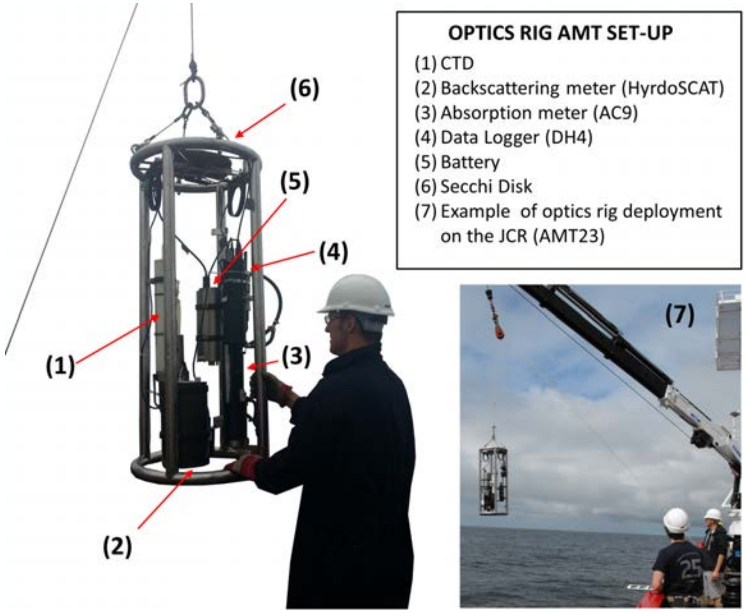
In water radiometry

Measurements of apparent optical properties



Above-water radiometry

Measurements of apparent optical properties



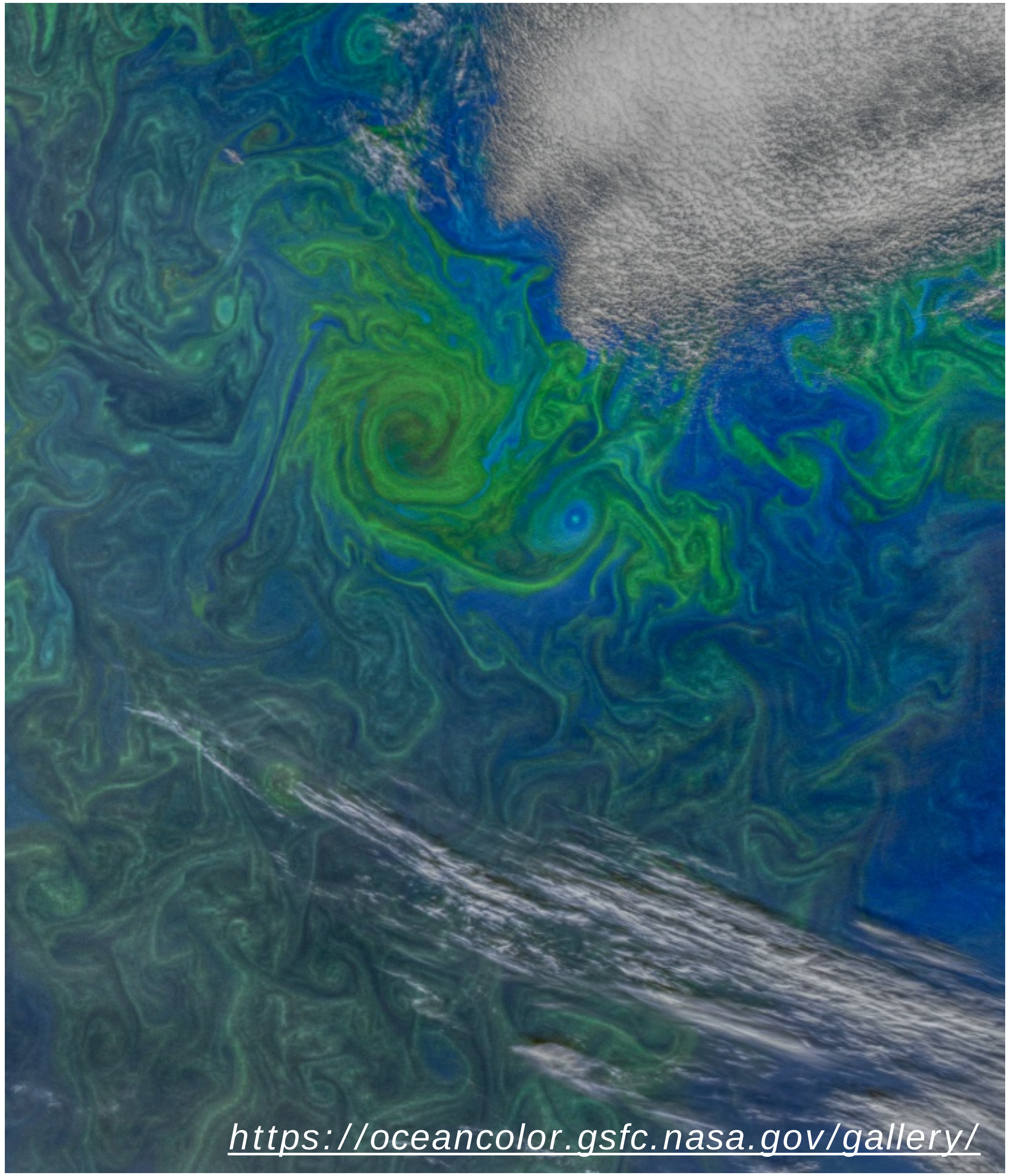
In water measurements of inherent optical properties

5) Satellite measurements of ocean colour

5) Satellite measurements of ocean colour

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

Revealed:
(1) Oceanography's chronic problem of undersampling;
(2) Dominance of mesoscale physical processes in determining the spatial distribution of phytoplankton;
(3) Effect of topography on biomass;
(4) Complexity of the seasonal progression of phytoplankton blooms
(5) Magnitude of interannual variability.



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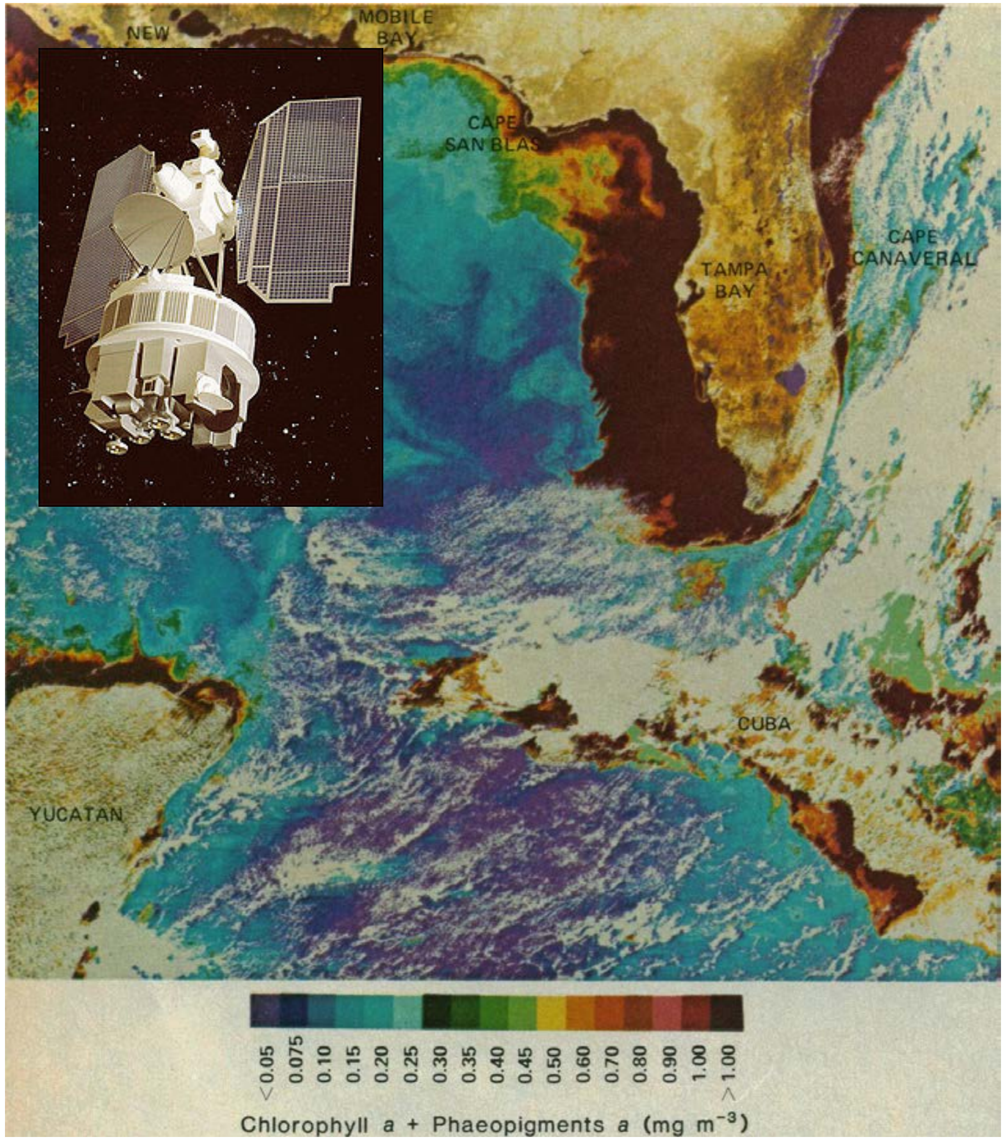
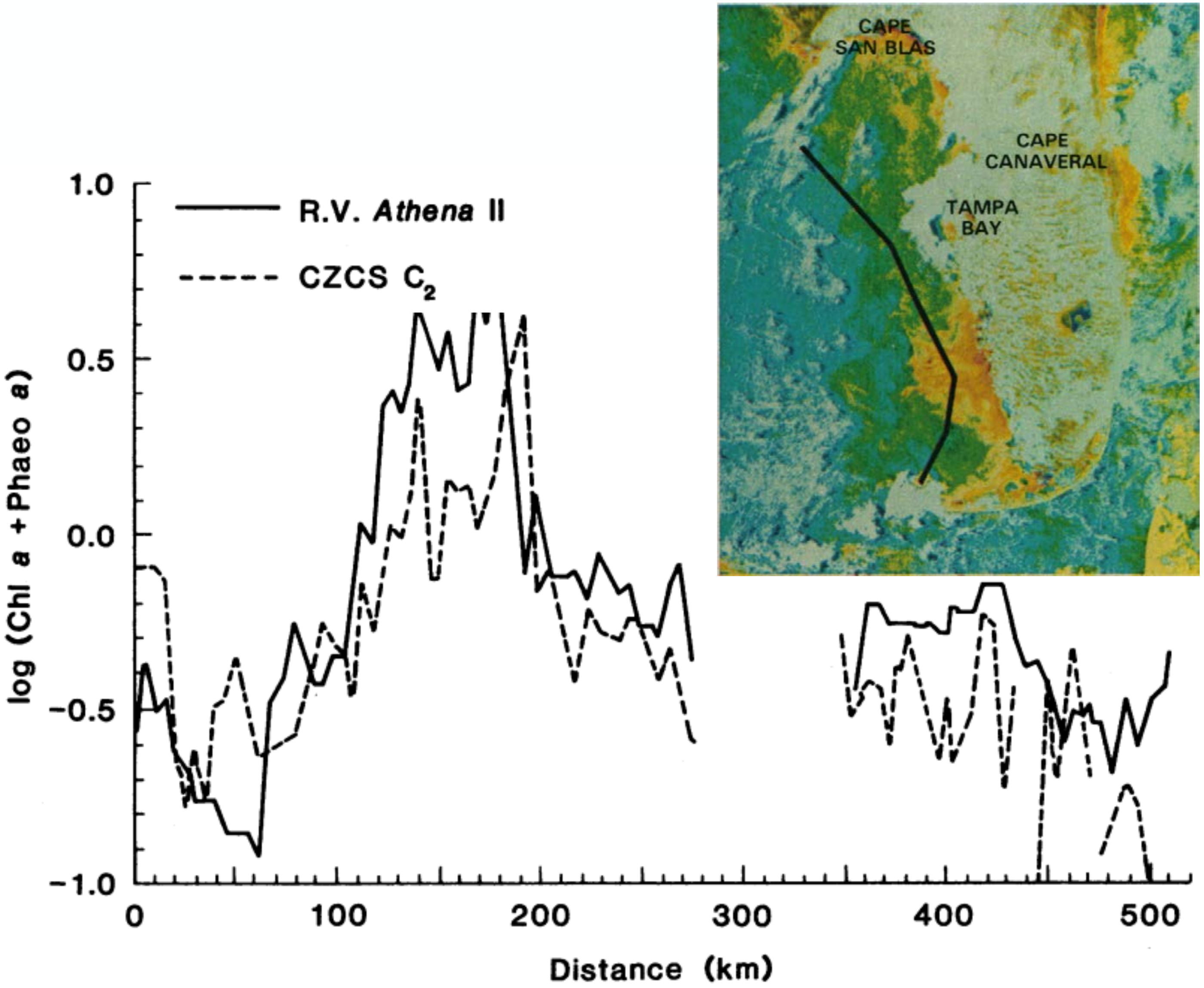
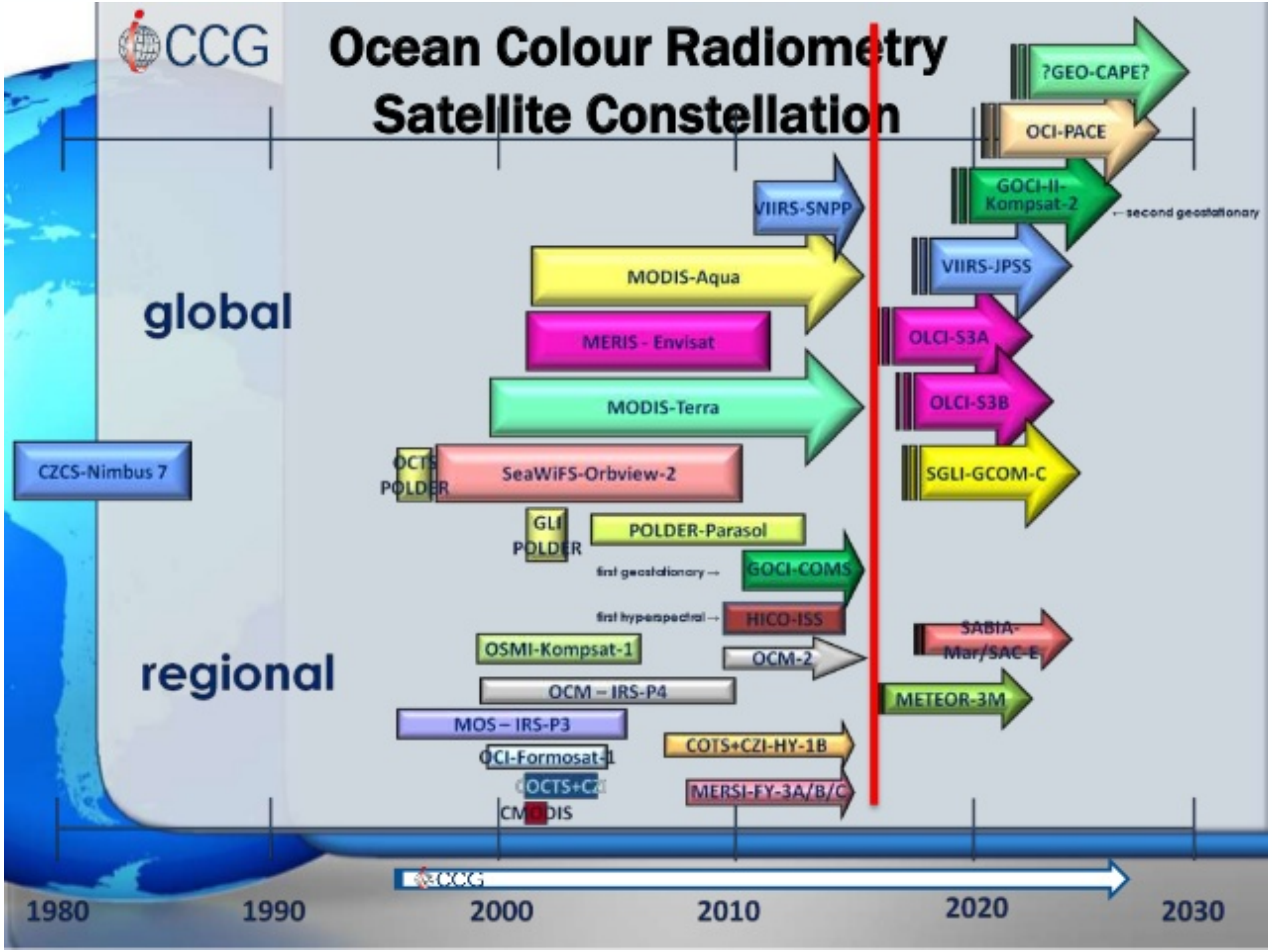




Hovis et al. (1980) Science
http://doi.org/10.1126/science.210.4465.60

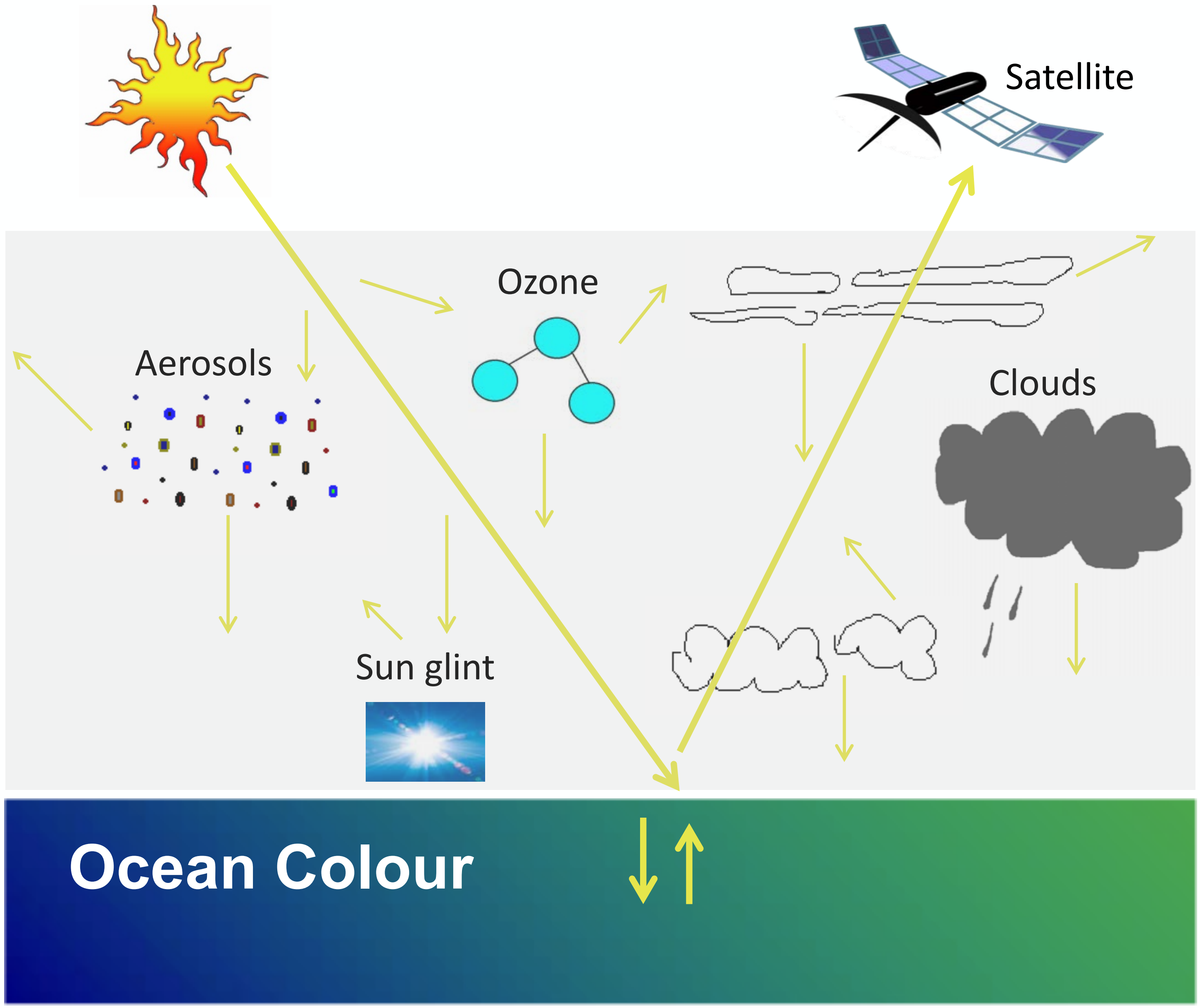
Gordon et al. (1980) Science
http://doi.org/10.1126/science.210.4465.63

5) Satellite measurements of ocean colour



http://chlo4msfd.azti.es/products-and-services-for-satellite-chlorophyll-a-data/

5) Satellite measurements of ocean colour

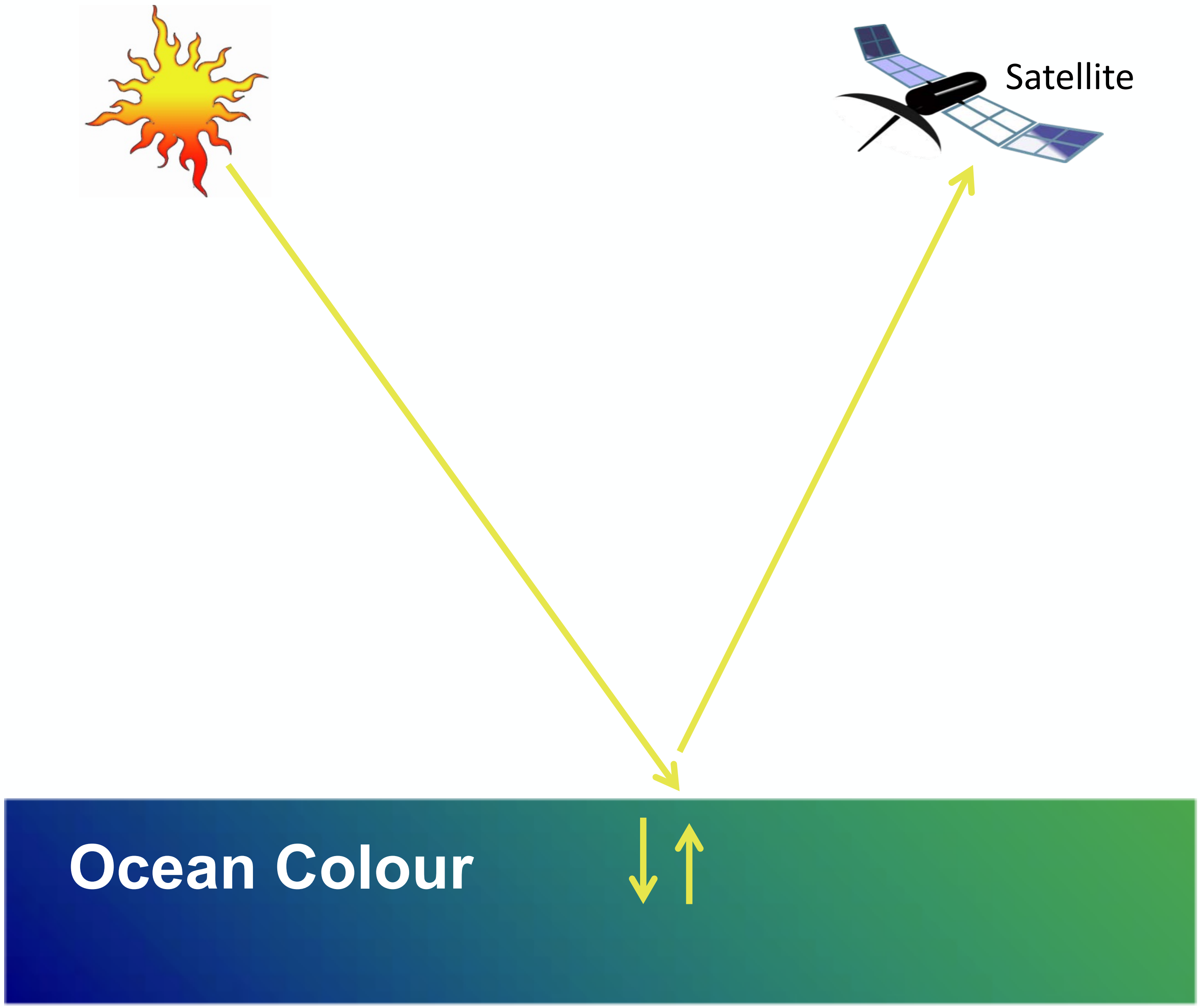


Atmosphere responsible for >90% of the satellite signal, the ocean only <10%

Atmosphere

Ocean

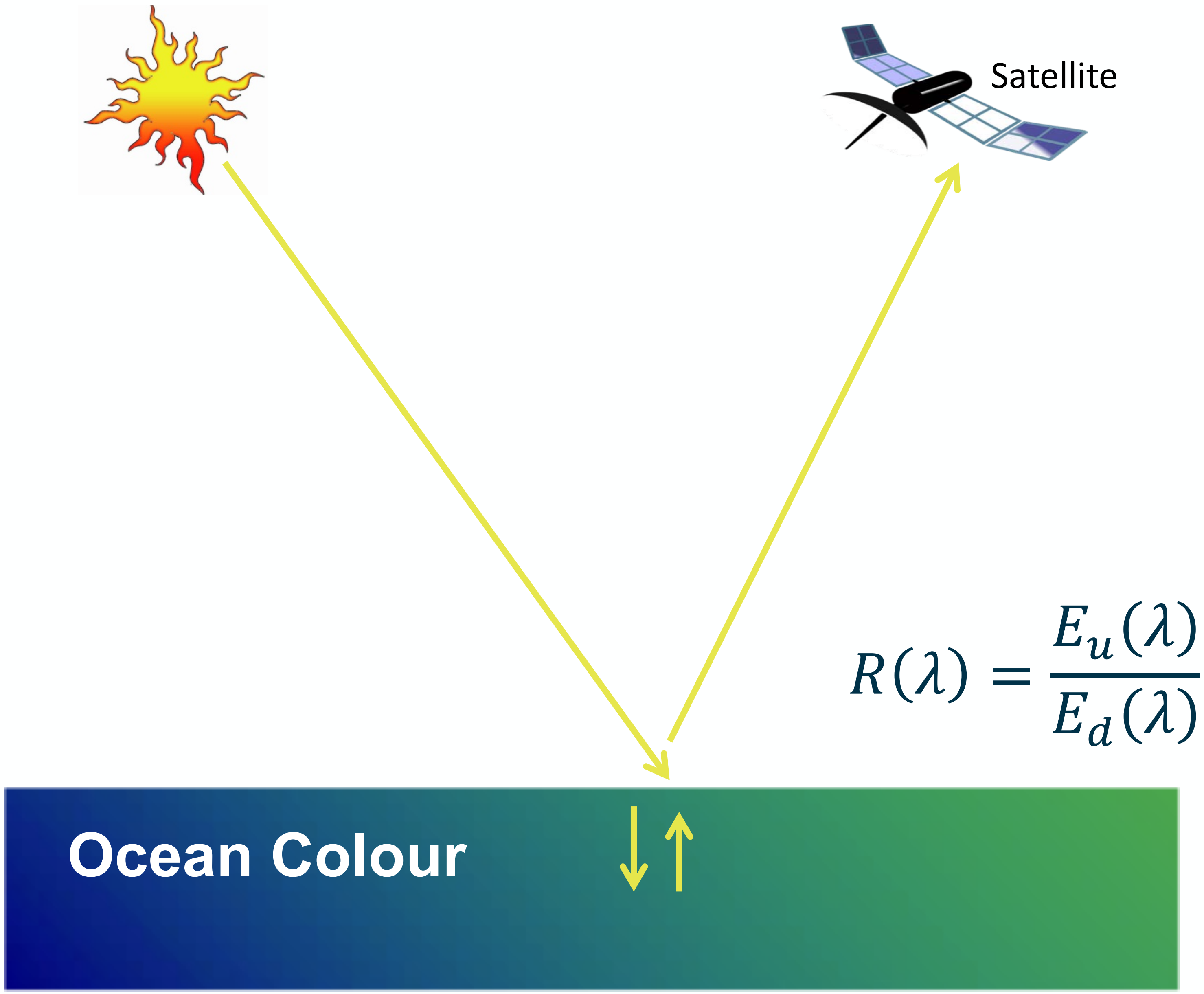
5) Satellite measurements of ocean colour



Remove atmosphere to capture the <10% ocean signal (water leaving radiance)

Ocean

5) Satellite measurements of ocean colour



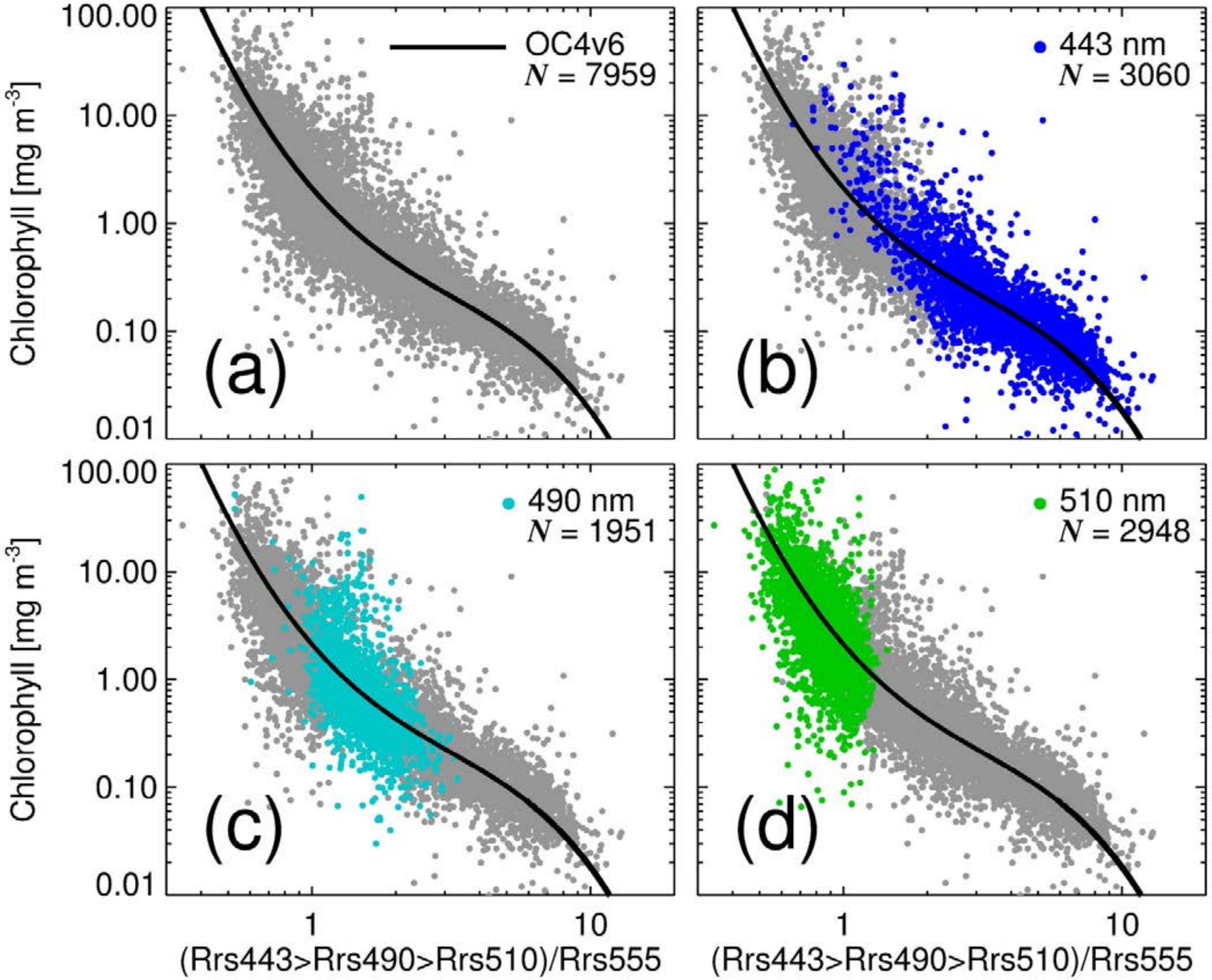
Convert ocean colour to derive bio-optical variables (e.g. biomass of phytoplankton)

$$R(\lambda) = \frac{E_u(\lambda)}{E_d(\lambda)} \approx r\,\frac{b_b(\lambda)}{a(\lambda)}$$

Ocean

5) Satellite measurements of ocean colour

Empirical algorithms



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

Semi-analytical algorithms

$$R(\lambda) = \frac{E_u(\lambda)}{E_d(\lambda)} \approx r\,\frac{b_b(\lambda)}{a(\lambda)}$$

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_g(\lambda) + a_d(\lambda)$$

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

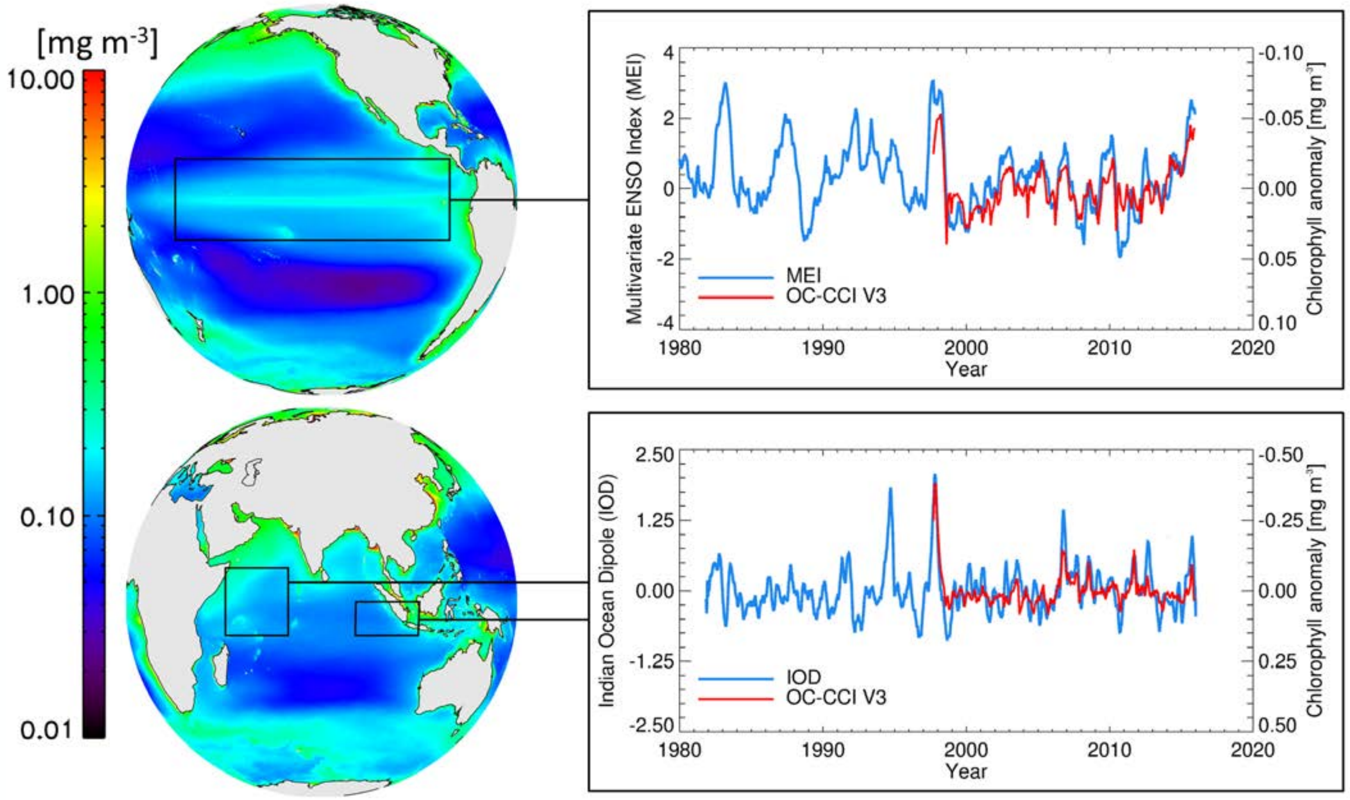
$$a_B(\lambda) = a_B^*(\lambda) + B$$

$$b_{bp}(\lambda) = b_{bp}^*(\lambda) + SPM$$

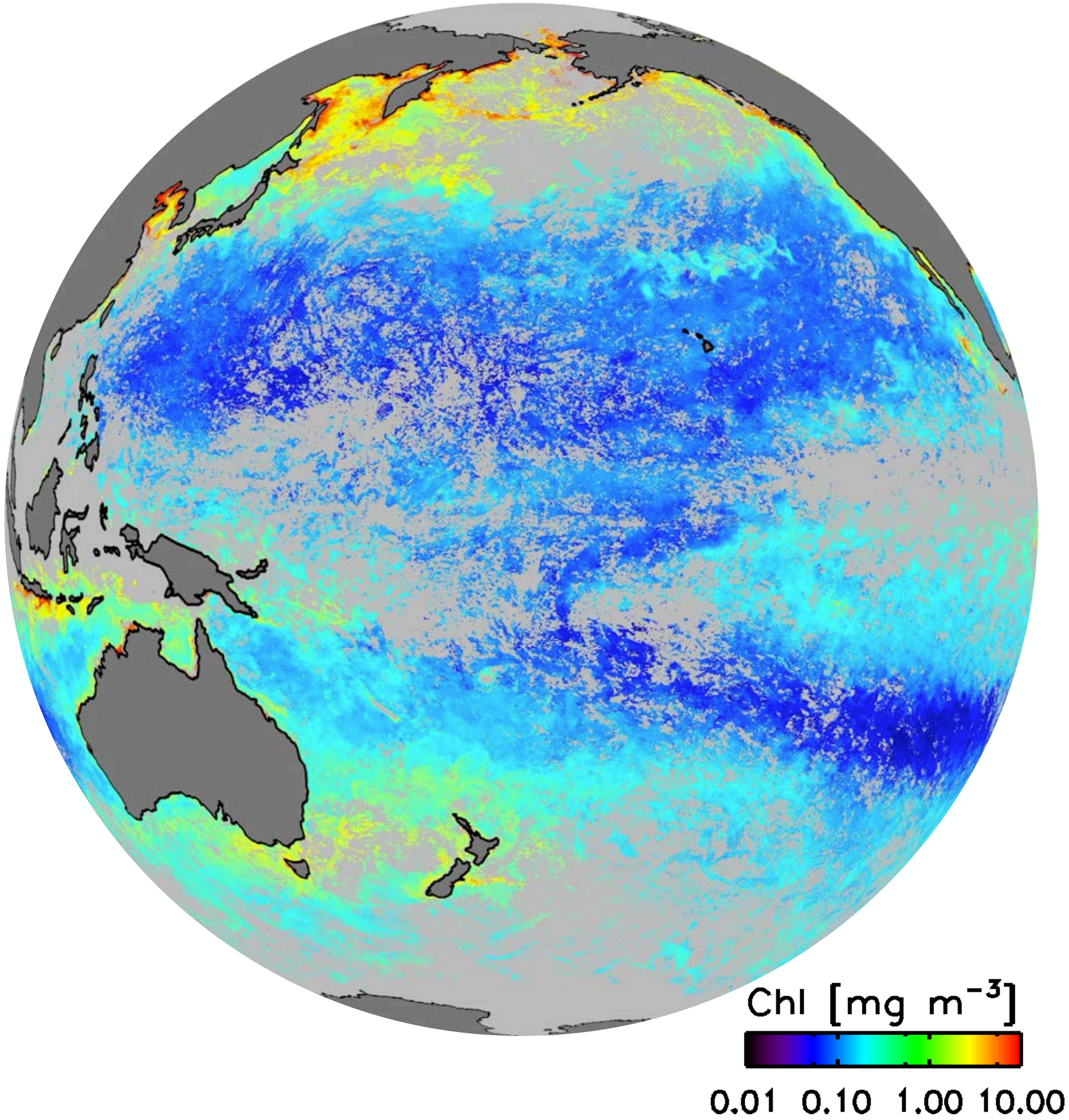
$$a_g(\lambda) = a_g^*(\lambda) + CDOM$$

IOCCG (2006) https://ioccg.org/wp-content/uploads/2015/10/ioccg-report-05.pdf

5) Satellite measurements of ocean colour



von Schuckmann et al. (2016)
https://doi.org/10.1080/1755876X.2016.1273446



Part 1: Outline

1) What is ocean colour?

2) History of ocean colour

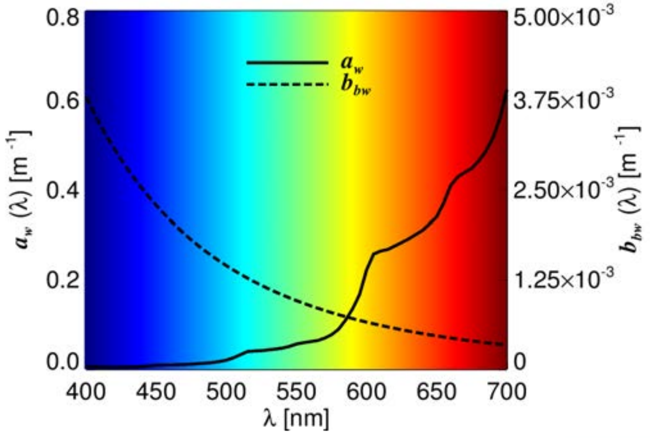
3) Optical properties of water and its constituents

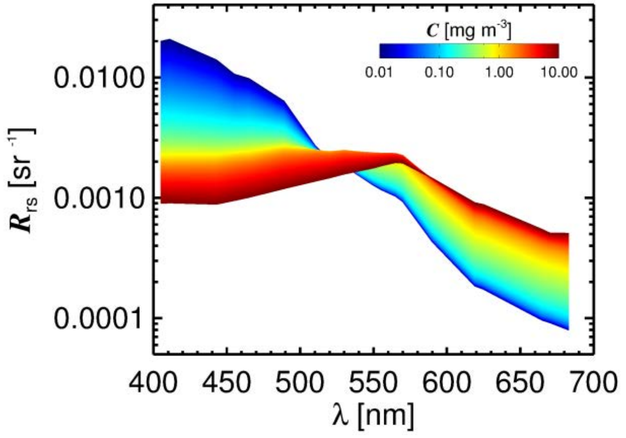
4) In situ measurements of ocean colour

5) Satellite remote-sensing of ocean colour

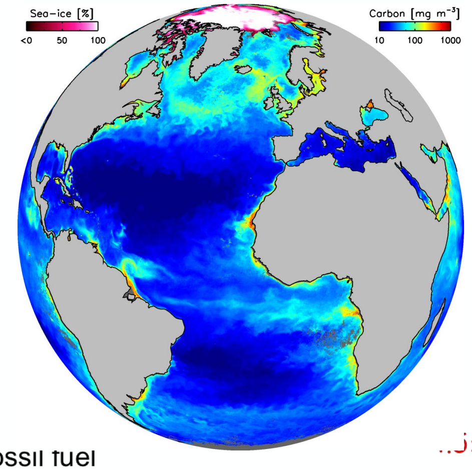
Lecture plan

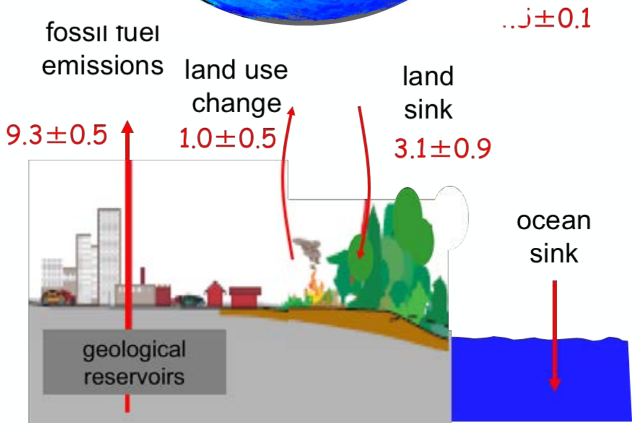
Ocean Colour theory (Part 1)



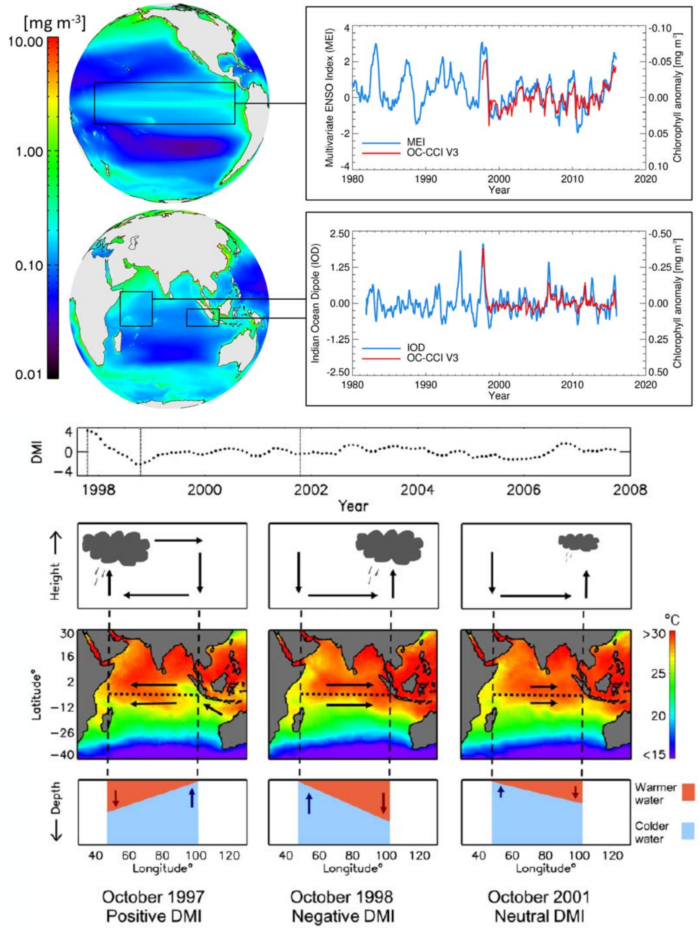


Ocean Colour applications: carbon cycle (Part 2)





Ocean Colour applications: climate (Part 3)



Part 2: Outline

1) Earth's Carbon Cycle

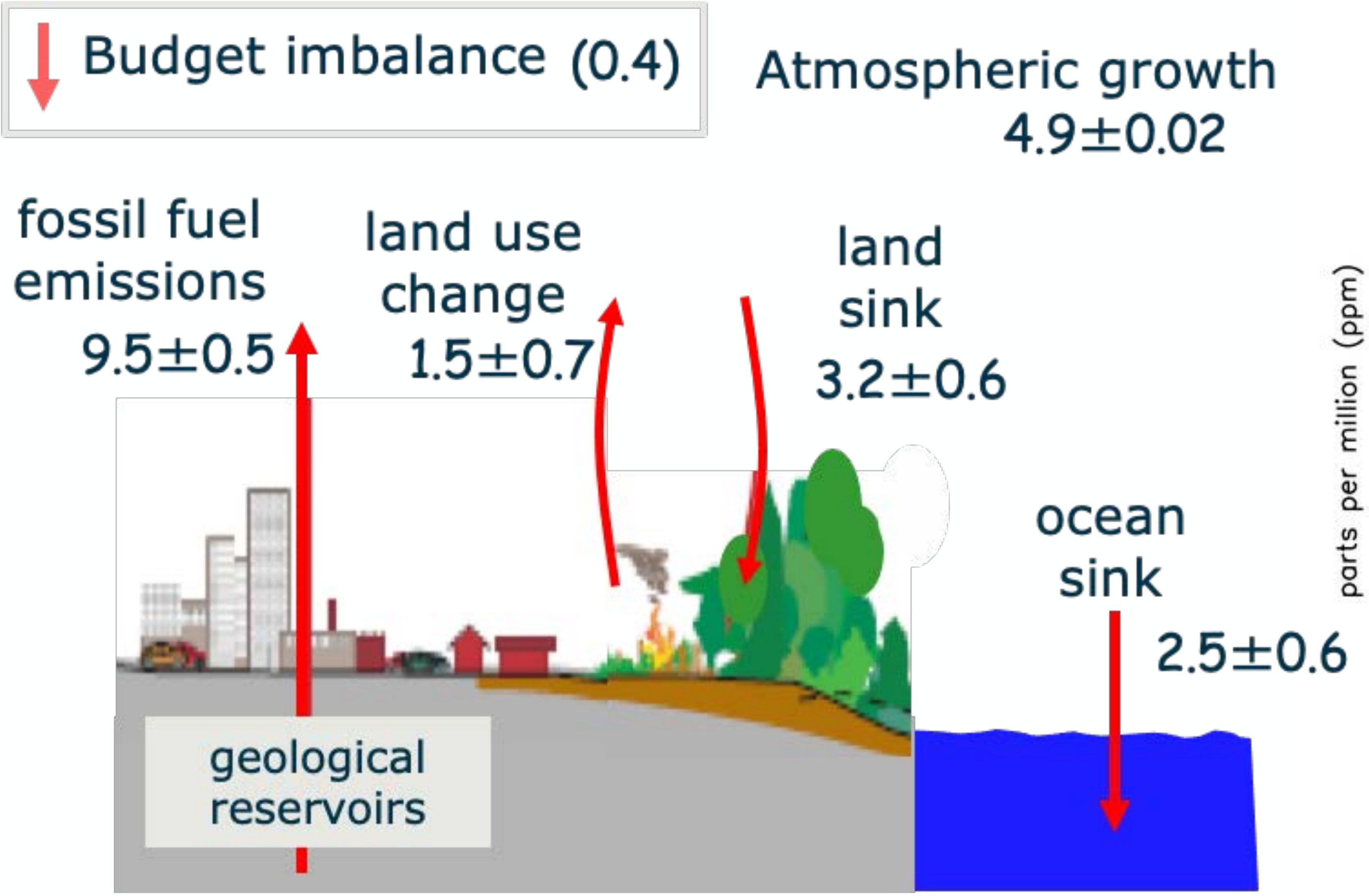
2) Ocean Carbon Cycle

3) Ocean carbon satellite products

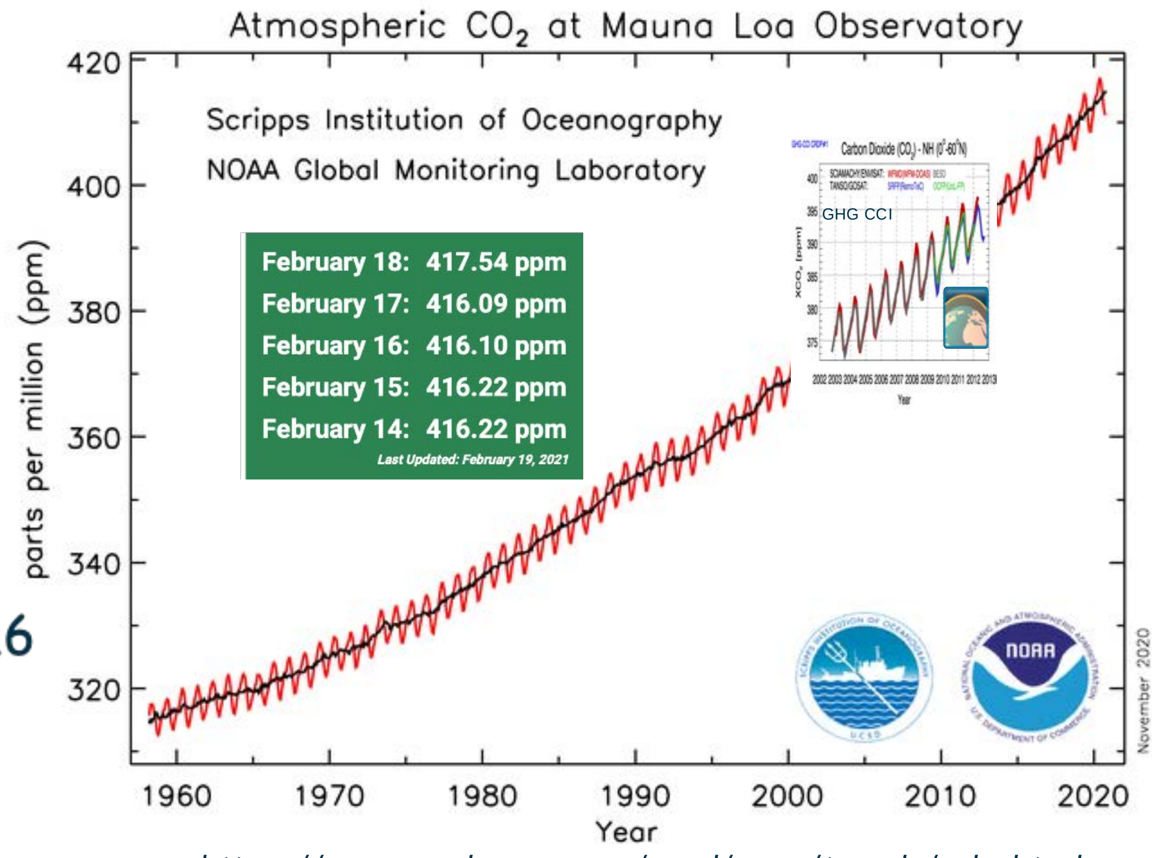
4) Integration with robotic platforms

5) Integration with models

1) Earth's Carbon Cycle

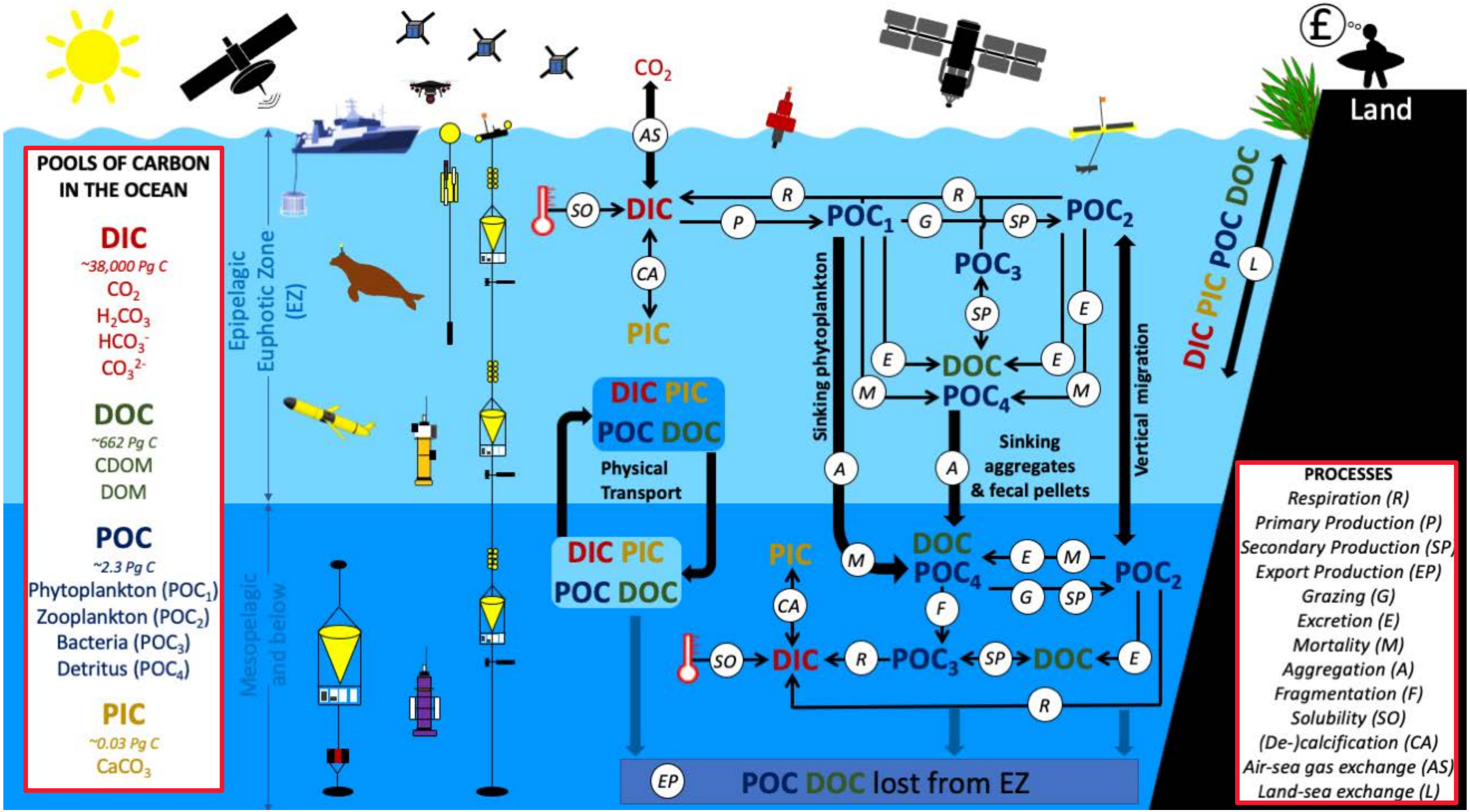


Friedlingstein et al. (2019) Global Carbon Budget (2019) Earth Syst. Sci. Data, 11, 1783–1838, https://doi.org/10.5194/essd-11-1783-2019



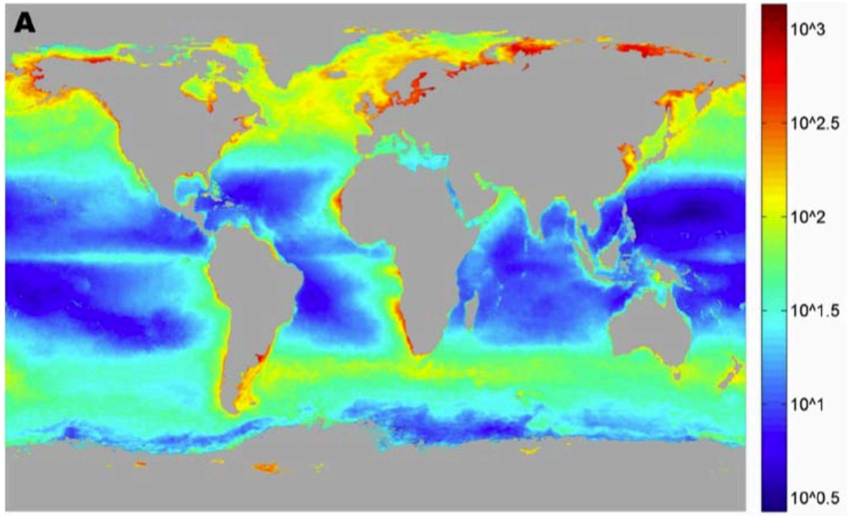
https://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html

2) Ocean Carbon Cycle

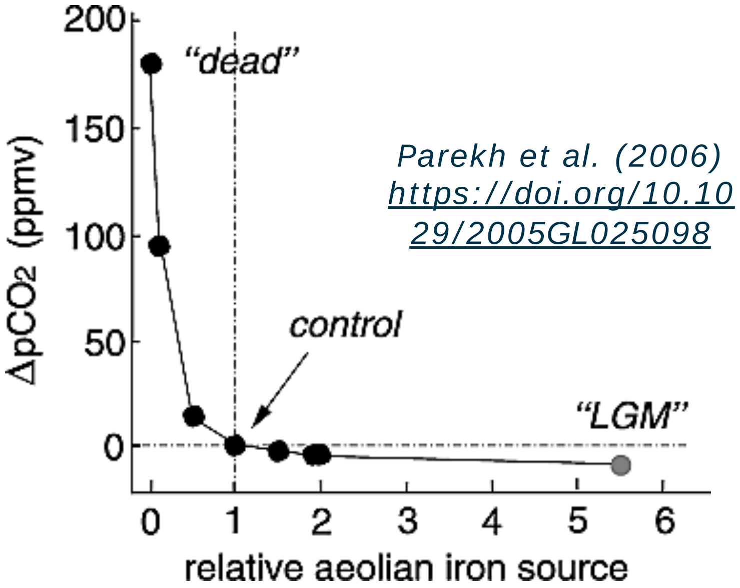


Brewin et al. (Under Review)

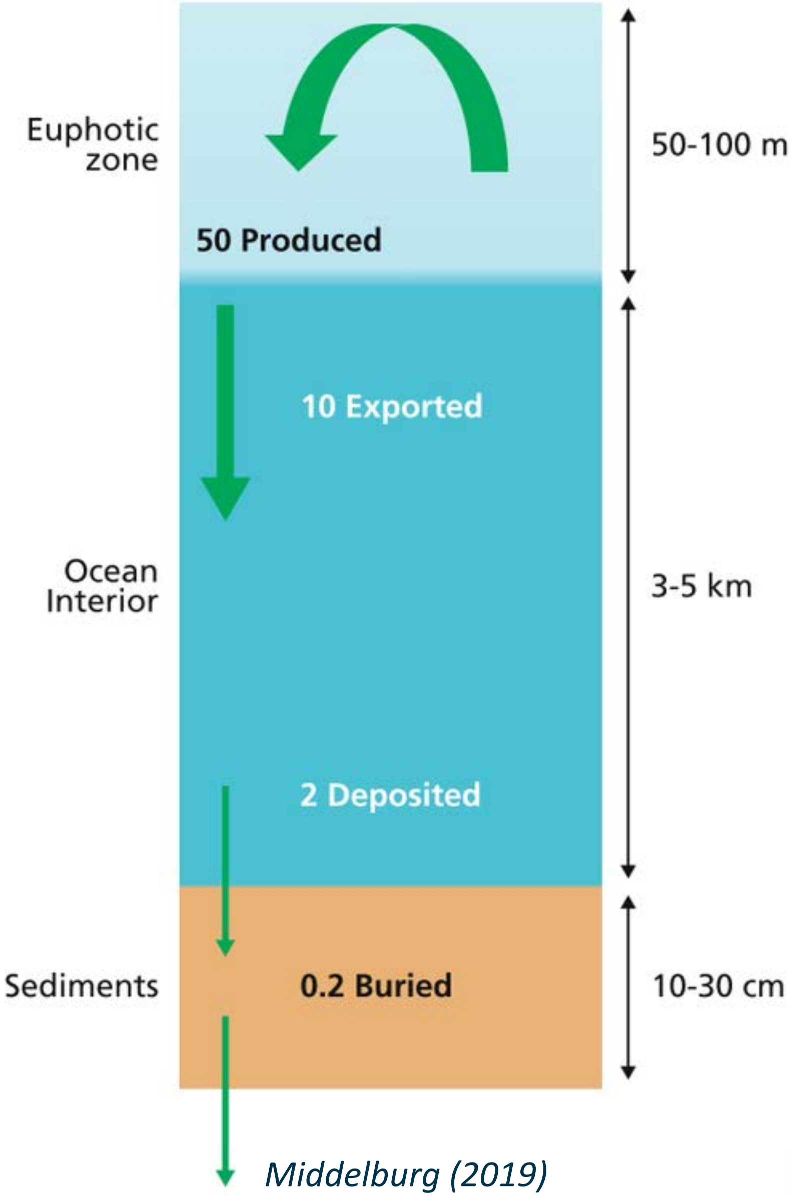
2) Ocean Carbon Cycle



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



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

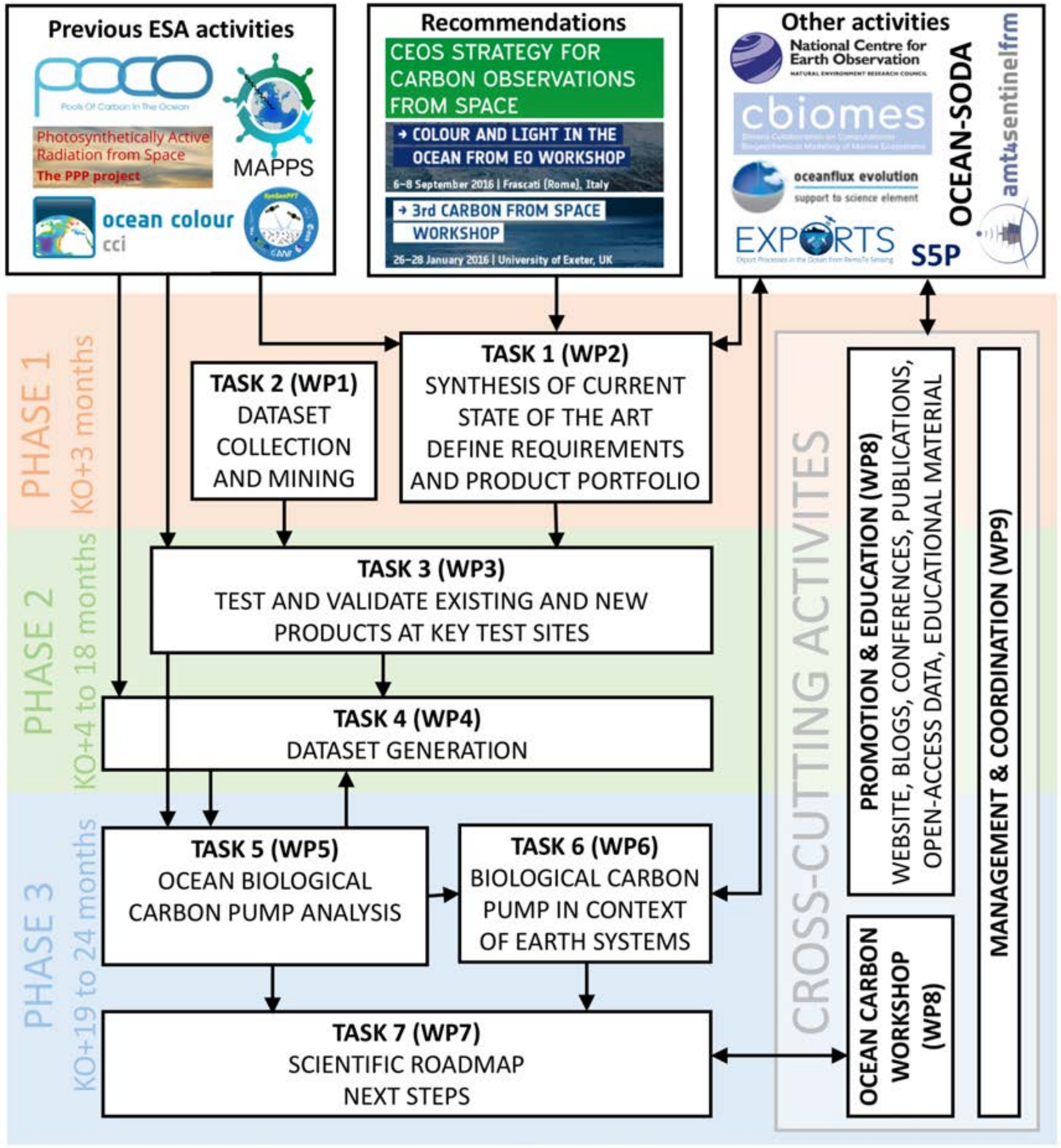


Middelburg (2019)
https://doi.org/10.1007/978-3-030-10822-9

Ocean Biological Carbon pump exports between 9-12 Gt C y^{-1} (Laws et al. 2011)

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

2) Ocean Carbon Cycle



https://bicep-project.org/Home

3) Ocean carbon satellite products: Phyto carbon

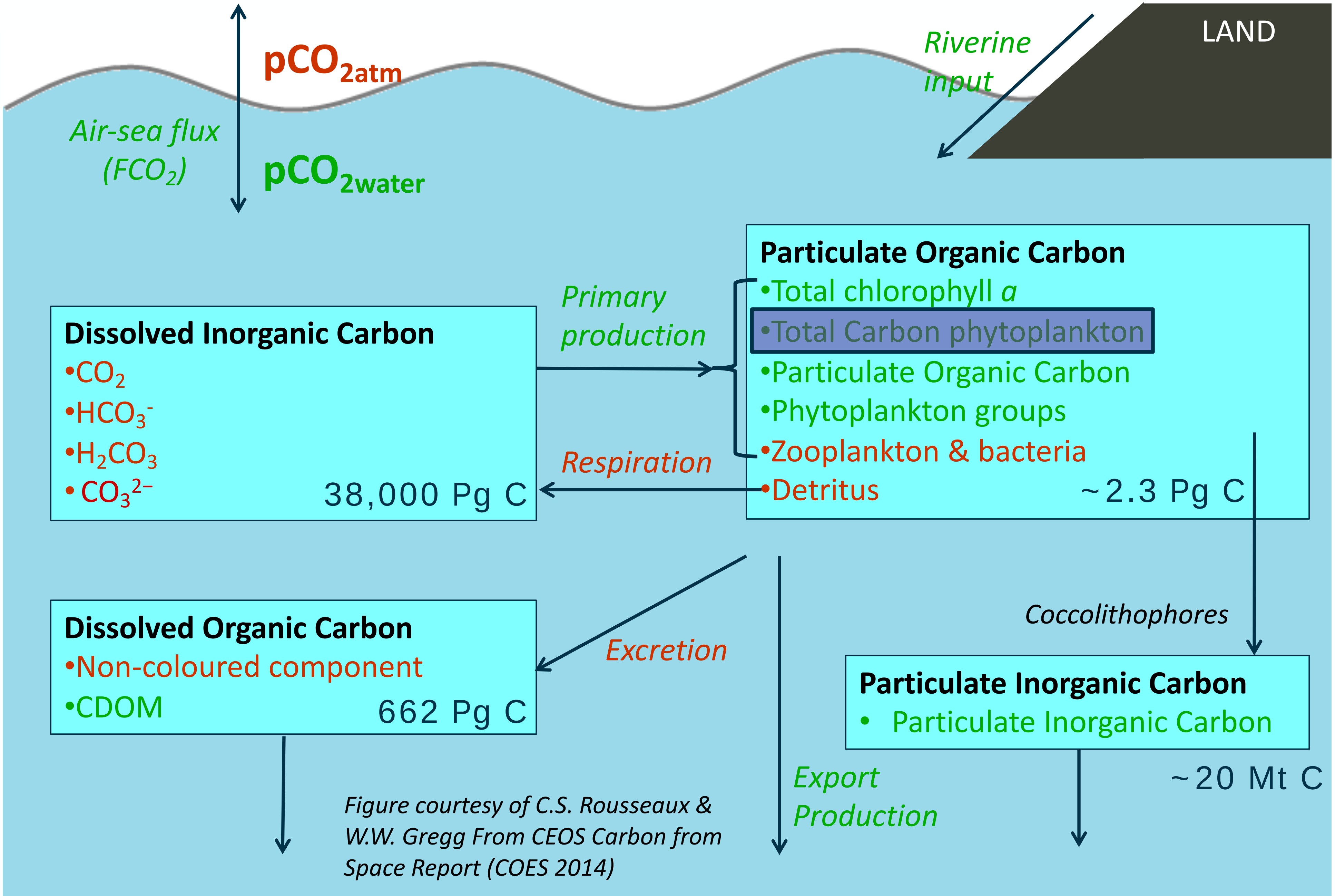
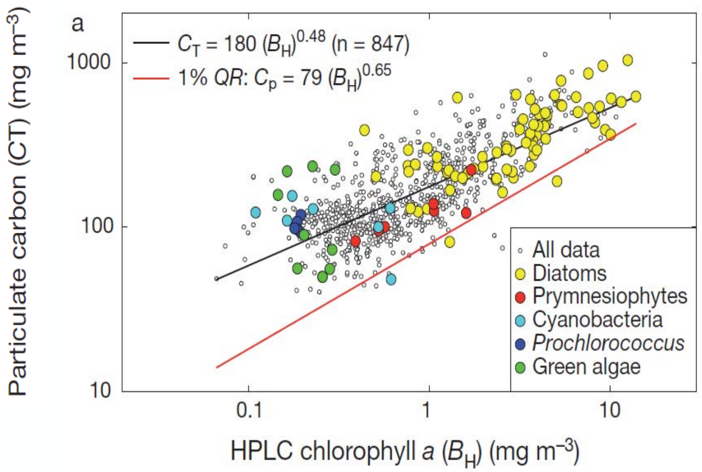


Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

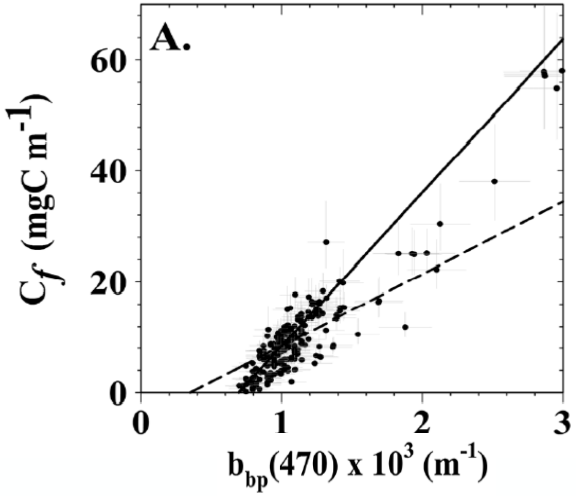
3) Ocean carbon satellite products: Phyto carbon

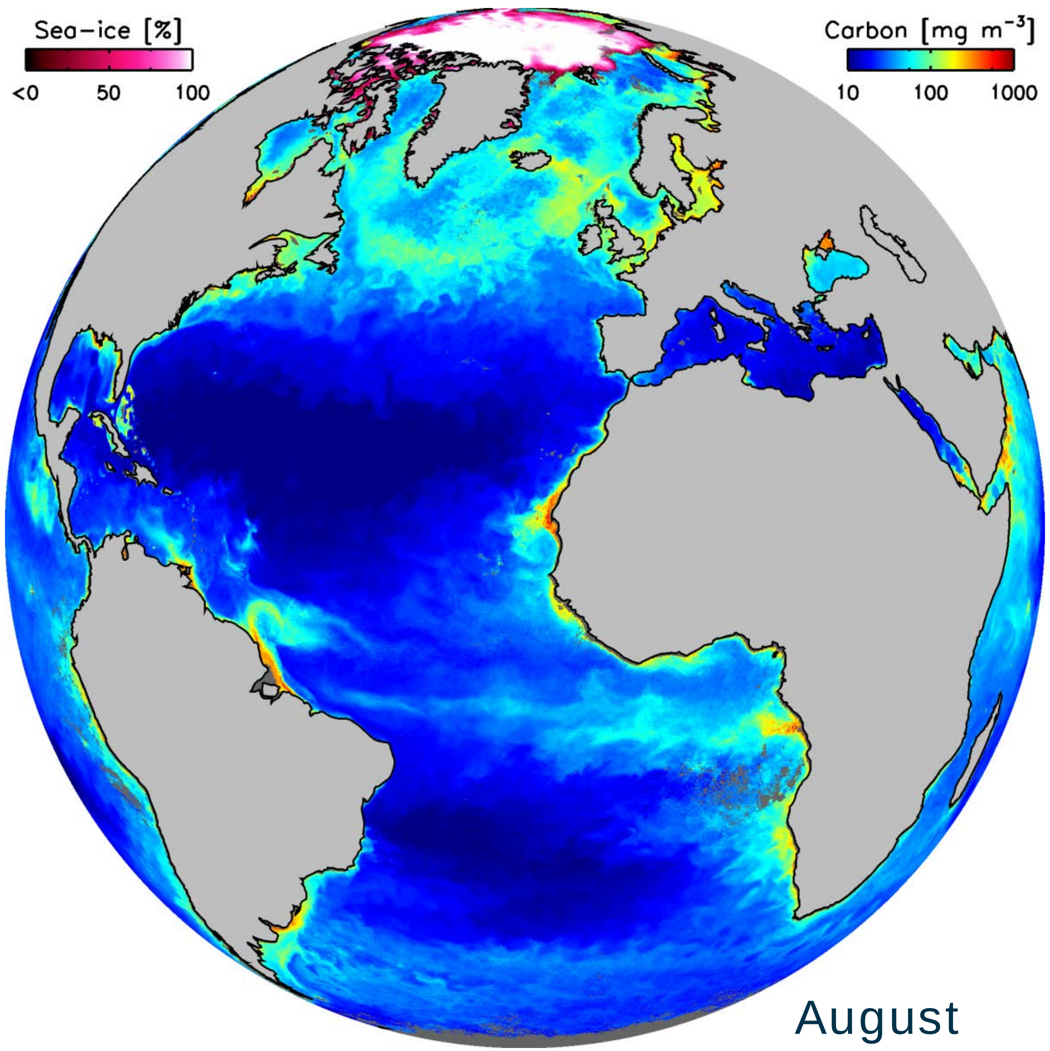


Sathyendranath et al. (2009)
https://doi.org/10.3354/meps07998

Martinez-Vicente et al. (2013)
https://doi.org/10.1002/grl.50252

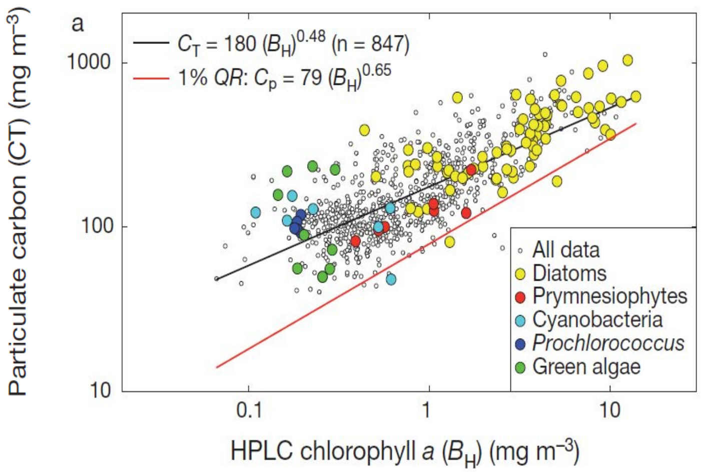
Kostadinov et al. (2016)
https://doi.org/10.5194/os-12-561-2016



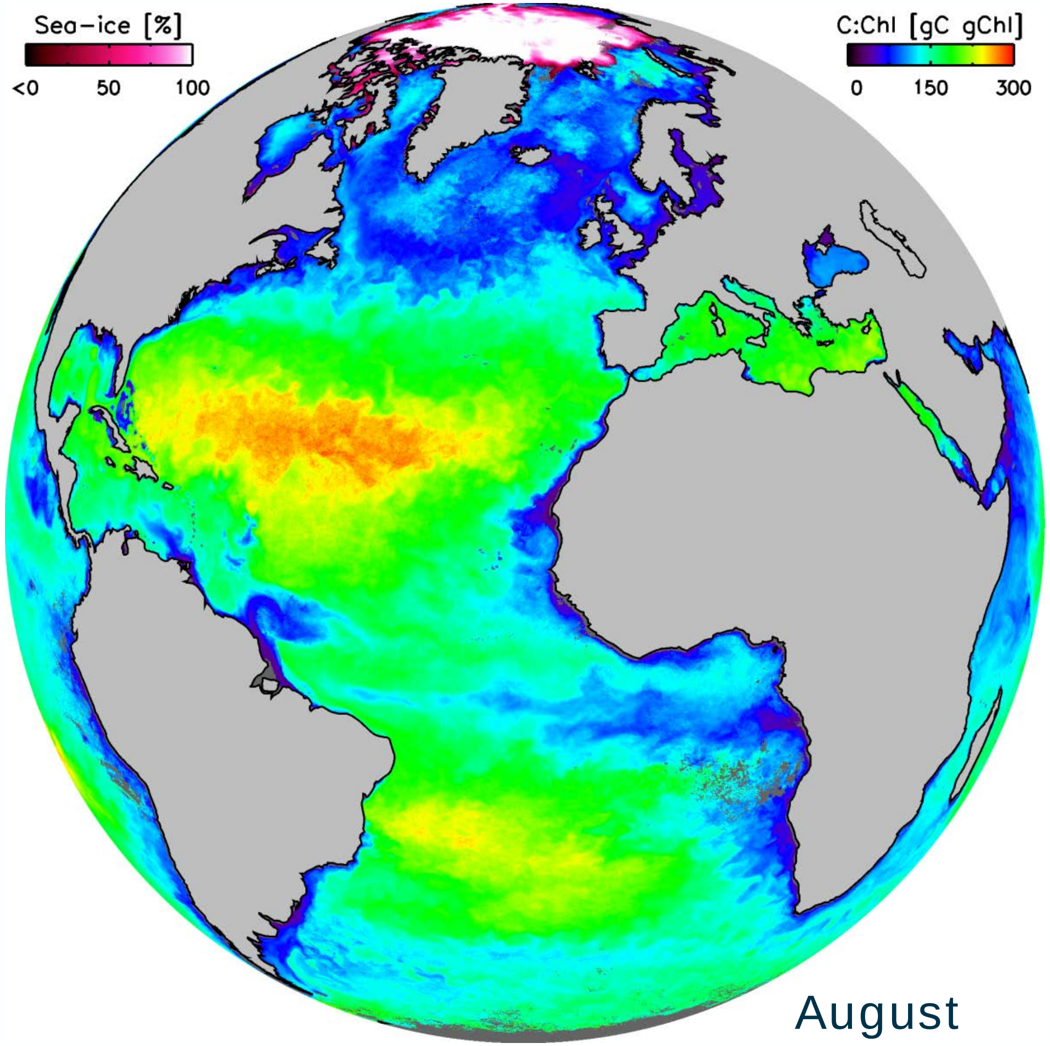


August 2003

3) Ocean carbon satellite products: Phyto carbon



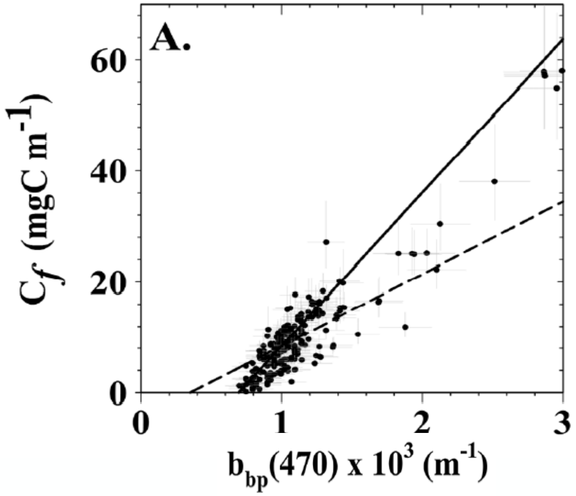
Sathyendranath et al. (2009)
https://doi.org/10.3354/meps07998



August 2003

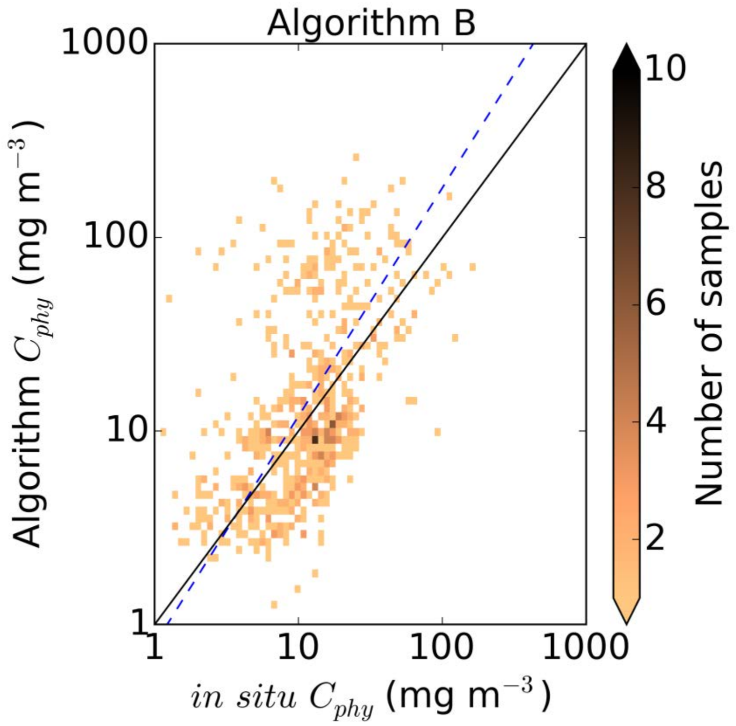
Martinez-Vicente et al. (2013)
https://doi.org/10.1002/grl.50252

Kostadinov et al. (2016)
https://doi.org/10.5194/os-12-561-2016

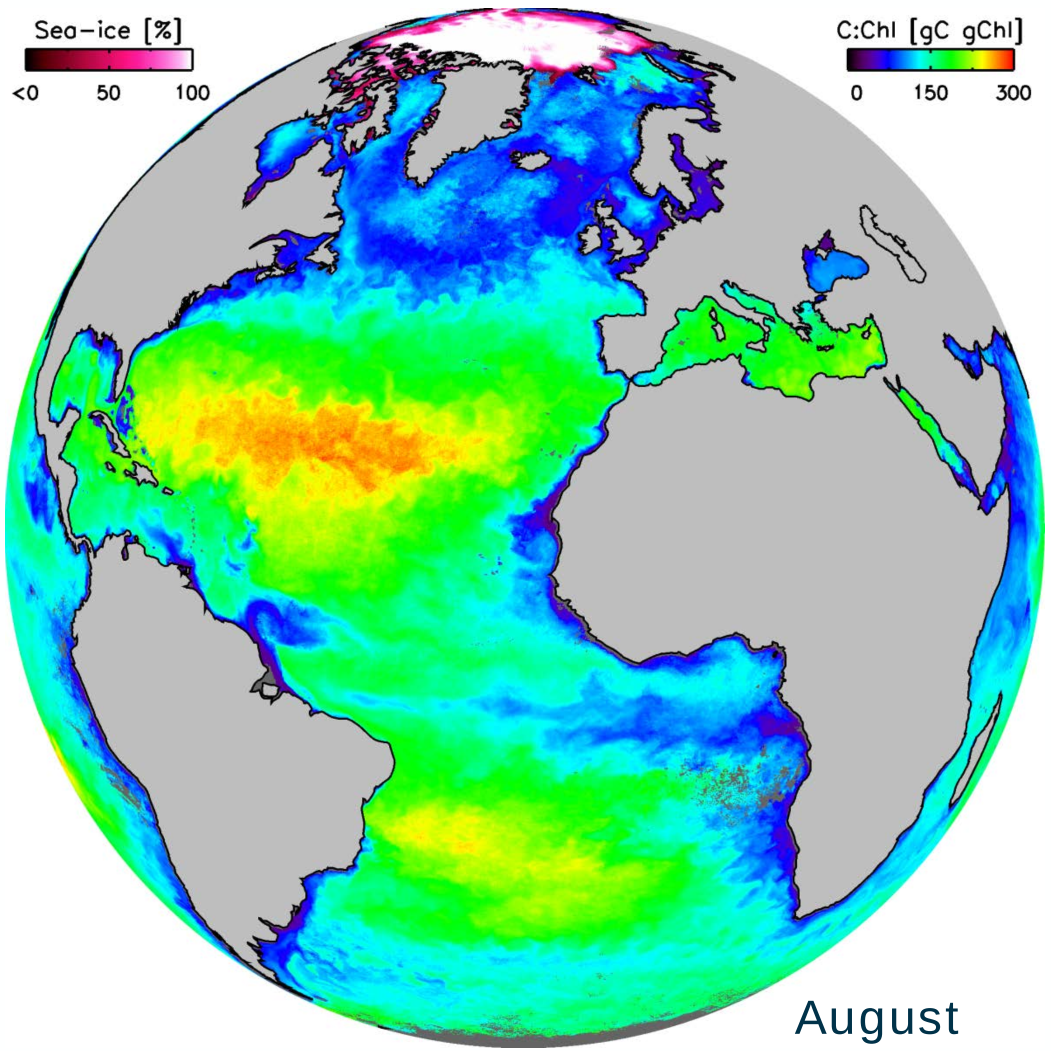


3) Ocean carbon satellite products: Phyto carbon

Validation



Martinez-Vicente et al. (2017)
https://doi.org/10.3389/fmars.2017.00378



August 2003

3) Ocean carbon satellite products: POC

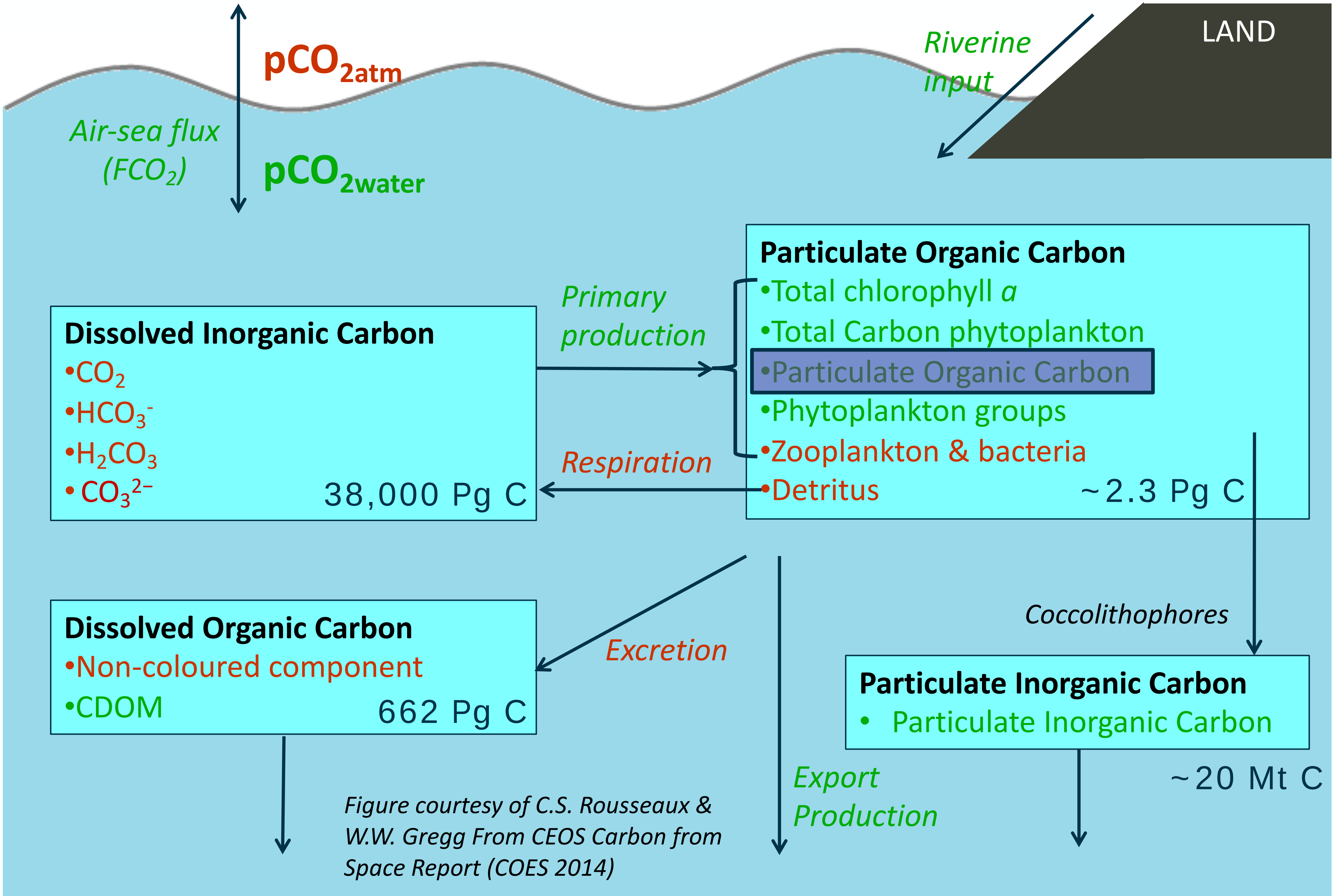
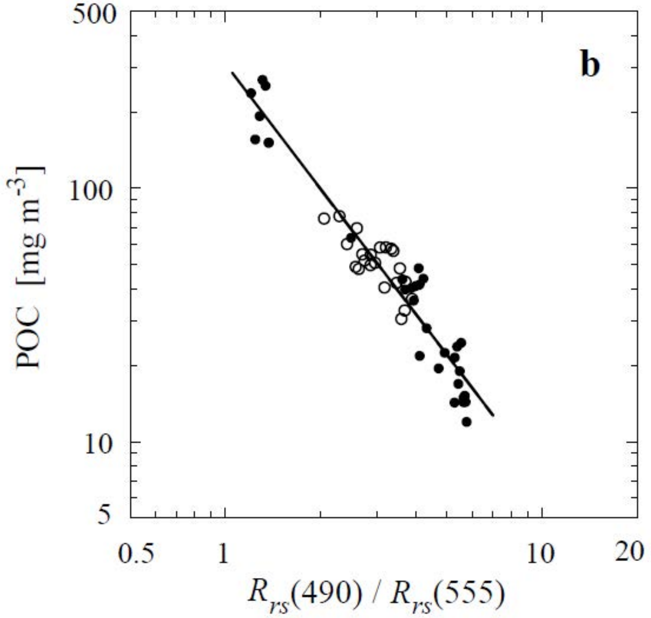


Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

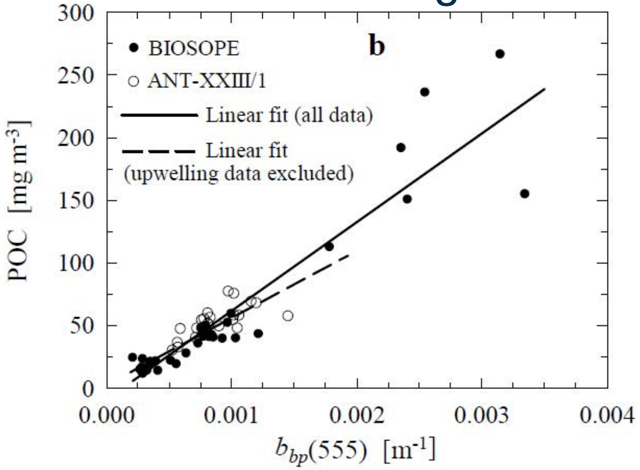
3) Ocean carbon satellite products: POC

Validation

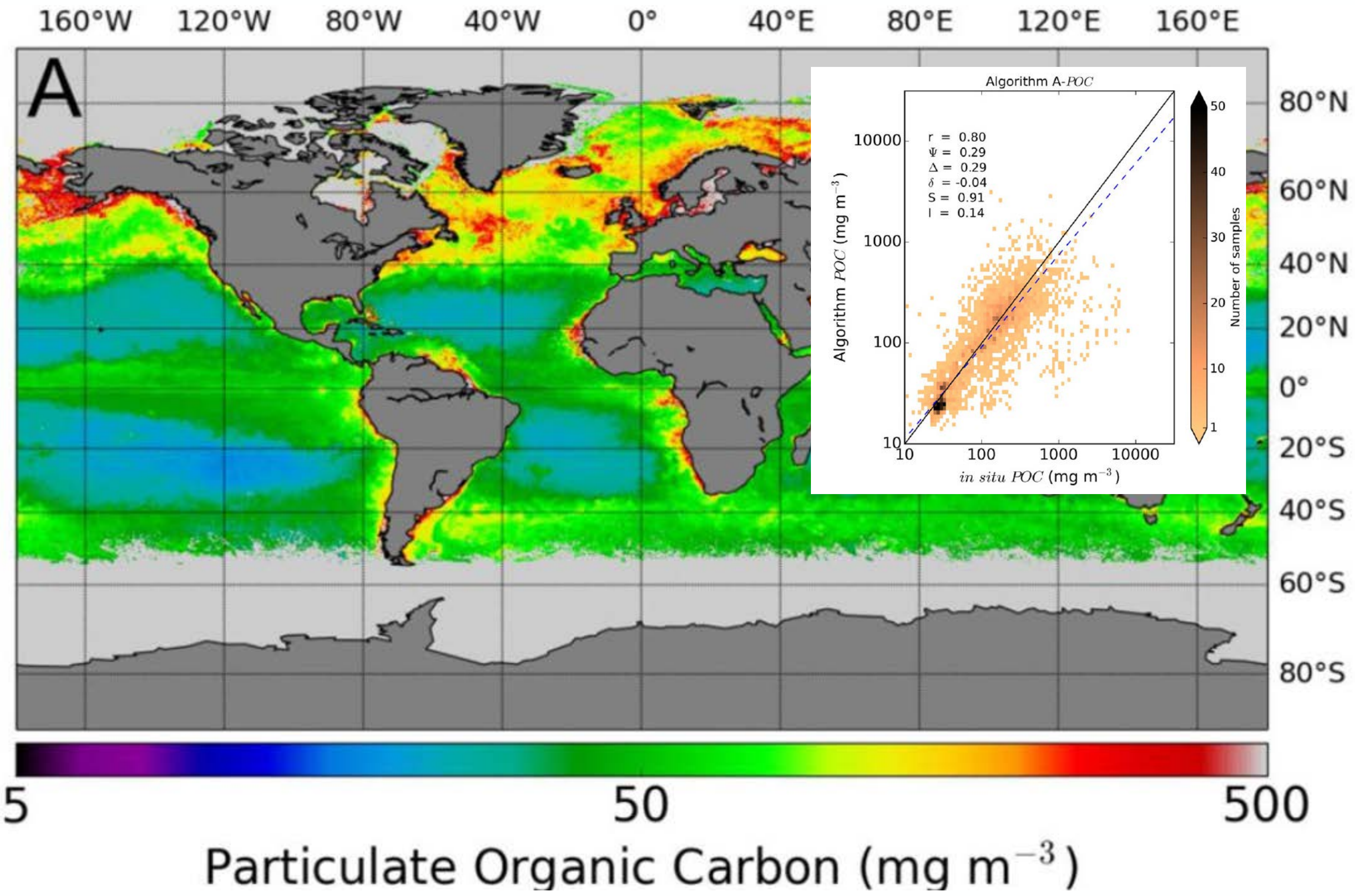
Reflectance-based



Backscattering-based



Stramski et al. (2008)
https://doi.org/10.5194/bg-5-171-2008



Evers-King et al. (2017) https://doi.org/10.3389/fmars.2017.00251

3) Ocean carbon satellite products: Phyto- groups

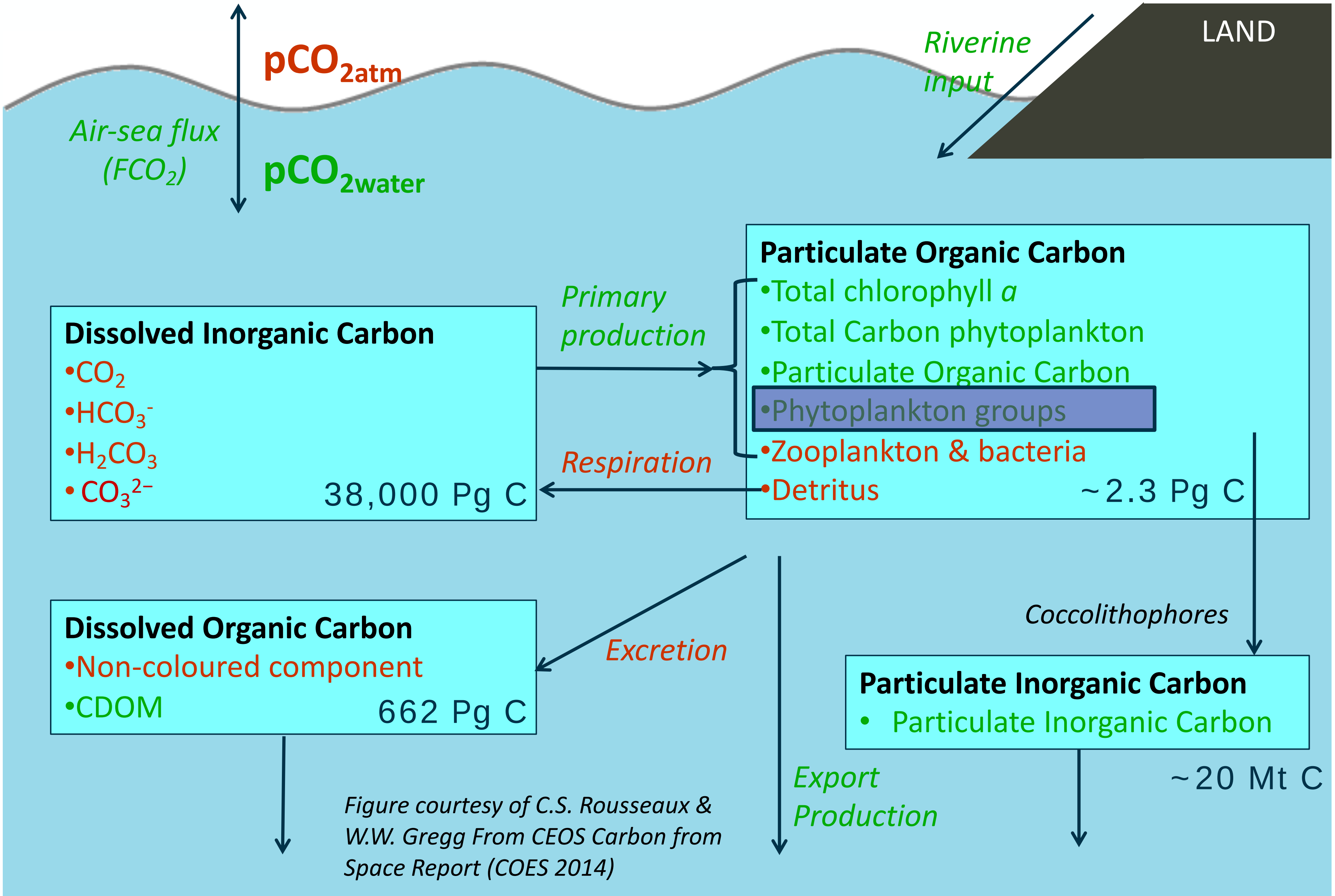
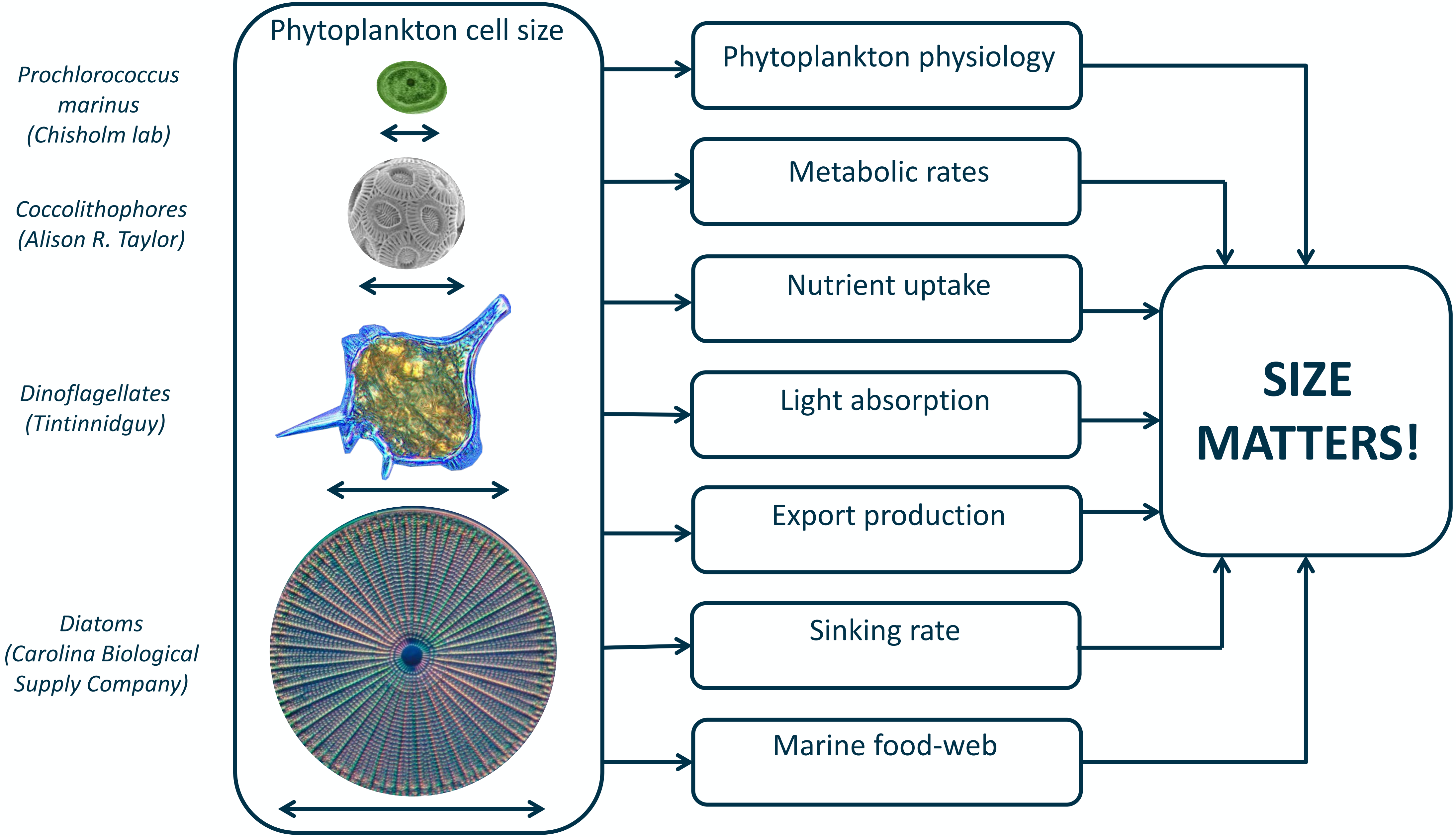


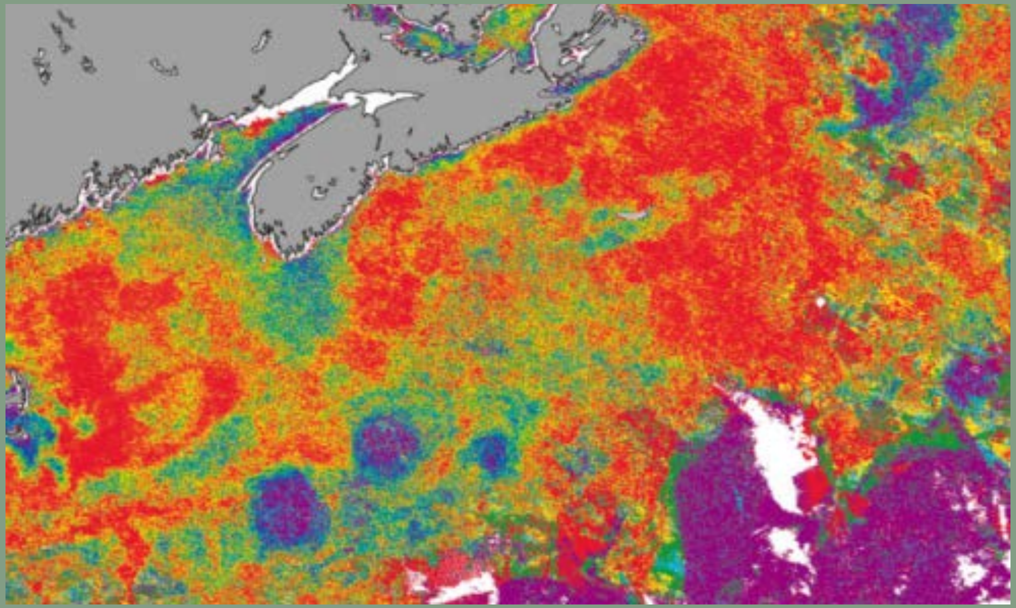
Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

3) Ocean carbon satellite products: Phyto- groups



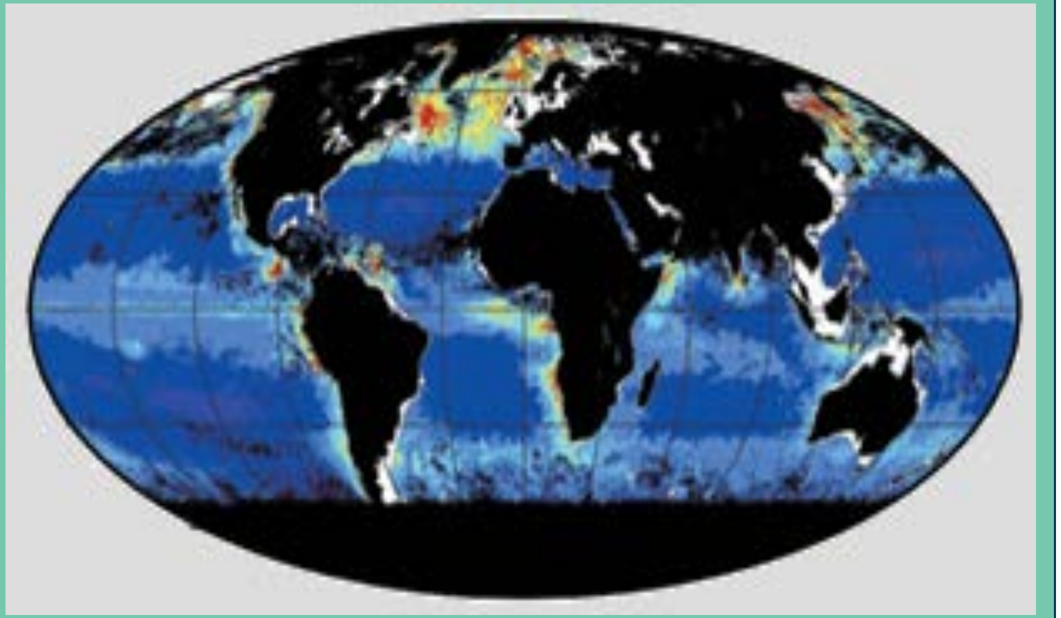
3) Ocean carbon satellite products: Phyto- groups

Detection-based



Sathyendranath et al. (2004) MEPS

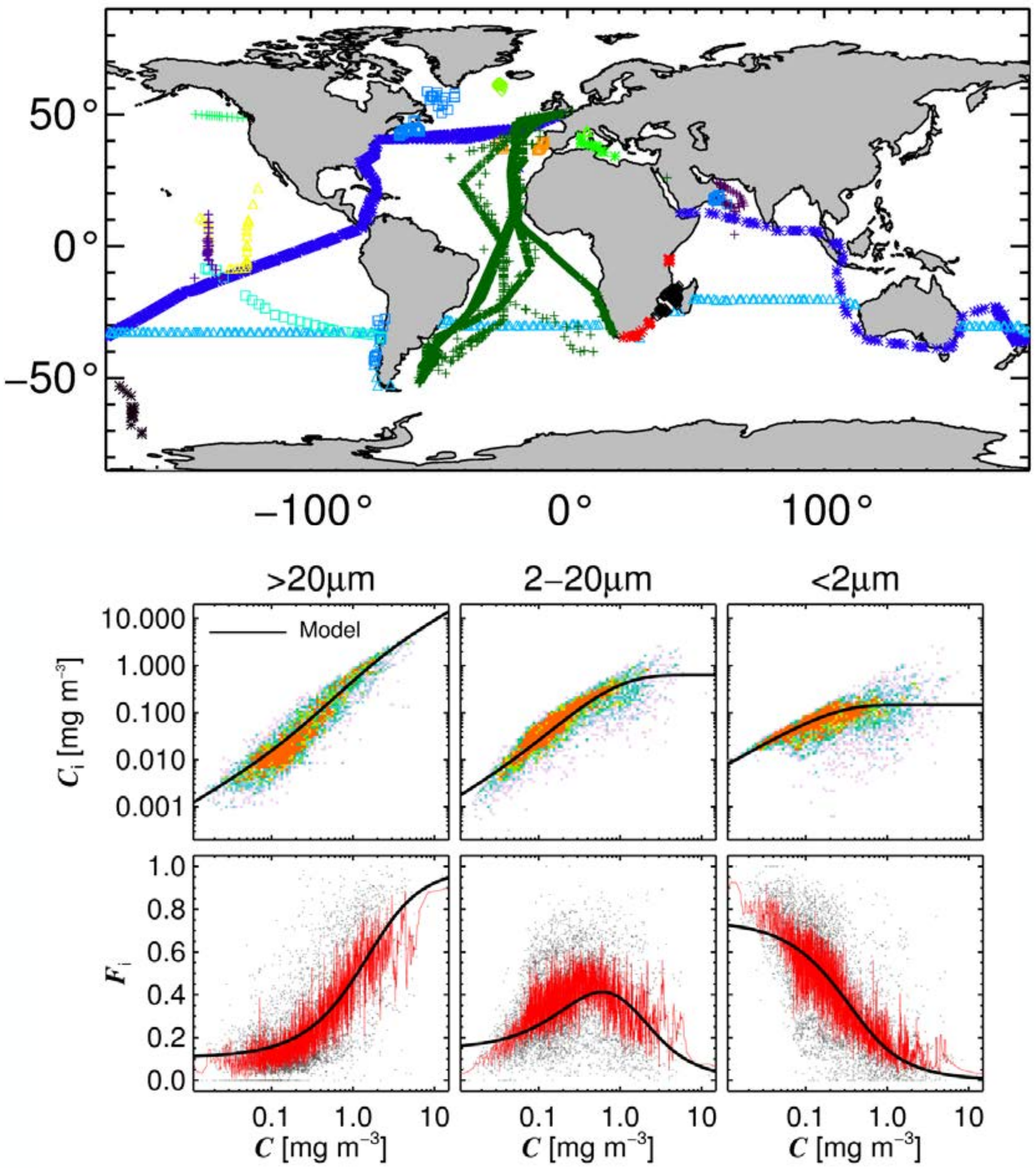
Extrapolation-based



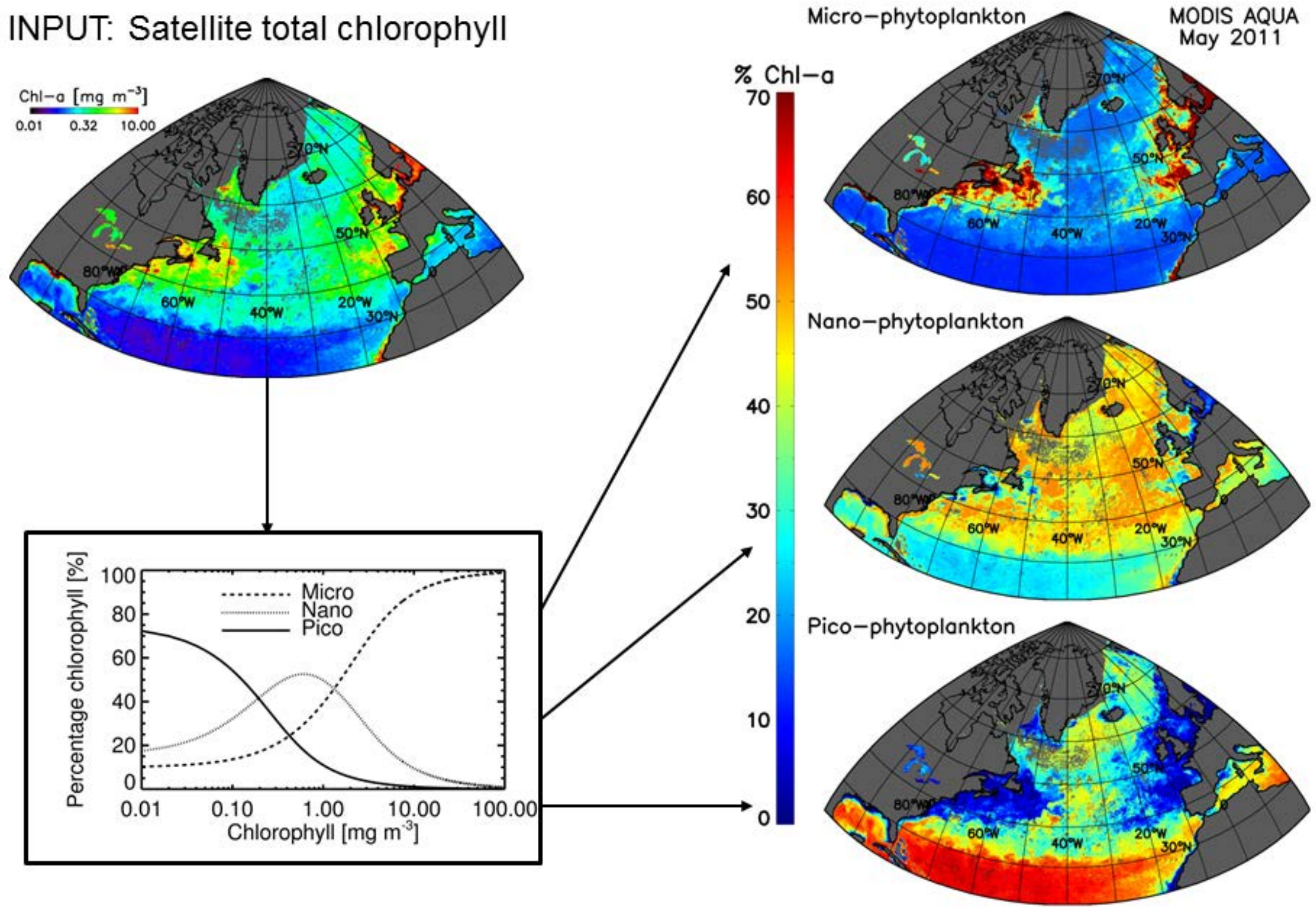
Uitz et al. (2006) J. Geophys. Res.

IOCCG (2014) Report Number 15 http://ioccg.org/wp-content/uploads/2018/09/ioccg_report_15_2014.pdf
Mouw et al. (2017) https://doi.org/10.3389/fmars.2017.00041

3) Ocean carbon satellite products: Phyto- groups

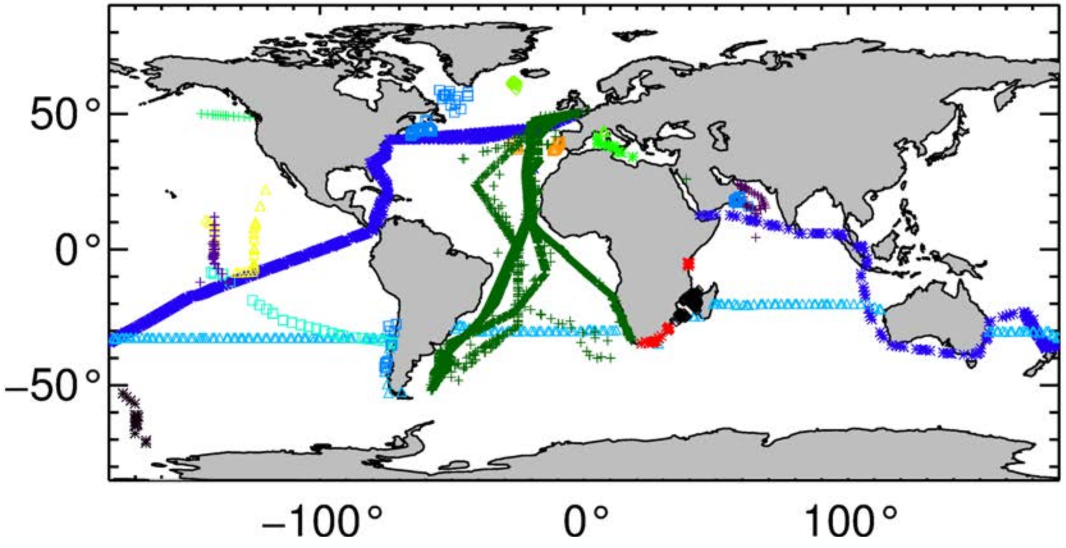


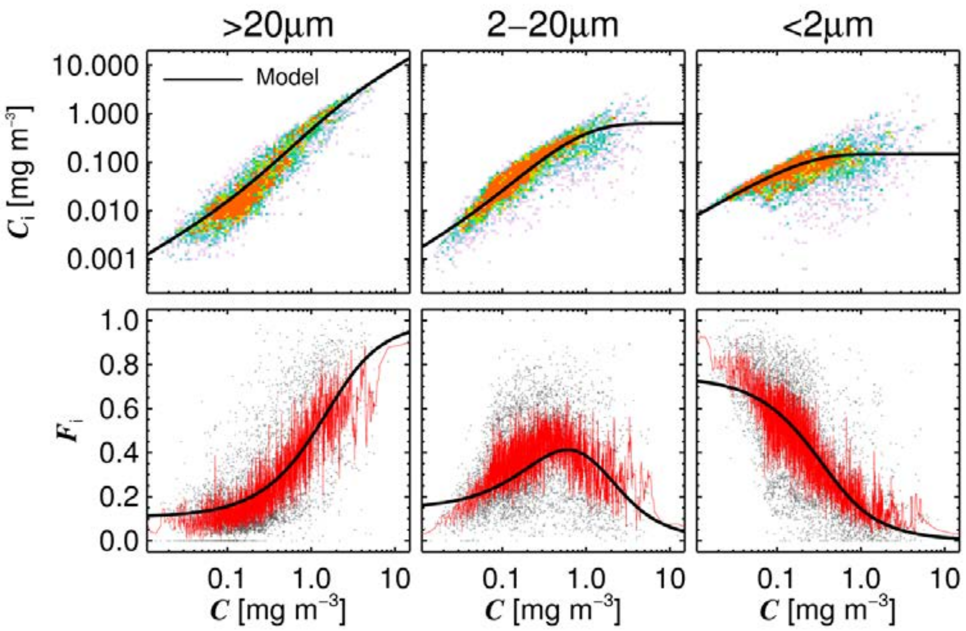
An example of an extrapolation-based approach



Brewin et al. (2010) https://doi.org/10.1016/j.ecolmodel.2010.02.014
Brewin et al. (2015) https://doi.org/10.1016/j.rse.2015.07.004

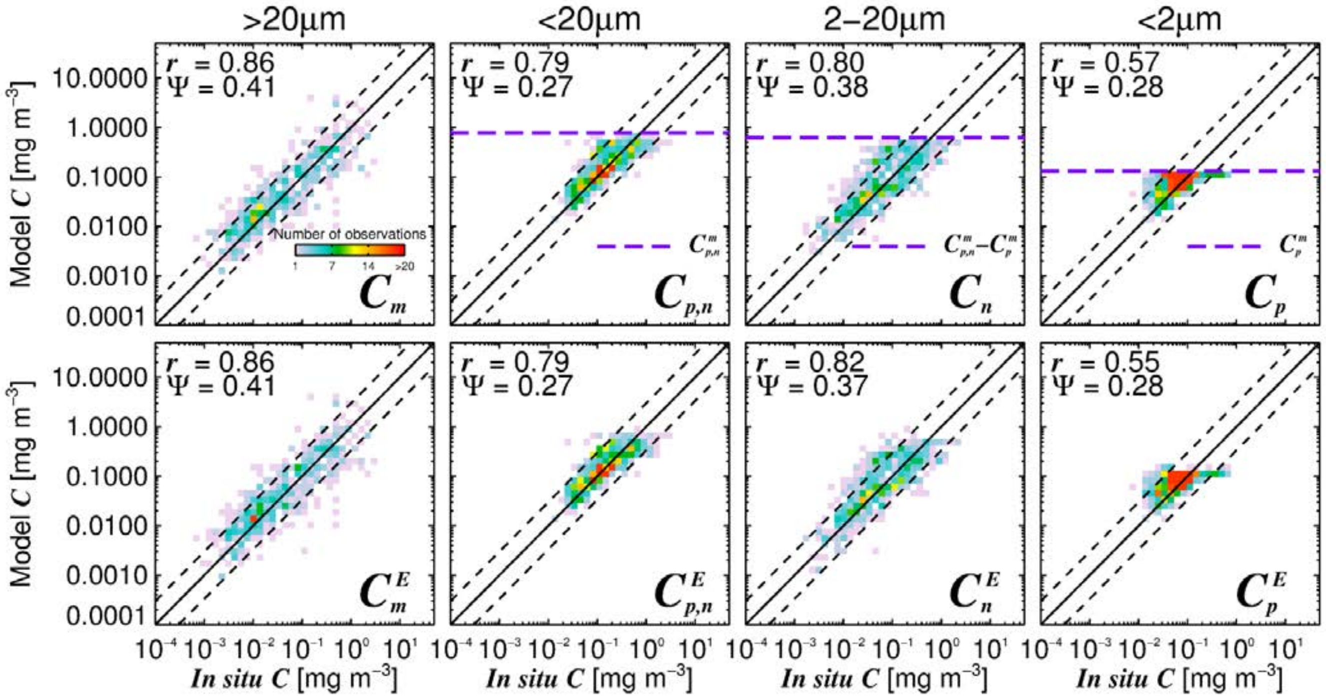
3) Ocean carbon satellite products: Phyto- groups





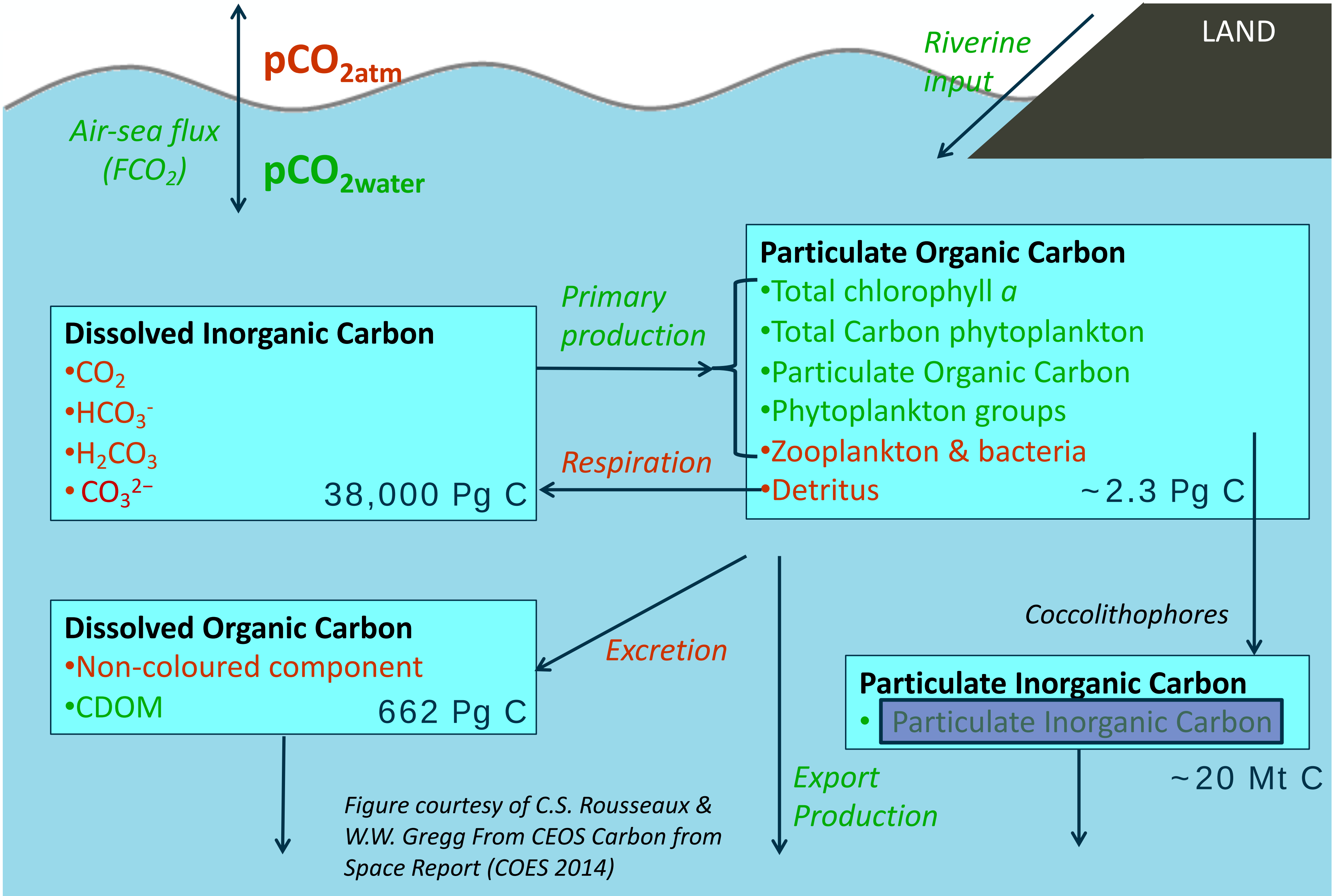
An example of an extrapolation-based approach

Validation

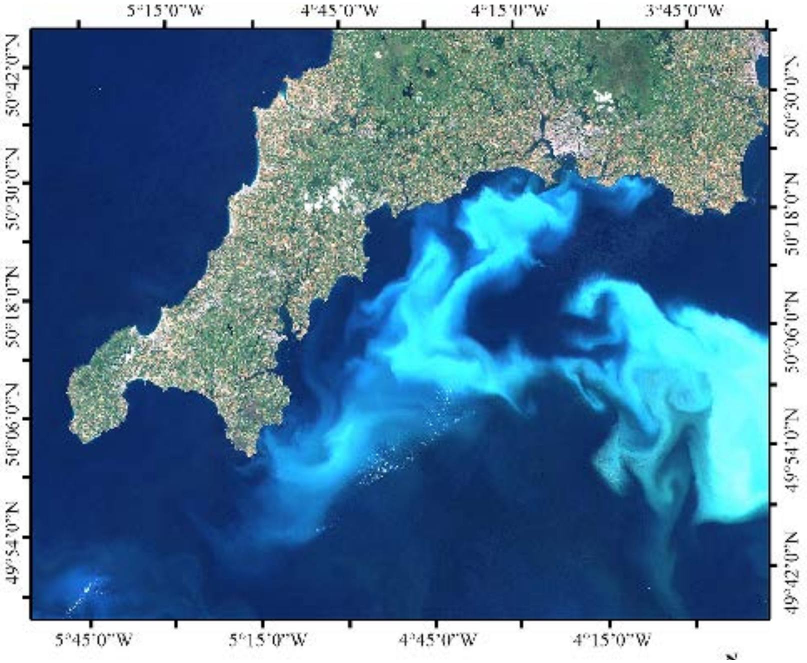


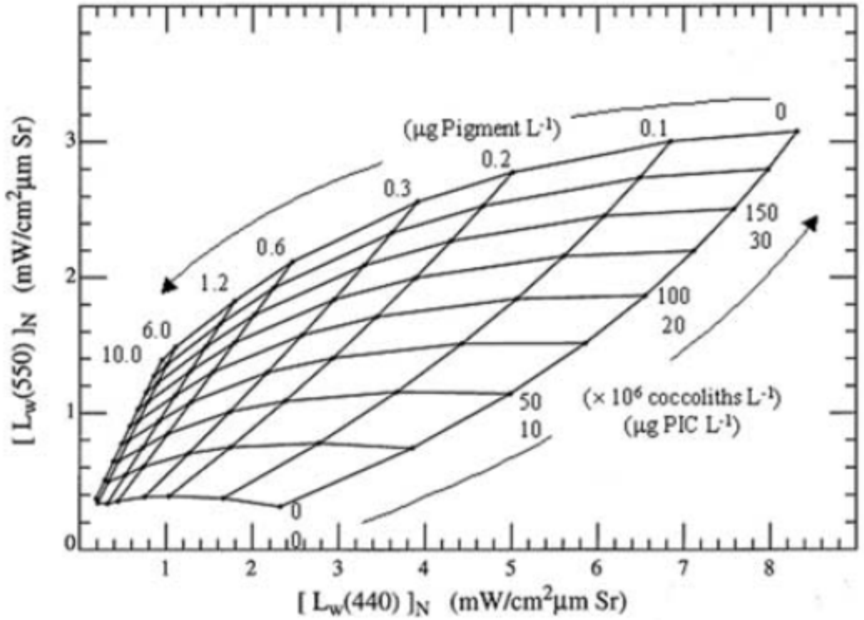
Brewin et al. (2010) https://doi.org/10.1016/j.ecolmodel.2010.02.014
Brewin et al. (2015) https://doi.org/10.1016/j.rse.2015.07.004

3) Ocean carbon satellite products: PIC

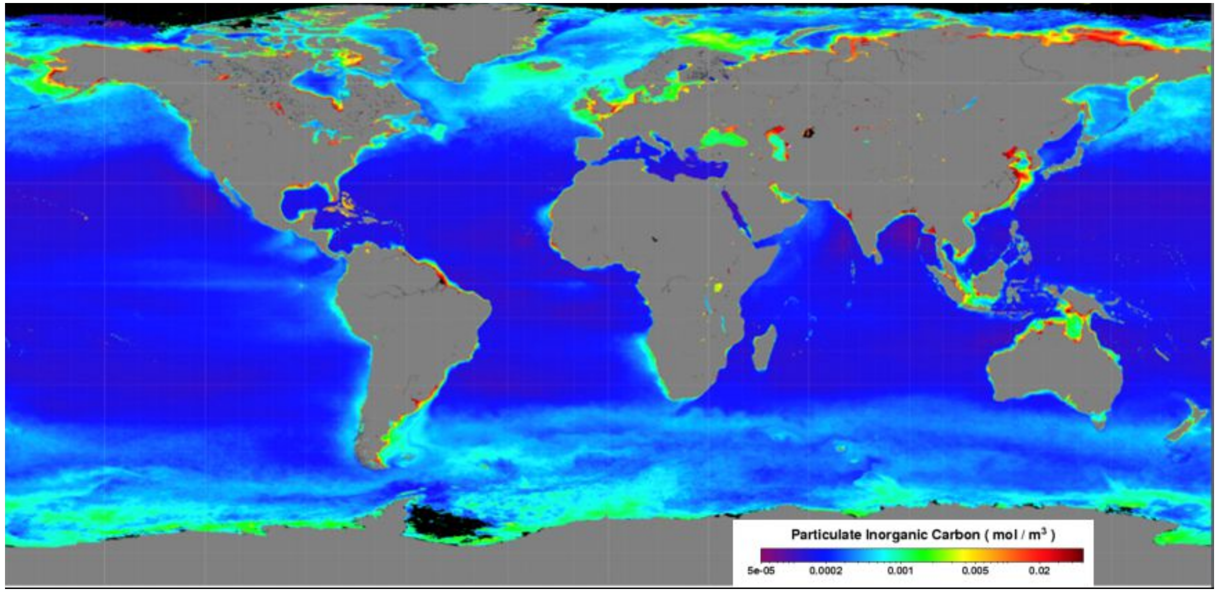


3) Ocean carbon satellite products: PIC





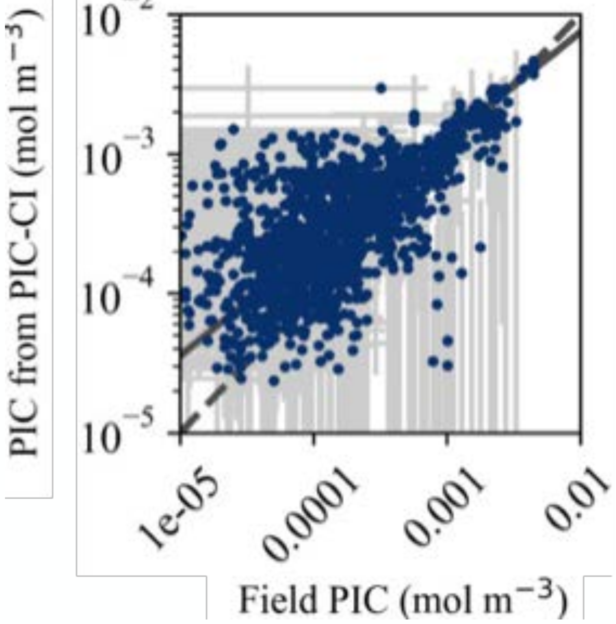
Coccolithophores
(Alison R. Taylor)



Balch et al. (2005)
https://doi.org/10.1029/2004JC002560

Mitchell et al. (2017)
https://doi.org/10.1002/2017JC013146

Validation



3) Ocean carbon satellite products: Primary Production

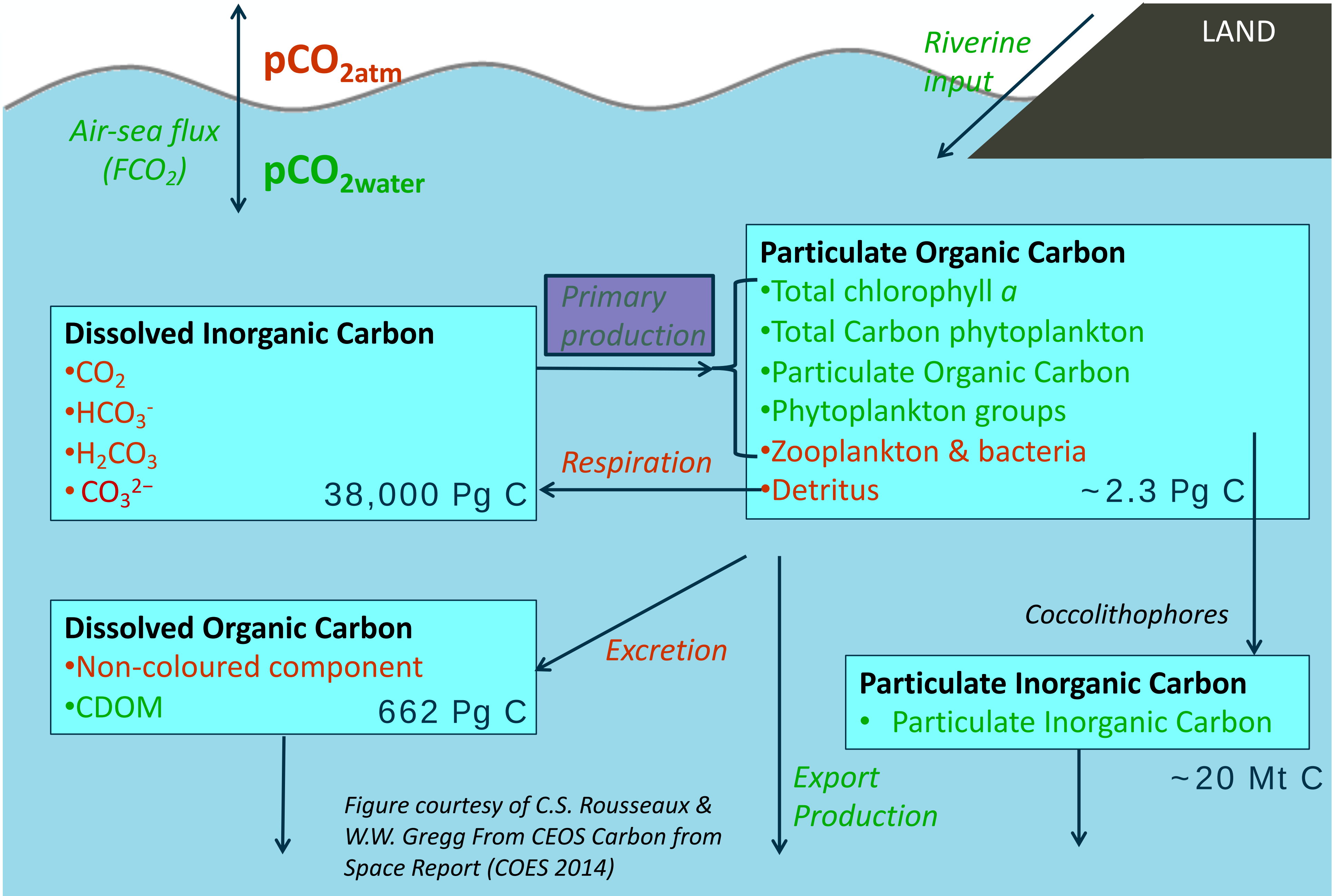
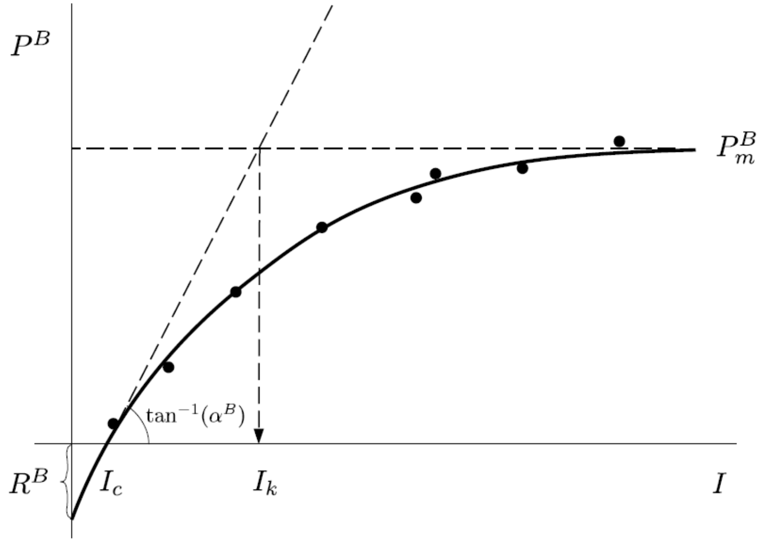
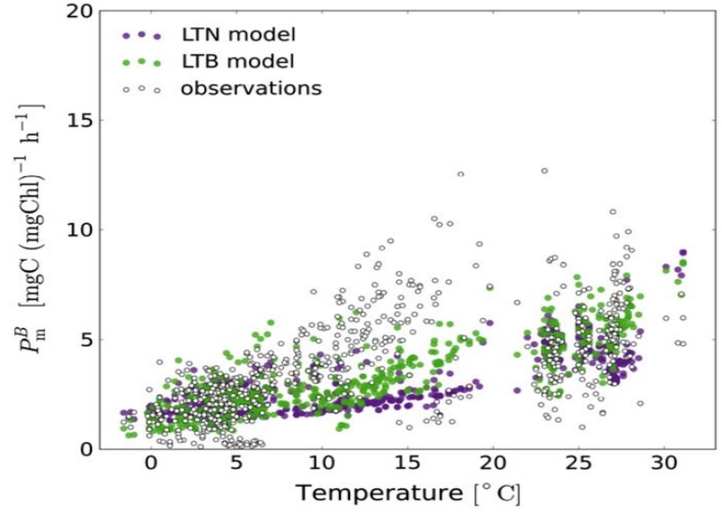


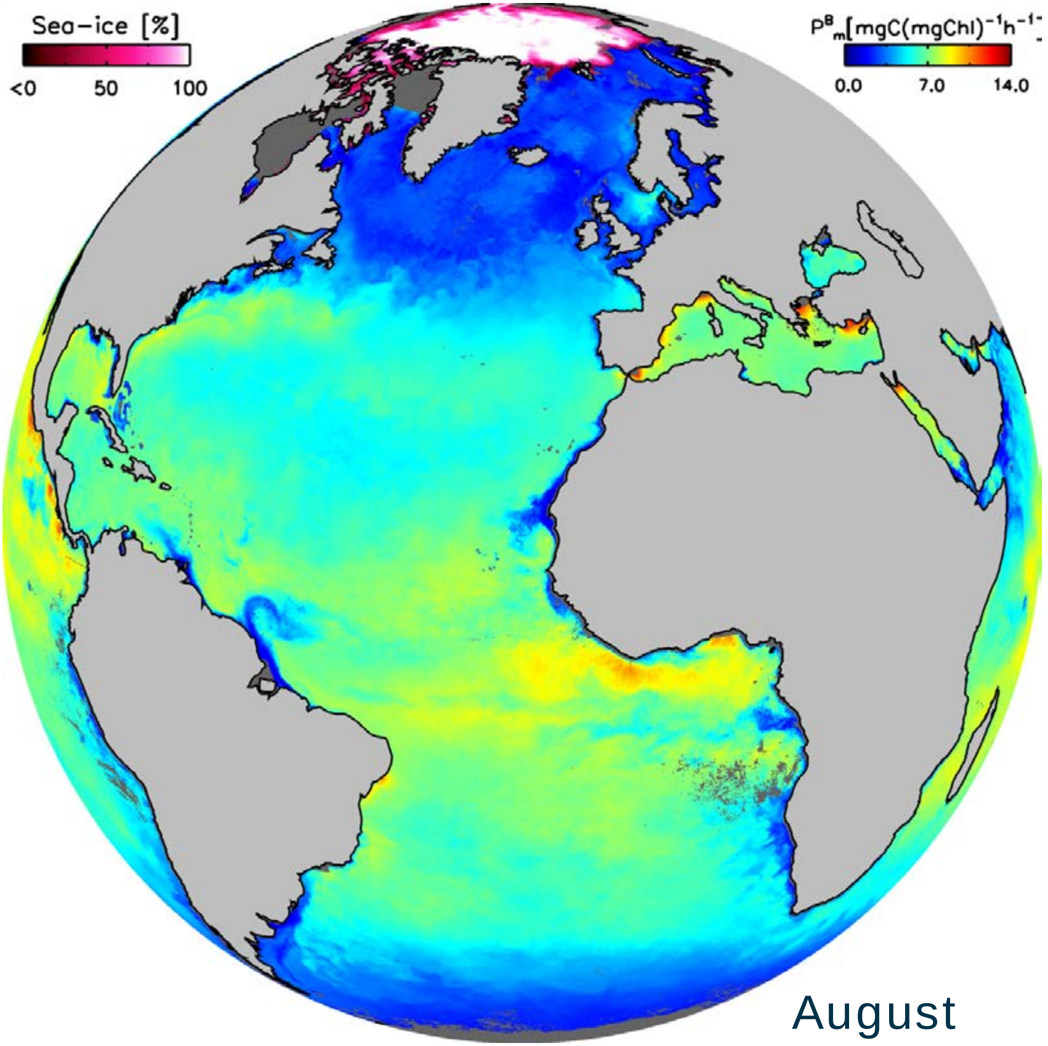
Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

3) Ocean carbon satellite products: Primary Production



Platt & Sathyendranath (2007)
Modelling Primary production article Series.

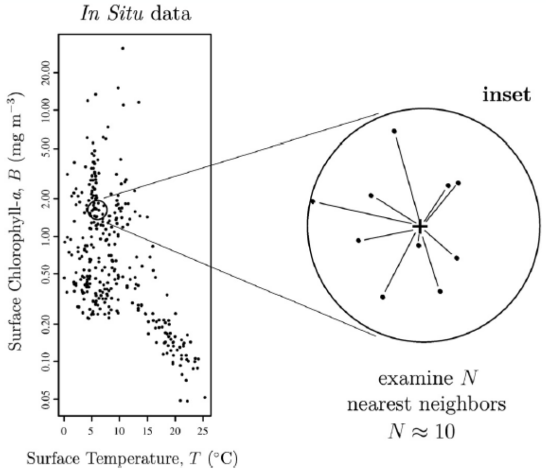




August 2003

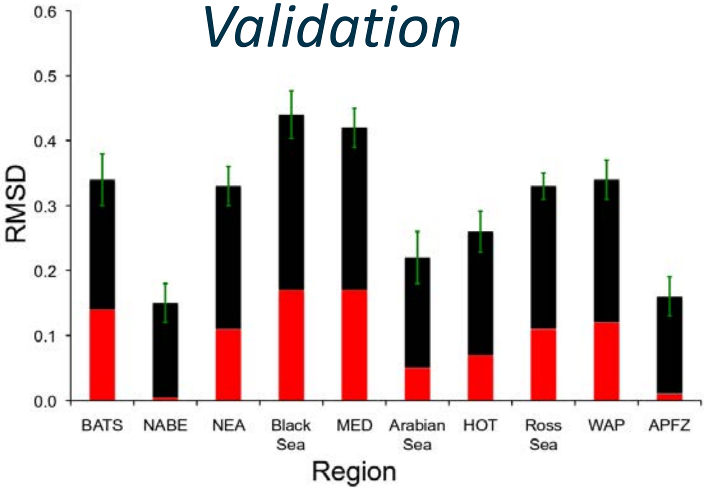
Saux Picart et al. (2014)
https://doi.org/10.1016/j.rse.2013.10.032

3) Ocean carbon satellite products: Primary Production

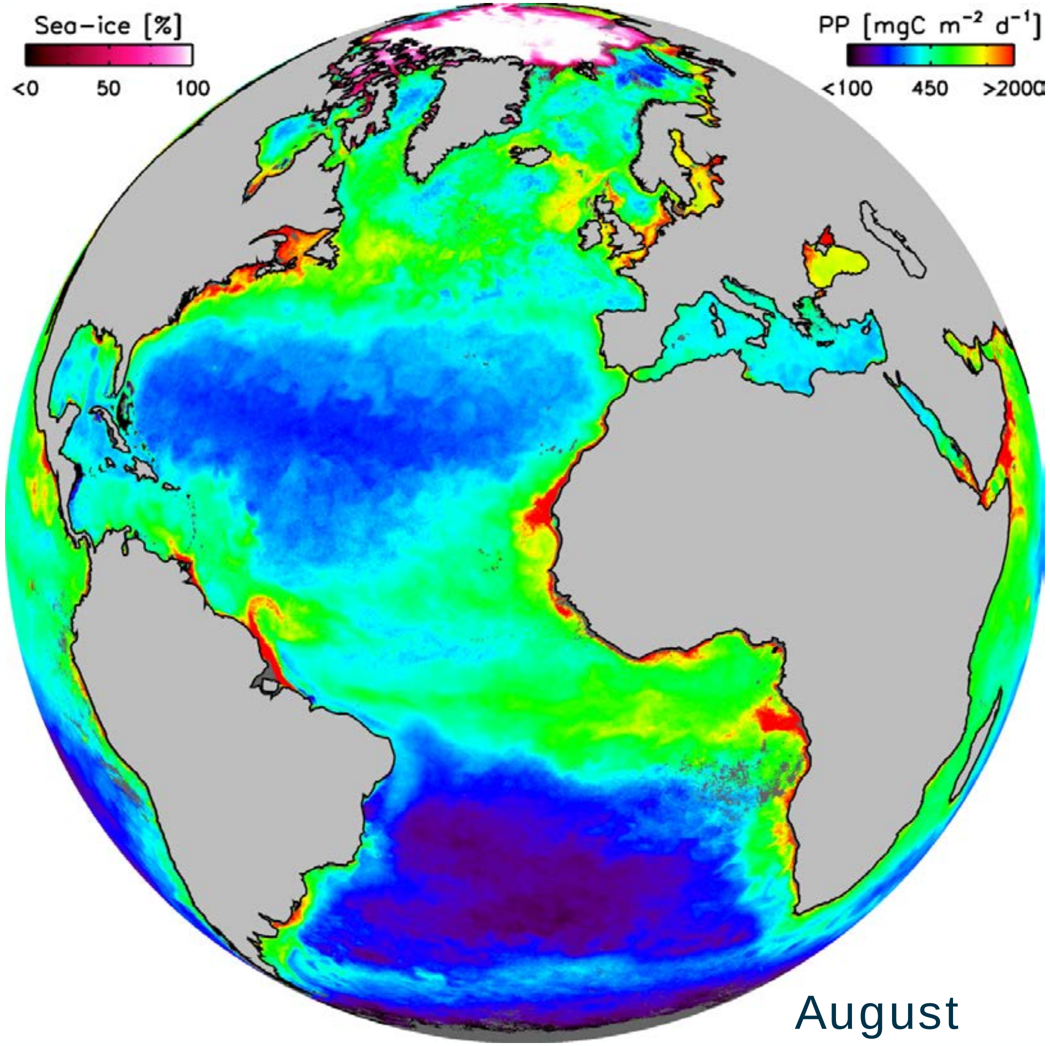


Platt et al. 2008
https://doi.org/10.1016/j.rse.2007.11.018

Validation



Saba et al. (2011)
https://doi.org/10.5194/bg-8-489-2011



August 2003

3) Ocean carbon satellite products: Export Production

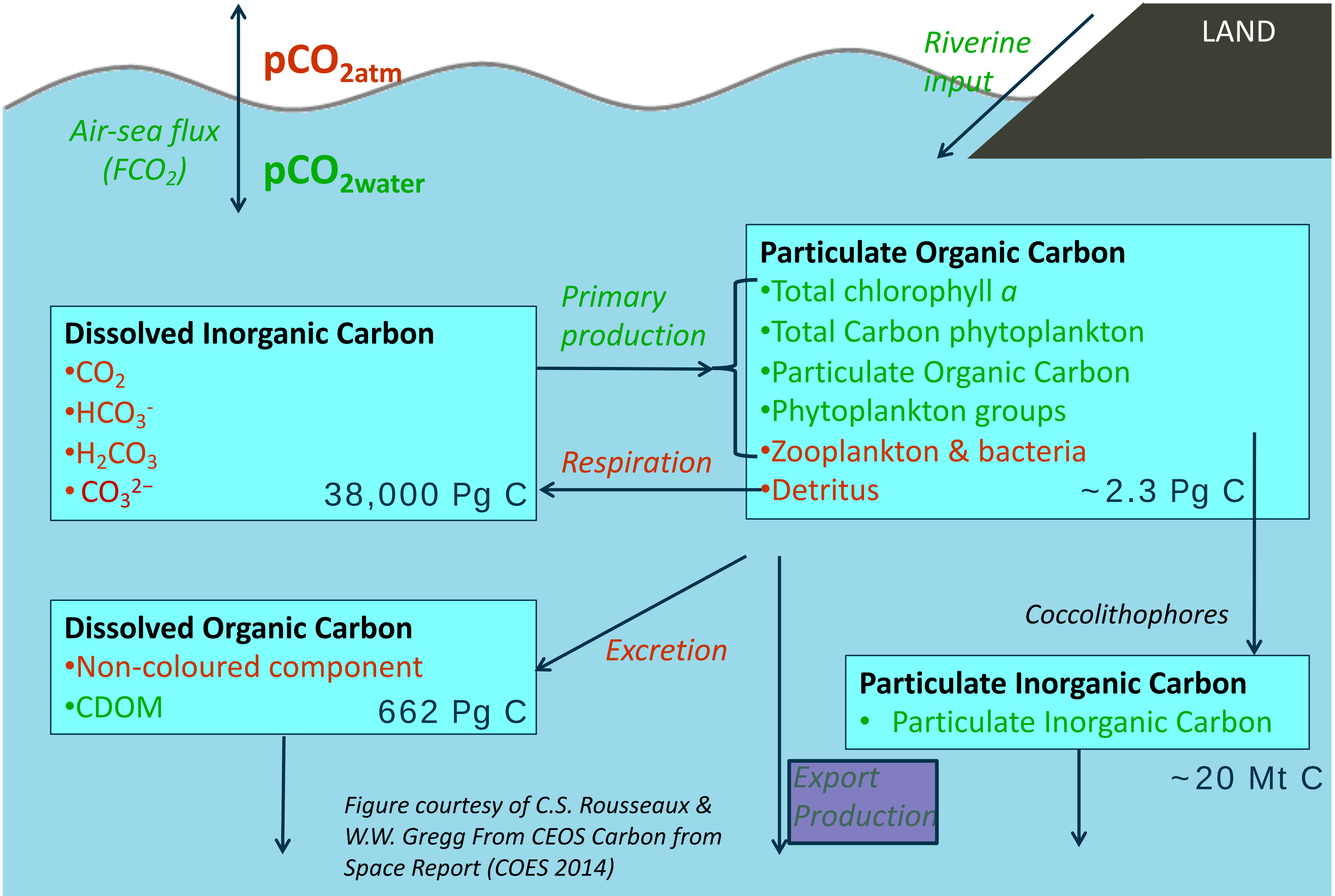
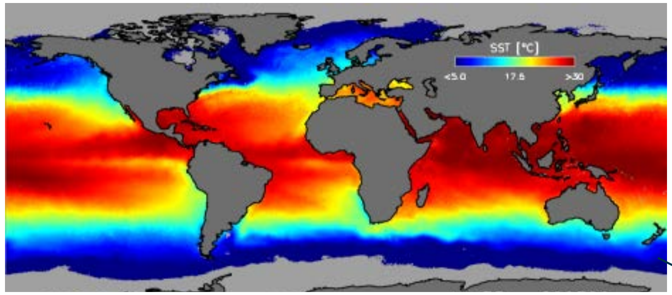
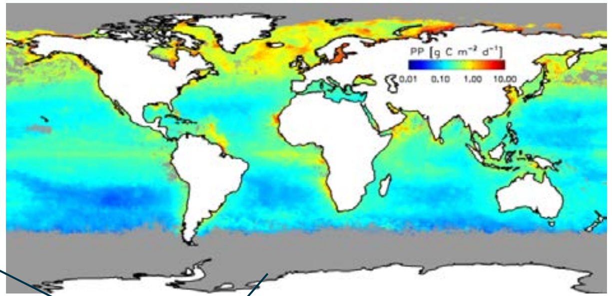


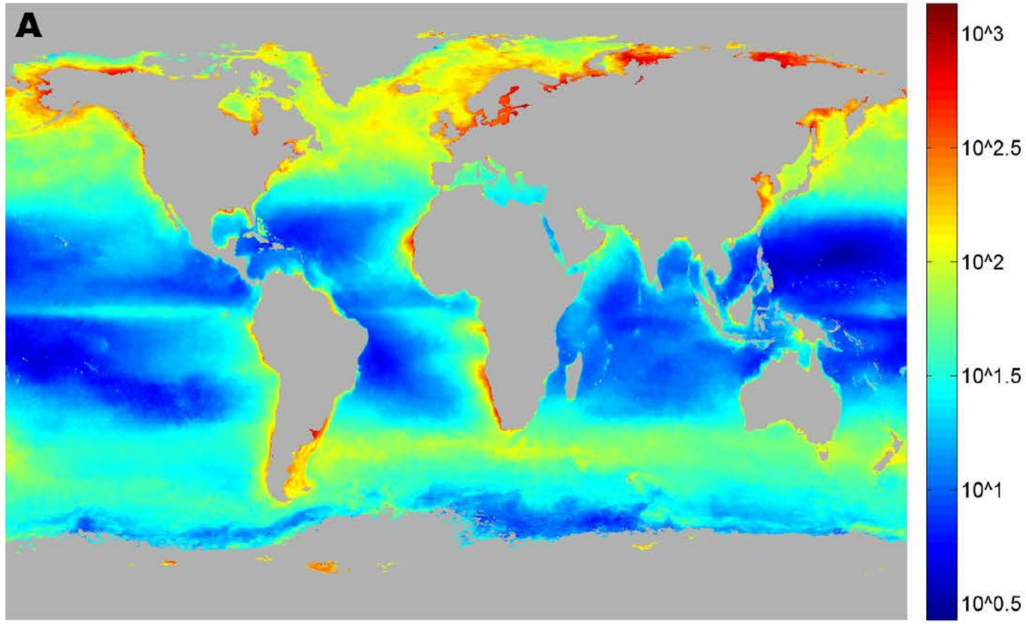
Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

3) Ocean carbon satellite products: Export Production

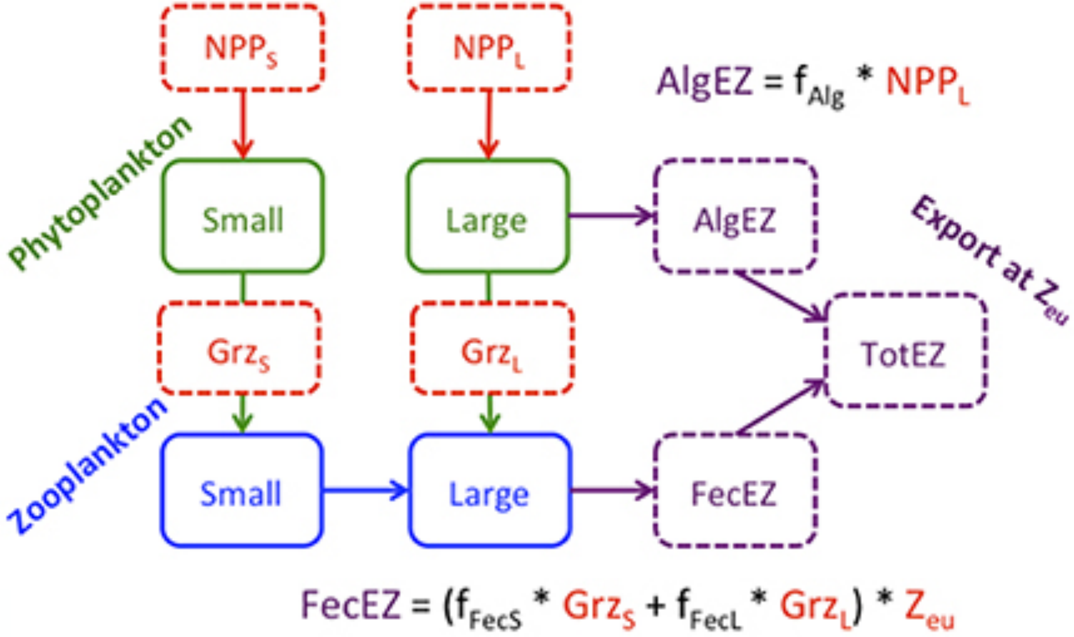


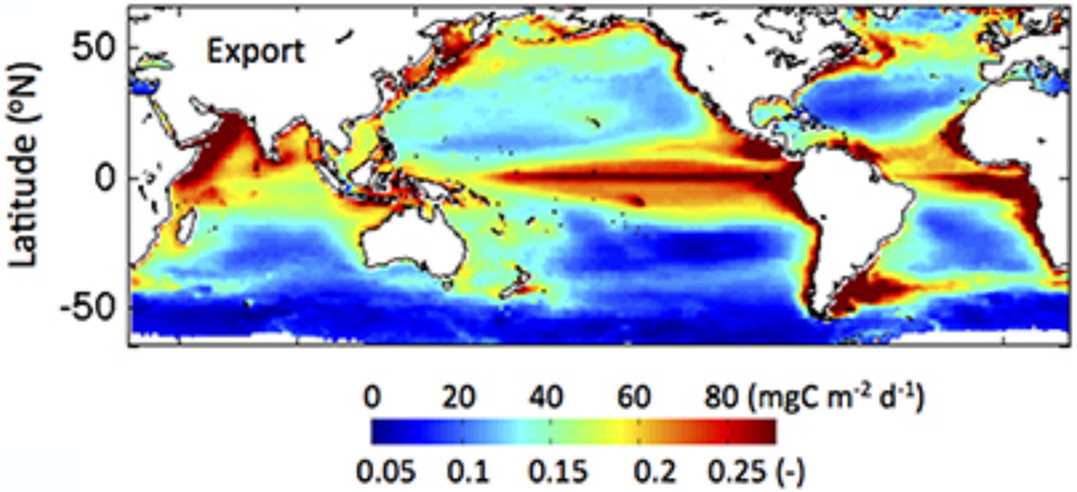


$$ef = 0.04756\left(0.78 - \frac{0.43T}{30}\right)tp^{0.307}$$



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





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

3) Ocean carbon satellite products: DOC

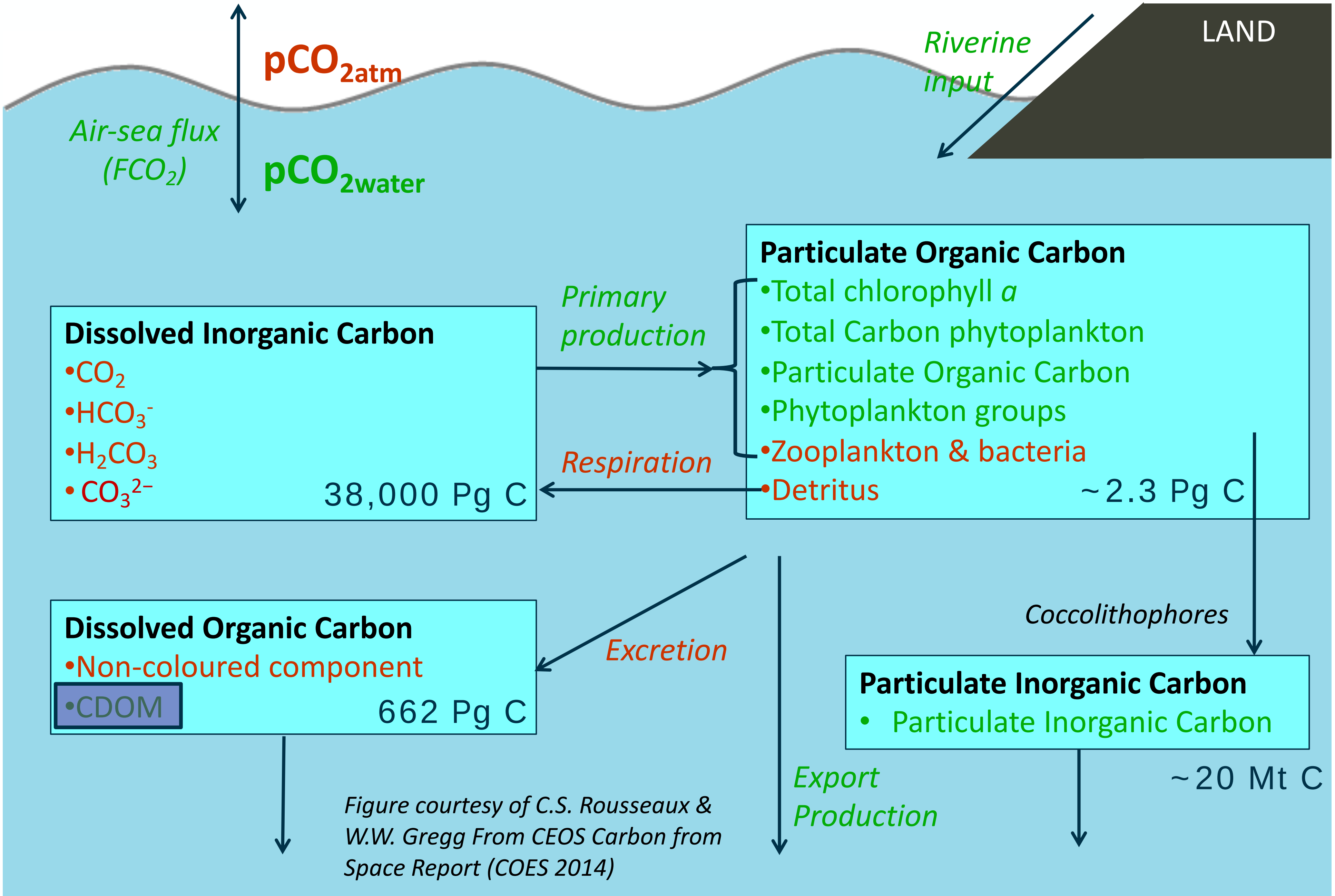
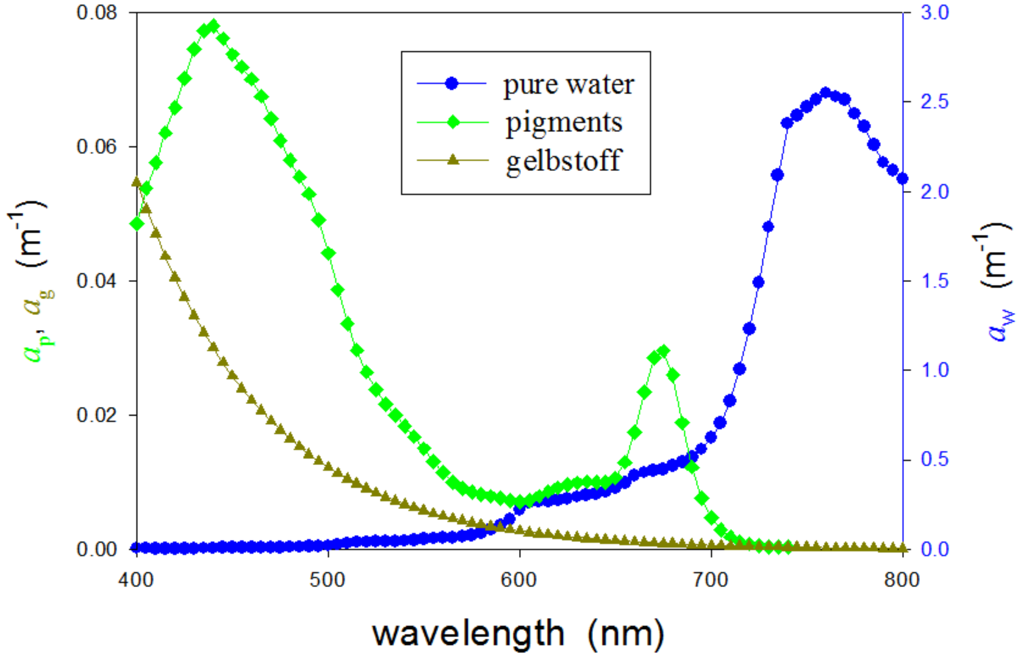
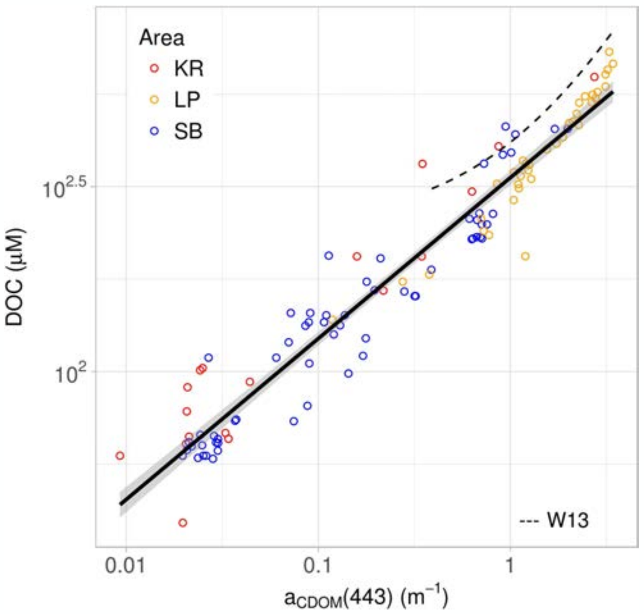


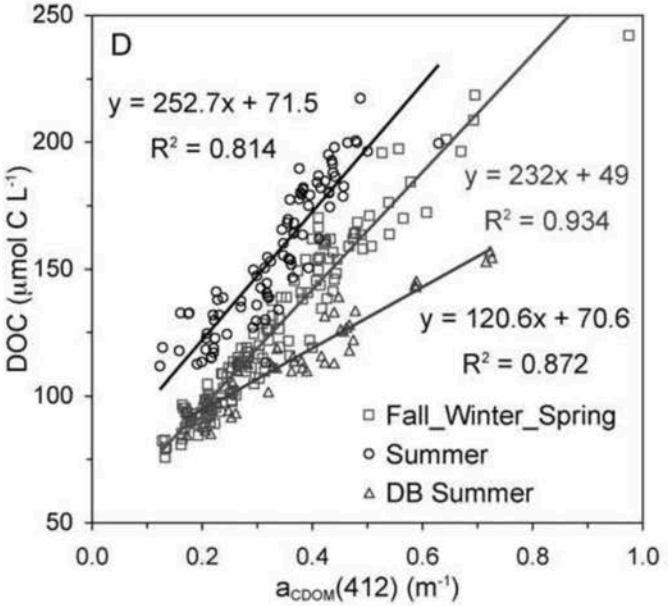
Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

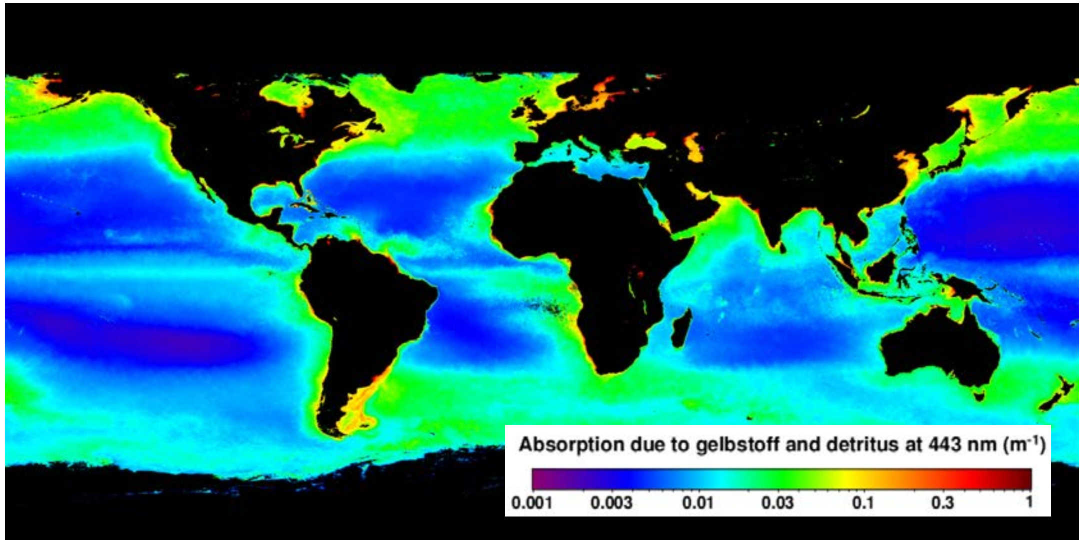
3) Ocean carbon satellite products: DOC

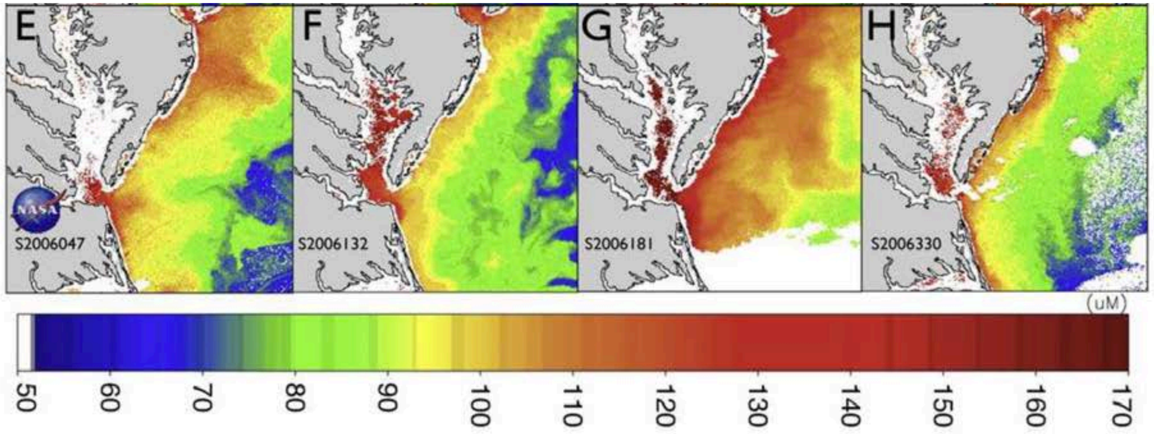
Arctic / Coastal







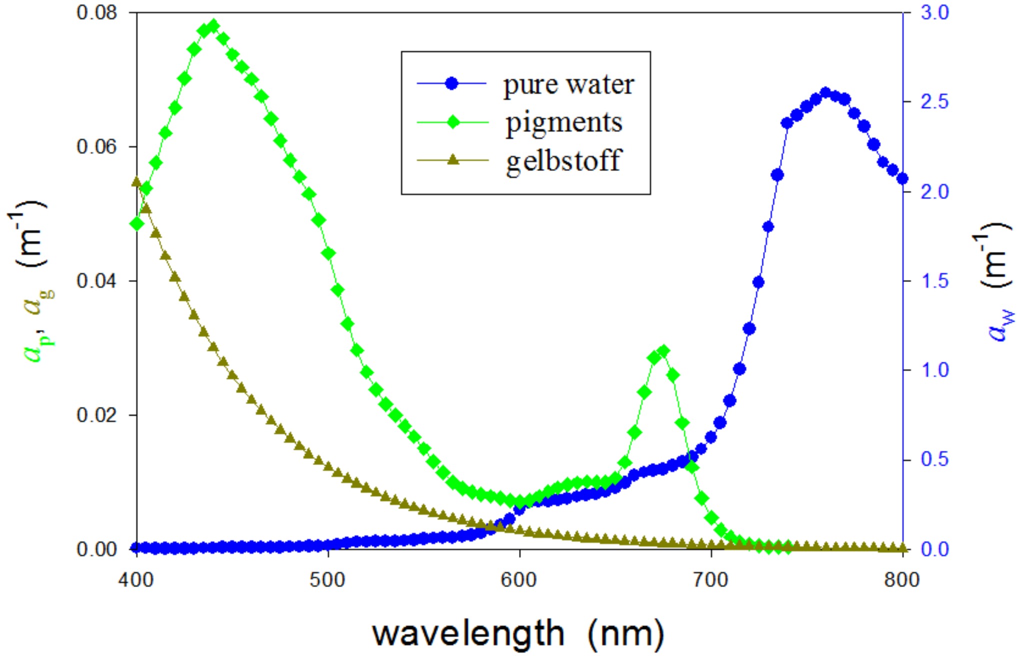


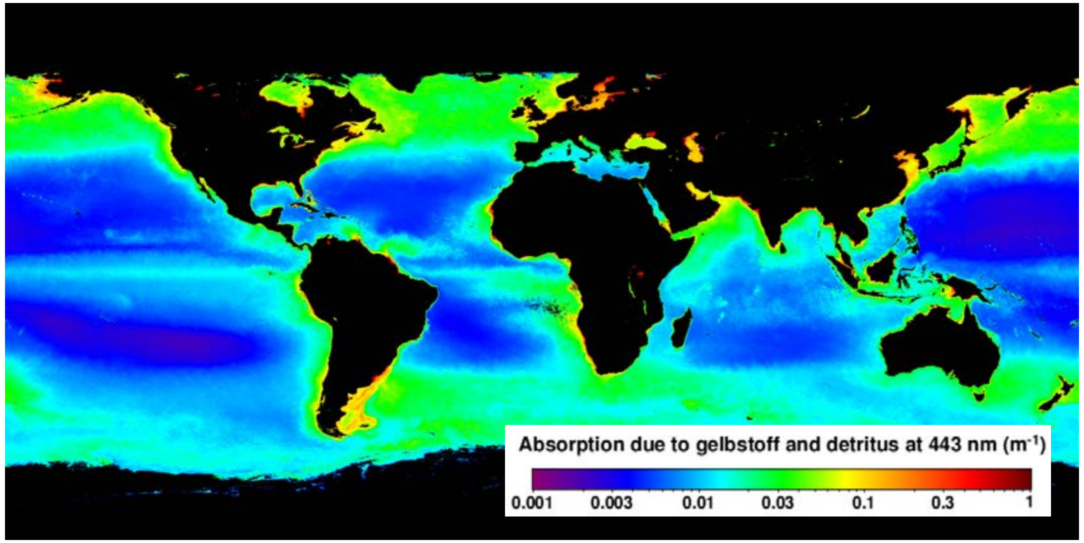


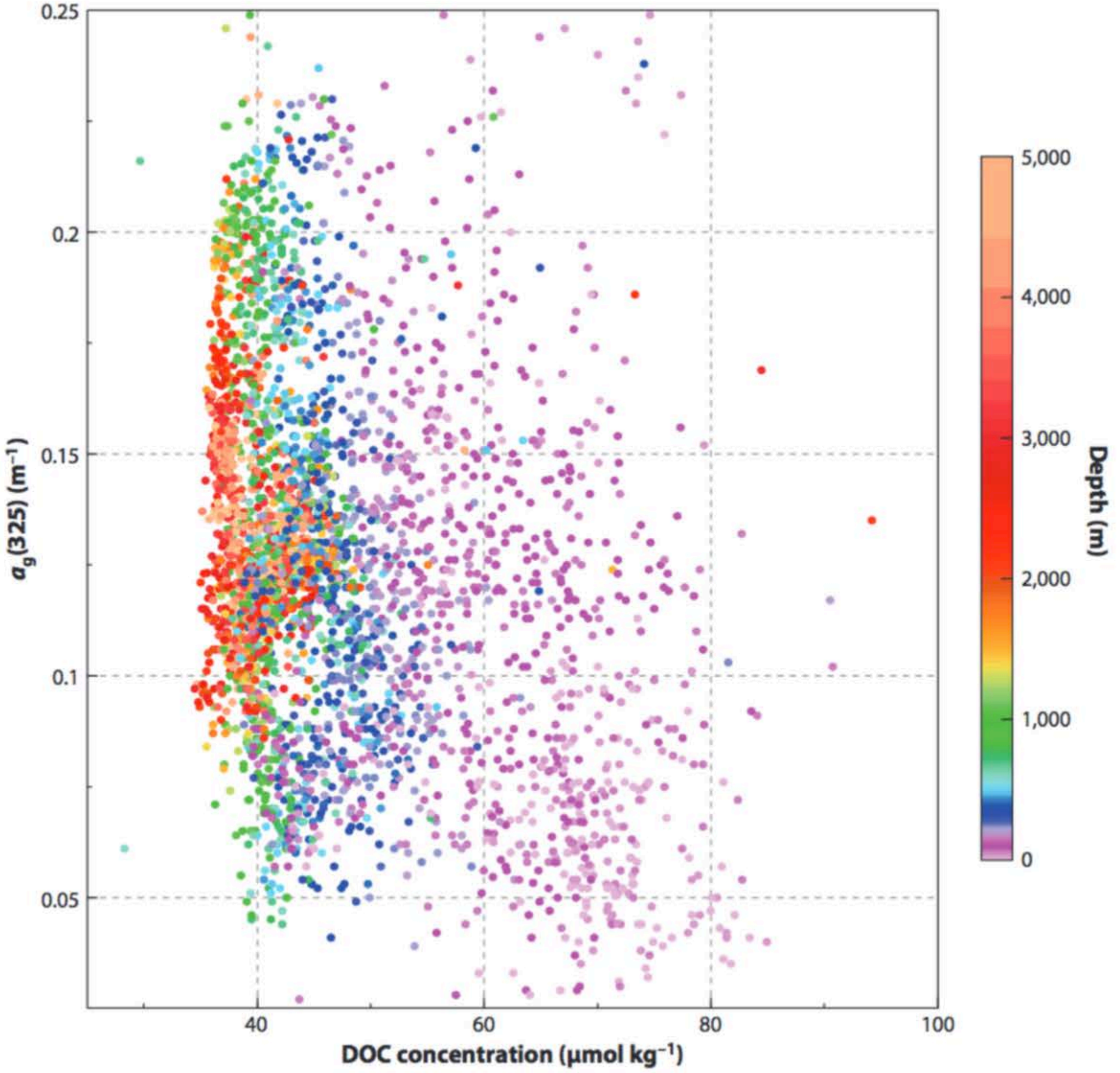
Mannino et al. (2008) https://doi.org/10.1029/2007JC004493
Matsuoka et al. (2017) https://doi.org/10.1016/j.rse.2017.08.009

3) Ocean carbon satellite products: DOC

Open ocean







Nelson and Siegel (2013)
https://doi.org/10.1146/annurev-marine-120710-100751

3) Ocean carbon satellite products: pCO_2

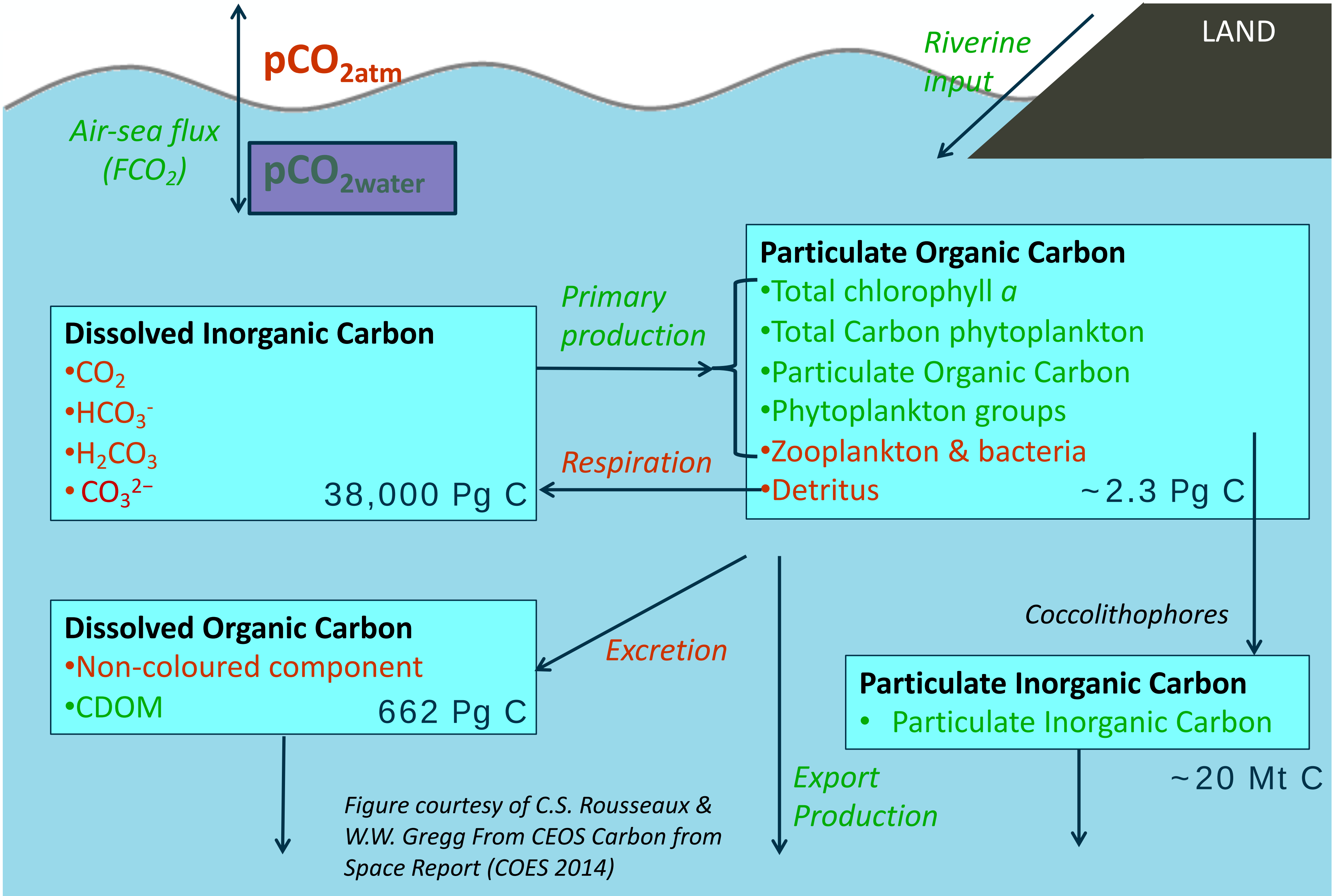


Figure courtesy of C.S. Rousseaux & W.W. Gregg From CEOS Carbon from Space Report (COES 2014)

3) Ocean carbon satellite products: pCO_2

$$pCO_2 = AT + BT^2 + CChla + DChla^2 + E$$

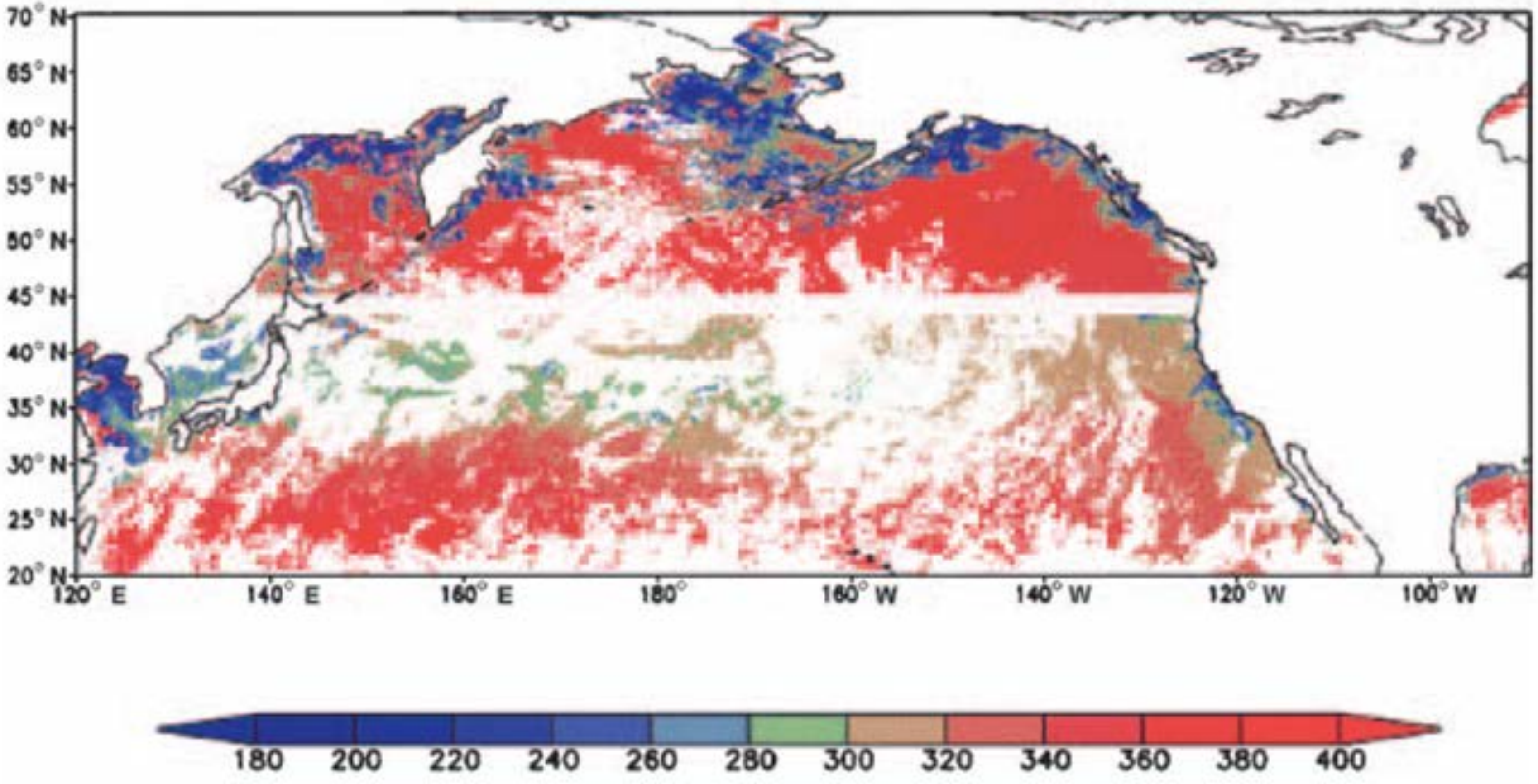


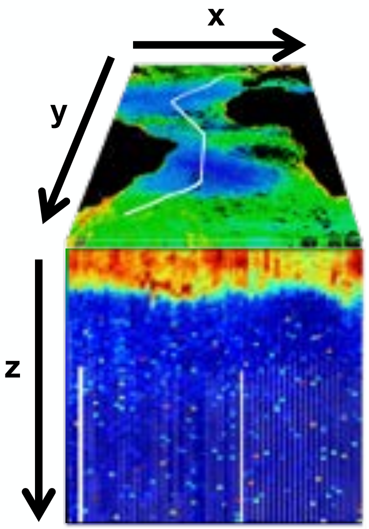
Figure 4. The basin-scale pCO_2 field of the North Pacific in May 1997 obtained from the ADEOS/OCTS monthly-average SST and monthly-maximum Chl*a* fields by using the multiple regression equations.

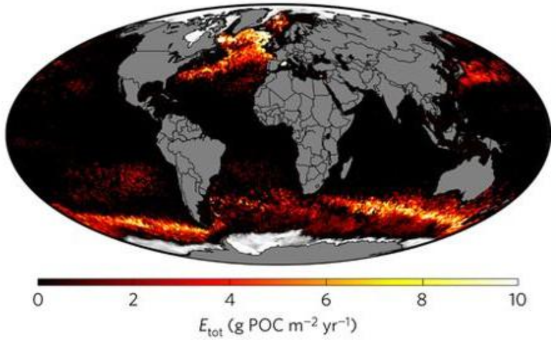
Ono et al. (2004) *https://doi.org/10.1080/01431160310001657515*

4) Integration with robotic platforms

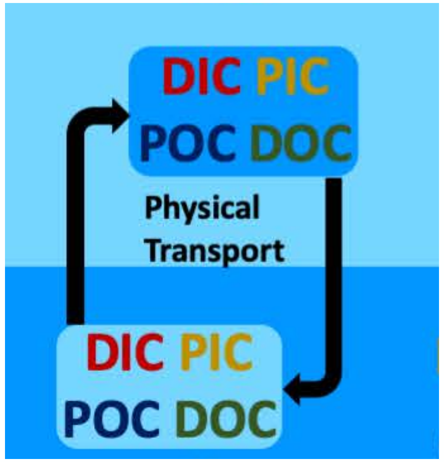
+

=



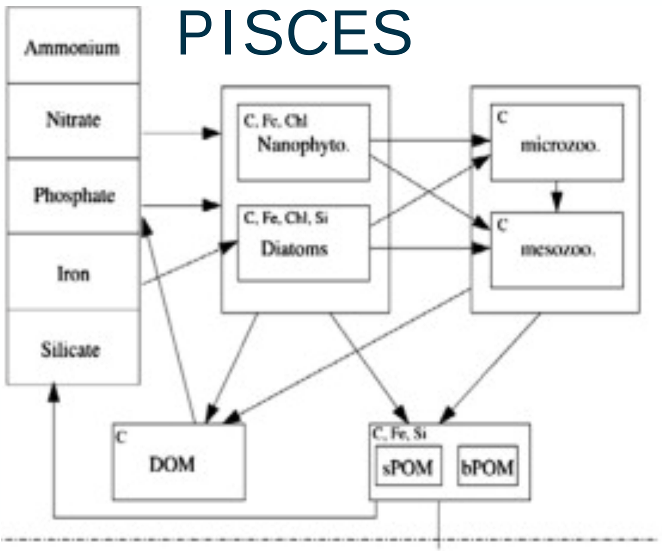


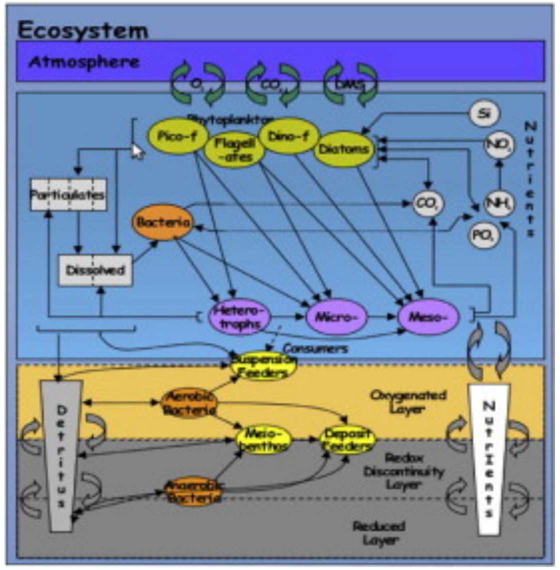
Mixed-layer pump
Dall'Olmo et al. (2016)
https://doi.org/10.1038/ngeo2818



5) Integration with models

PISCES

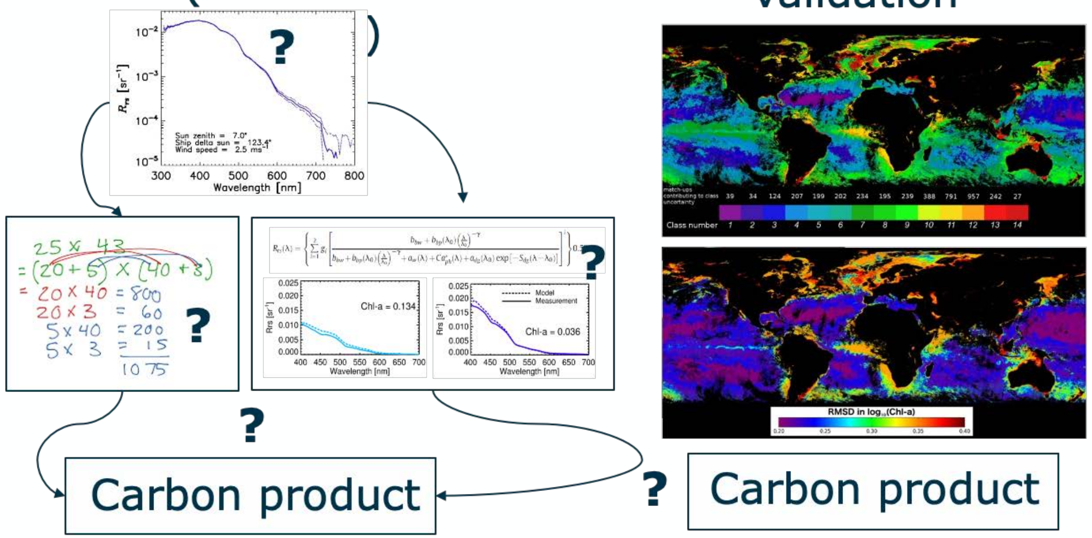




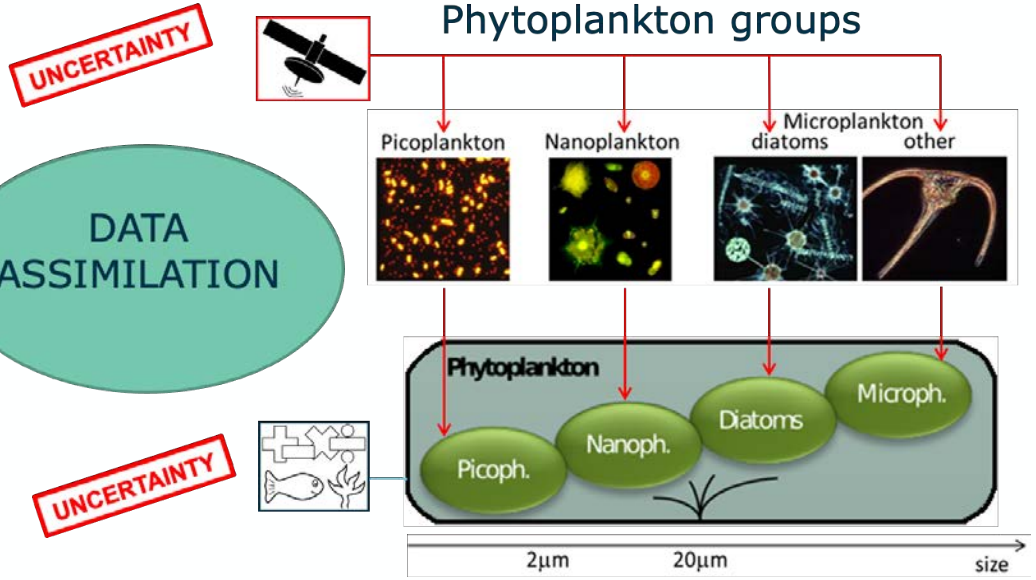
ERSEM

Model-based error (error)

Errors based on validation



Phytoplankton groups



Improve understanding of pools and fluxes not seen from space

Part 2: Outline

1) Earth's Carbon Cycle

2) Ocean Carbon Cycle

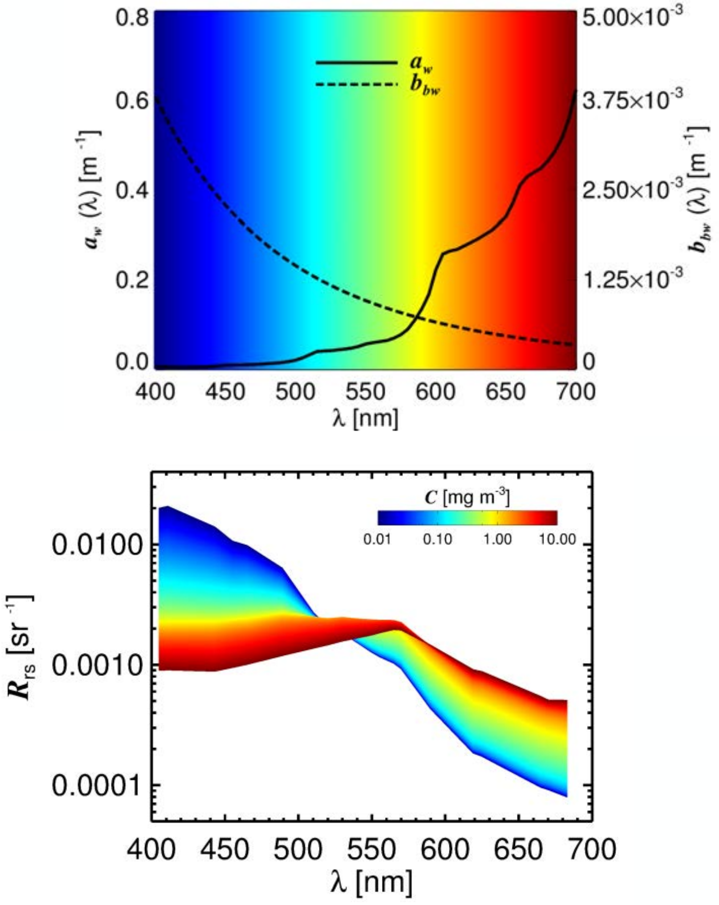
3) Ocean carbon satellite products

4) Integration with robotic platforms

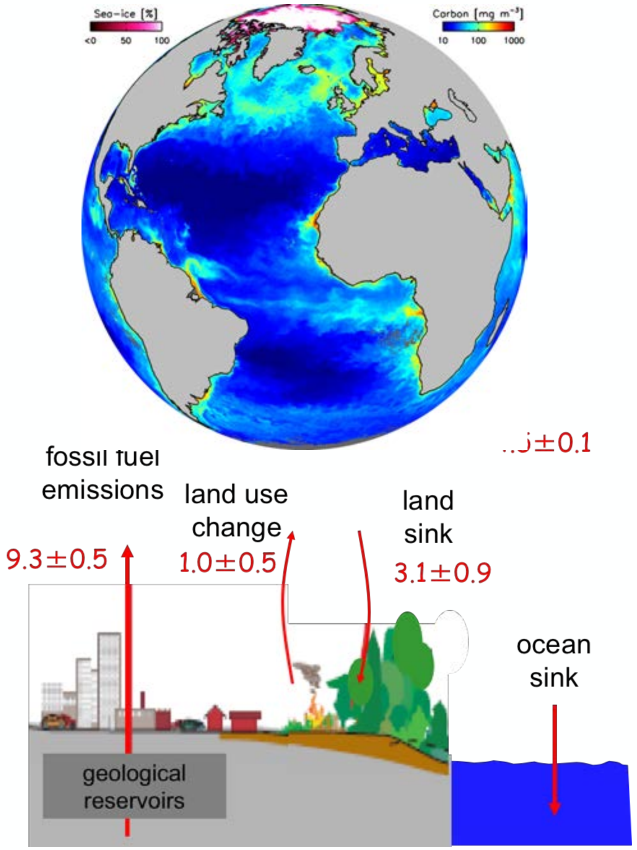
5) Integration with models

Lecture plan

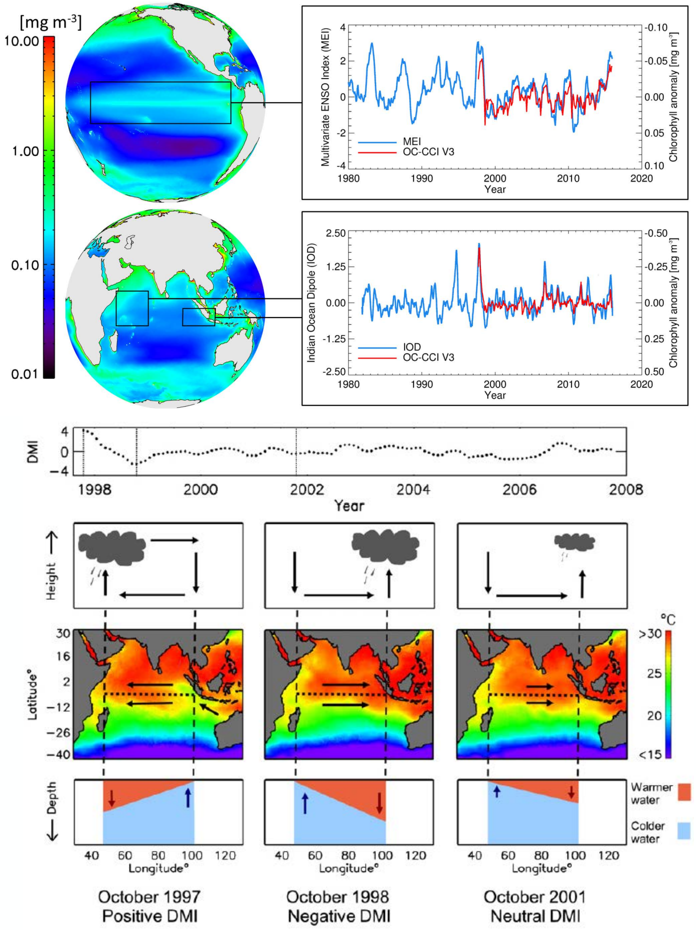
Ocean Colour theory (Part 1)



Ocean Colour applications: carbon cycle (Part 2)



Ocean Colour applications: climate (Part 3)



Part 3: Outline

1) The Greenhouse effect

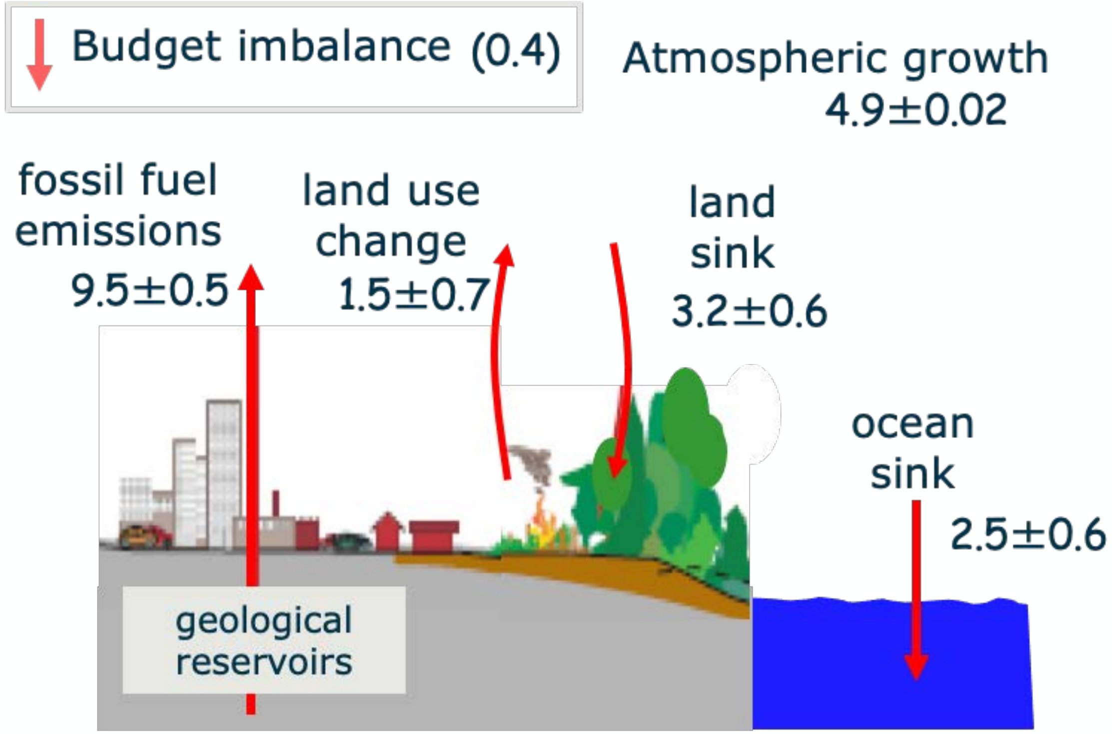
2) Essential Climate Variables

3) Ocean colour datasets requirements for climate

4) Responses of the marine ecosystem to climate change
    - Total phytoplankton biomass
    - Phytoplankton community structure
    - Phytoplankton phenology
    - Other responses

5) Other applications

1) The Greenhouse Effect



Friedlingstein et al. (2019) Global Carbon Budget (2019) Earth Syst. Sci. Data, 11, 1783–1838, https://doi.org/10.5194/essd-11-1783-2019

Credit: NASA/JPL-Caltech https://climatekids.nasa.gov/climate-change-meaning/

2) Essential Climate Variables

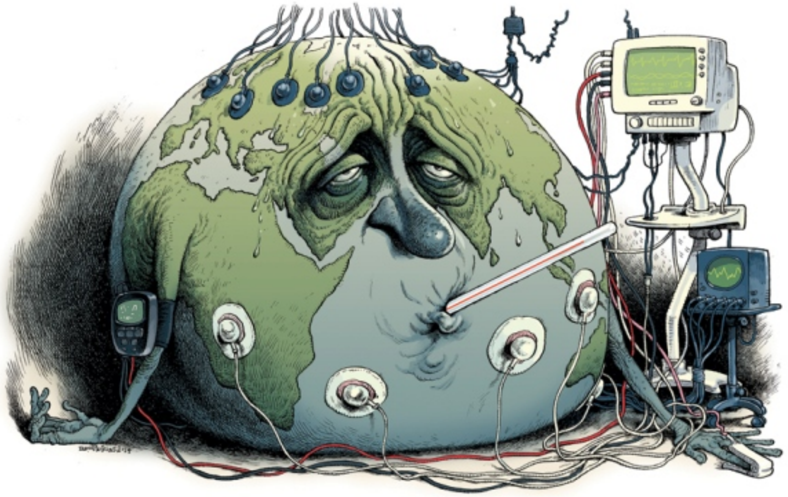
Established in 1992, the Global Climate Observing System (GCOS) identified 50 Essential Climate Variables (ECVs) to support the work of the intergovernmental expert group on the evolution of climate, the UNFCCC and IPCC.

An ECV is a physical, chemical or biological variable, or a group of linked variables, that critically contributes to the characterisation of Earth's climate.

IPCC
INTERGOVERNMENTAL PANEL ON climate change

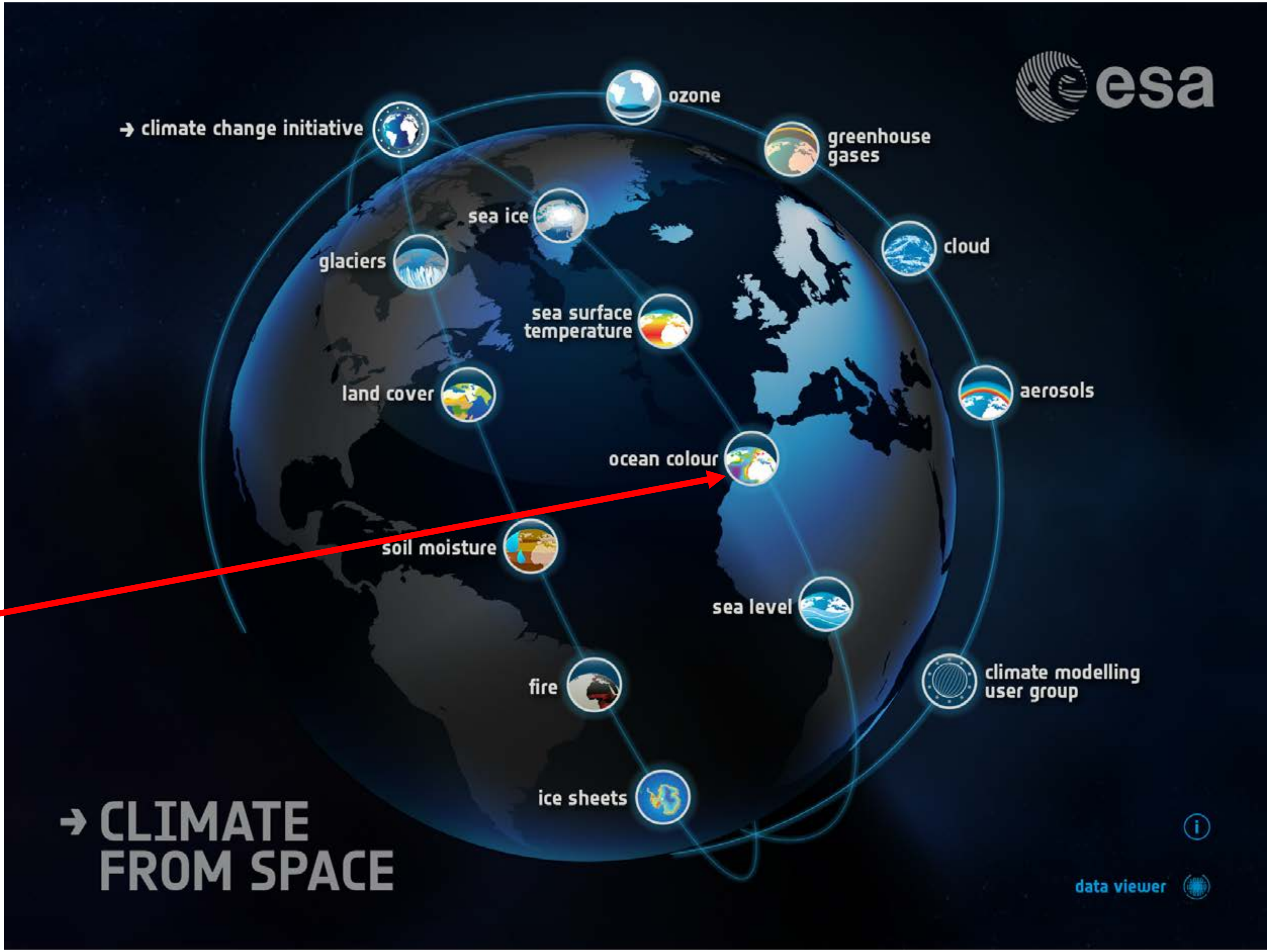
United Nations
Framework Convention on Climate Change

2) Essential Climate Variables

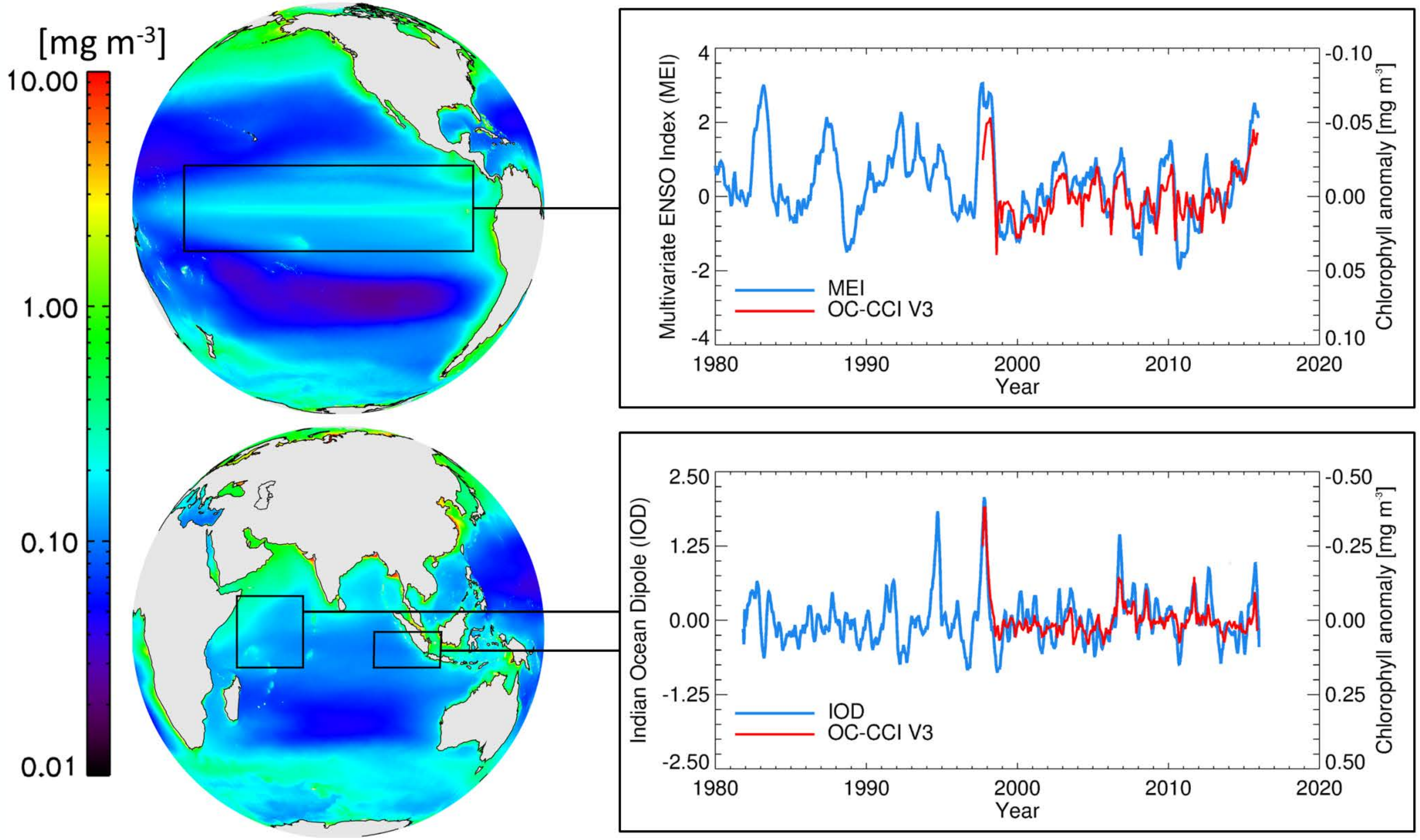


Victor & Kennel (2014) Nature

Water leaving radiance
Chlorophyll-a concentration



2) Essential Climate Variables

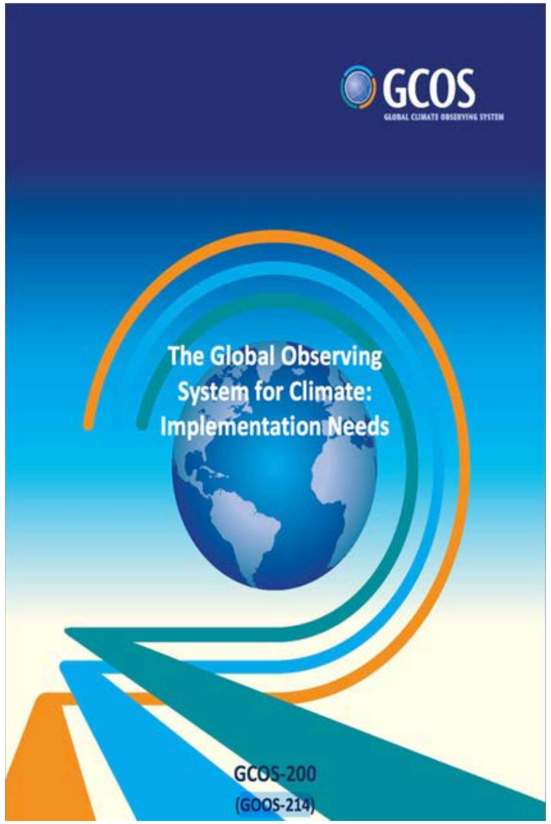


von Schuckmann et al. (2016)
https://doi.org/10.1080/1755876X.2016.1273446

3) Ocean colour datasets requirements for climate

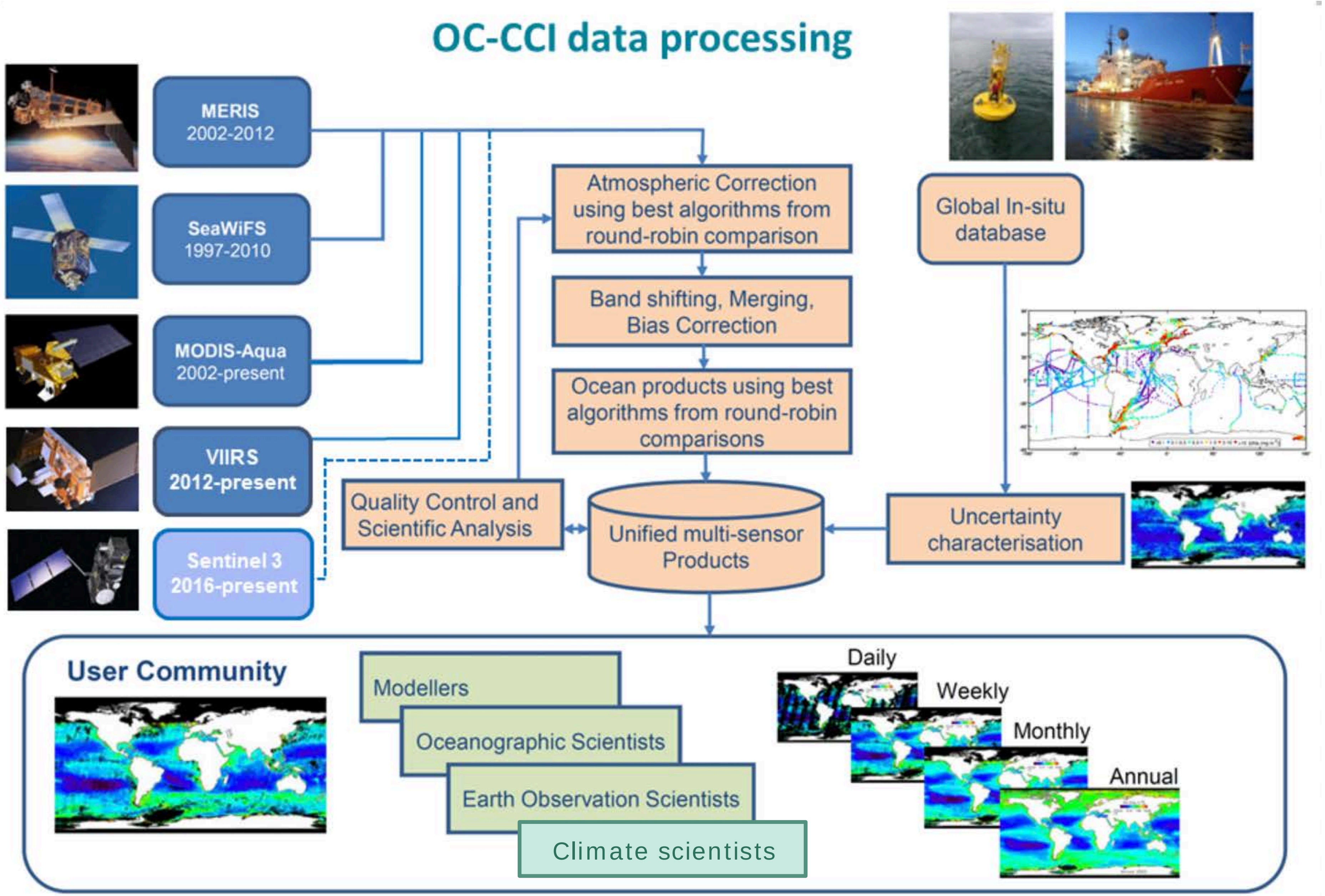
Goal: create the most complete and consistent, error- characterized time series of multi-sensor global satellite ECV products for climate research and modeling meeting GCOS requirements

GCOS-200 October 2016					
Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Water Leaving Radiance	4km	N/A	daily	5% (blue to green)	0.5%
Chlorophyll-a concentration	4km	N/A	weekly averages	30%	3%



https://www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-ocean-biogeochemistry-ecv-ocean-color

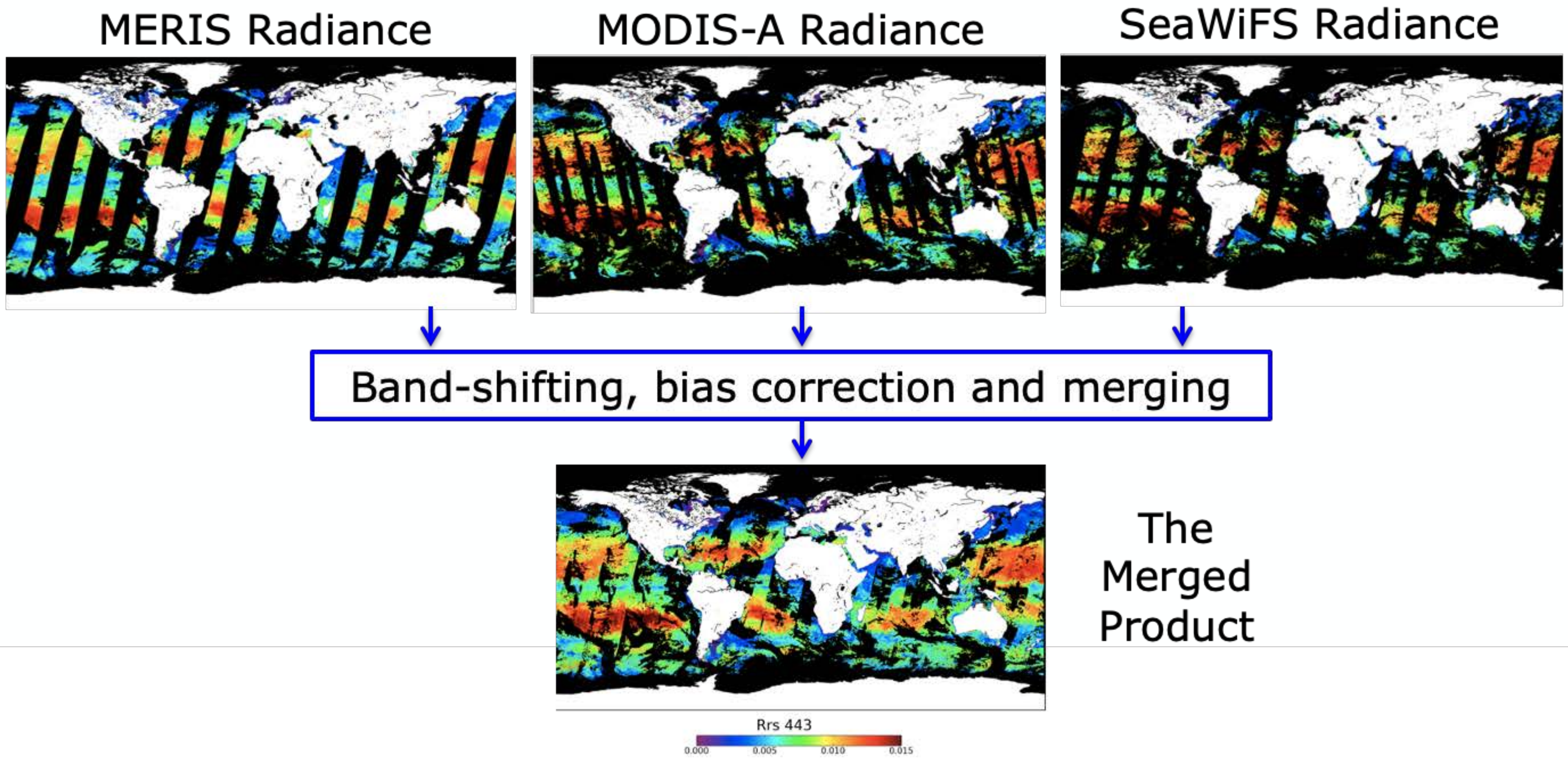
3) Ocean colour datasets requirements for climate



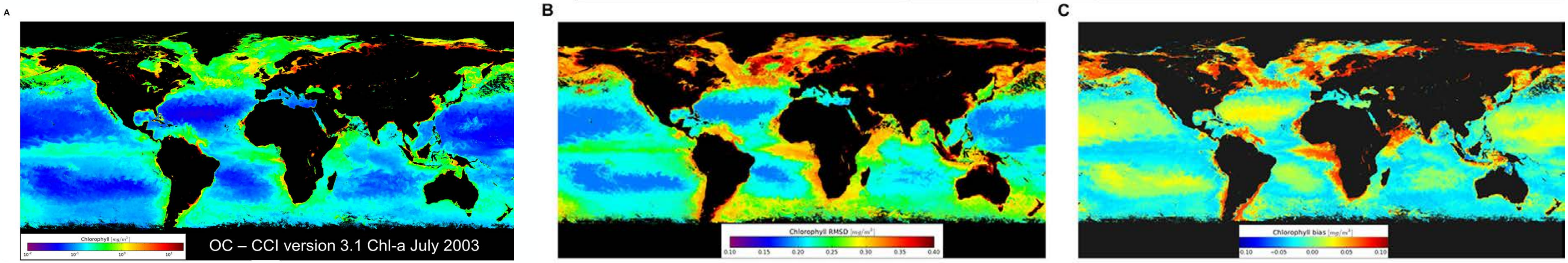
Sathyendranath et al. (2019) *https://doi.org/10.3390/s19194285*

http://www.esa-oceancolour-cci.org

3) Ocean colour datasets requirements for climate



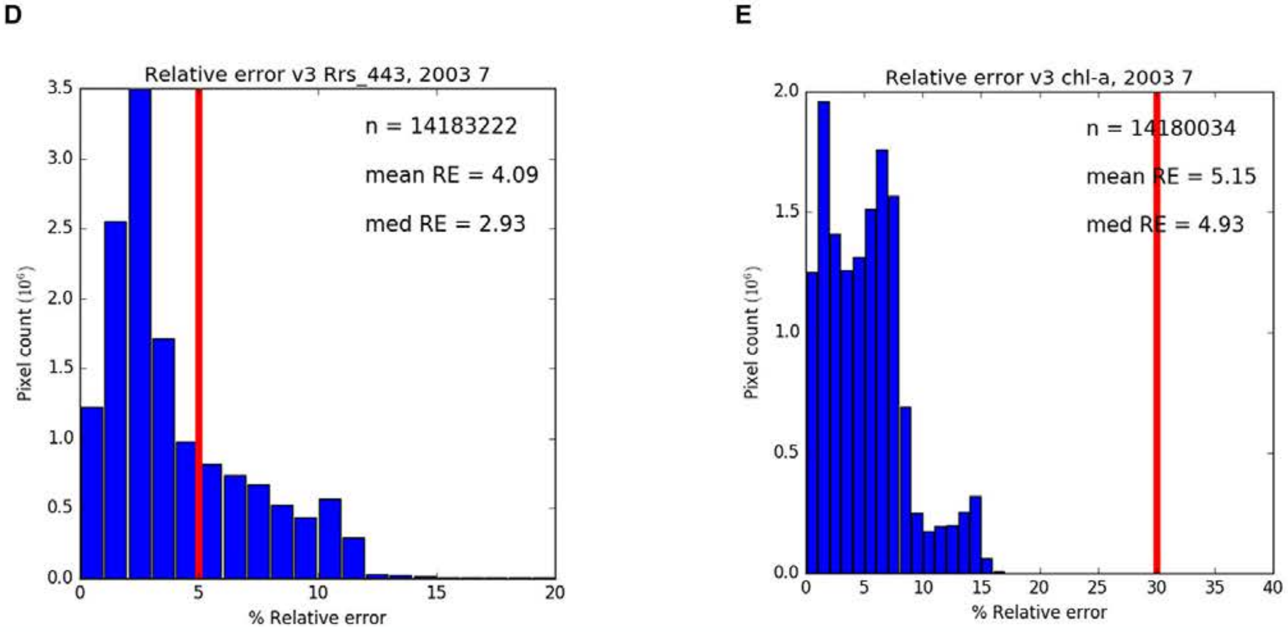
3) Ocean colour datasets requirements for climate



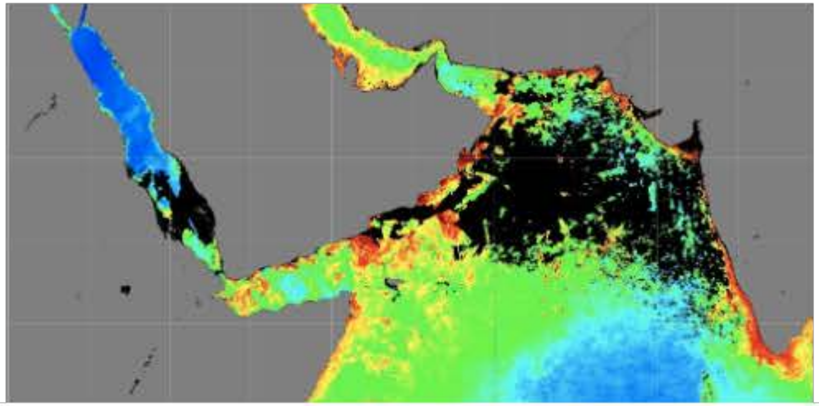
Uncertainty according to a method that uses optical water classification

Moore et al. 2009
https://doi.org/10.1016/j.rse.2009.07.016
Jackson et al. 2017
https://doi.org/10.1016/j.rse.2017.03.036)

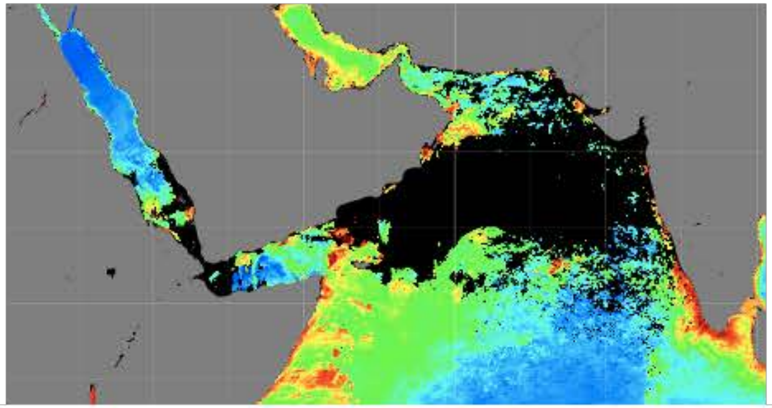
Meeting current GCOS requirements for majority of ocean



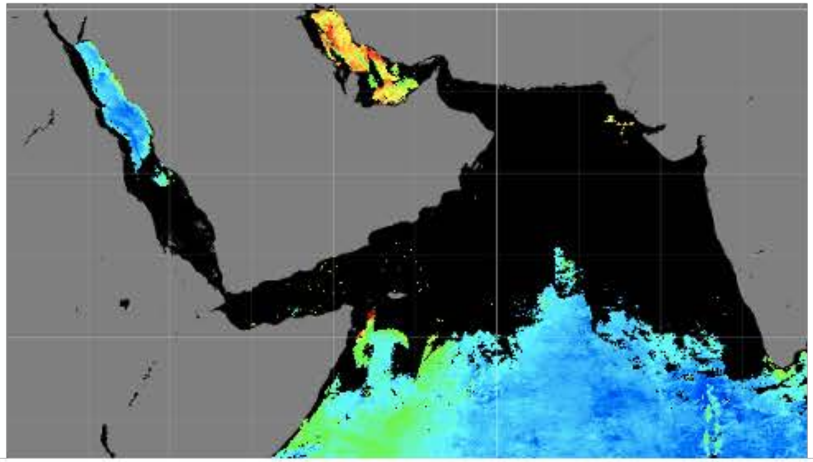
3) Ocean colour datasets requirements for climate



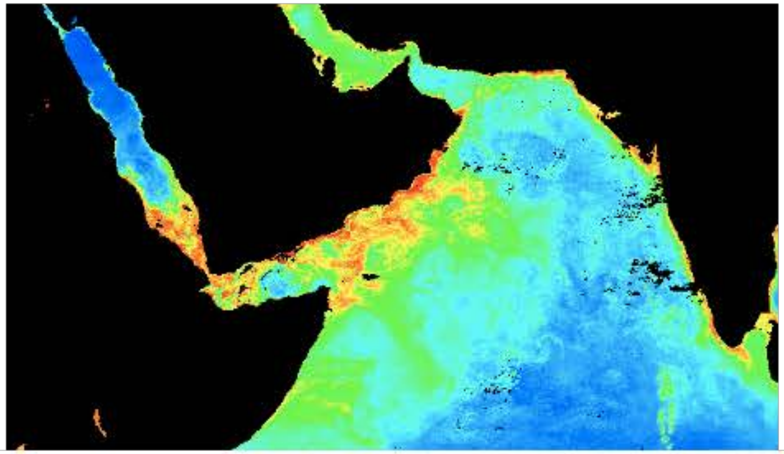
MODIS July Climatology from NASA



SeaWiFS July Climatology from NASA

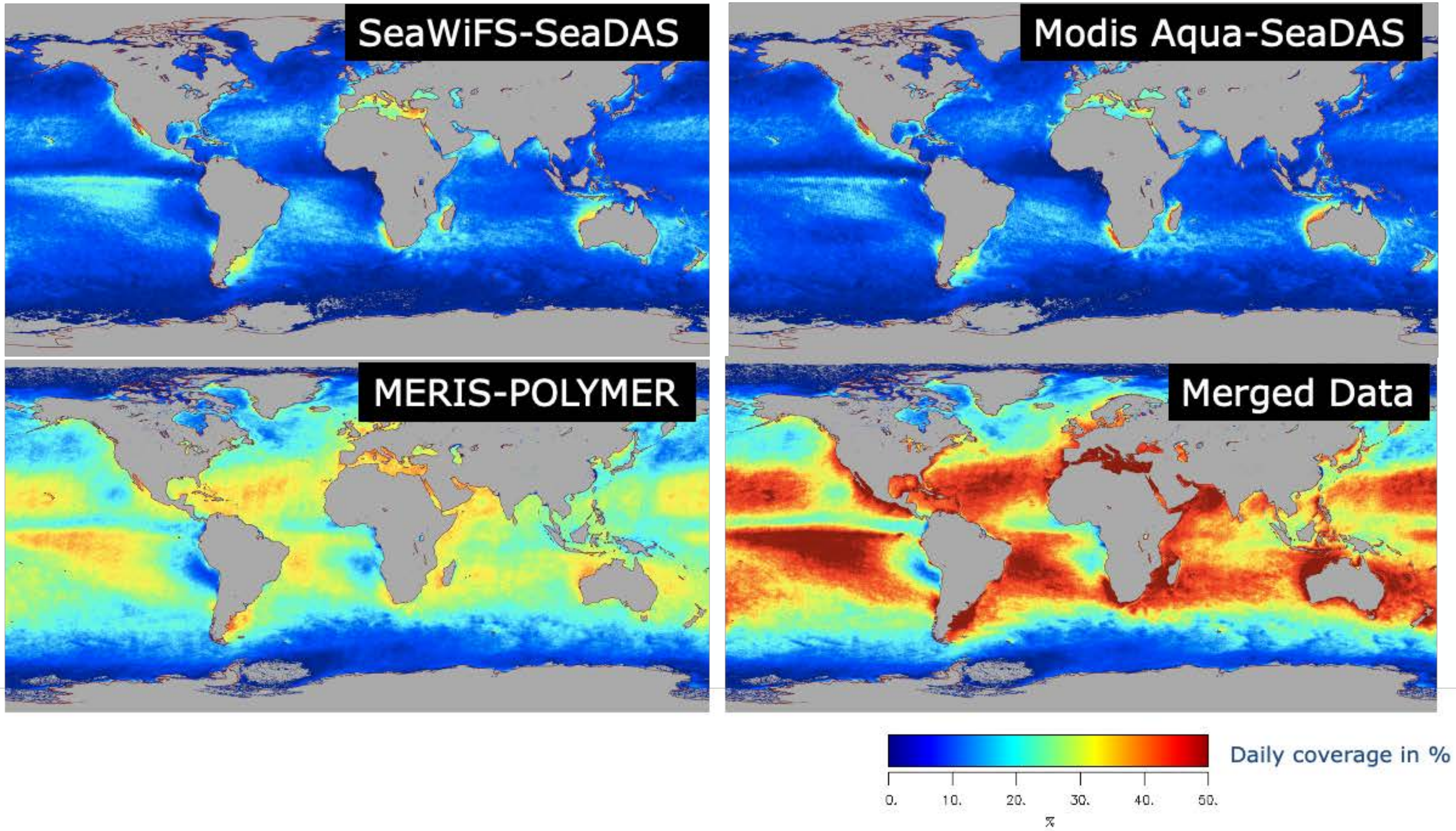


CZCS July Climatology from NASA

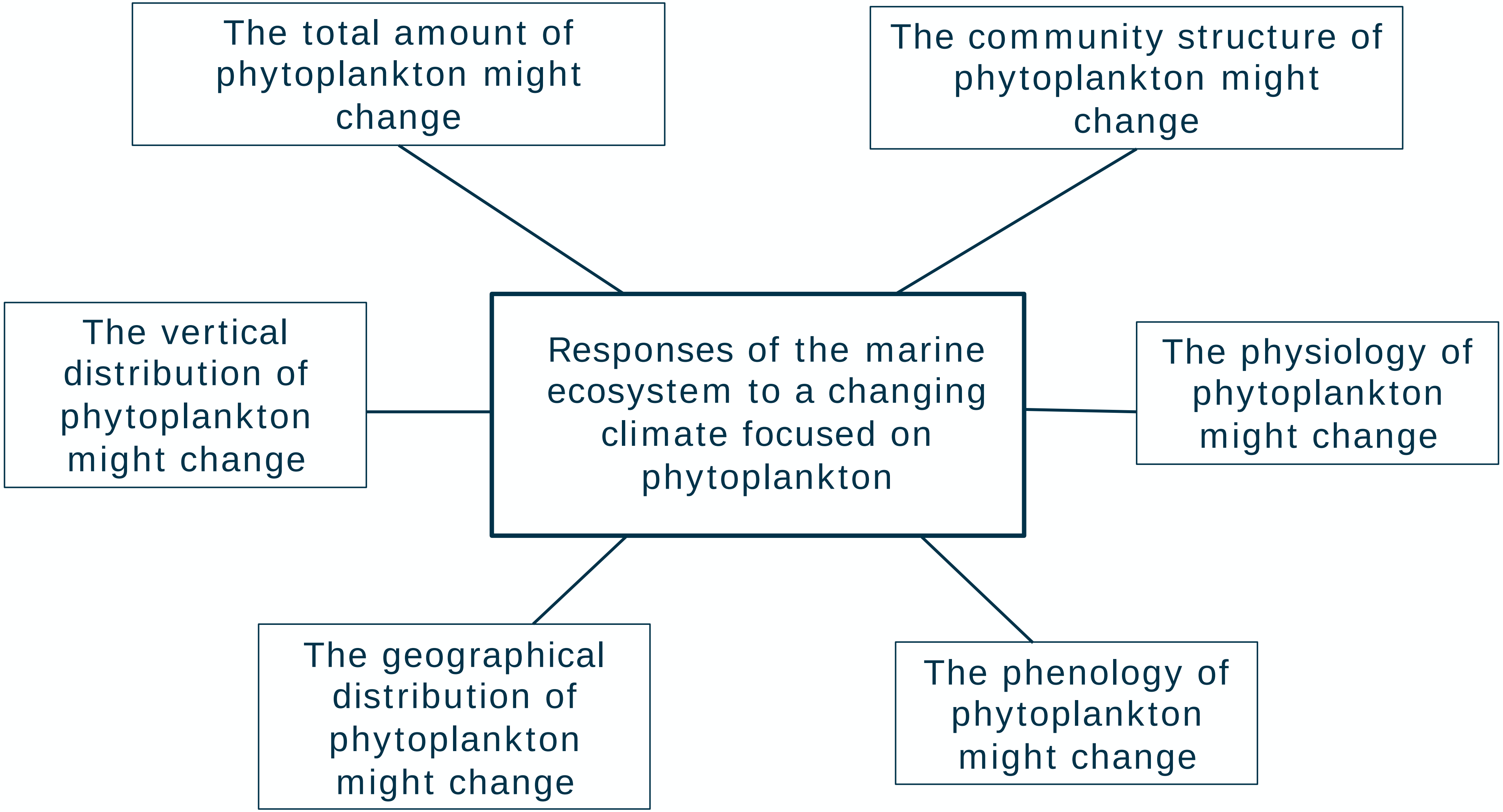


OC-CCI July 2003

3) Ocean colour datasets requirements for climate



4) Responses of the marine ecosystem to climate change



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

4) Responses: Total phytoplankton biomass may change

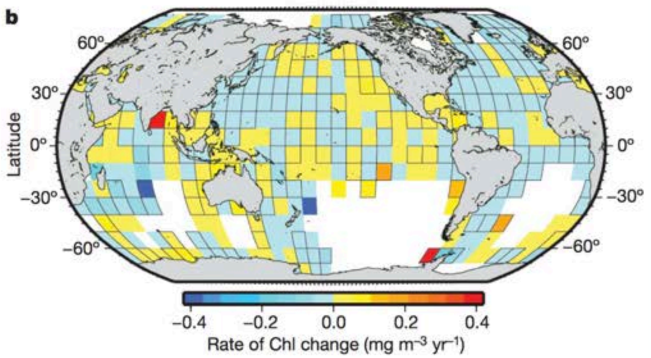
esa

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.

In 1865, Father Pietro Angelo Secchi was asked to map the clarity of the Mediterranean Sea for the Papal navy. He invented the simplest of oceanographic instruments: a 20-centimetre-wide white disk that is lowered until the observer loses sight of it, and for nearly 100 years determinations of Secchi depth were a routine part of oceanographic observations[1,2] (Fig. 1, overleaf). Secchi-depth determinations assess light penetration in the upper ocean, and can be related to phytoplankton abundance. Along with measurements of the upper-ocean concentration of chlorophyll, which is found in all phytoplankton, Secchi-disk depths provide the only data available for assessing changes in the global

nature International journal of science

Access provided by ESA-ESTEC European Space Agency

Brief Communications Arising | Published: 13 April 2011

Does blending of chlorophyll data bias temporal trend?

David L. Mackas

Nature 472, E4–E5 (14 April 2011) Download Citation

Abstract

ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm Nature 466, 591–596 (2010)10.1038/nature09268; Boyce et al. reply

nature International journal of science

Access provided by ESA-ESTEC European Space Agency

Brief Communications Arising | Published: 13 April 2011

A measured look at ocean chlorophyll trends

Ryan R. Rykaczewski & John P. Dunne

Nature 472, E5–E6 (14 April 2011) Download Citation

Abstract

ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm Nature 466, 591–596 (2010)10.1038/nature09268; Boyce et al. reply

nature International journal of science

Access provided by ESA-ESTEC European Space Agency

Brief Communications Arising | Published: 13 April 2011

Is there a decline in marine phytoplankton?

Abigail McQuatters-Gollop, Philip C. Reid, Martin Edwards, Peter H. Burkill, Claudia Castellani, Sonia Batten, Winfried Gieskes, Doug Beare, Robert R. Bidigare, Erica Head, Rod Johnson, Mati Kahru, J. Anthony Koslow & Angelica Pena

Nature 472, E6–E7 (14 April 2011) Download Citation

Abstract

ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm Nature 466, 591–596 (2010)10.1038/nature09268; Boyce et al. reply

“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.”

LIMNOLOGY and OCEANOGRAPHY: METHODS

Limnol. Oceano
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Integrating global chlorophyll data from 1890 to 2010

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

Abstract

Contents lists available at ScienceDirect

ELSEVIER

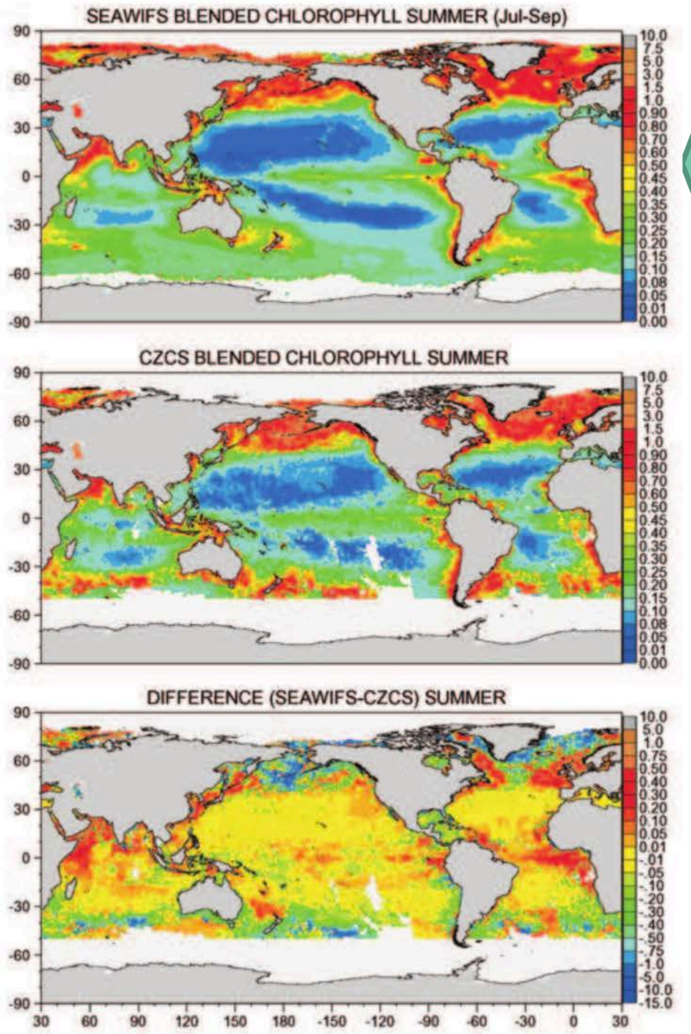
Progress in Oceanography

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

Estimating global chlorophyll changes over the past century

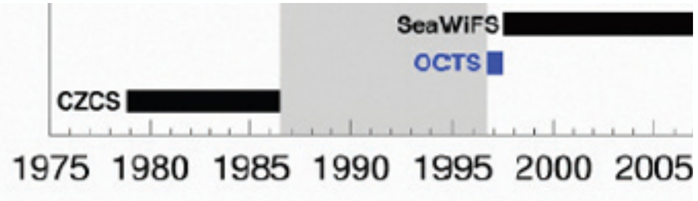
Daniel G. Boyce[a,b,c,*], Michael Dowd[d], Marlon R. Lewis[e], Boris Worm[a]

4) Responses: Total phytoplankton biomass may change



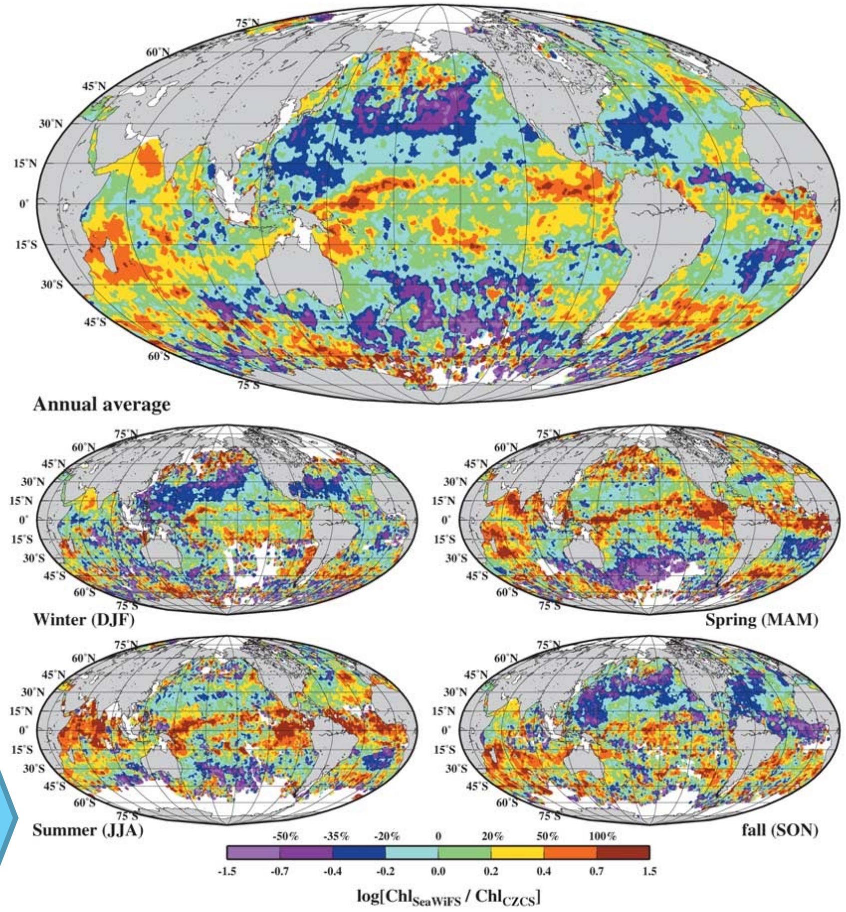
Global spatial distributions and seasonal variability of ocean chlorophyll were similar, but global means decreased over the two observational segments.

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

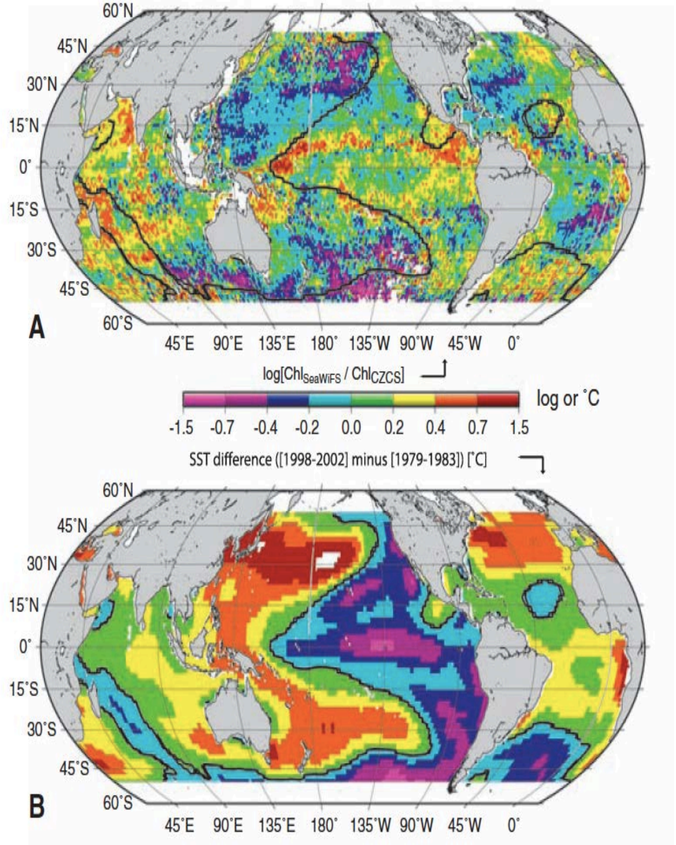


The analysis of decadal changes from the CZCS to the SeaWiFS era shows an overall increase of the world ocean average chlorophyll concentration by about 22%, mainly due to large increases in the intertropical areas

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

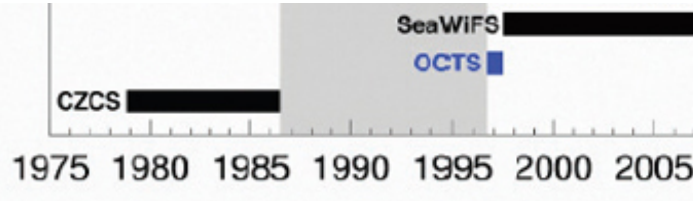


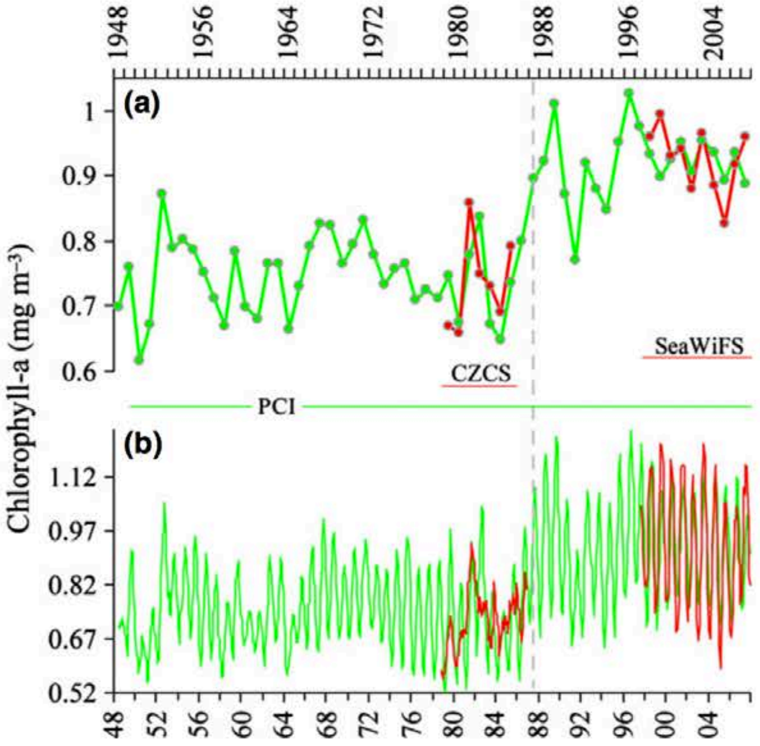
4) Responses: Total phytoplankton biomass may change



Multidecadal changes in global phytoplankton abundances are related to basin-scale oscillations of the physical ocean.

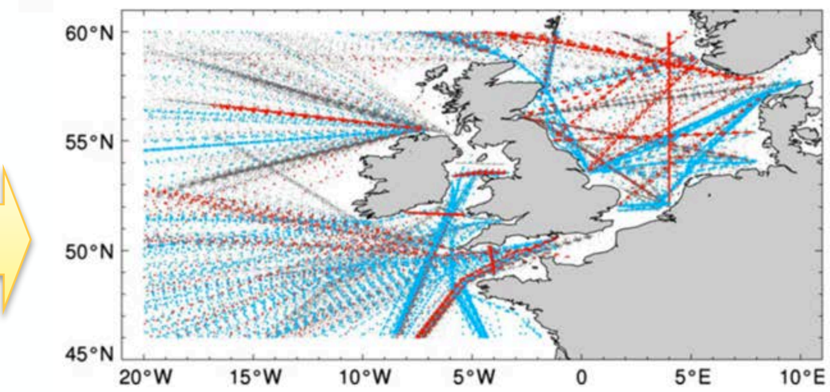
Martinez et al .(2009)
https://doi.org/10.1126/science.1177012



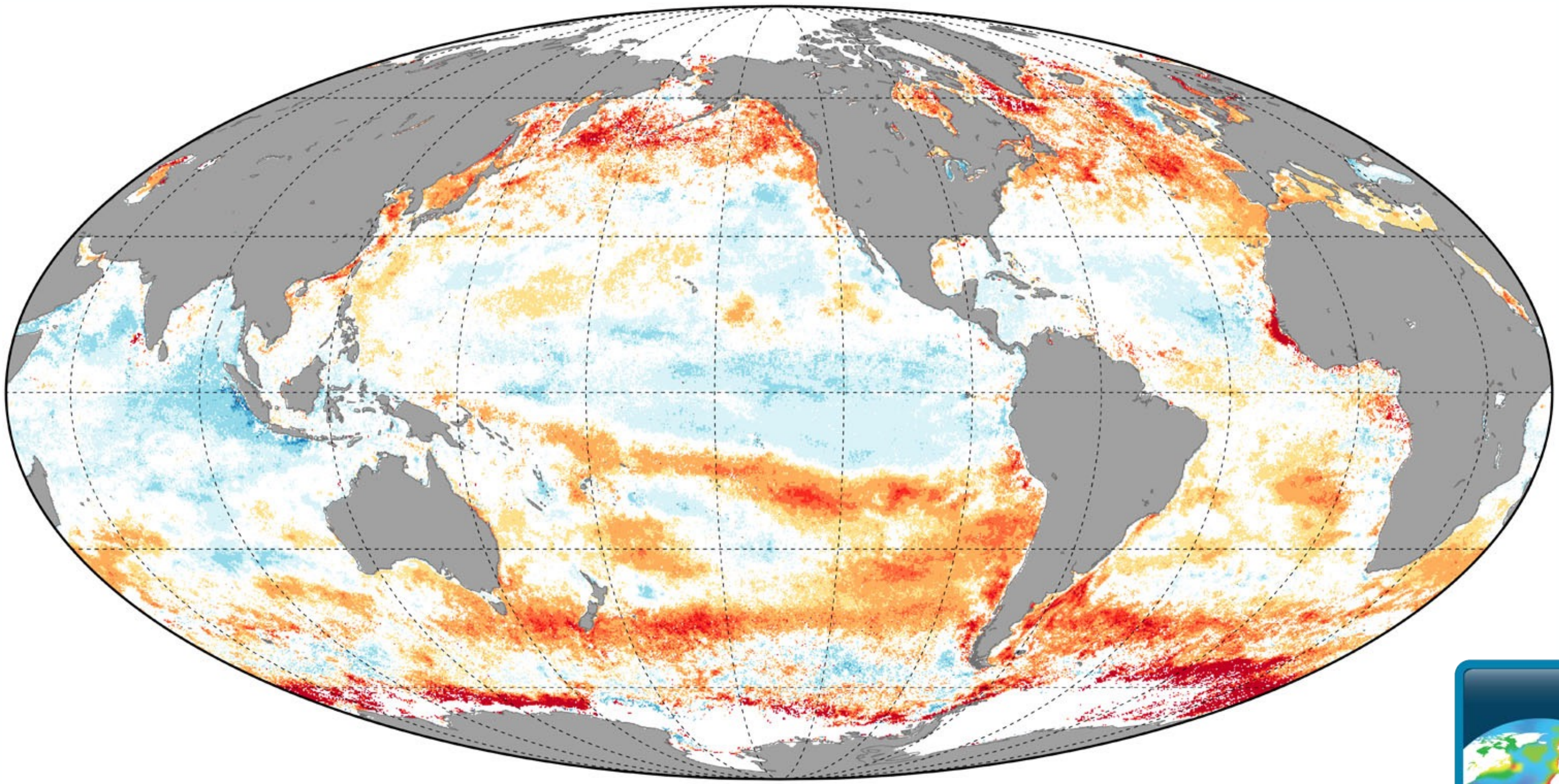


Results from merging CPR data with CZCS and SeaWiFS reflect a clear increasing pattern of Chl-a in the North East Atlantic

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



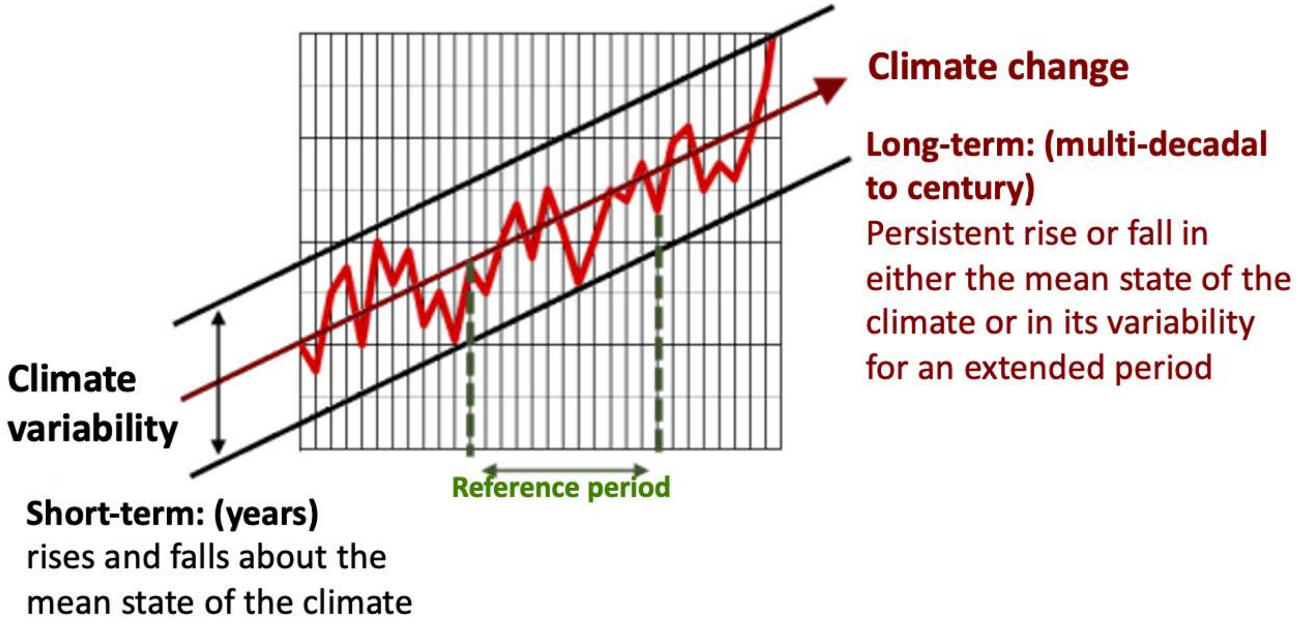
4) Responses: Total phytoplankton biomass may change



Global chlorophyll trend map (September 1997 to December 2016)

von Schuckmann et al. (2018) https://doi.org/10.1080/1755876X.2018.1489208

4) Responses: Total phytoplankton biomass may change



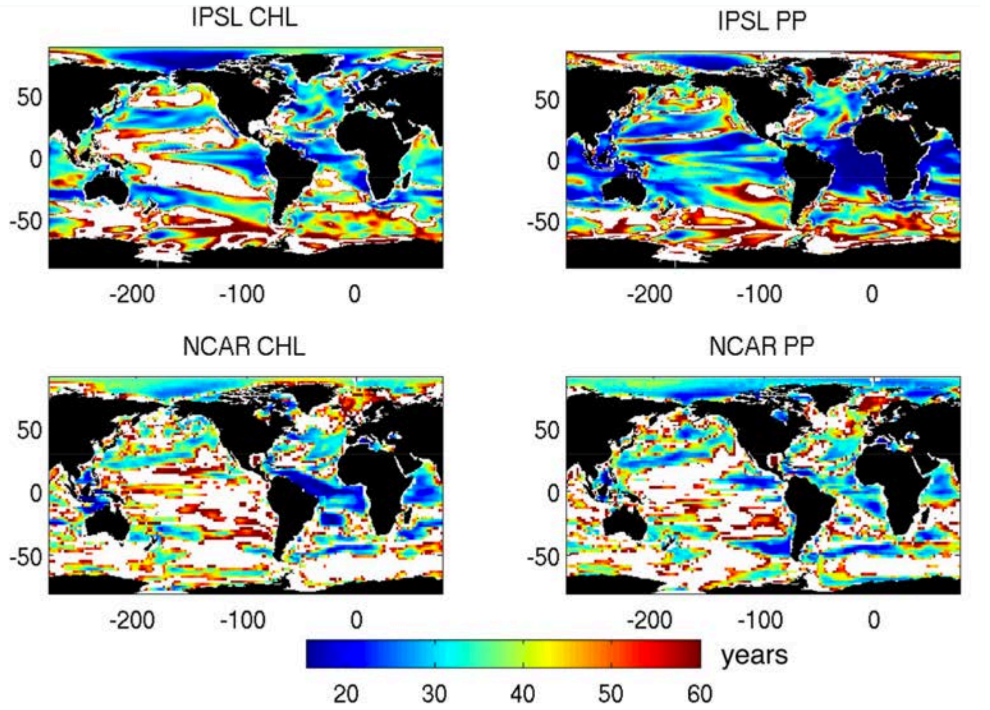
Adapted from E. Barrow, http://www.cccsn.ec.gc.ca
With help from Marie-Fanny Racault (PML)

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

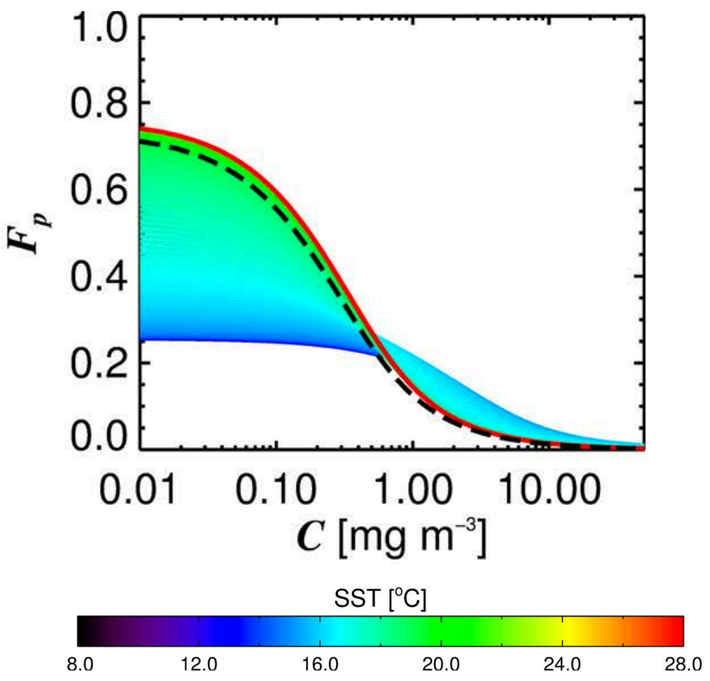
Biogeosciences

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]

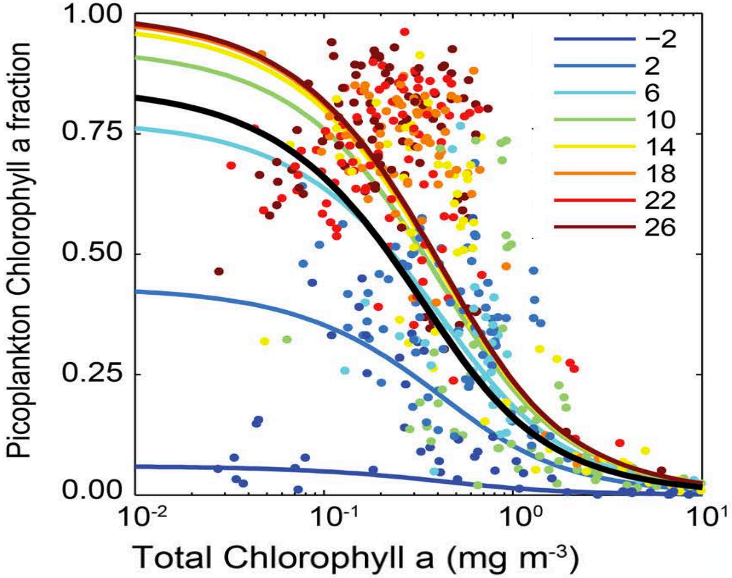


4) Responses: Total phytoplankton biomass may change



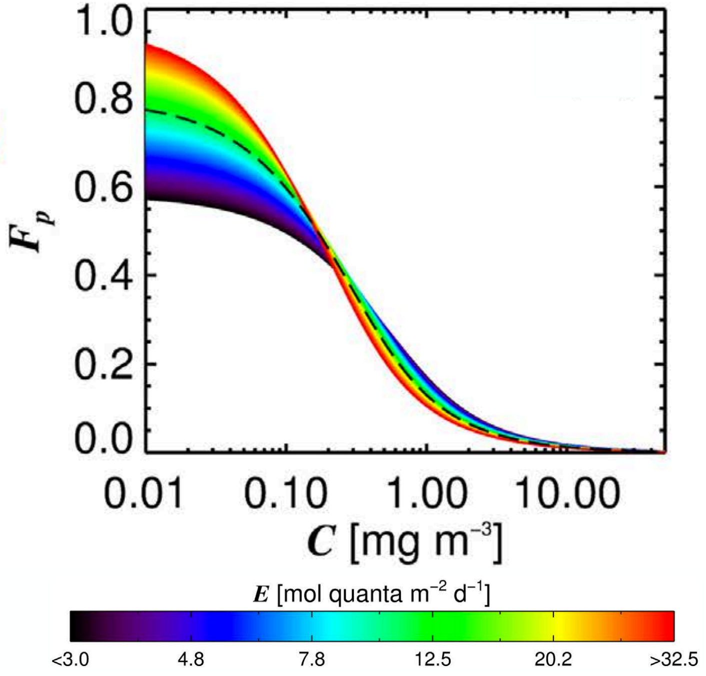
Fraction of picoplankton to total chl-a in the North Atlantic as a function of SST.

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

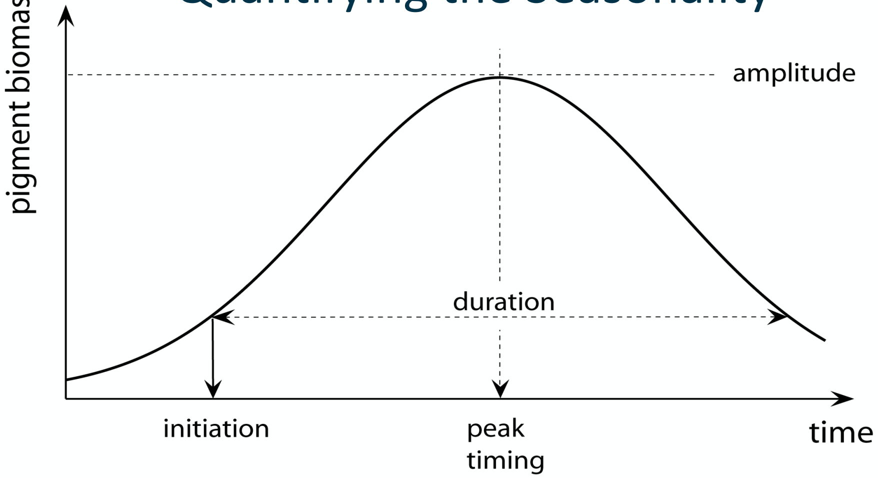


Fraction of picoplankton to total chl-a in the Global Ocean as a function of light

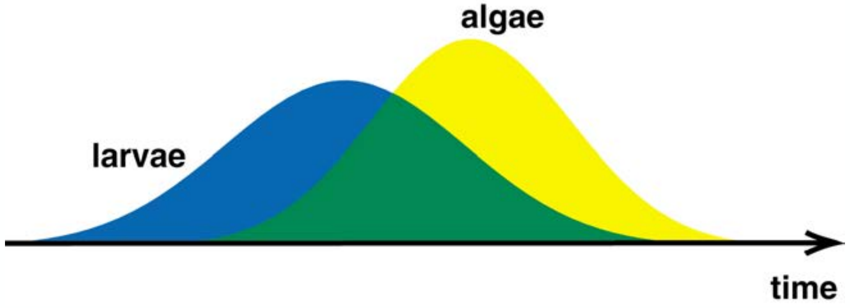
Brewin et al. (2015)
https://doi.org/10.1016/j.rse.2015.07.004

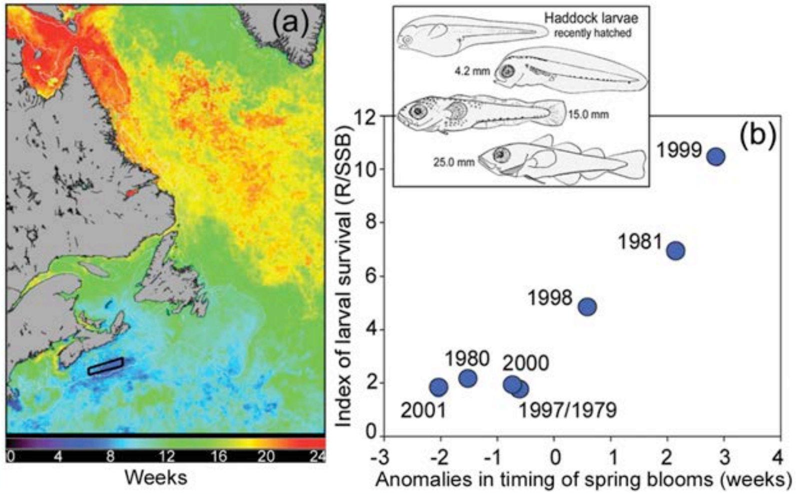
4) Responses: Phytoplankton phenology

Quantifying the Seasonality



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



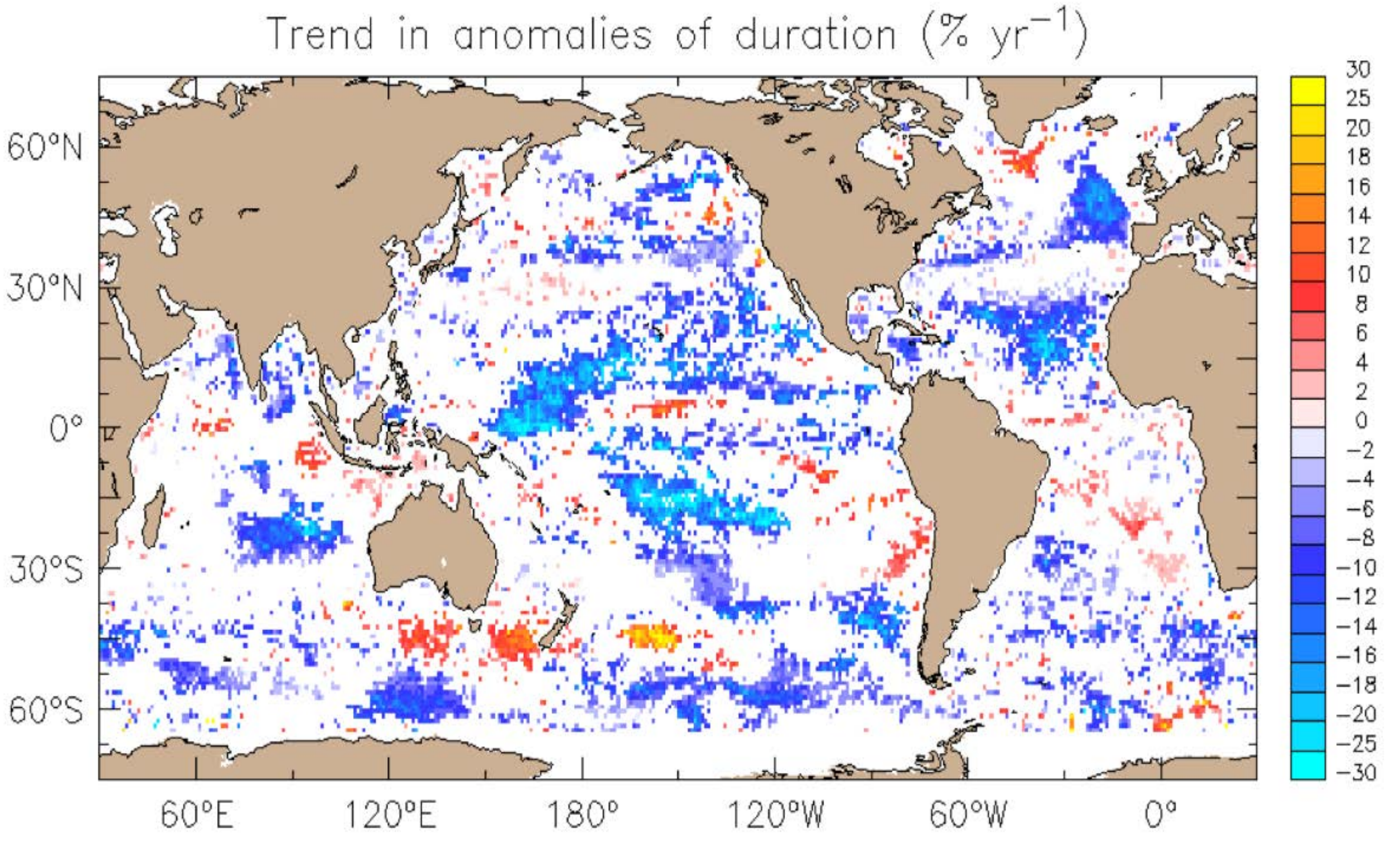


Inter-annual variations in the timing of the spring bloom impacts survival of larval fish

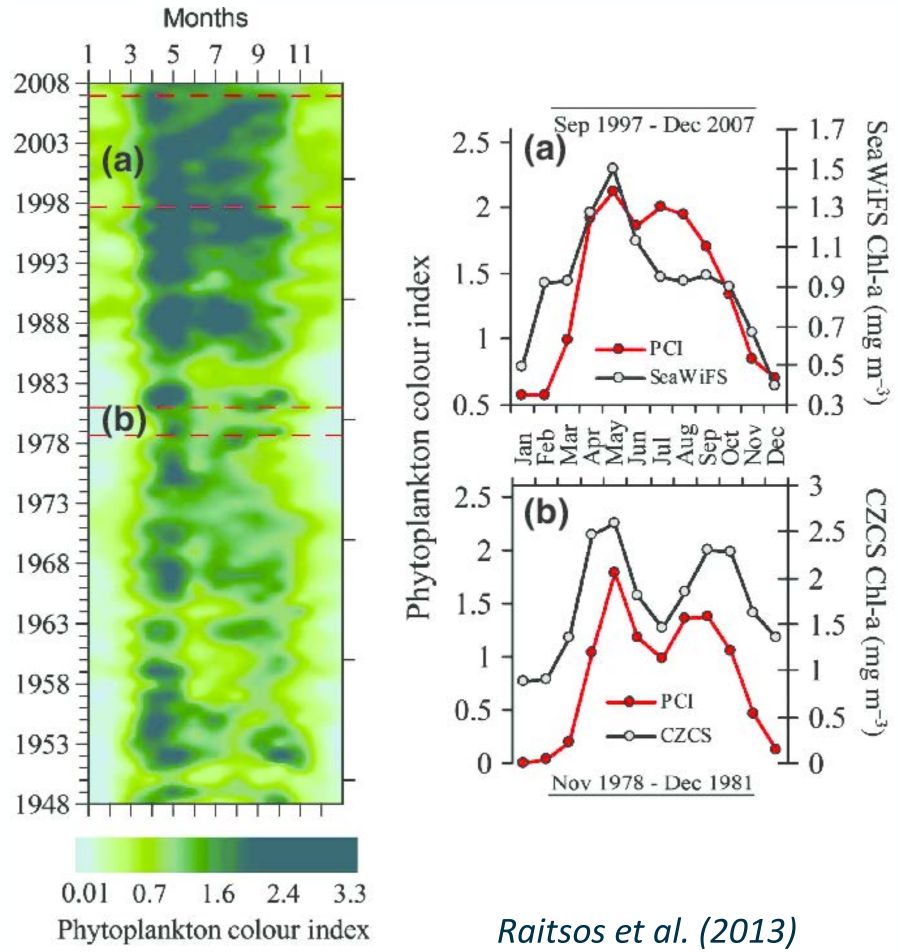
Platt et al. (2003)
https://doi.org/10.1038/423398b

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

4) Responses: Phytoplankton phenology

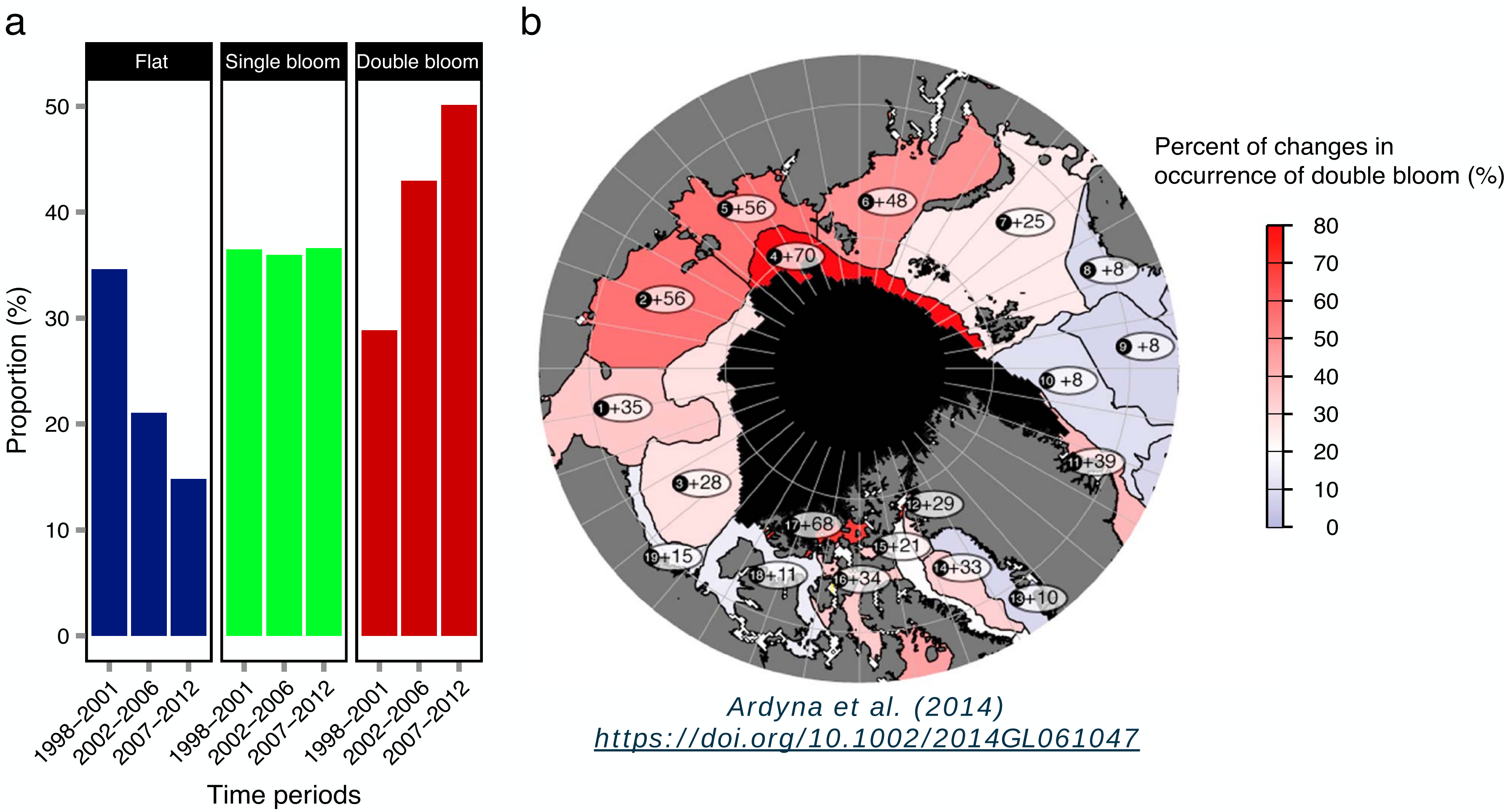


Racault et al. (2012) https://doi.org/10.1016/j.ecolind.2011.07.010



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

4) Responses: Changing polar regions

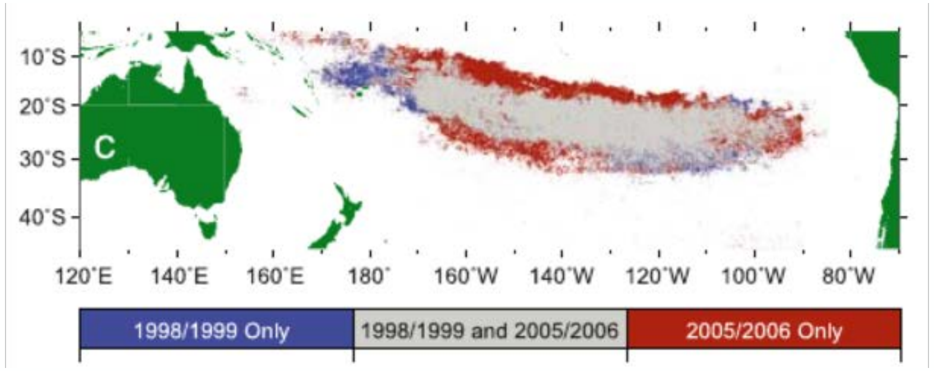


Ardyna et al. (2014)
https://doi.org/10.1002/2014GL061047

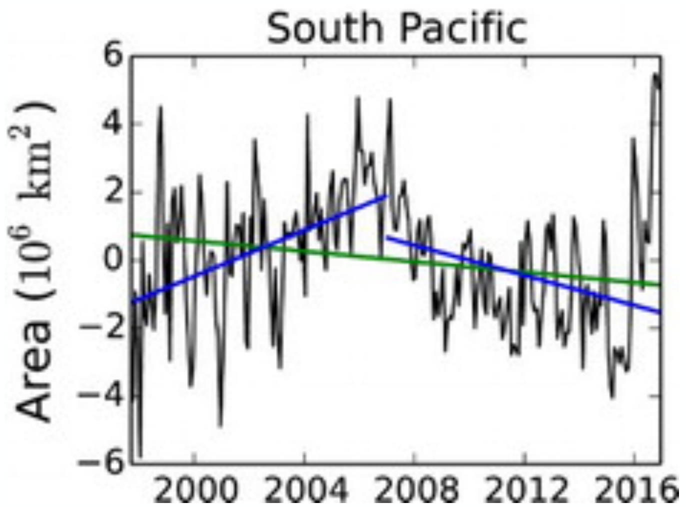
In a changing Arctic Ocean, a phenology of biological productivity with two phytoplankton blooms and two peaks of sedimentation may become prevalent.

4) Responses: Other

Oligotrophic regions

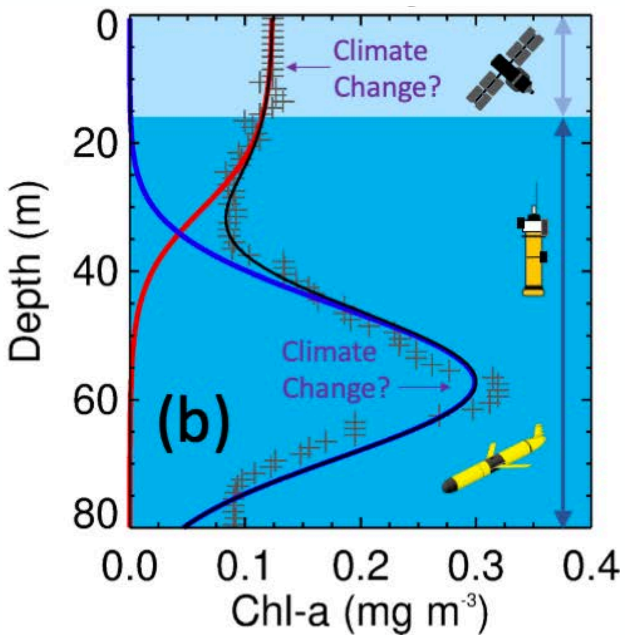


Polovina et al. (2008) Geophys. Res. Lett.
https://doi.org/10.1029/2007GL031745



von Schuckmann et al. (2018)
https://doi.org/10.1080/1755876X.2018.1489208

Vertical structure



Changes in other optically-active substances

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$

Water CONSTANT | Phyto-plankton | Detritus | CDOM

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

5) Other applications

Fisheries

Water Quality

Harmful algal blooms

Aquaculture

Marine pollution

Bio-feedback mechanisms

Marine biodiversity and function


IOCCG
International Ocean Colour Coordinating Group

Ocean Colour Bibliography

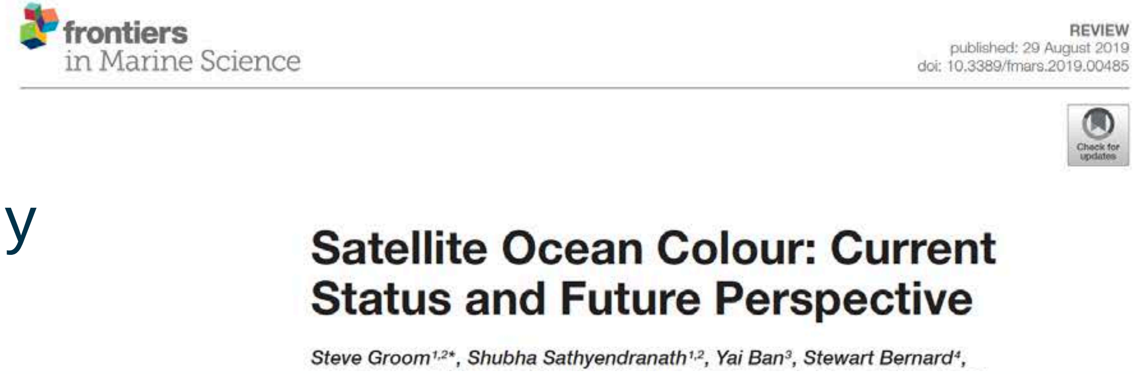
Home » Resources » Ocean Colour Bibliography

The IOCCG bibliography is updated periodically with new references submitted by readers. Another useful ocean colour bibliography is the searchable Historic Ocean Colour Archive assembled by Marcel Wernand, with articles and books written between the 17th and early 20th century.

http://ioccg.org/what-we-do/ioccg-publications/

http://ioccg.org/resources/ocean-colour-bibliography/

http://ioccg.org/what-we-do/ioccg-publications/ioccg-reports/


frontiers in Marine Science

REVIEW
published: 29 August 2019
doi: 10.3389/fmars.2019.00485

Check for updates

Satellite Ocean Colour: Current Status and Future Perspective

Steve Groom[1,2], Shubha Sathyendranath[1,2], Yai Ban[3], Stewart Bernard[4],*

Groom et al. (2019)
https://doi.org/10.3389/fmars.2019.00485

Part 3: Outline

1) The Greenhouse effect

2) Essential Climate Variables

3) Ocean colour datasets requirements for climate

4) Responses of the marine ecosystem to climate change
   - Total phytoplankton biomass
   - Phytoplankton community structure
   - Phytoplankton phenology
   - Other responses

5) Other applications