

→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Ocean Colour and the marine carbon cycle

Bob Brewin^{1,2}

¹ Plymouth Marine Laboratory (PML), Prospect Place, The Hoe, Plymouth PL1 3DH, UK

² National Centre for Earth Observation, PML, Plymouth PL1 3DH, UK



National Centre for
Earth Observation

NATIONAL ENVIRONMENT RESEARCH COUNCIL

PML

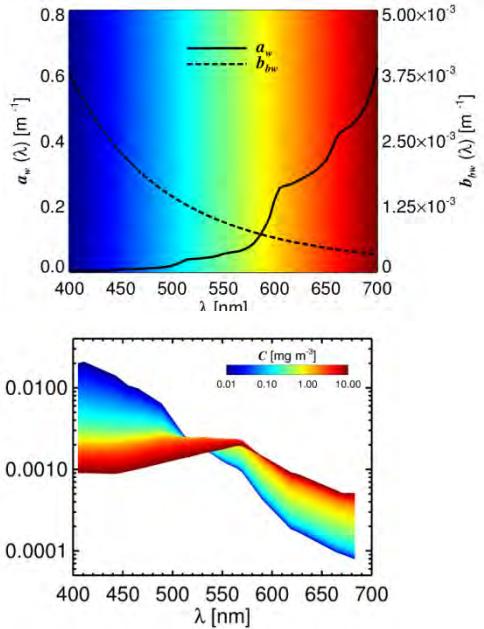
Plymouth Marine
Laboratory

Overview of ocean colour lectures



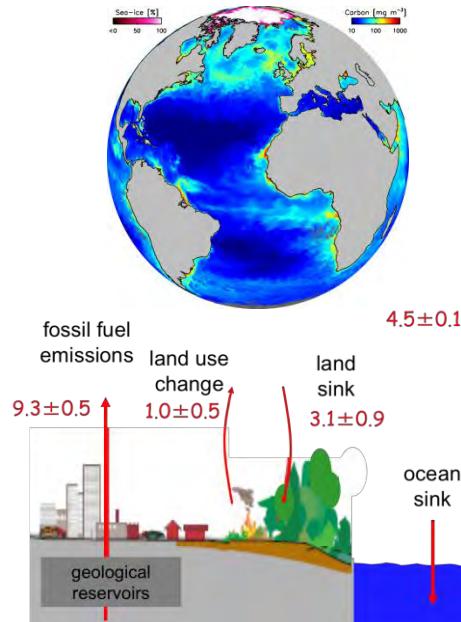
Ocean Colour theory

11:30 -12:30 1st August



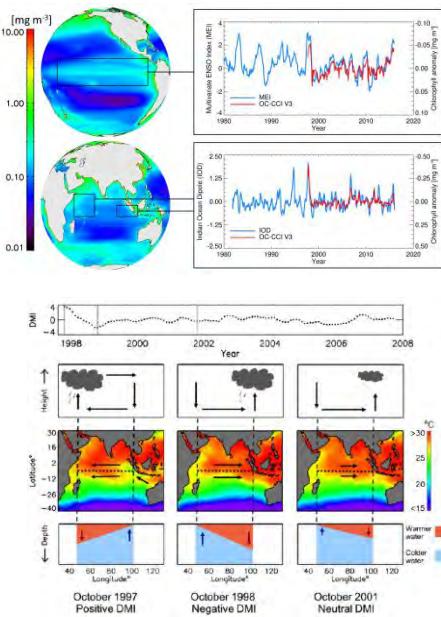
Ocean Colour and the marine carbon cycle

12:30 -13:30 2nd August

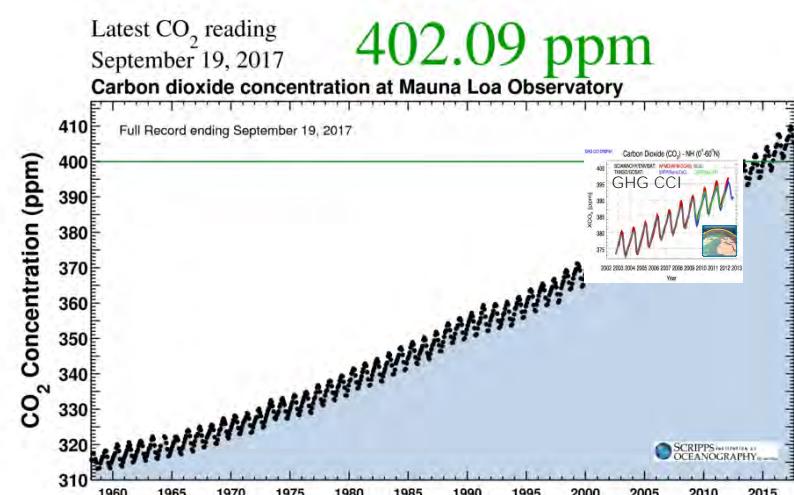
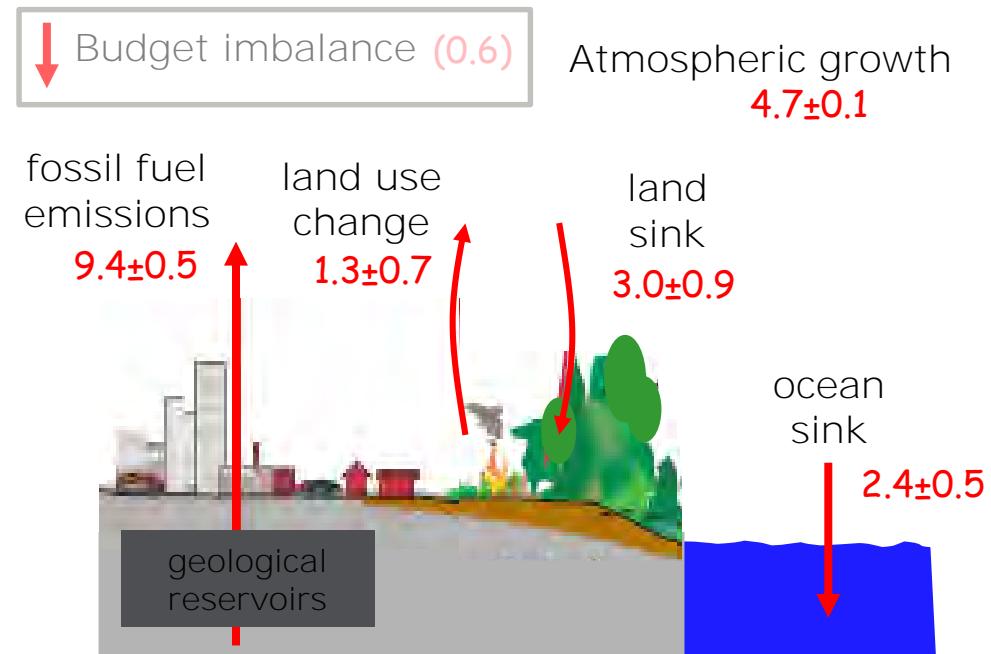


Ocean Colour and climate

11:30 -12:30 3rd August



2007-2016 Earth Carbon budget (GtC y^{-1})



Sources: Le Quéré et al. (2018) *Earth Syst. Sci. Data.*, 10, 405-448



POOLS OF CARBON IN THE OCEAN

DIC

~38,000 Pg C

CO_2

H_2CO_3

HCO_3^-

CO_3^{2-}

DOC

~662 Pg C

CDOM

DOM

POC

~2.3 Pg C

Phytoplankton

Zooplankton

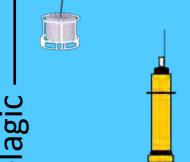
Bacteria

Detritus

PIC

~0.02 Pg C

CaCO_3



Epipelagic

Mesopelagic

Mesopelagic



Phytoplankton

Primary production

grazing

respiration
excretion

Zooplankton

Bacteria

Riverine input

Land

Physical
Transport

Sinking phytoplankton

Aggregation

Sinking aggregates

Sinking fecal pellets

Diel vertical migration

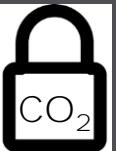
Bacteria

respiration
solubilization

excretion

consumption

Export



CO_2

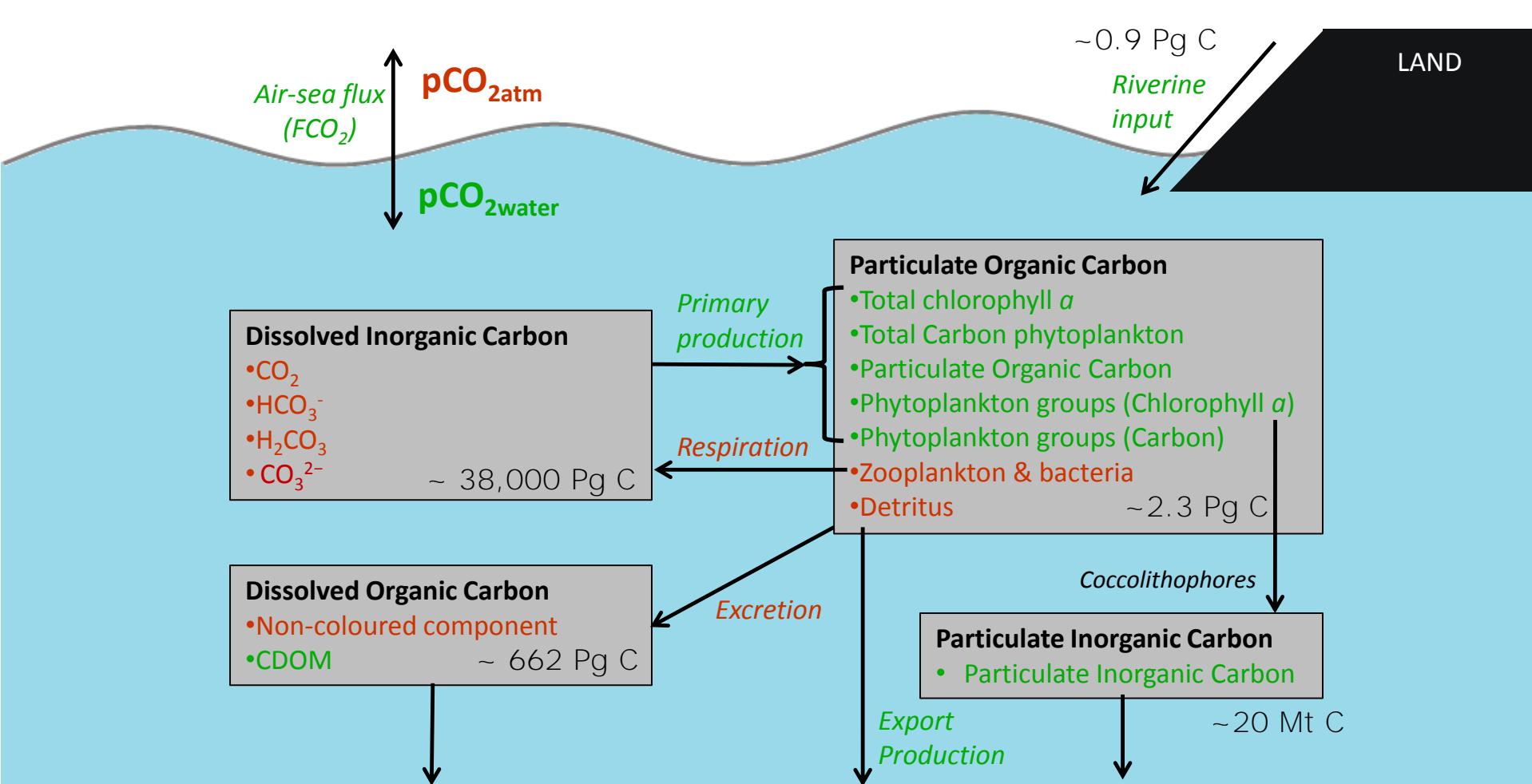


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

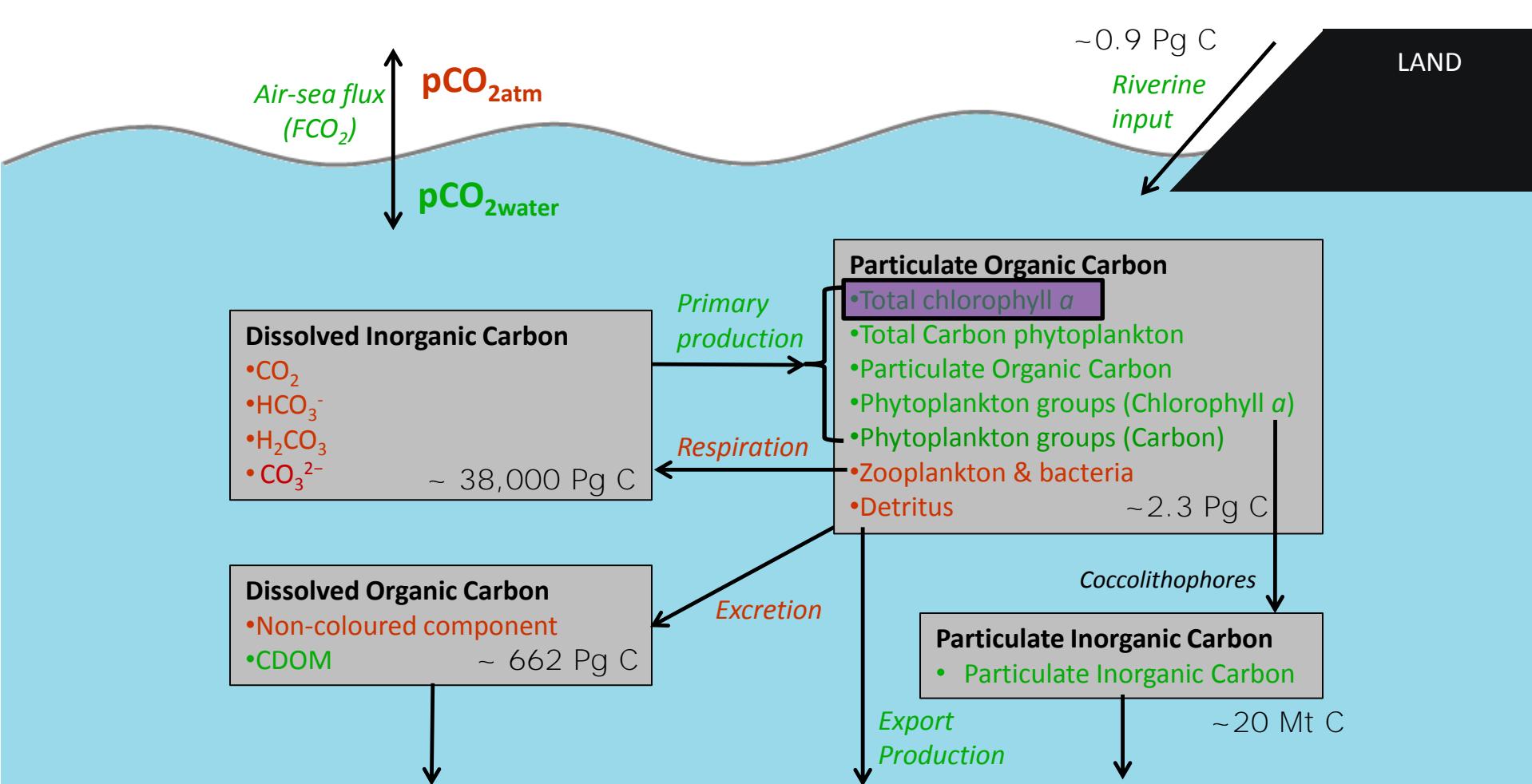
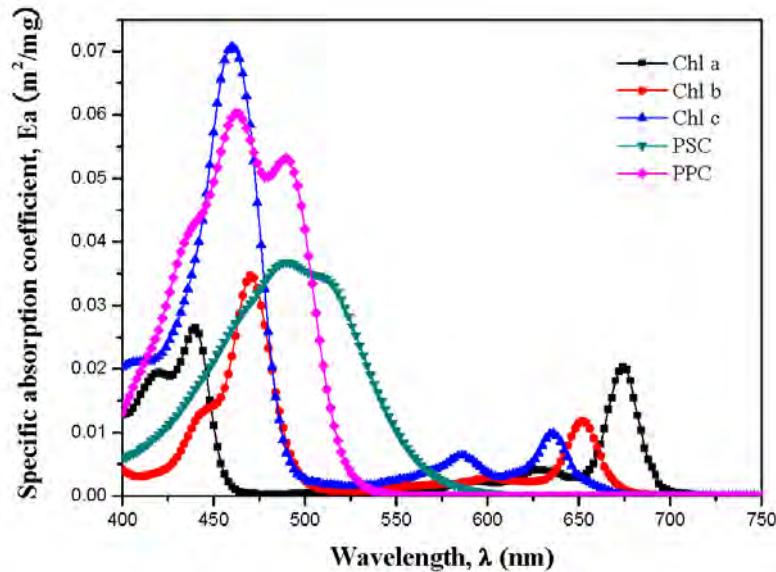


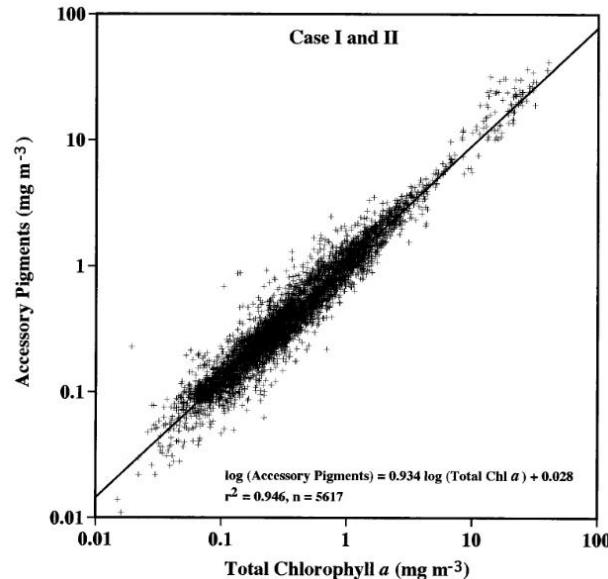
Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Total chlorophyll-a

Total Chlorophyll-a = Monovinyl Chl *a* + divinyl Chl *a* + Chl *a* allomer + Chl *a* epimer + chlorophyllide *a*

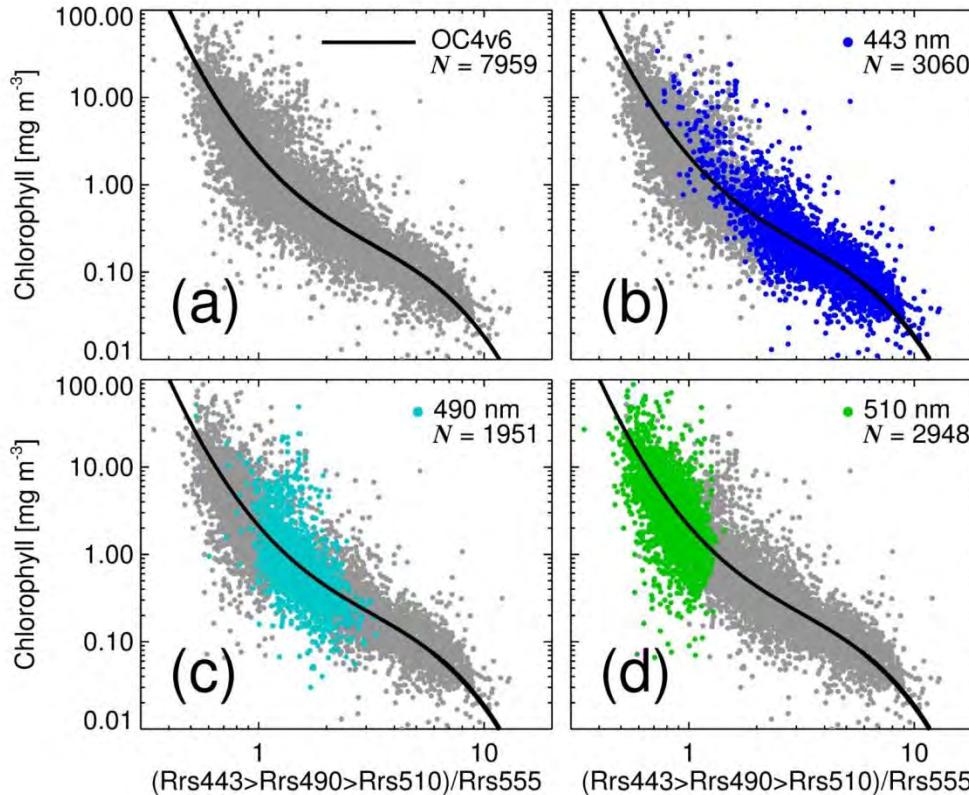


Bidigare et al. (1990). *Ocean Optics X*

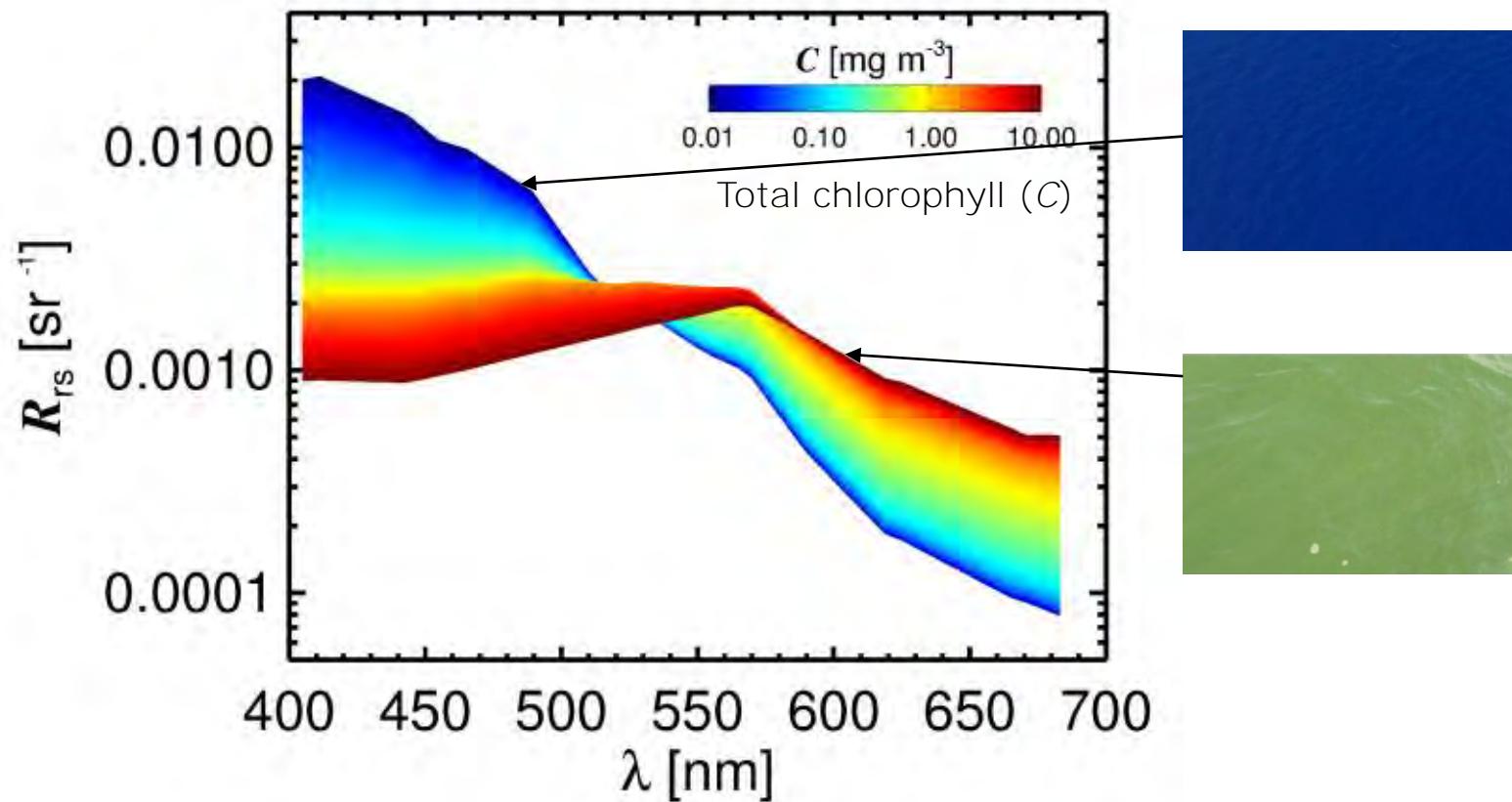


Trees et al. (2000) *Limnol. Oceanogr.*

Total chlorophyll-a



Total chlorophyll-a



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

Water CONSTANT

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

\propto Chlorophyll (C)

$$R(\lambda) \approx r \frac{b_b(\lambda)}{a(\lambda)}$$

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)

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



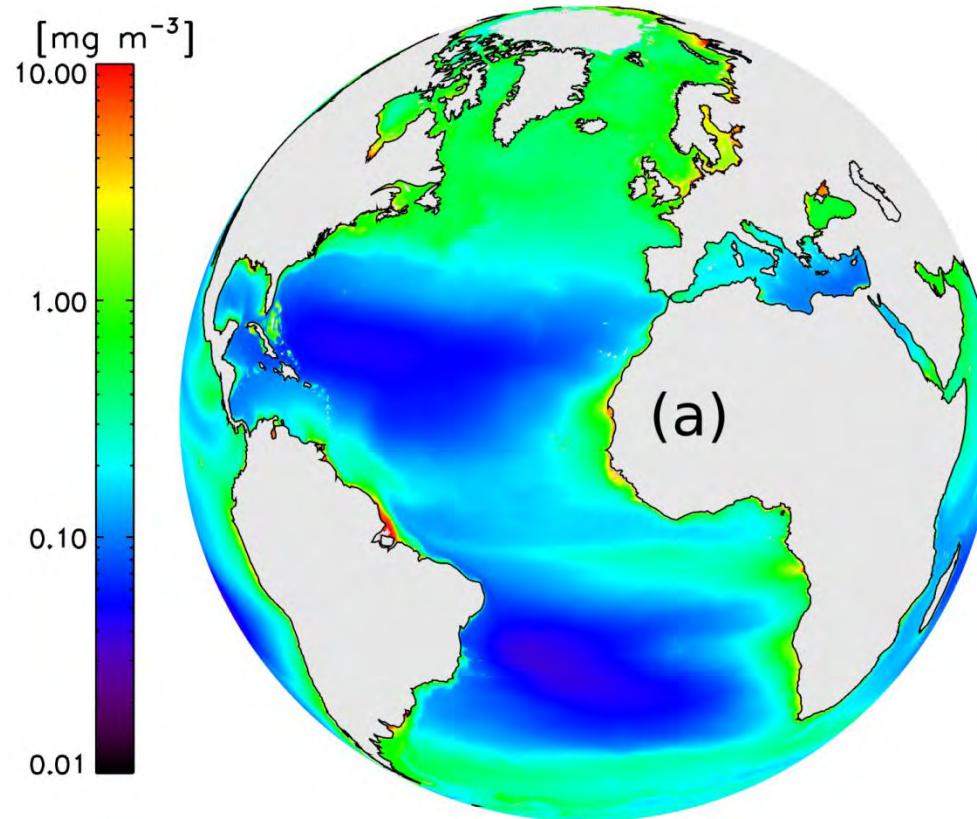
$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

$$R(\lambda) \approx r \frac{b_b(\lambda)}{a(\lambda)}$$

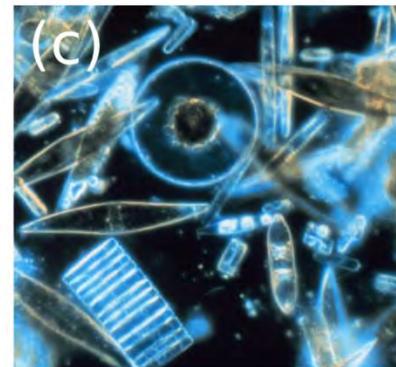
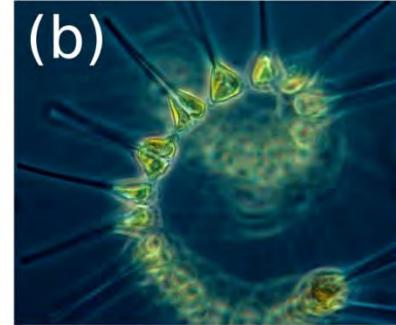
Case-2: Phytoplankton biomass does not covary with detritus and CDOM

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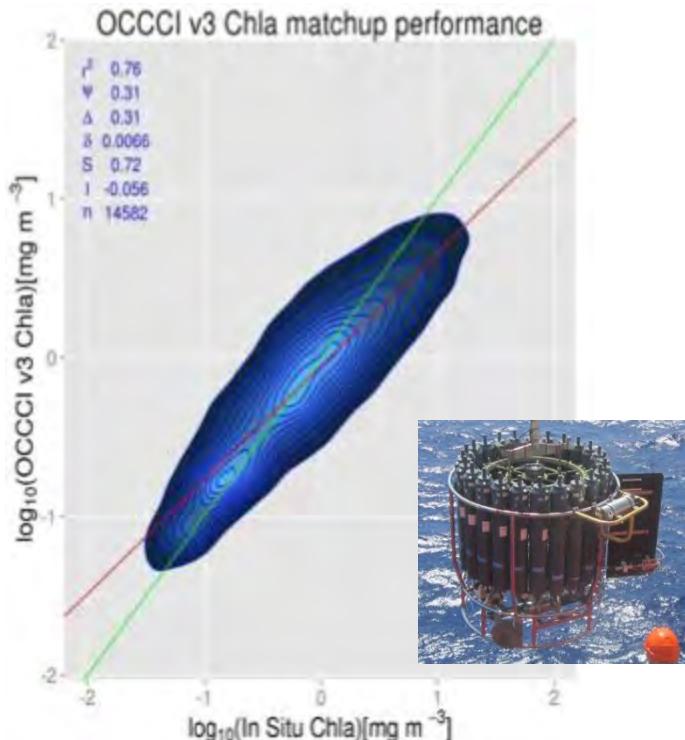
Total chlorophyll-a



(a)

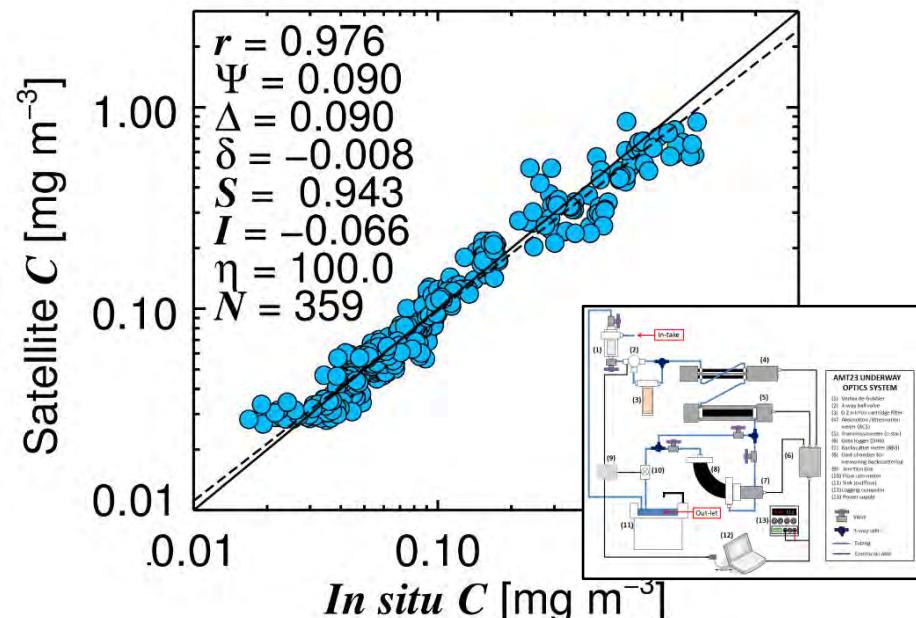


Total chlorophyll-a



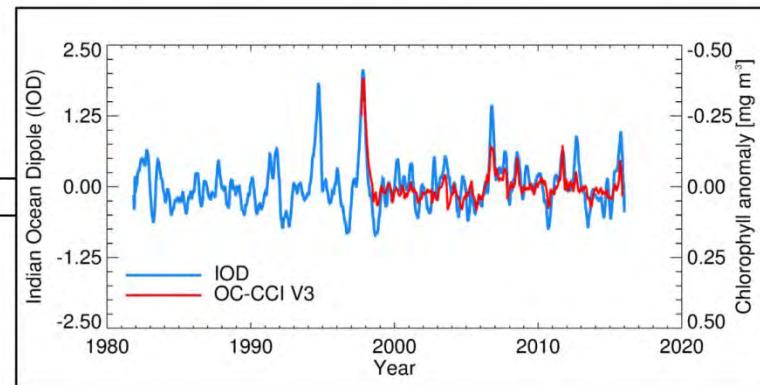
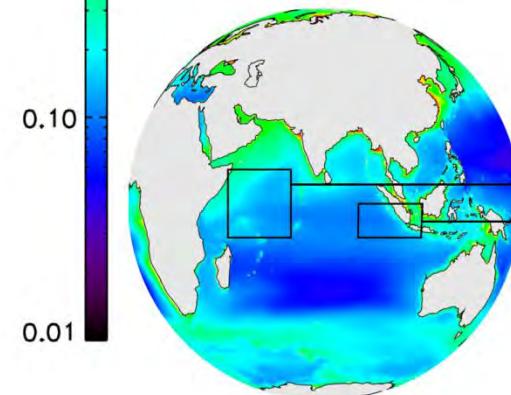
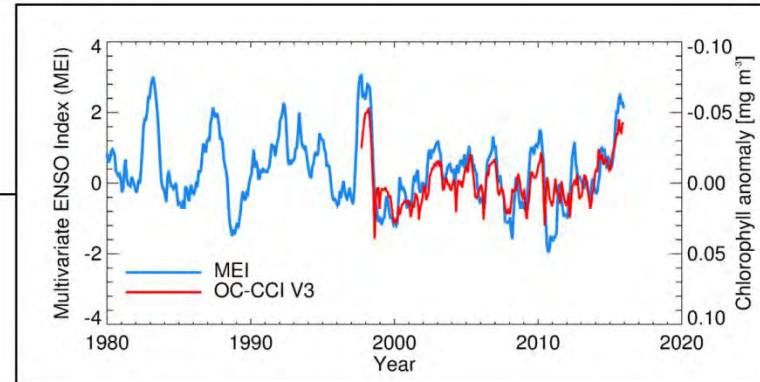
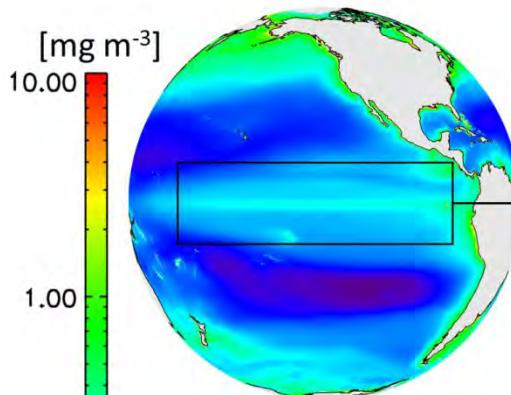
Ocean-Colour Climate Change
Initiative

Validation



Brewin et al. (2016) RSE

Total chlorophyll-a



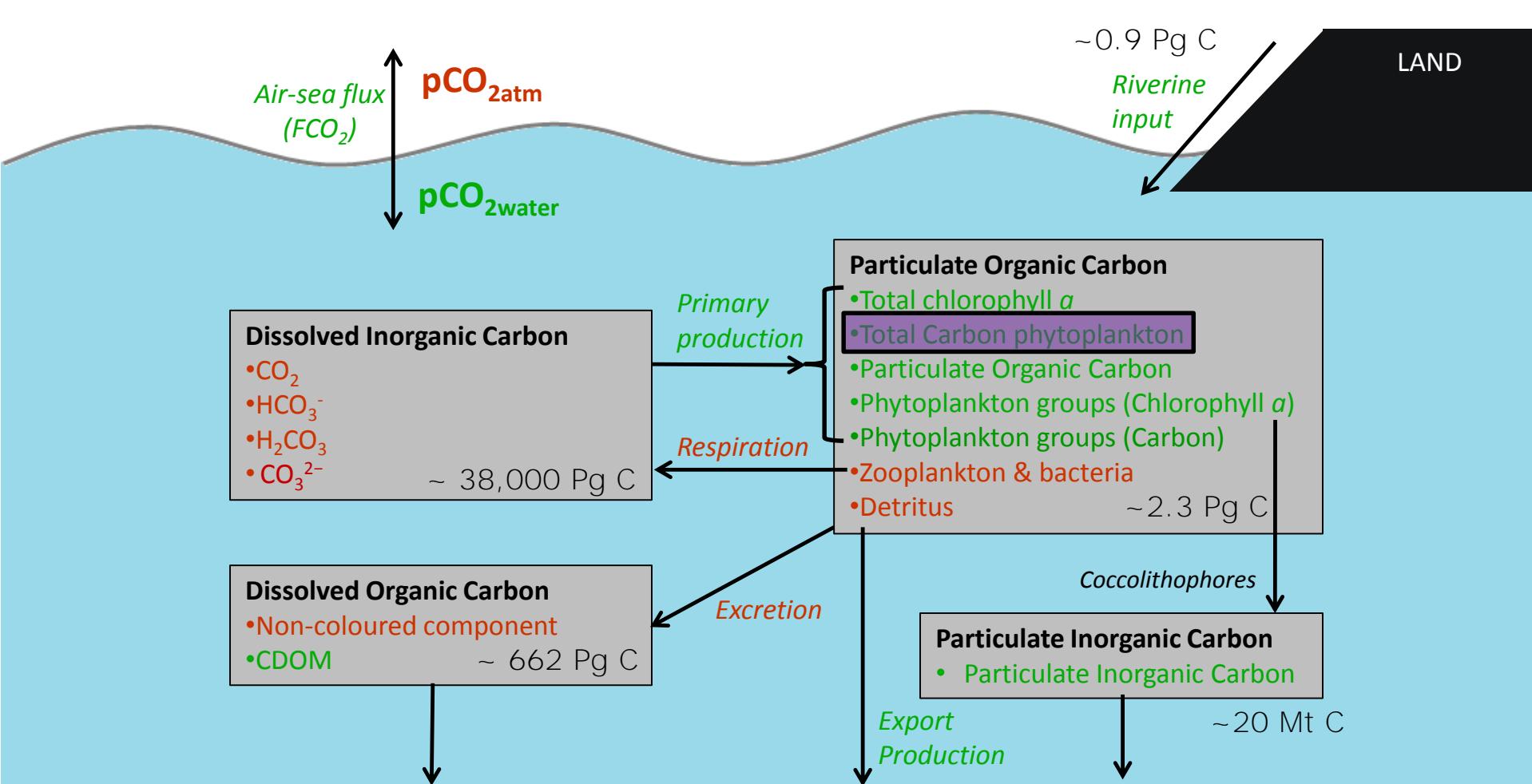
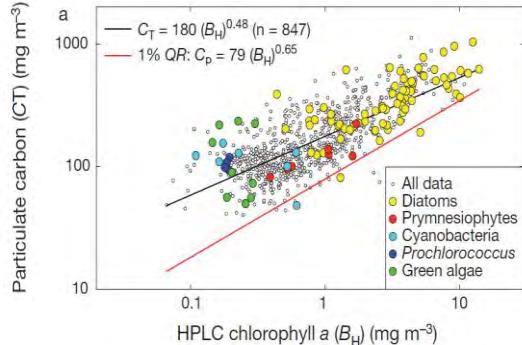
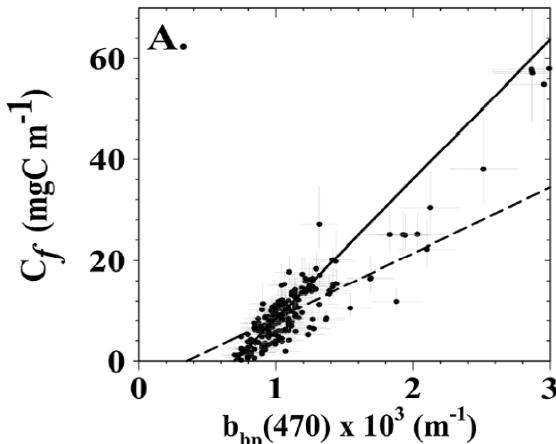


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Phytoplankton Carbon



Sathyendranath *et al.* (2009) MEPS



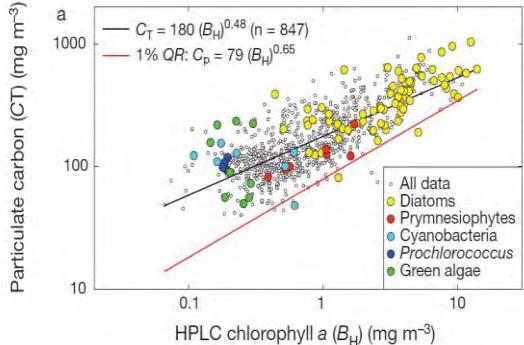
Martinez-Vincente *et al.* (2013) GRL



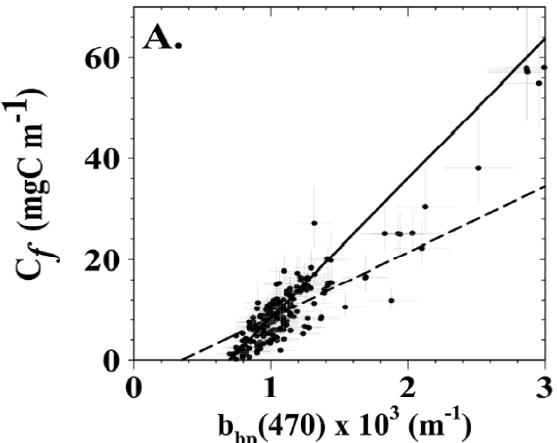
August
2003

See also Behrenfeld *et al.* (2005) GBC, Kostadinov *et al.* (2016) OS, and Roy *et al.* (2016) RSE, Jackson *et al.* (2017) FMS

Phytoplankton Carbon



Sathyendranath *et al.* (2009) MEPS



Martinez-Vincente *et al.* (2013) GRL



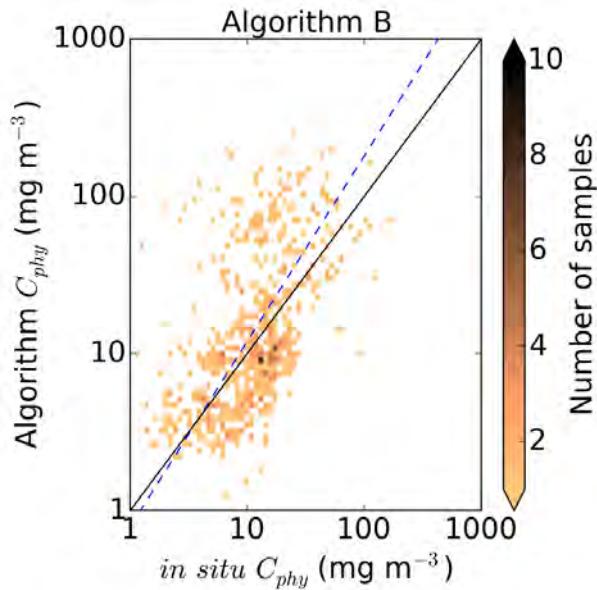
August
2003

See also Behrenfeld *et al.* (2005) GBC, Kostadinov *et al.* (2016) OS, and Roy *et al.* (2016) RSE, Jackson *et al.* (2017) FMS

Phytoplankton Carbon



Validation



Martinez-Vicente et al. (2017)
Frontiers in Marine Science

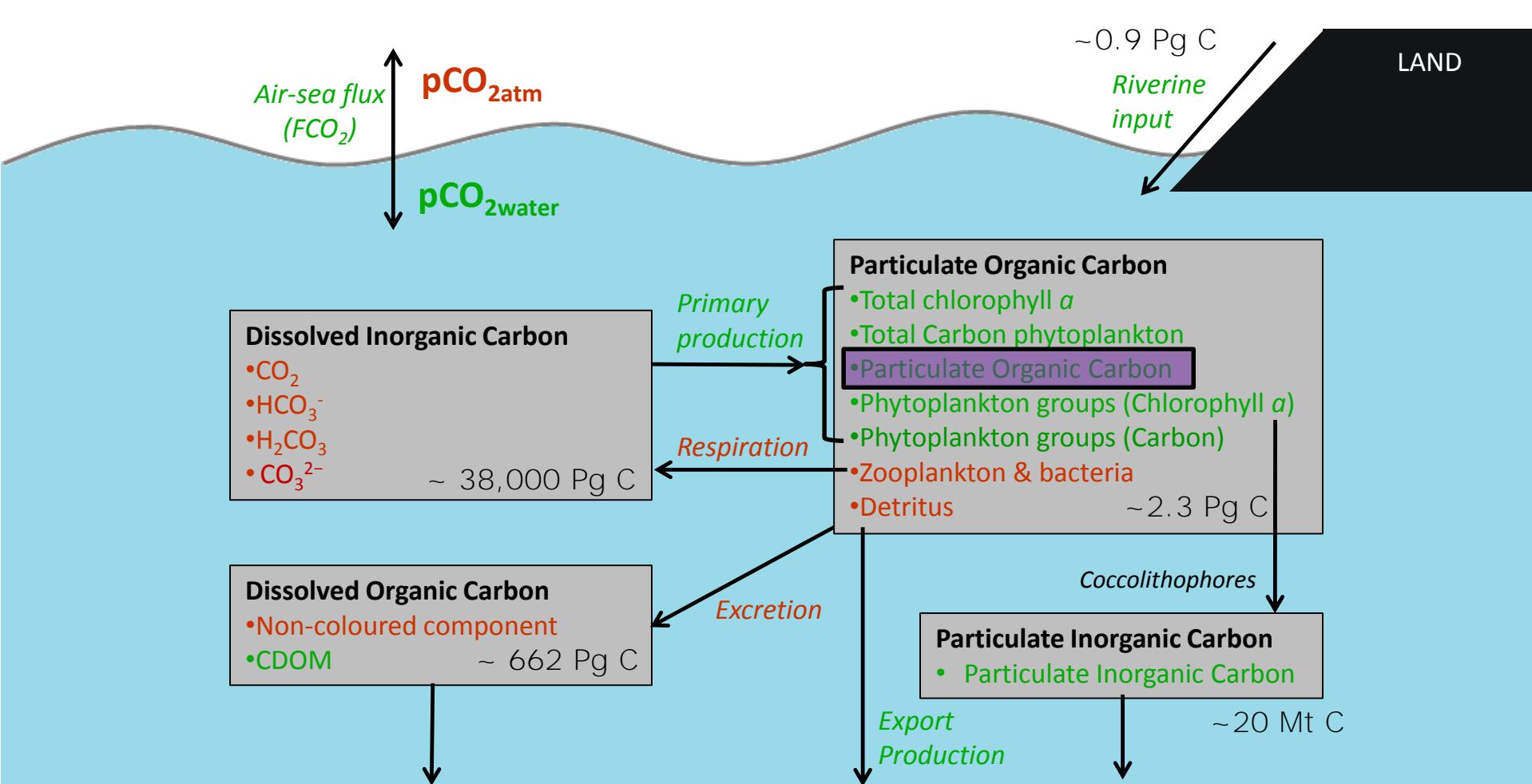
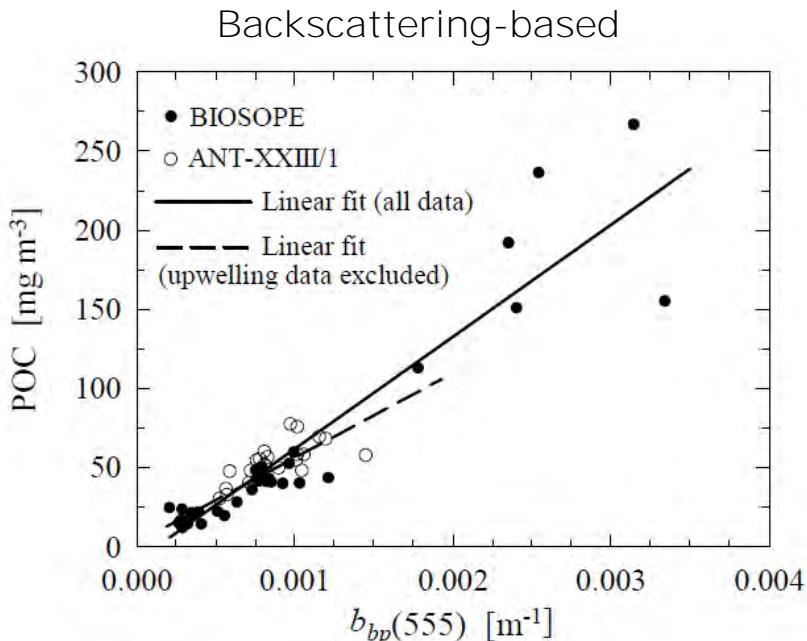
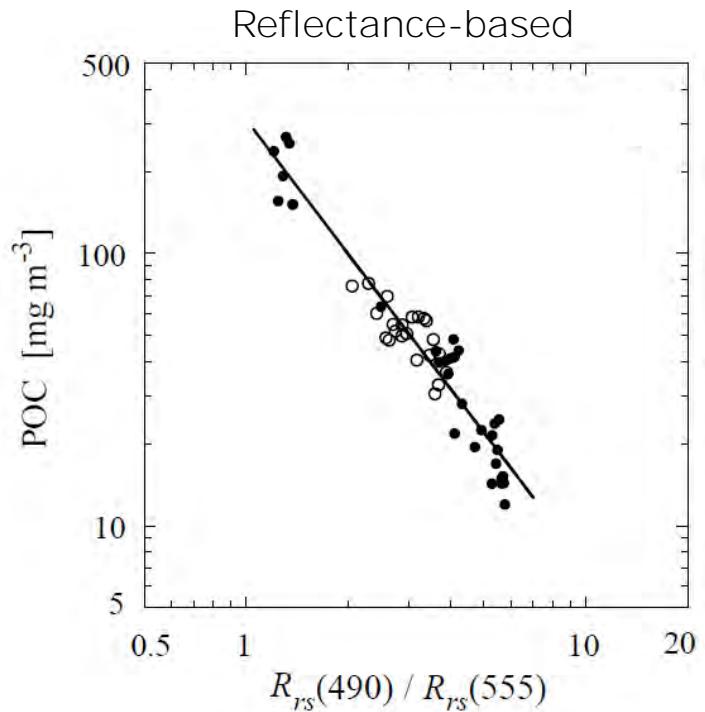


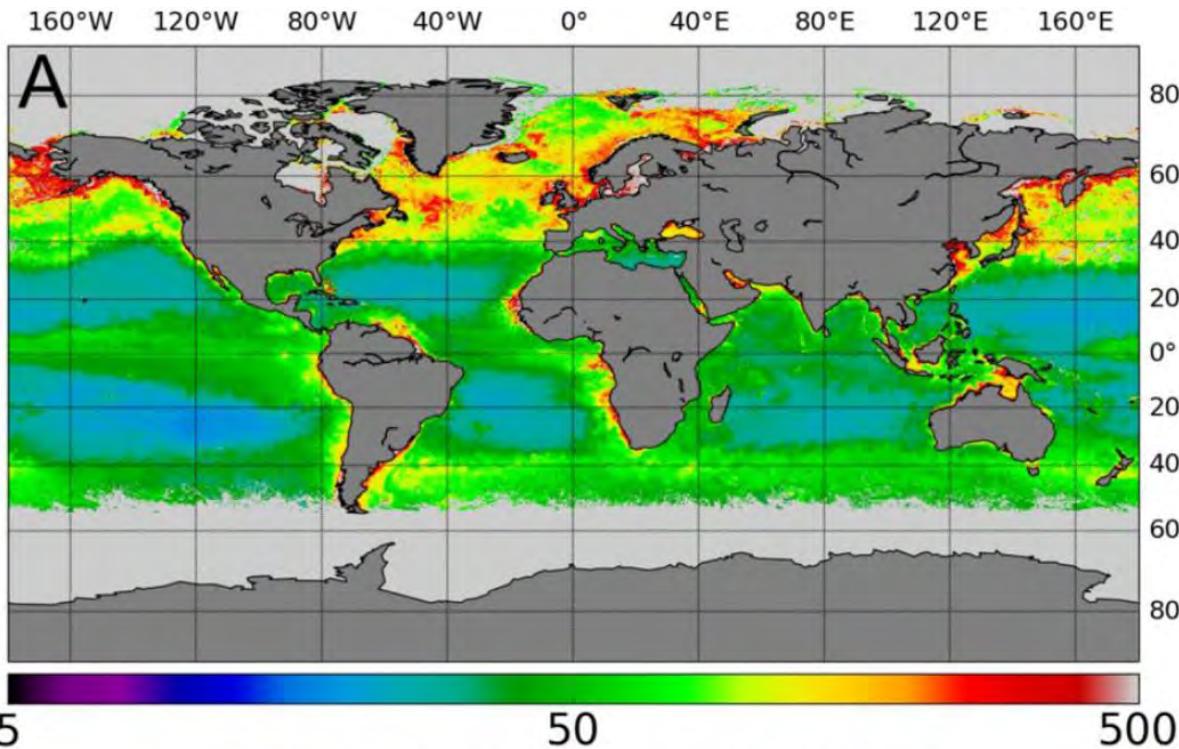
Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Particulate Organic Carbon

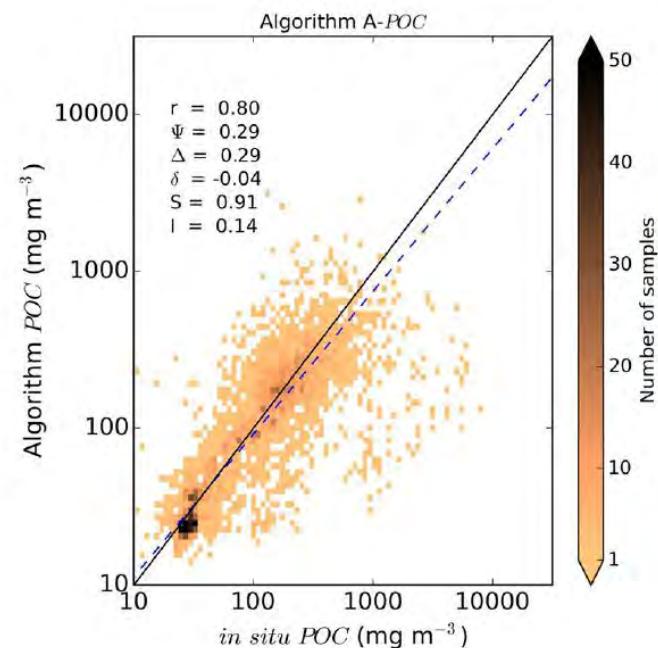


Stramski *et al.* (2008) Biogeosciences

Particulate Organic Carbon



Validation



Stramski et al. (2008) Biogeosciences
Evers-King et al. (2017) Frontiers in Marine Science

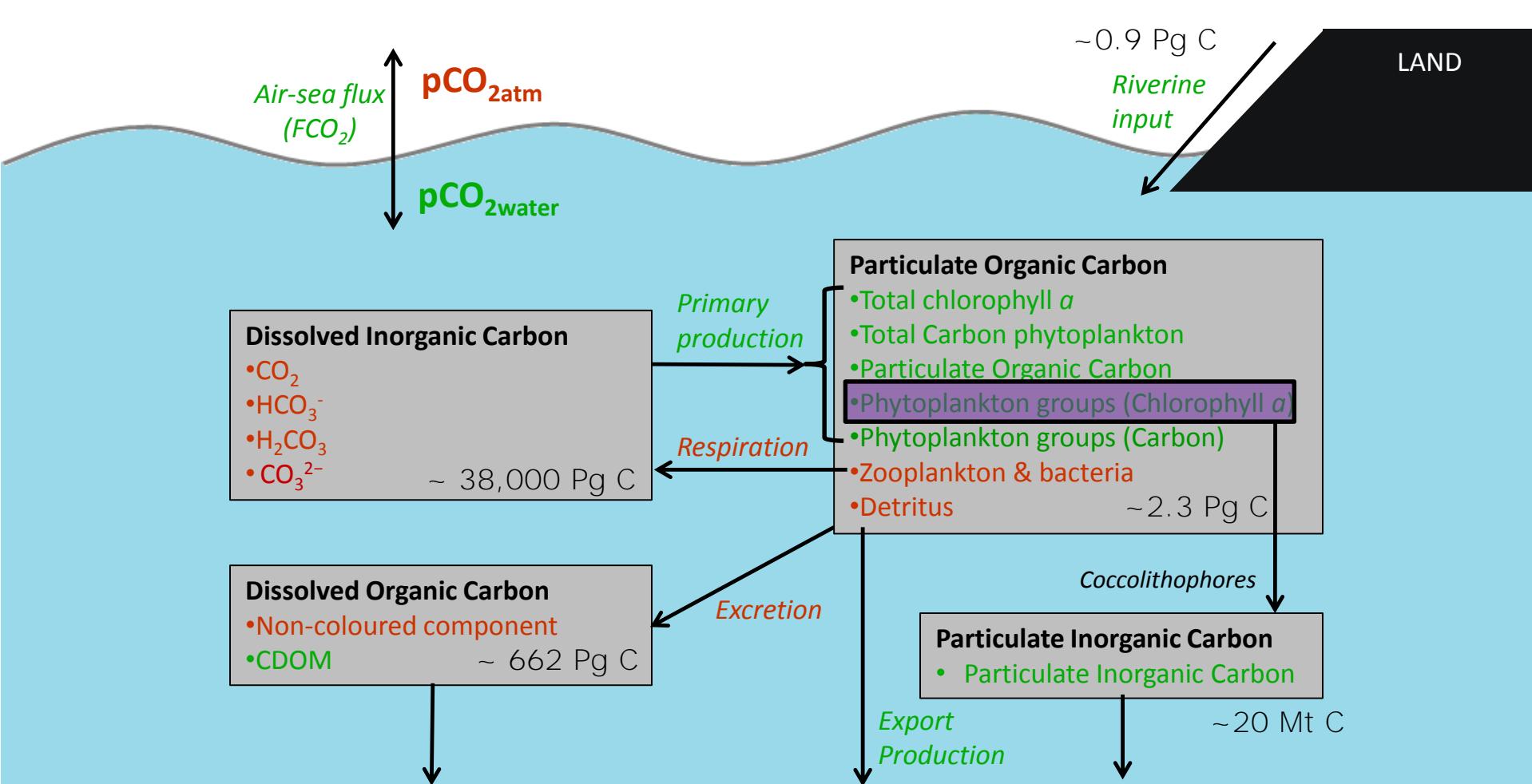
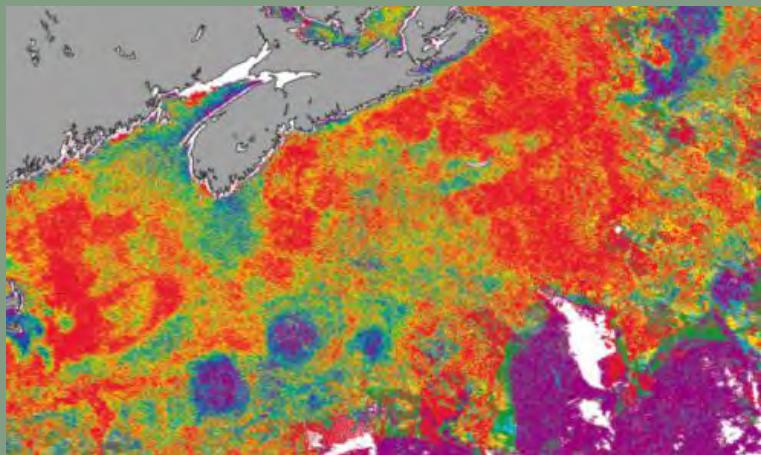


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

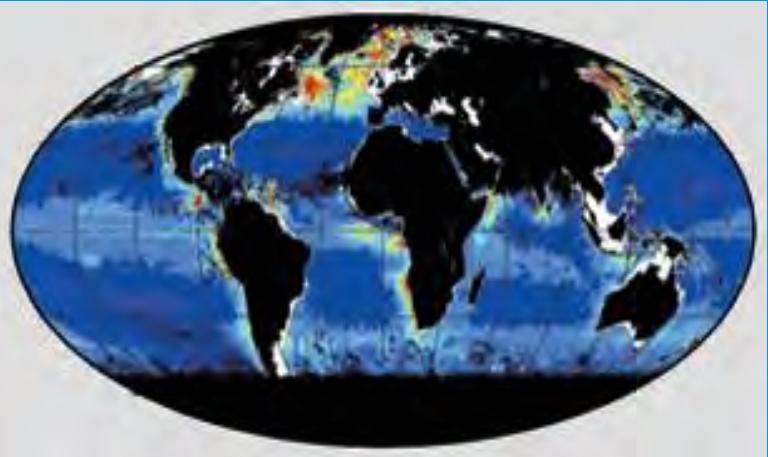
Phytoplankton Group Chlorophyll

Detection-based



Sathyendranath et al. (2004) MEPS

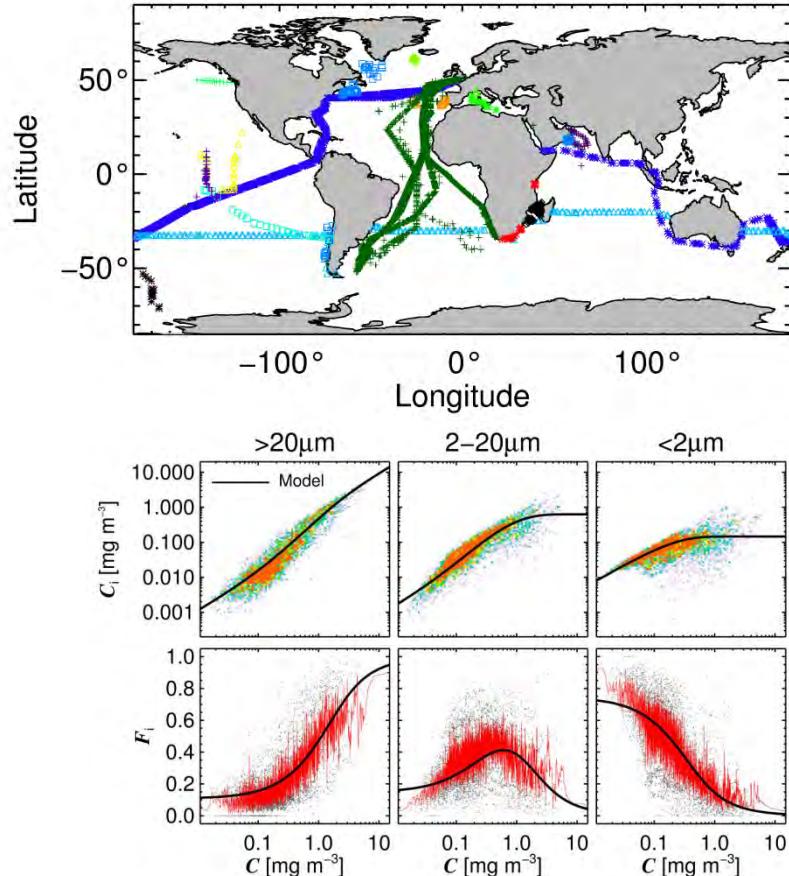
Extrapolation-based



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

see IOCCG (2014) Report Number 15,
Mouw et al. (2017) *Front. Mar. Sci*

Phytoplankton Group Chlorophyll



An example of an extrapolation-based approach

$$C_{1,2} = C_{1,2}^m [1 - \exp(-S_{1,2}C)]$$

$$C_1 = C_1^m [1 - \exp(-S_1C)]$$

$$C_2 = C_{1,2} - C_1$$

$$C_3 = C - C_{1,2}$$

Brewin et al. (2010) *Ecol. Model.*

Brewin et al. (2011) *Appl. Optics*

Brewin et al. (2012a) *Opt. Express*

Brewin et al. (2012b) *Deep Sea Res. II*

Brotas et al. (2013) *Rem. Sens. Environ.*

Brewin et al. (2014b) *J Geophys. Res.*

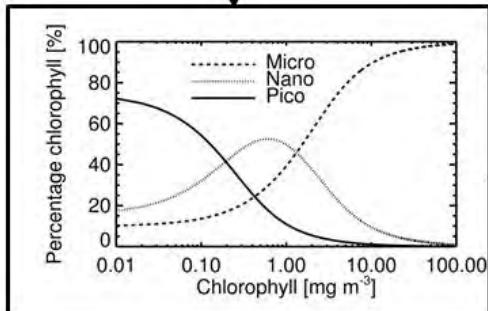
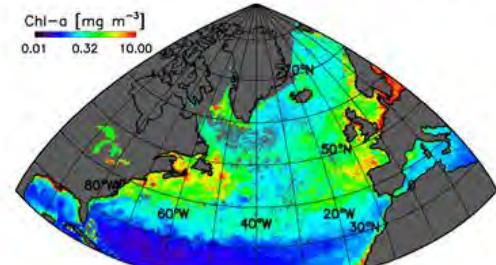
Lin et al. (2014) *Mar. Pollut. Bull.*

Brewin et al. (2015) *Rem. Sens. Environ.*

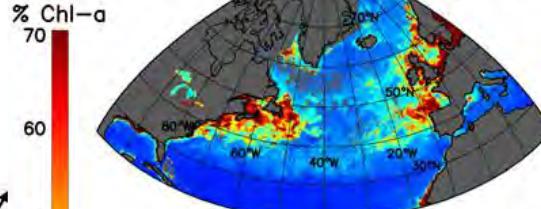
Brewin et al. (2017) *Frontiers in Marine science*

Phytoplankton Group Chlorophyll

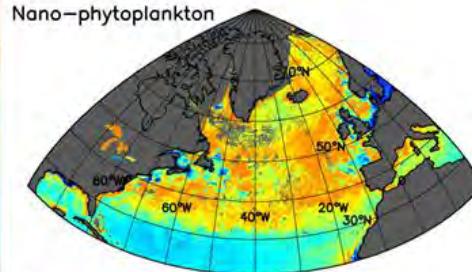
INPUT: Satellite total chlorophyll



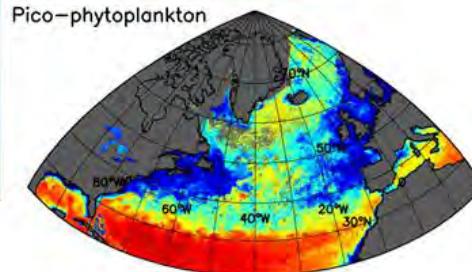
Micro-phytoplankton
MODIS AQUA
May 2011



Nano-phytoplankton

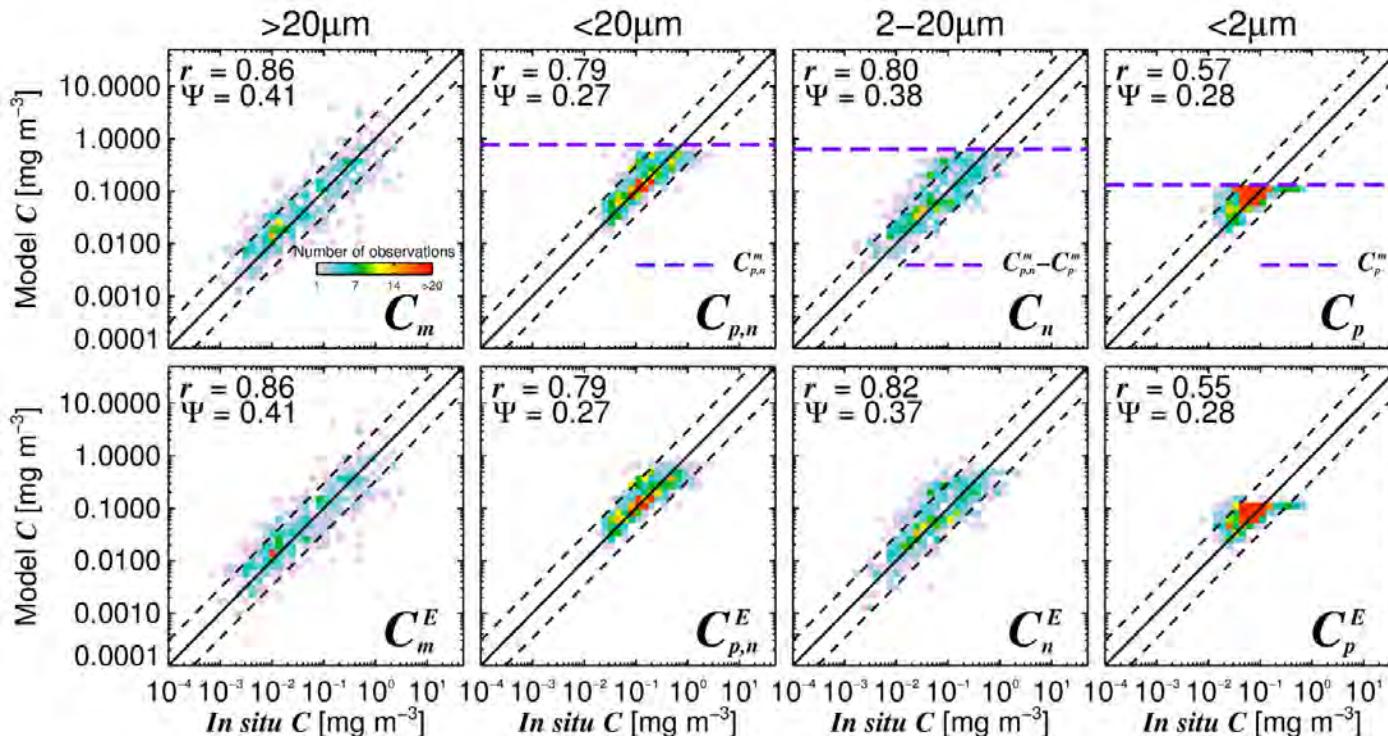


Pico-phytoplankton



Brewin et al. (2010) *Ecol. Model.*

Validation



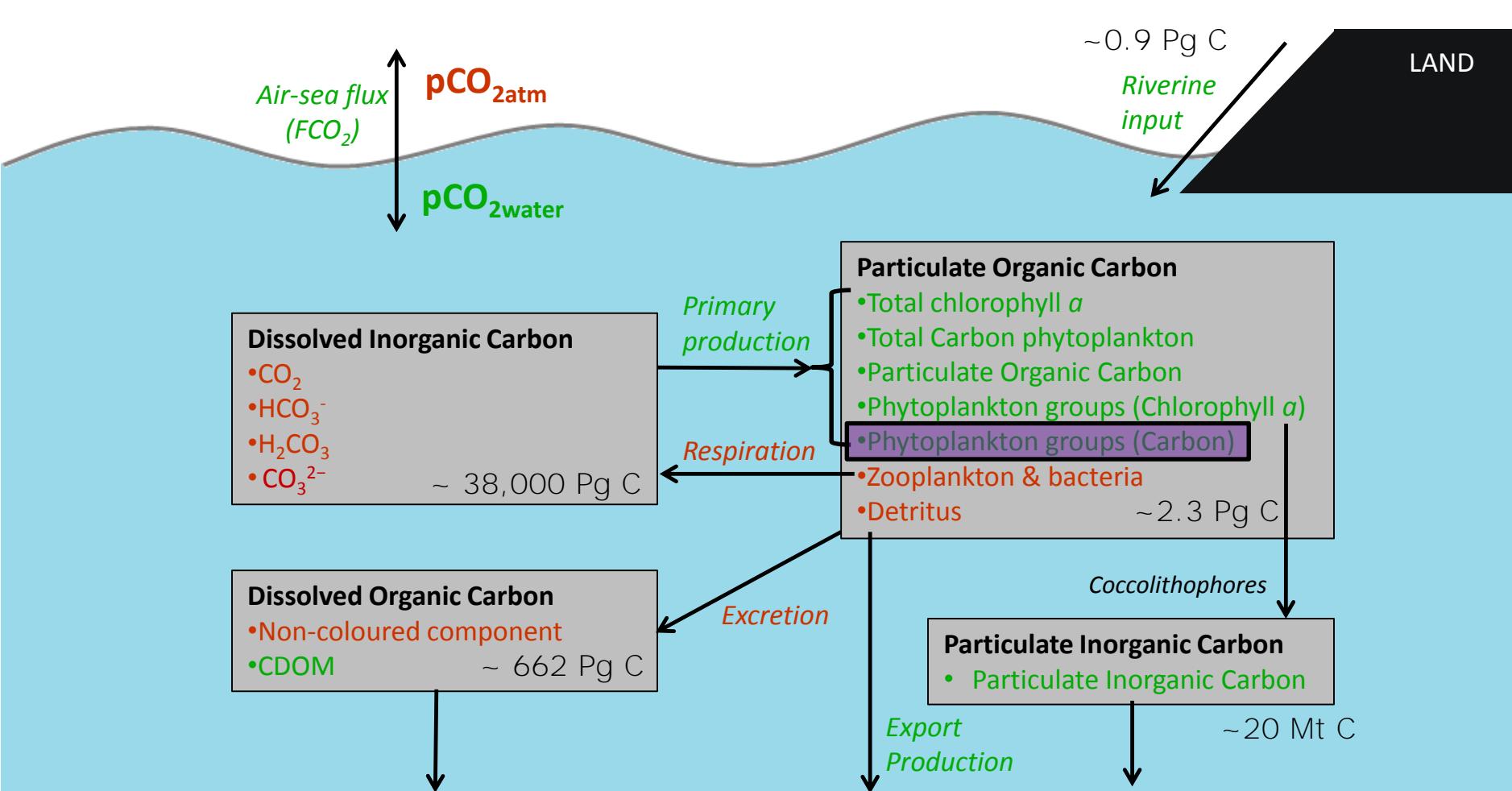
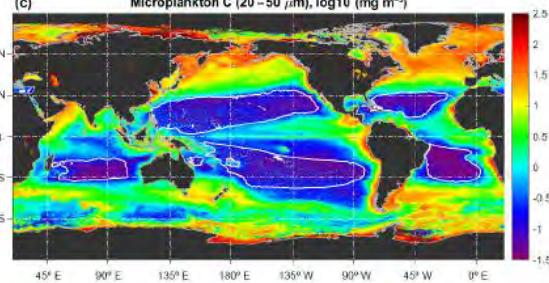
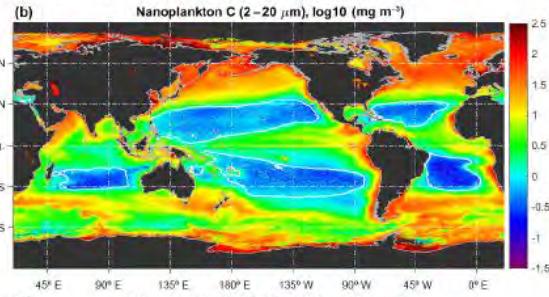
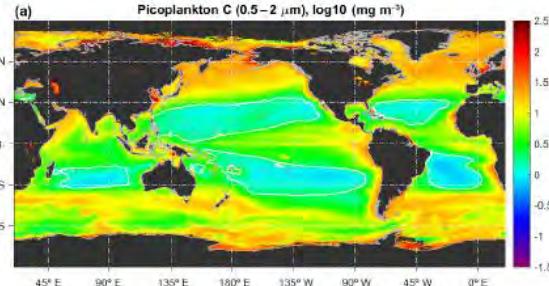


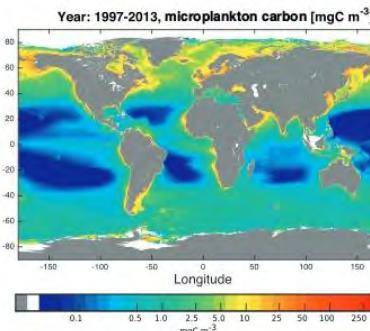
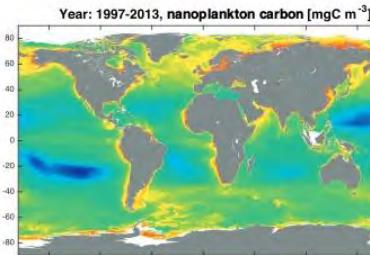
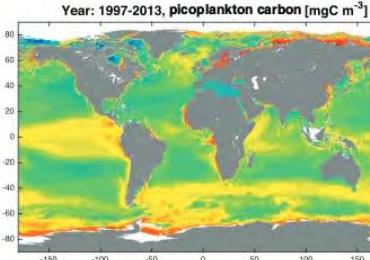
Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Phytoplankton Group Carbon



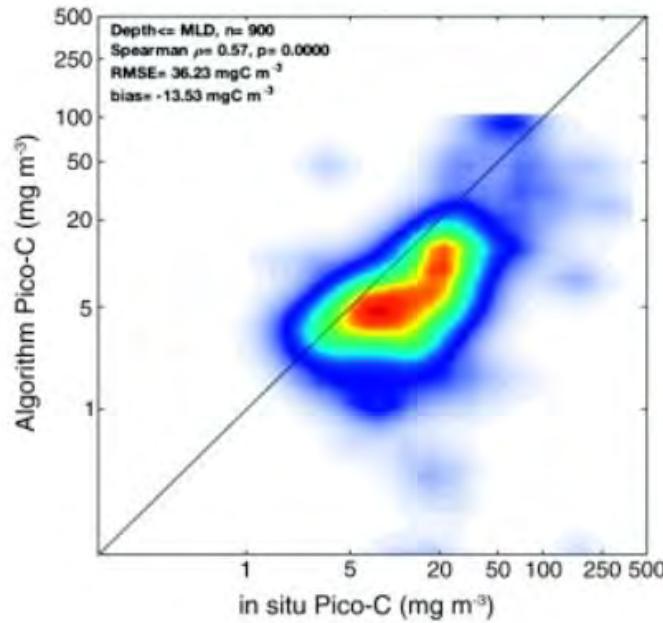
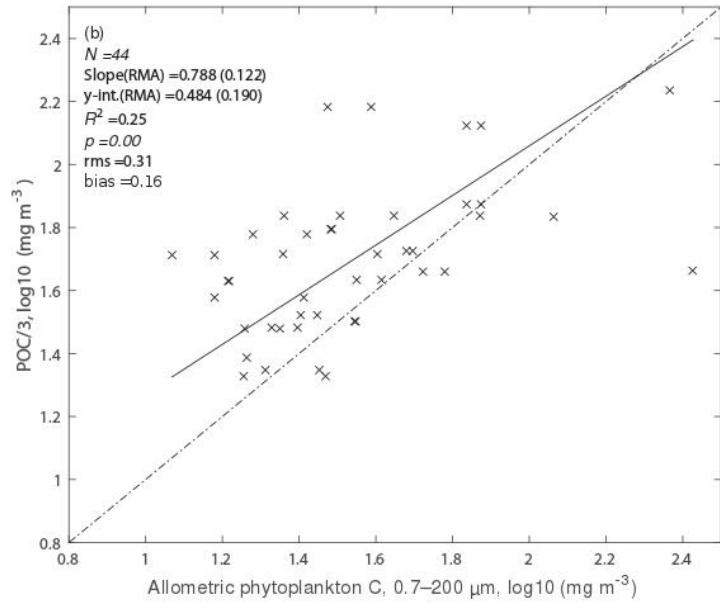
Backscattering-based
Kostadinov et al. (2016) Ocean Sciences

Allometric scaling – based approaches



Absorption-based
Roy et al. (2017) Rem. Sens. Environ.

Validation



Backscattering-based
Kostadinov et al. (2016) Ocean Sciences

Absorption-based
Roy et al. (2017) Rem. Sens. Environ.

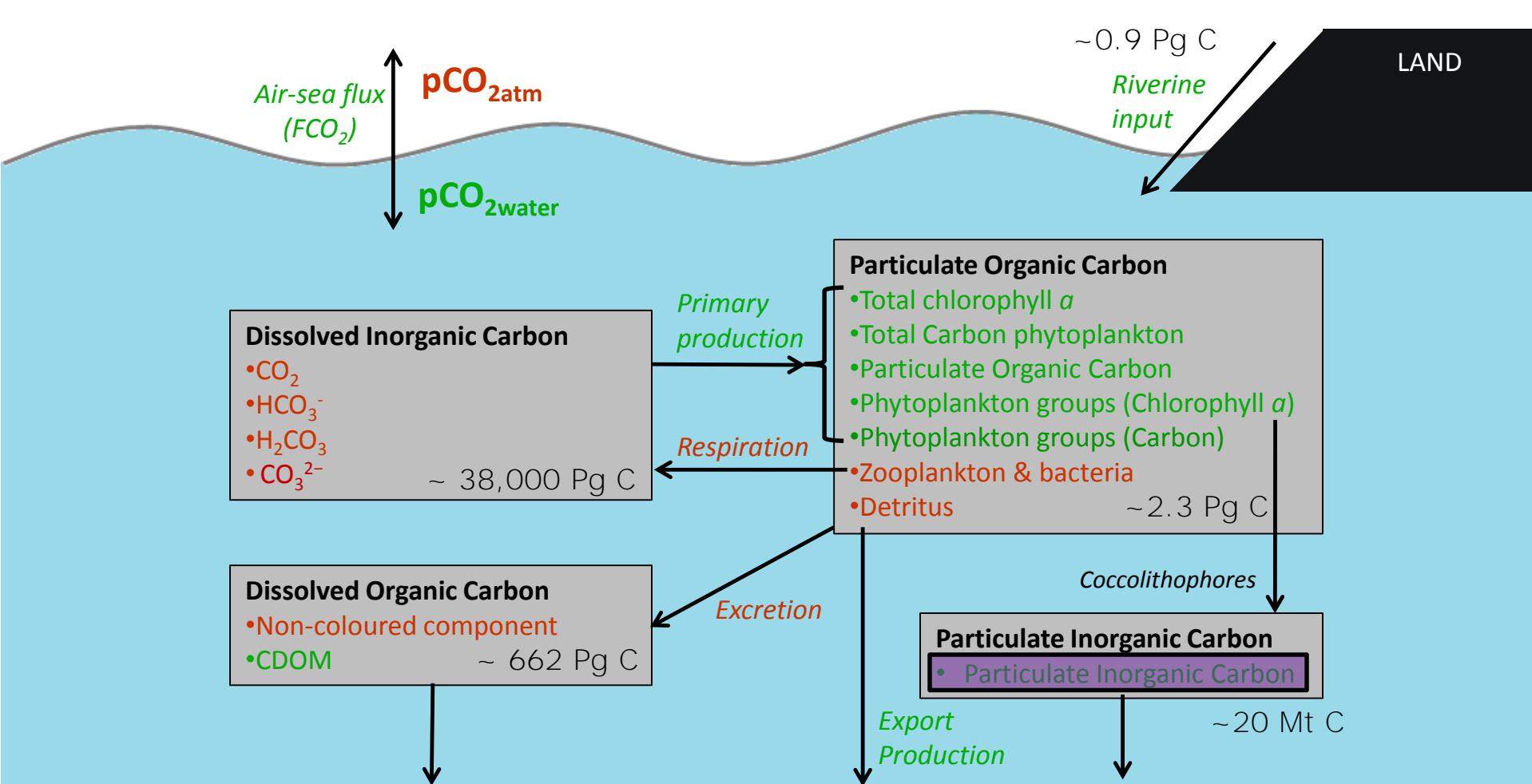
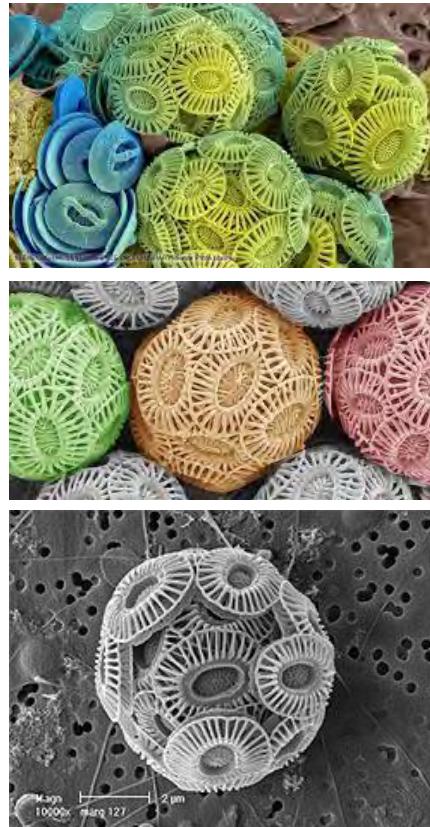
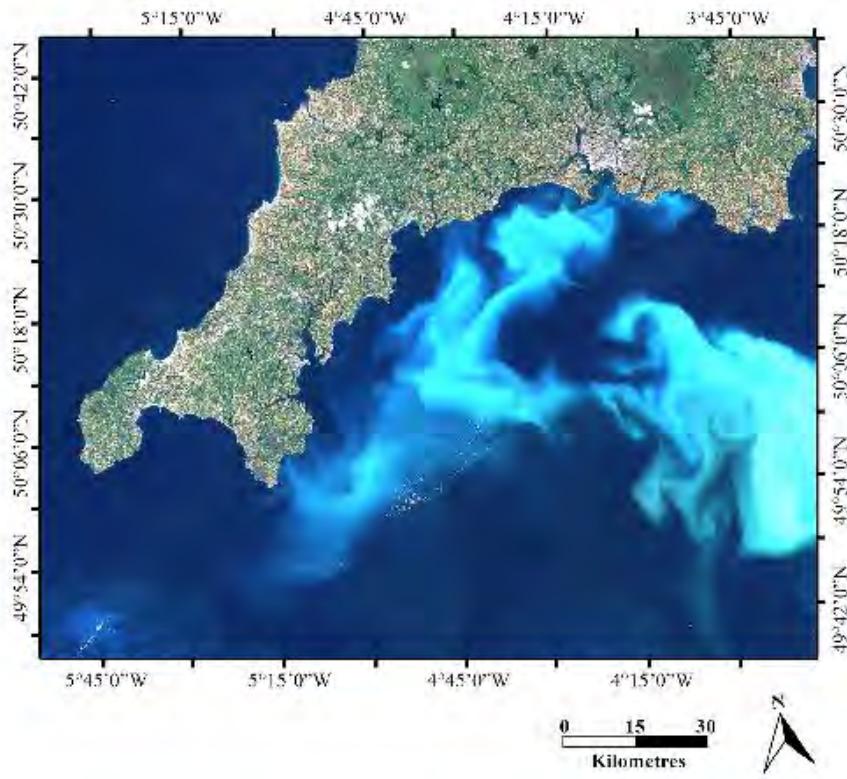
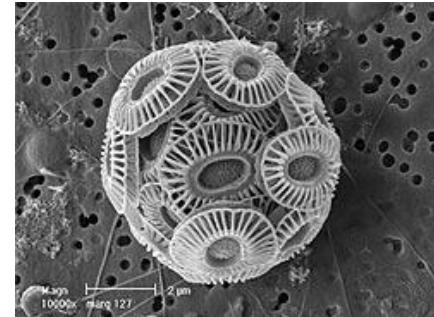
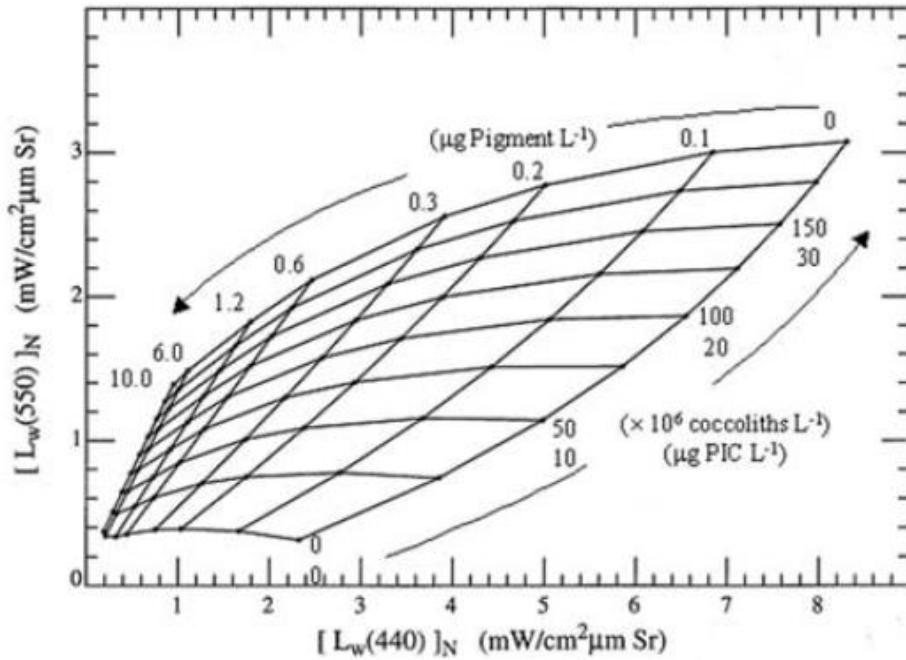


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Particle Inorganic Carbon

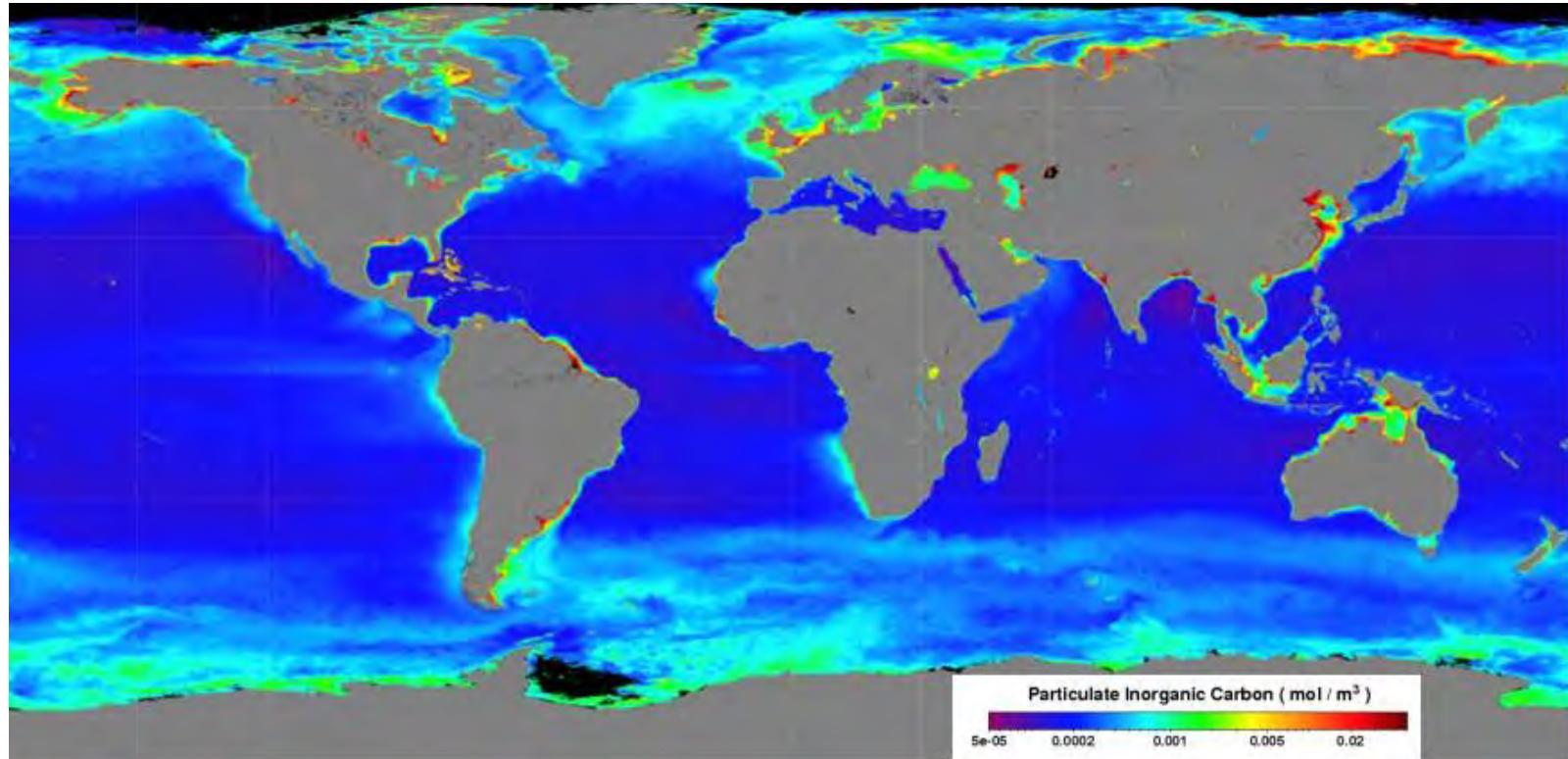


Particle Inorganic Carbon



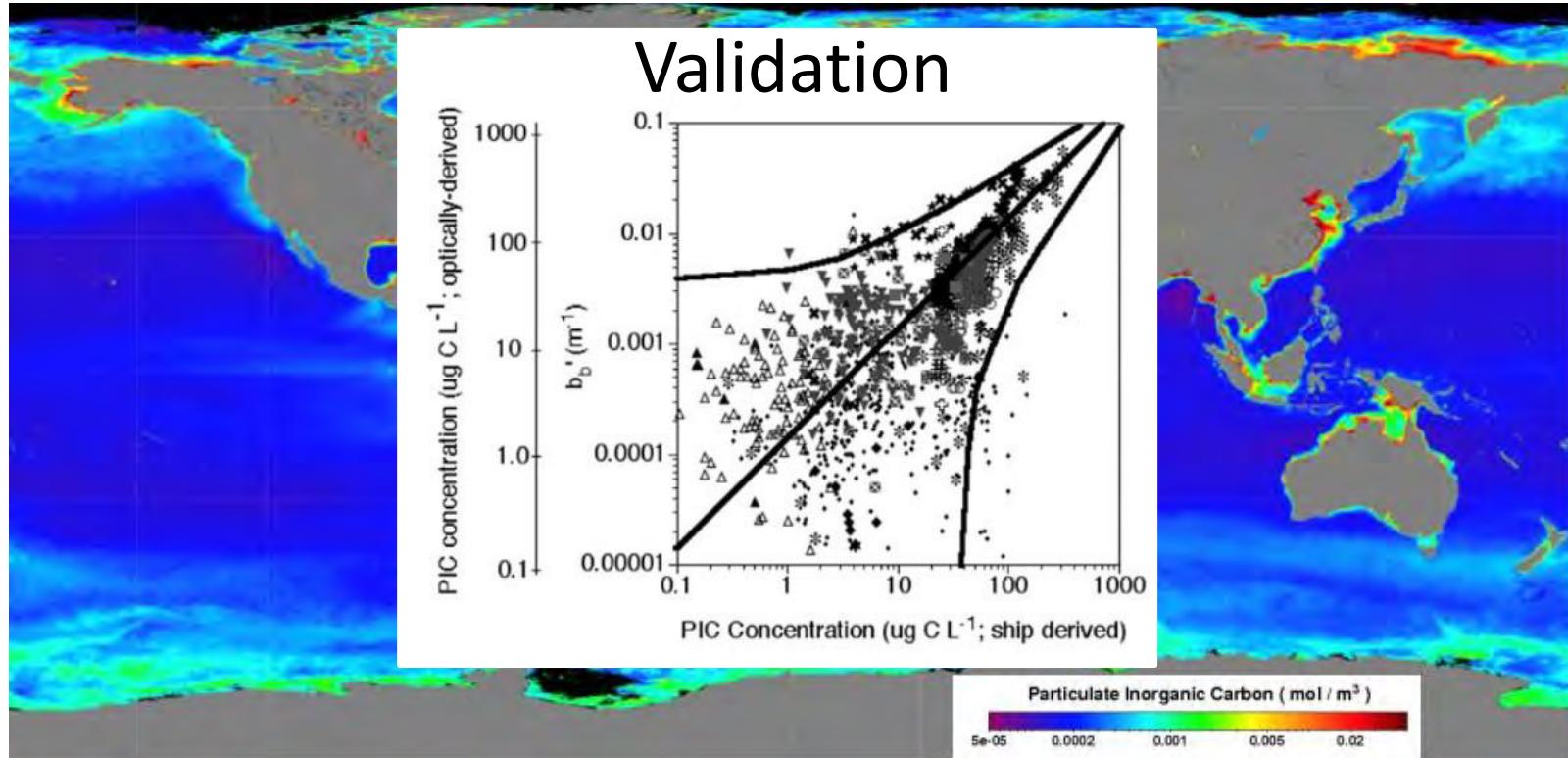
Balch et al. (2005) *Journal of Geophysical Research*
Gordon et al. (2001) *Geophysical Research Letters*

Particle Inorganic Carbon



Balch et al. (2005) *Journal of Geophysical Research*
Gordon et al. (2001) *Geophysical Research Letters*

Particle Inorganic Carbon



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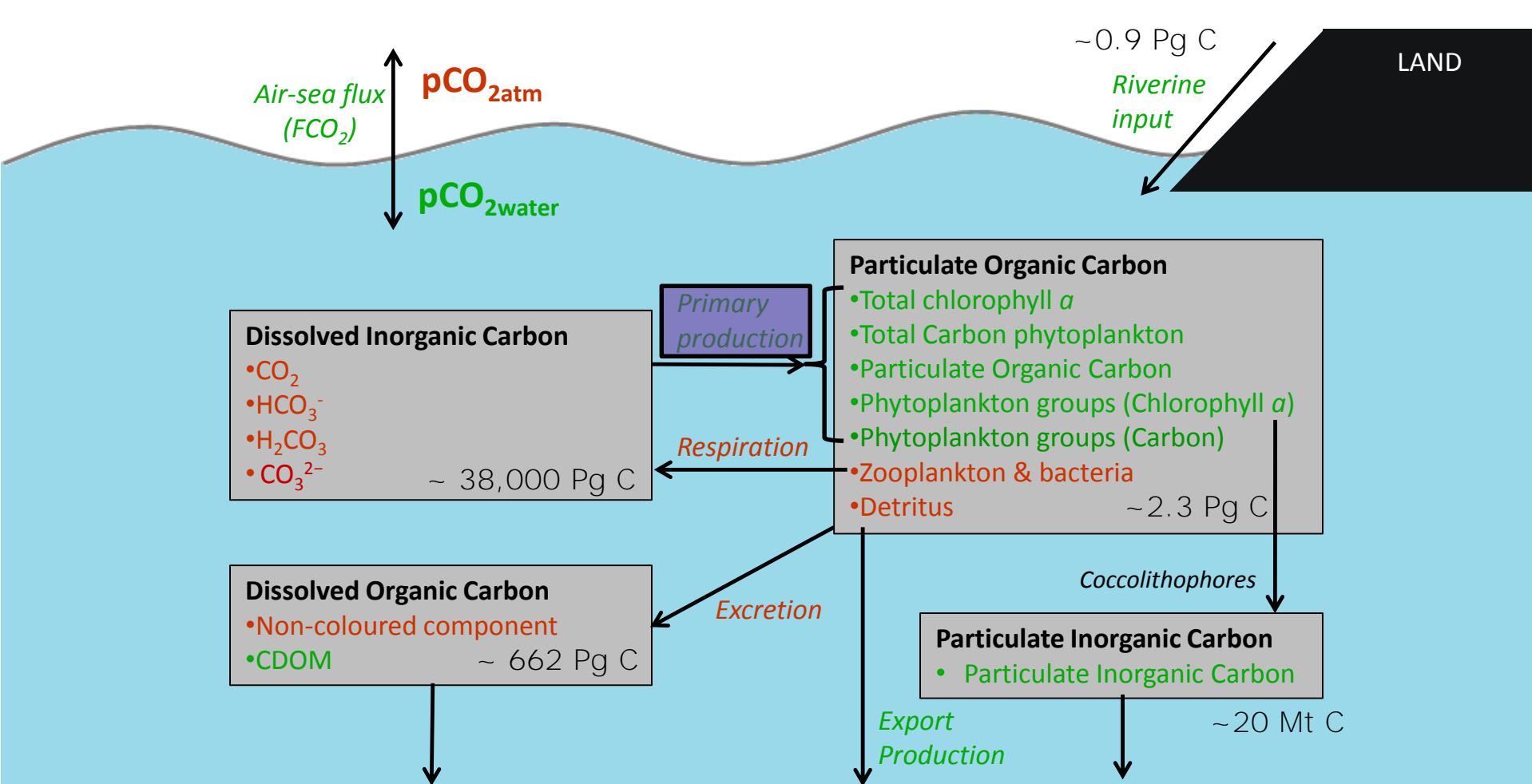
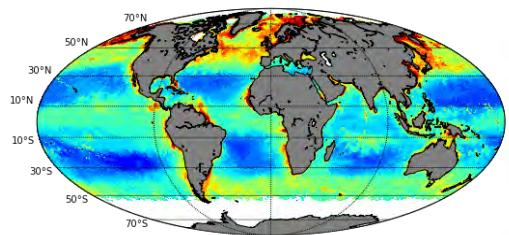


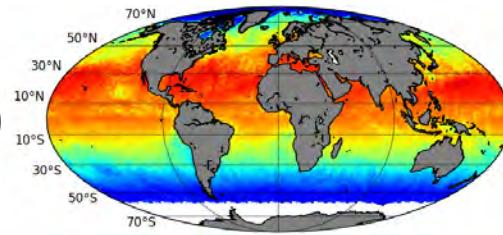
Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Primary production

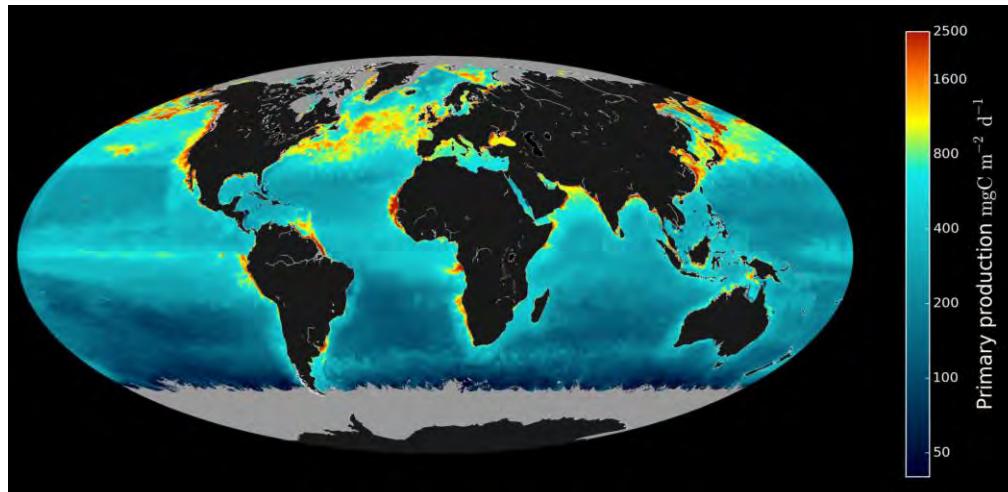
ESA OC-CCI CHL-A



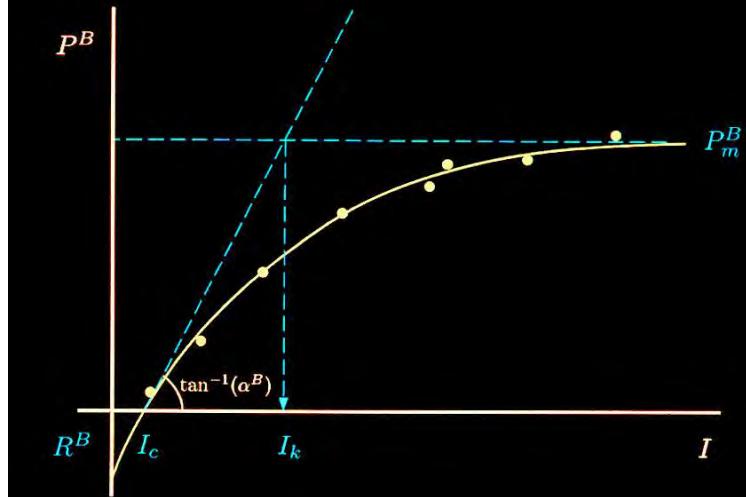
ESA PAR PRODUCT (NEW)



ESA INTEGRATED PRIMARY PRODUCTION PRODUCT



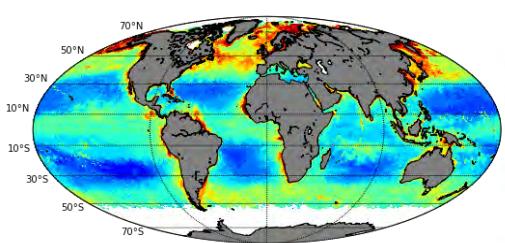
PHOTOSYNTHESIS-IRRADIANCE CURVE



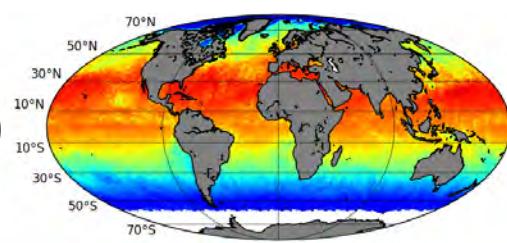
Bouman et al. (2018) ESSD

Primary production

ESA OC-CCI CHL-A

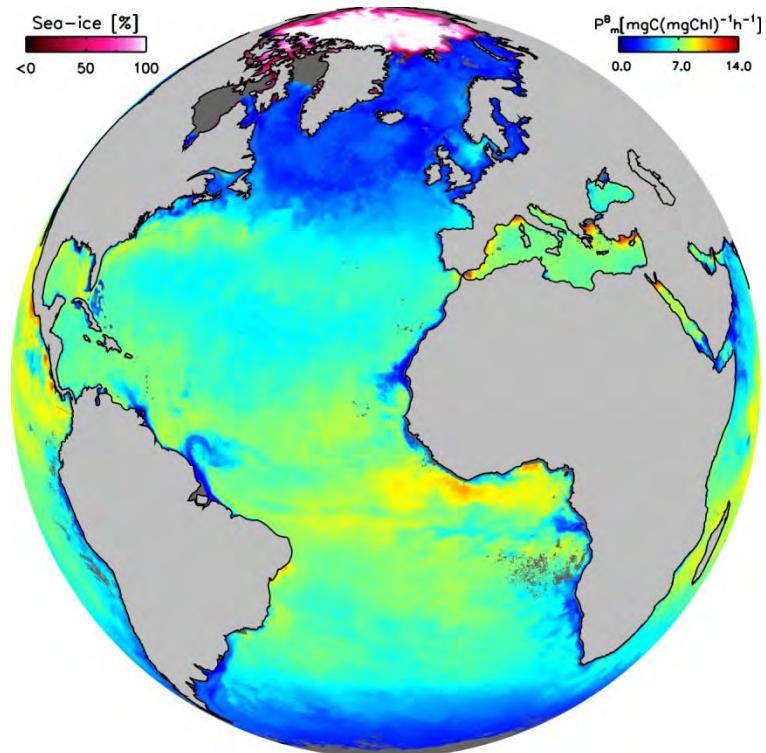


ESA PAR PRODUCT (NEW)

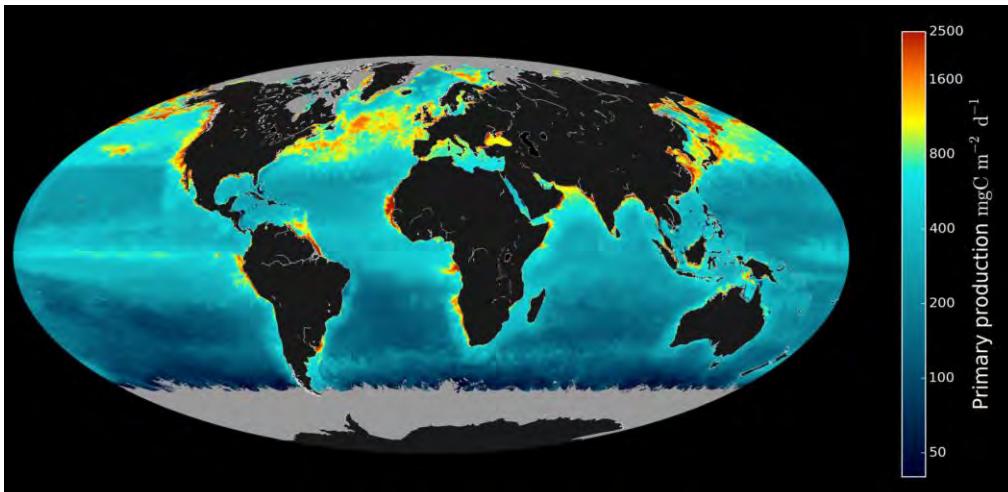


Sea-ice [%]
0 < 50 100

P_m^B [mgC(mgChl) $^{-1}$ h $^{-1}$]
0.0 7.0 14.0

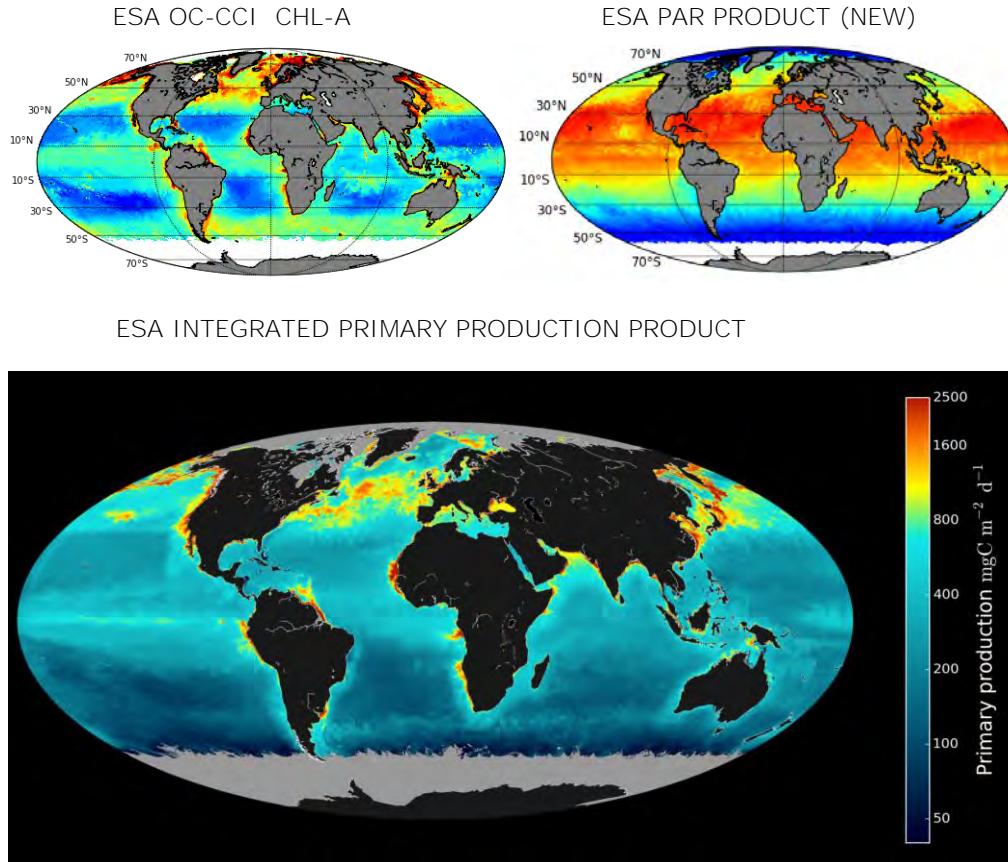


ESA INTEGRATED PRIMARY PRODUCTION PRODUCT

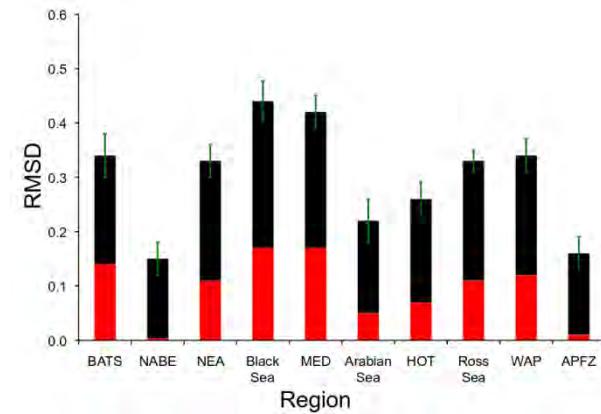


Saux Picart et al. (2014) RSE

Primary production



Validation



*NASA PPARR Series
Campbell et al. (1996) GBC
Carr et al. (2006) DSRI
Friedrichs et al. (2009) JMS
Saba et al. (2011) BGS
Lee et al. (2015) JGR*

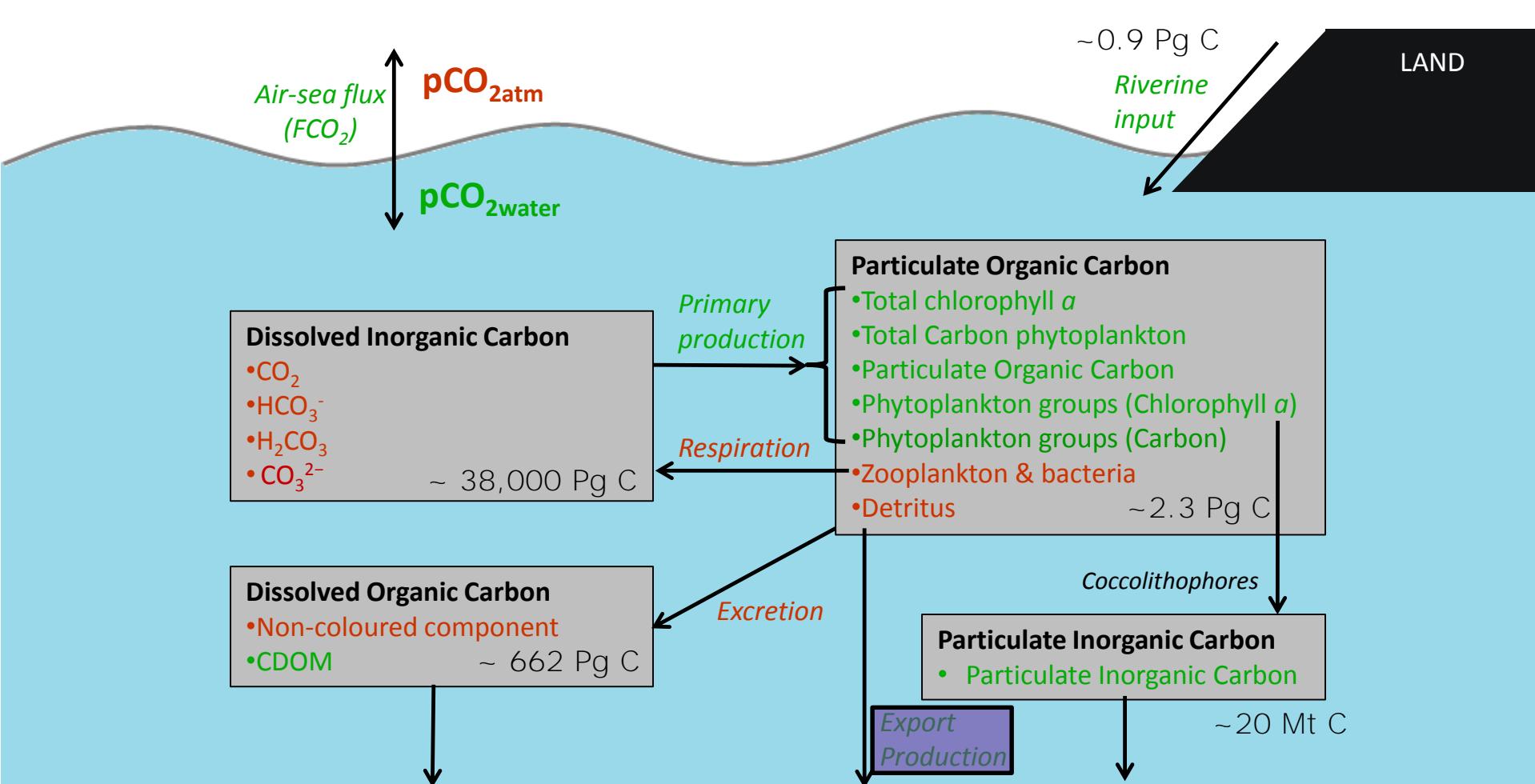
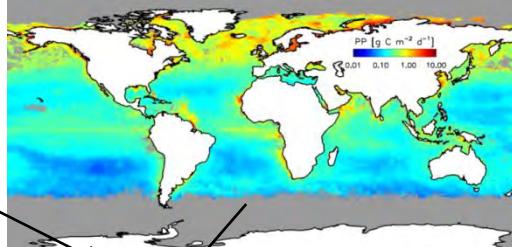
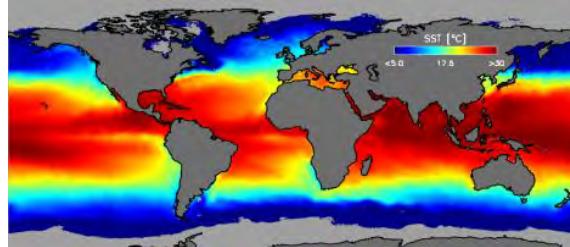
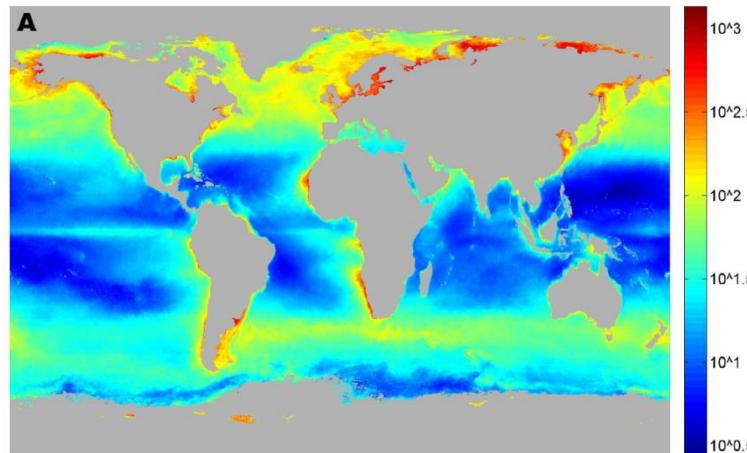


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

Export production



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



Laws et al. (2011) Limnology & Oceanography: Methods

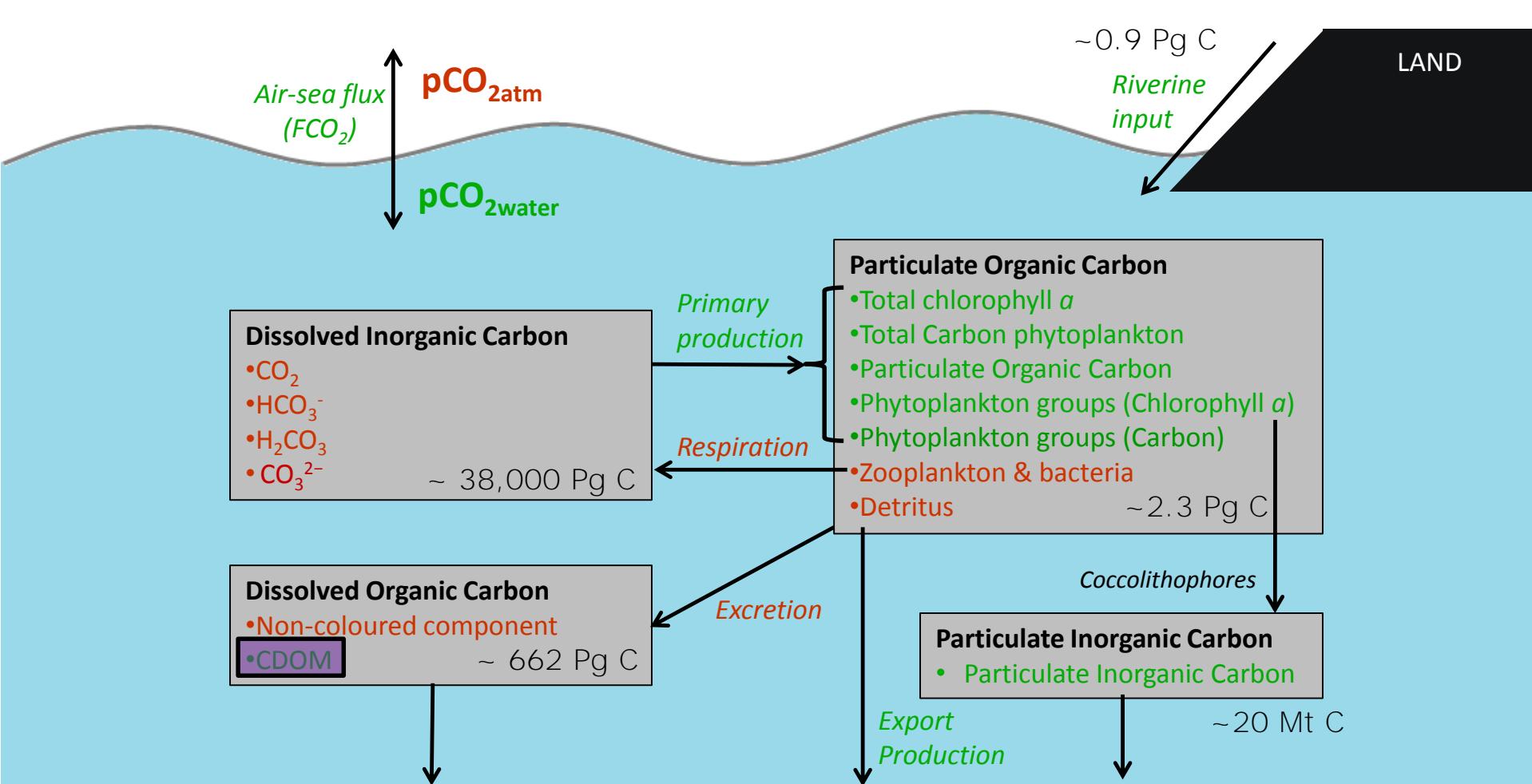
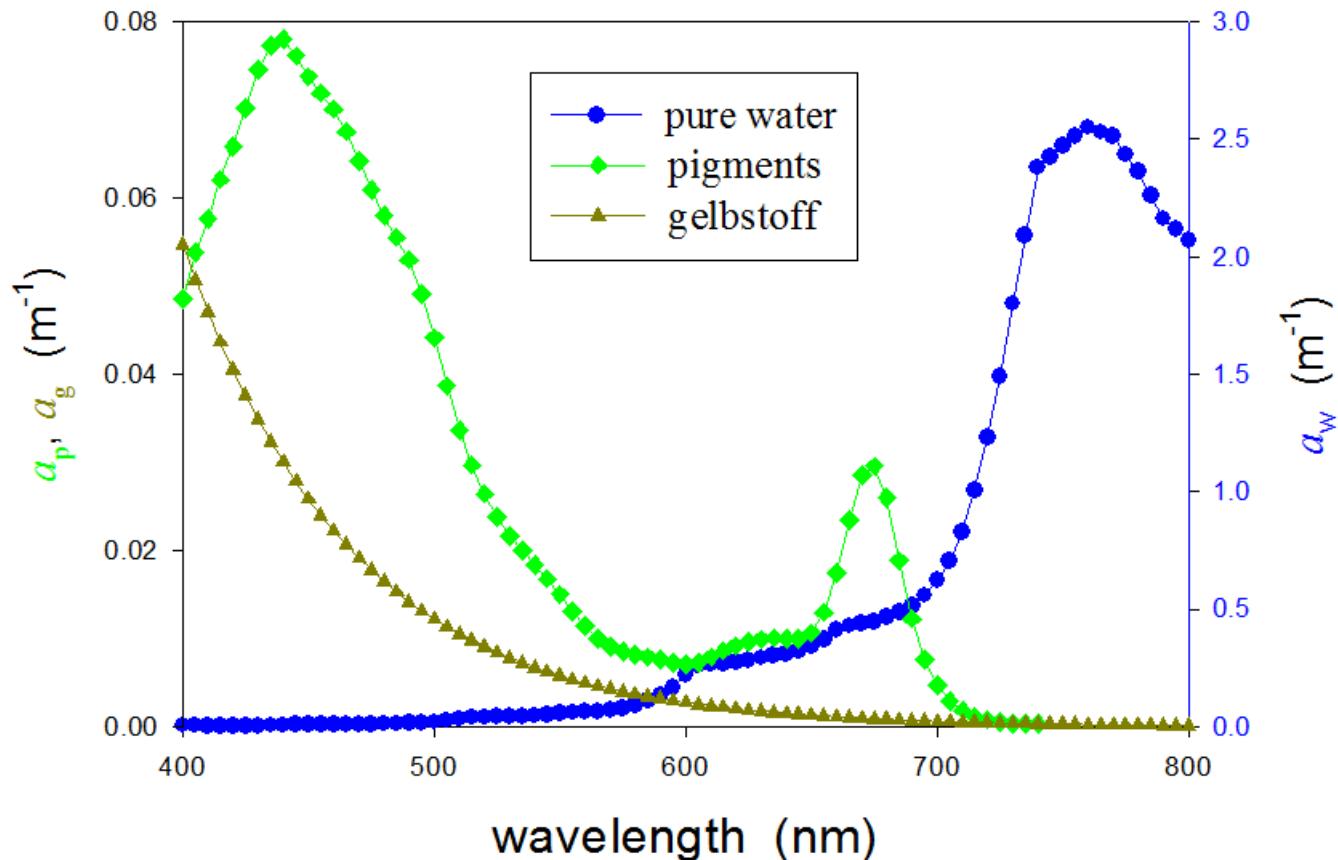
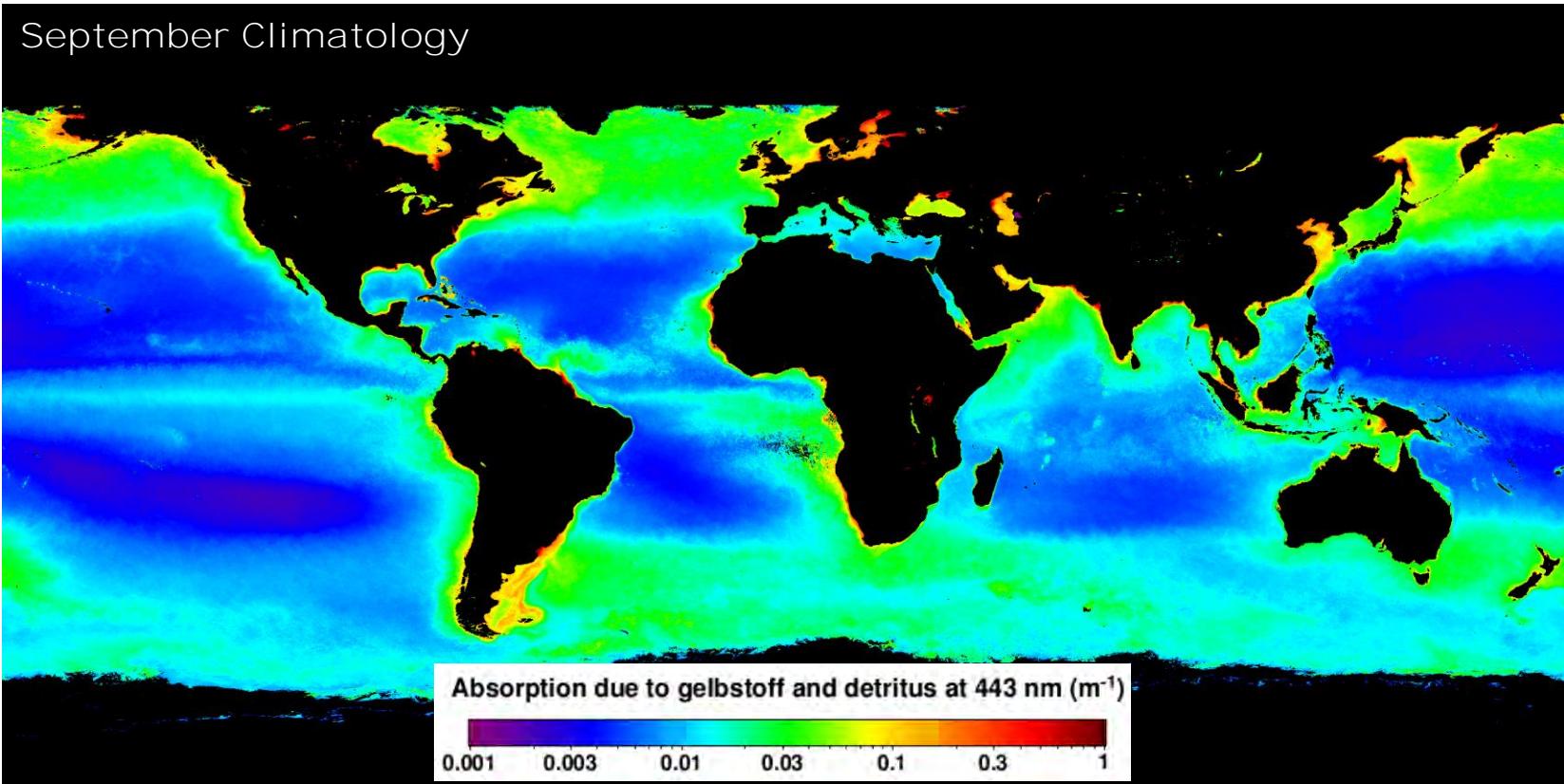


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

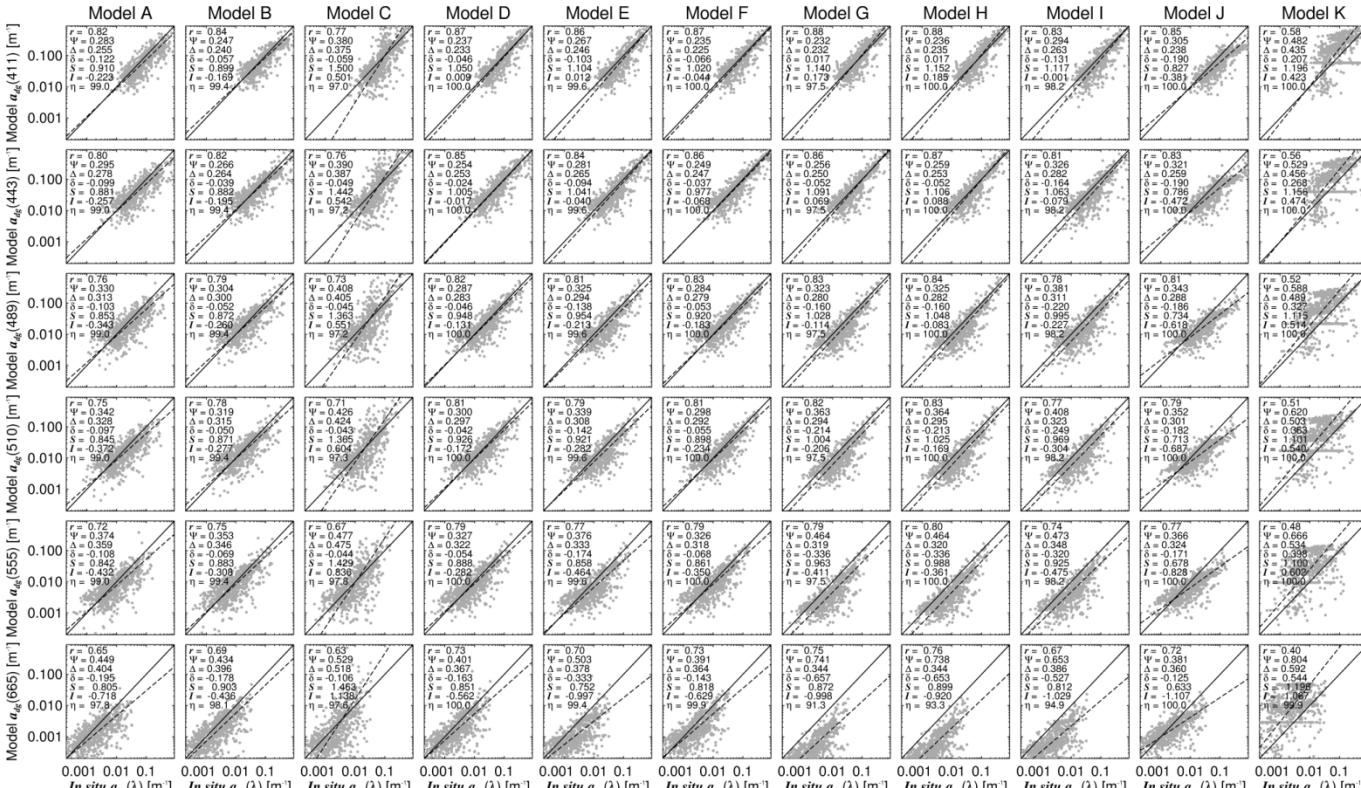
Coloured Dissolved Organic Matter



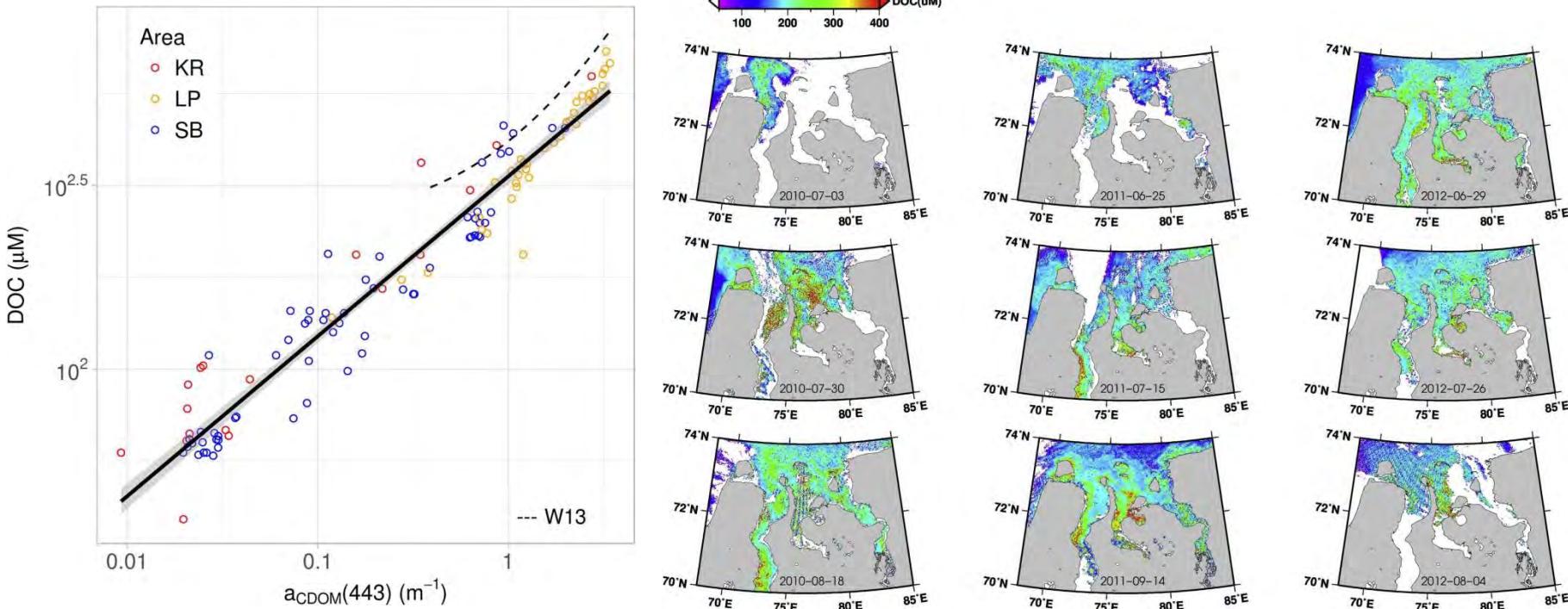
Coloured Dissolved Organic Matter



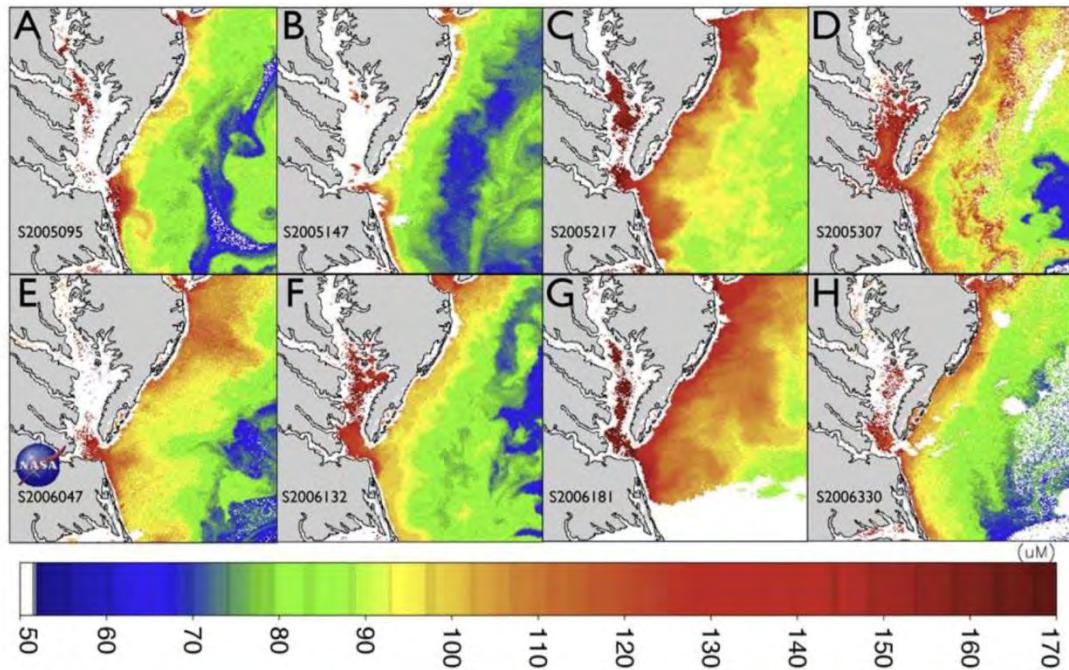
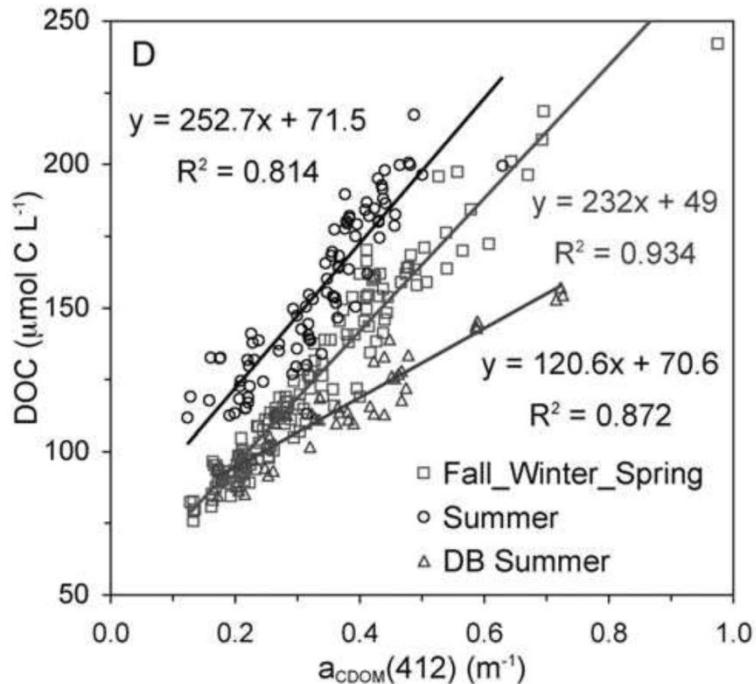
Validation

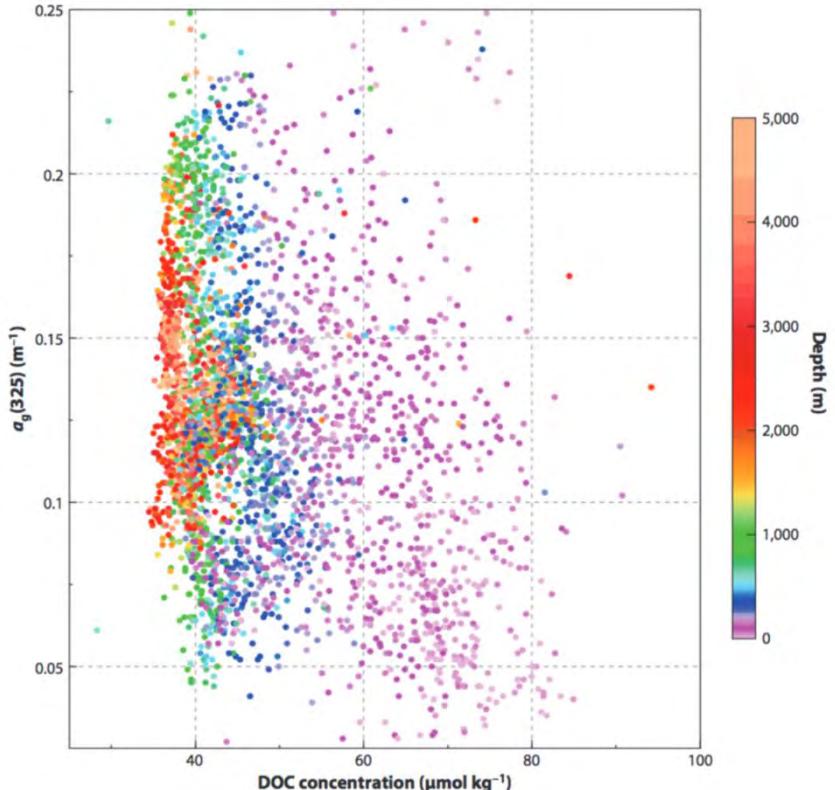


DOC and CDOM in Arctic



DOC and CDOM in Coastal waters





DOC and CDOM in open ocean

“There is a complete lack of relationship between open ocean observations of CDOM abundance and DOC concentrations”

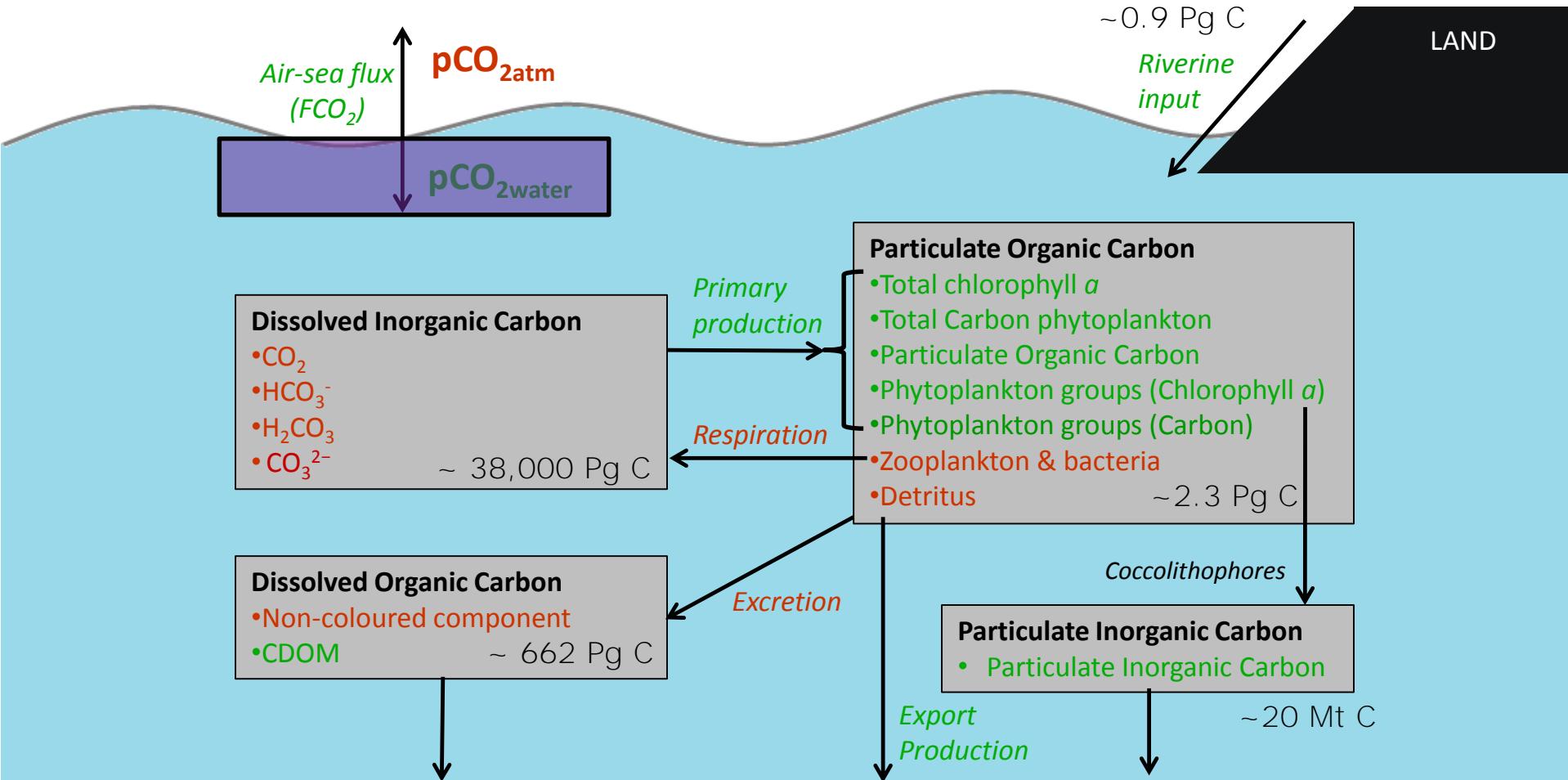


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

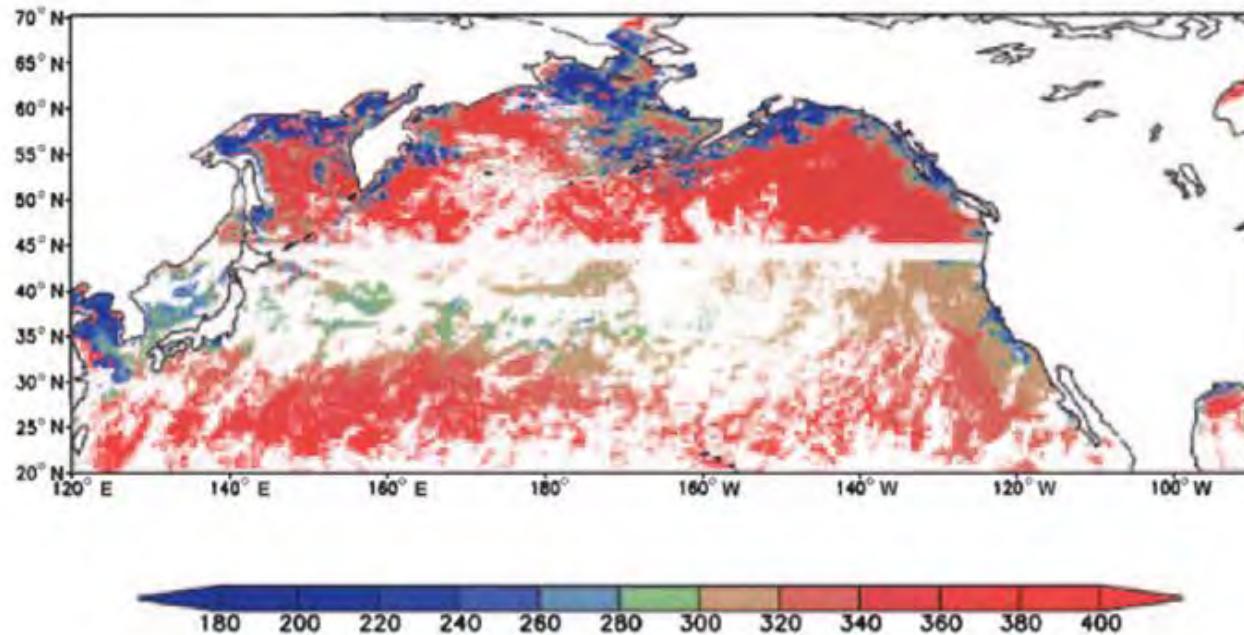


Figure 4. The basin-scale pCO₂ field of the North Pacific in May 1997 obtained from the ADEOS/OCTS monthly-average SST and monthly-maximum Chla fields by using the multiple regression equations.

$$p\text{CO}_2 = A\text{T} + B\text{T}^2 + C\text{Chla} + D\text{Chla}^2 + E$$

Ono et al. (2004) IJRS

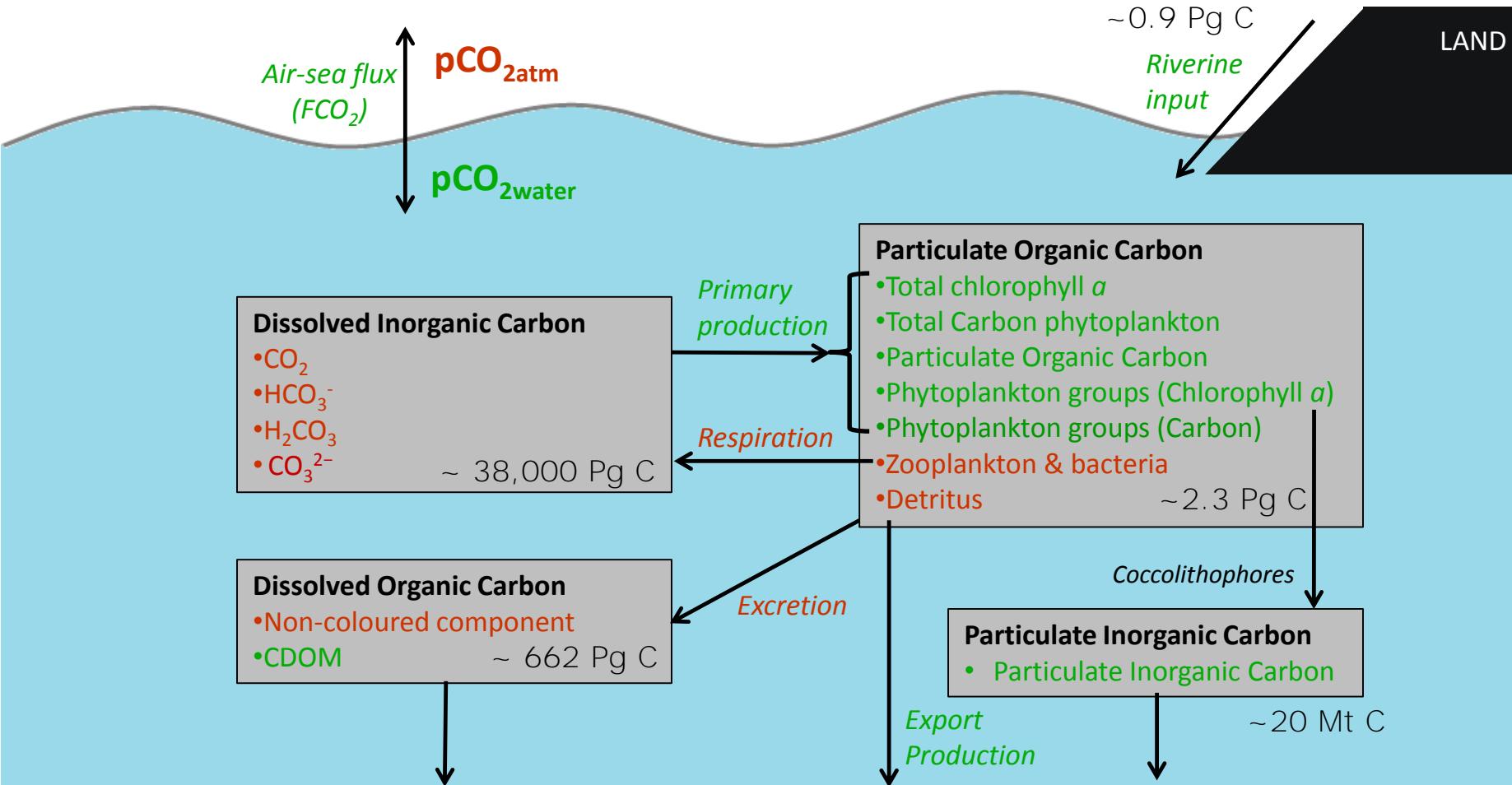


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

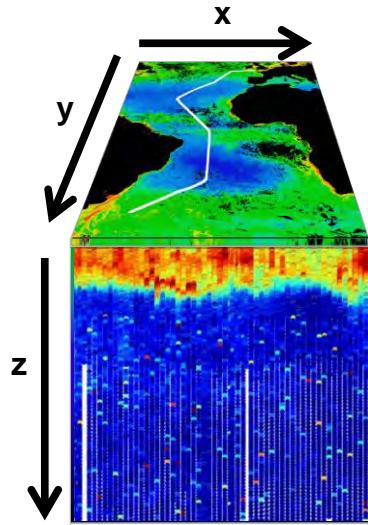
Autonomous Observations



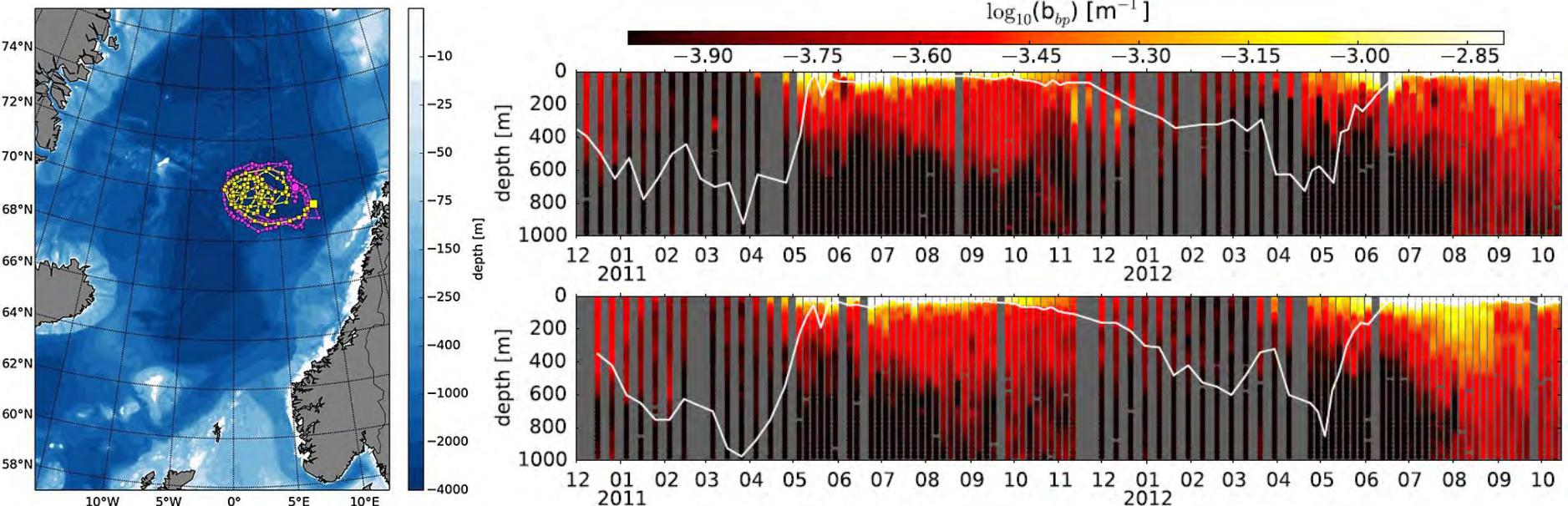
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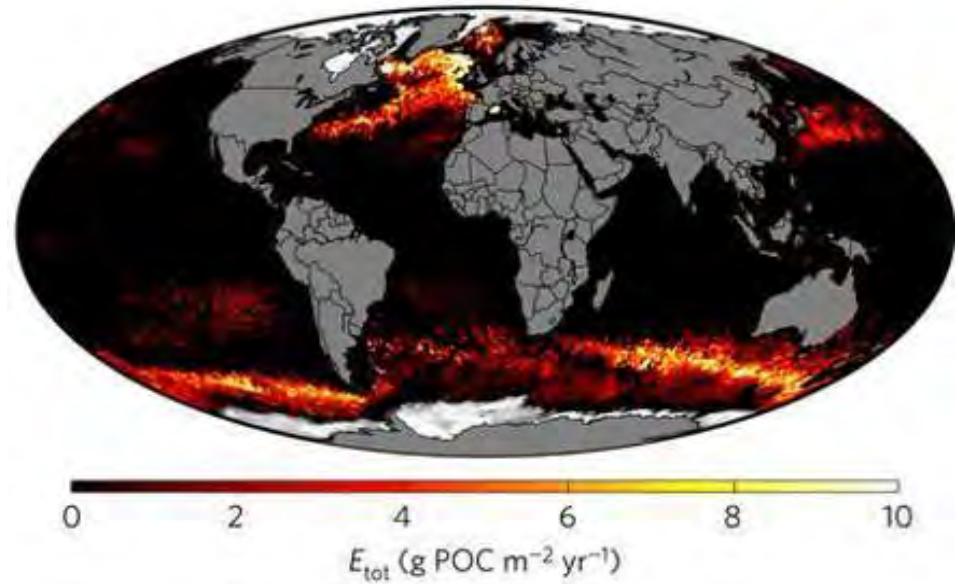
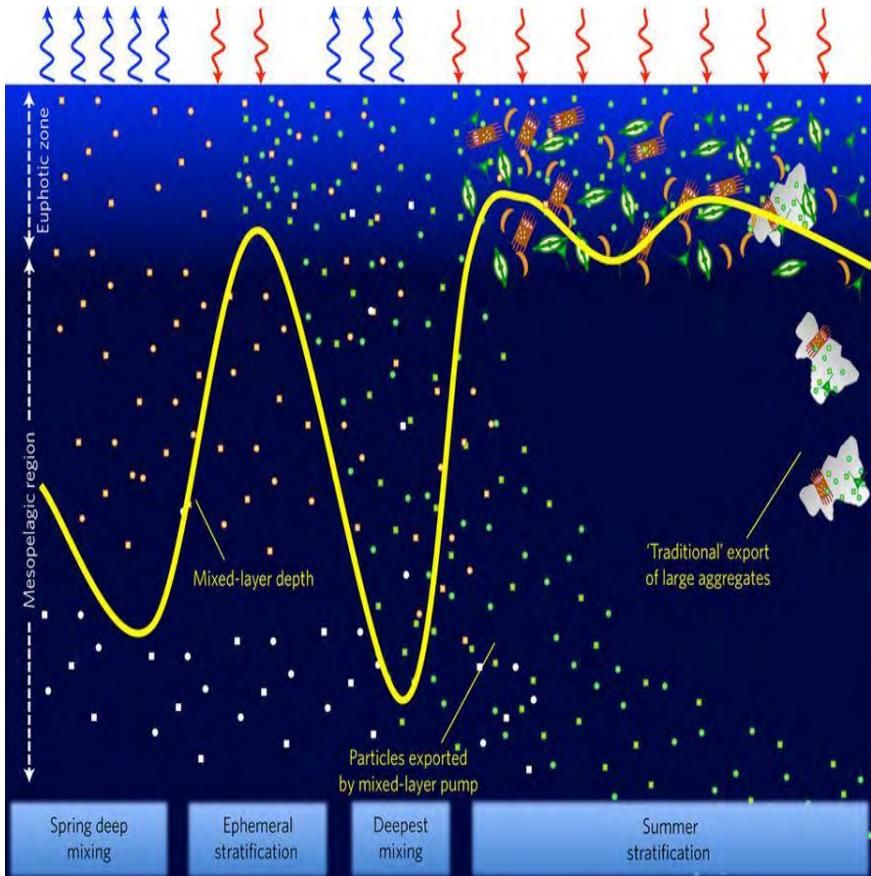


Autonomous Observations



Dall'Olmo and Mork (2014) GRL

Autonomous Observations



Mixed-layer pump supplies between 0.1 to 0.5 Pg C yr^{-1} to the mesopelagic

Dall'Olmo et al. (2016) Nature Geoscience

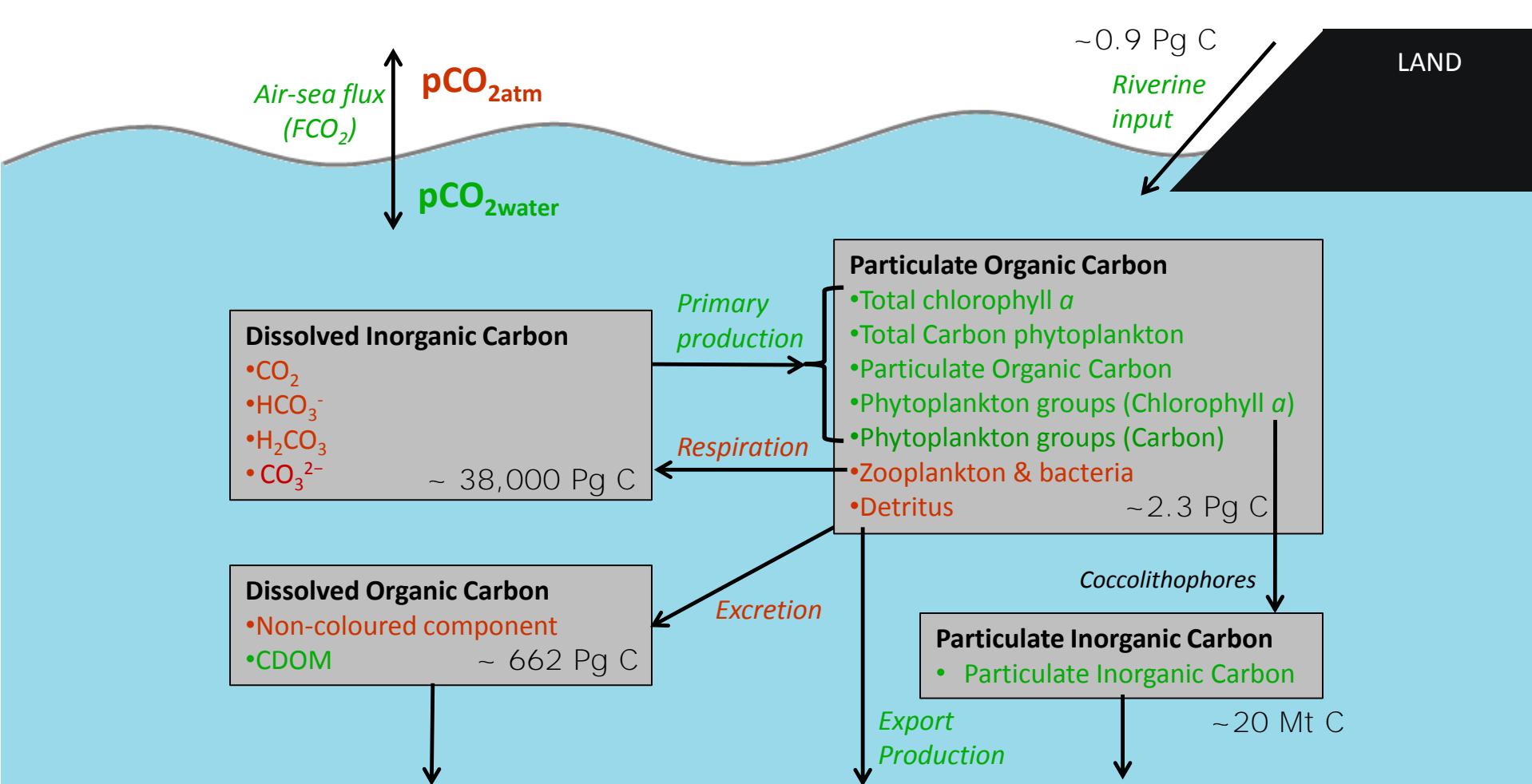
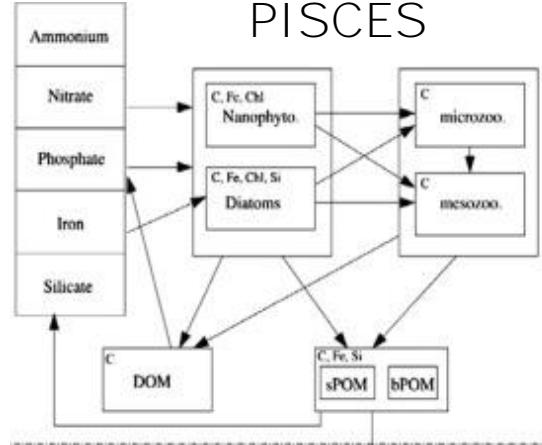
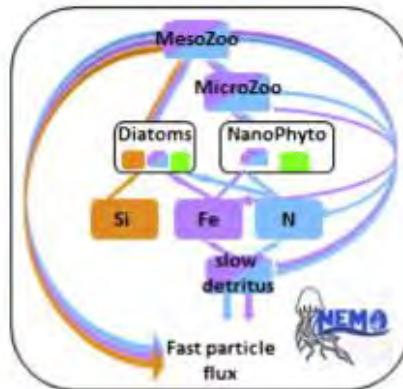


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report

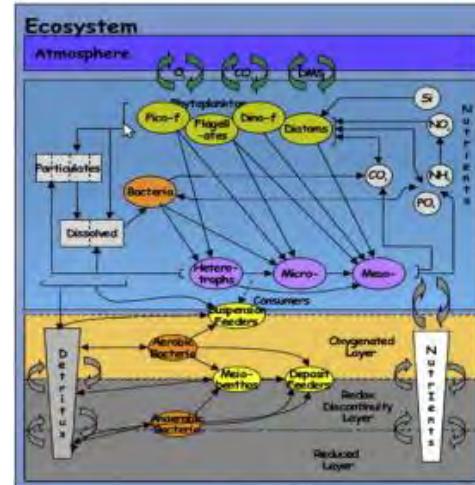
Data assimilation



MEDUSA

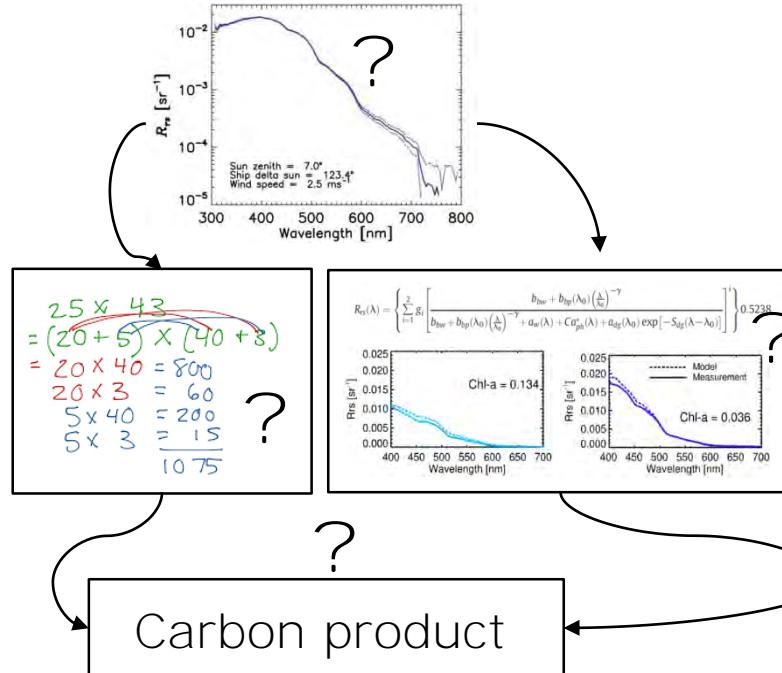


ERSEM

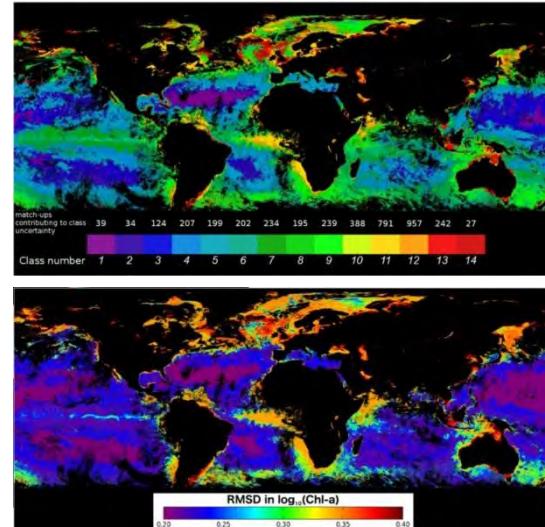


Uncertainties in satellite ocean colour products

Model-based error (error propagation)



Errors based on validation



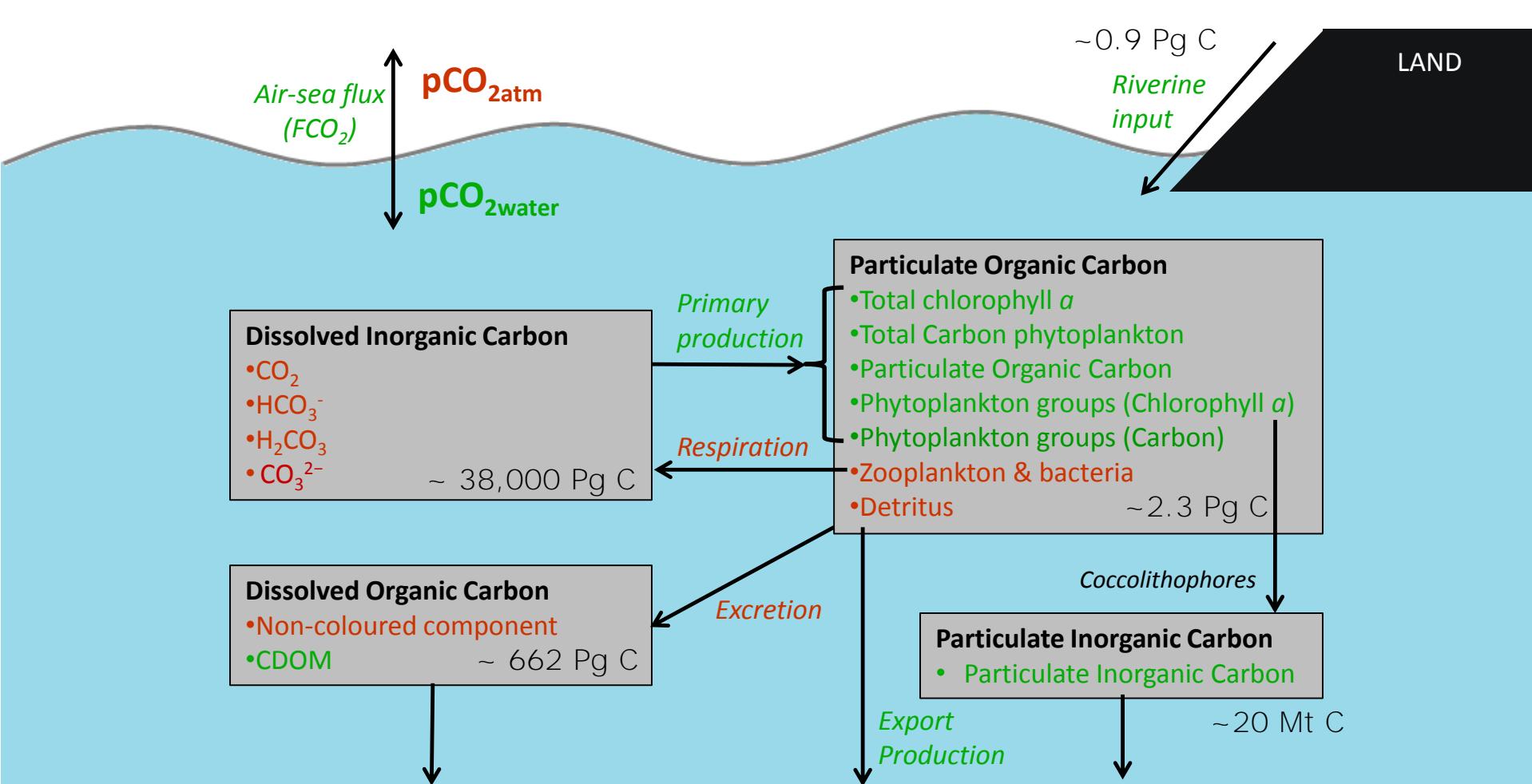


Figure courtesy of C.S. Rousseaux & W.W. Gregg
From CEOS Carbon from Space Report



Ocean Colour Bibliography

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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/>



http://ceos.org/document_management/Publications/WGClimate_CEOS-Strategy-for-Carbon-Observations-from-Space_Apr2014.pdf

Further reading



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Global Carbon Budget 2017

Corinne Le Quéré¹, Robbie M. Andrew², Pierre Friedlingstein³, Stephen Sitch⁴, Julia Pongratz⁵,
Andrew C. Manning⁶, Jan Ivar Korsbakken², Glen P. Peters², Josep G. Canadell⁷, Robert B. Jackson⁸,
Thomas A. Boden⁹, Pieter P. Tans¹⁰, Oliver D. Andrews¹, Vivek K. Arora¹¹, Dorothee C. E. Bakker⁶,
Leticia Barbero^{12,13}, Meike Becker^{14,15}, Richard A. Betts^{16,4}, Laurent Bopp¹⁷, Frédéric Chevallier¹⁸,
Louise P. Chini¹⁹, Philippe Ciais¹⁸, Catherine E. Cosca²⁰, Jessica Cross²⁰, Kim Currie²¹,
Thomas Gasser²², Ian Harris²³, Judith Hauck²⁴, Vanessa Haverd²⁵, Richard A. Houghton²⁶,
Christopher W. Hunt²⁷, George Hurtt¹⁹, Tatiana Ilyina⁵, Atul K. Jain²⁸, Etsushi Kato²⁹,
Markus Kautz³⁰, Ralph F. Keeling³¹, Kees Klein Goldewijk^{32,33}, Arne Körtzinger³⁴,
Peter Landschützer⁵, Nathalie Lefèvre³⁵, Andrew Lenton^{36,37}, Sebastian Lienert^{38,39}, Ivan Lima⁴⁰,
Danica Lombardozzi⁴¹, Nicolas Metzl³⁵, Frank Millero⁴², Pedro M. S. Monteiro⁴³, David R. Munro⁴⁴,
Julia E. M. S. Nabel⁵, Shin-ichiro Nakaoka⁴⁵, Yukihiro Nojiri⁴⁵, X. Antonio Padin⁴⁶, Anna Peregon¹⁸,
Benjamin Pfeil^{14,15}, Denis Pierrot^{12,13}, Benjamin Poulter^{47,48}, Gregor Rehder⁴⁹, Janet Reimer⁵⁰,
Christian Rödenbeck⁵¹, Jörg Schwinger⁵², Roland Séférian⁵³, Ingunn Skjelvan⁵²,
Benjamin D. Stocker⁵⁴, Hanqin Tian⁵⁵, Bronte Tilbrook^{36,37}, Francesco N. Tubiello⁵⁶,
Ingrid T. van der Laan-Luijkx⁵⁷, Guido R. van der Werf⁵⁸, Steven van Heuven⁵⁹, Nicolas Viovy¹⁸,
Nicolas Vuichard¹⁸, Anthony P. Walker⁶⁰, Andrew J. Watson⁴, Andrew J. Wiltshire¹⁶, Sönke Zaehle⁵¹,
and Dan Zhu¹⁸