COCCOLITHOPHORES

Optical properties, ecology, and biogeochemistry

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Marie
Skłodowska-
Curie Actions

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SCIENCES
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Griet Neukermans

PhD in optical oceanography

MSc. Mathematics (VUB-Belgium)

MSc. Oceans & Lakes (VUB-Belgium)

Core expertise : development and application of remote and in situ optical sensing of marine particles

2008

PhD

Remote sensing and light scattering properties of suspended particles in European coastal waters

(PhD, ULCO-France, advisors: H. Loisel and K. Ruddick)

2012

Post doc 1

Optical detection of particle concentration, size, and composition in the Arctic Ocean

(Postdoc SIO UCSD-USA, advisors: D. Stramski and R. Reynolds)

2014

Postdoc 2

Impact of climate change on phytoplankton blooms on the Arctic Ocean's inflow shelves

(Banting Postdoctoral Fellow, ULaval-Canada, advisor: M. Babin)

Remote sensing of ocean colour and physical environment

+ Modeling the light scattering properties of coccolithophores (with G. Fournier)

2017

Postdoc 3

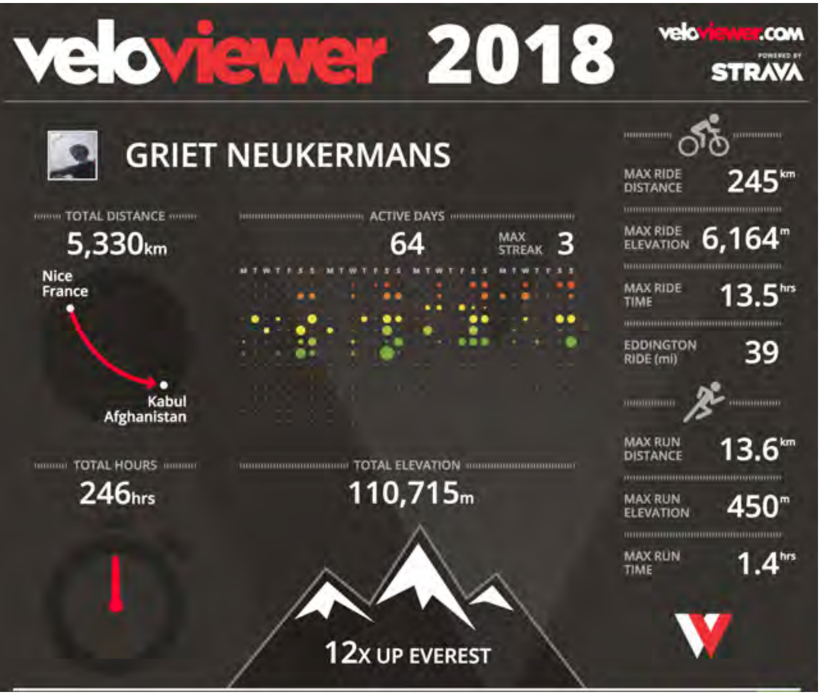
Poleward expansion of coccolithophore blooms and their role in sinking carbon in the Subarctic Ocean

(Marie Curie Postdoctoral Fellow, LOV-France, advisor: H. Claustre + co-advisors: G. Beaugrand and U. Riebesell)

Optical remote sensing + Ecological niche modeling + optical modeling + Biogeochemical-Argo floats

now

When not at work… I ride my bike!



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GRIET NEUKERMANS

TOTAL DISTANCE 5,330km

Nice France → Kabul Afghanistan

ACTIVE DAYS 64

MAX STREAK 3

TOTAL HOURS 246hrs

TOTAL ELEVATION 110,715m

12x UP EVEREST

MAX RIDE DISTANCE 245km

MAX RIDE ELEVATION 6,164m

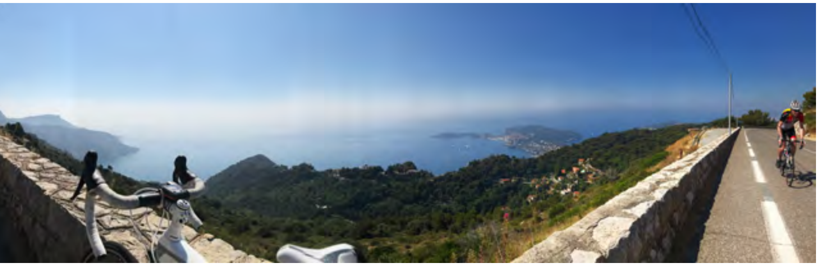
MAX RIDE TIME 13.5hrs

EDDINGTON RIDE (mi) 39

MAX RUN DISTANCE 13.6km

MAX RUN ELEVATION 450m

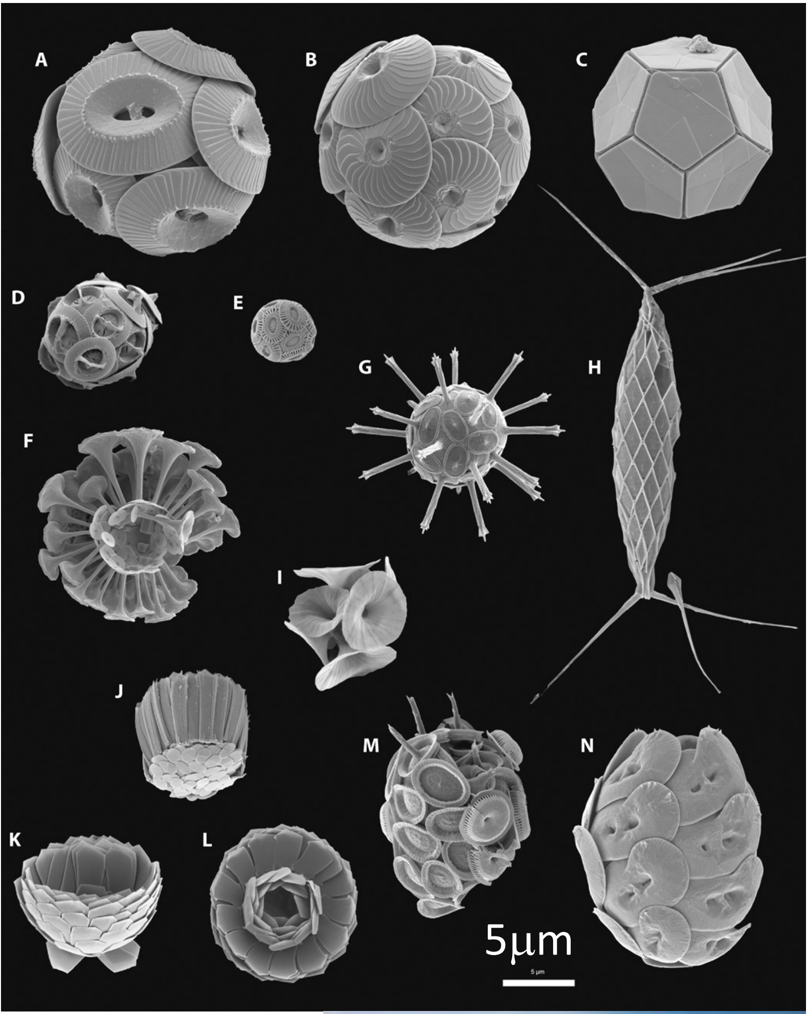
MAX RUN TIME 1.4hrs



This course covers

- Coccolithophore biology and ecology
  - Diversity, distribution, and biomass
- Remote sensing of coccolithophores and their calcite mass (PIC)
  - Bloom observations and classification
  - Quantifying PIC in the ocean
  - Caveats of remotely sensed PIC
- Optical properties of coccolithophores
  - Scattering, backscattering, and absorption
  - Reflectance
  - Birefrigence
- Some applications of optical oceanography in coccolithophore research
  - Ecology (environmental control of coccolithophore blooms, phenology, ocean albedo)
  - Climate change impacts
  - Biogeochemistry (influence on $pCO_{2,}$ calcite ballast effect)

What are coccolithophores?



Monteiro *et al.* (2016 – *Sci. Adv.*)

- Calcifying phytoplankton
- Haptophyta; Prymnesiophyceae
- Produce $CaCO_3$ scales (coccoliths)
- About 200 species
- Occur throughout the world ocean
- $5\ \mu m \leq D \leq 40\ \mu m$
- Considered as a single functional group within the phytoplankton (>biogeochemistry)
- Comprise about 10% of global phytoplankton biomass
- Major $CaCO_3$ producers in the open ocean (besides forams and pteropods)

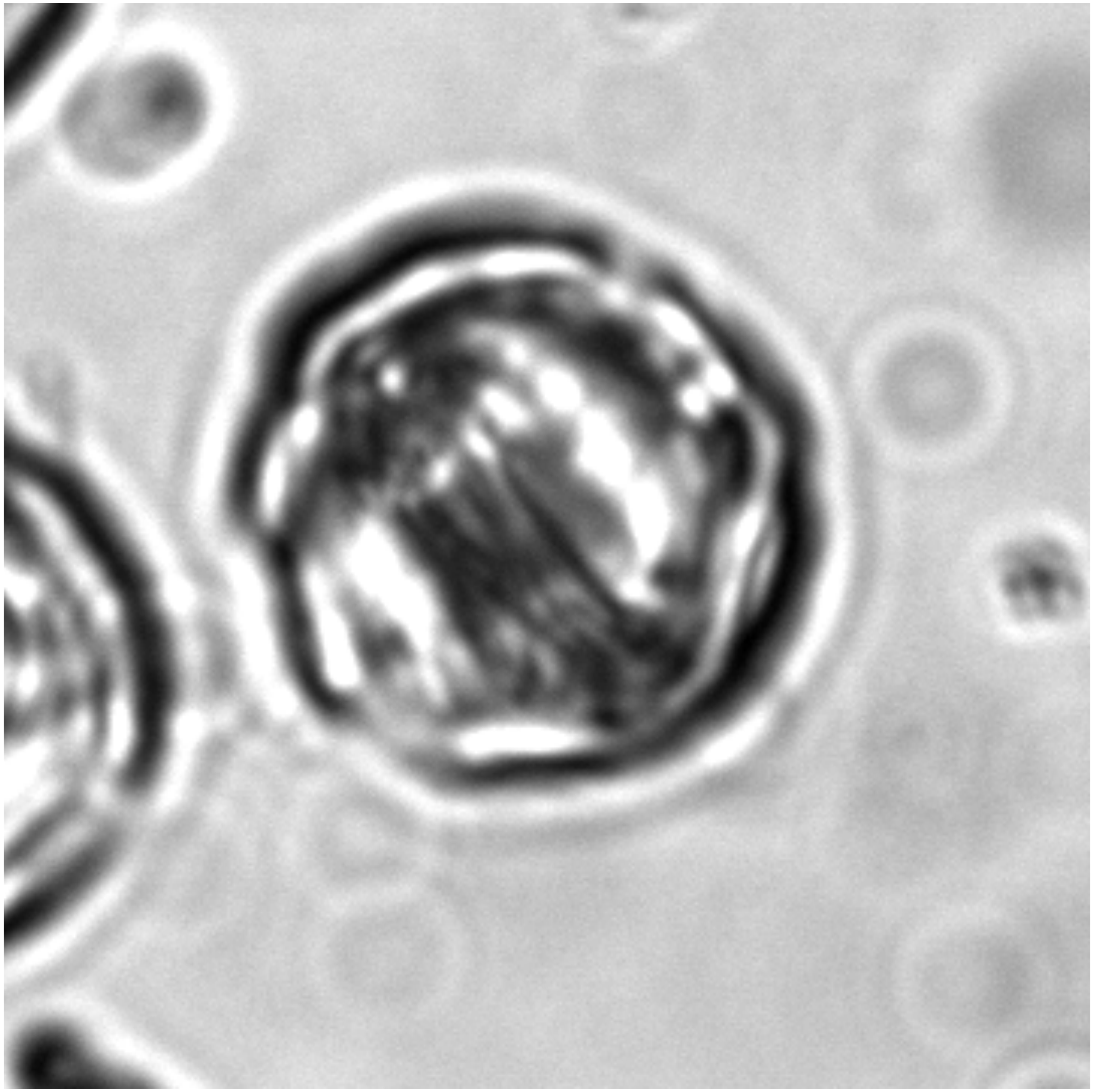
Coccolith production

Coccolithus pelagicus

D = 10-40 µm

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Produces about 1 coccolith every 1.5-2h

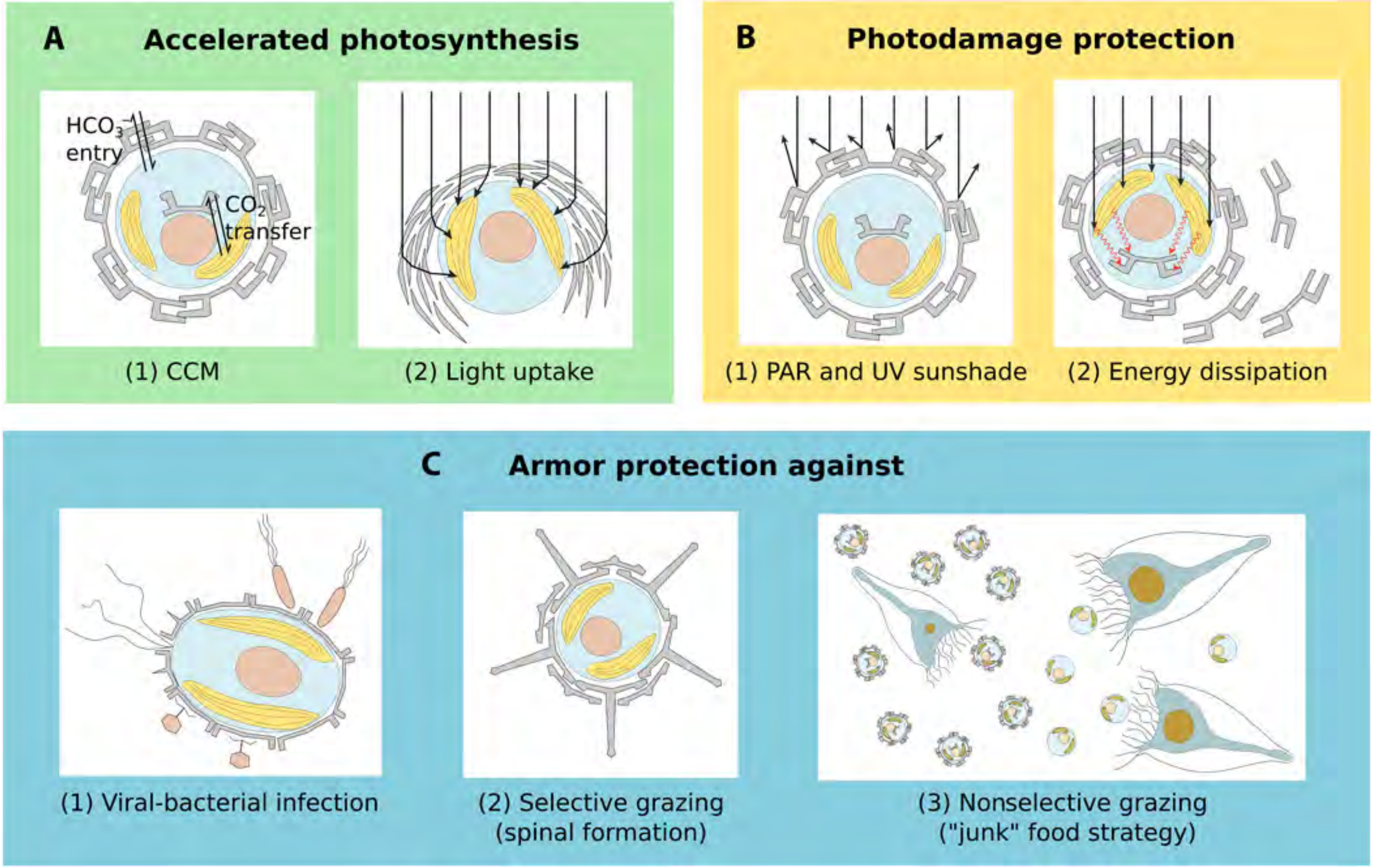


Video microscopy Courtesy: Alison Taylor

Taylor et al. 2007 *Eur. J. Phycol.*

Coccolith function

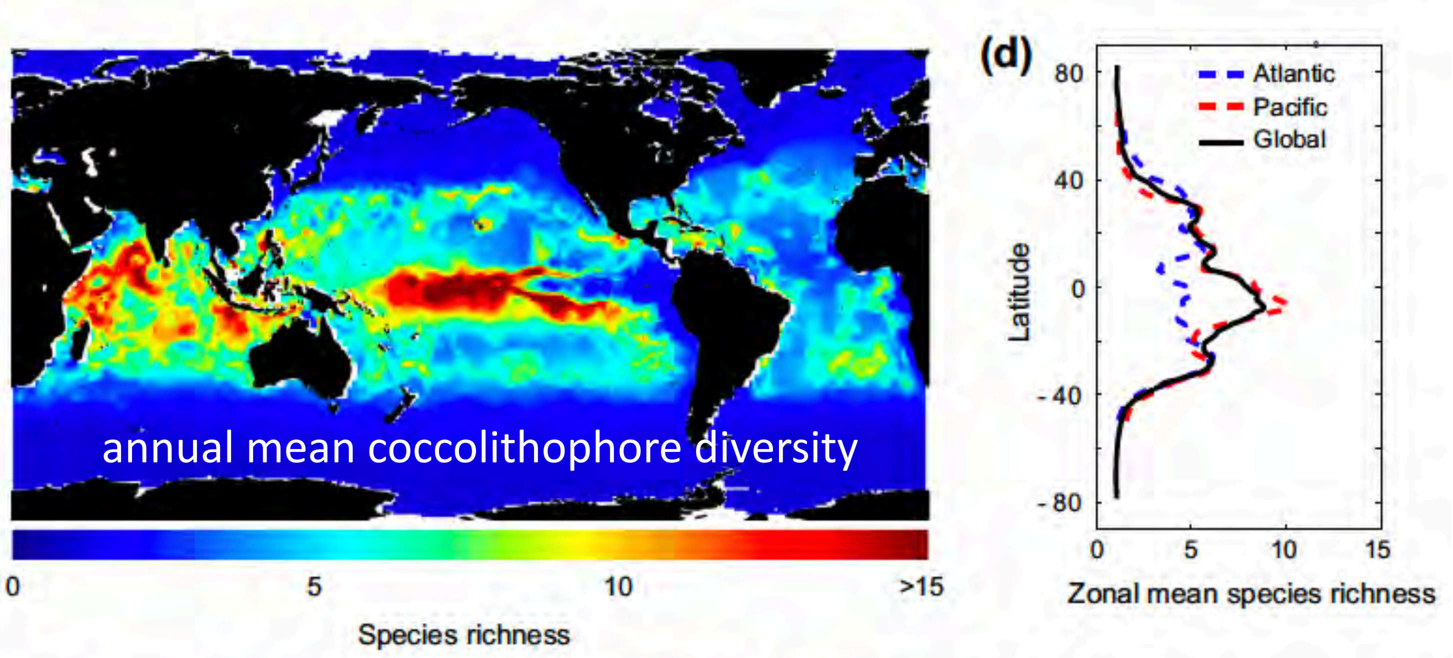
Why do coccolithophores calcify?



Monteiro *et al.* (2016 – *Sci. Adv.*)

Coccolithophore distribution and diversity

Coccolithophore species exhibit distinct vertical and **latitudinal zonation.**



O'Brien et al., 2016 – Progr. Oceanogr.

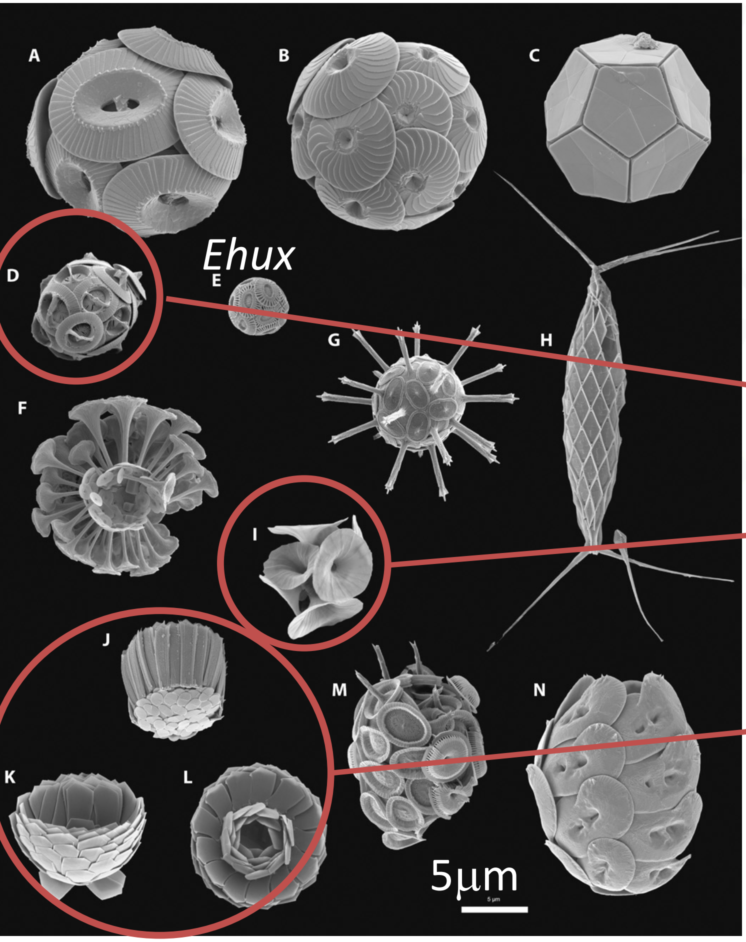
- Temperature and light are key drivers of latitudinal diversity patterns
- Diversity is highest in the lower latitudes
- Diversity is lowest at higher latitudes, where assemblages are often dominated by the bloom-forming species *E. huxleyi* (*Ehux*)

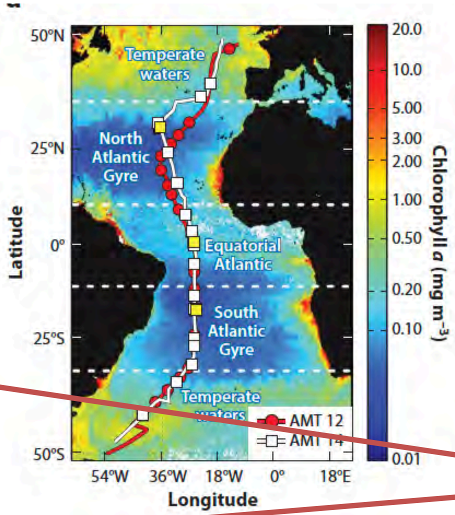
Coccolithophore distribution and diversity

Coccolithophore species exhibit distinct **vertical** and latitudinal **zonation**

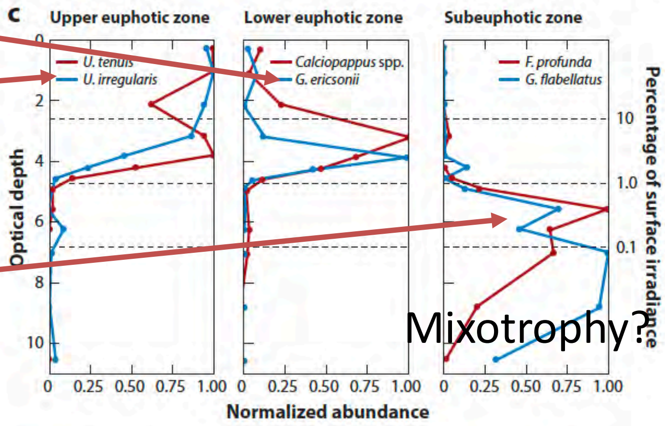
Throughout the euphotic and aphotic zone, according to their ecological preferences.

Monteiro *et al.* (2016 – *Sci. Adv.*)





Balch *et al.*, 2017 – *Ann. Rev. Mar. Sci.*



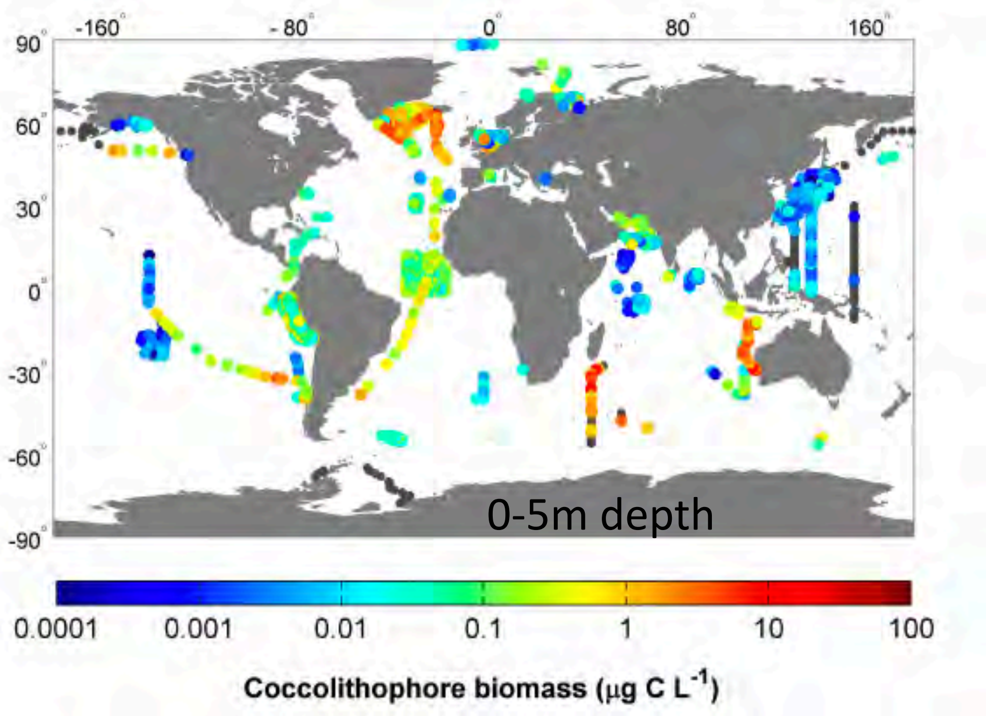
Mixotrophy?

Ehux is distinct from many other species in that it is common in all photic zones

Coccolithophore biomass distribution

- Most comprehensive in situ dataset of coccolithophore biomass from microscopy or flow cytometry (1929-2008)
- About 11000 observations of total coccolithophore abundance and biomass (O'Brien et al., 2013 – ESSD)

(O'Brien et al., 2013 – ESSD)



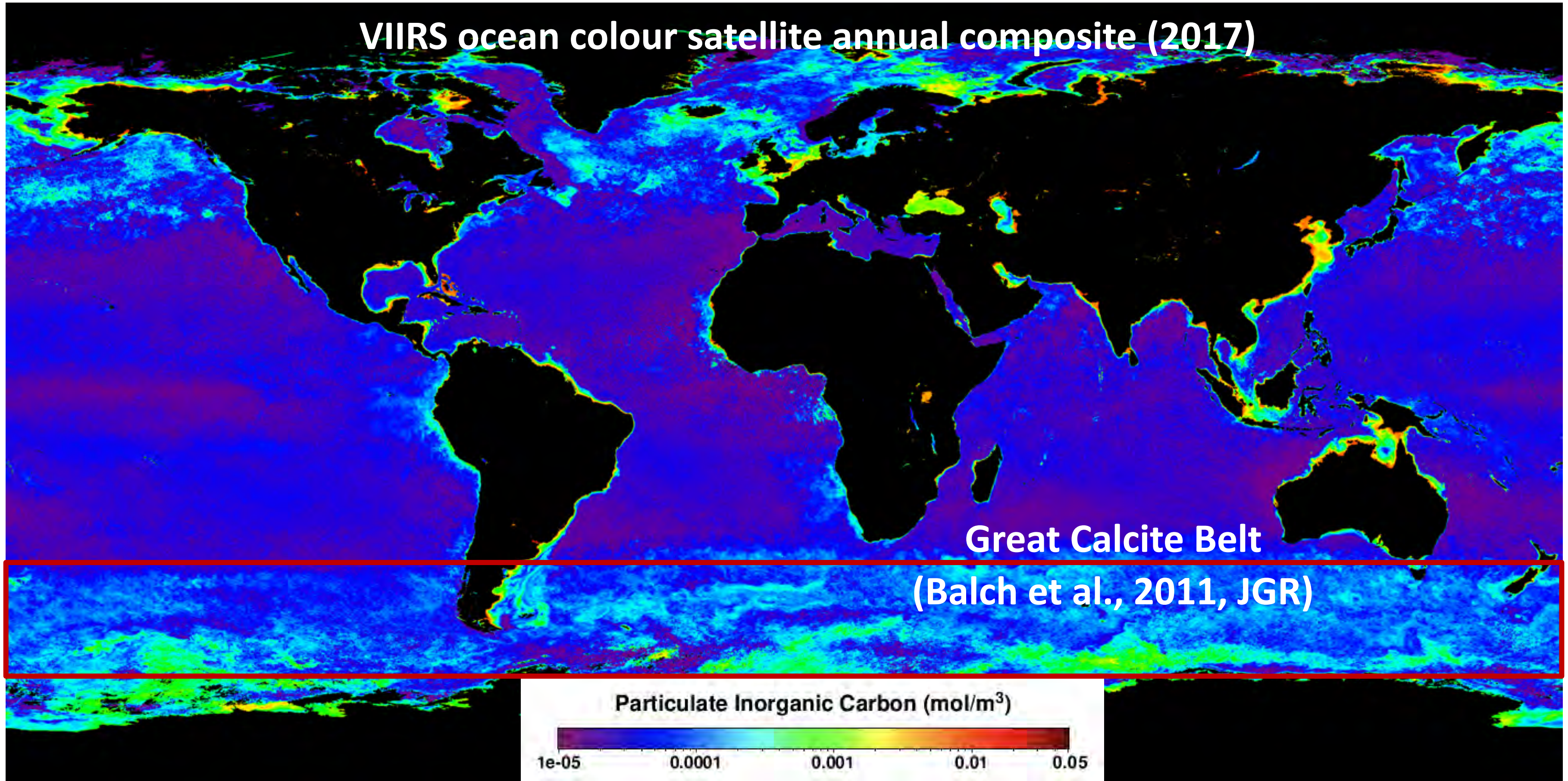
0-5m depth

This is Organic biomass or POC

Coccolithophore PIC in the ocean

- OCRS provides daily global observations of PIC
- …but the algorithm has limitations…

Barney Balch
Bigelow (USA)



VIIRS ocean colour satellite annual composite (2017)

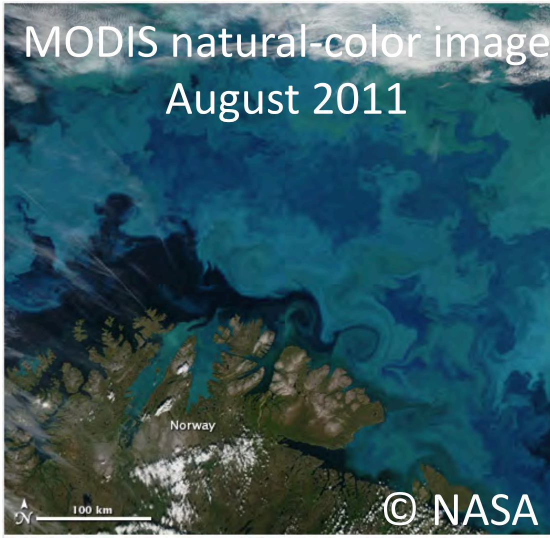
Great Calcite Belt
(Balch et al., 2011, JGR)

Remote sensing of coccolithophores and their calcite mass (PIC): a chronological overview of approaches

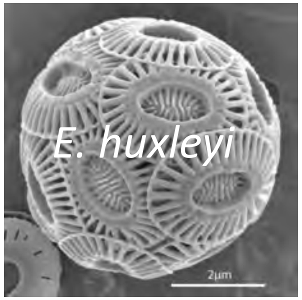
1. Holligan et al. (1983): bloom observations from CZCS Rrs at 550nm
2. Balch et al. (1991): bloom observations from AVHRR + in situ IOPs
3. Brown and Yoder (1994): coccolithophore bloom classifier for CZCS
4. Gordon et al. (2001): quantification of PIC (high), **NASA's standard algorithm**
5. Balch et al. (2005): quantification of PIC (low-med), **NASA's standard algorithm**
6. Shutler et al. (2010): coccolithophore bloom extent in shelf seas and coastal zones – probably the only case 2 algorithm
7. Sadeghi et al. (2012): SCIAMACHY, based on absorption
8. Moore et al. (2012): bloom classifier based on fuzzy logic for all OC sensors
9. Mitchel et al. (2017): quantification of PIC based on reflectance-difference approach

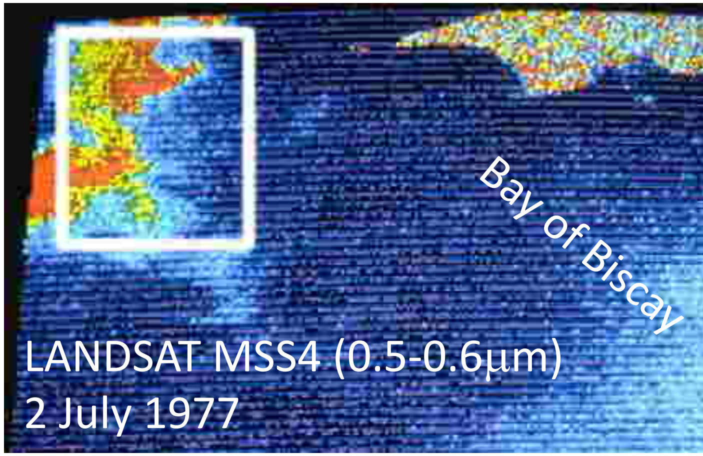
First observations of coccolithophore blooms

- From ships in Norwegian fjords:
  « **unusual milky turquoise colour** caused by enourmous concentrations of the calcareous flagellate *Coccolithus huxleyi* up to 115 x 10^6 cells/L in surface water» (Birkenes and Braarud 1952; Berge, 1962).
- First blooms discovered from space:
  - Landsat in 1977 (Le Fevre et al., 1983)
  - CZCS in 1982 + ship (Holligan et al. 1983)


MODIS natural-color image
August 2011

© NASA

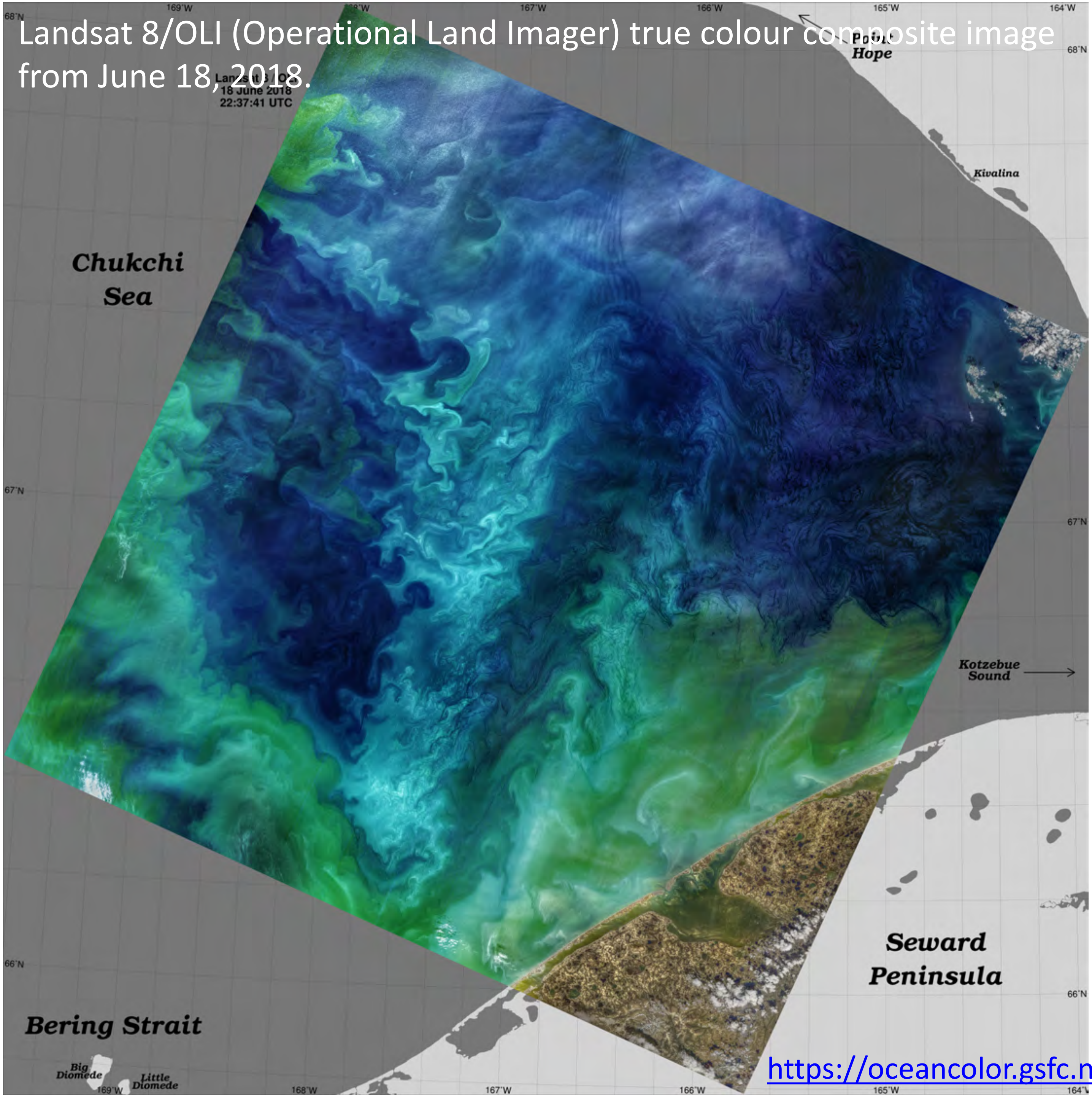




LANDSAT MSS4 (0.5-0.6µm)
2 July 1977

See http://www.noc.soton.ac.uk/soes/staff/tt/eh/v_0.htm for details

Landsat 8/OLI (Operational Land Imager) true colour composite image from June 18, 2018.

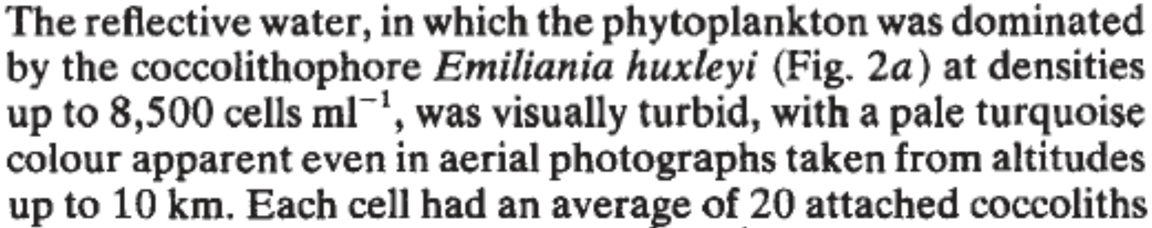


https://oceancolor.gsfc.nasa.gov/

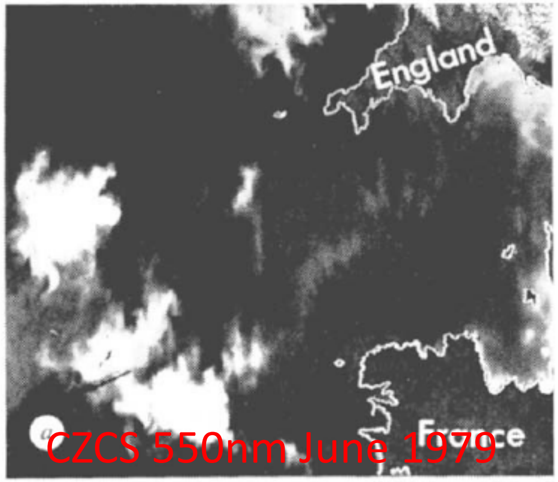
First OCRS observations of blooms - CZCS

Ship- and satellite-borne observations of *Ehux* blooms at a European continental shelf edge.

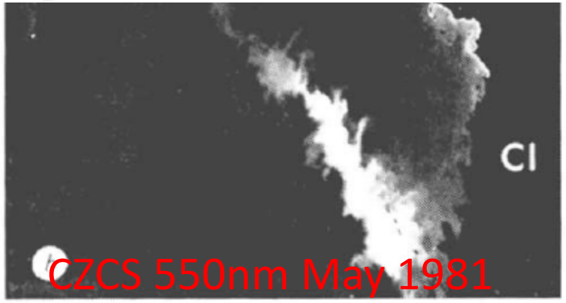
Holligan *et al.*, 1983 – *Nature Lett.*



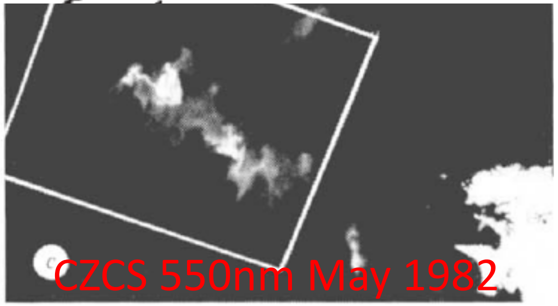
The reflective water, in which the phytoplankton was dominated by the coccolithophore *Emilianía huxleyi* (Fig. 2*a*) at densities up to 8,500 cells ml^{-1}, was visually turbid, with a pale turquoise colour apparent even in aerial photographs taken from altitudes up to 10 km. Each cell had an average of 20 attached coccoliths



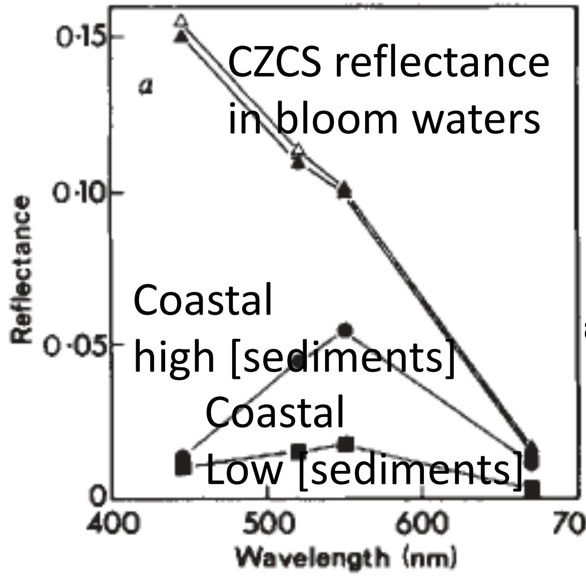
CZCS 550nm June 1979

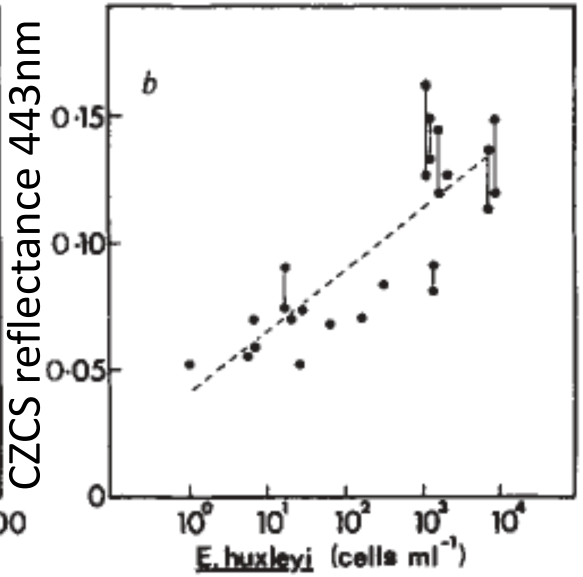


CZCS 550nm May 1981



CZCS 550nm May 1982



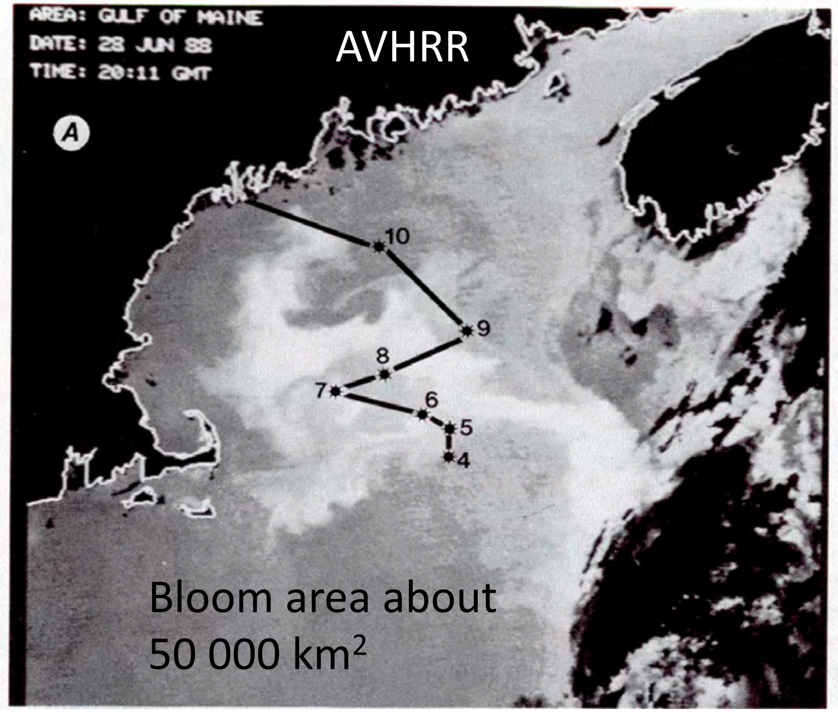


Significant positive correlation was found between reflectance from each of the CZCS channels (443, 520, and 550 nm) and the surface abundance of coccolithophores.

Bloom observations from AVHRR (1)

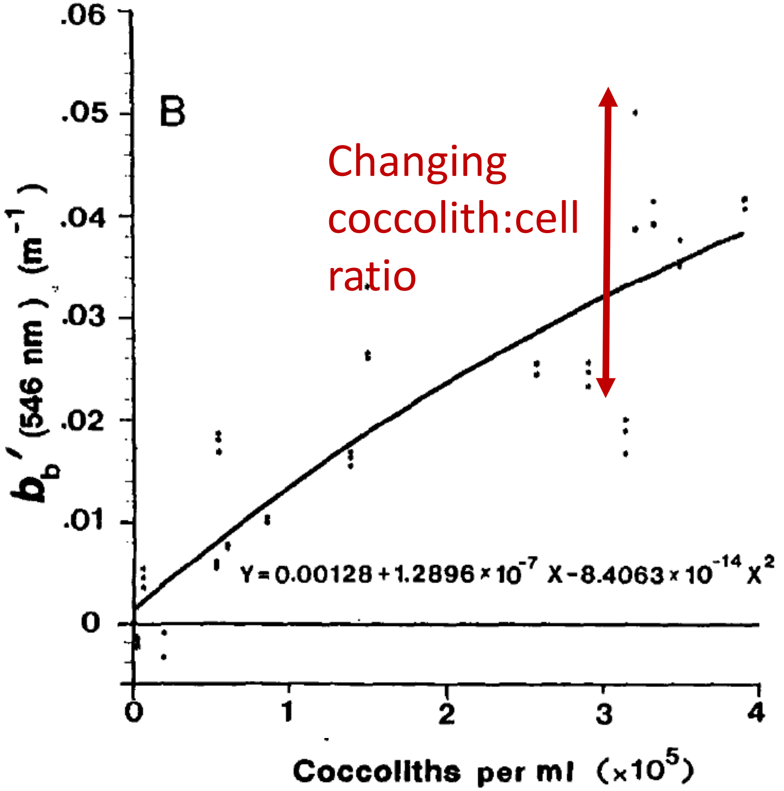
Ship- and satellite-borne observations of *Ehux* blooms in the Gulf of Maine

Balch et al. , *L&O* (1991)



Bloom area about 50 000 km^2

In situ backscattering due to coccoliths



Changing coccolith:cell ratio

Balch et al. (1991) and Ackleson and Holligan (1989) suggested that the high backscattering was caused principally by the presence of **detached coccoliths**, rather than by coated cells.

“Free coccoliths do the bulk of the light scattering in *Ehux* blooms but reflectance is more likely a function of coccoliths and (coated) cells.” [Balch et al. (1991)]

Bloom observations from AVHRR (2)

First study connecting in situ biogeochemical and optical measurements with satellite data (AVHRR) during an *Ehux* bloom South of Iceland in 1991

Holligan et al., 1993 – *GBC*

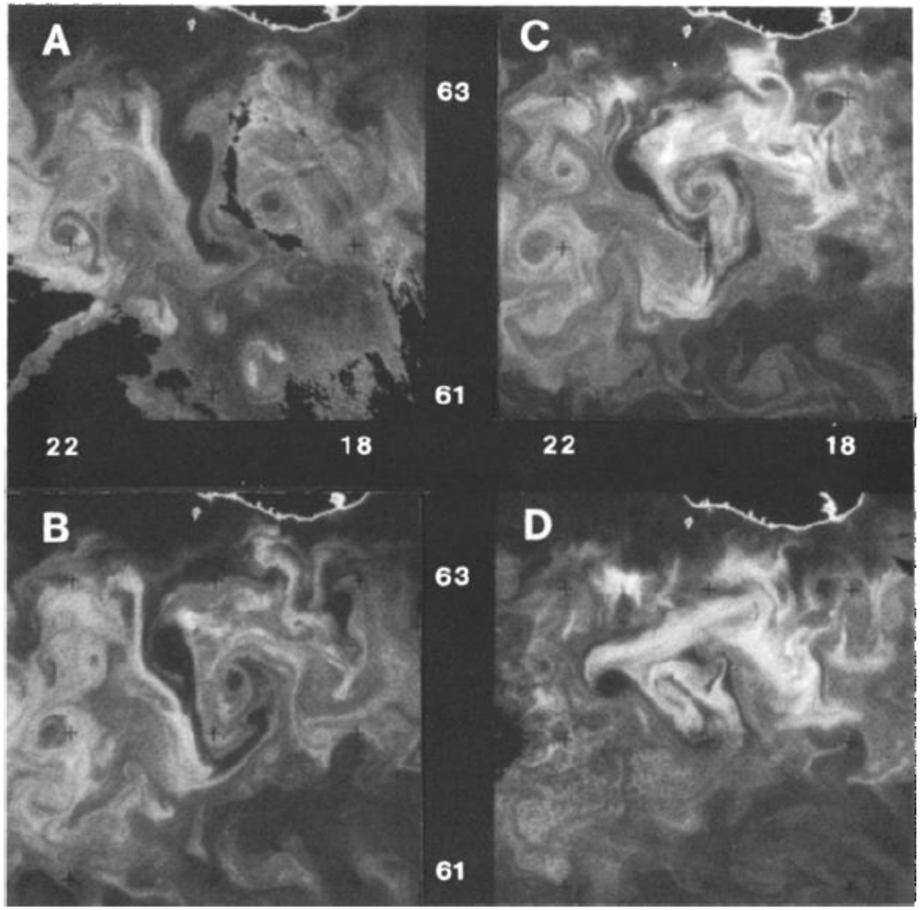


Fig. 3. AVHRR visible (channel 1) images of the central area of the *E. huxleyi* bloom to the south of Iceland for (a) Jun 15; (b) June17; (c) June 19; and (d) June 21, 1991, showing changes in the distribution of coccolith reflectance due to water motion. The images were all received on the early afternoon passes of NOAA 11. The speckled appearance of the SW quadrant of Figure 3d is due to atmospheric effects.

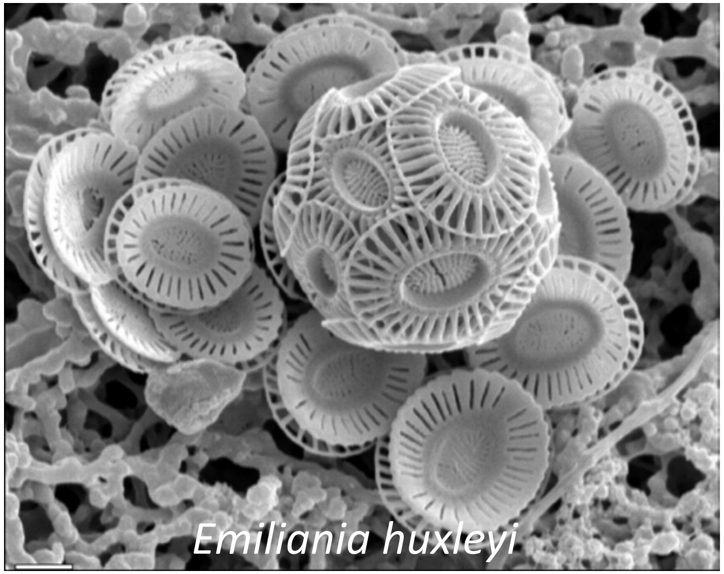
Bloom area: 0.5 million km^2
(size of Spain)

Levels of dimethylsulphide (**DMS**) in surface waters were high compared to average ocean values, with the greatest concentrations in localized areas
Characterized by high rates of Photosynthesis, calcification, and grazing by microzooplankton.

Coccolith production had a significant impact on the state of the in-water **pCO$_2$**

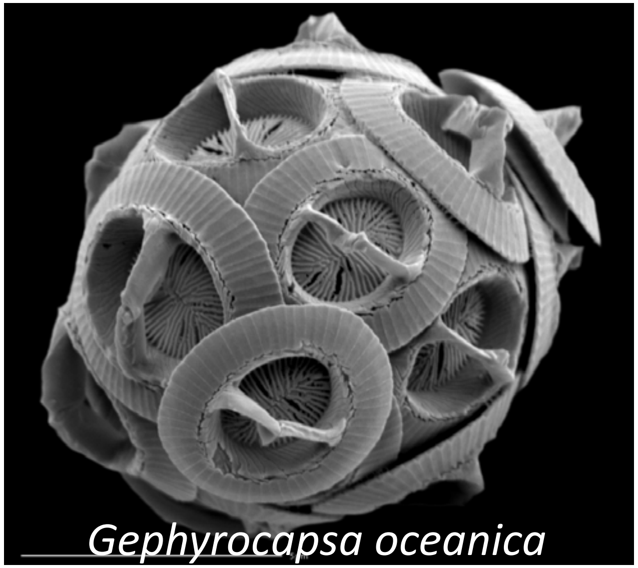
Coccolithophore blooms

Two known bloom forming species ("bloom" means >10^6 cells / L)



Emiliania huxleyi

Coccospheres, D 5 to 10 µm;
coccoliths, 2 to 5 µm long.



Gephyrocapsa oceanica

Coccospheres, D 6 to 10 µm;
coccoliths, 3.5 to 6 µm long.

Ubiquitous species, dominant bloom-former in temperate and subpolar waters.

Predominantly low-latitude warm-water eutrophic species. More widespread in the Pacific than in the Atlantic Ocean.

Ehux is thought to be **unique** in overproducing coccoliths and then shedding the excess ones into the water (Paasche 2002) -> hardly any of the open-ocean bright waters are attributable to species other than *Ehux*. But see (Blackburn and Cresswell, 1993) for *G. oceanica* bloom in AUS.

Young, J.R., Bown P.R., Lees J.A. (2017) Nannotax3 website. International Nannoplankton Association. www.mikrotax.org/Nannotax3

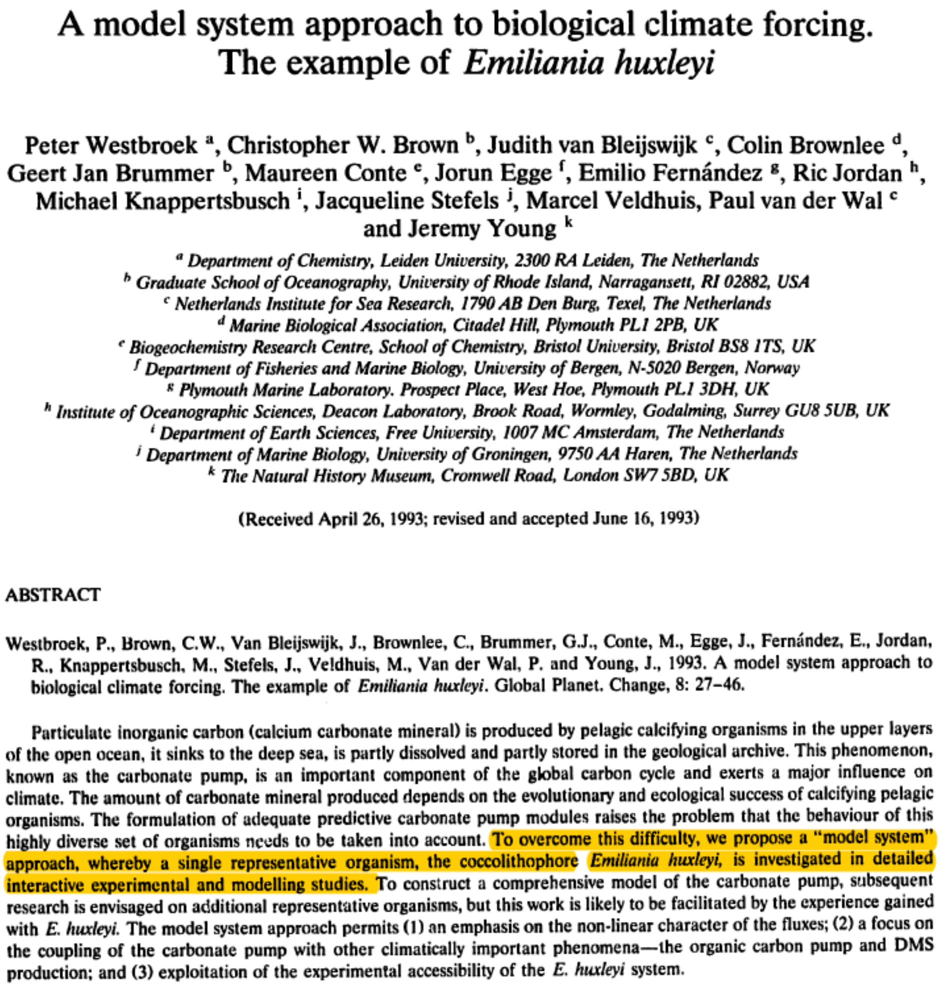
Emiliania huxleyi (*Ehux*)

***Emiliania huxleyi* Home Page**

Welcome to the home page for "Ehux"

http://www.noc.soton.ac.uk/soes/staff/tt/eh/

Created by Toby Tyrrell at Southampton University



A model system approach to biological climate forcing. The example of *Emiliania huxleyi*

Peter Westbroek [a], Christopher W. Brown [b], Judith van Bleijswijk [c], Colin Brownlee [d], Geert Jan Brummer [b], Maureen Conte [e], Jorun Egge [f], Emilio Fernández [g], Ric Jordan [h], Michael Knappertsbusch [i], Jacqueline Stefels [j], Marcel Veldhuis, Paul van der Wal [c] and Jeremy Young [k]

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[b] *Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882, USA*
[c] *Netherlands Institute for Sea Research, 1790 AB Den Burg, Texel, The Netherlands*
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[e] *Biogeochemistry Research Centre, School of Chemistry, Bristol University, Bristol BS8 1TS, UK*
[f] *Department of Fisheries and Marine Biology, University of Bergen, N-5020 Bergen, Norway*
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[h] *Institute of Oceanographic Sciences, Deacon Laboratory, Brook Road, Wormley, Godalming, Surrey GU8 5UB, UK*
[i] *Department of Earth Sciences, Free University, 1007 MC Amsterdam, The Netherlands*
[j] *Department of Marine Biology, University of Groningen, 9750 AA Haren, The Netherlands*
[k] *The Natural History Museum, Cromwell Road, London SW7 5BD, UK*

(Received April 26, 1993; revised and accepted June 16, 1993)

ABSTRACT

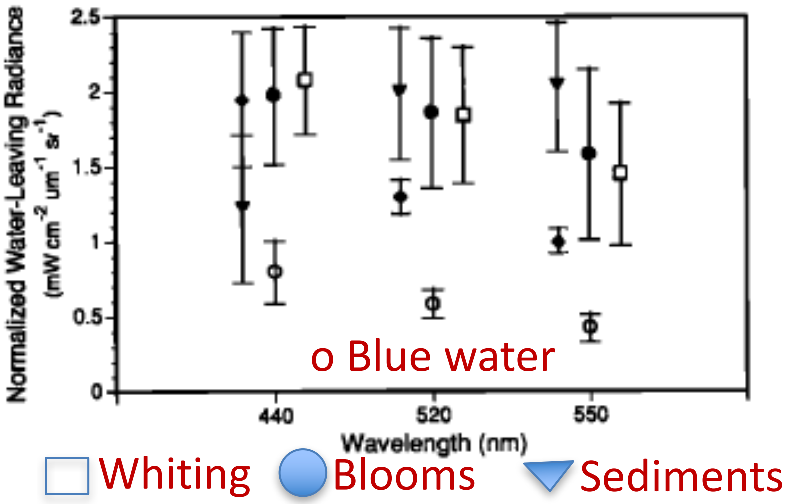
Westbroek, P., Brown, C.W., Van Bleijswijk, J., Brownlee, C., Brummer, G.J., Conte, M., Egge, J., Fernández, E., Jordan, R., Knappertsbusch, M., Stefels, J., Veldhuis, M., Van der Wal, P. and Young, J., 1993. A model system approach to biological climate forcing. The example of *Emiliania huxleyi*. Global Planet. Change, 8: 27–46.

Particulate inorganic carbon (calcium carbonate mineral) is produced by pelagic calcifying organisms in the upper layers of the open ocean, it sinks to the deep sea, is partly dissolved and partly stored in the geological archive. This phenomenon, known as the carbonate pump, is an important component of the global carbon cycle and exerts a major influence on climate. The amount of carbonate mineral produced depends on the evolutionary and ecological success of calcifying pelagic organisms. The formulation of adequate predictive carbonate pump modules raises the problem that the behaviour of this highly diverse set of organisms needs to be taken into account. To overcome this difficulty, we propose a "model system" approach, whereby a single representative organism, the coccolithophore *Emiliania huxleyi*, is investigated in detailed interactive experimental and modelling studies. To construct a comprehensive model of the carbonate pump, subsequent research is envisaged on additional representative organisms, but this work is likely to be facilitated by the experience gained with *E. huxleyi*. The model system approach permits (1) an emphasis on the non-linear character of the fluxes; (2) a focus on the coupling of the carbonate pump with other climatically important phenomena—the organic carbon pump and DMS production; and (3) exploitation of the experimental accessibility of the *E. huxleyi* system.

Coccolithophore bloom classification - CZCS

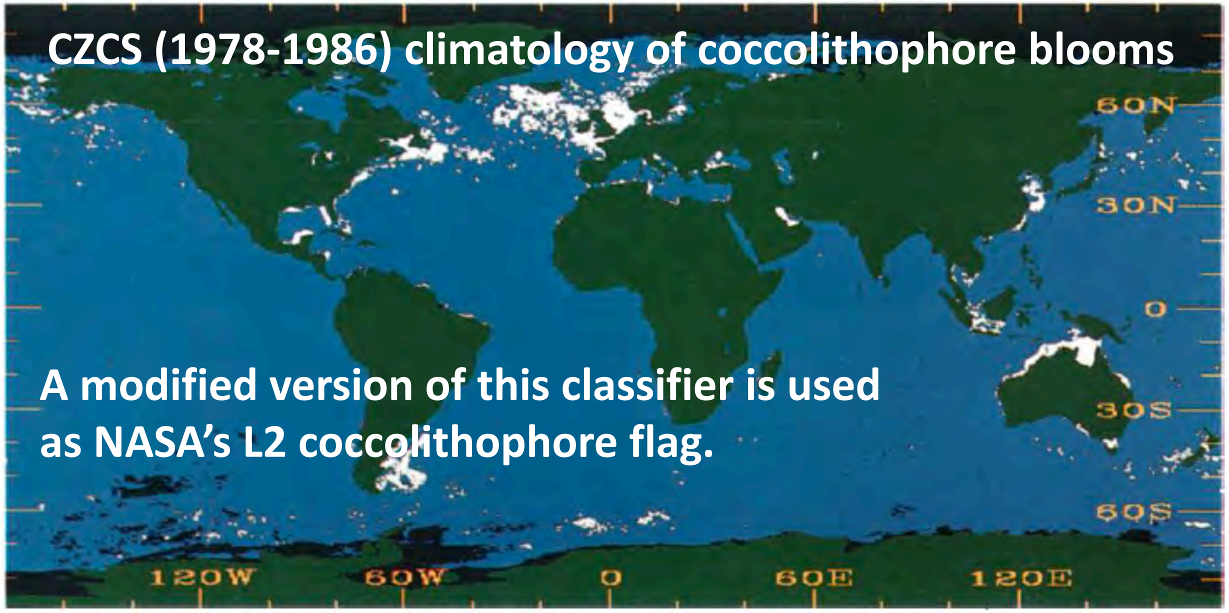
Brown and Yoder (1994)

Brown and Yoder , *J. Geophys. Res.* (1994)



Supervised multispectral classification scheme from weekly CZCS data (1978-1986) from nL_w magnitude and band-ratios.

Coccolithophorid blooms annual coverage: 1.4×10^6 km^2



CZCS (1978-1986) climatology of coccolithophore blooms

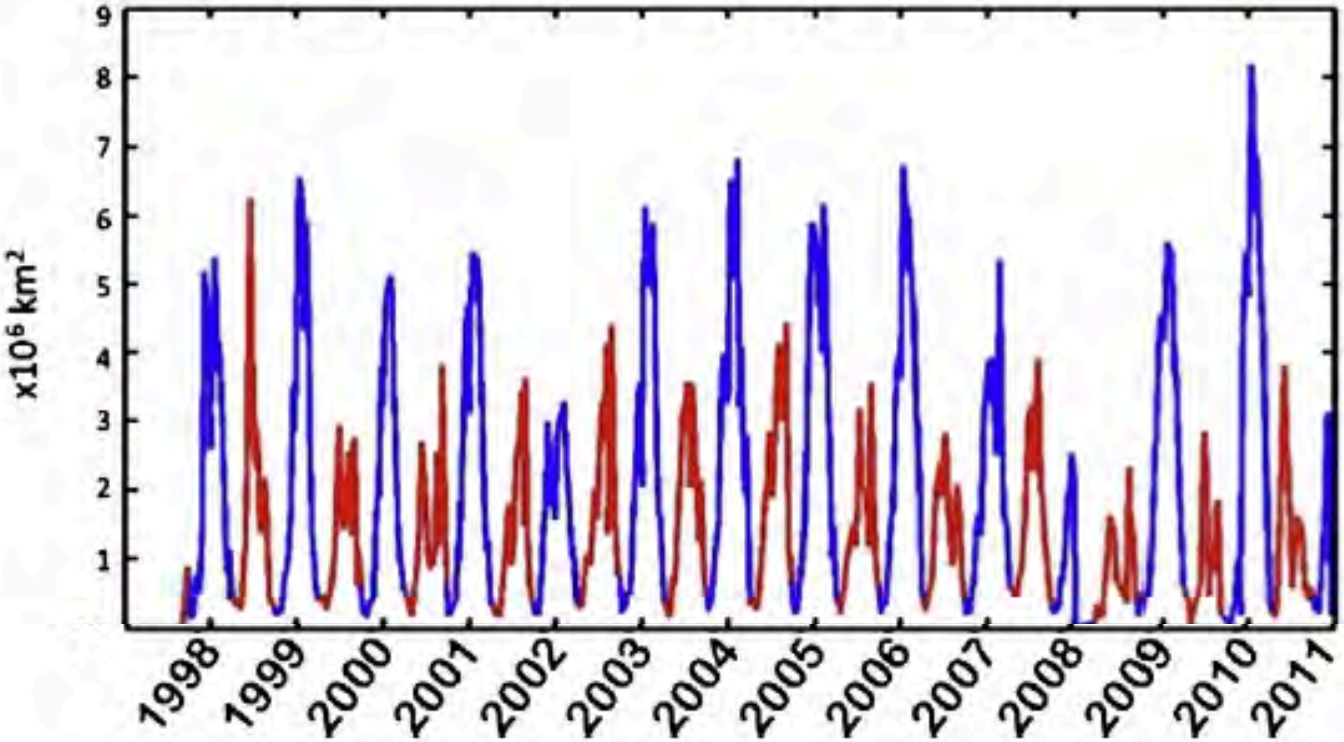
A modified version of this classifier is used as NASA's L2 coccolithophore flag.

Misclassifications of blooms due to similarity with Whitings Sediments

Coccolithophore bloom classification

Moore *et al.* (2012), RSE

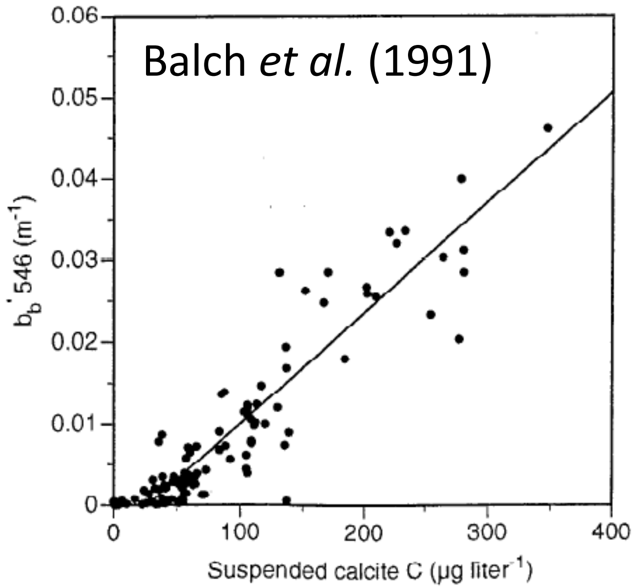
Generalized bloom classifier for all ocean colour sensors (SeaWiFS, MODIS, MERIS) based on fuzzy logic.
Detection levels: 1500-1800 cells/mL and 43000-78000 liths/mL



Global annual coccolithophore bloom coverage of about 2.75 x 10^6 km^2:
2 x 10^6 km^2 in Southern Hemisphere and 0.75 x 10^6 km^2 in Northern Hemisphere.

PIC in blooms from SeaWiFS

Gordon *et al*. (2001)



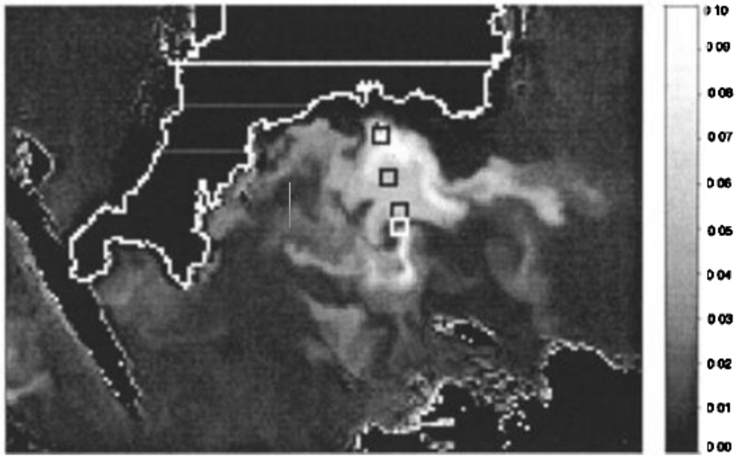
Balch *et al.* (1991)

Heart of the algorithm:

b_{bpic}(546 nm)= 1.6x[PIC in mol m^{-3}]-0.0036

$b_{bpic}(\lambda)=b_{bpic}(546)\times(546/\lambda)^{1.35}$

[Based on in situ measurements by Balch *et al.* (1991)]



Gordon *et al*. (2001)

Figure 1. $b_b(546)$ in m^{-1} retrieved from the July 30, 1999 SeaWIFS image of Plymouth, UK. Areas of enhanced backscat-

3-band algorithm retrieving ρ_w(546 nm) from SeaWiFS reflectance in Red and NIR bands (670, 765, 865nm)

Suitable for high concentrations of $CaCO_3$, when B-G bands often saturate (not accurate for PIC concentrations < 3 mmol m^{-3})

Assumptions:

- ρ_w(765, 865nm)=0
- $\rho_w(\lambda)=b_b(\lambda)/(6(a_w(\lambda)+b_b(\lambda)))$ with λ=670nm

maximum RMS error of the algorithm is +/- 15 μg/L (or 1.2 mmol m^{-3})
= about 5-10% of PIC in dense bloom (Balch, 2004)

PIC from MODIS

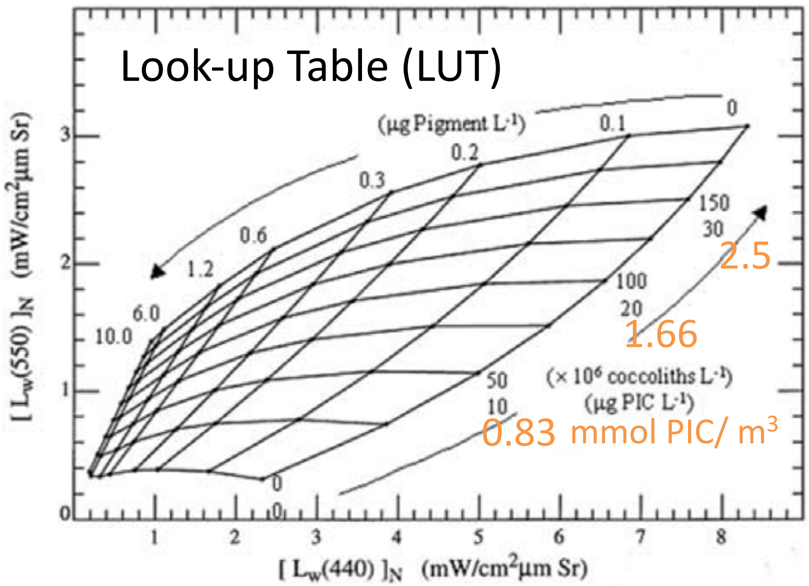
Balch *et al*. (2005)

Balch *et al*. (2005)

Heart of the algorithm (same as Gordon algo)**:**
$b_{bpic}(546\ nm) = 1.6 \times [PIC\ in\ mol\ m^{-3}] - 0.0036$
$b_{bpic}(\lambda) = b_{bpic}(546) \times (546/\lambda)^{1.35}$

PIC is retrieved from a LUT based on semi-analytical OCRS model of Gordon *et al.* (1988)

Validated with in situ data of b_{bpic}, PIC, Chl*a*, and L_w mainly in Maine waters (*Ehux* dominated)



1 µg PIC/L= 0.083 mmol PIC/ m^3
1 mmol PIC /m^3= 12 µg PIC/L

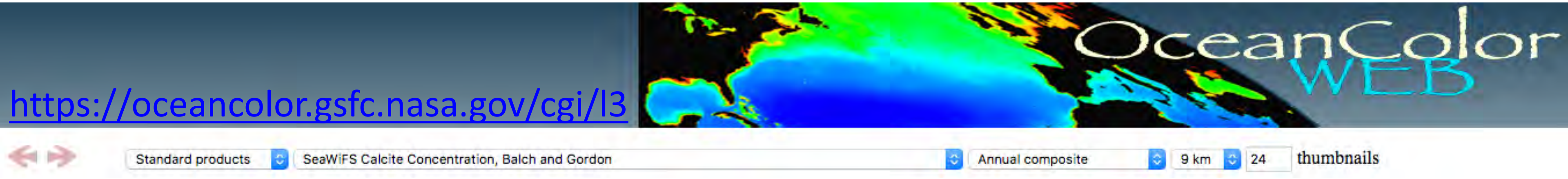
Retrieval uncertainty: due to natural variability in phytoplankton-detritus b_b corresponds to 25 x 10^6 coccoliths/L = 5 µg PIC/L = 0.41 mmol PIC/ m^3

Major limitations:

- dependency on the reflectance model (assumed constant phyto-detritus b_b)
- absolute radiance -> sensitivity to atmospheric correction errors
- Estimate of “excess backscatter” -> particles other than PIC may also cause excess backscatter

NASA's standard PIC algorithm

"Balch and Gordon"



https://oceancolor.gsfc.nasa.gov/cgi/l3

Standard products | SeaWiFS Calcite Concentration, Balch and Gordon | Annual composite | 9 km | 24 thumbnails

a **hybrid** of 2-band approach of Balch *et al.* (2005) and the 3-band approach of Gordon *et al.* (2001)

The 2-band approach of Balch et al. (2005) is applied, unless reflectance values fall outside the bounds of the LUT (<40 μg PIC/L or 3 mmol PIC/m^3); then the 3-band algorithm of Gordon et al. (2001) is used.

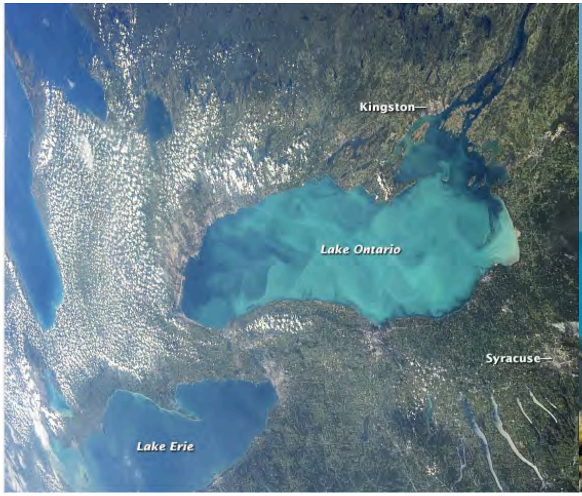
The algorithm is applicable to all current ocean color sensors.

Mainly validated in Maine and Southern Ocean waters.

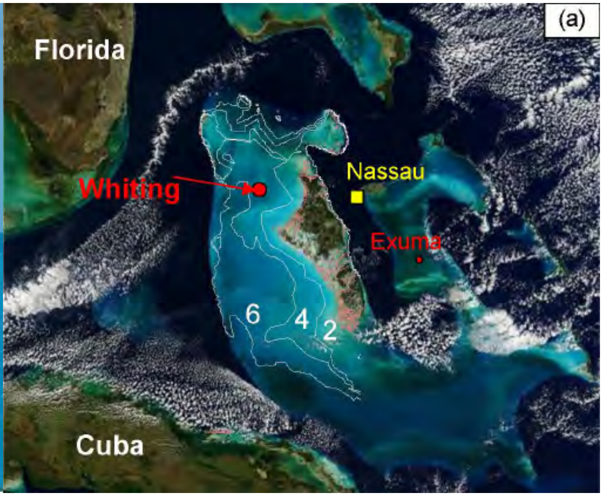
PIC algorithm caveats

False positives for high PIC (highly reflective waters) produced by:

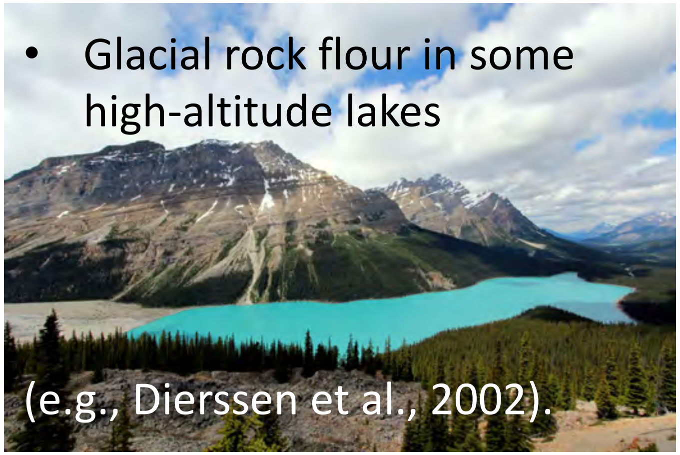
- Whitings = patches of suspended fine-grained calcium carbonate



https://earthobservatory.nasa.gov/



(Dierssen et al., 2009 – Biogeosciences)



- Glacial rock flour in some high-altitude lakes

(e.g., Dierssen et al., 2002).

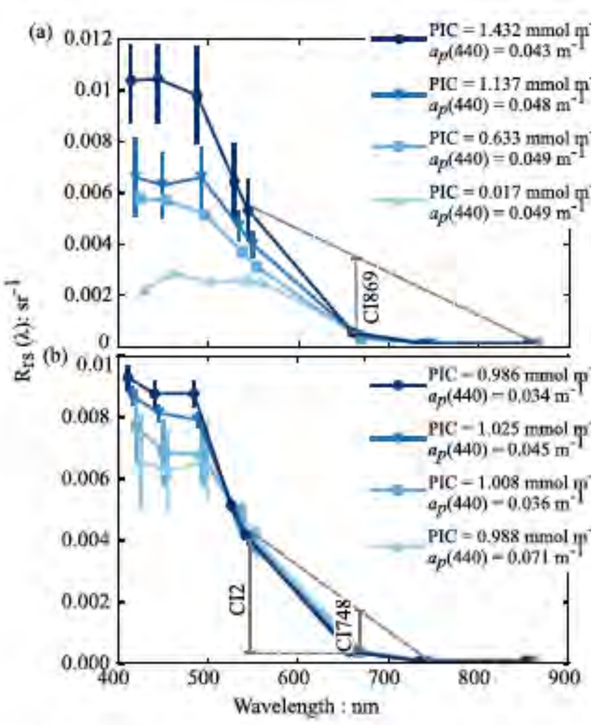
- High concentrations of empty diatom frustules (e.g. on shallow shelves, Broerse et al., 2003) or suspended sediments
- In polar waters: Floating sea-ice
- Bubbles
- Phaeocystis foam

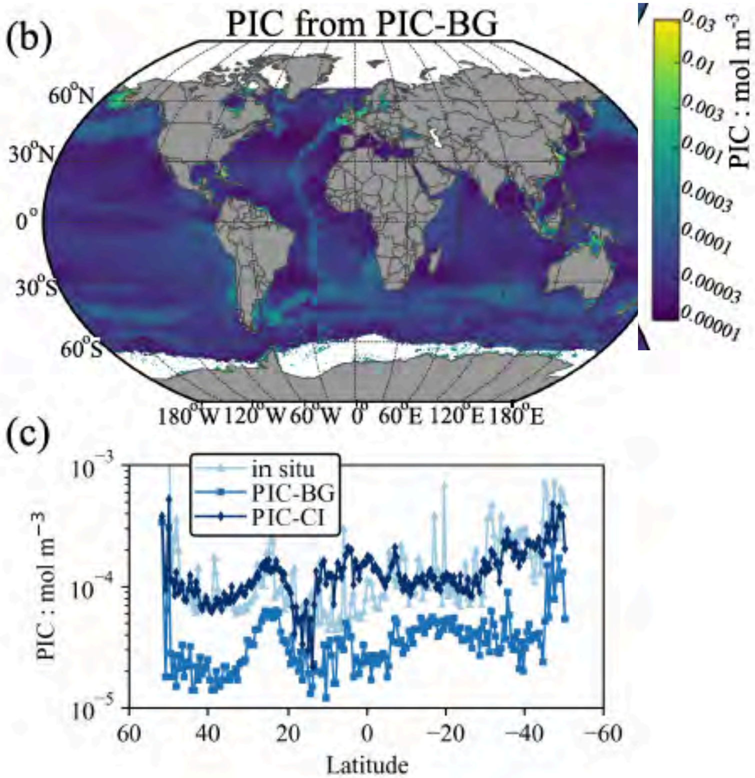
(See Balch, 2018, Ann. Rev. Mar. Sci. or Tyrrell and Merico, 2004)

Alternative PIC algorithm

Mitchell *et al.* (2017)

Reflectance difference approach, inspired by Hu et al. (2012) for Chl*a*





More resistant to atmospheric correction errors and residual errors in sun glint corrections than the Balch *et al.* (2005) algorithm.

Potential to replace the Balch *et al.* (2005) algorithm currently being investigated

This course covers

- Coccolithophore biology and ecology
  - Diversity, distribution, and biomass
- Remote sensing of coccolithophores and their calcite mass (PIC)
  - Bloom observations and classification
  - Quantifying PIC in the ocean
  - Caveats of remotely sensed PIC
- **Optical properties of coccolithophores**
  - **Scattering, backscattering, and absorption**
  - **Reflectance**
  - **Birefrigence**
- Some applications of optical oceanography in coccolithophore research
  - Ecology (environmental control of coccolithophore blooms, phenology, ocean albedo)
  - Climate change impacts
  - Biogeochemistry (influence on $pCO_{2,}$ calcite ballast effect)

Light absorption properties of coccoliths

Measurements of $a_p(\lambda)$ (filter-pad technique) in *Ehux* bloom in the Gulf of Maine.

Balch et al. , *L&O* (1991)

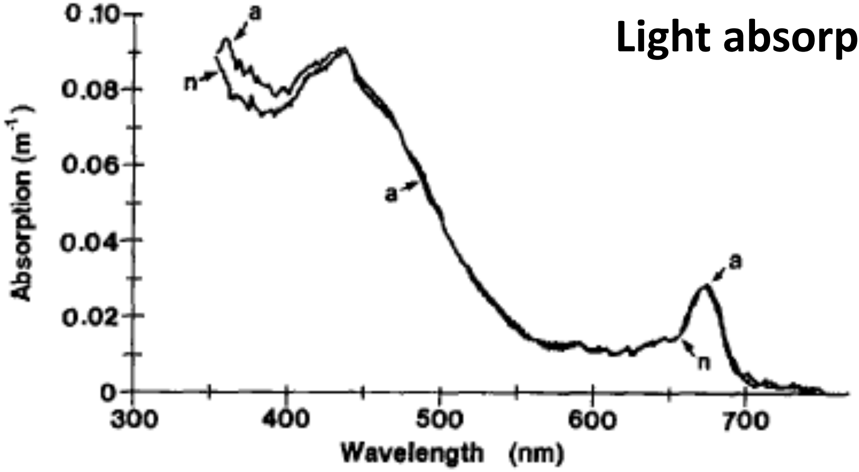


Fig. 9. Particulate absorption spectrum (m^{-1}) from station 8 at 5 m. Data represent two scans, one of a glass-fiber filter through which raw coccolithophore bloom water was passed (curve n) and an identical filter through which bloom water was passed following dissolution of coccoliths (curve a).

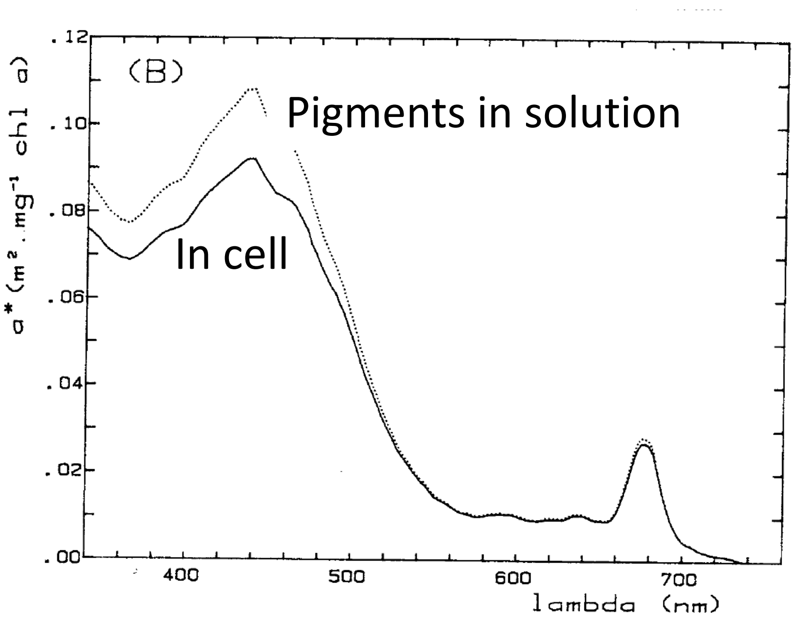
Light absorption by coccoliths is negligible

Consistent with the absorption properties of calcite for which the absorption is negligible even in the far UV (Palik, 1998- *Handbook of Optical Constants of Solids*).

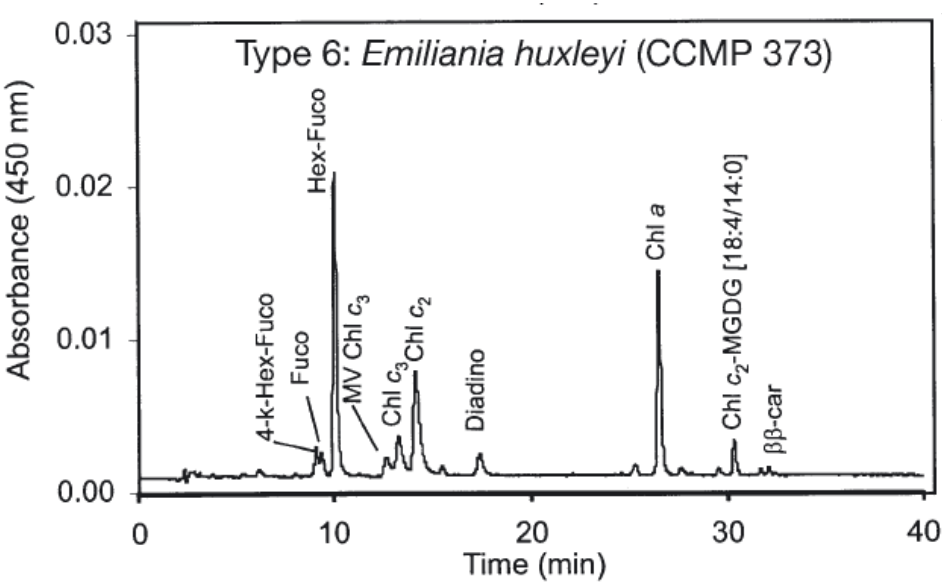
Light absorption by *Ehux* cells

Measurements from *Ehux* cultures

Morel and Bricaud, *Deep Sea Res.* (1981)



Measured in *Ehux* culture



Chromatogram (HPLC method)

Zapata et al., *MEPS* (2004)

Typical Chl*a* content for *Ehux* = 0.24 pg Chl*a*/cell (Ahn et al., 1992 – *Deep Sea Res.*), up to 0.4 pg Chla / cell (Daniels et al., 2014 – *Biogeosciences*)

-> 0.24 pg - 0.40 pg Chl*a* x 10^6 cells/L in a bloom = 0.24-0.40 μg/L in a bloom.

Light scattering properties

They are made of calcite with refractive index = 1.20 relative to water (other refractive indices for reference: 1.05 for POC, 1.07 for BSi), which makes them highly efficient light scatterers

Morel (1991)

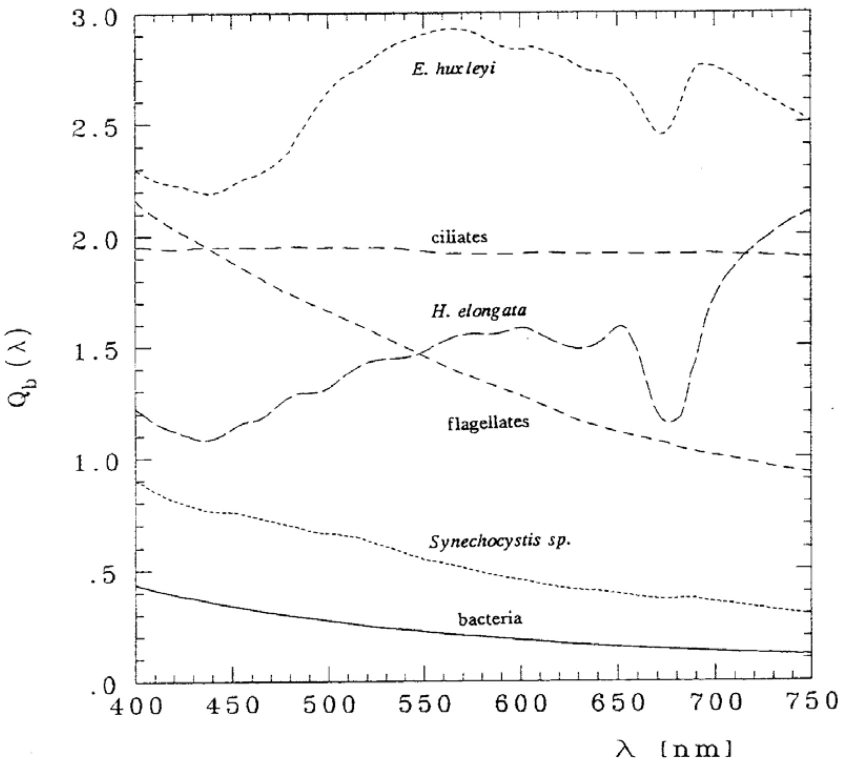
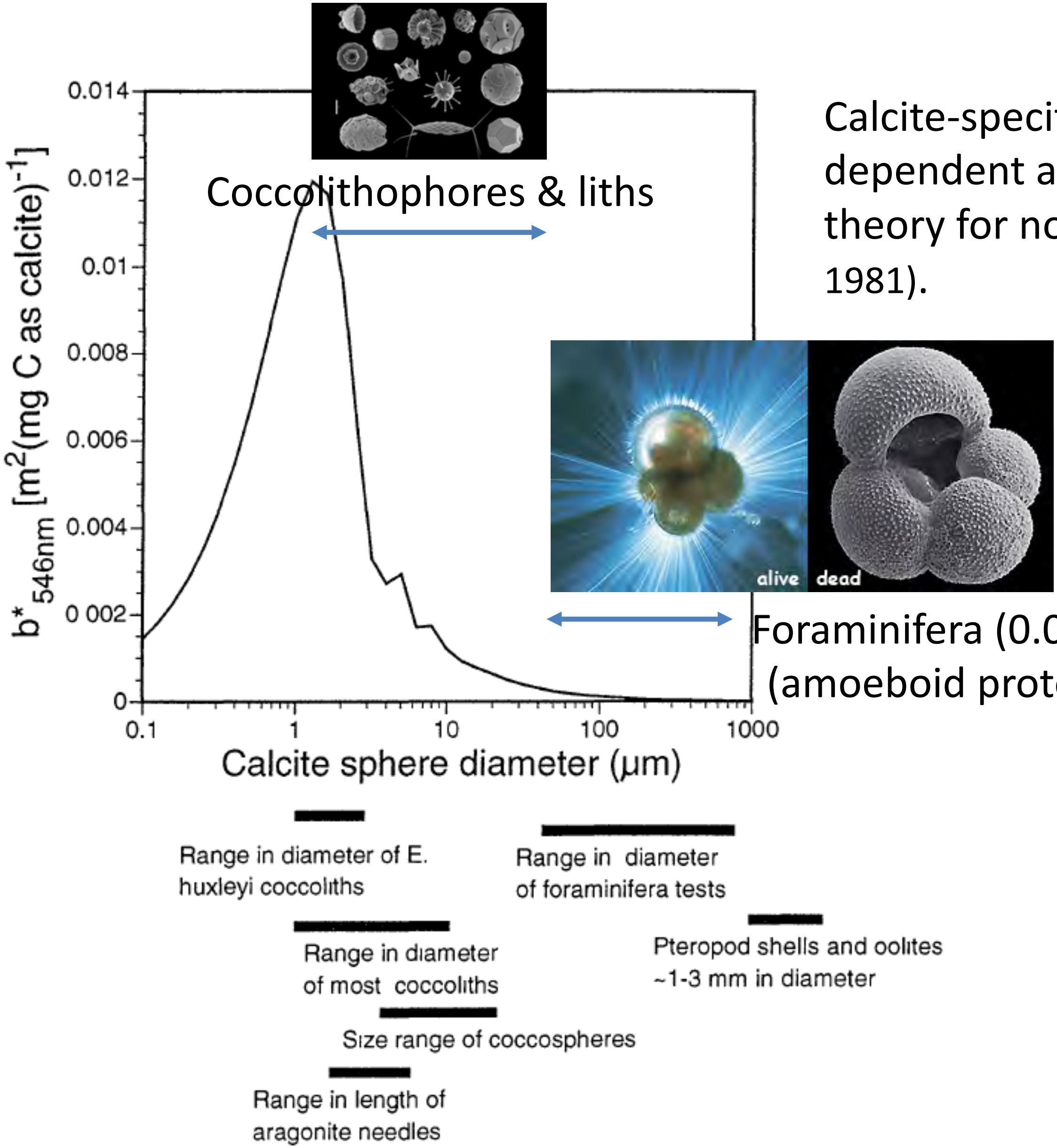


Figure 3. Spectral variations of Q_b within the 400-750 nm range of various phototrophic and heterotrophic organisms as experimentally determined (Morel and Ahn, 1990, 1991).

Light scattering properties of calcite particles in the ocean



Balch et al. , *L&O* (1996)

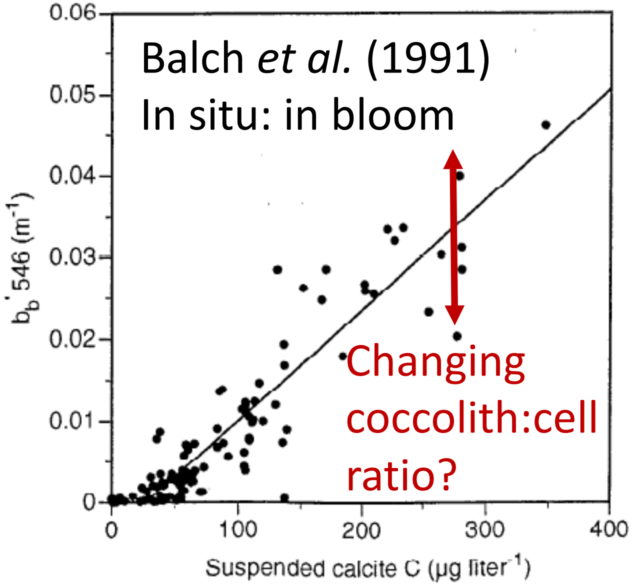
Calcite-specific scattering coefficient is size-dependent according to anomalous diffraction theory for non-absorbing spheres (Van de Hulst, 1981).

Negligible contribution from larger calcite particles (forams and pteropods) to b_b and thus to R_{rs}

Foraminifera (0.05-1mm)
(amoeboid protozoans)

Pteropods (1-3mm)
”sea snails”

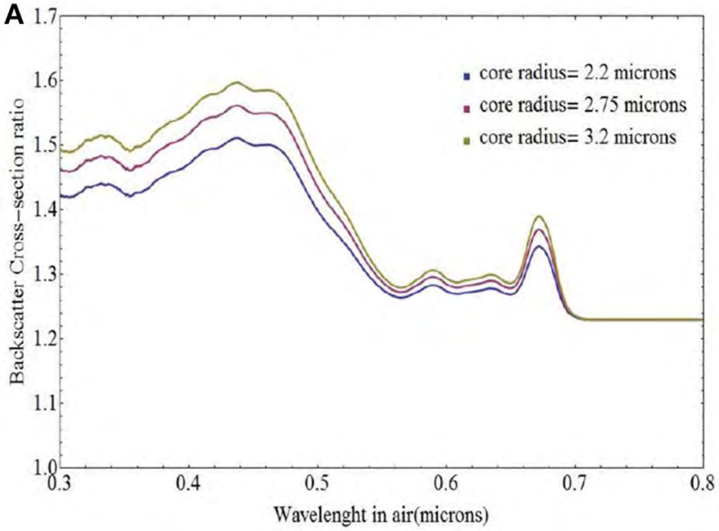
Light backscattering vs. PIC



Balch *et al.* (1991)
In situ: in bloom

Changing coccolith:cell ratio?

basis of NASA's standard PIC algorithm:
b_{bpic}/PIC = constant



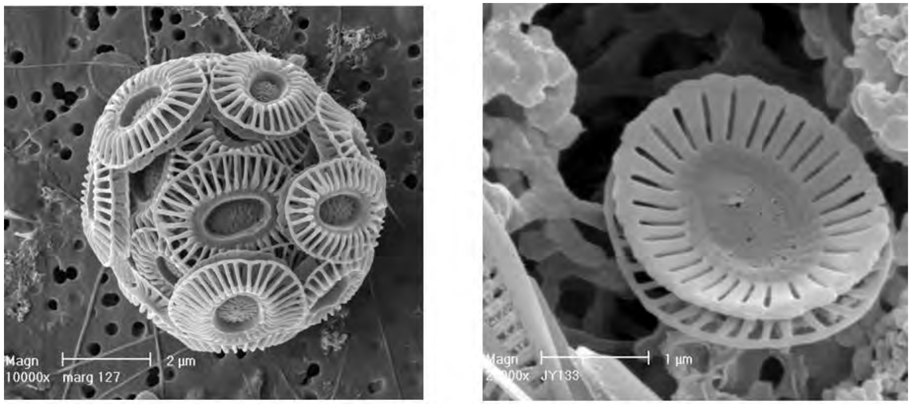
Neukermans and Fournier (2018) – F.Mar.Sci.

Optical modeling studies (ADA, DDA) show that b_{bpic}/PIC does not depend much on whether coccoliths are attached to are freed from the coccoshpere

(see also Gordon et al., 2009, Appl. Opt.)

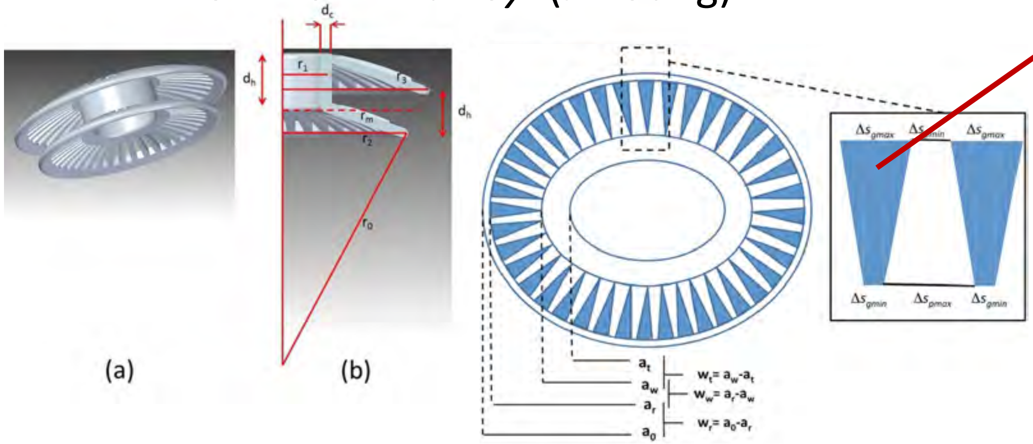
Light backscattering properties of *Ehux*

Strongly depend on coccolith morphology (and size, indirectly)

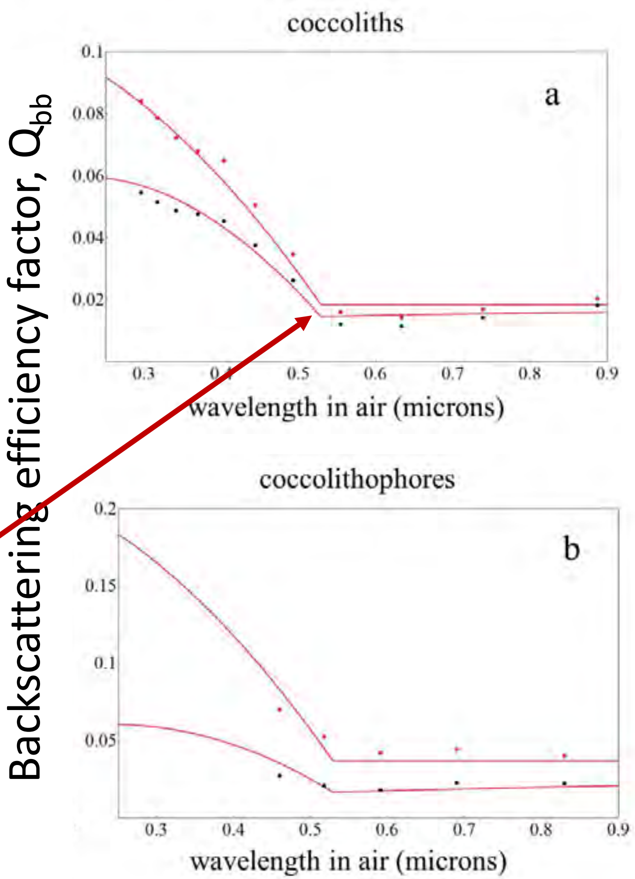


coccosphere **coccolith**

SEM of *E. huxleyi* (J. Young)



Model of *E. huxleyi* coccolith

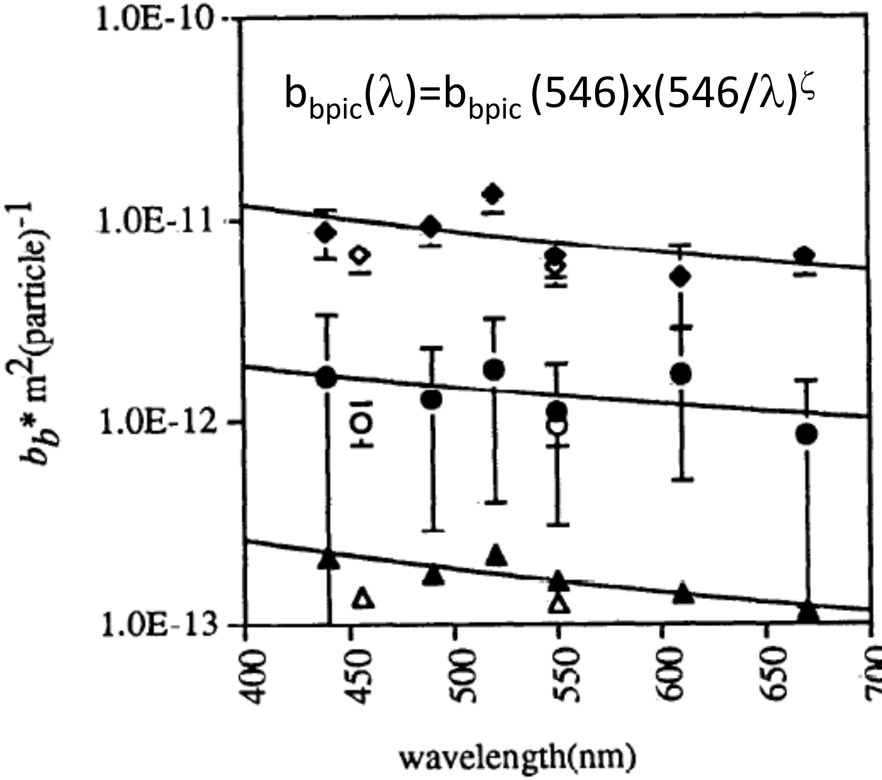


(Fournier and Neukermans, 2017, Opt. Expr.; Neukermans and Fournier, 2018, F.Mar.Sci.)

(see Gordon, 2006, Appl. Opt.; Gordon et al., 2009, Appl. Opt.; Zhai et al., 2013, Opt. Expr.)

Light backscattering properties of *Ehux*

Voss et al. , *L&O* (1998)



$$b_{bpic}(\lambda)=b_{bpic}(546)\times(546/\lambda)^{\zeta}$$

Fig. 6. Specific b_b coefficients (b_b*) as a function of wavelength for both the BP-derived and GASM-derived measurements. Open symbols are the GASM-derived coefficients; filled symbols are the BP-derived coefficients. Triangles correspond to coccoliths, diamonds to plated cells, and circles to naked cells. Also shown is the power law fit to each component (as discussed in the text). The exponent found for each component was −1.4, −1.2 and −1.0 for coccoliths, plated cells, and naked cells, respectively.

In culture

Note: high measurement uncertainty

Plated cells

ζ=1.2 ζ=0.77

Naked cells

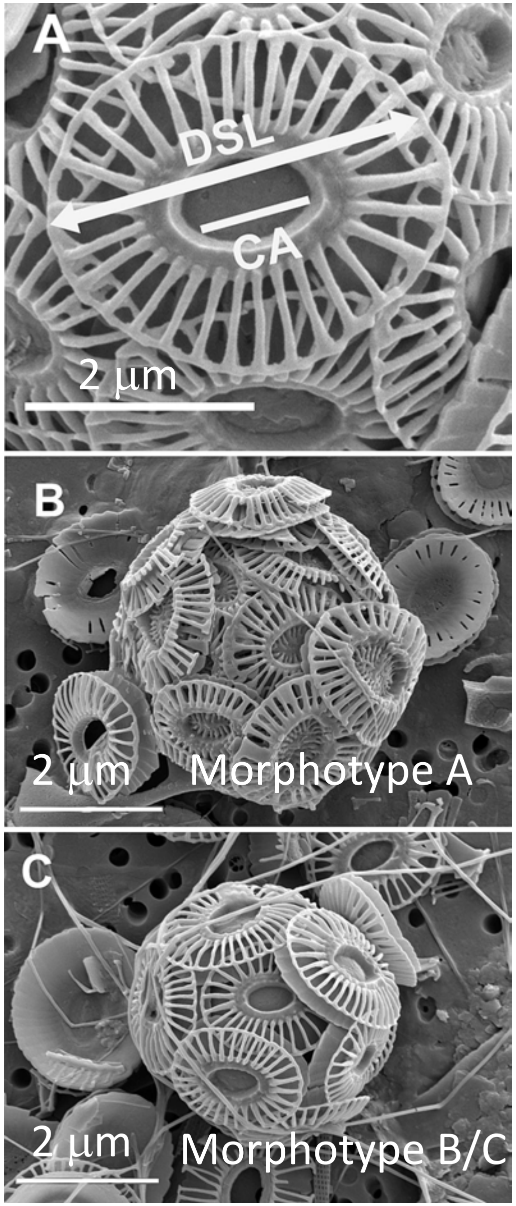
ζ=1.0

Free coccoliths

ζ=1.4 ζ=0.94

Model of Neukermans and Fournier (2018) – F.Mar.Sci.

Ehux has various morphotypes



Poulton et al., 2011 (MEPS)

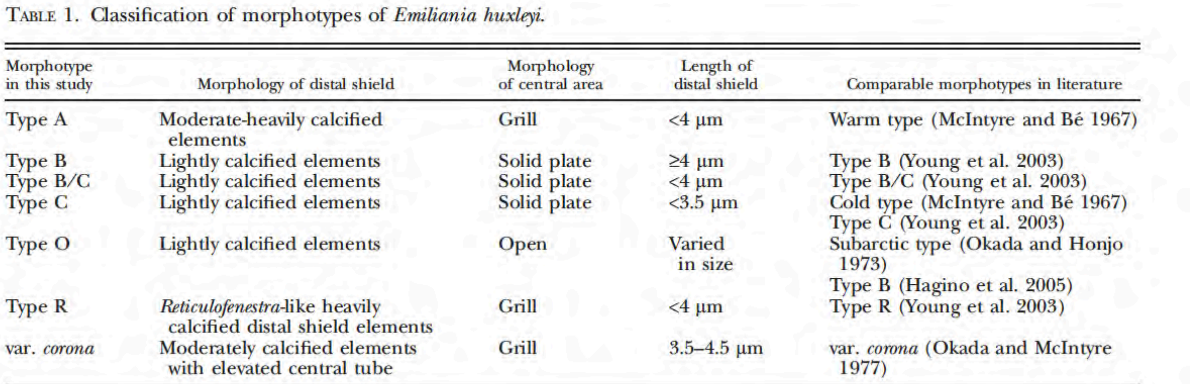
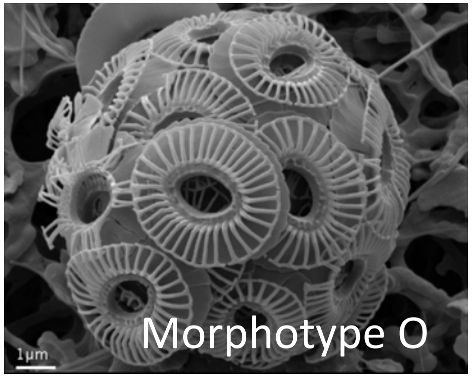


Table 1. Classification of morphotypes of *Emiliania huxleyi*.

Morphotype in this study	Morphology of distal shield	Morphology of central area	Length of distal shield	Comparable morphotypes in literature
Type A	Moderate-heavily calcified elements	Grill	<4 µm	Warm type (McIntyre and Bé 1967)
Type B	Lightly calcified elements	Solid plate	≥4 µm	Type B (Young et al. 2003)
Type B/C	Lightly calcified elements	Solid plate	<4 µm	Type B/C (Young et al. 2003)
Type C	Lightly calcified elements	Solid plate	<3.5 µm	Cold type (McIntyre and Bé 1967) Type C (Young et al. 2003)
Type O	Lightly calcified elements	Open	Varied in size	Subarctic type (Okada and Honjo 1973) Type B (Hagino et al. 2005)
Type R	*Reticulofenestra*-like heavily calcified distal shield elements	Grill	<4 µm	Type R (Young et al. 2003)
var. *corona*	Moderately calcified elements with elevated central tube	Grill	3.5–4.5 µm	var. *corona* (Okada and McIntyre 1977)

Hagino et al., 2011 (J. Phycol)

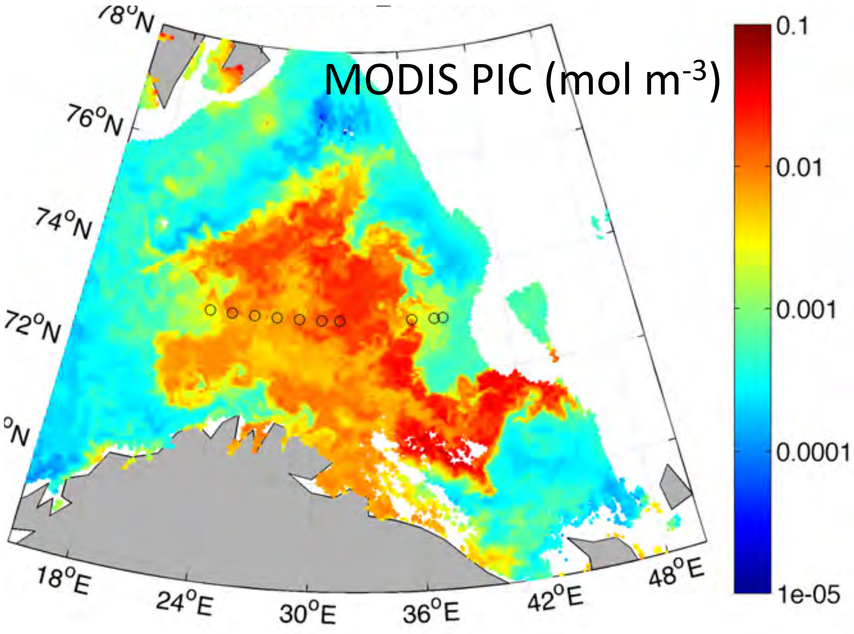
Different *Ehux* morphotypes are expected (in theory) to have different magnitude and spectral shapes for backscattering

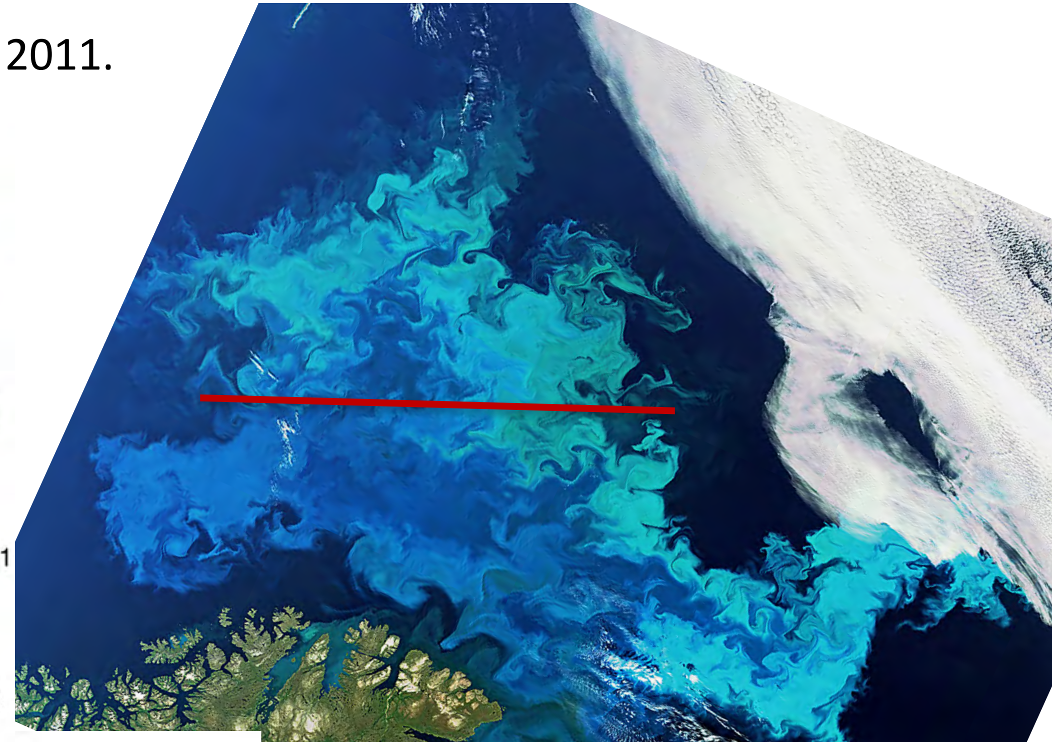


Images: Young, J.R., Bown P.R., Lees J.A. (2017) Nannotax3 website. International Nannoplankton Association. www.mikrotax.org/Nannotax3

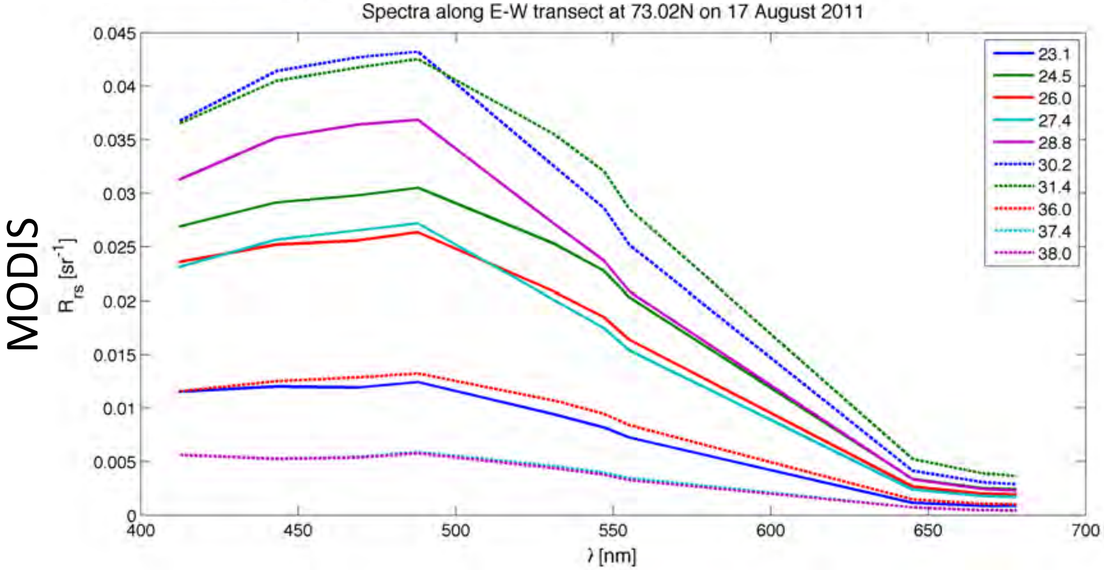
The milky-turquoise hue of *Ehux* bloom waters?

Ehux bloom in the Barents Sea, 17 August 2011.





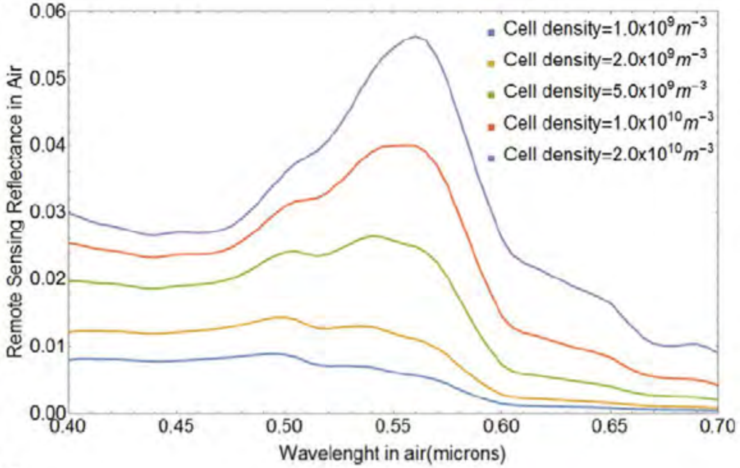
True Colour Composite from MODIS Aqua



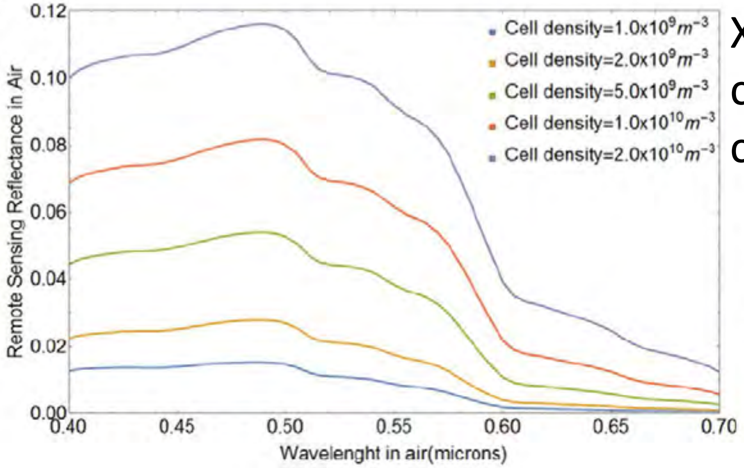
Spectra along E-W transect at 73.02N on 17 August 2011

The milky-turquoise hue of *Ehux* bloom waters?

All liths attached

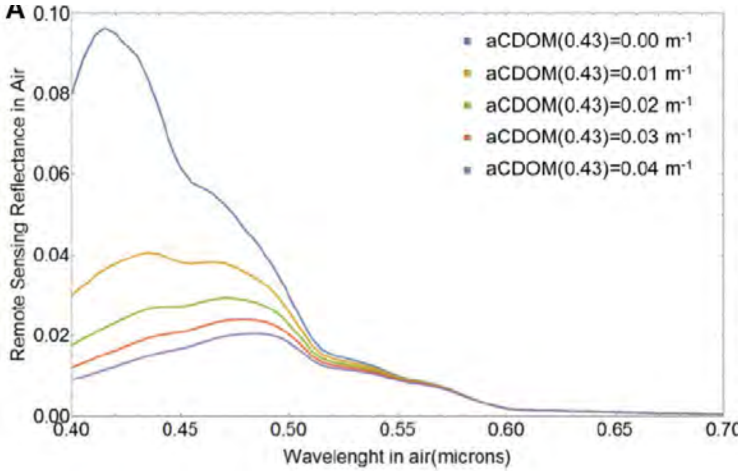


All liths freed

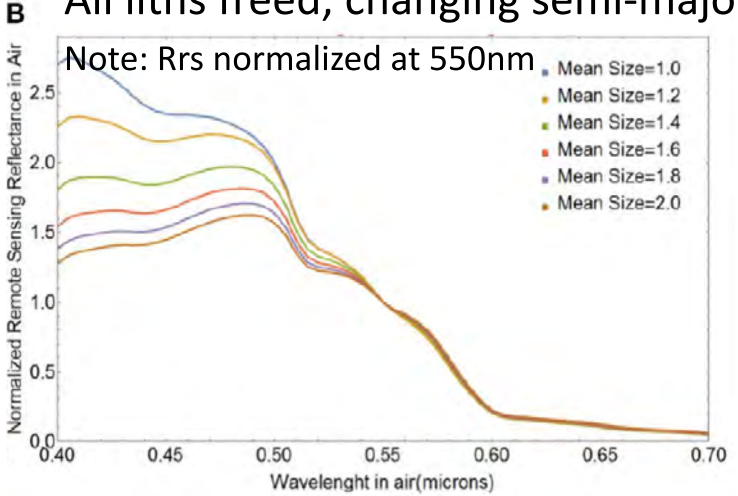


X 36 to get coccolith concentr.

All liths freed, changing CDOM



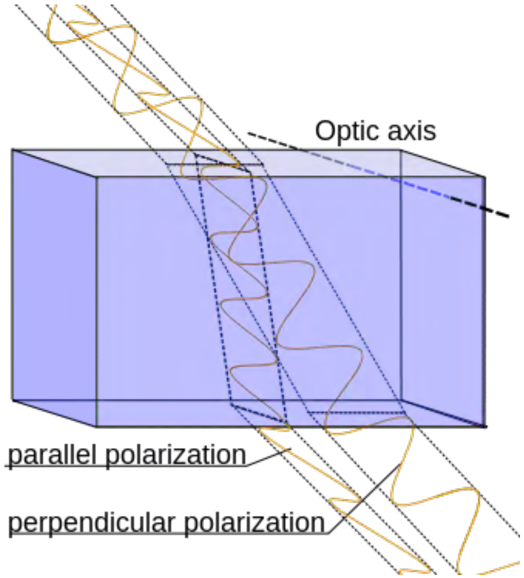
All liths freed, changing semi-major axis



Note: Rrs normalized at 550nm

Neukermans and Fournier, F.Mar.Sci. (2018)

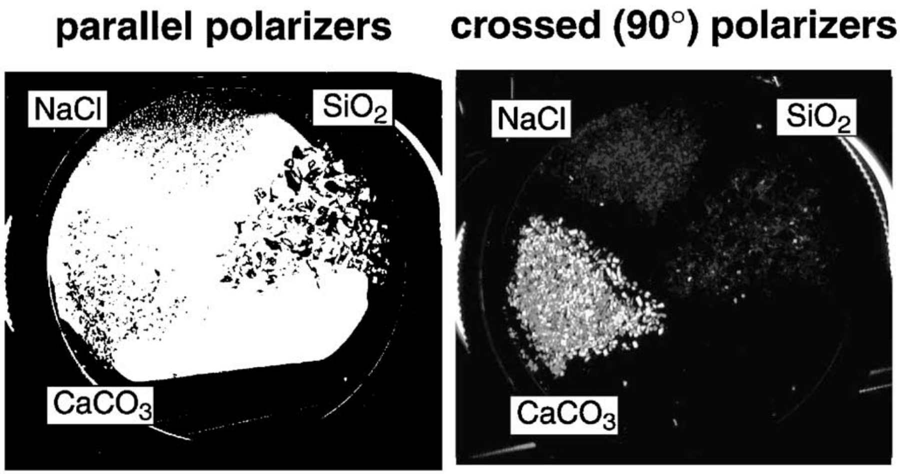
Calcite is strongly birefrigent



https://en.wikipedia.org/wiki/Birefringence

"Birefringence refers to the ability of a mineral crystal to split an incident beam of linearly polarized light into two beams of unequal velocities (corresponding to two different refractive indices of the crystal), which subsequently recombine to form a beam of light that is no longer linearly polarized."

Birefringence can be detected by measuring the changes in the polarization of light passing through the material (e.g., polarized light microscopy)



Guay and Bishop, *Deep Sea Res.* (2002)

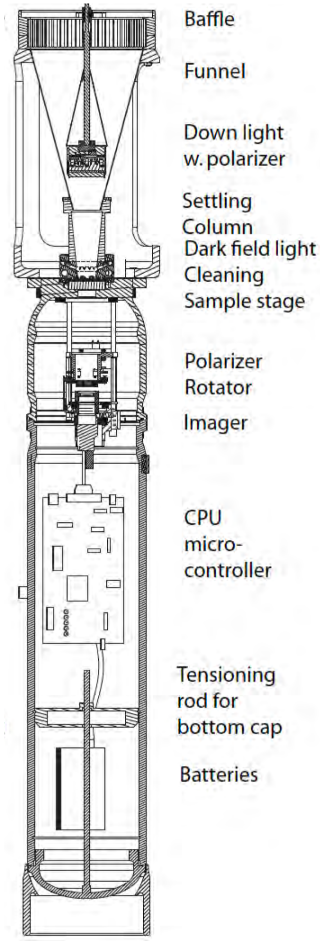
Provided the basis for an in situ marine PIC sensor (the Carbon Flux Explorer – Bishop *et al.*, 2016, Biogeosciences)

Spectrophotometer technique= transmittance + linear polarizers

Carbon Flux Explorer

Designed to perform sustained high-frequency observations of POC and PIC sedimentation within the ocean’s twilight zone

Bishop *et al.*, 2016,Biogeosciences



marine-snow aggregate of about 1cm

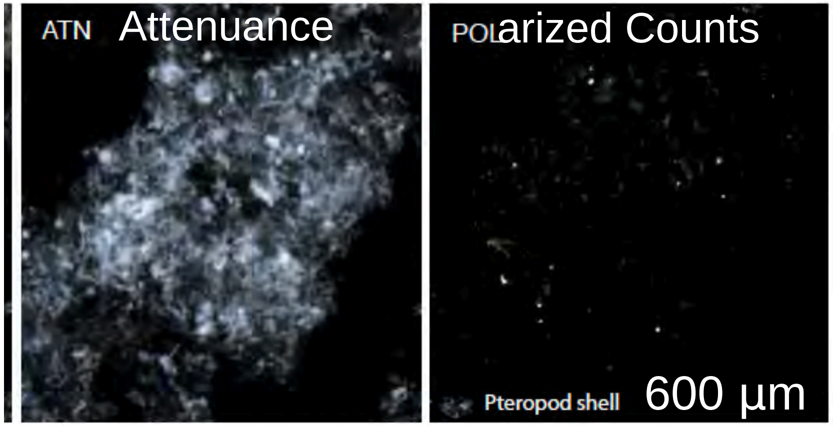


Image resolution is 13 µm.

Bright spheres = 200 µm sized foraminifera shells

Not (yet) fully autonomous (due to image processing)

Resolution too coarse to resolve coccolithophores…

This course covers

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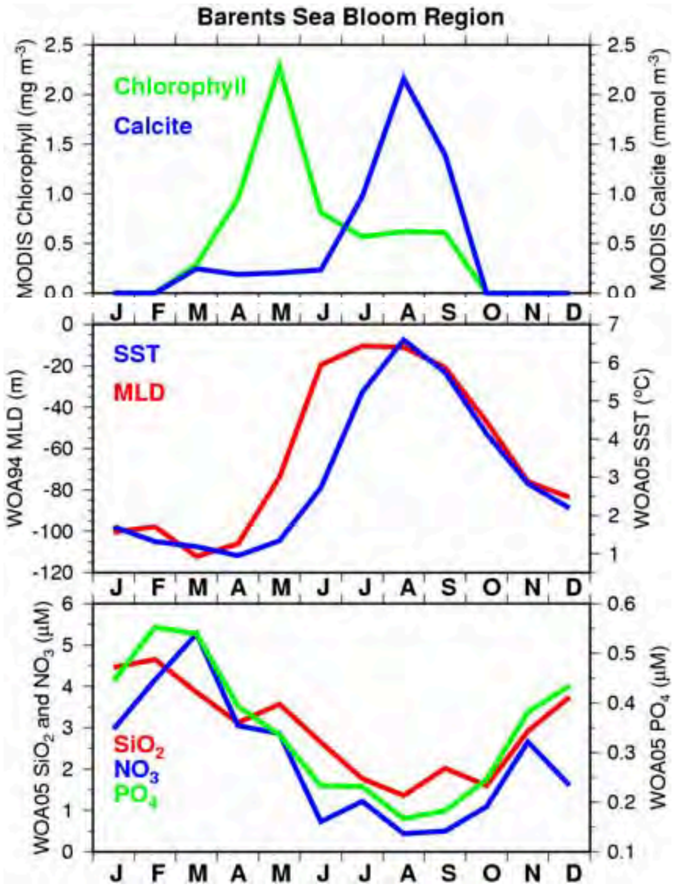
  - Quantifying PIC in the ocean
  - Caveats of remotely sensed PIC
- Optical properties of coccolithophores
  - Scattering, backscattering, and absorption
  - Reflectance
  - Birefrigence
- **Some applications of optical oceanography in coccolithophore research**
  - **Ecology (environmental control of coccolithophore blooms, phenology, ocean albedo)**
  - **Climate change impacts**
  - **Biogeochemistry (influence on $pCO_{2,}$ calcite ballast effect)**

Environmental control of coccolithophore blooms

Signorini and McClain (2009 –GRL)

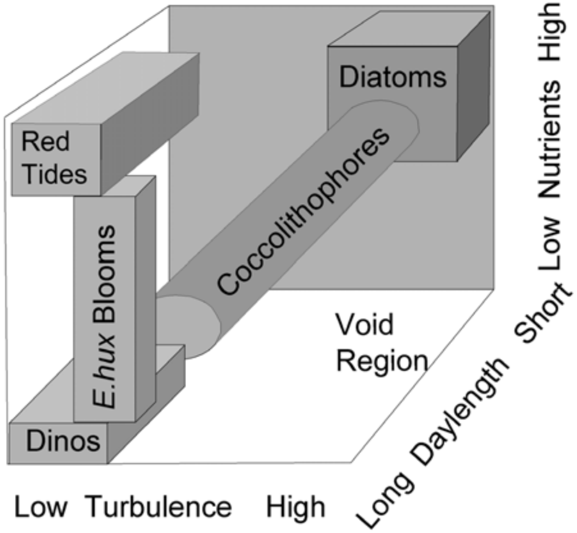


Large-scale seasonal blooms of *Ehux* detected by OC satellites are generally associated with:

- Temperate and subpolar waters
- After a diatom Spring bloom (succession)
- Relatively high critical irradiances
- Stable water column
- Declining nutrients

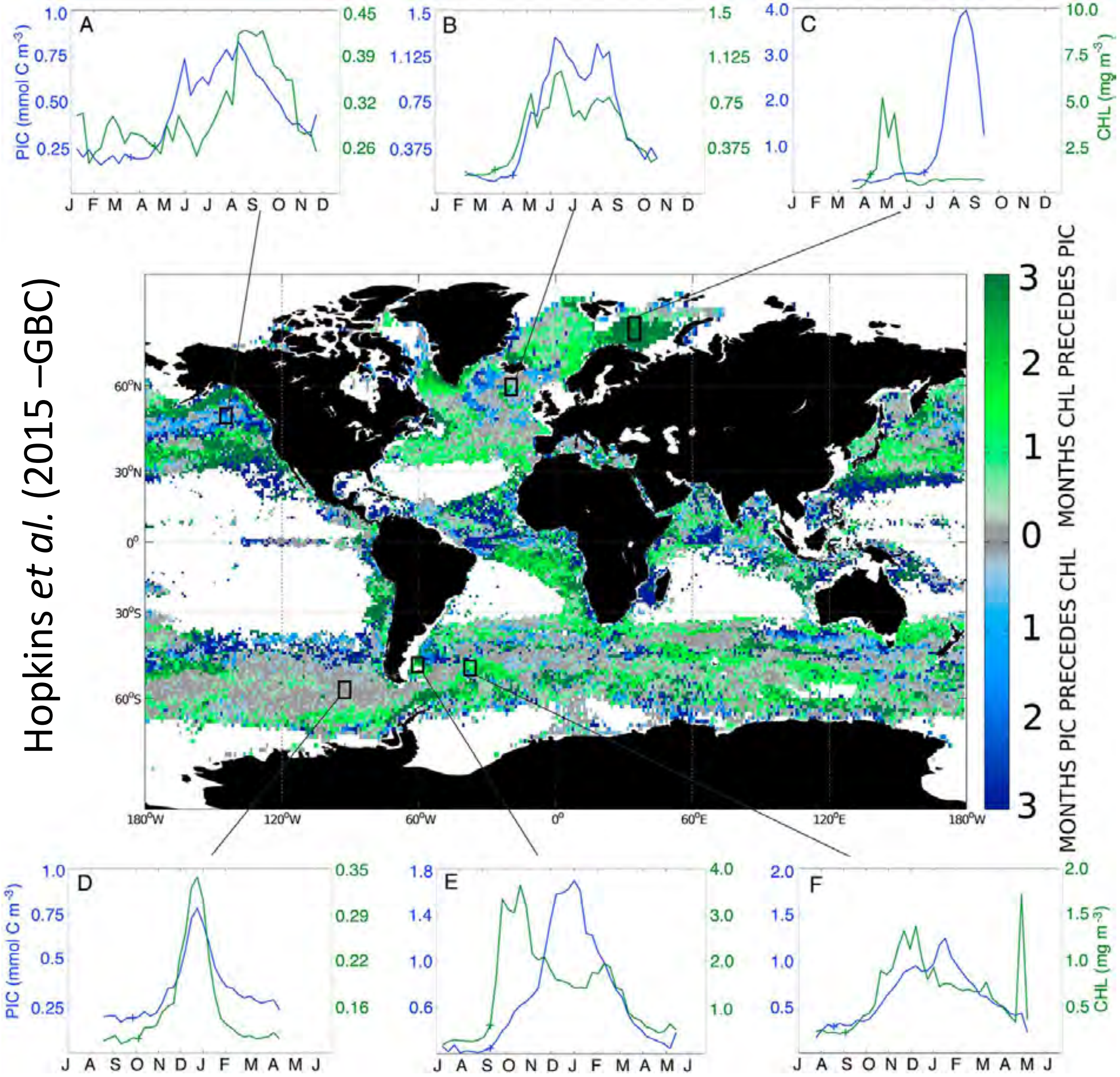
[see Iglesias-Rodrigez et al., 2002; Tyrrell and Mercio, 2004; Balch 2004; Signorini and McClain, 2009]

Balch (2004), adapted from Margalef (1978)



Succession or coexistence of phytoplankton populations

Margalef's (1978)   Barber and Hiscock (2006)



Hopkins *et al.* (2015 –GBC)

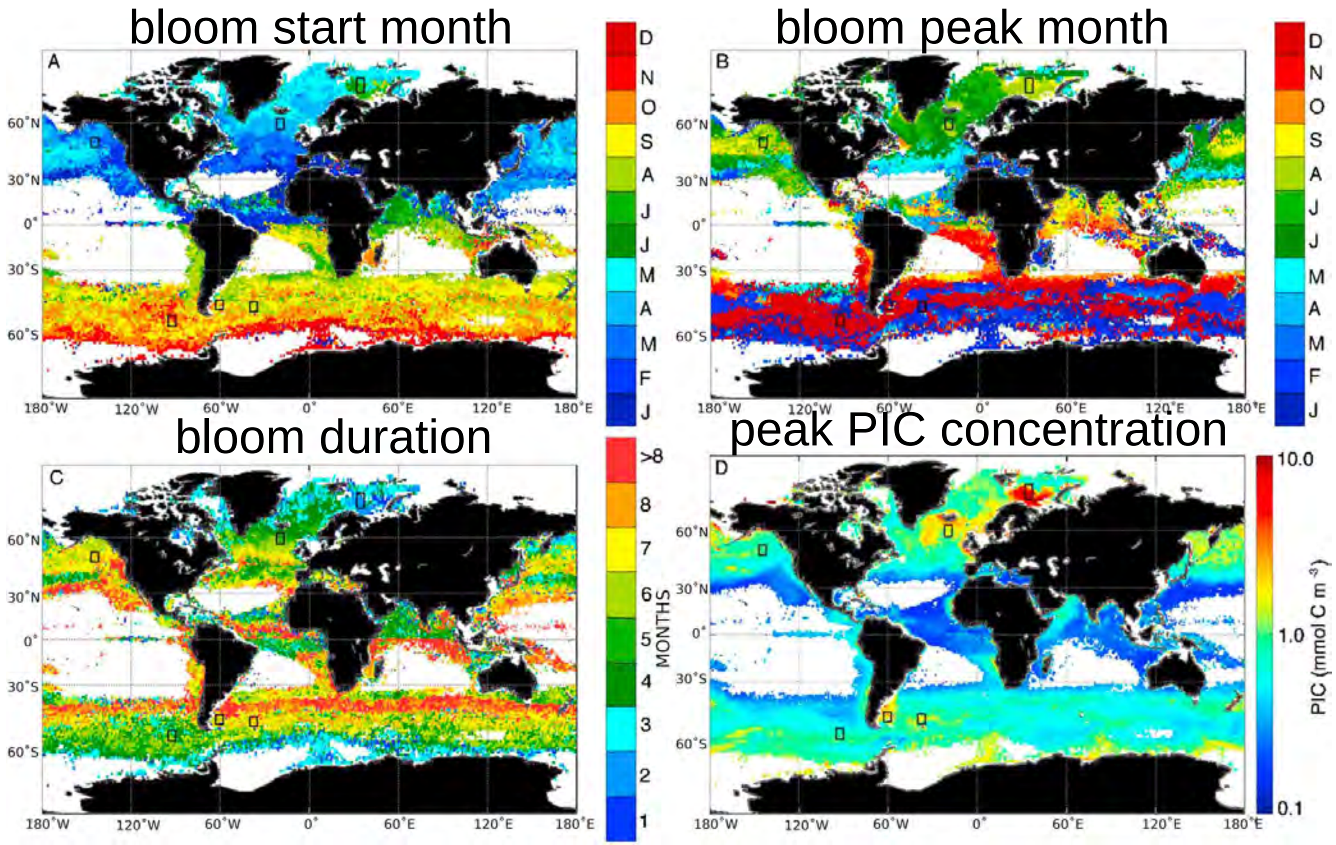
Succession: shelf regions, upwelling areas, and the HLNA in support of Margalef's suggestion that environmental changes promote the proliferation of one taxa at the expense of another.

Coexistence: across much of the open ocean in support of Barber and Hiscock (2006)'s suggestion of coexistence through differences in biomass accumulation rates, while actual competition between the two populations is kept in check through variability in nutrient uptake rates and shifts in the dominant grazers and the overall food web structure.

Coccolithophore phenology

Seasonal variability in PIC is identified across much of the global ocean

Hopkins *et al.* (2015 –GBC)



bloom start month

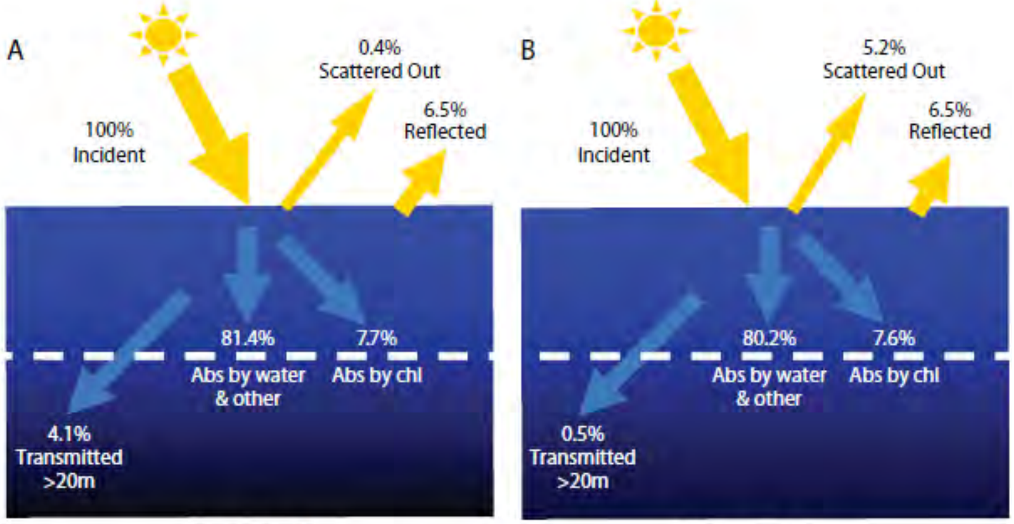
bloom peak month

bloom duration

peak PIC concentration

Based on MODIS 8-day PIC climatology (2003-2012)

Ehux blooms: brighter surface ocean, darker deeper down



0 mg PIC m^{-3} 300 mg PIC m^{-3} =0.025 mol C m^{-3}

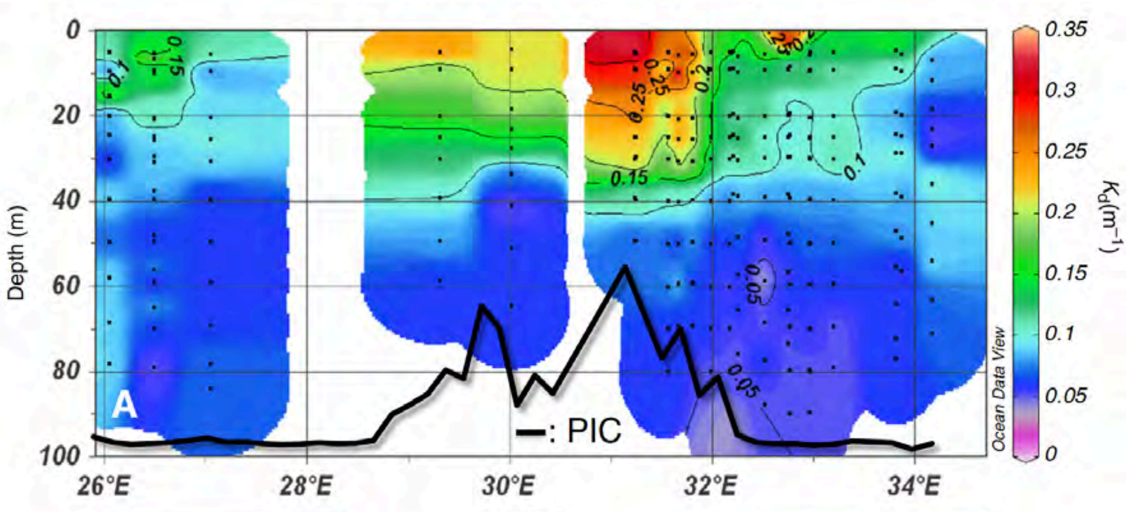
Figure 2. Photon budgets for water with (A) no particulate inorganic carbon (PIC) vs. (B) 300 μgPIC L^{-1}. Values are based on incoming irradiance of 1100 μEin m^{-2} s^{-1}, wind speed = 5 m s^{-1}, cloud cover = 25%, chl = 0.75 μg L^{-1}, and solar zenith angle = 45°. 1 Einstein = 1 mole of photons (or Avogadro's number of photons: 6.02×10^{23}). *Optical modeling results redrawn from Tyrell et al. (1999)*

Ehux blooms increases ocean albedo

Contribution to global annually averaged planetary albedo is about 0.13%

(Tyrrell *et al.*, 1999 - *JGR*)

But, strong local effects:



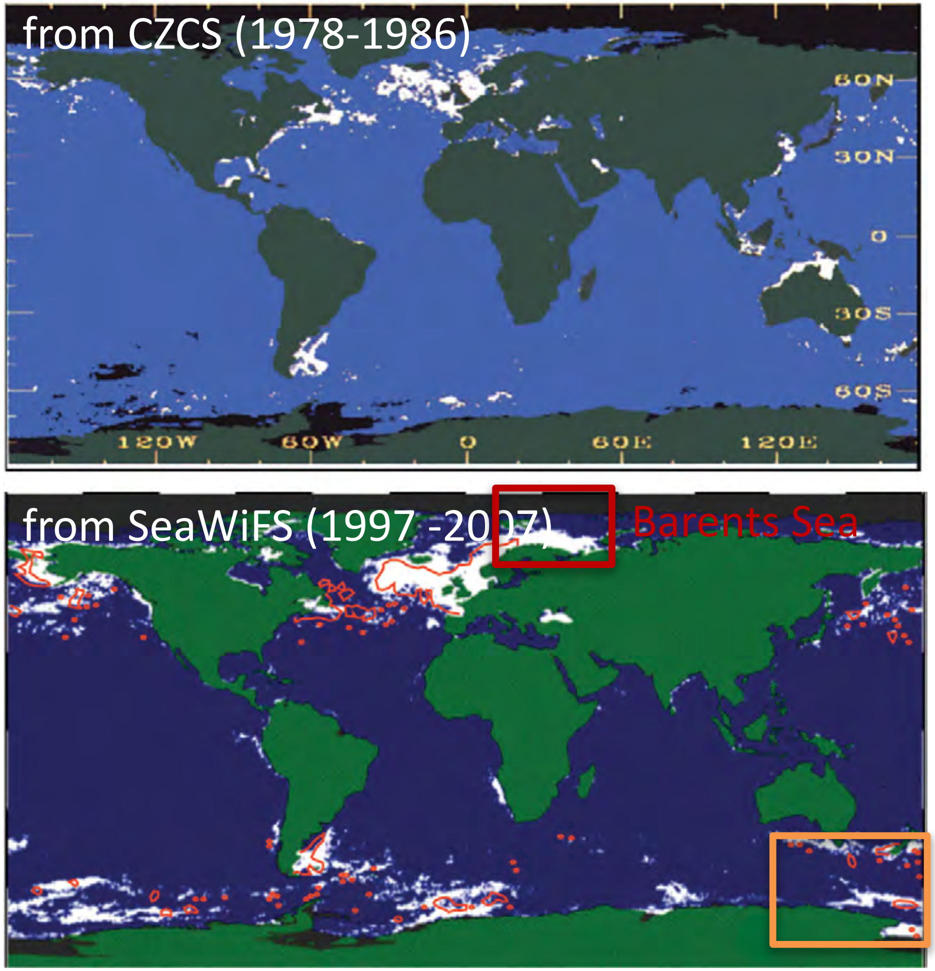
Ehux blooms shoal the euphotic zone, diminishing the light available for deeper algal species, **limiting photosynthesis at depth by** 20–40% where nutrient levels are otherwise sufficient

(Hovland *et al.*, 2013- *J. Mar. Sys.*)

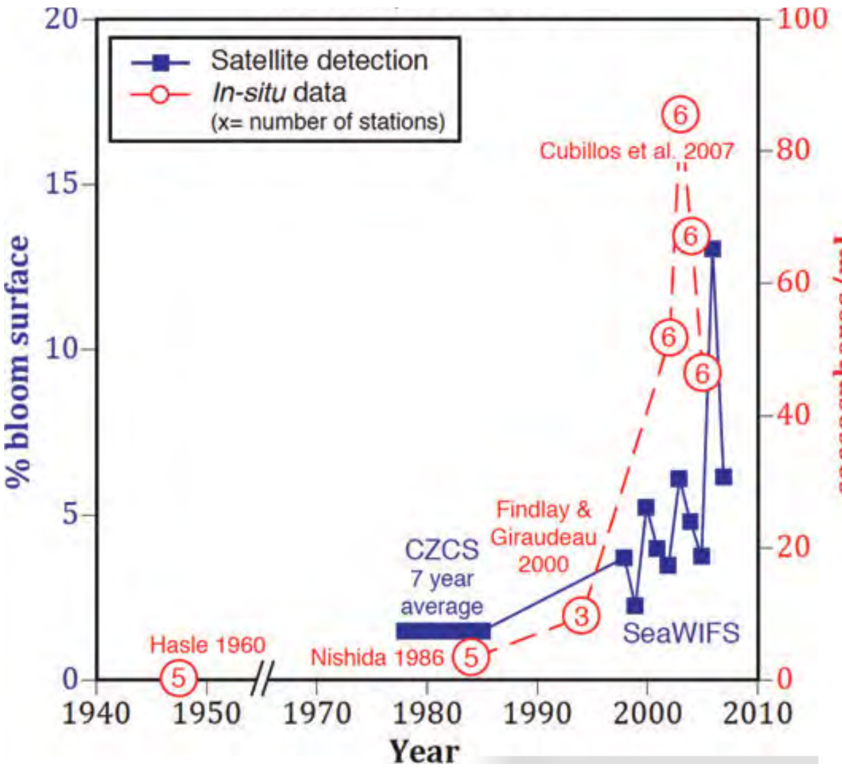
Poleward expansion of *Ehux*

Proposed by Winter *et al.* (2014 – *J. Plankton Res.*), based on OCRS (CZCS and SeaWiFS) and in situ data.

Climatology of classified coccolithophore blooms



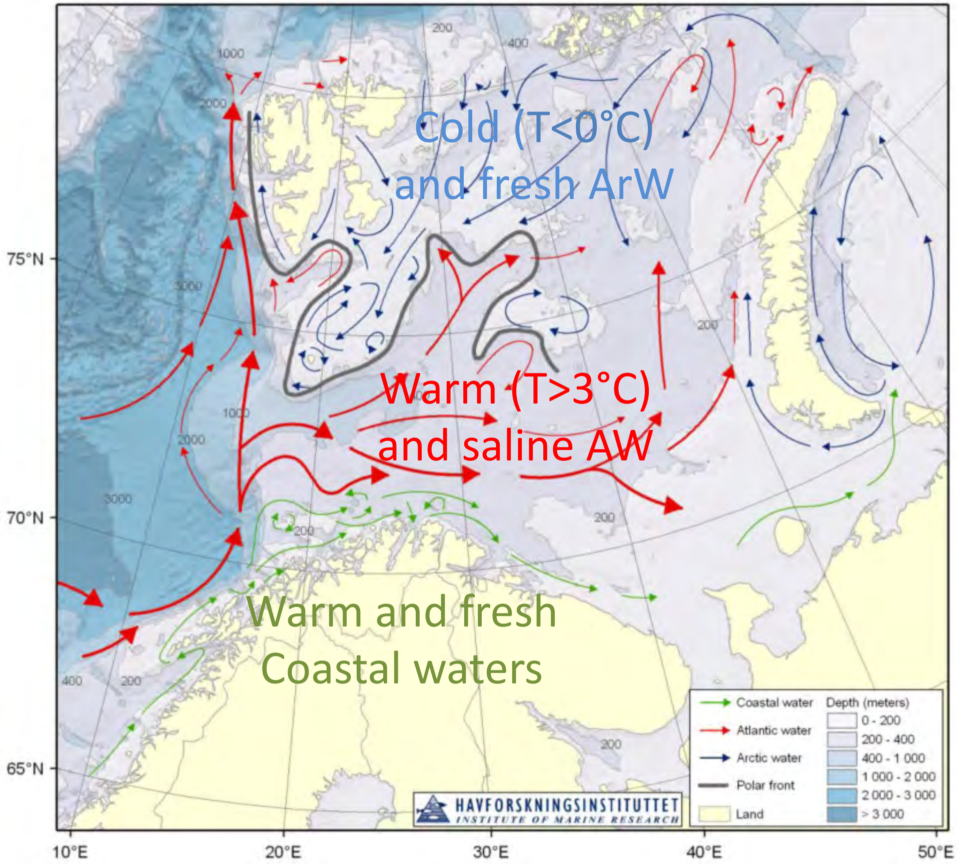
Coccolithophore data within 30°-70°S /130°-170°E



Bloom size and intensity increased in the 1990s. Why?

Poleward expansion of *E. huxleyi* blooms: On an Arctic inflow shelf (Barents Sea)

Neukermans *et al.* (*Glob. Change Biol., 2018*)

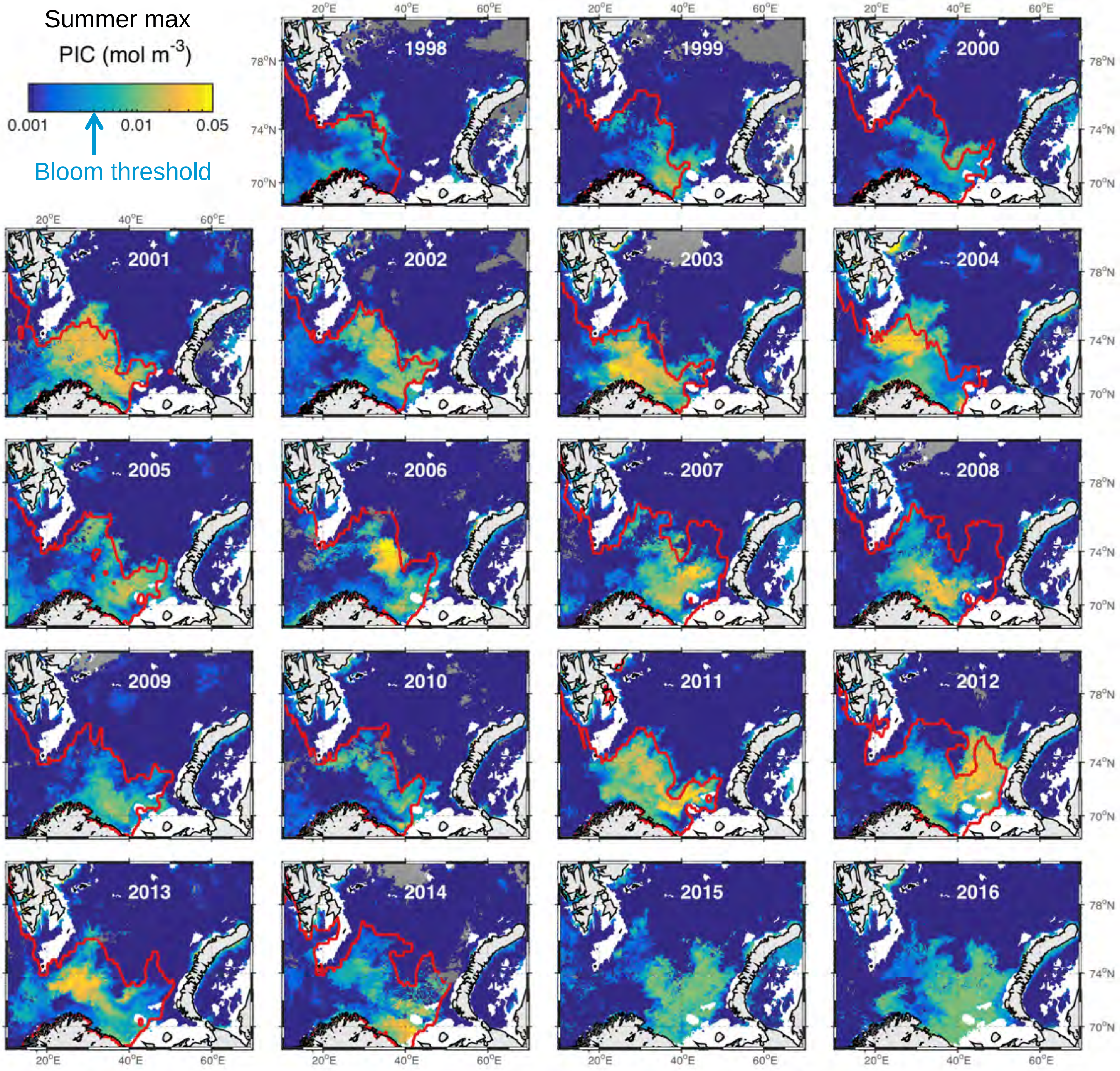


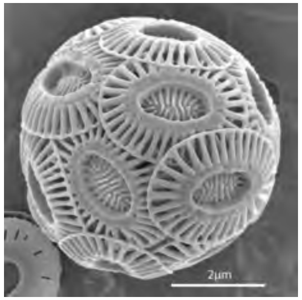
Approach:

Combine long-term (1980s-2016) remote sensing data of *Ehux* blooms with remote sensing data of the physical environment (sea surface temperature and sea ice)

Poleward expansion of *Emiliania huxleyi* blooms in the Barents Sea

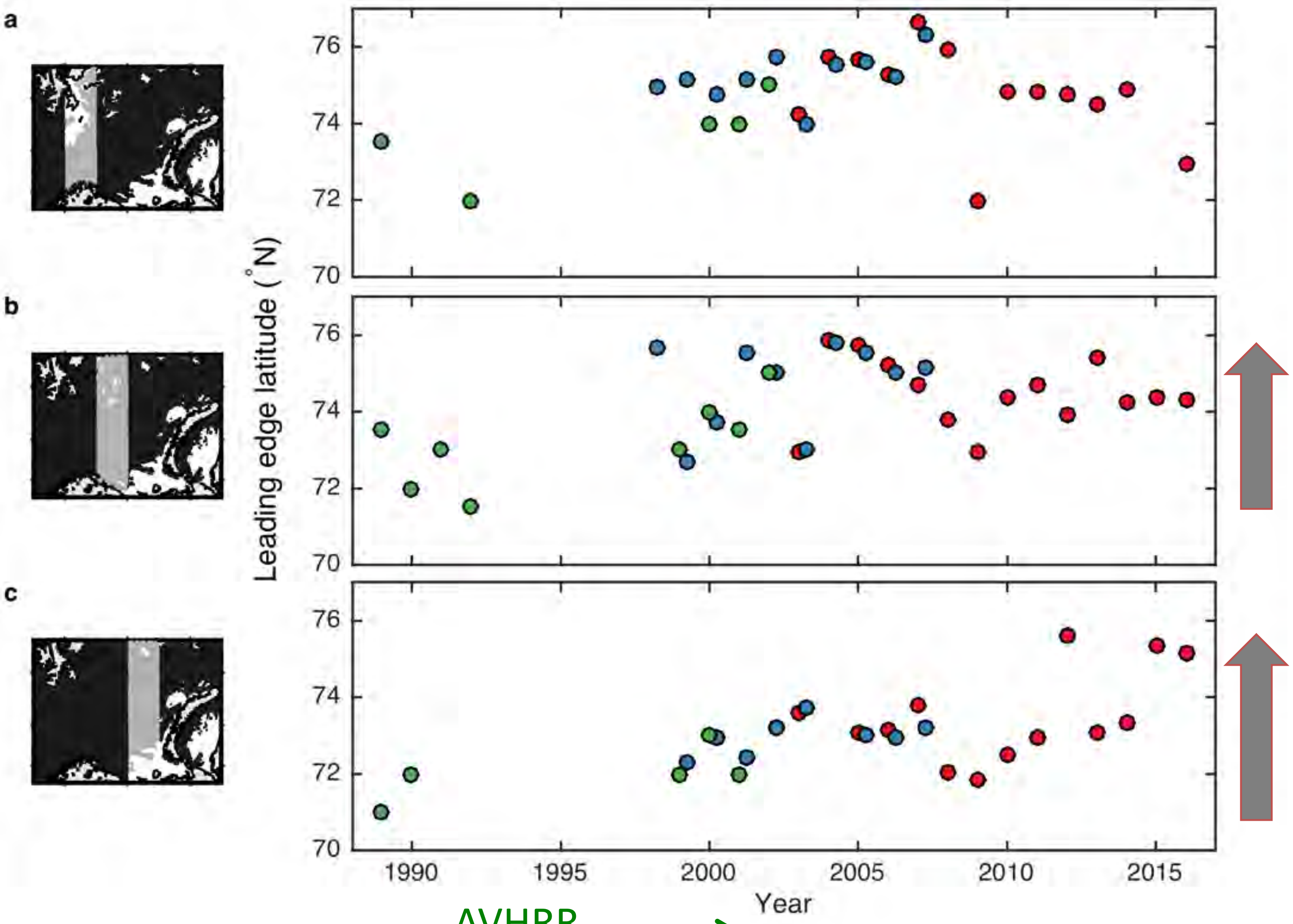
and Atlantic waters





Neukermans *et al.* (*Glob. Ch. Biol.*, 2018)

Poleward expansion of *E. huxleyi* blooms



Range shift

n.s.

390 km
(1989-2016)

501 km
(1989-2016)
56 km/yr
(2010-2016)

Neukermans *et al.* (*Glob. Ch. Biol.*, 2018)

AVHRR

SeaWiFS

MODIS

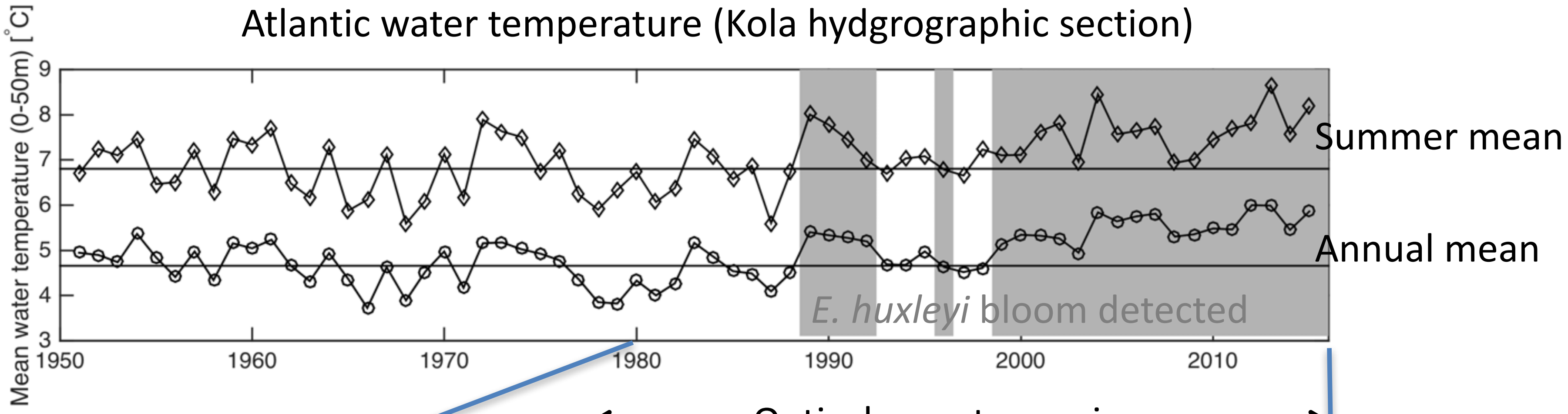
Smyth *et al.* (2004 – *Geophys. Res. Lett.*)

Global mean rate for: marine species = 7.2 km/yr, phytoplankton = 35.8 km/yr, zooplankton = 14.2 km/yr

Poloczanska *et al.* (2013– *Nat. Clim. Ch.*)

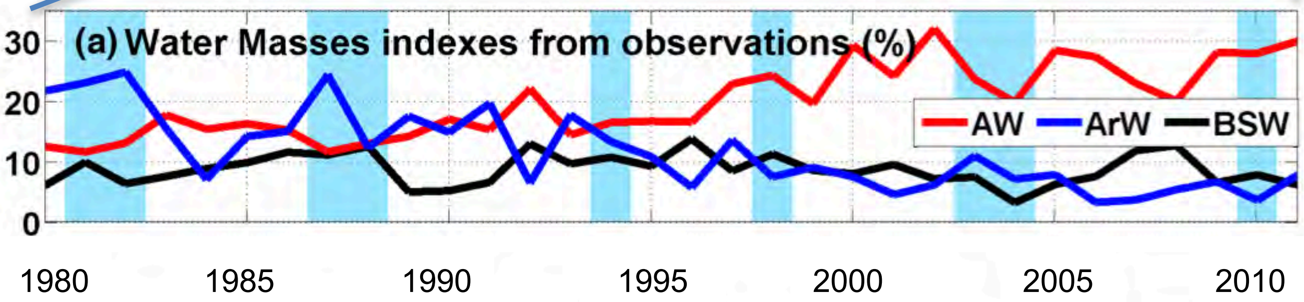
Poleward expansion of *E. huxleyi* blooms

Atlantic water temperature (Kola hydgrographic section)



Neukermans *et al.* (*Glob. Ch. Biol., 2018*)

⟵ Optical remote sensing ⟶



(Oziel *et al.*, 2016 – *Ocean Sci.*)

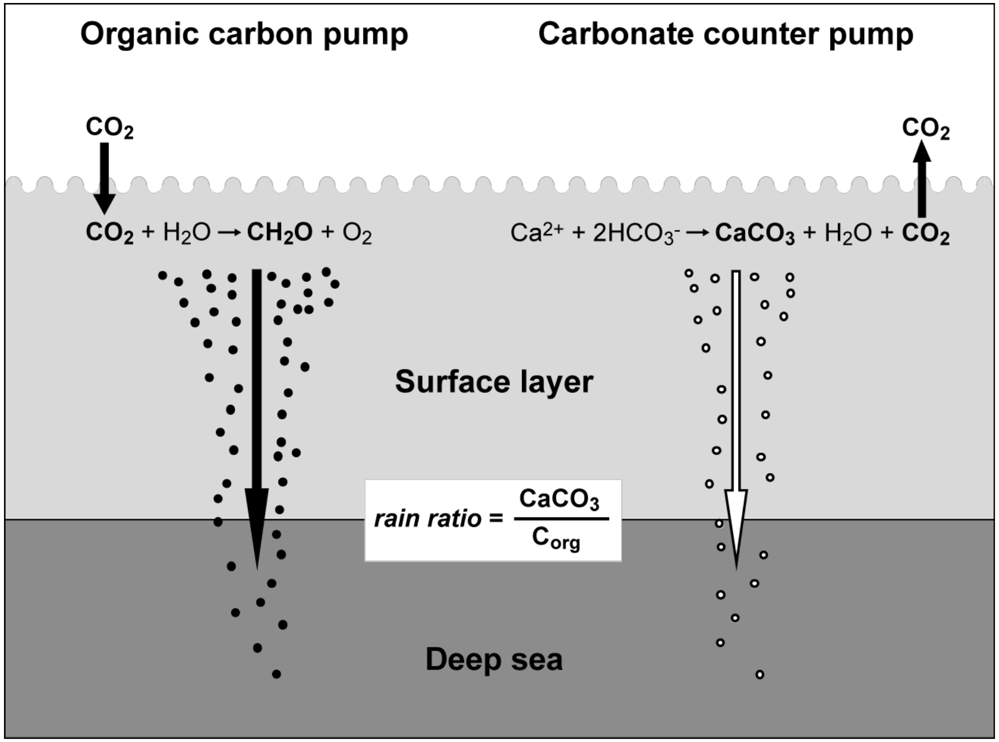
Atlantic Water volume tripled ➔*Atlantification* (Arthun *et al.*, 2012 – *J. Clim.*)

Poleward expansion in the Barents Sea is driven by increased intrusion and warming of Atlantic waters

Role of Coccolithophores in Ocean carbon cycle

The biological carbon pumps

Organic carbon pump: Photosynthetic production of organic matter in the surface layer and its subsequent transport to depth generates a CO_2 sink in the ocean.



Carbonate counter pump: $CaCO_3$ production and its transport to depth, releases CO_2 in the surface layer.

The relative strengths of these two pumps (rain ratio) largely determine the biologically mediated ocean atmosphere CO_2 exchange.

Rost and Riebesell (2004)

Role of Coccolithophores in Ocean carbon cycle

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Using 10 years of SeaWiFS data of classified *Ehux* blooms in the North Atlantic and climatologies of pCO_2 in air, seawater, salinity, solubility and gas transfer velocity :

It was estimated that *Ehux* blooms can **reduce the annual net sink of atmospheric CO_2 by 3–28 %.**

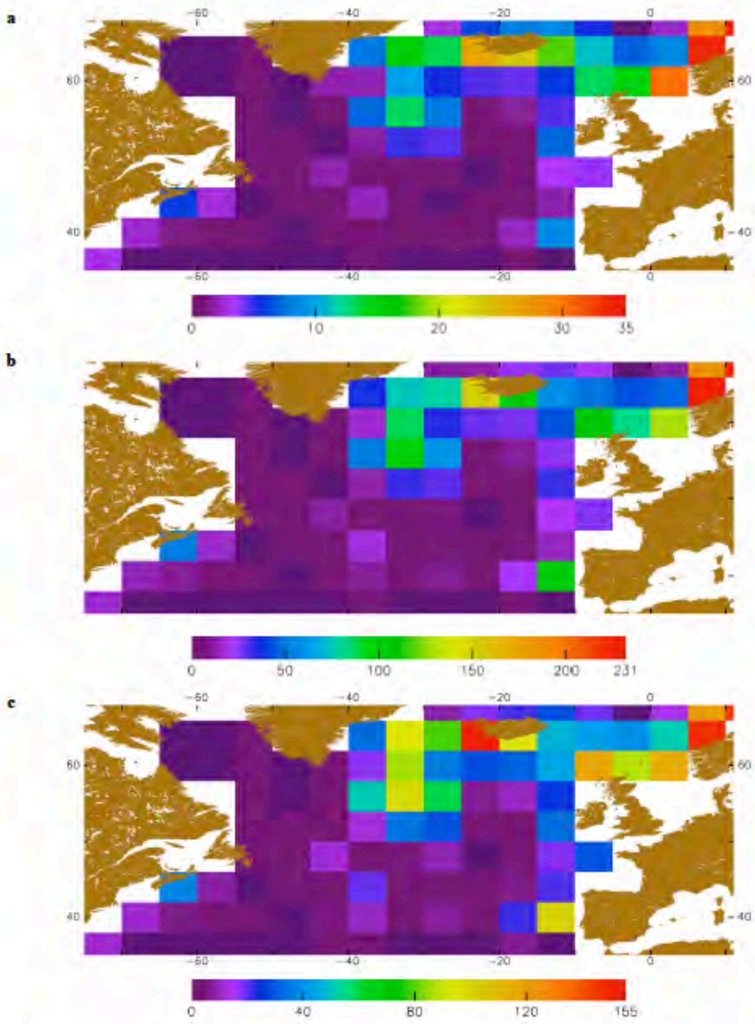


Fig. 4. Spatial distribution of the maximum impact of Emiliania huxleyi on the monthly air-sea CO_2 flux for years 1998–2007. **(a)** Percentage increase in seawater partial pressure pCO_2 (0–35 %); **(b)** Percentage decrease in air-water partial pressure difference ΔpCO_2 (0-231 %); **(c)** Percentage decrease in air-sea CO_2 flux (0–155 %).

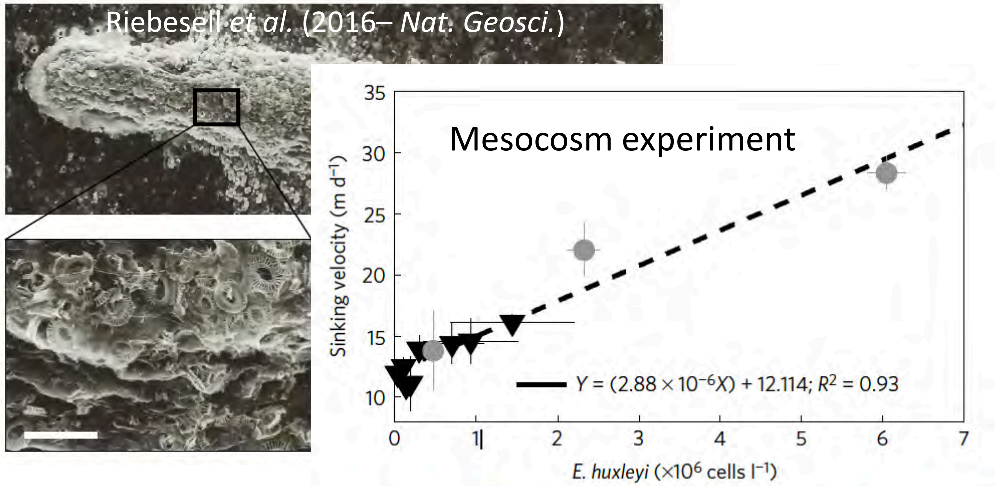
Shutler *et al.* (2013– *Biogeosciences*)

Role of Coccolithophores in Ocean carbon cycle

Ballast hypothesis: *E. huxleyi* calcite material ballasts organic carbon by increasing sinking speed and protecting organic carbon from remineralisation (François *et al.*, 2002)

widely debated and poorly understood

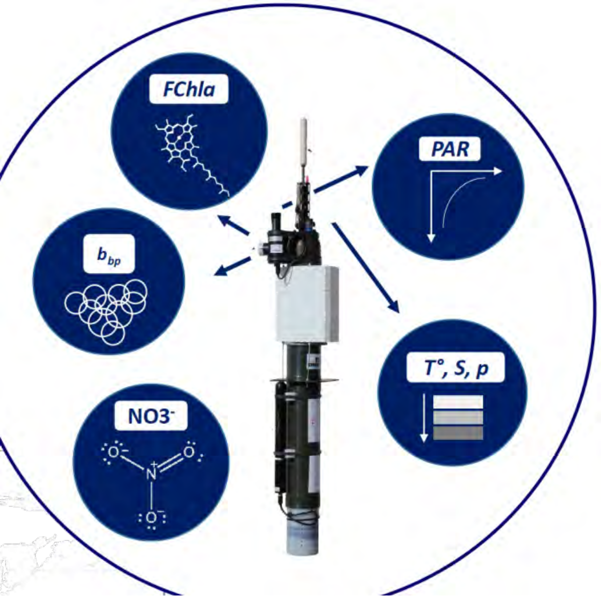
Hampered by paucity and limited resolution of traditional particle flux measurements (from sediment traps and radiochemical tracers)

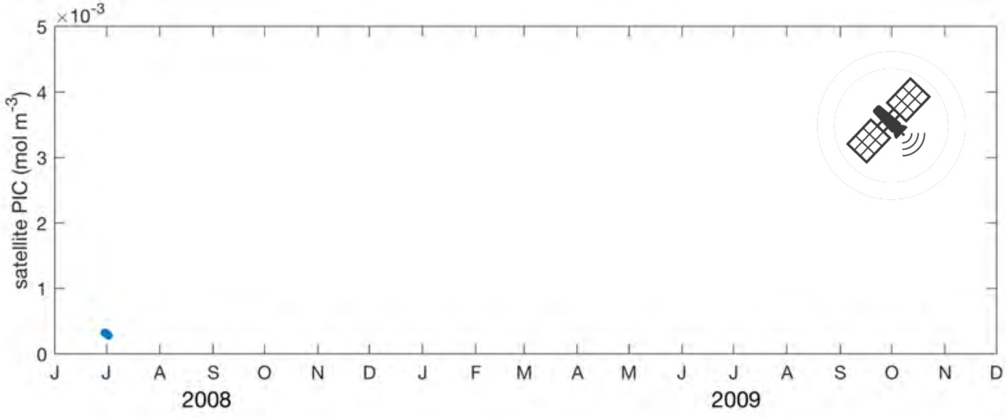

Riebesell *et al.* (2016– *Nat. Geosci.*)

Can we **examine calcite ballasting** using bio-optical measurements on Biogeochemical-Argo floats?

1. Can we identify coccolithophore blooms from floats?
2. Can we quantify associated sinking particle (carbon) fluxes?

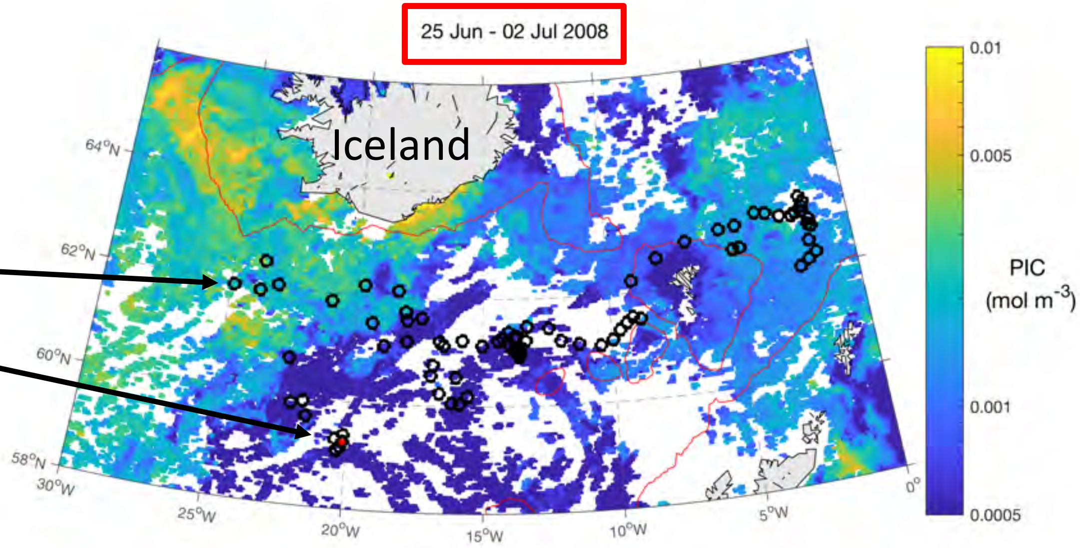
Observing *E. huxleyi* blooms with BGC-Argo floats





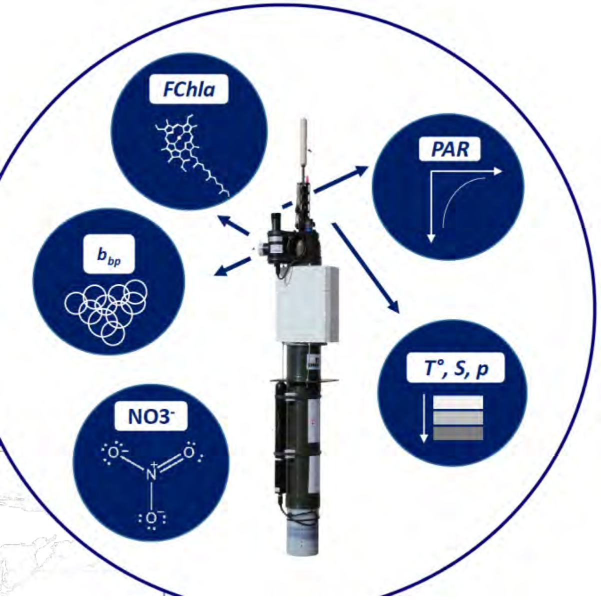
Profiles on float trajectory ○

Current float position 🔴



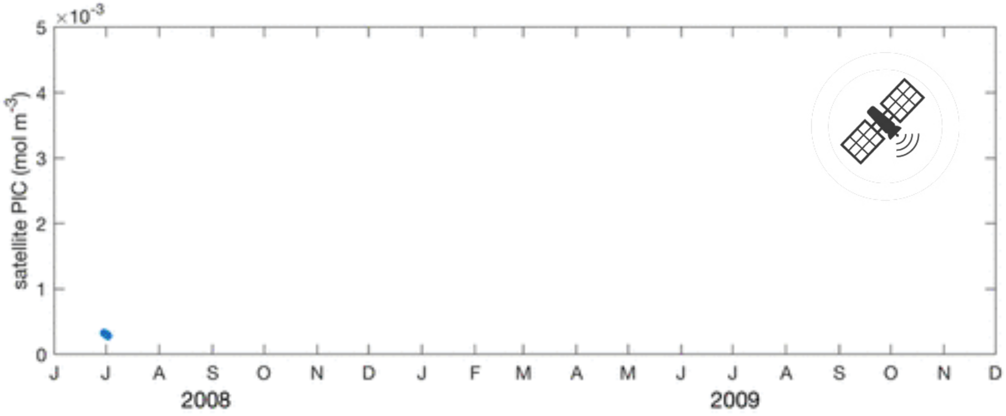
Neukermans *et al.* (*in prep.*)

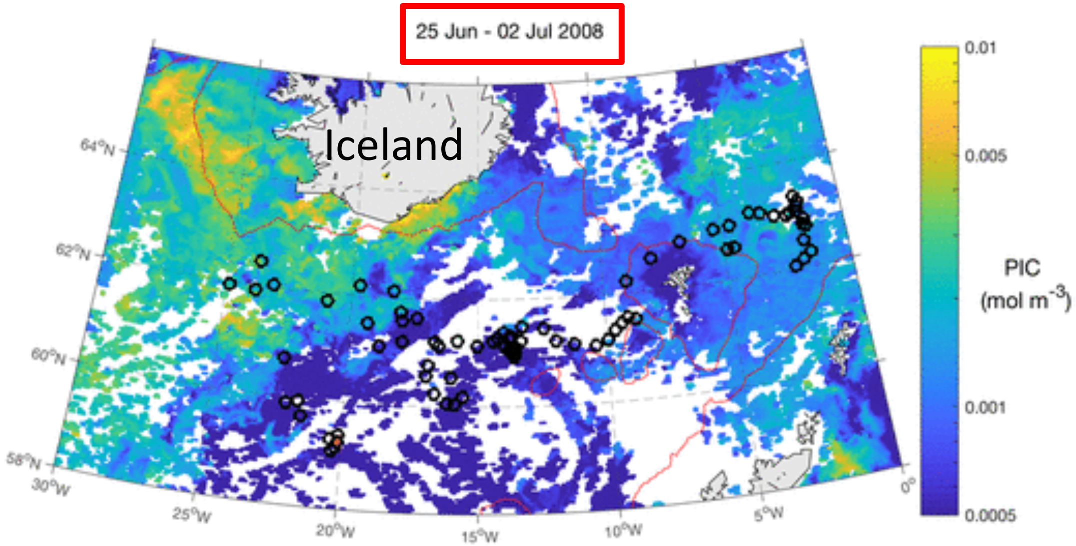
Observing *E. huxleyi* blooms with BGC-Argo floats



Profiles on float trajectory ○→

Current float position ●→





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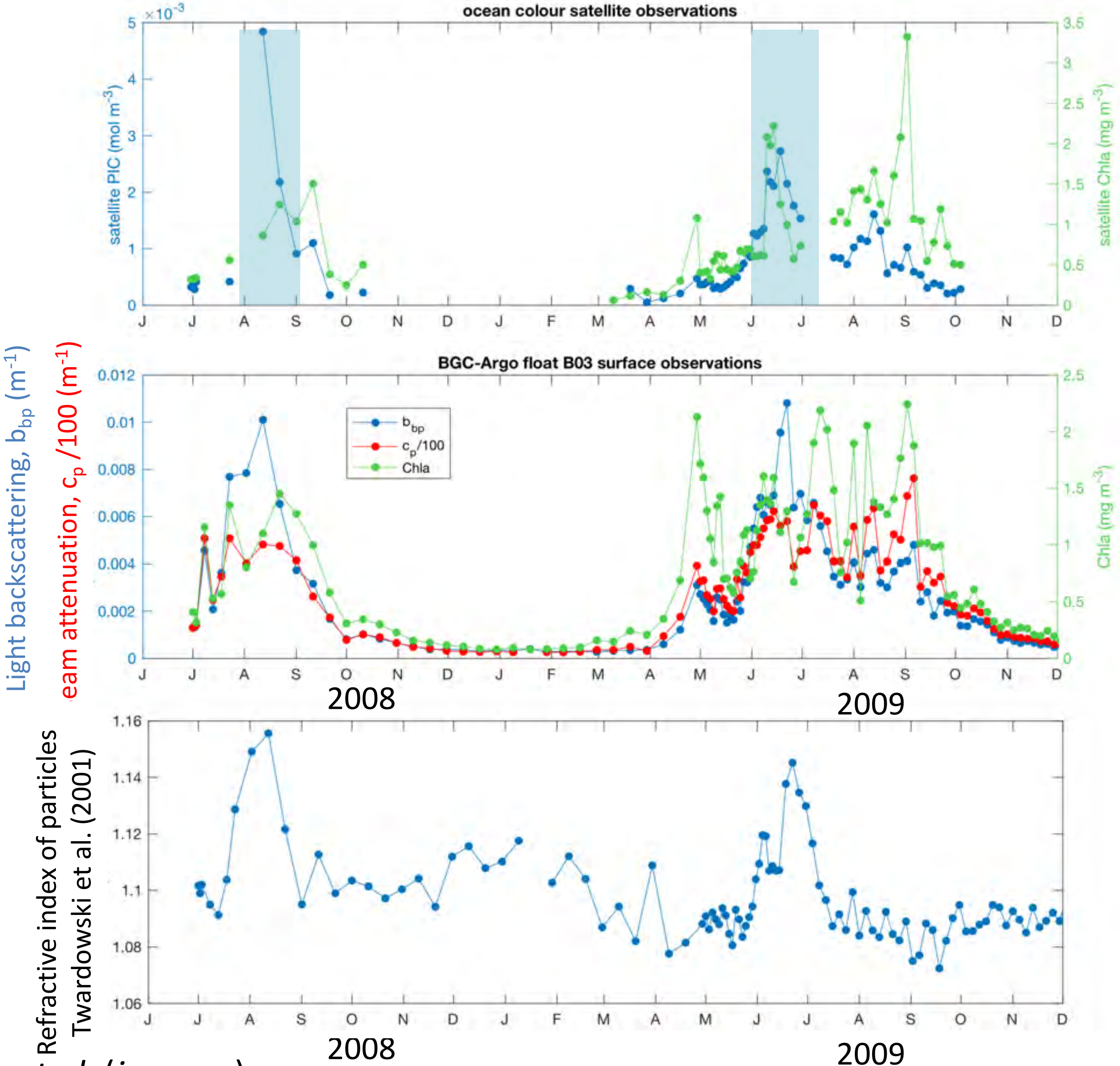

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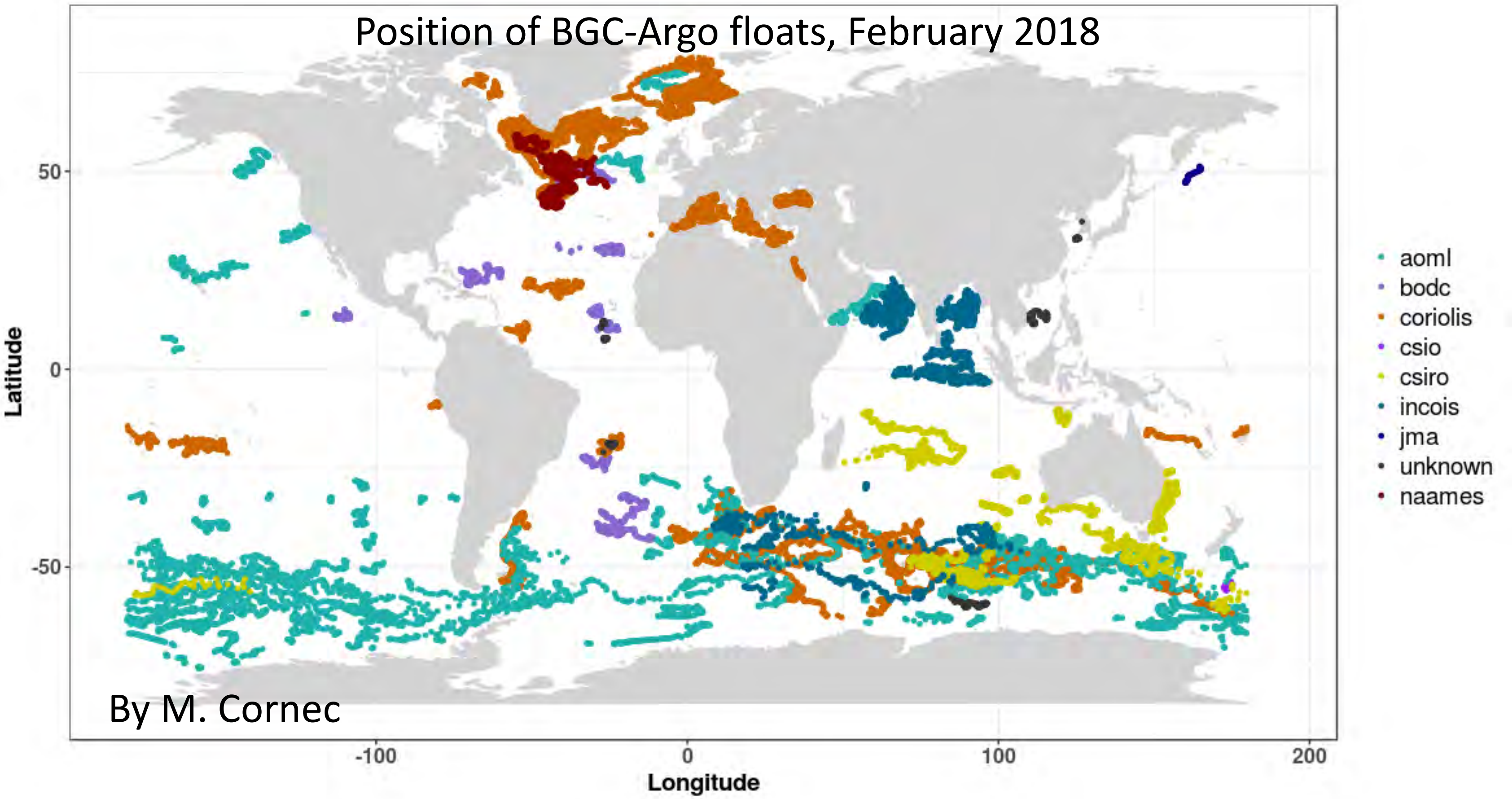
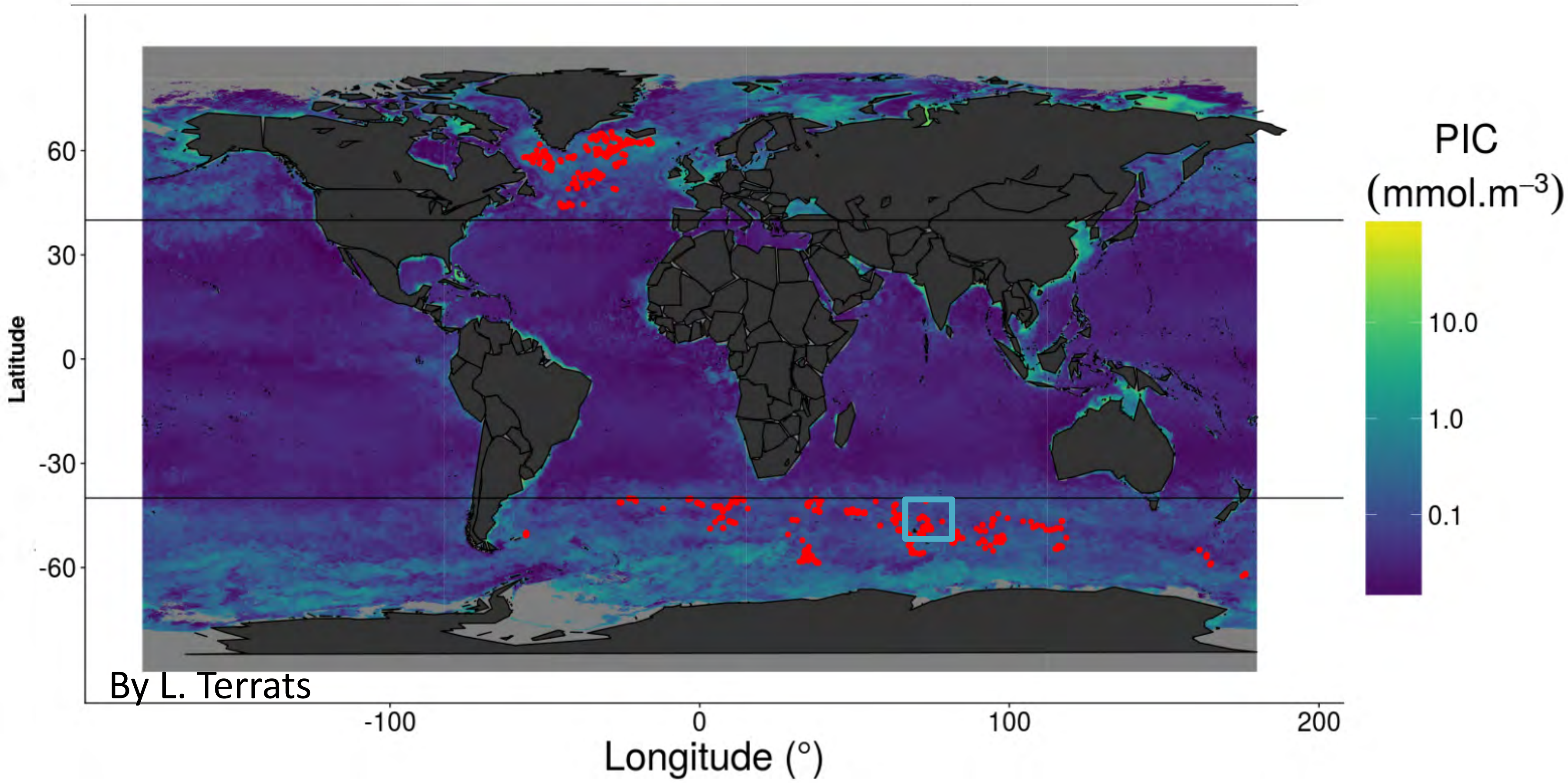


Position of BGC-Argo floats, February 2018

By M. Cornec

● have a c_p sensor and sampled a coccolithophore bloom

Observing *E. huxleyi* blooms with BGC-Argo floats



By L. Terrats

● have a c_p sensor and sampled a coccolithophore bloom

Thank you!