Optical properties and remote sensing of coccolithophores

Recent advances and selected applications

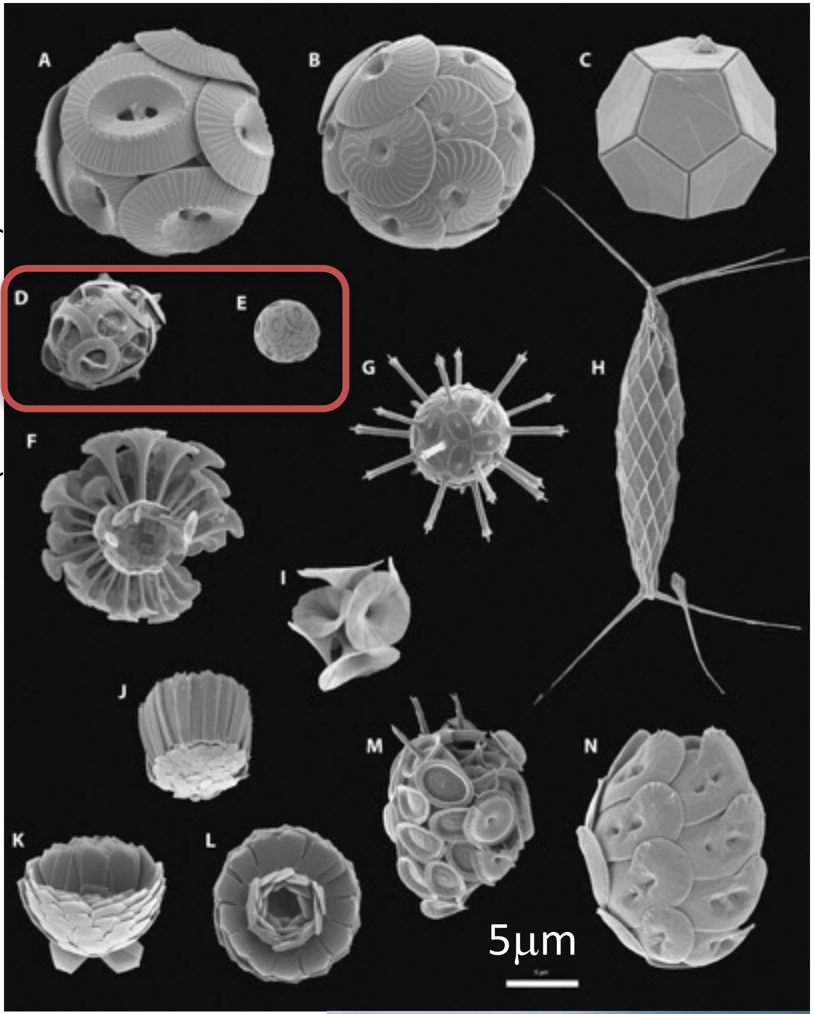
Griet Neukermans

Marie Sklodowska-Curie Postdoctoral Fellow

Laboratoire d'Océanographie de Villefranche-sur-Mer (LOV)

Sorbonne University/CNRS

What are coccolithophores?



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

- Calcifying phytoplankton
- Haptophyta; Prymnesiophyceae
- Produce $CaCO_3$ scales (coccoliths)
- About 200 species, 2 bloom-formers
- Occur throughout the world ocean
- $5\ \mu m \leq D \leq 40\ \mu m$
- Considered a single PFT
- Comprise about 10% of global phytoplankton biomass
- Major $CaCO_3$ producers in the open ocean (besides forams and pteropods)

Outline

- OCRS of coccolithophores and their calcite mass (PIC)
  - Quantifying PIC in the ocean + uncertainties
  - Recent advances
  - Caveats of remotely sensed PIC
- Optical properties of coccolithophores
  - (back)Scattering
  - Recent advances
- Applications of optical oceanography in coccolithophore research:
  - Climate change impacts
  - Role in ocean biological carbon sink (calcite ballast effect)

Quantifying PIC in the ocean

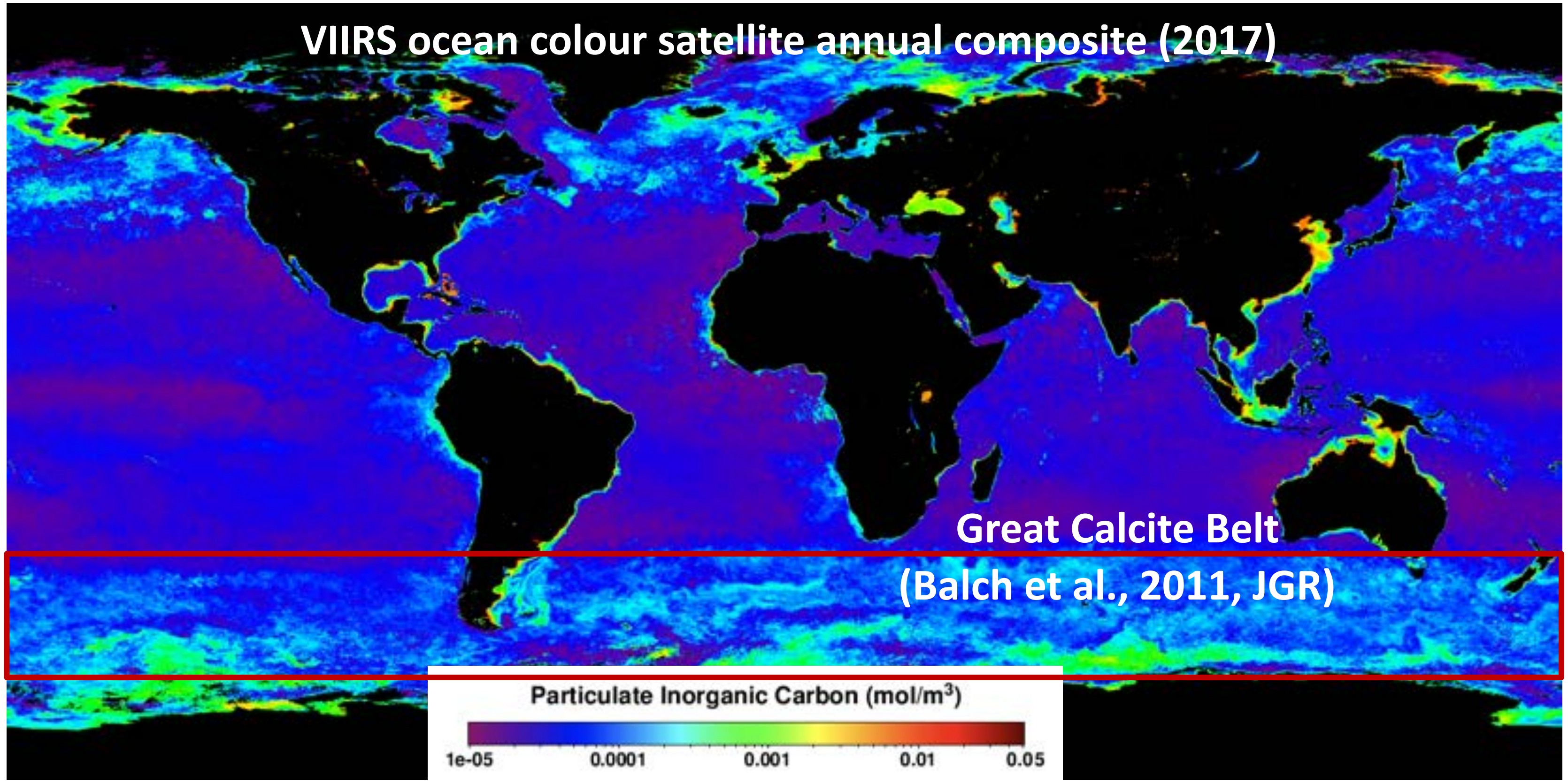
High latitudes: High PIC, low diversity (blooms dominated by *E. huxleyi*)

Low latitudes: Low PIC, low diversity

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

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.

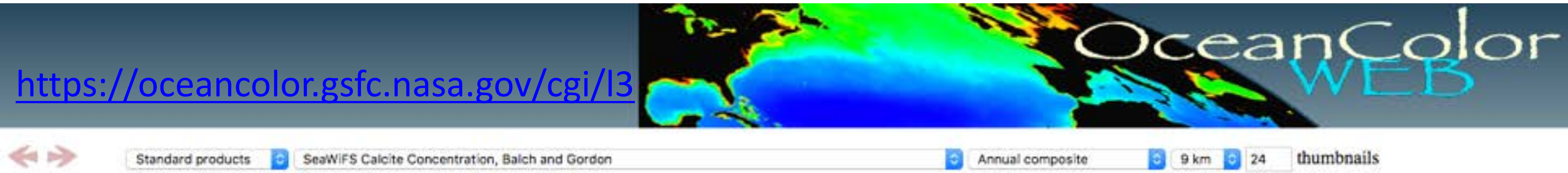
Moore et al., 2012 – RSE



NASA's standard PIC algorithm

"Balch and Gordon"

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

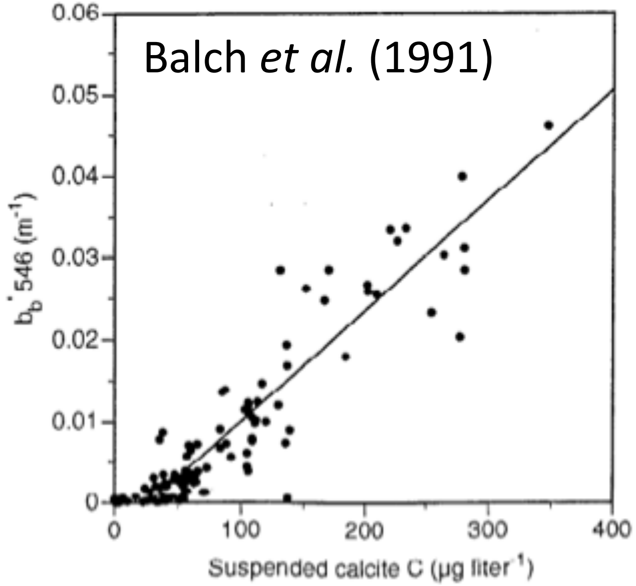


a **hybrid** algorithm, switching between:
The 2-band approach of Balch *et al.* (2005) for Low-Medium PIC or
The 3-band approach of Gordon *et al.* (2001) for high PIC

The 2-band approach is applied, unless PIC > 40 μg PIC/L or 3 mmol C/m^3;
then the 3-band algorithm is used.

The "Balch and Gordon" algorithm is **applicable to all current ocean color sensors**.

Algorithm **calibration** in Maine waters and in UK waters (*E. huxleyi* dominated).
Mainly **validated** in Maine waters and high latitude oceans and seas.



PIC algorithm for high PIC

Gordon *et al*. (2001)

Heart of the algorithm:

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

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

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

Gordon *et al.* (2001)

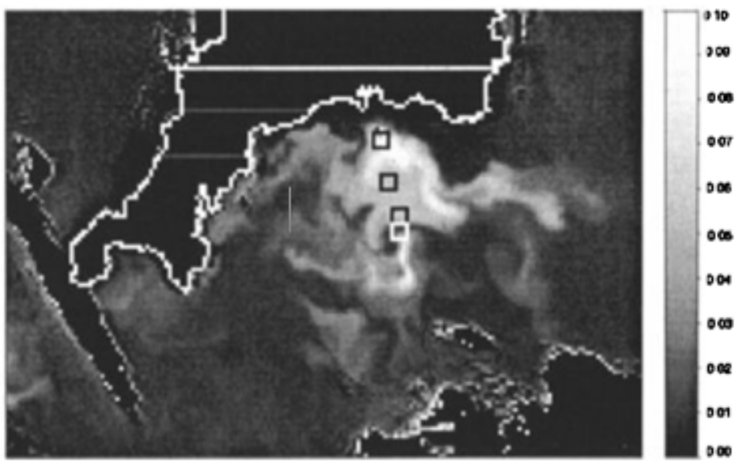


Figure 1. $b_b(546)$ in m^{-1} retrieved from the July 30, 1999 SeaWIFS image of Plymouth, UK. Areas of enhanced backscat-

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

Assumptions:

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

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

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 algorithm for low-med PIC

Balch *et al.* (2005)

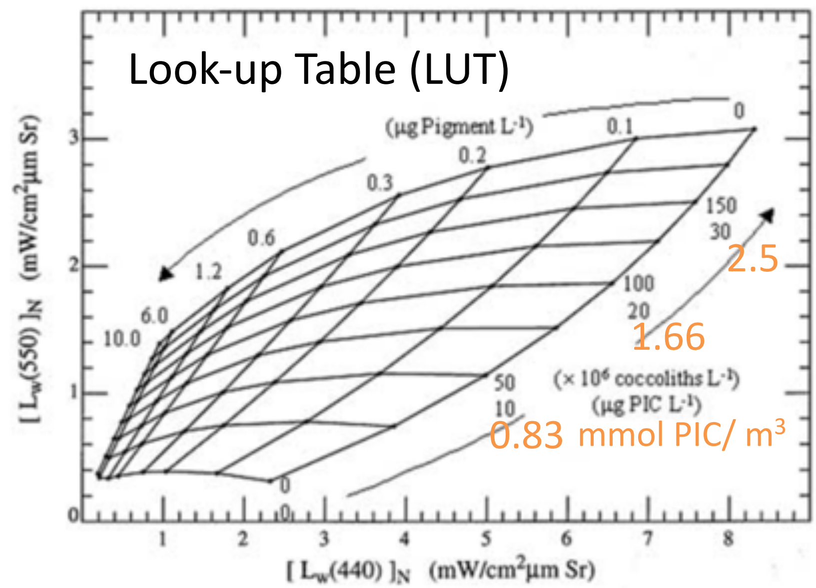
Heart of the algorithm (same as Gordon algo)**:**

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

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

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
25×10^6 coccoliths/L = 5 µg PIC/L = 0.41 mmol PIC/ m^3

Major limitations:

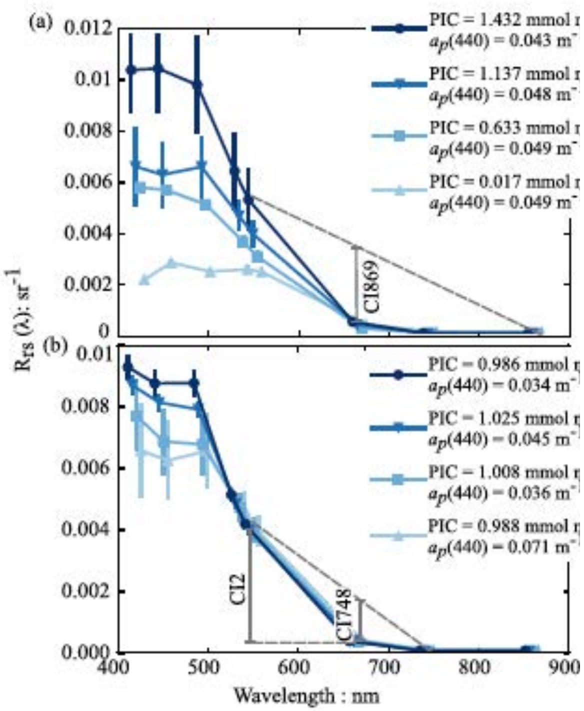
- dependency on the reflectance model (assumed constant phyto-detritus b_b)
- Estimate of "excess backscatter" -> particles other than PIC may also cause excess backscatter
- absolute radiance -> sensitivity to atmospheric correction errors

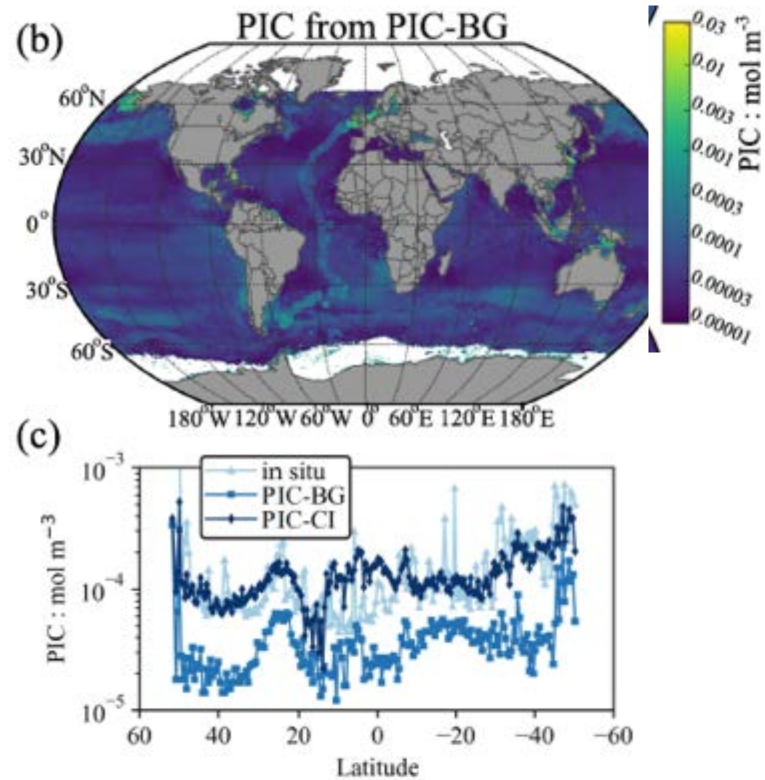
Alternative PIC algorithm

Referred to as calcite_CI2, status=test

Mitchell *et al.* (2017)

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





Color index using 547 and 667 nm, denoted CI2

$$CI2 = R_{rs}(547) - R_{rs}(667)$$

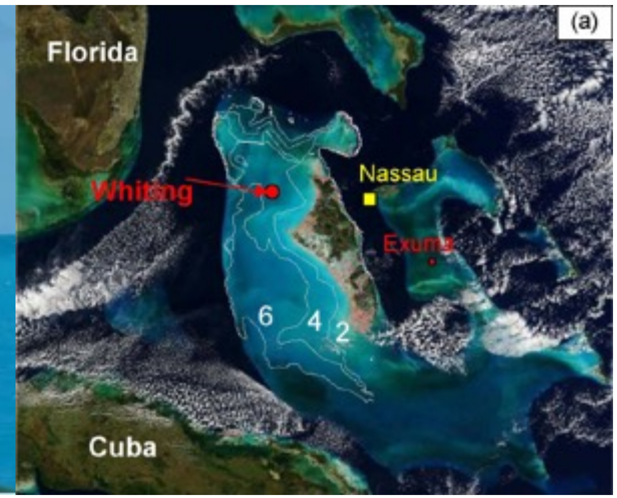
More **resistant** to atmospheric correction errors and residual errors in sun glint corrections than the Balch *et al.* (2005) algorithm.

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

PIC algorithm caveats

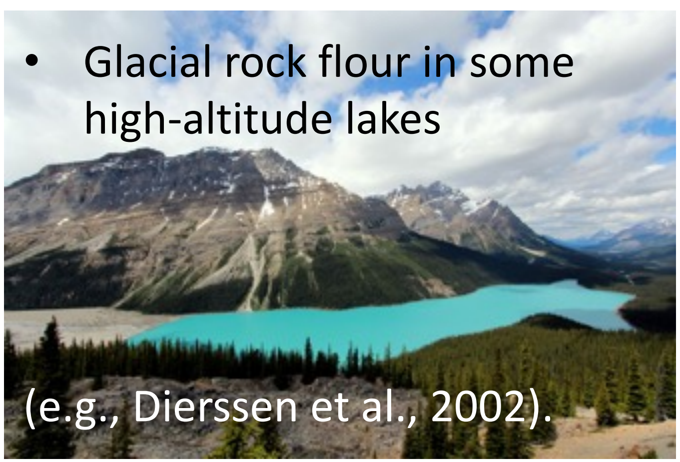
False positives for high PIC (highly reflective waters) produced by:

- Whitings = patches of suspended fine-grained calcium carbonate



https://earthobservatory.nasa.gov/

(Dierssen et al., 2009 – Biogeosciences)



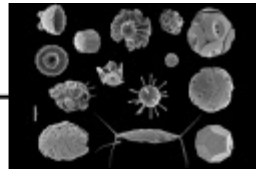
- Glacial rock flour in some high-altitude lakes

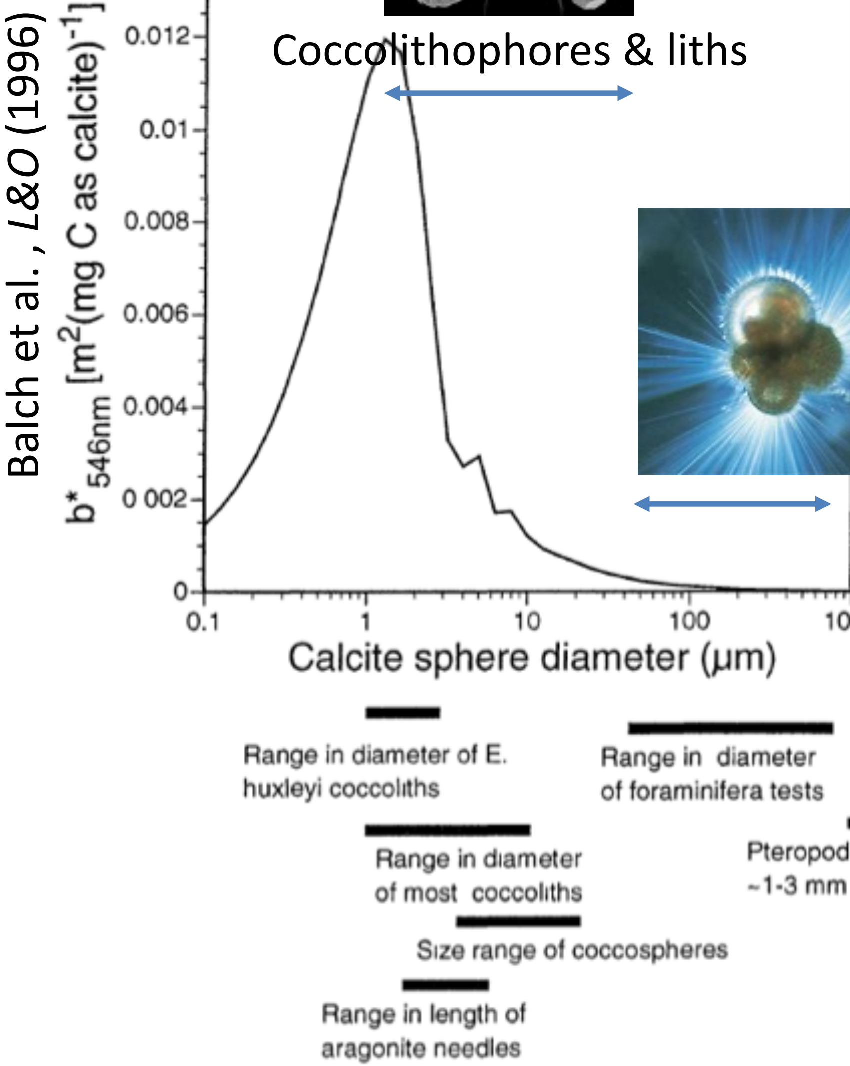
(e.g., Dierssen et al., 2002).

- 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)

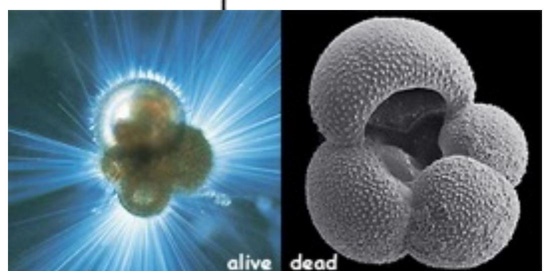
Light scattering properties of $CaCO_3$ particles in the ocean





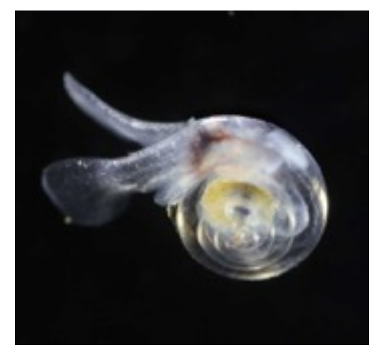
Coccolithophores & liths

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



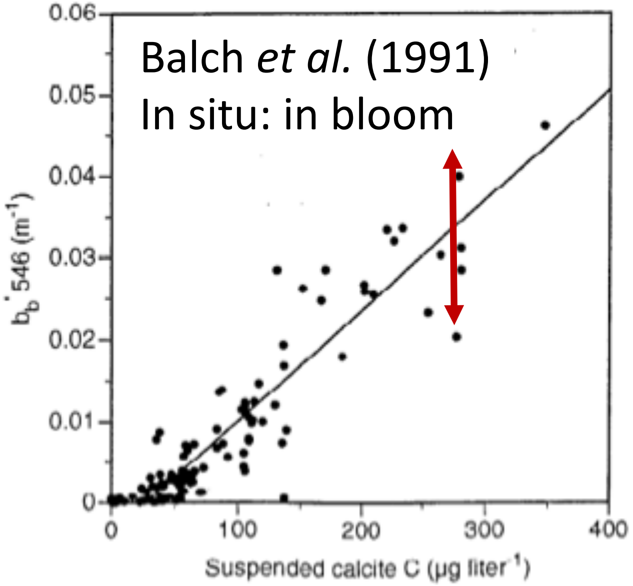
Foraminifera (0.05-1mm)
(amoeboid protozoans)

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



Pteropods (1-3mm)
"sea snails"

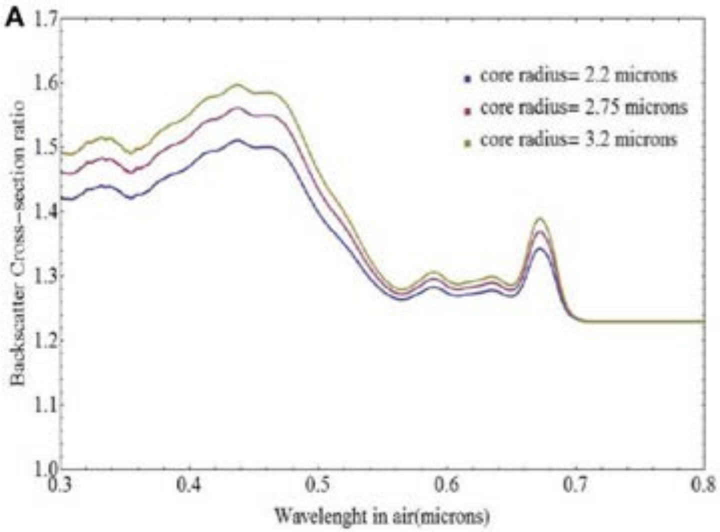
Light backscattering vs. PIC



Heart of NASA's PIC algorithm :

b_{bpic}/PIC = constant

Variability in b_{bpic} /PIC due to coccolith detachment?



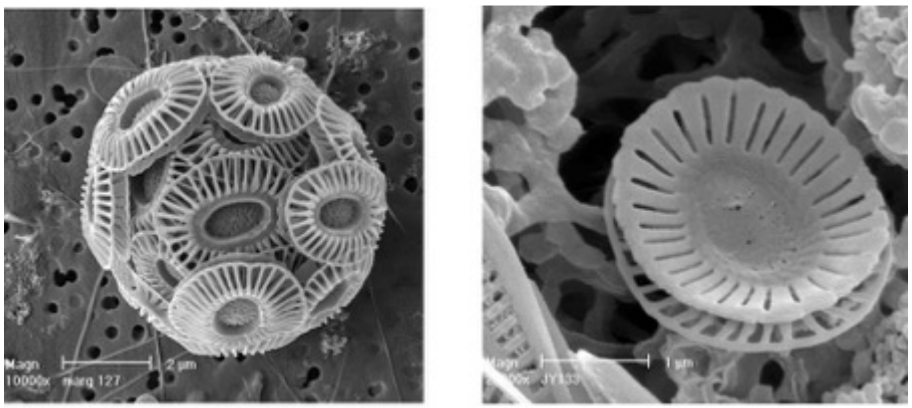
Neukermans and Fournier (2018) – F.Mar.Sci.

Optical modeling studies 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.)

Spectral backscattering properties of *E.huxleyi*

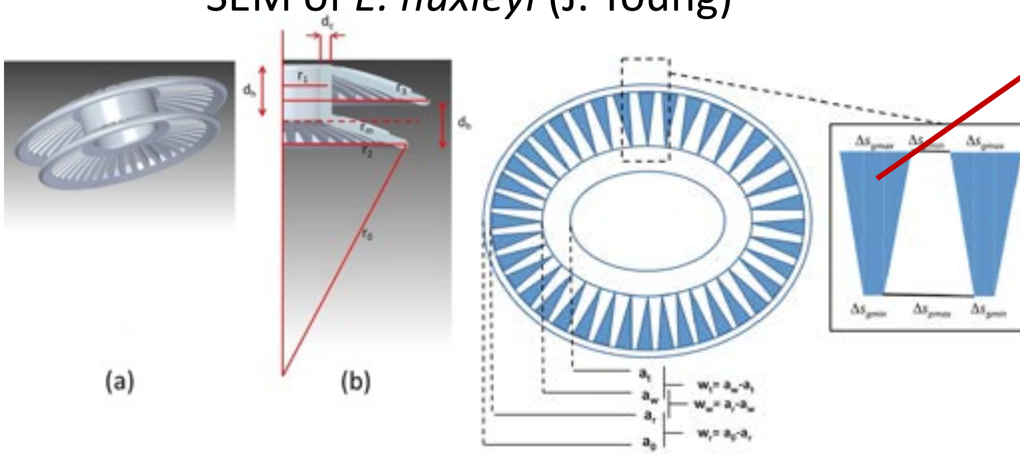
Strongly depend on coccolith morphology (and size, indirectly)



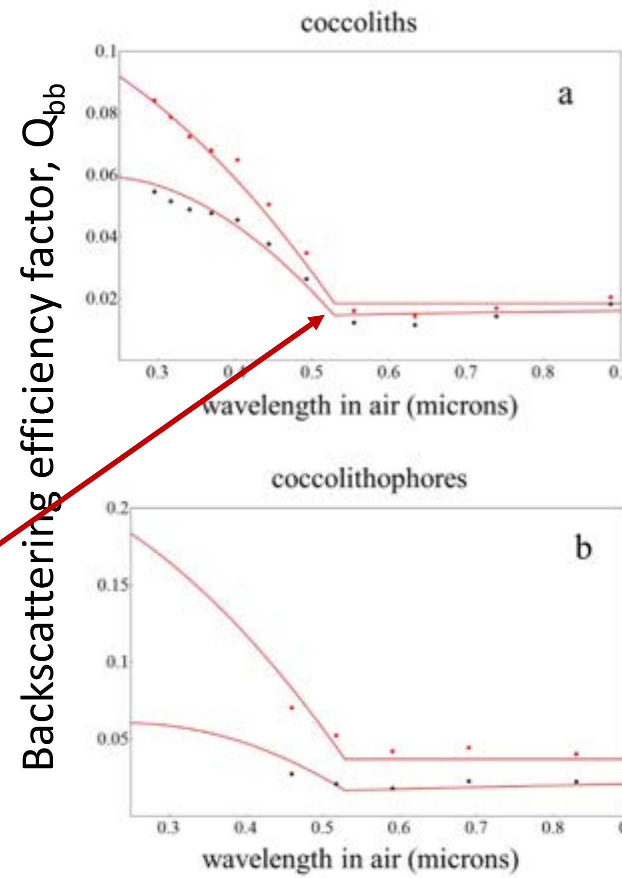
coccosphere

coccolith

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



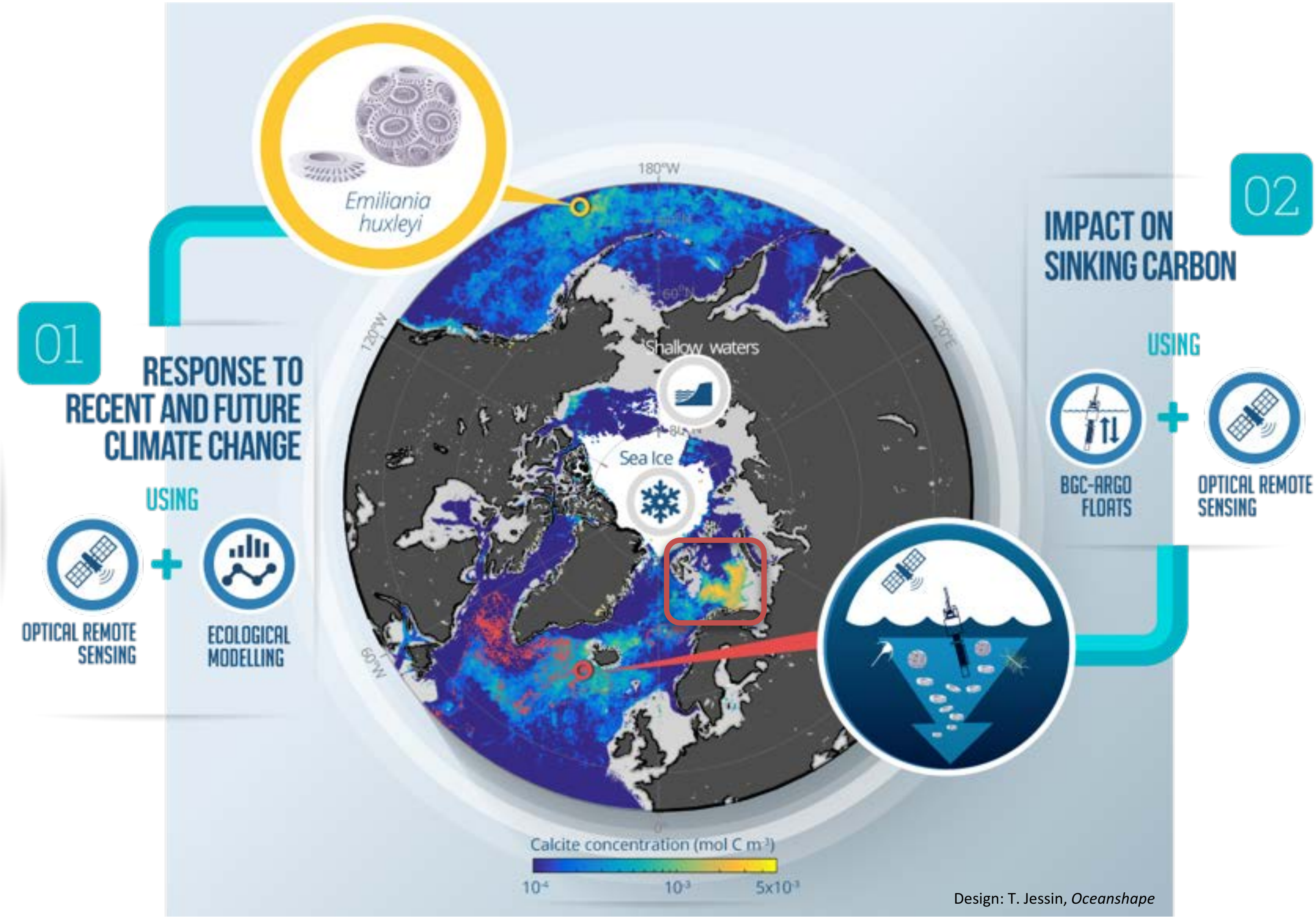
Model of *E. huxleyi* coccolith



(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.)

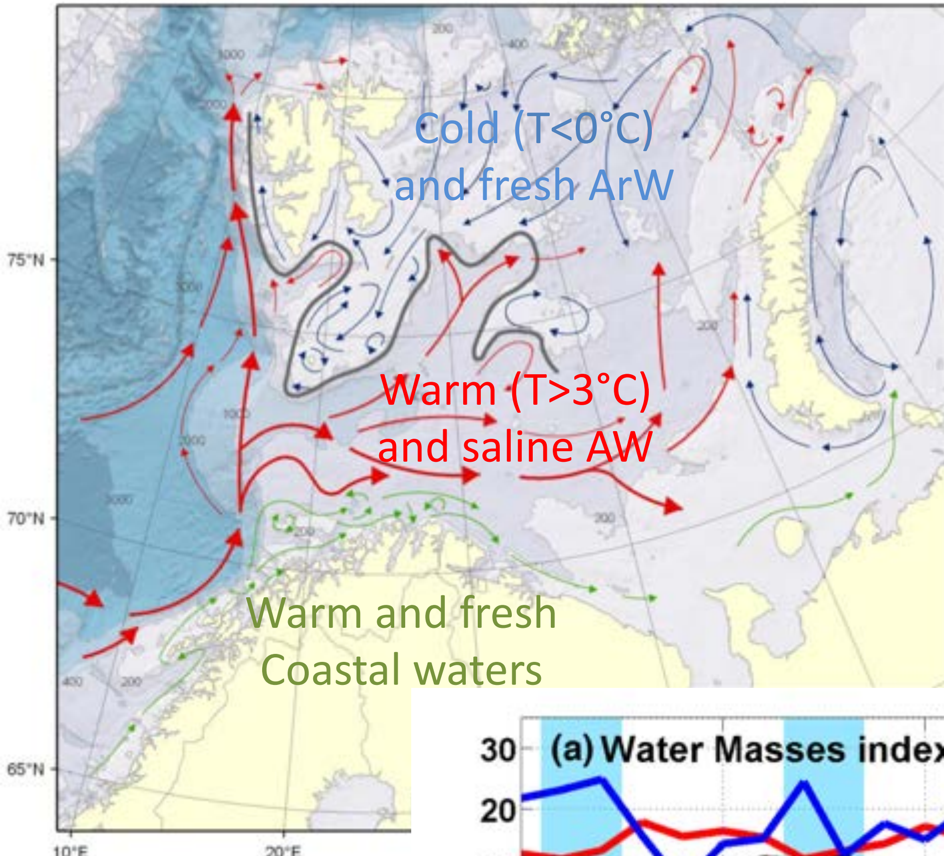
Selected applications: WhiteShift project

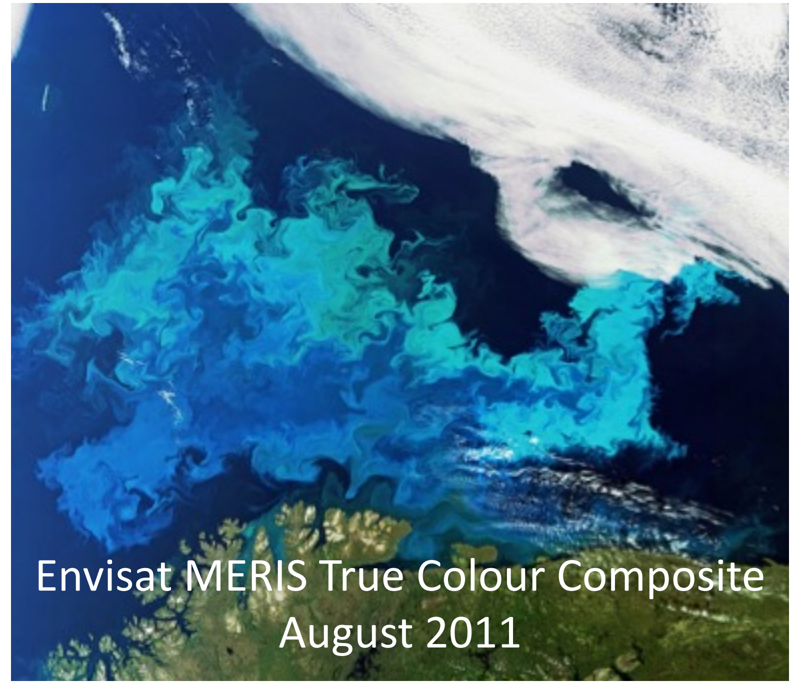


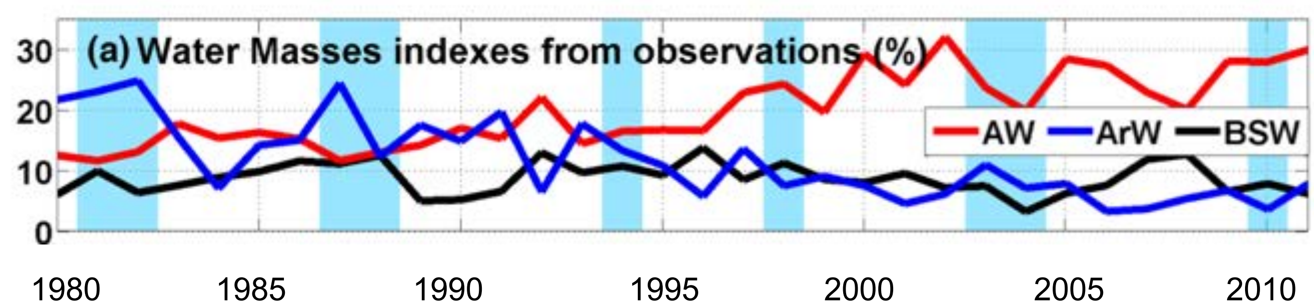
Design: T. Jessin, *Oceanshape*

01 RESPONSE TO CLIMATE CHANGE

A case study in the Barents Sea (70°-80°N)







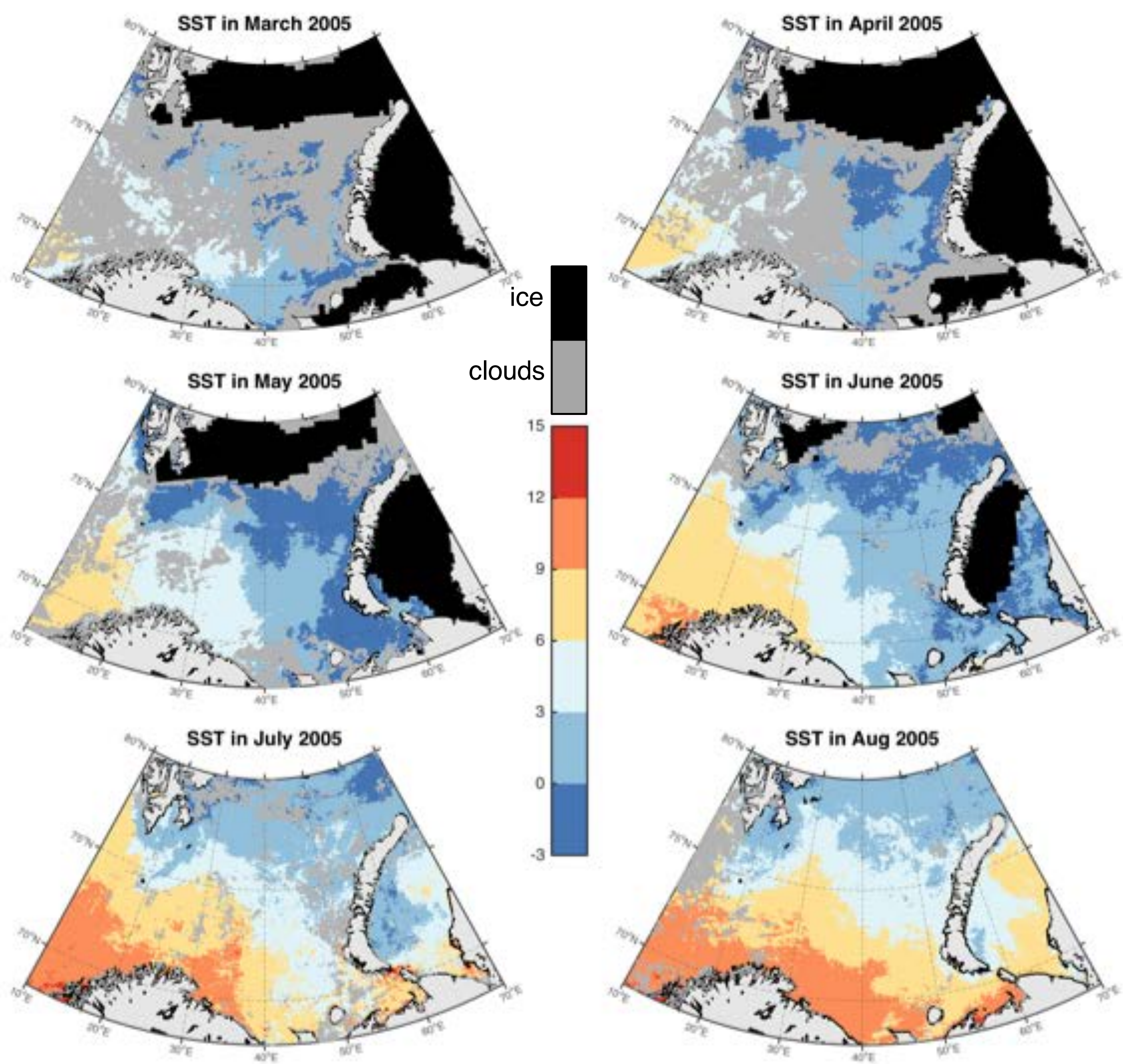
(Oziel *et al.*, 2016 – *Ocean Sci.*)

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

“increase in Atlantic heat transport due to both strengthening and warming of the inflow”

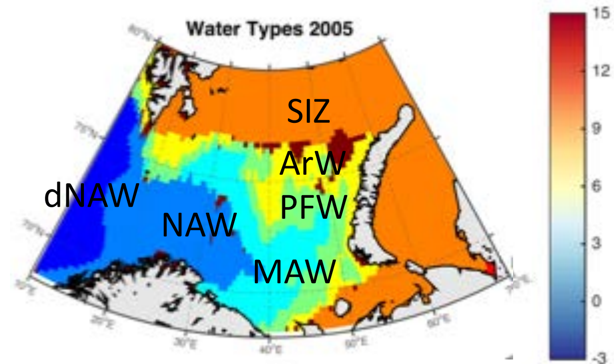
Space-based water mass classification

Example 2005: SST from AVHRR, Sea ice from SSMI



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

-0.49C<T(PFW)< 0.62C



(d)NAW: SST>3C (Loeng, 1991)

MAW: PFW_u<SST<3C

PFW: PFW_l<SST<PFW_u

ArW: SST<PFW_l

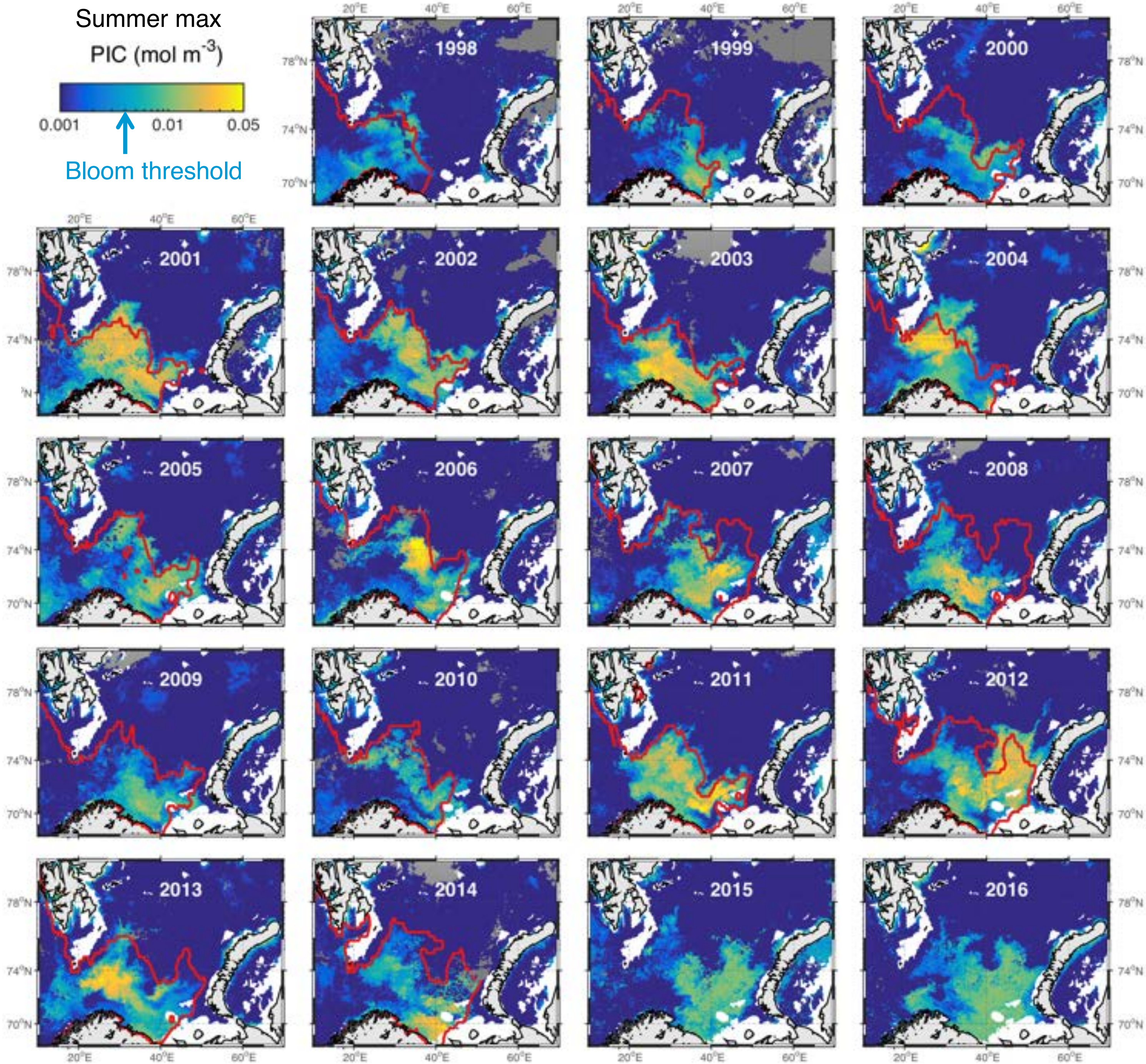
SIZ: seasonally ice-covered

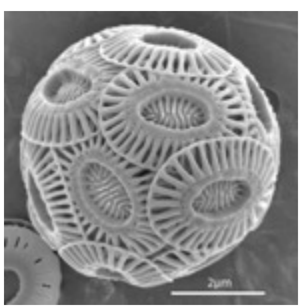
U: Unclassified (no SST)

Classification successfully validated with hydrographic dataset of Oziel et al. (2016)

Interannual variability in extent of *E. huxleyi* blooms

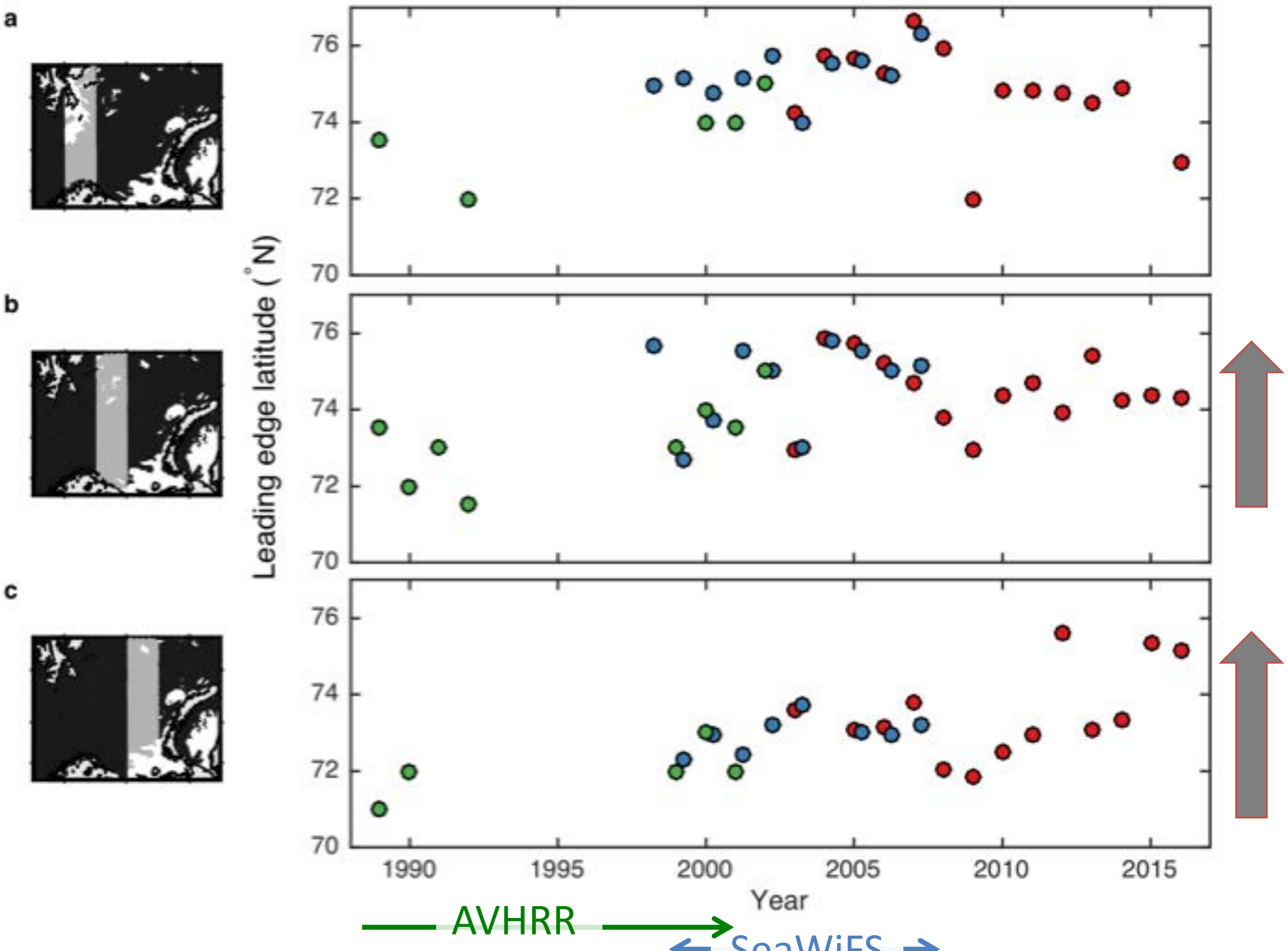
and Atlantic waters





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

Poleward expansion of *E. huxleyi* blooms



MODIS

Range shift

n.s.

390 km
(1989-2016)

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

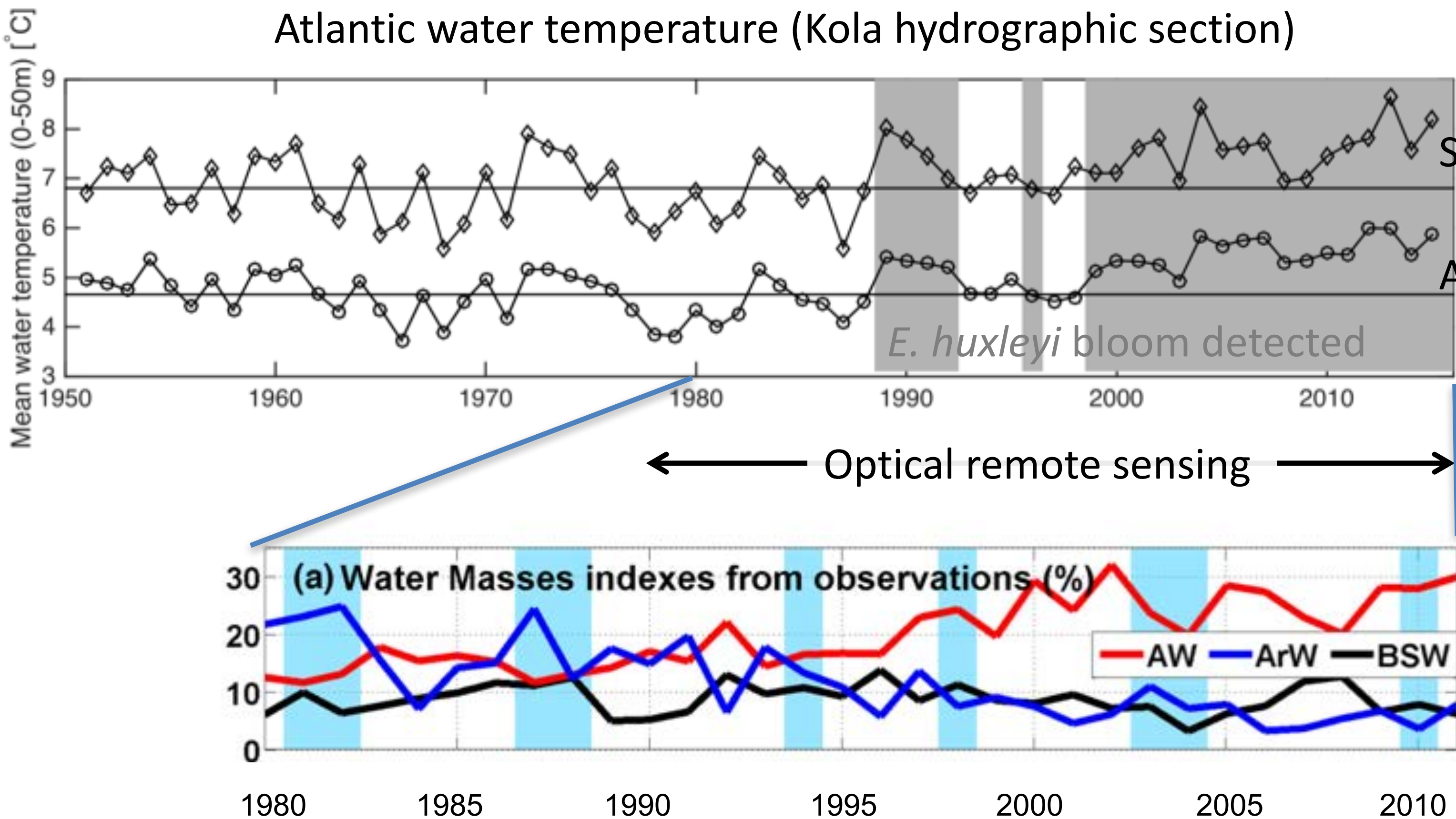
Neukermans *et al.* (*Glob. Ch. Biol.*, 2018)

Smyth *et al.* (2004 – *Geophys. Res. Lett.*)
Loveday and Smyth (2018 – *ESSD*)

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



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

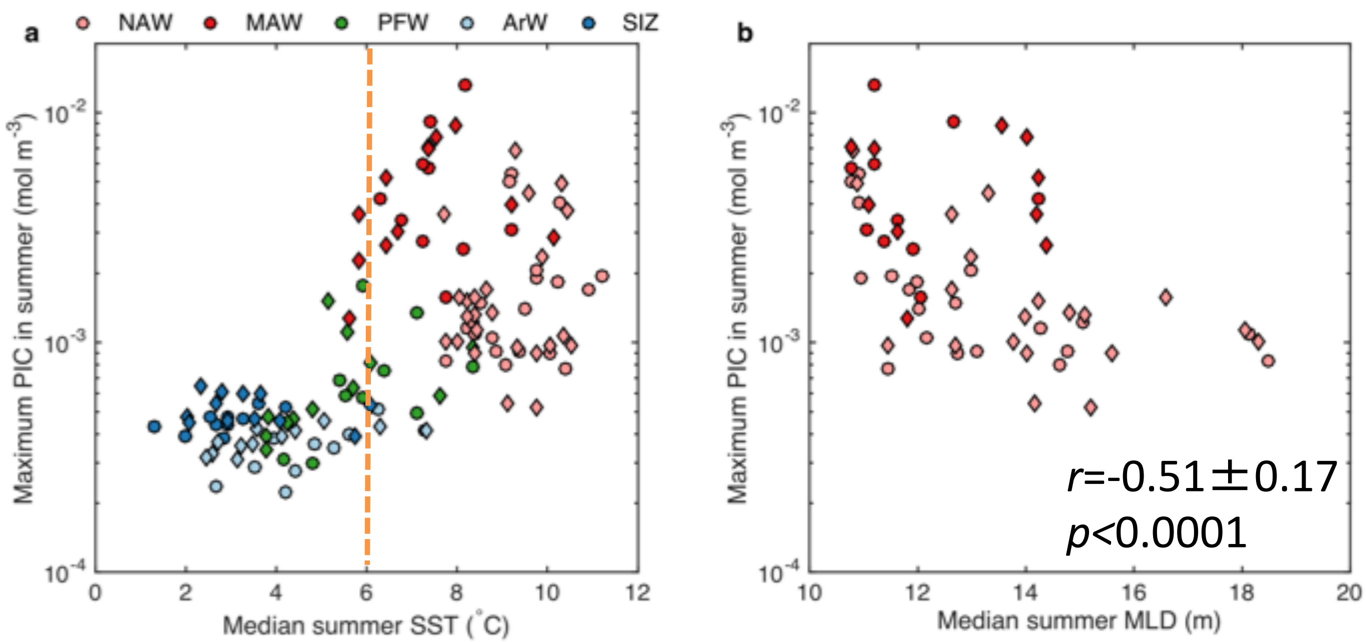
(Oziel *et al.*, 2016 – *Ocean Sci.*)

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

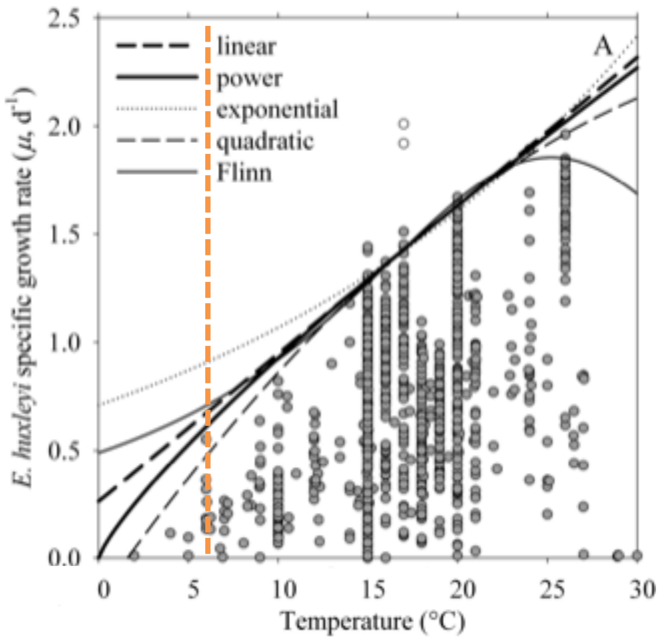
Poleward expansion in the Barents Sea is driven by increased intrusion and warming of Atlantic waters

E. huxleyi blooms – environmental drivers

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



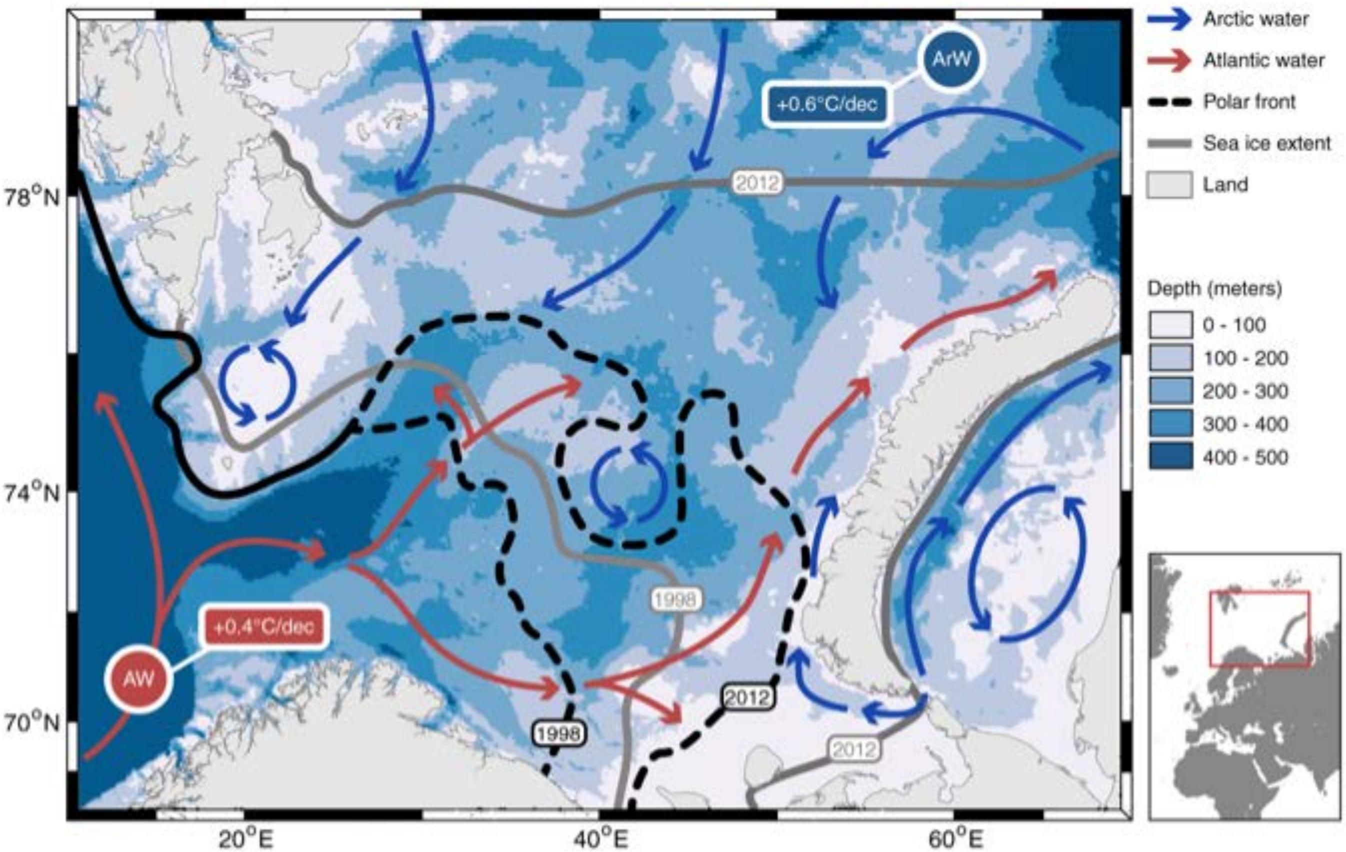
Fielding *et al.* (2013– *Limnol. Oceanogr.*)



E. huxleyi requires T>6C in order to form blooms

MLD between 10 and 20m are known to favor *E. huxleyi* blooms (Nanninga and Tyrell, 1996)

Will *E. huxleyi* blooms continue to expand poleward?

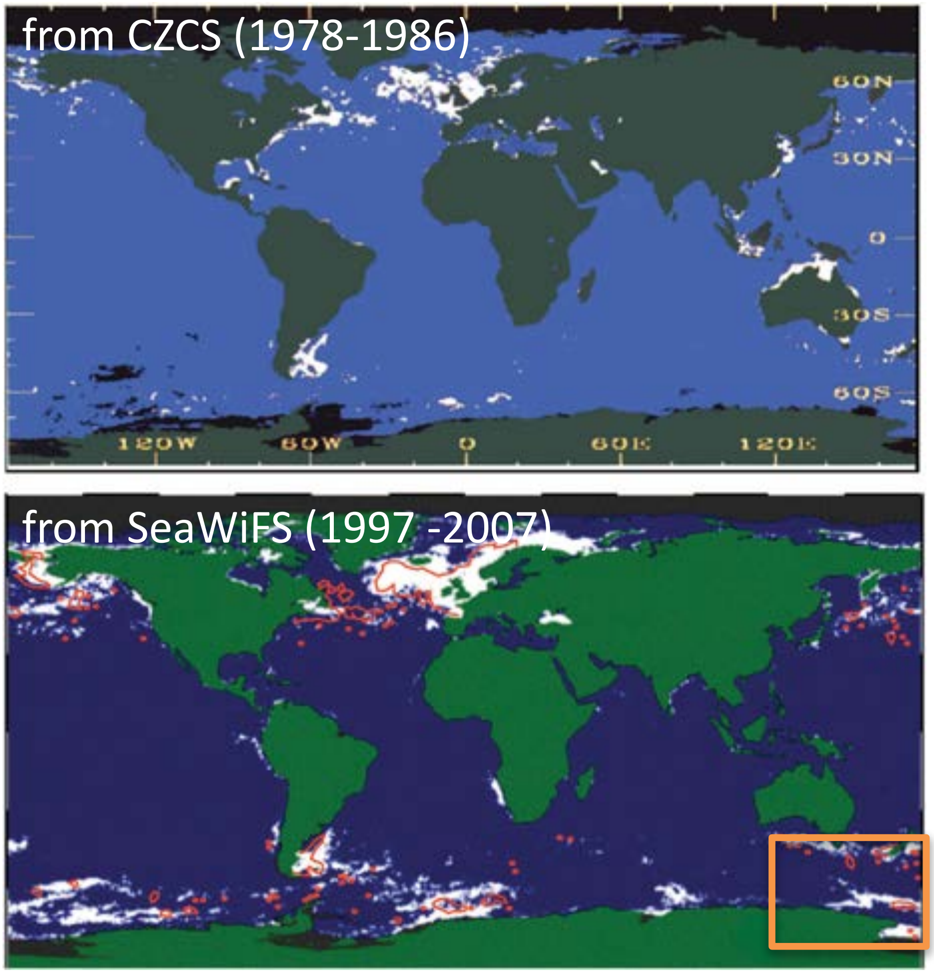


- \+ Self-amplifying feedback loop promotes further atlantification (Smedsrud *et al.*, 2013)
- \+ T is rising faster in ArW than in AW –> weakening of polar front in next century
- \+ Nutrients in Atlantic waters are declining: Silicates faster than Nitrates, 20% vs. 7% in 1990-2010 (Rey, 2012) –> favorable for non-silicifiying phytoplankton
- \- Deepening of Mixed layer trend since 1979 (Peralta-Ferriz and Woodgate, 2015; Oziel et al., 2017)

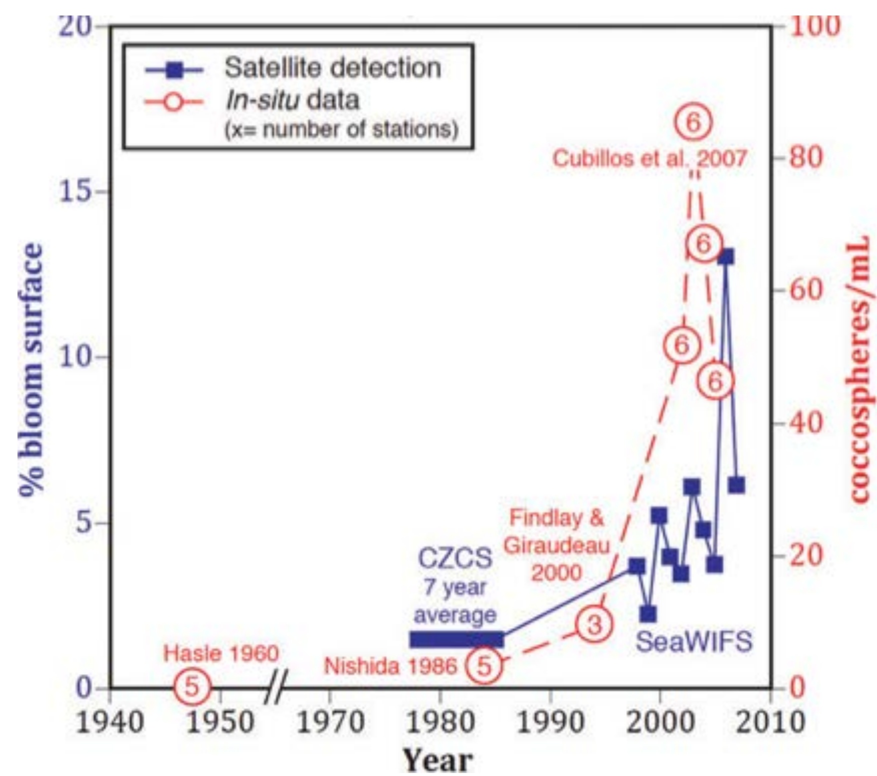
Poleward expansion of *E. huxleyi*

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

Climatology of classified coccolithophore blooms



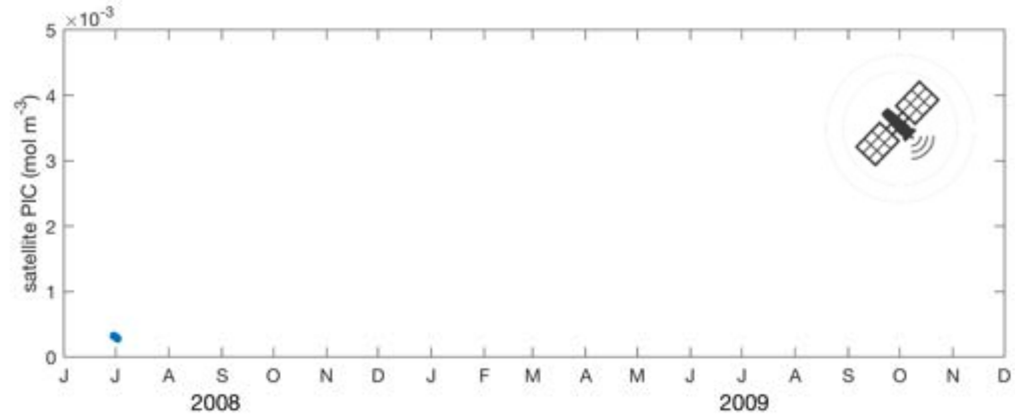
Coccolithophore data within 30°-70°S /130°-170°E

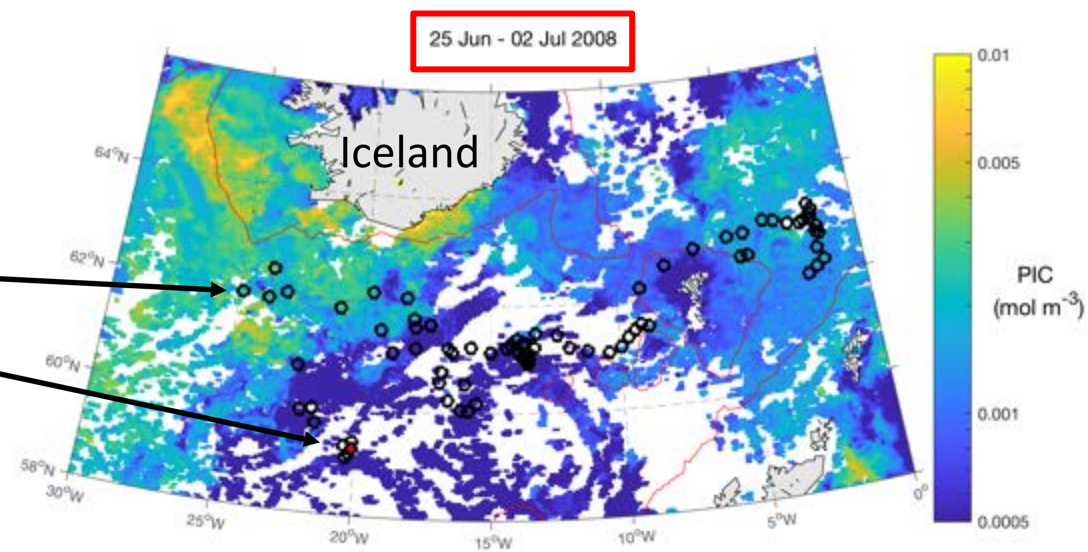


Bloom size and intensity increased in the 1990s. Why?

IMPACT ON SINKING CARBON

A case study in the Irminger Sea





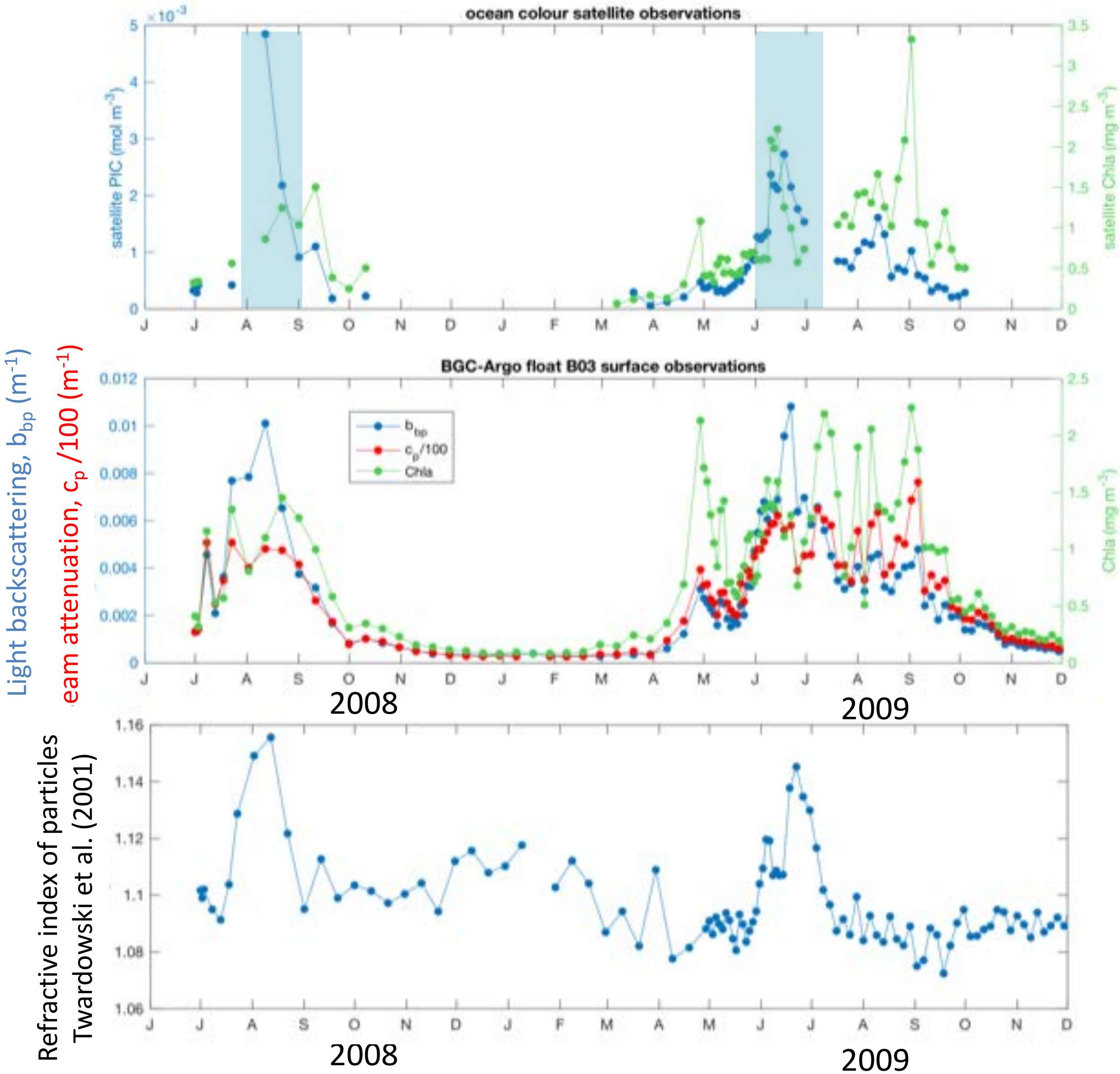
Profiles on float trajectory

Current float position

02

IMPACT ON SINKING CARBON

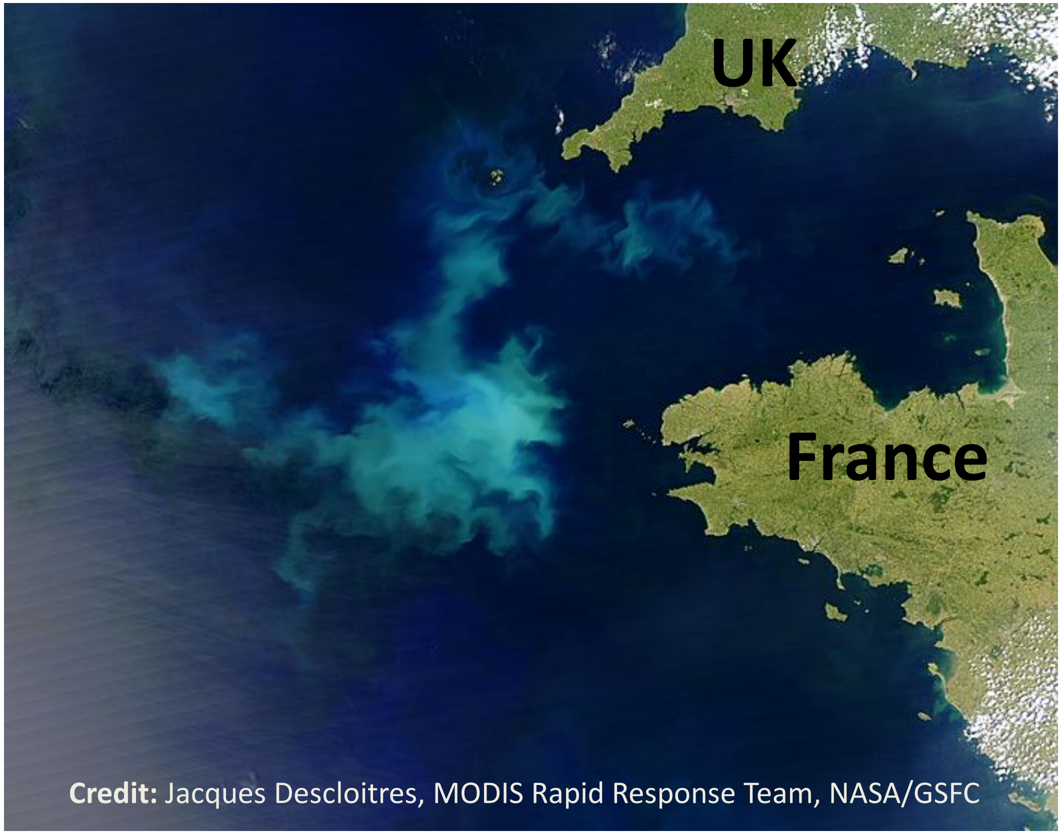
A case study in the Irminger Sea



Future work: Brittany *E. huxleyi* bloom monitoring

Objective: Monitoring biogeochemistry of an *E. huxleyi* bloom off the coast of Brittany in April-June 2019

Sampling platforms: IODYSSÉUS and TARA +
https://www.iodysseus.org/



Optics:
- backscattering
- Hyperspectral absorption and scattering
- Chla + CDOM fluorescence
- Particle size (LISST-100X)

Discrete samples:
POC, PIC, HPLC

Biogeochemistry:
- in-water pCO_2
- Carbon export from BGC-Argo float

Aerosols

Collaborators: Roscoff, UMaine, ICCF, Weizmann Institute, …


Thank you!