Response of phytoplankton to elevated CO_2

How do we find the ocean's mean?

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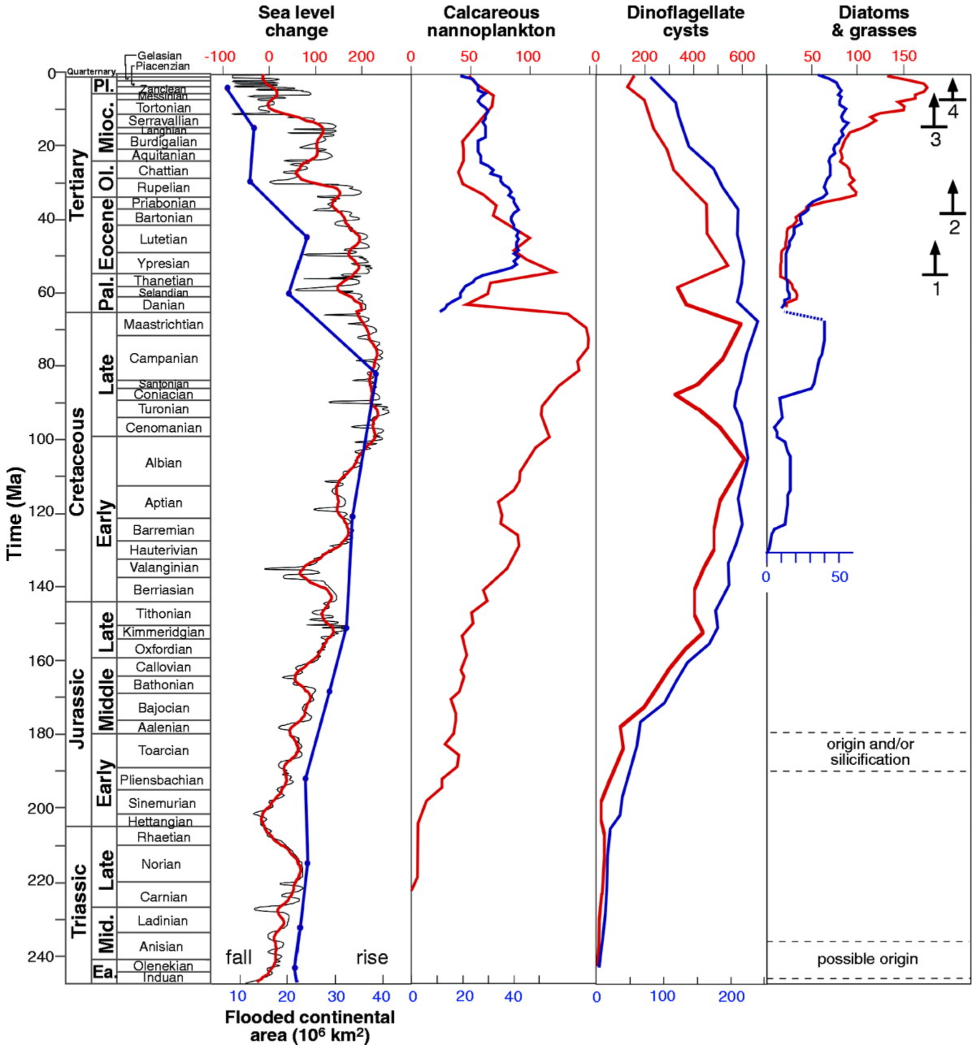
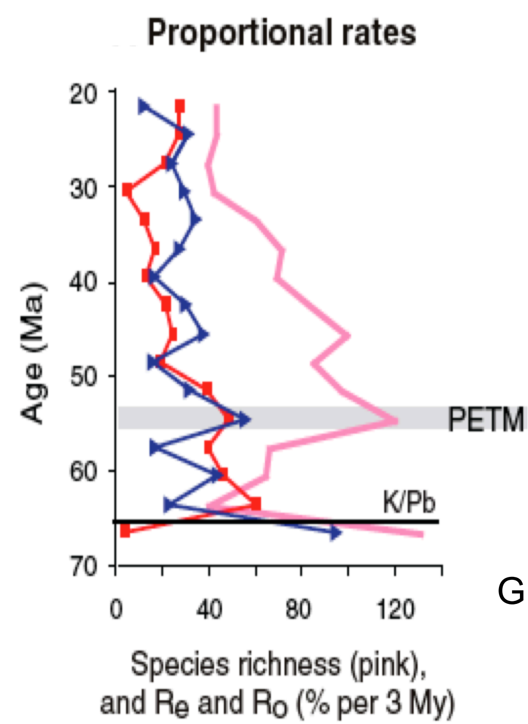
Changes in diversity through geological time



Sea-level change
Flooded continental areas

Falkowski et al., 2004.



Gibbs et al., 2006.

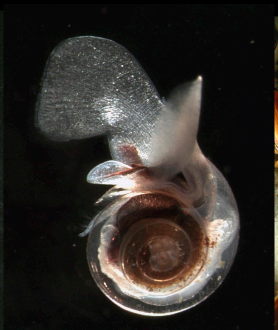
Functional properties of calcifyers:
No changes in lith calcification, despite increasing geologic evidence for massive carbonate undersaturation - resilience to climate change?

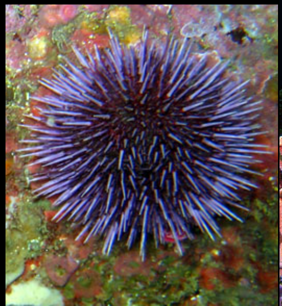
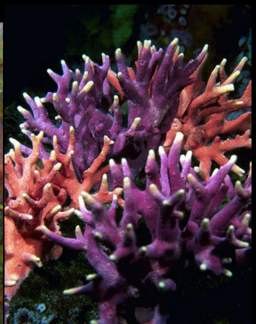
Ocean acidification

What do we know about the response of calcifyers to ocean acidification?

Pelagic

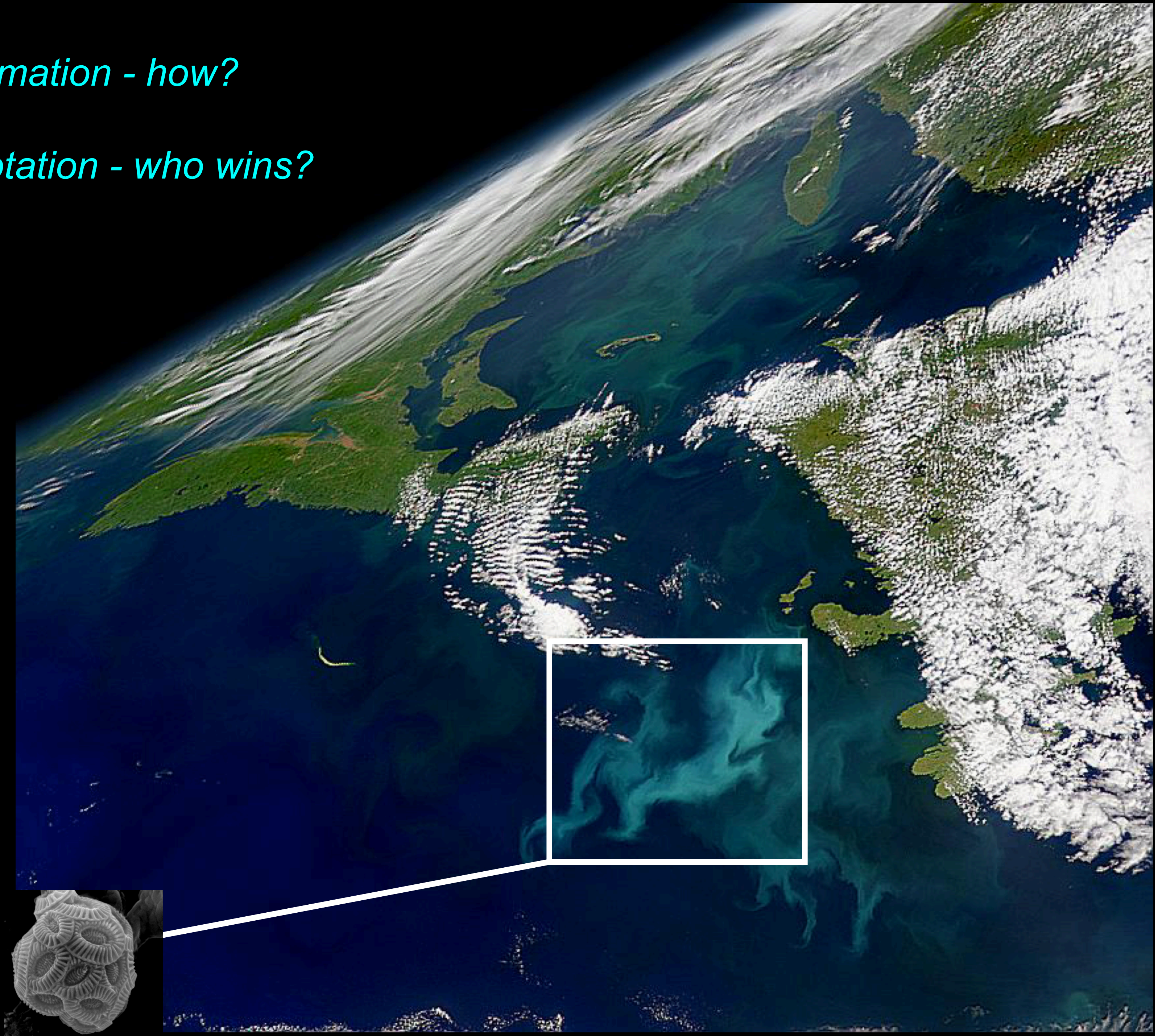


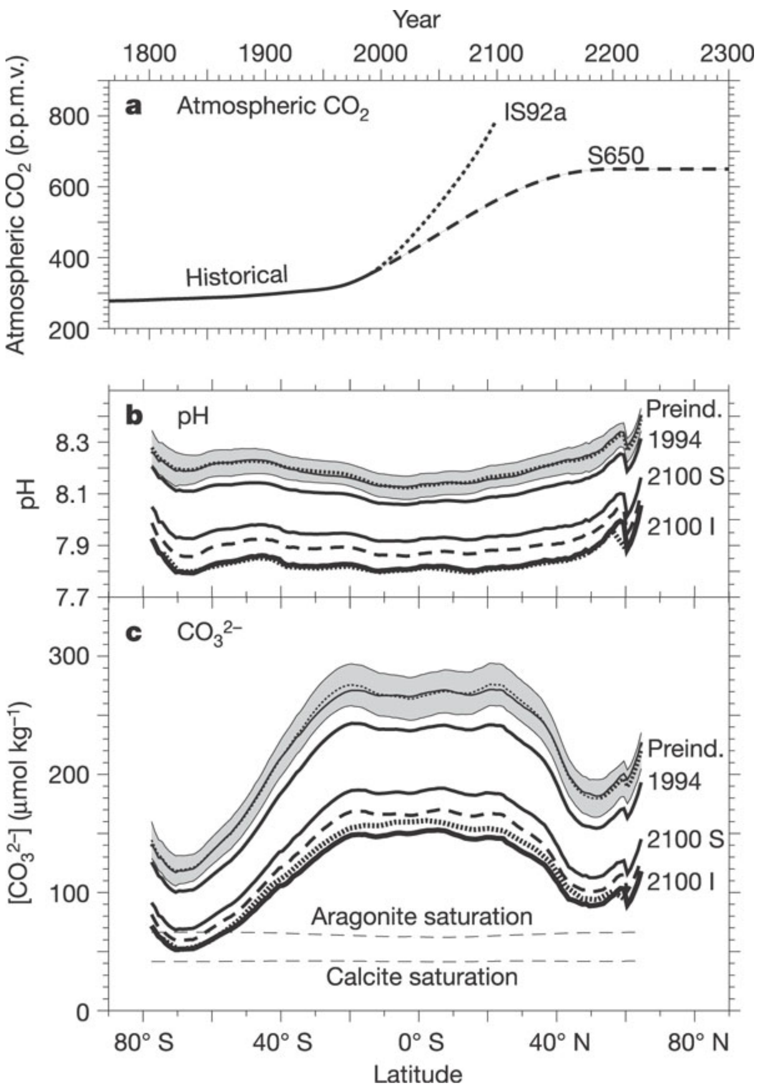



Acclimation - how?

Adaptation - who wins?



Ocean acidification



Orr et al., 2005.

	Pre-industrial	Today	2 × pre-industrial	3 × pre-industrial	4 × pre-industrial	5 × pre-` industrial	6 × pre-industrial
Atmospheric concentration of CO_2	280 ppm	380 ppm	560 ppm	840 ppm	1120 ppm	1400 ppm	1680 ppm
H_2CO_3 (mol/kg)	9	13	19	28	38	47	56
HCO_3^- (mol/kg)	1768	1867	1976	2070	2123	2160	2183
CO_3^{2-} (mol/kg)	225	185	141	103	81	67	57
Total dissolved inorganic carbon (mol/kg)	2003	2065	2136	2201	2242	2272	2296
Average pH of surface oceans	8.18	8.07	7.92	7.77	7.65	7.56	7.49
Calcite saturation	5.3	4.4	3.3	2.4	1.9	1.6	1.3
Aragonite saturation	3.4	2.8	2.1	1.6	1.2	1.0	0.9

Royal Society report on ocean acidification, 2005
St. Petersburg report on ocean acidification, 2007

Some facts about ocean acidification

• Increasing pCO_2 in seawater causes the formation of carbonic acid (H_2CO_3), which causes acidification.

• $H_2CO_3 + CO_3^{2-} + H_2O \Leftrightarrow HCO_3^-$ (decrease in $[CO_3^{2-}]$) and the ocean's saturation state with respect to calcite (Ω-cal), the form of calcium carbonate ($CaCO_3$) produced by coccolithophores.

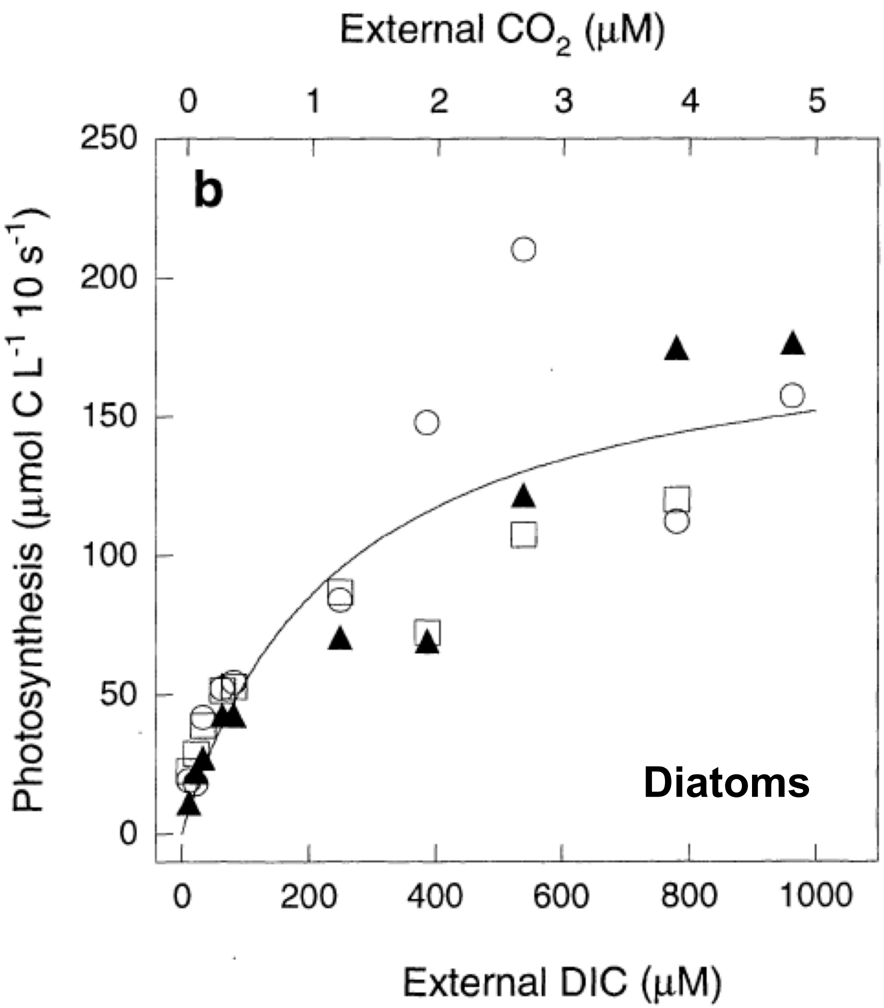
$$\Omega\text{-cal} = f\{[CO_3^{2-}], [Ca^{+2}]\}$$

• Elevated pCO_2 causes an increase in **$[CO_2]$**, the source of carbon for photosynthesis, and also in **$[HCO_3^-]$**, the source of carbon for calcification (**?**) in coccolithophores:

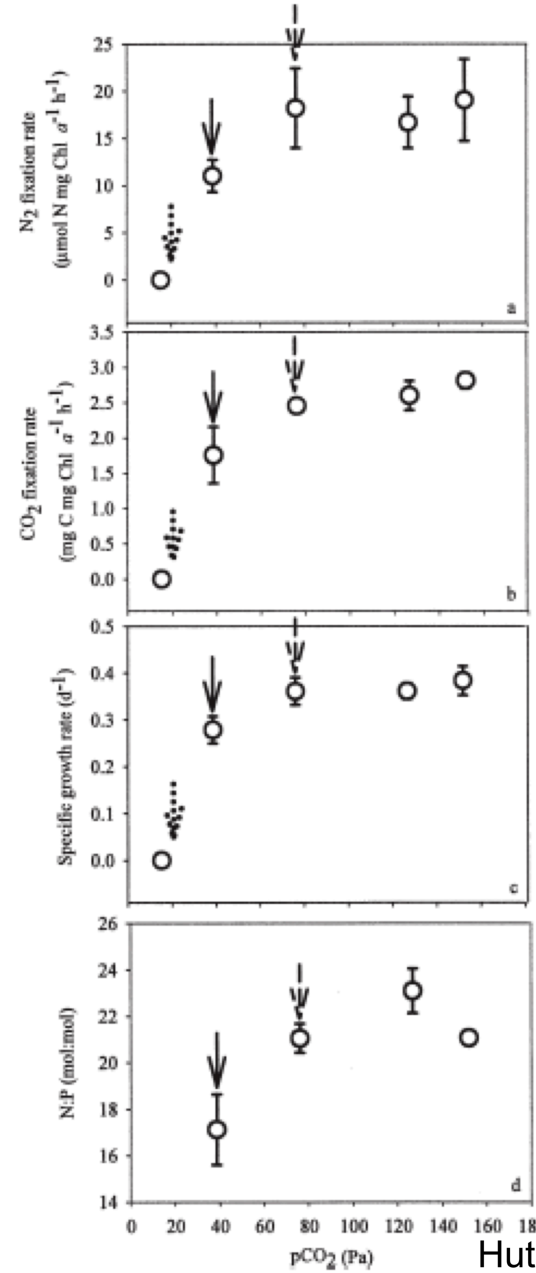
$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

• Consequently, a decrease in marine calcification without a concomitant decrease in organic carbon export would lead to an increased drawdown of atmospheric CO_2.

Effect of pCO_2 on diatoms and cyanobacteria



Tortell et al., 2000.

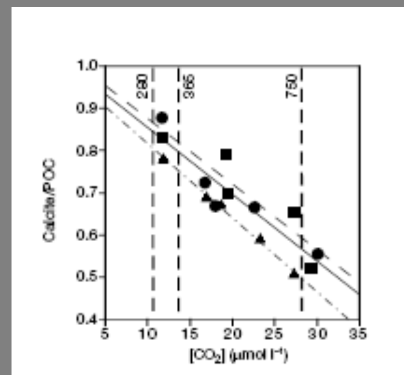


Cyanobacteria

Hutchins et al., 2007.

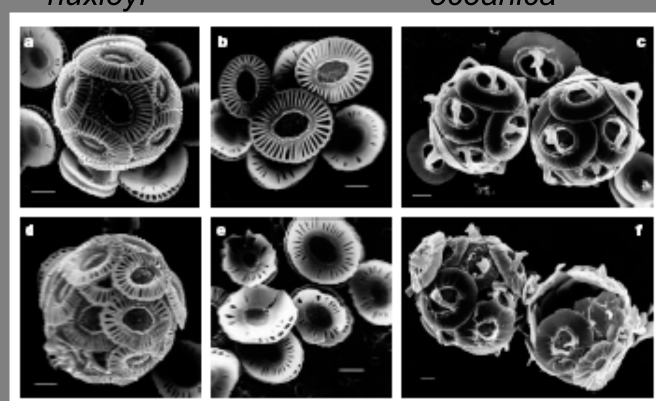
Short-term CO_2 incubations with coccolithophore species
<u>Batch cultures</u>

Riebesell et al. (2000):



Emiliania huxleyi

Gephyrocapsa oceanica



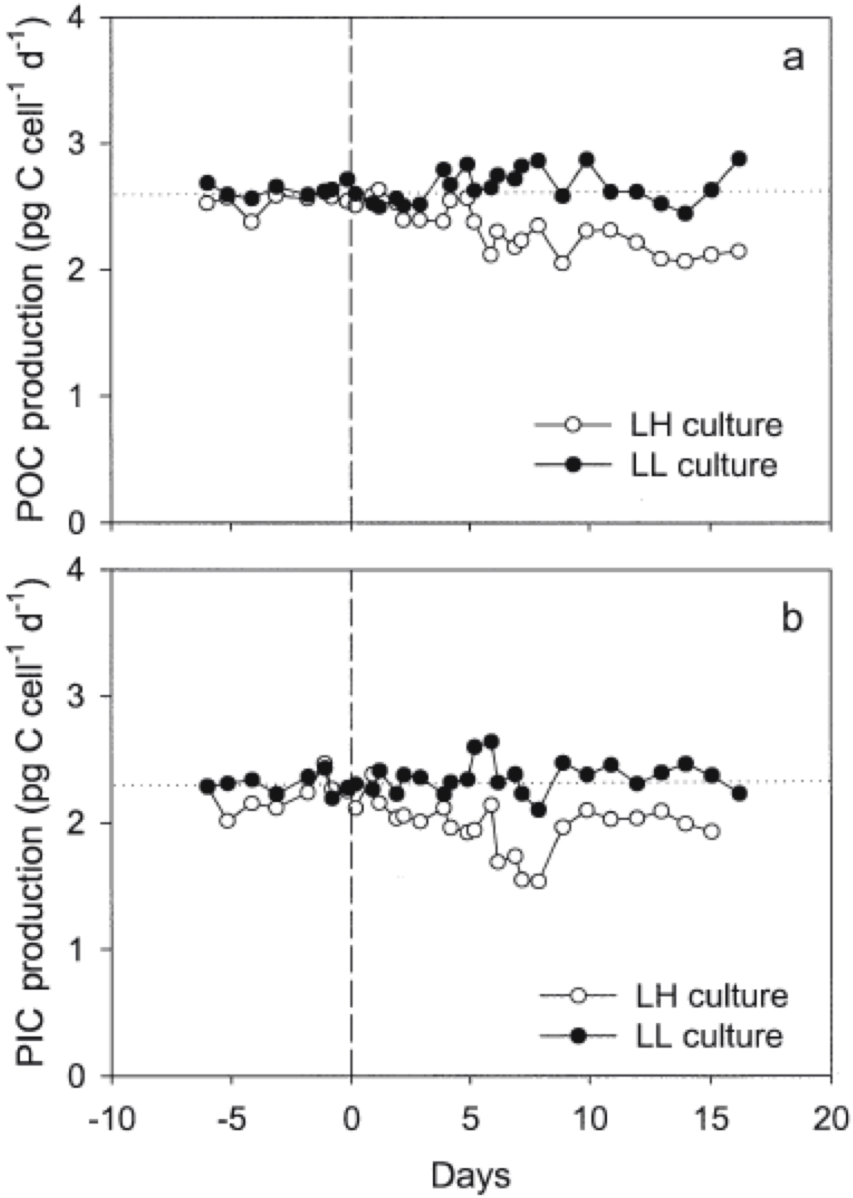
Present-day CO_2

Elevated CO_2

pH controlled with HCl

Short-term CO_2 incubations with coccolithophore species

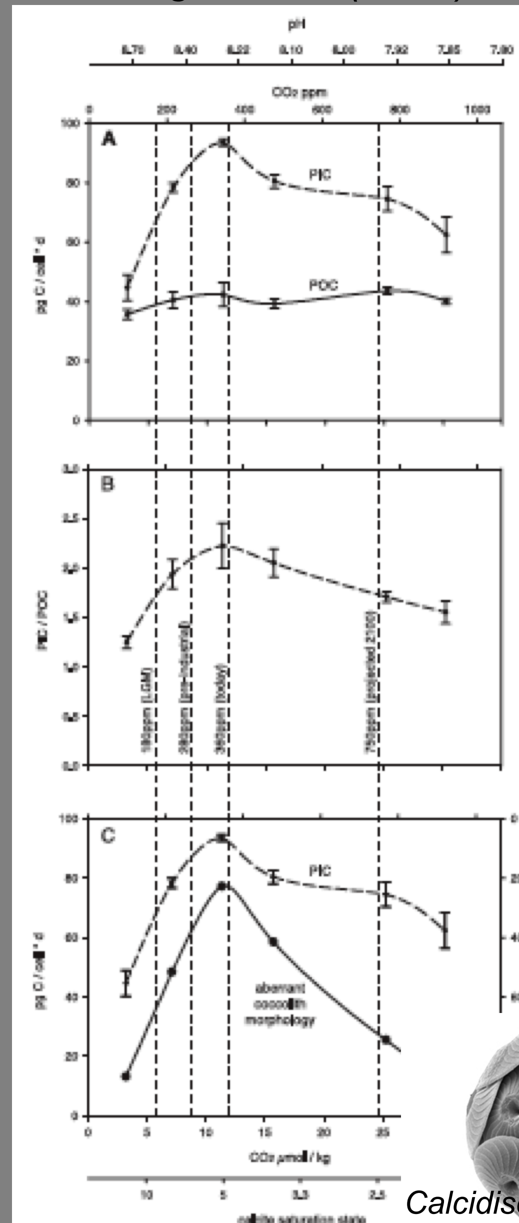
Continuous cultures



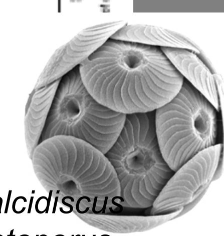
Sciandra et al., 2003

Short-term CO_2 incubations with coccolithophore species

Langer et al. (2006):

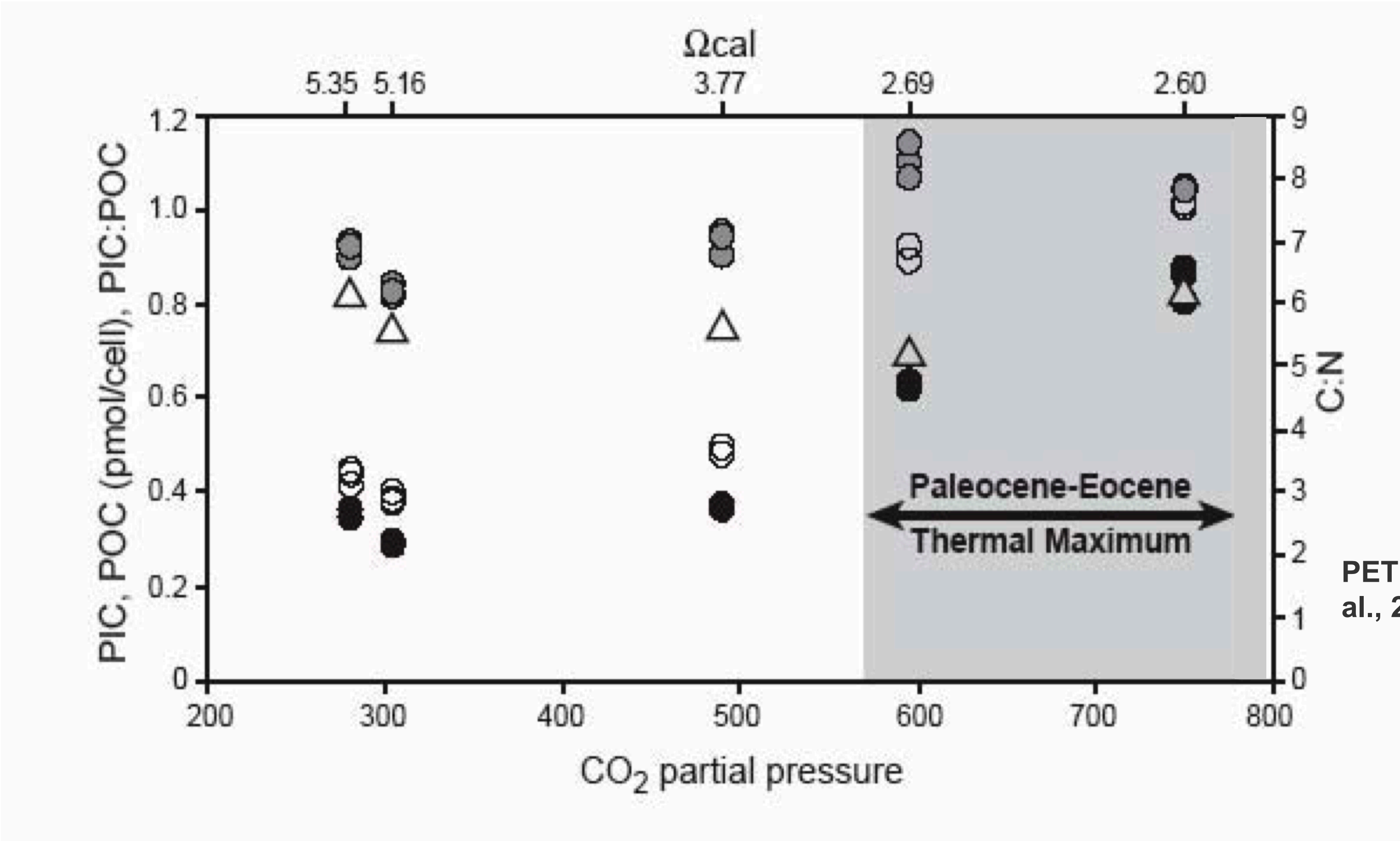


pH controlled with HCl



Calcidiscus leptoporus

Effect of CO_2 partial pressure on carbon physiology in *E. huxleyi*

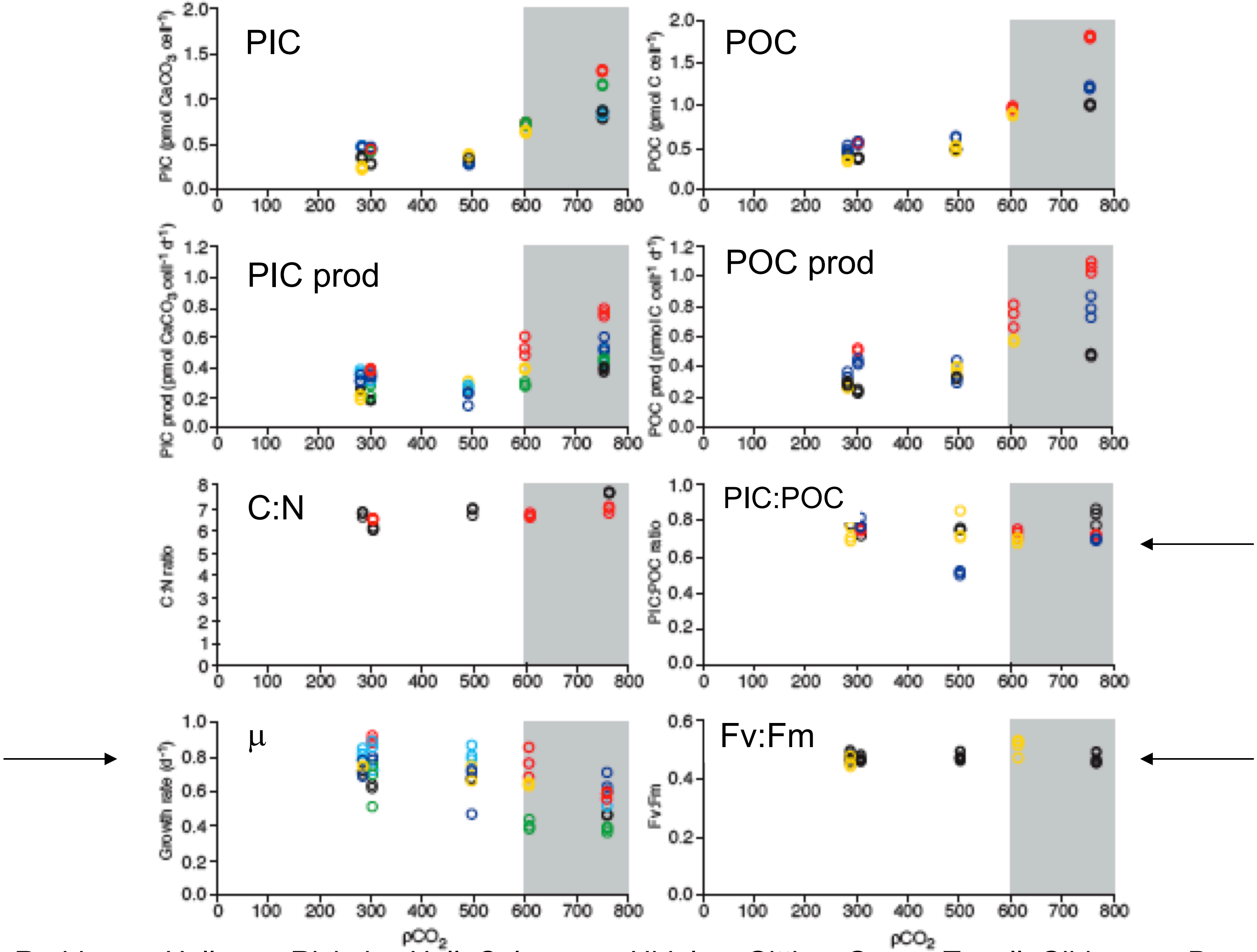


PETM: Royer et al., 2004

If PIC:POC > 1.5 ⇒ coccolithophores are a source of CO_2 (Frankignoulle et al., 1989)

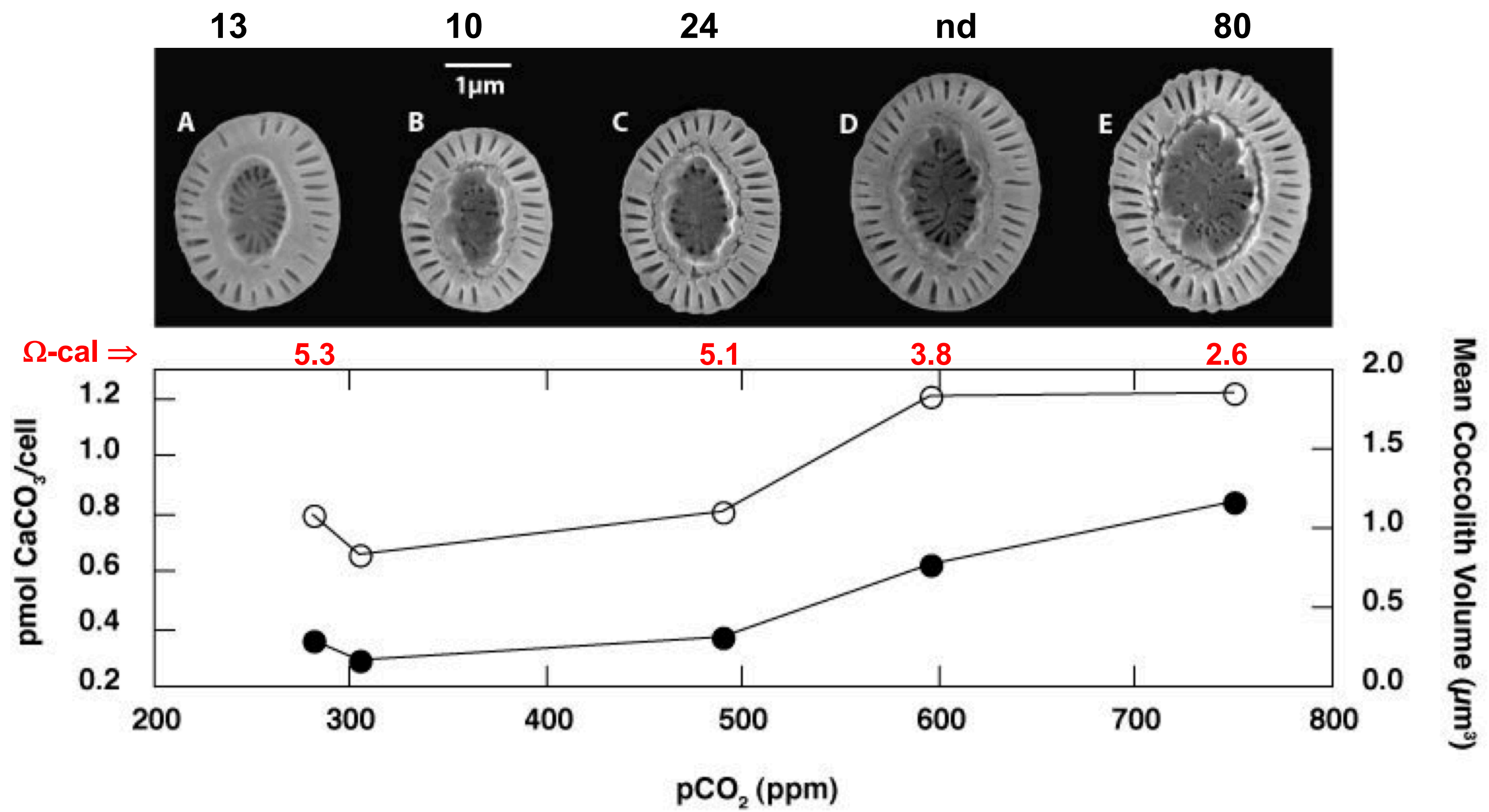
Iglesias-Rodriguez, Halloran, Rickaby, Hall, Colmenero-Hidalgo, Gittins, Green, Tyrrell, Gibbs, von Dassow, Rehm, Armbrust and Boessenkool, 2008.

Effect of CO_2 partial pressure on *E. huxleyi* physiology



Iglesias-Rodriguez, Halloran, Rickaby, Hall, Colmenero-Hidalgo, Gittins, Green, Tyrrell, Gibbs, von Dassow, Rehm, Armbrust and Boessenkool, 2008.

Cellular calcification and coccolith volume increase with increasing pCO_2



Iglesias-Rodriguez, Halloran, et al., 2008.

Will coccolithophore PIC:POC ratios decline as CO_2 increases?

YES

Riebesell et al, 2000

Zondervan et al, 2001

Zondervan et al, 2002

Herfort et al, 2004

DeLille et al, 2005

Feng et al, 2008

NO

Nimer & Merrett, 1993

Buitenhuis et al, 1999

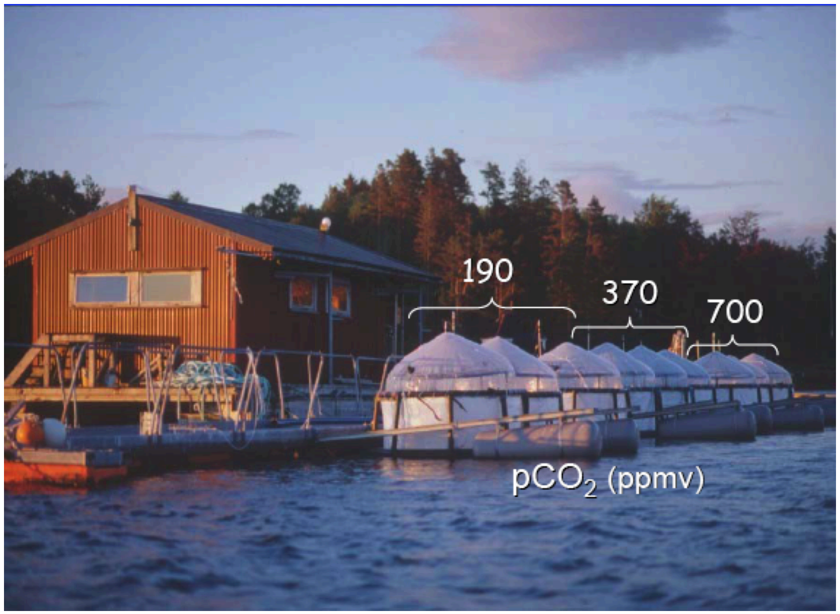
Sciandra et al, 2003

Iglesias-Rodriguez et al, 2008

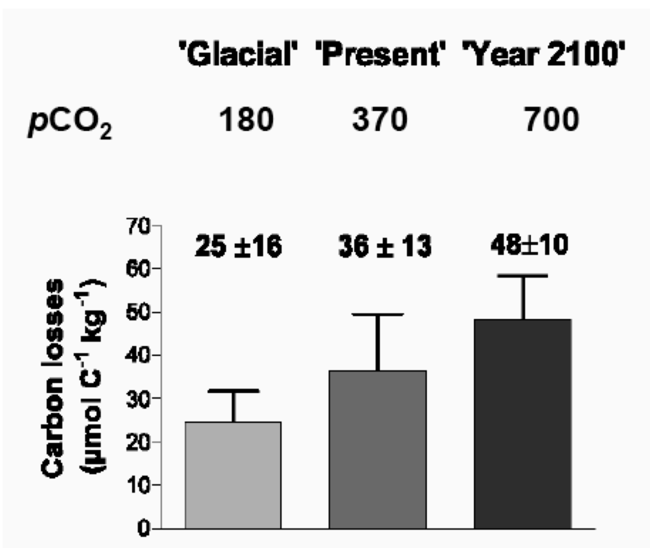
DEPENDS ON SPECIES

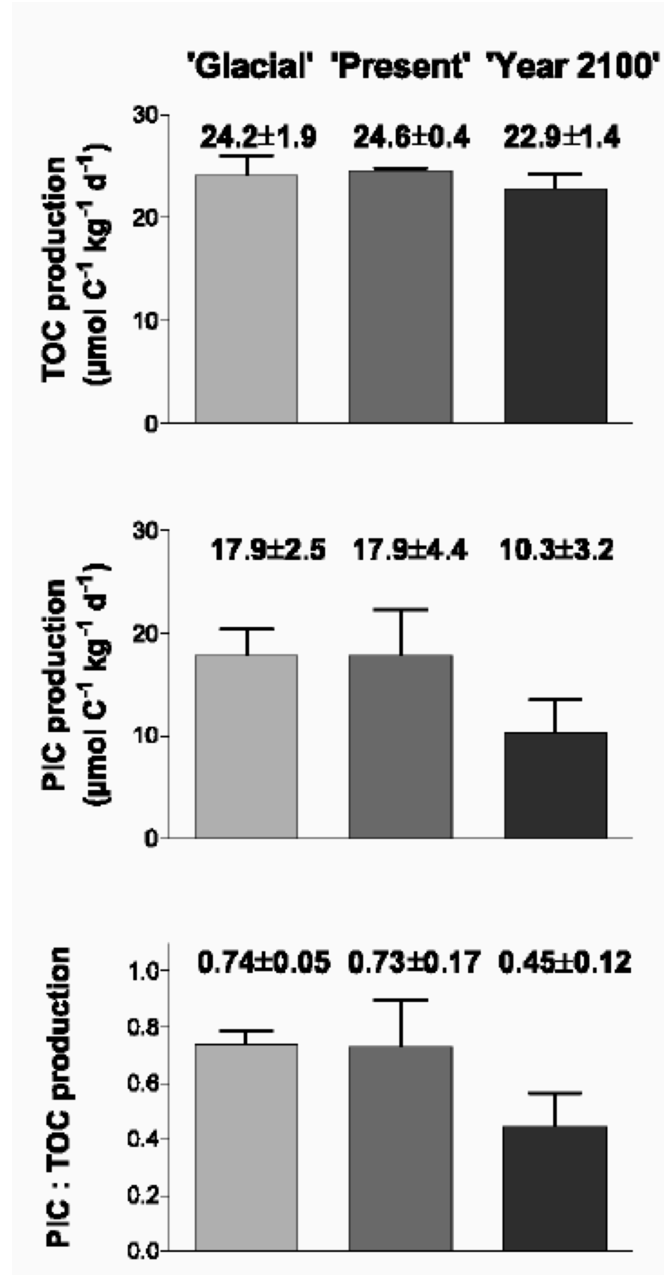
Langer et al, 2006

Mesocosm experiments



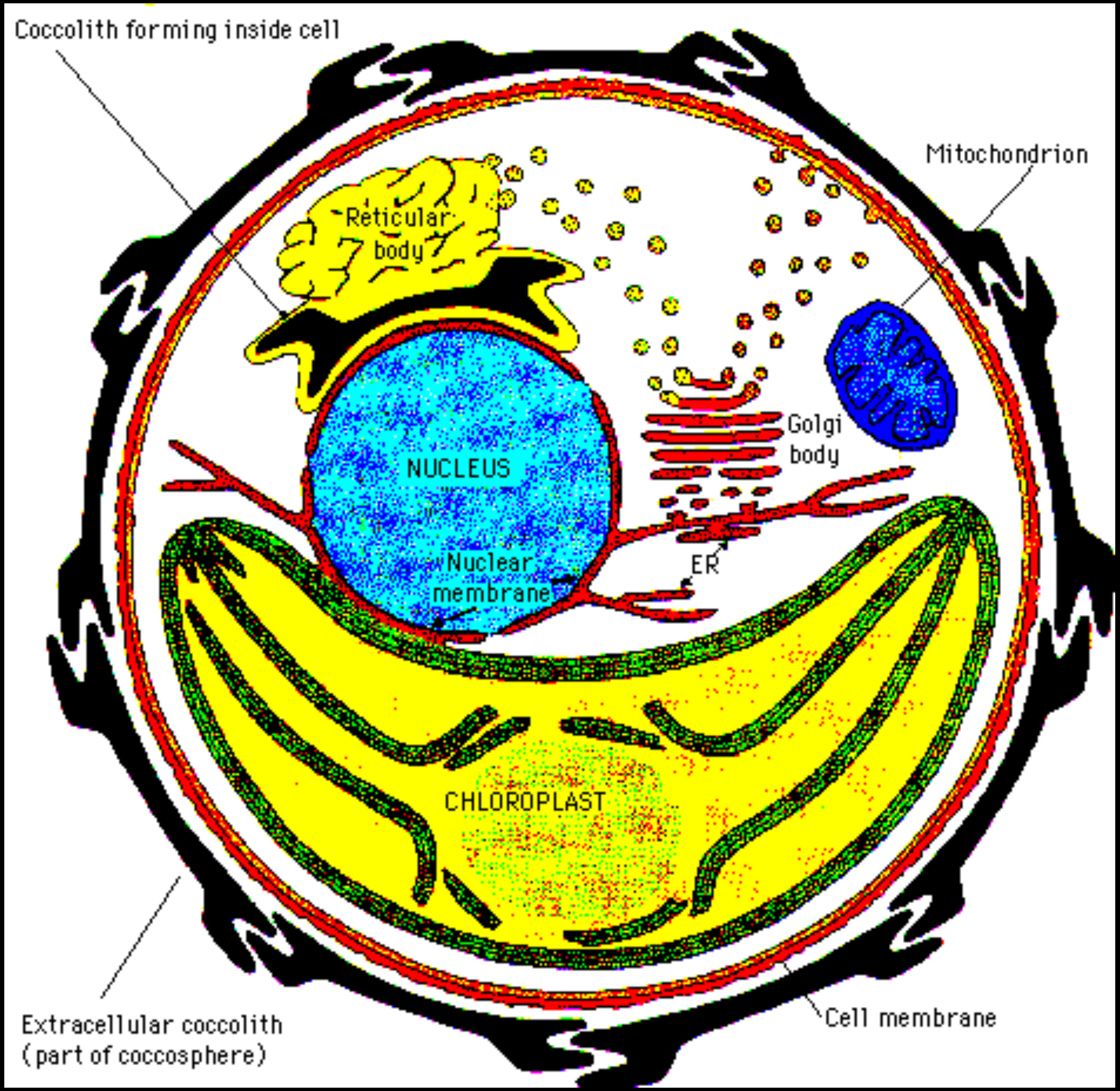
TEP:

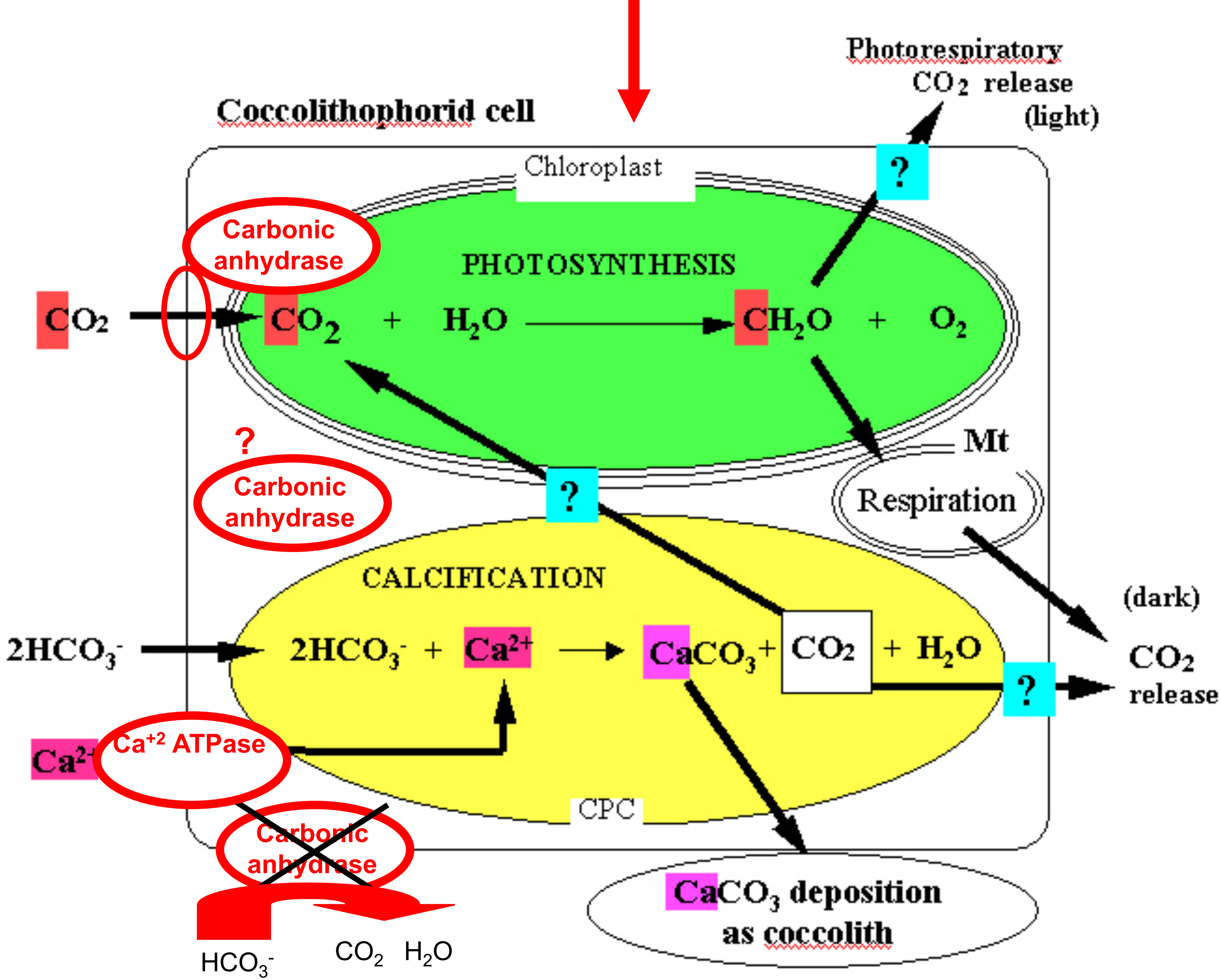




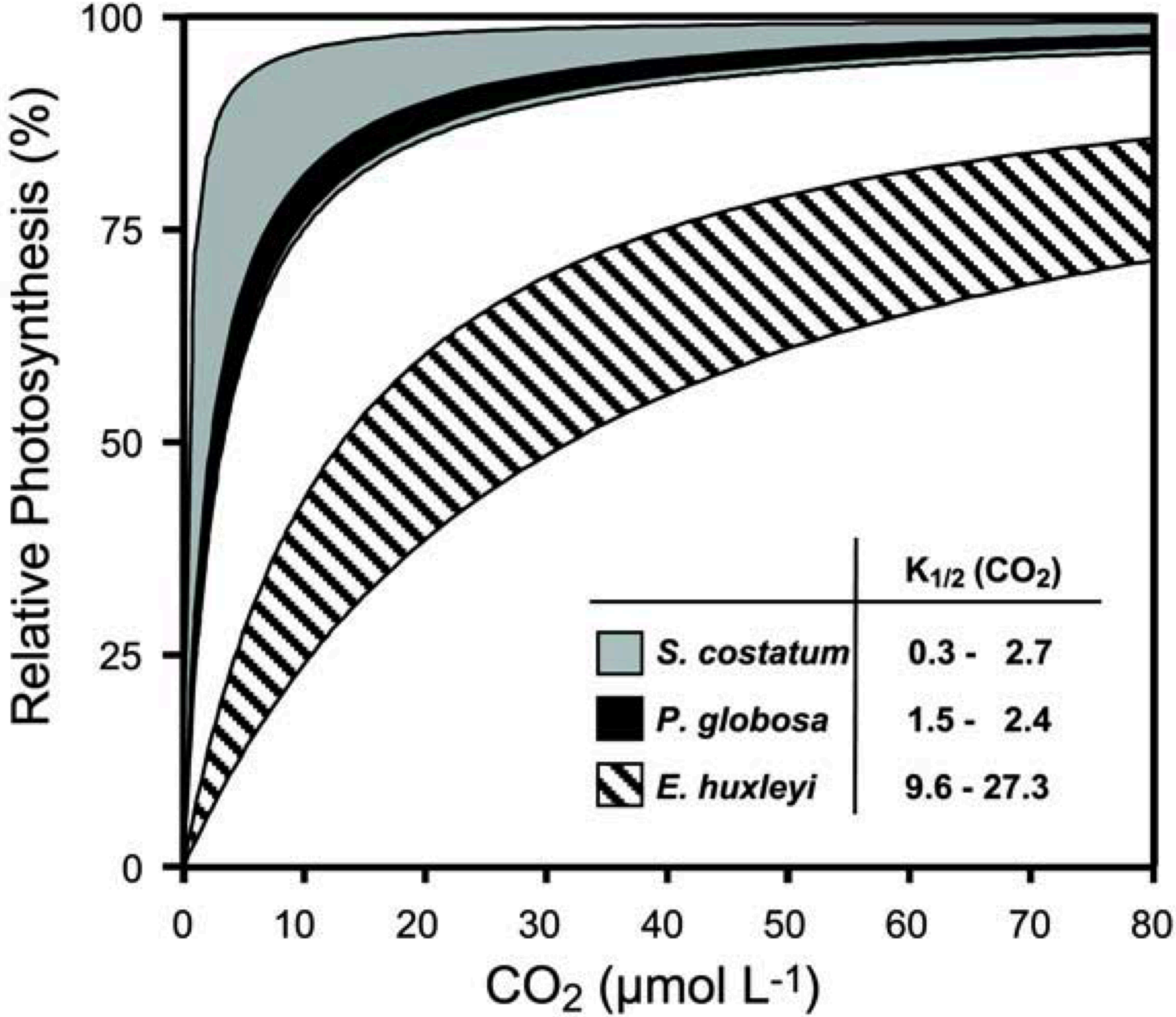
Delille et al., 2005.

Acclimation - Coccolithogenesis





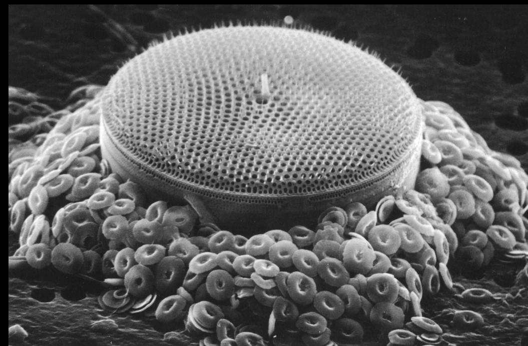
Coccolithophorid cell
Photorespiratory
CO_2 release
(light)
Chloroplast
?
Carbonic anhydrase
PHOTOSYNTHESIS
CO_2
CO_2 + H_2O → CH_2O + O_2
?
Carbonic anhydrase
?
Mt
Respiration
CALCIFICATION
(dark)
$2HCO_3^-$
$2HCO_3^-$ + Ca^{2+} → $CaCO_3$ + CO_2 + H_2O
?
CO_2 release
Ca^{2+}
Ca^{+2} ATPase
CPC
Carbonic anhydrase
$CaCO_3$ deposition as coccolith
HCO_3^-
CO_2 H_2O

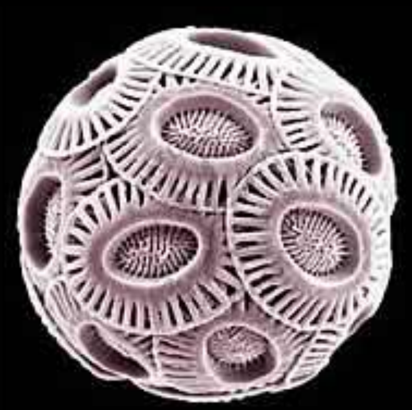


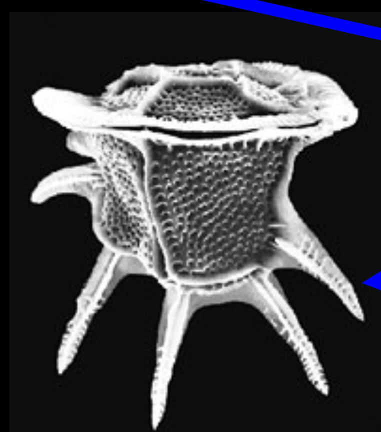
Relative Photosynthesis (%)
100
75
50
25
0
0
10
20
30
40
50
60
70
80
CO_2 (µmol L-1)
$K_{1/2}$ (CO_2)
S. costatum 0.3 - 2.7
P. globosa 1.5 - 2.4
E. huxleyi 9.6 - 27.3

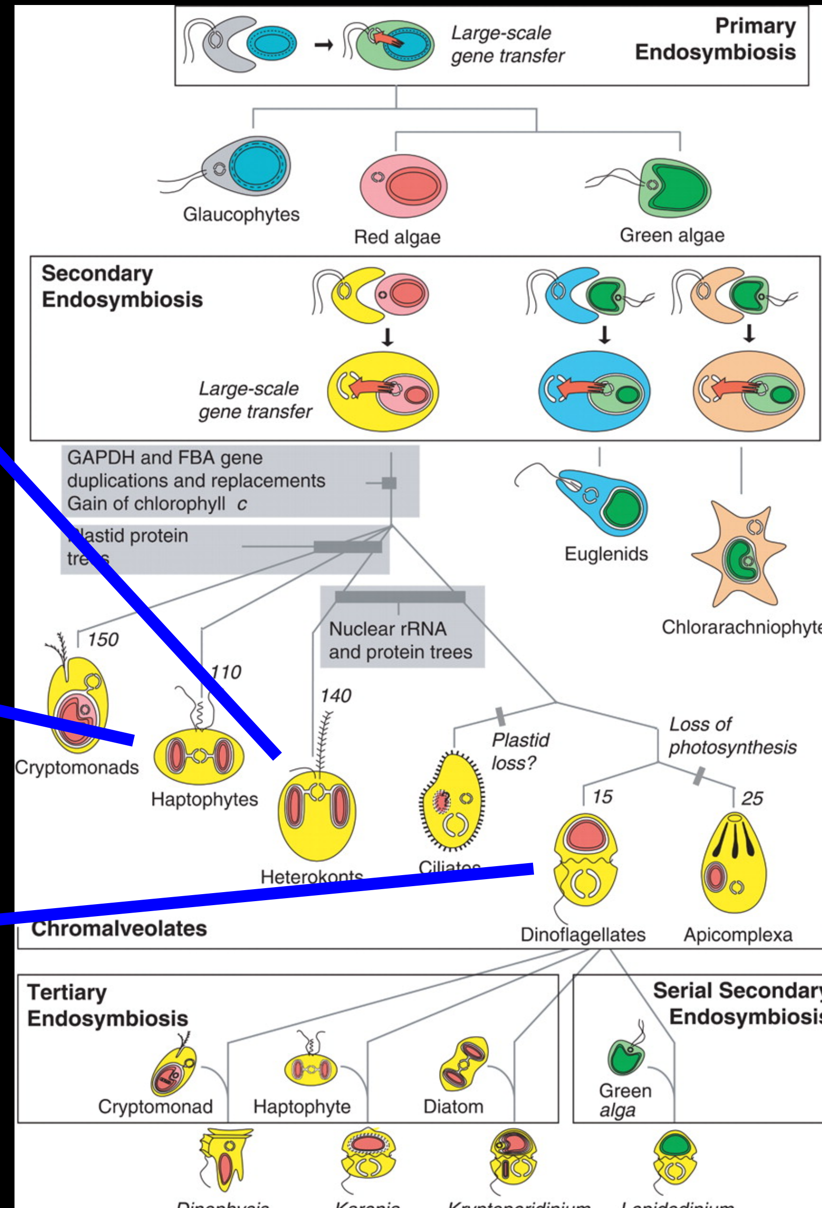
Phytoplankton functional groups and global biogeochemical cycles

Algal evolution and the origin and spread of plastids by endosymbiosis





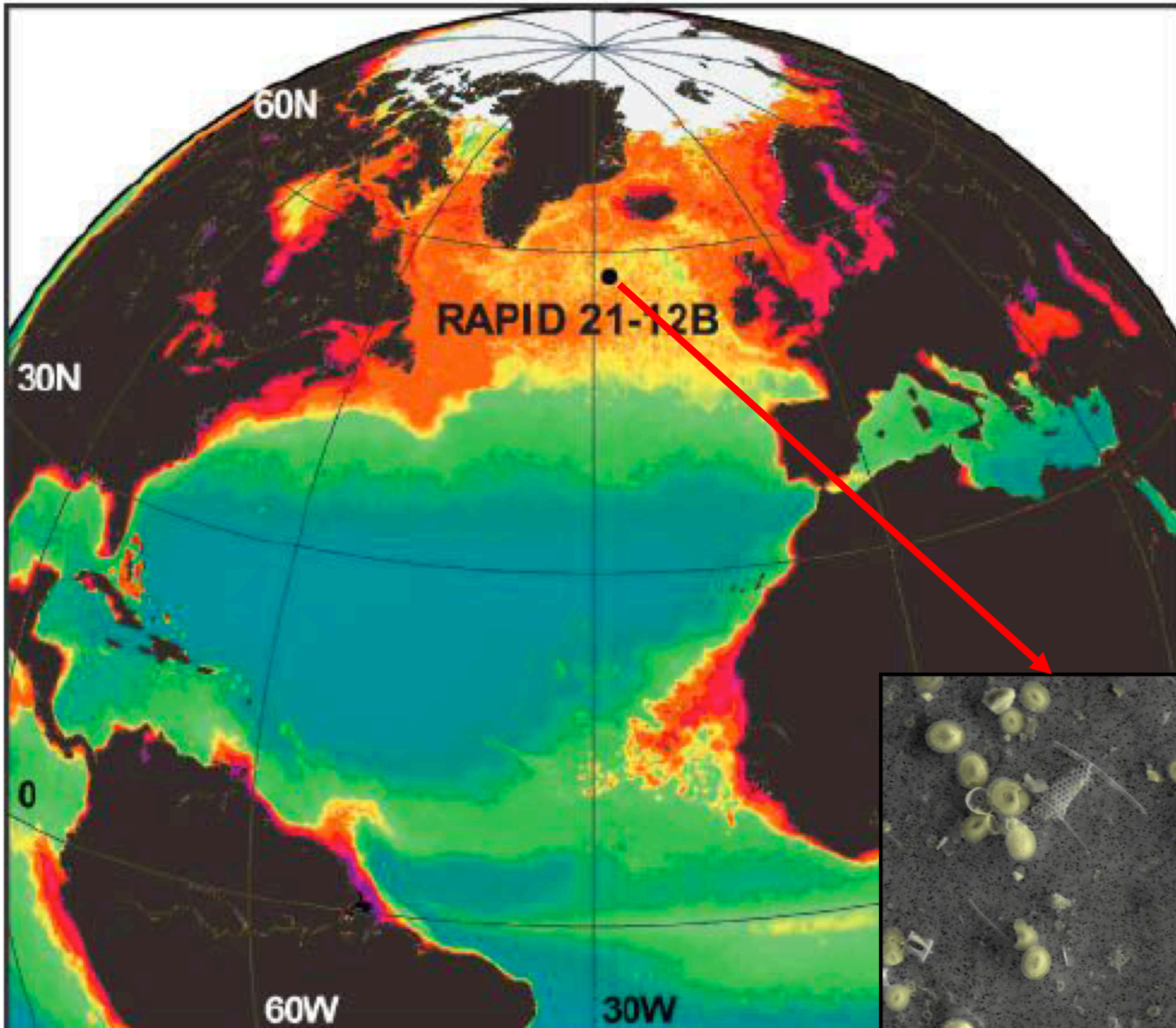


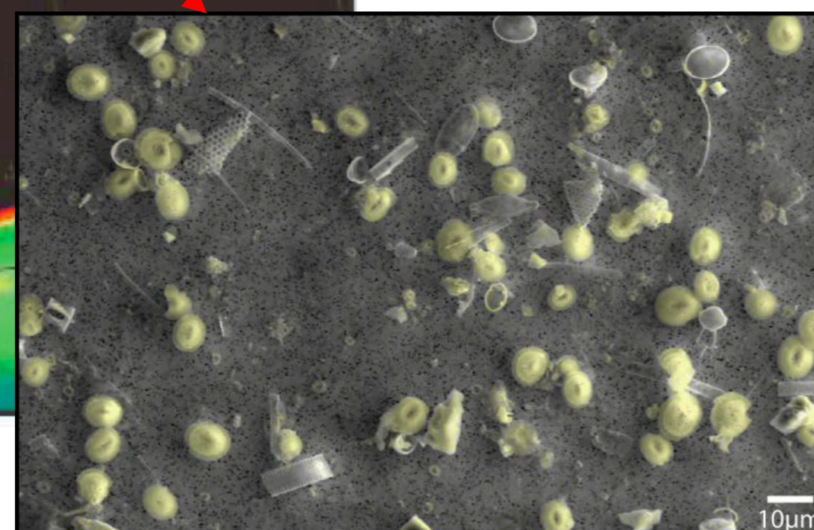


Diatom,: www.palomar.edu/ oceanography/iron.htm,
Coccolithophore image courtesy of Jeremy Young, Natural History Museum, London.Dinoflagellate: http://marinebio.org/Oceans/TheForests/

Charles Delwiche, modified by Falkowski et al, 2004.

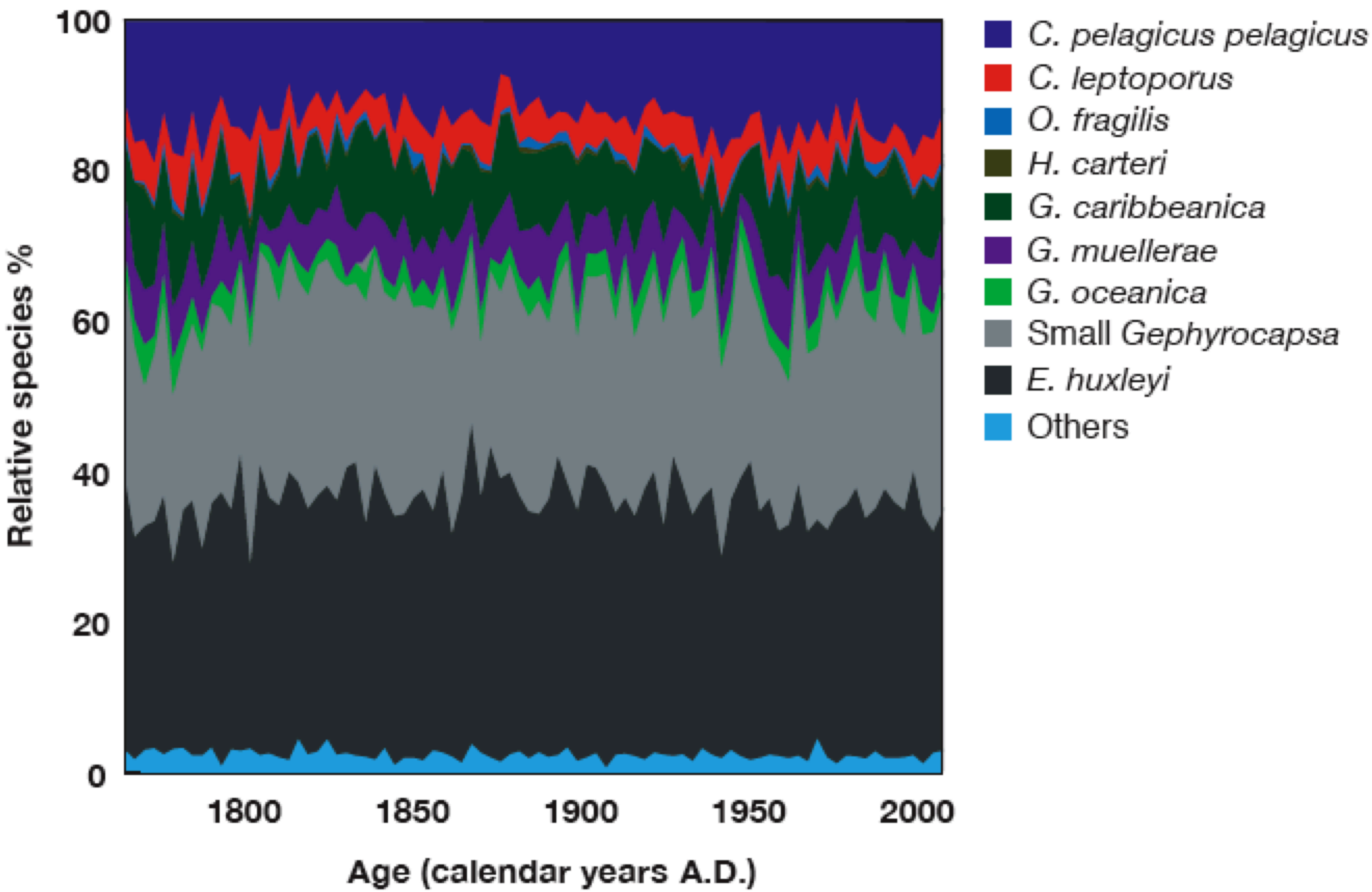
Evolutionary adaptation of coccolithophores since industrialization





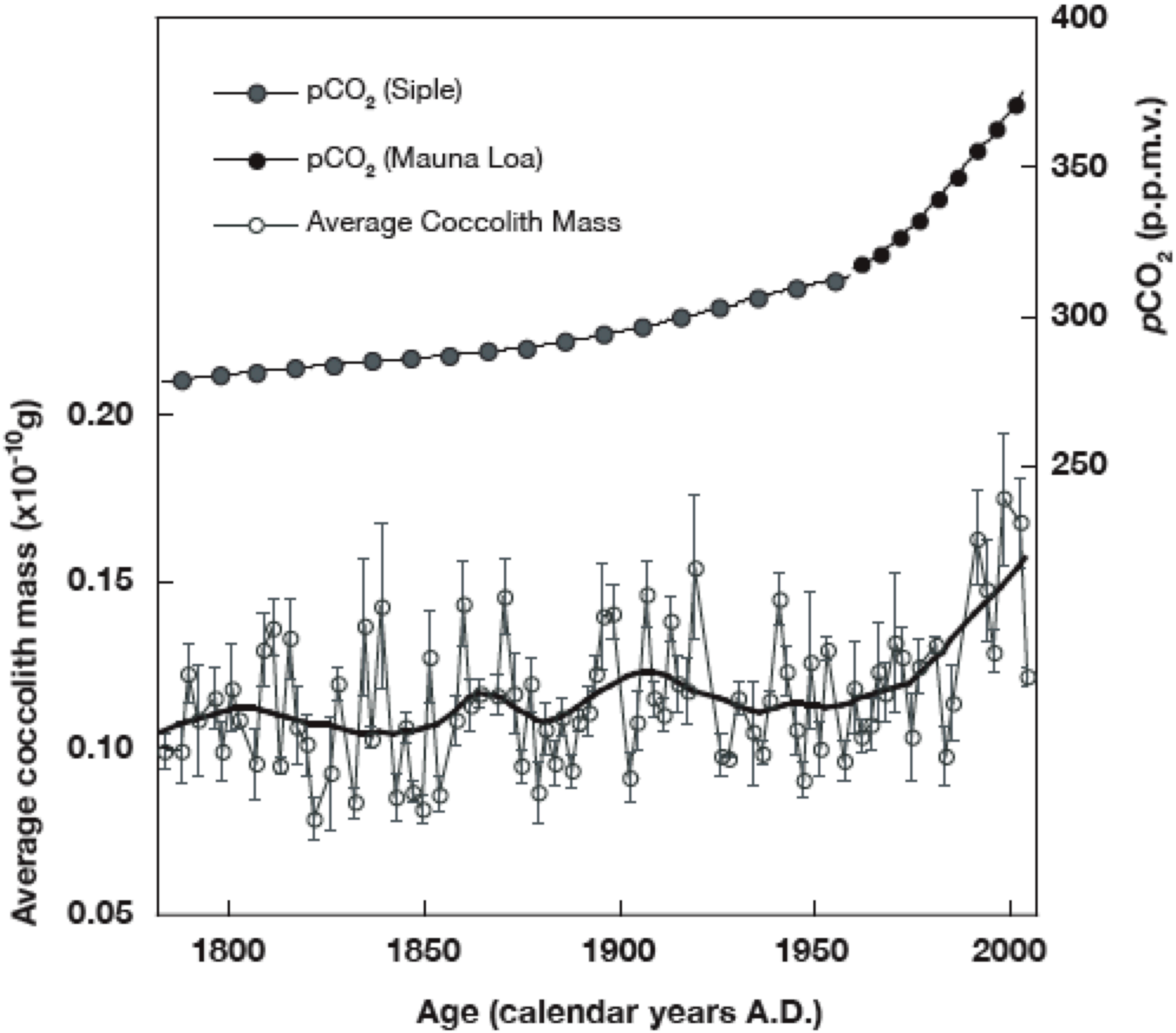
Paul Halloran, pers com)

Contribution of coccolithophore species during Anthropocene



Iglesias-Rodriguez, **Halloran**, **Rickaby**, **Hall**, **Colmenero-Hidalgo**, Gittins, Green, Tyrrell, Gibbs, von Dassow, Rehm, Armbrust and **Boessenkool**, 2008.

Changes in coccolithophore mass during Anthropocene



What do we know about the response of coccolithophores to high CO_2?

Carbonate chemistry manipulations

- **Calcification is controlled by Ω-cal**, rather than pH alone (Langer et al., 2006, Trimborn et al., 2007)
- **Ω-cal is controlled by both [DIC] and pH**
- Achieving the required pH by CO_2 **bubbling induces a greater percentage increase in [HCO_3^-]** than when the same pH reduction is achieved through acid addition (which does not affect [DIC])
- To investigate calcification under future CO_2 scenarios, **it is important to correctly simulate [HCO_3^-].**

Conclusions

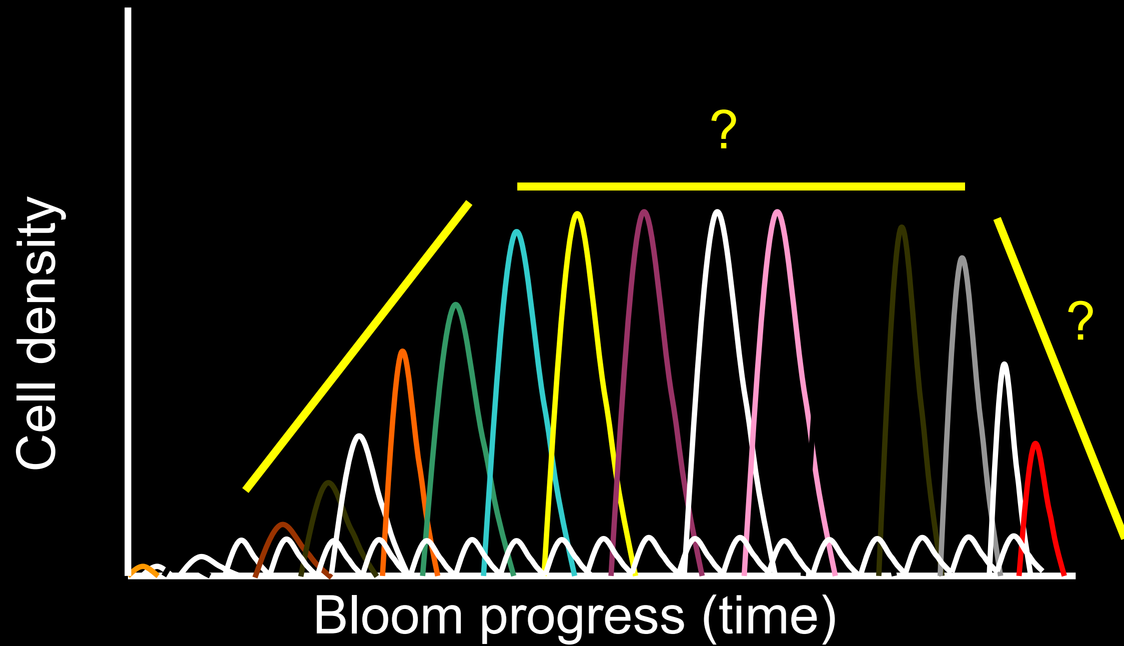
• **Increase in calcification and net primary production** in the coccolithophore species *Emiliania huxleyi* under elevated pCO_2.

• Field evidence from the deep ocean is consistent with these laboratory conclusions: **over the last 220 years there has been a 40% increase in average coccolith mass**.

• **Physiological and ecological versatility of coccolithophores** and their evolutionary adaptation through changes in ocean carbonate chemistry associated with past and projected pCO_2 levels.

• Coccolithophores are already responding, and will likely continue to respond to rising atmospheric CO_2 partial pressures and this likely to be a non-uniform response. Implications for **biogeochemical modelling of future oceans** and climate and **paleoceanographic reconstructions**.

So what do we know?



C:P > **1.7** ⇒ source C:P < **1.7** ⇒ sink

M. Frankignoulle, C. Canon, J.-P. Gattuso, *Limnol Oceanogr* **39**, 456-462 (1994).

Who wins? **DIATOM - COCCOLITHOPHORE - DINOFLAGELLATE**

Long term adaptation?

Mixed communities (bloom *versus* non-bloom)

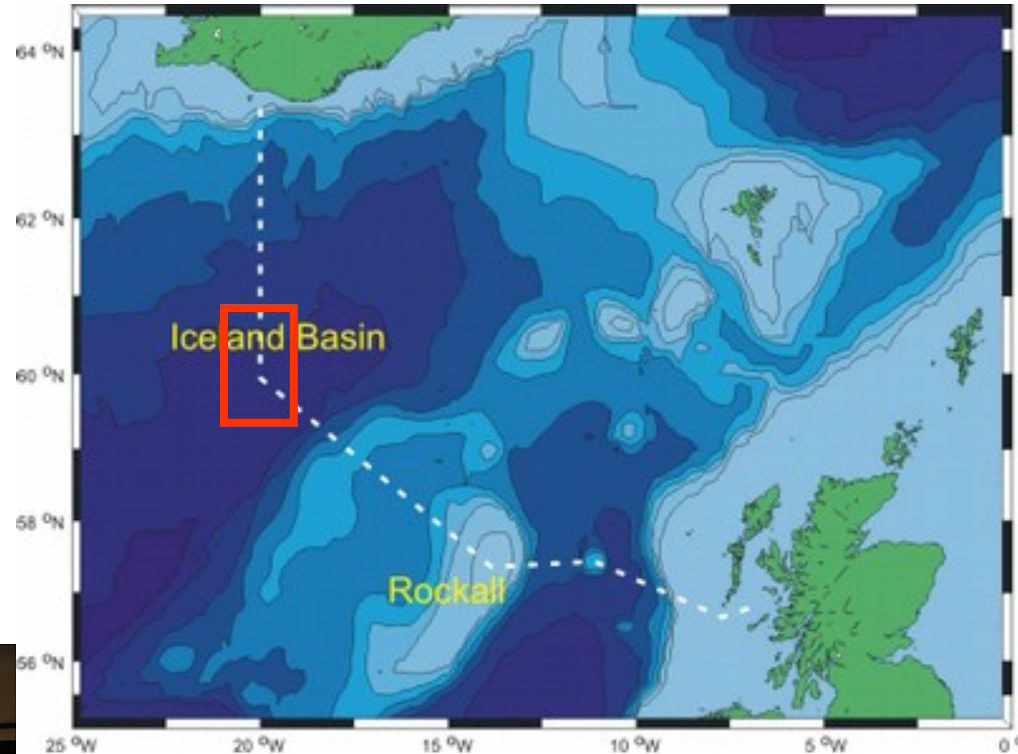
What's next?

- What's behind the signal? Big export bloomers or non-bloomers?
- How long is a long-term experiment?
- Generation time - mutation rates - adaptation to ESP
- Co-evolution (effect on other functional groups) - diatoms, dinos, grazers, viruses (more/less susceptible?)
- Continuous cultures - test decadal changes
- Flow cytometry (single cell genomics) - changes in population calcification, synchrony of adaptation, inherent variability.
- Genomics and proteomics - genes and phenes (coupling of gene expression and catalytic activities of important genes.

From the lab to the field (July-August 2007, D321A)

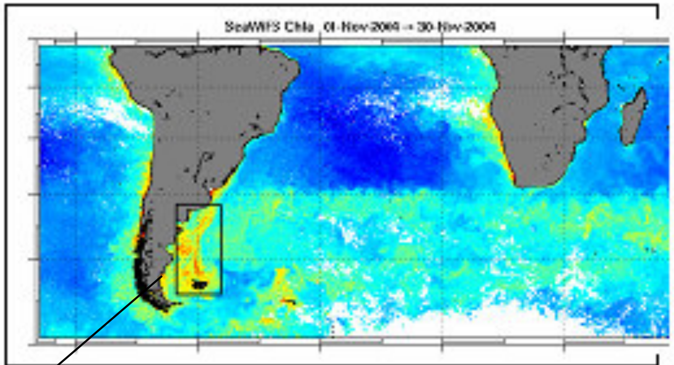
Chief scientist: John Allen

- Adaptation: who wins?
- *Acclimation to high CO_{2}:*
  - *Population functionality:*
    - *PIC*
    - *POC*
    - *Proteomics*

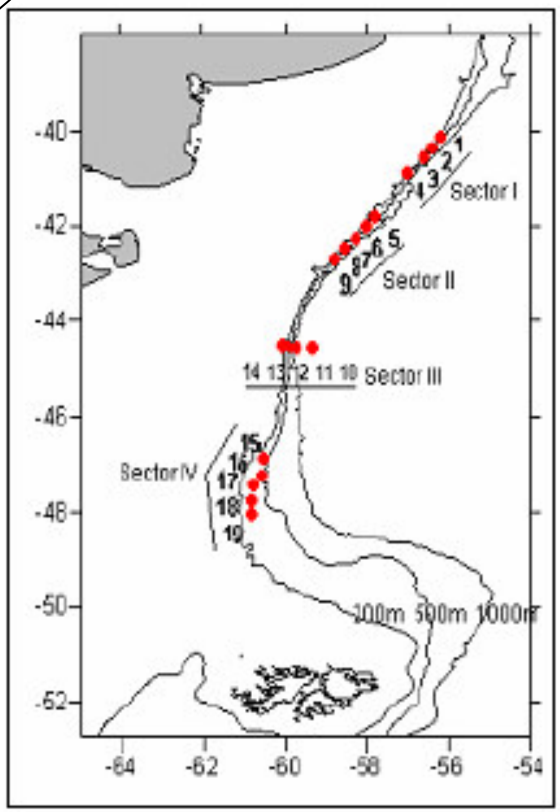


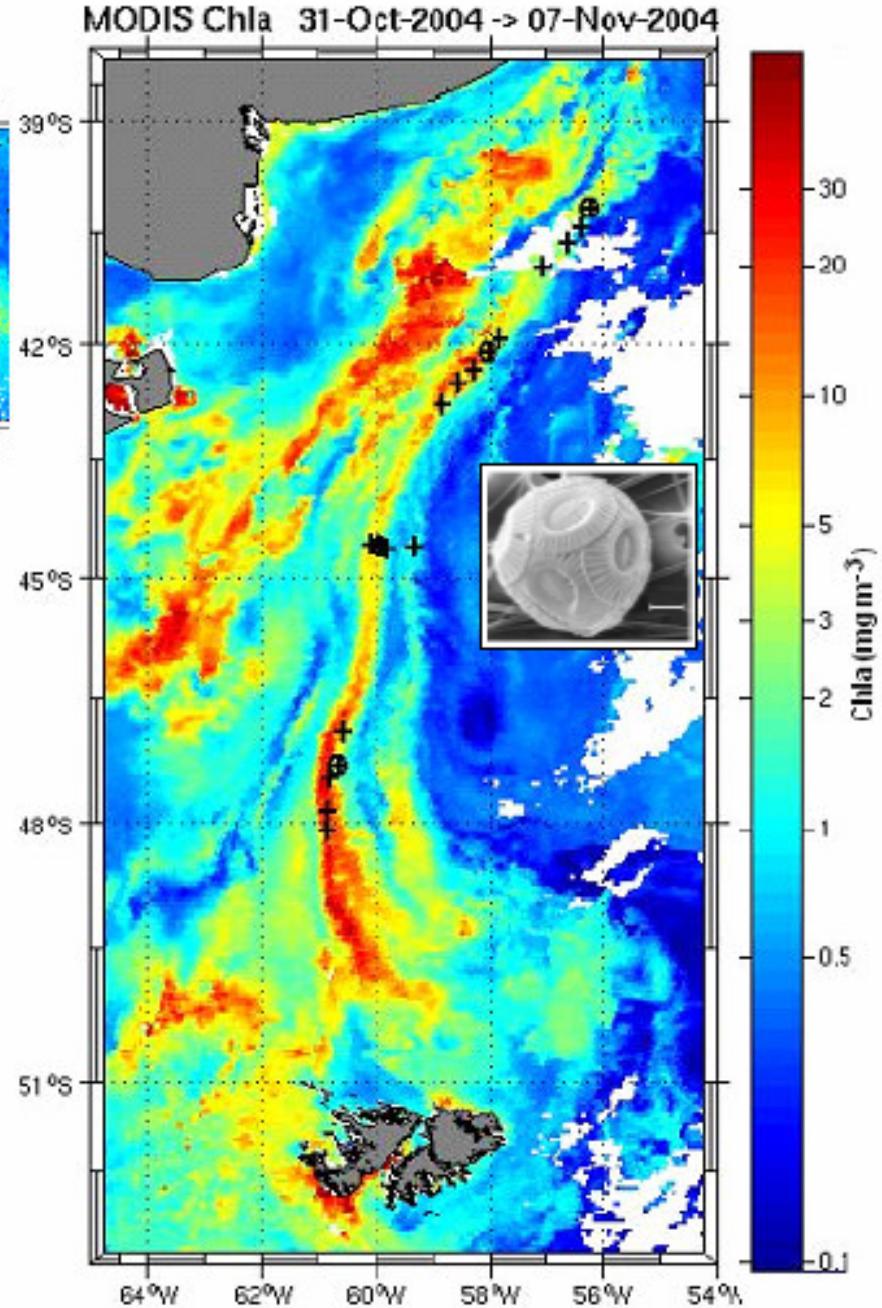
CO_2 incubations
Debora Iglesias-Rodriguez, Alex Poulton, Maria Salta

Proteomics field test trial (Bethan Jones)



Low Ω-cal

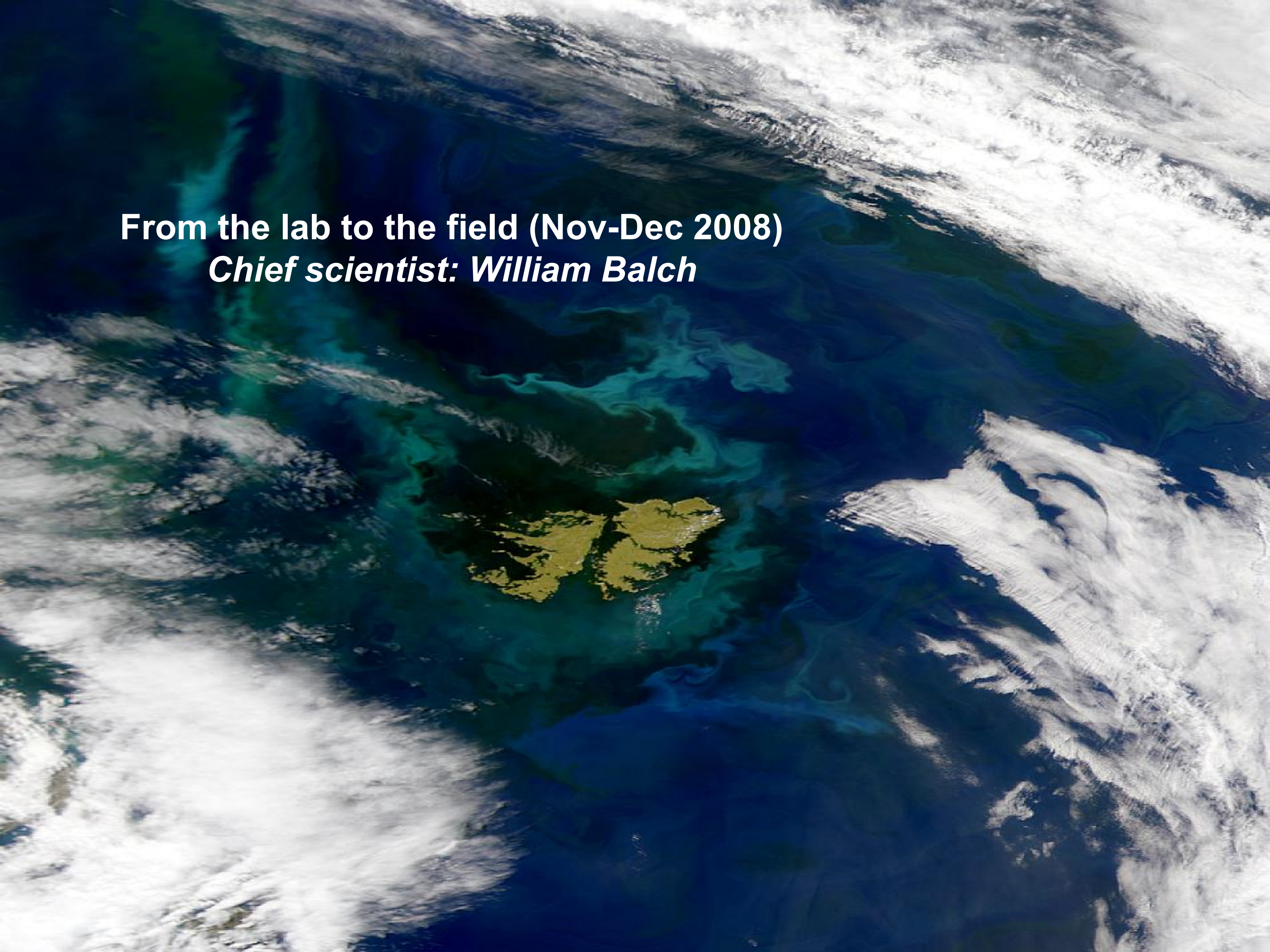




Garcia, Iglesias-Rodriguez et al et al, DSR, in press.

From the lab to the field (Nov-Dec 2008)

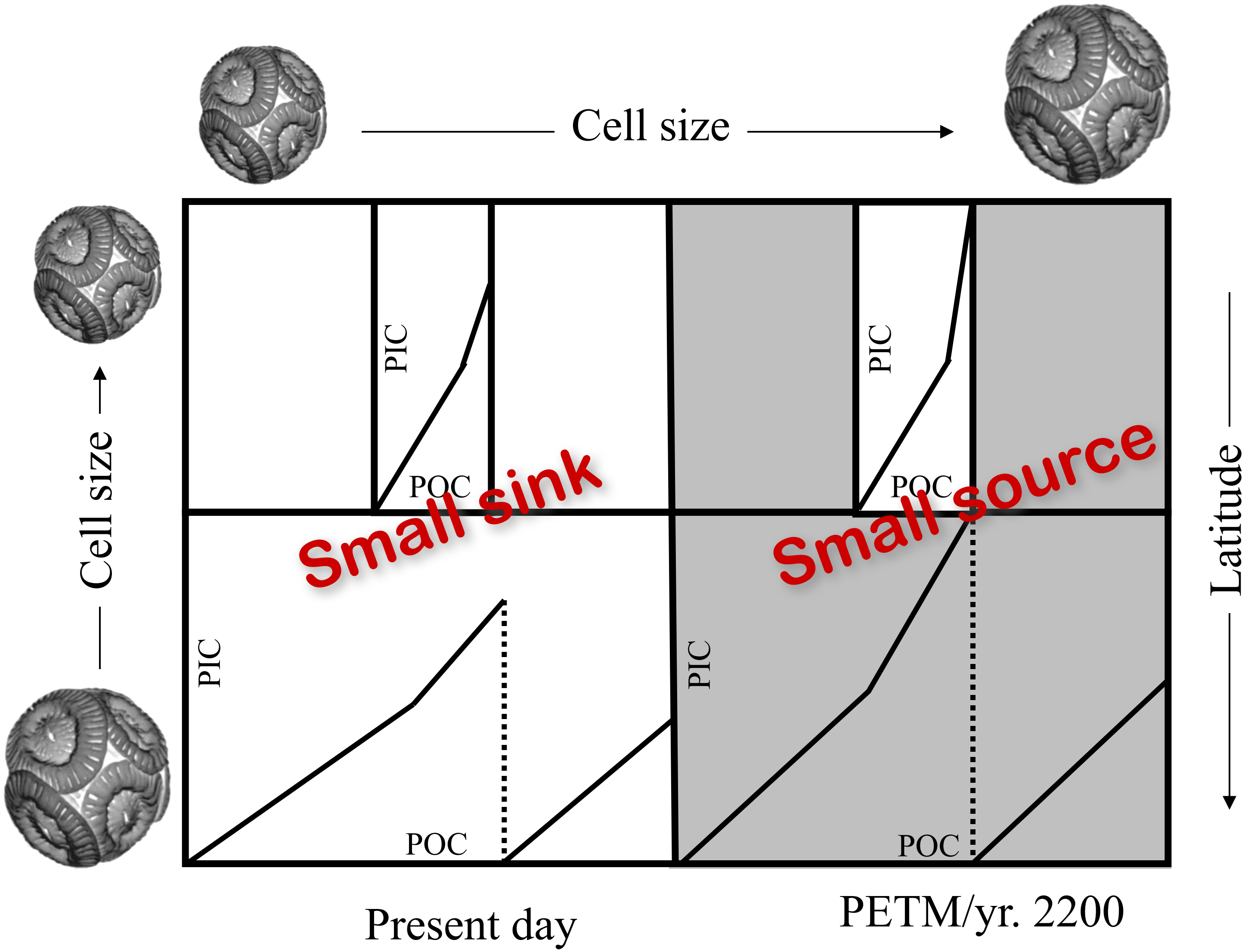
Chief scientist: William Balch



Evolution of functional groups

Organism	**Generation time**
Coccolithophores →→→→	Days
(autotrophic)	
Foraminifera →→→ →→→	Weeks
(heterotrophs)	
Pteropods →→→ →→→ →	Months
(heterotrophs)	

Present and past ocean acidification



PIC:POC > **1.5** ⇒ source

PIC:POC < **1.5** ⇒ sink

M. Frankignoulle, C. Canon, J.-P. Gattuso, *Limnol Oceanogr* **39**, 456-462, (1994).

EUROPEAN INITIATIVES ON OCEAN ACIDIFICATION

- EPOCA (**E**uropean **P**roject on **OC**ean **A**cidification) - proteomics of calcification (one PDRA, one PhD)

- CALMARO (**CAL**cification in **MAR**ine **O**rganisms) - diversity and functionality in response to climate change (one PhD)

Next:

- Calibrating paleorecord by conducting lab experiments: Sam Gibbs (NOC)
- Patagonian Shelf experiments: Barney Balch (Bigelow, USA)
- Shotgun proteomics to study functional properties of phytopankton (SoB CPR): Bethan Jones, Paul Skipp, David O'Conor, Richard Edwards)

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Sam Gibbs
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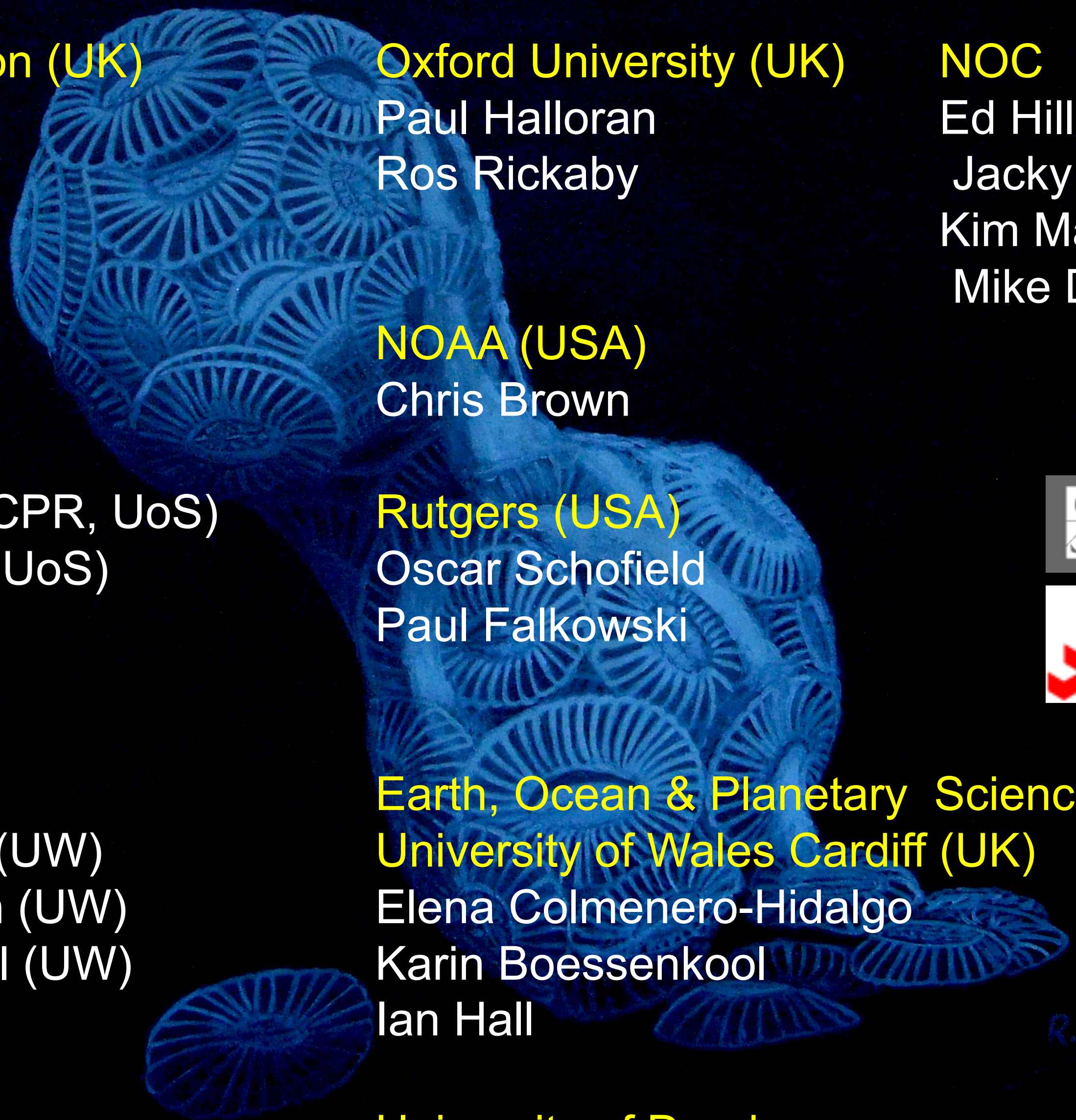

Coccolife Series, Rosa Seaoane, Vigo, Spain.