Rising pCO$_2$
and oligotrophic ocean biology:
winners and losers in the central gyres

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1. Laboratory experiments using cultures of major algal functional groups

2. Shipboard continuous culture experiments using natural phytoplankton communities in the North Atlantic spring bloom, the Bering Sea, and the Ross Sea.

3. Interactions between changing pCO$_2$ and other global change co-variables, including temperature, nutrients, light, and Fe.
Lab experiments using dominant groups of oligotrophic phytoplankton

**Prokaryotes:**

- *Synechococcus* and *Prochlorococcus*
- N$_2$-fixing *Trichodesmium*
- Unicellular N$_2$-fixing cyanobacteria (*Crocosphaera*)

**Eukaryotes:**

- Coccolithophore (*E. hux*)
- Diatoms
Interactions between CO$_2$ and temperature: A factorial experimental design

- **Control**: Present day temperature and pCO$_2$
- **High pCO$_2$**: Present day temperature and 750 ppm CO$_2$
- **High Temperature**: +3-5$^\circ$C and present day pCO$_2$
- **Greenhouse**: +3-5$^\circ$C and 750 ppm CO$_2$
Combined pCO$_2$ and temperature effects on growth rates of picocyanobacteria

(Fu et al. 2007, J. Phycol. 43)
Photosynthesis versus irradiance curves: Different responses of *Synechococcus* and *Prochlorococcus* to elevated pCO$_2$ and temperature (Fu et al. 2007, J. Phycol. 43)
Synechococcus CCMP1334 photosynthesis, growth and elemental ratios are all responsive to changing pCO$_2$ and temperature.

Prochlorococcus CCMP1986 physiology is relatively unaffected by these variables.

Individual picocyanobacteria groups will respond in very different ways to increasing pCO$_2$ and temperature—beware of overgeneralizing!
How does *Trichodesmium* growth and nitrogen fixation respond to changing pCO$_2$?

*Trichodesmium erythraeum* strain GBR cultured at a range of pCO$_2$: 150, 380, 750, 1250 and 1500 ppm
CO₂ limitation of *Trichodesmium*

1. N₂ fixation rates increase by 63% between 380 and 750 ppm pCO₂
2. CO₂ fixation rates increase by 54% between 380 and 750 ppm pCO₂
3. Specific growth rates increase by 37% between 380 and 750 ppm pCO₂
4. *Trichodesmium* was unable to grow at all at a pCO₂ of 150 ppm
5. N:P (and C:P) ratios increase by 35% between 380 ppm and 1250 ppm CO₂

(Hutchins et al. 2007, L&O 52(4): 1293- 1304)
pCO$_2$ and P co-limitation of *Trichodesmium* N$_2$ fixation

Adding either P or CO$_2$ increases N$_2$ fixation and growth rates of P-limited cultures at present day pCO$_2$

(Hutchins et al. 2007, L&O 52)
The unicellular $N_2$-fixing cyanobacterium *Crocosphaera*

Interactions between pCO$_2$ and Fe availability

Treatments:
- Fe-replete, 380 ppm CO$_2$
- Fe-replete, 750 ppm CO$_2$
- Fe-limited, 380 ppm CO$_2$
- Fe-limited, 750 ppm CO$_2$

Fu et al. in prep
pCO$_2$ effects on N$_2$ fixation rates of Fe-replete and Fe-limited *Crocosphaera*

Fu et al. in prep
**Crocosphaera**

**N$_2$ fixation rates**

- **Fe-replete**
  - pCO$_2$ (ppm): 190, 380, 750
  - $N_2$ fixation (nmol cell$^{-1}$ hour$^{-1}$): 0, 1e-8, 3e-8

- **Fe-limited**
  - pCO$_2$ (ppm): 190, 380, 750
  - $N_2$ fixation (nmol cell$^{-1}$ hour$^{-1}$): 0, 1e-8, 2e-8, 3e-8

**Cellular Fe quota**

- **Fe replete**
  - Fe:P ratio (mmol:mol): 0, 10, 20, 30, 40, 50

- **Fe limited**
  - Fe:P ratio (mmol:mol): 0, 10, 20, 30, 40, 50

**Fu et al. in prep**
**Crocosphaera:**

\[
pCO_2 \quad \rightarrow \quad N_2 \text{ fixation} \quad \rightarrow \quad \text{Fe quota}
\]
Biogeochemical Implications

• Global marine N$_2$ fixation could increase dramatically (~50%?) with doubled pCO$_2$ over the next 100 years.

• CO$_2$-mediated increases in N:P ratios may drive oligotrophic regimes further towards P limitation. Elevated Fe requirements may drive diazotrophs further towards Fe limitation as well.

• Rising CO$_2$ thus directly impacts the N cycle by increasing new N supply from N$_2$ fixation, and thereby also indirectly controls both P and Fe biogeochemistry.
Interactive effects of light, temperature and pCO$_2$ on calcification by a Sargasso Sea *E. hux.* isolate

Feng et al. in press, European Journal of Phycology

The primary control on calcification in this strain is light intensity—pCO$_2$ exerts a secondary effect, but only under saturating light conditions.
North Atlantic Spring Bloom CO₂/temperature experiment: coccolithophores and DMSP

Feng et al. in prep.
North Atlantic Bloom CO$_2$/temperature experiment: PIC production

Feng et al. in prep.
Biogenic silica:POC ratio:
Warmer temperatures shift communities away from diatoms in the North Atlantic Spring Bloom

[Graph showing the relationship between biogenic silica:particulate organic carbon (BSi:POC) molar ratio and environmental conditions]

Feng and Hutchins in prep.
“Greenhouse” conditions preferentially stimulate the growth of coccolithophores, while paradoxically greatly reducing calcification.

Light and temperature interactive effects can be at least as important as rising pCO₂ alone for coccolithophore dominance and calcification.
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Proposal for a Workshop on Environmental Change and Biological Adaptation in the Ocean
Dave Hutchins
Donal Manahan

• What questions are best addressed by an integrative approach combining oceanography and evolutionary biology to address biological responses to rapid environmental change in the ocean?

• How can studies of present-day organisms and communities be used to predict long-term adaptations and biological responses to rapid regime shifts?

• Can accurate models be developed to predict future effects of multiple environmental changes on organismal, population, and ecosystem-level adaptations?
Light/CO$_2$ interactions in *Trichodesmium*

**N$_2$ fixation**

- Low light:
  - 380 ppm: 0 N pmol Chl a mg h$^{-1}$
  - 750 ppm: 5 N pmol Chl a mg h$^{-1}$

- High light:
  - 380 ppm: 25 N pmol Chl a mg h$^{-1}$
  - 750 ppm: 30 N pmol Chl a mg h$^{-1}$

**CO$_2$ fixation**

- Low light:
  - 380 ppm: 2 ug C ug Chl a h$^{-1}$
  - 750 ppm: 2 ug C ug Chl a h$^{-1}$

- High light:
  - 380 ppm: 30 ug C ug Chl a h$^{-1}$
  - 750 ppm: 35 ug C ug Chl a h$^{-1}$
Ross Sea

*Phaeocystis antarctica*

CO$_2$/Fe experiment:

Higher Zn and Cd quotas at lower pCO$_2$
Synechococcus  Prochlorococcus

Carbon quota (fg cell\(^{-1}\))

Nitrogen quota (fg cell\(^{-1}\))

Phosphorus quota (fg cell\(^{-1}\))
Crocosphaera: Effects of pCO₂ on cellular Mo quota

Fu et al in prep
Effects of changing pCO$_2$ on the Co quota of the unicellular N$_2$-fixing cyanobacterium *Crocosphaera*