Ocean Acidification, Marine Organisms and the Marine Carbon Cycle

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Carbon Cycle

The Problem:
Fossil Fuel Emission Resulting Increase in CO_2

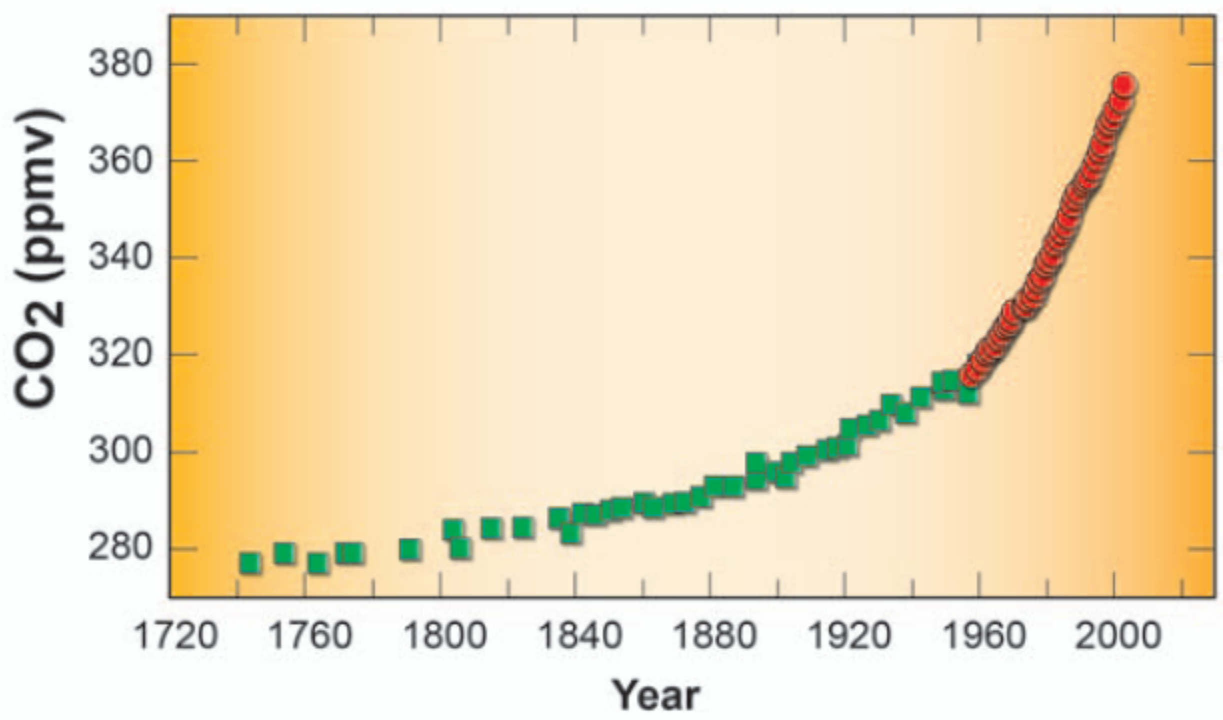


FIGURE 1 The increase of carbon dioxide in the atmosphere as determined from atmospheric samples at Hawai'i (Keeling and Whorf 2004; red circles) and from air trapped in ice cores (Neftel et al. 1994; green squares) as a function of time.

Millero& DiTrollio 2010

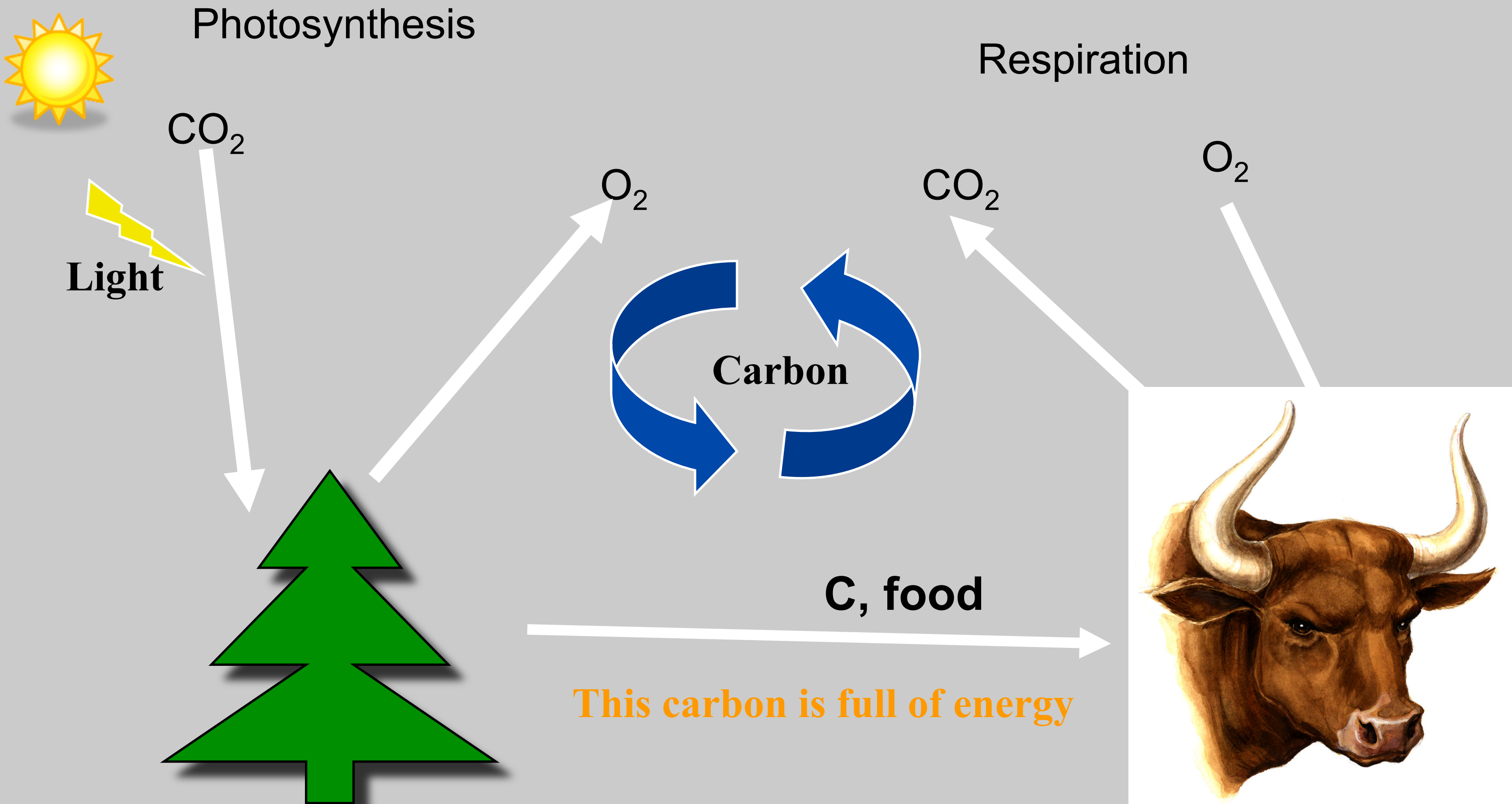
Discussion:
The basics: plants and animals and oil

Carbon Cycle

C = carbon

CO_2 = carbon dioxide

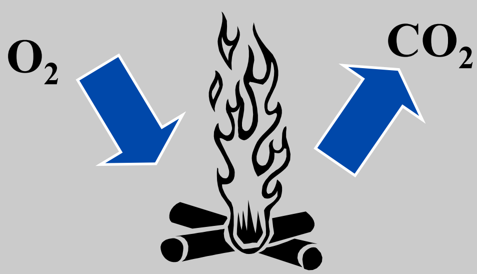
O_2 = oxygen



Carbon Cycle

65 million years ago (no humans)

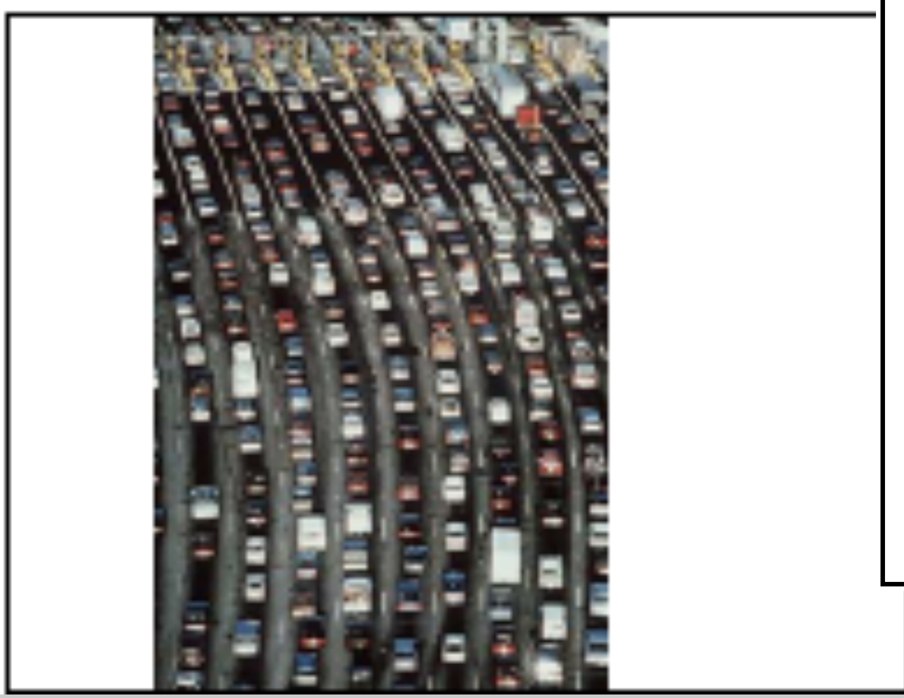
These plants are now oil and coal. When oil or wood is burned to use the energy CO_2 is released.

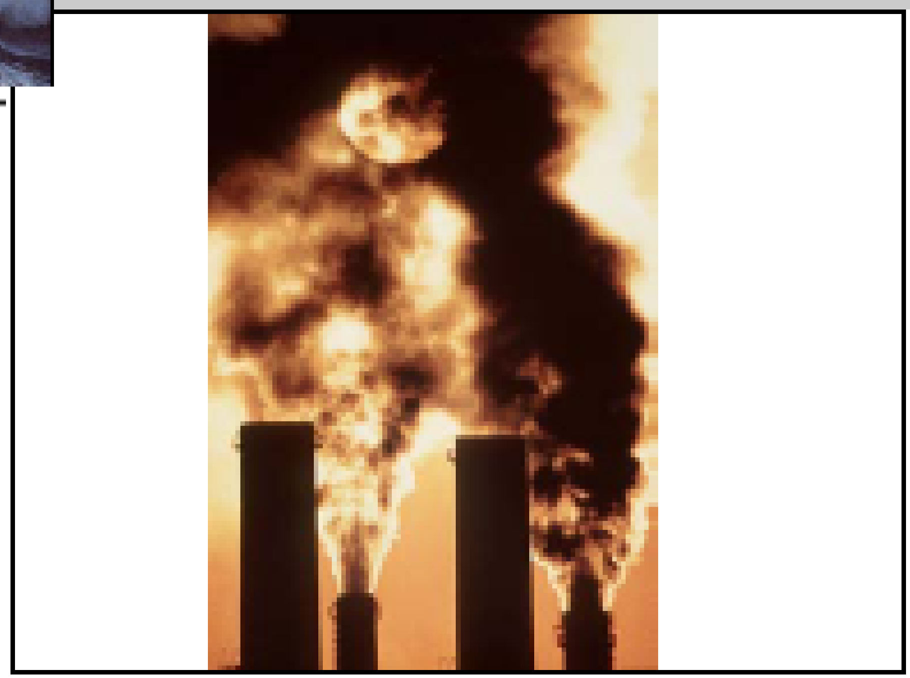


Carbon Cycle

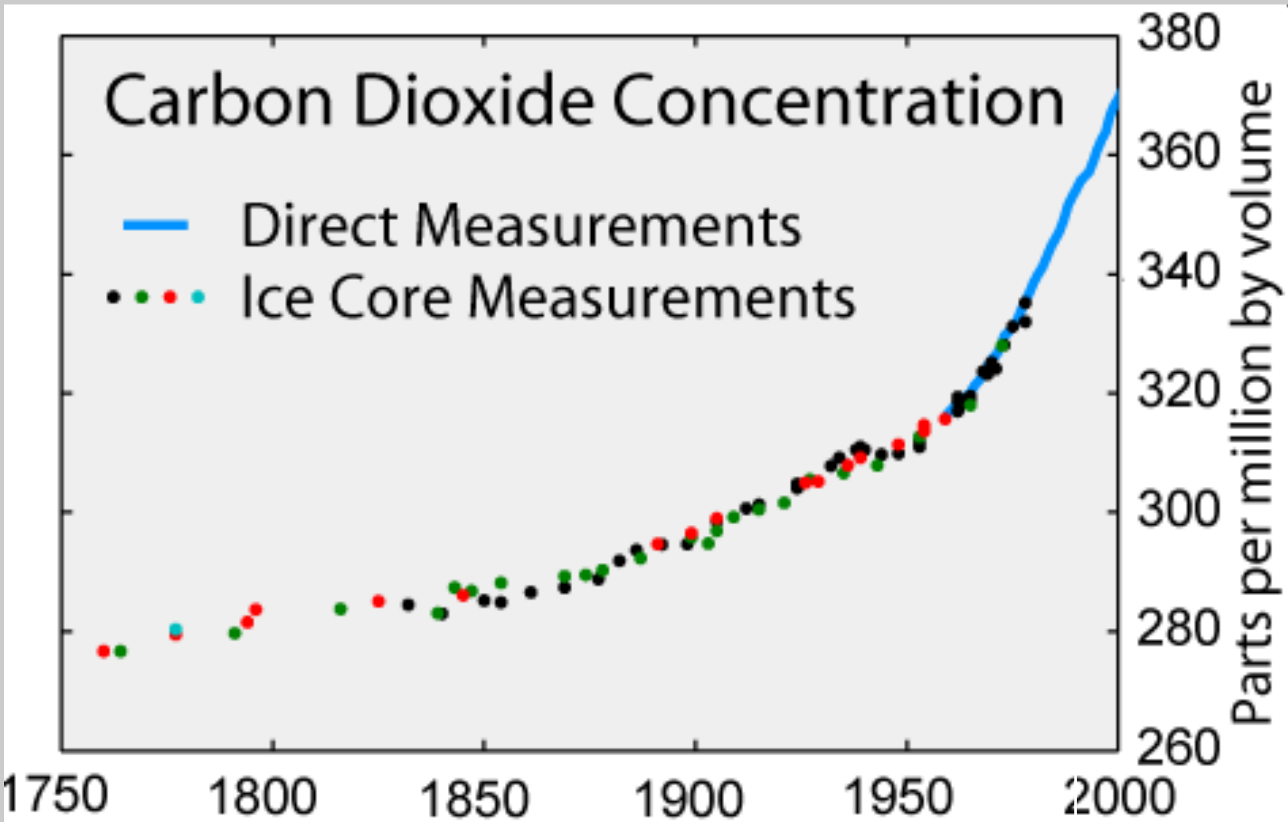
What can we do?

- Reduce your CO_2 foot print
  - Reduce gasoline / energy usage
  - Use CO_2 neutral energy (solar/ wind..)
  - plant trees
- Lobby for Reduction of CO_2 foot print
  - Public transportation
  - Development of “alternative technology”





Carbon Cycle



Revolutionary war

First cars

Grand parents born

Your parents born

You were born

250 years ago!

Carbon Cycle

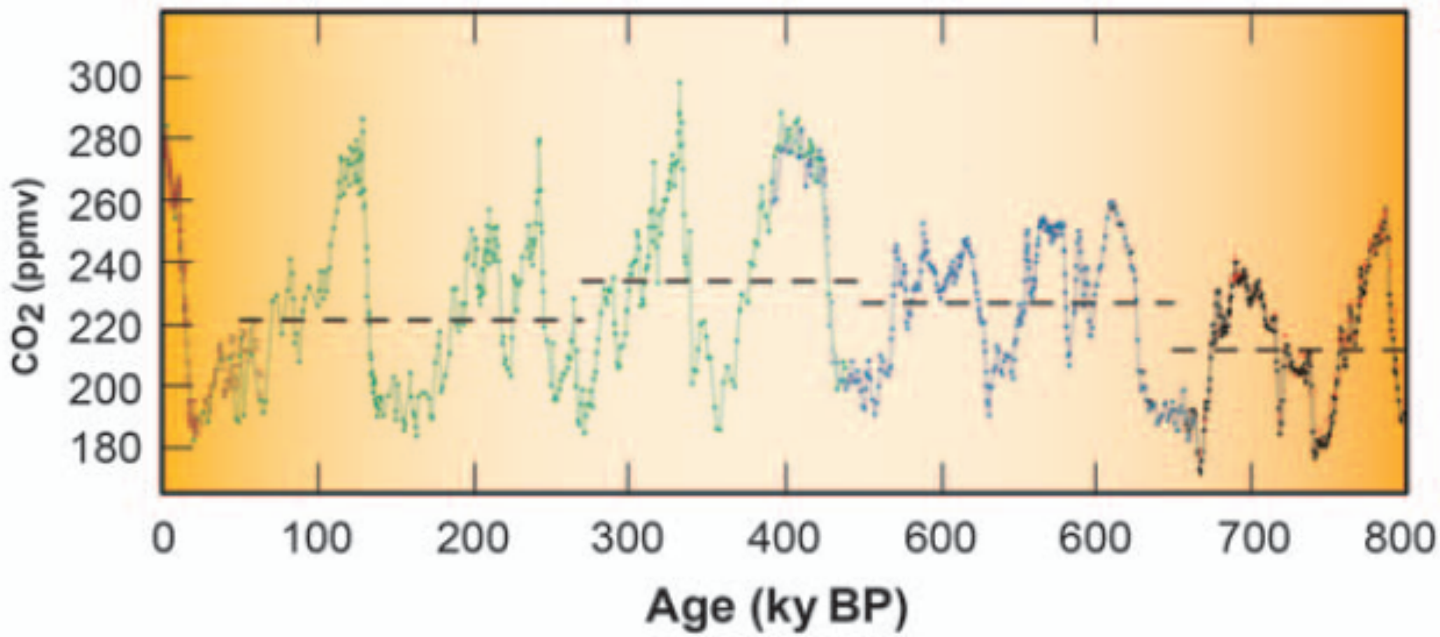
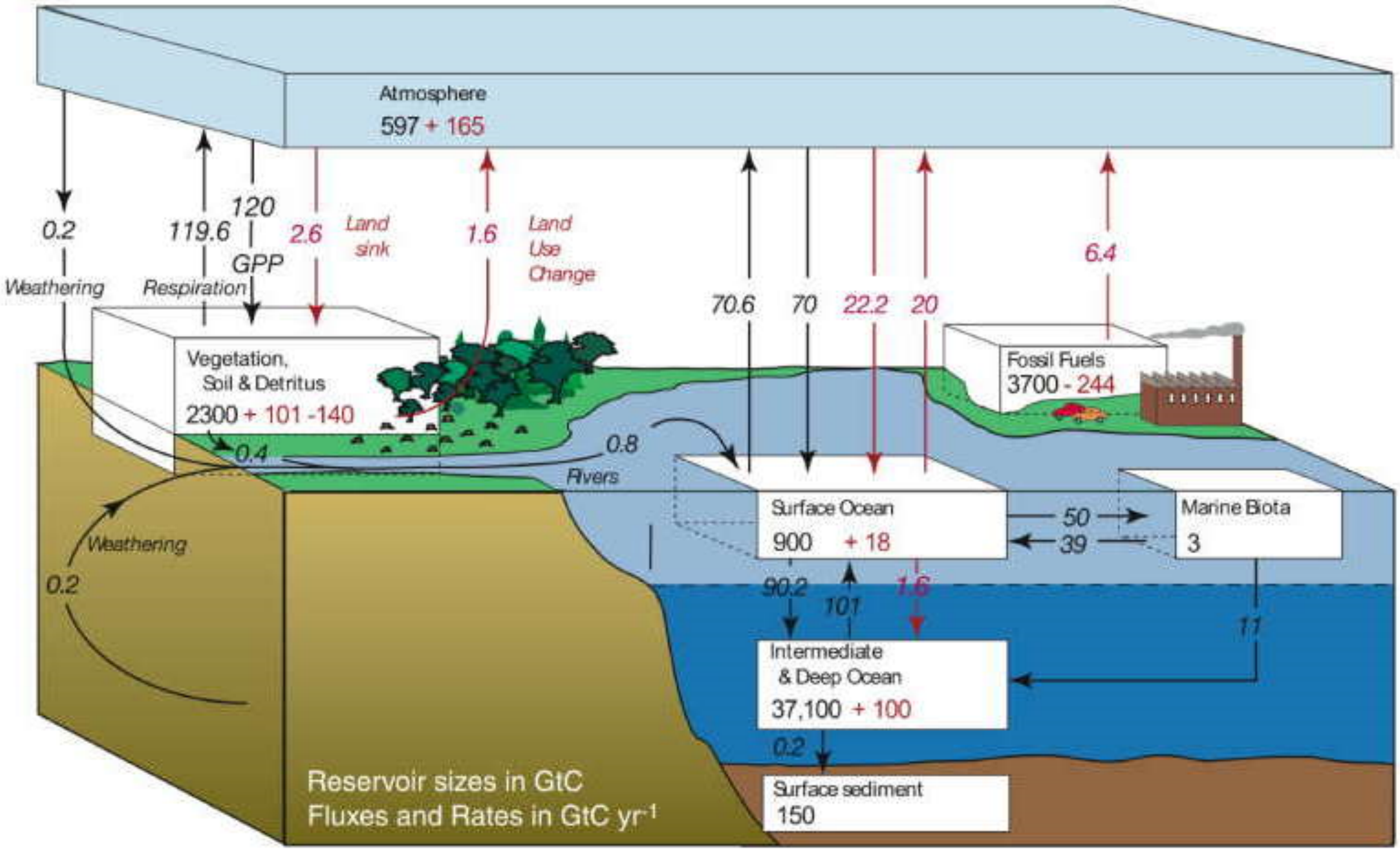


FIGURE 2 The variations of carbon dioxide concentration (in volume parts per million) since the Holocene, as recorded in the Vostok ice core. ADAPTED FROM SIEGENTHALER ET AL. (2005)

Millero& DiTrollio 2010

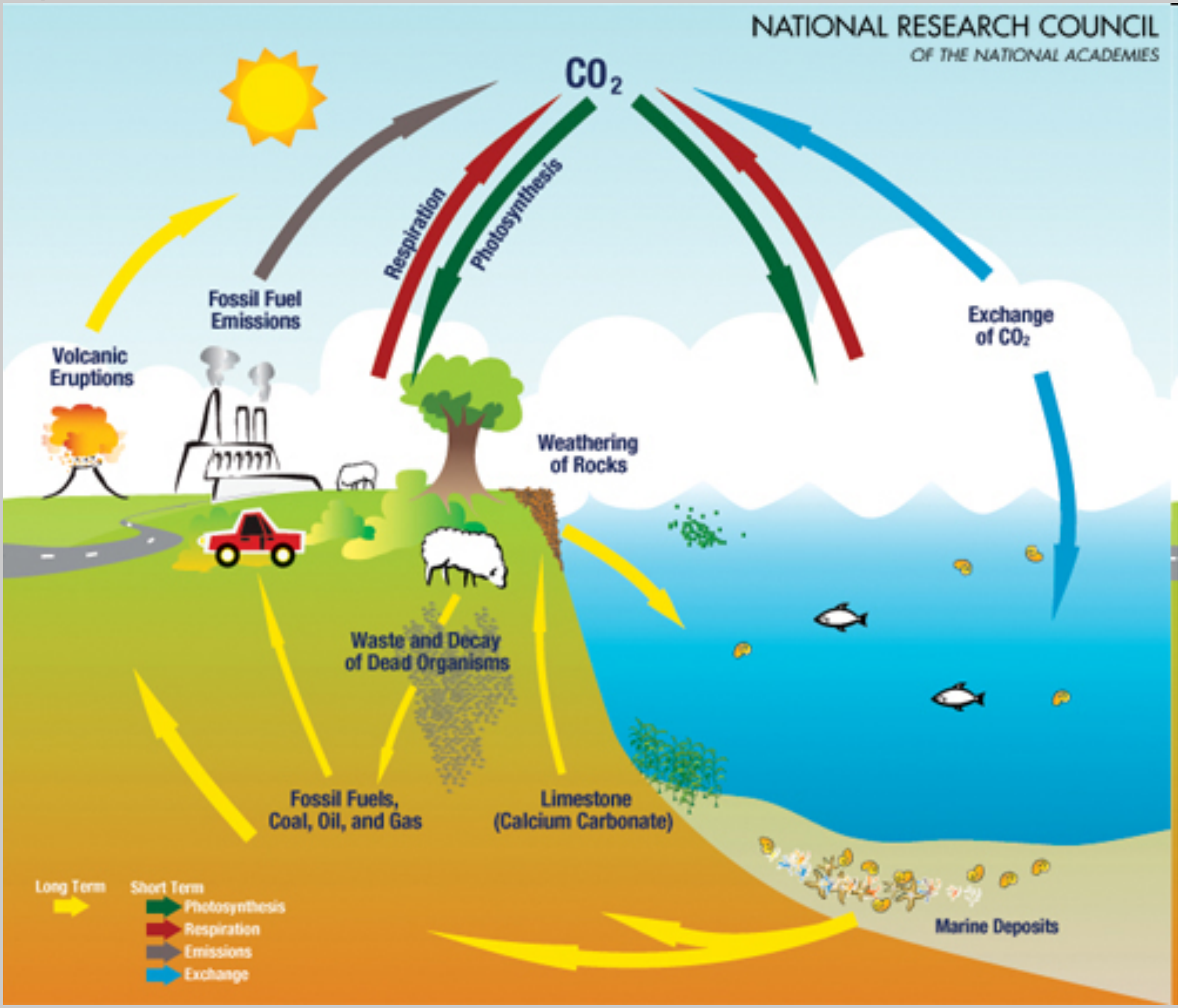
800,000 years ago!

Carbon Cycle



http://carboncycle.aos.wisc.edu/index.php?page=global-carbon-cycle

Carbon Cycle



http://oceanacidification.nas.edu/

Carbon Cycle

Fate of Anthropogenic CO_2 Emissions (2000-2008)

1.4 PgC y^{-1}

+

7.7 PgC y^{-1}

4.1 PgC y^{-1}

45%

3.0 PgC y^{-1}

29%

26%

2.3 PgC y^{-1}

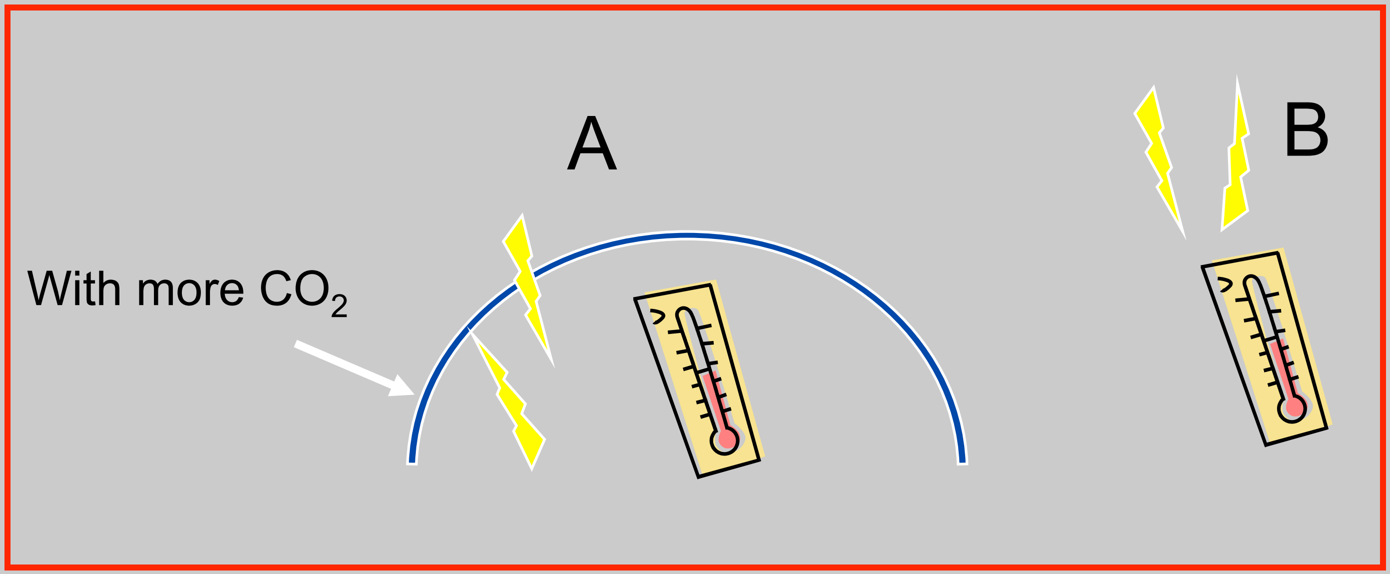
Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS, updated

Global Warming

Carbon dioxide (CO_2) acts like glass, it lets heat in but nor out!

Lets vote:

both same temperature
A warmer
B warmer



Hint: when you get into a car that was parked in the sun, is it hotter or colder than outside?

Carbonate Chemistry

We can already measure the anthropogenic CO_2 in the ocean in the upper 1000 m.

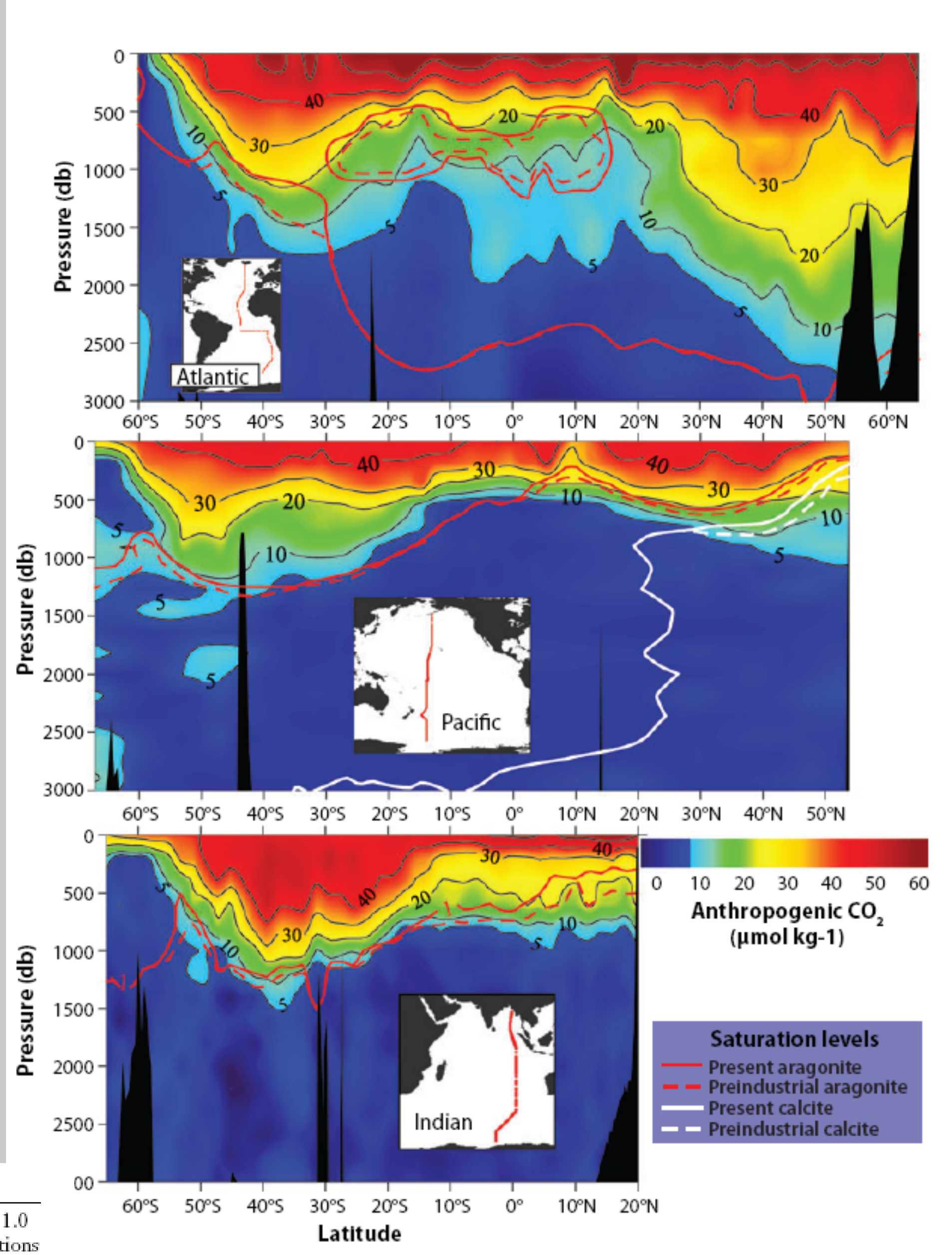
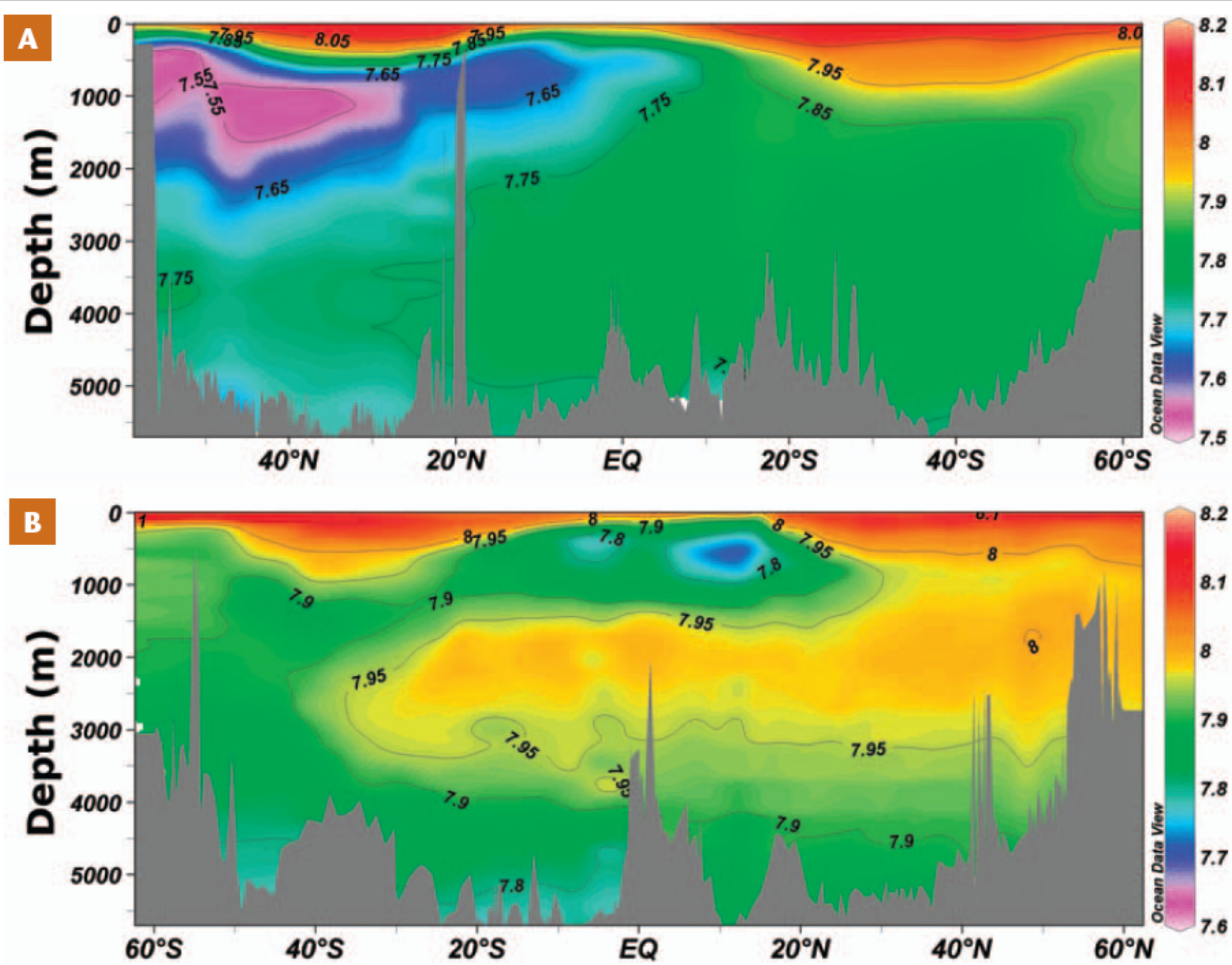


Figure 2

Vertical distributions of anthropogenic CO_2 concentrations in $\mu mol\ kg^{-1}$ and the saturation state $\Omega = 1.0$ horizons for aragonite (*red*) and calcite (*white*) for present (*solid line*) and preindustrial (*dashed line*) conditions along north-south transects in the (*a*) Atlantic, (*b*) Pacific, and (*c*) Indian Oceans as in Feely et al. (2004). Adapted with permission from AAAS.

Carbonate Chemistry

FIGURE 4 pH sections in the Pacific (**A**) and Atlantic (**B**) oceans. Bathymetry is shown in grey. The north-south transit in the Atlantic is along 30° W and in the Pacific along 150° W.



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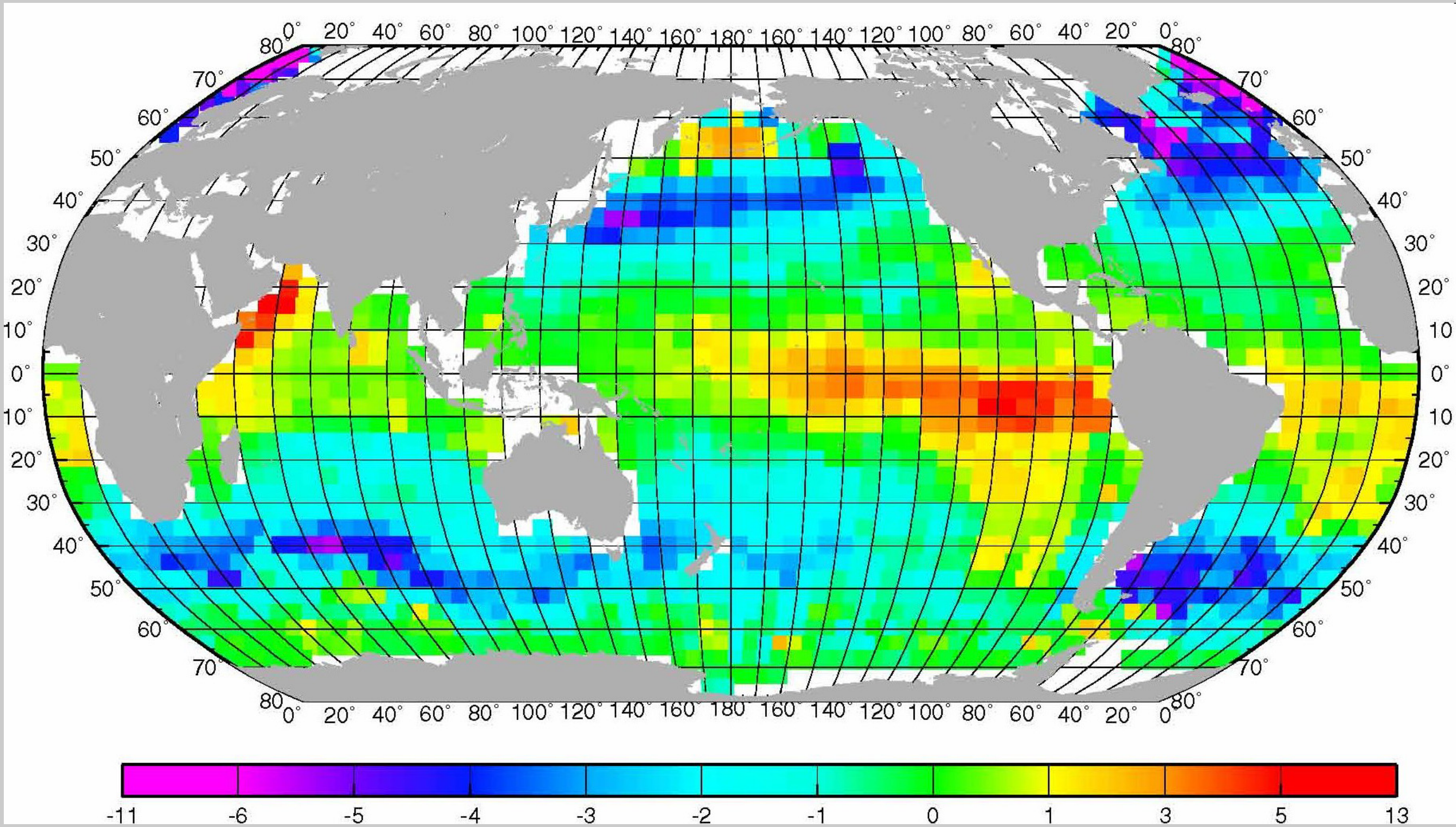
Carbon Flux: Ocean- Atmosphere



Flux into the ocean | **Flux out of the ocean**

Think of Champagne

Takahashi 2009

Teaching tools

http://www.carboeurope.org/education/indoorhands.php

Test the ability of seawater to take up CO_2 depending on the temperature.

http://www.carboschools.org

CarboSchools

How does Temperature Affect the Solubility of CO_2 in Water?

Increasing CO_2 concentrations in the atmosphere leads to increasing air temperatures and consequently, warming of the oceans. Does this increase of water temperature have a positive or negative feedback to CO_2 concentrations in the atmosphere? Will this effect be seen on a global or regional basis?

Preparation time:	10 Minutes
Duration of activity:	15-20 minutes
Target age group:	11-14 years old / Grades 5-8
Application:	Chemistry and Physics lessons/ Geography/ After school activity
Time for data analysis and discusion:	20 minutes
Previous knowledge required:	None
Cost:	0.50 € for the effervescent tablets

Materials:

500 ml graduated cylinder
Funnel
Petri dish cover
Transparent basin or an aquarium
Stand and Clamp
Ice cubes/ cold water
Water heater/Warm water
Effervescent (Fizz) tablets

Procedure:

1. Fill the basin half-full with cold water. Place the stand beside the basin.
2. Fill the graduated cylinder to the brim with cold water and place it carefully upside down in the basin. Be sure that no water spills out of the cylinder so that no air bubble is formed. To do this, cover the mouth of the full cylinder with a Petri dish. Invert the cylinder and immerse this in the basin. Remove the Petri dish after the mouth of the cylinder is already underwater. (Younger pupils may need assistance here).

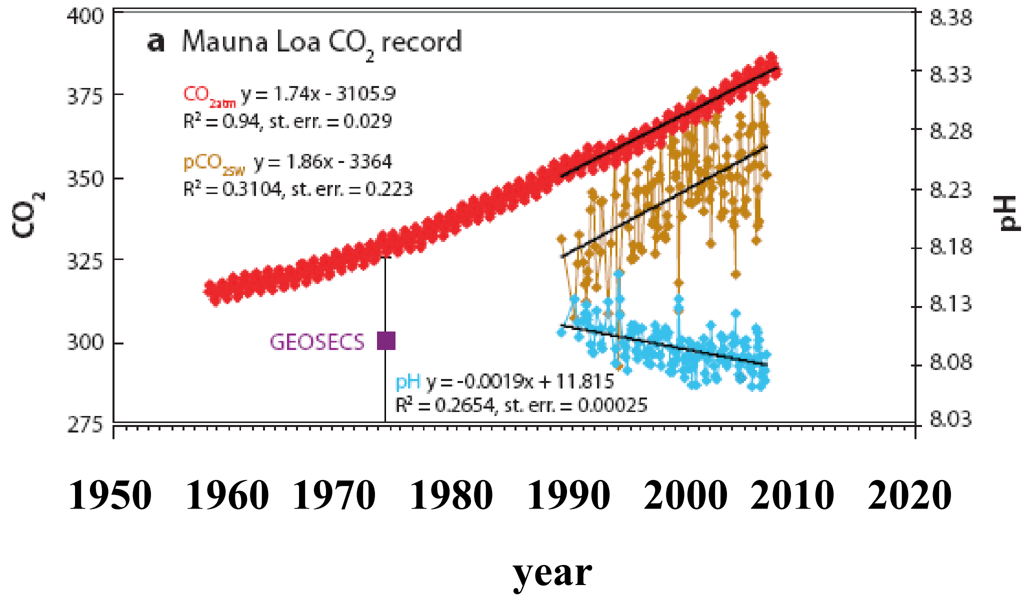
Cold water

Warm water

Carbon Chemistry

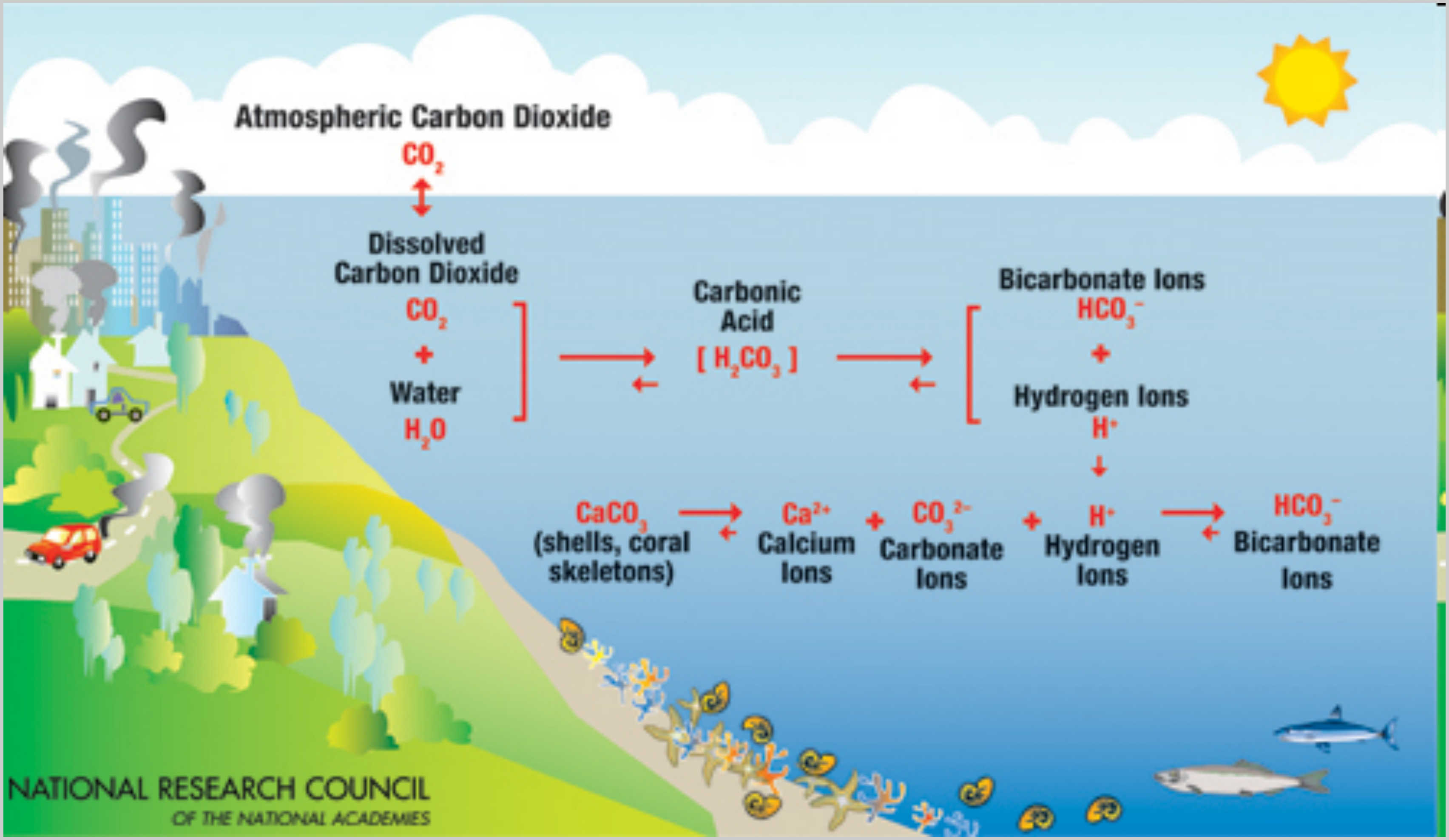
As atm. CO_2 increases

- DIC in seawater increases
- pH decreases



Carbon Chemistry

Ocean acidification

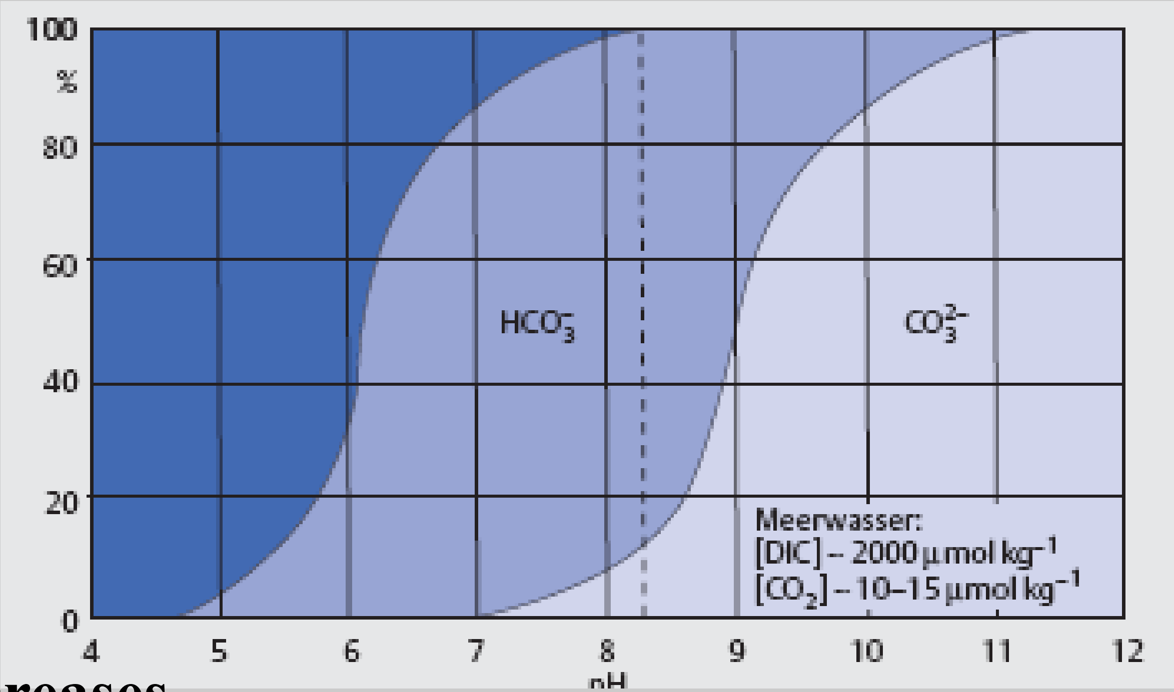


http://oceanacidification.wordpress.com/

Carbon Chemistry

Dissolved Inorganic Carbon in Seawater

$$DIC = CO_2 + HCO_3^- + CO_3^{2-}$$



As pH decreases

- DIC increases
- Composition of DIC shifts (Impact cells as it matters what type of ion they have available)

Biological Impacts

Not much question that ocean acidification is happening!
The question is how the marine ecosystems react to this.

- **Stress**
- **Acclimatization**
- **Adaptation**

Biological Impacts of Ocean Acidification

&

How the ocean works in 3 slides!

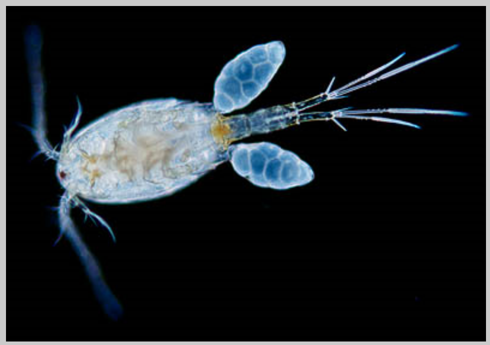

Diatoms:
Phaeocystis
Cyanobacteria
Phytoplankton
Coccolithophores
Dinoflagellates
20 µm

Zooplankton –

Episodic
appearance:
2 d reproduction

salps

copepods

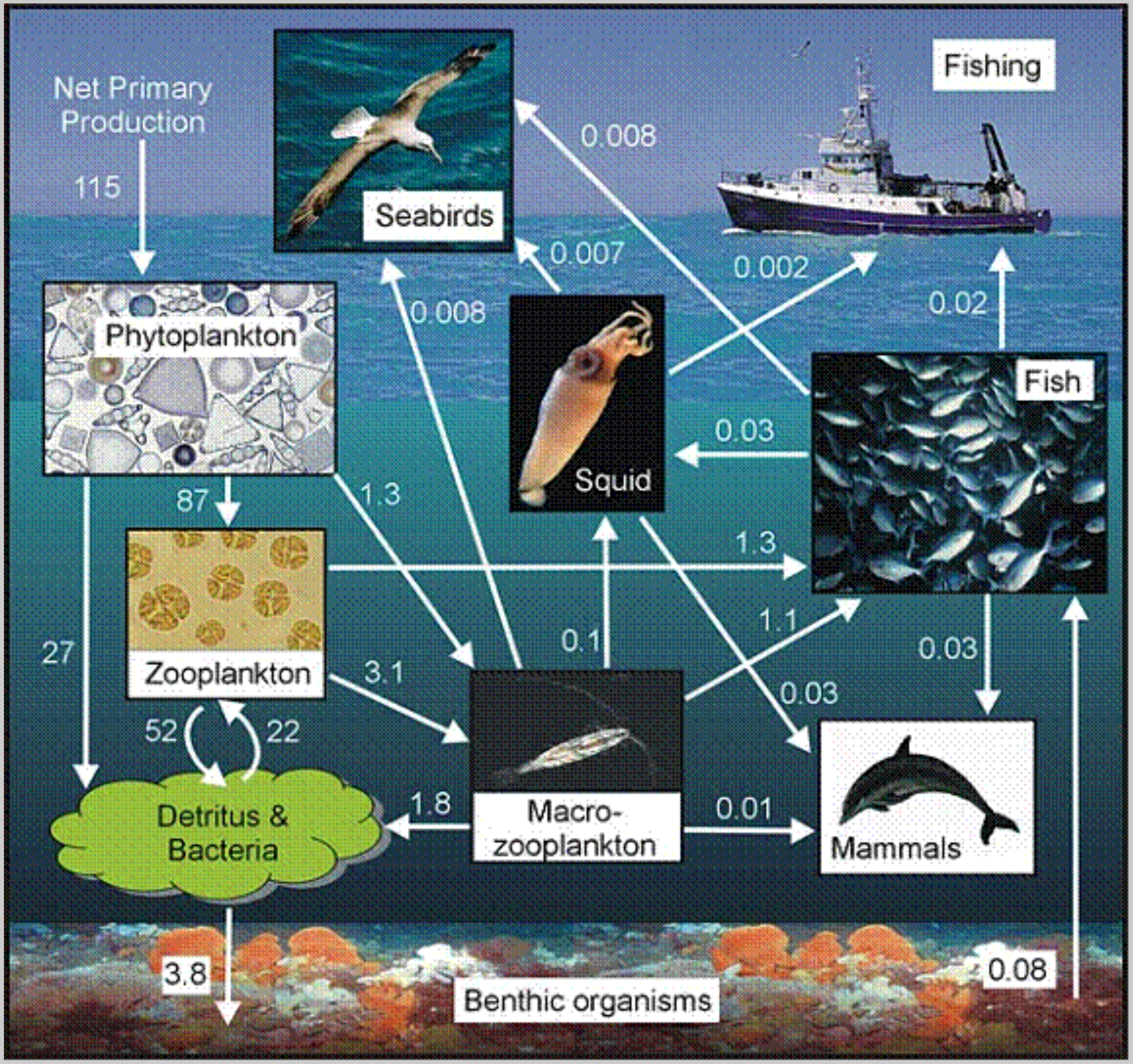


Life cycle ≥ 1 year

pteropods

krill

Food webs



Net Primary Production
115
Fishing
Seabirds
0.008
0.007
0.002
0.02
Phytoplankton
0.008
Squid
Fish
0.03
87
1.3
1.3
Zooplankton
27
3.1
0.1
1.1
0.03
0.03
52
22
Detritus & Bacteria
1.8
Macro-zooplankton
0.01
Mammals
3.8
Benthic organisms
0.08

Photosynthesis

Eelgrass

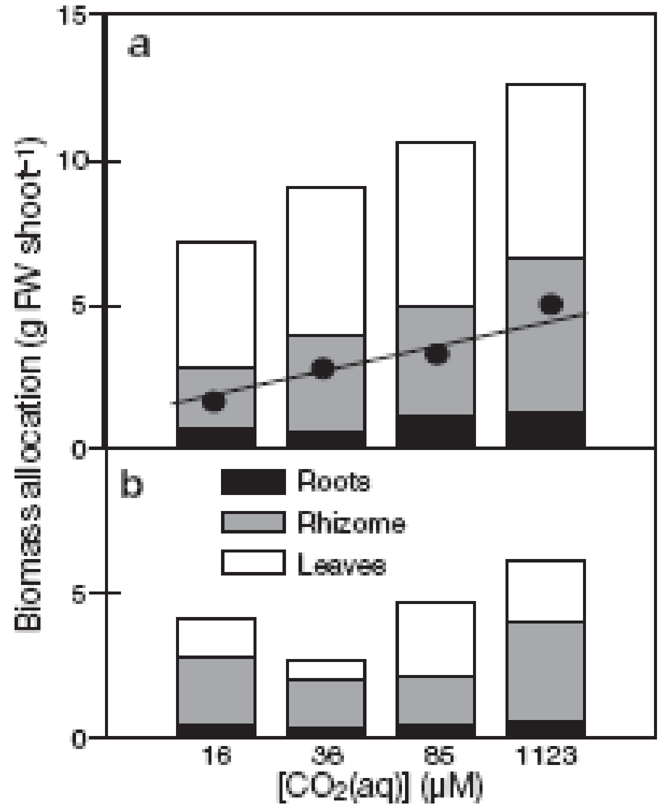


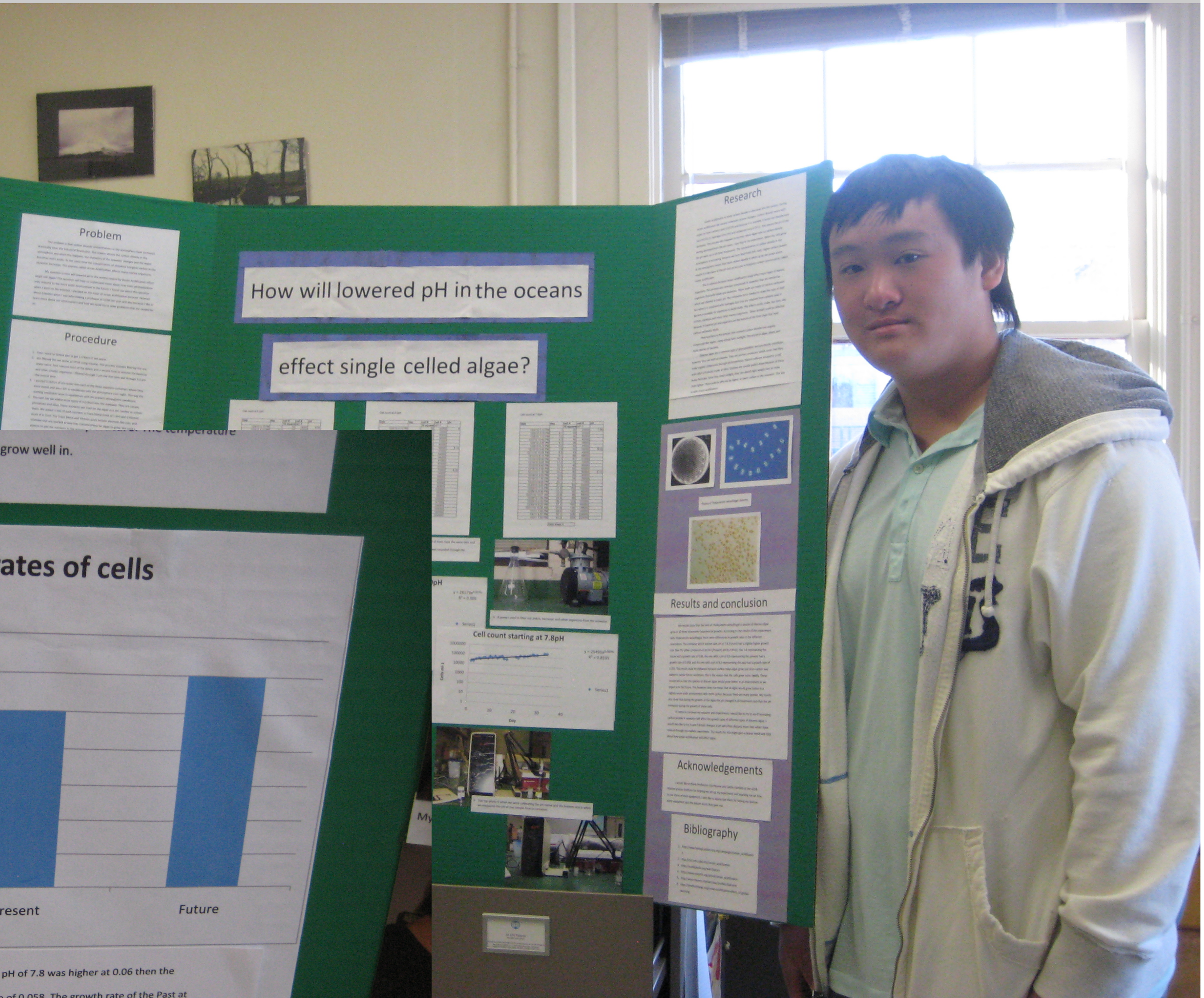
Fig. 4. *Zostera marina*. Biomass allocation (g FW shoot^{-1}) among roots, rhizomes and leaves after 1 yr growth under CO_2 enrichment, plotted as a function of CO_2(aq) concentration for (a) light-replete and (b) light-limited treatments. Mean rhizome biomass (●) with fitted line shown for light-replete treatments ($r^2 = 0.99$, $p < 0.01$)

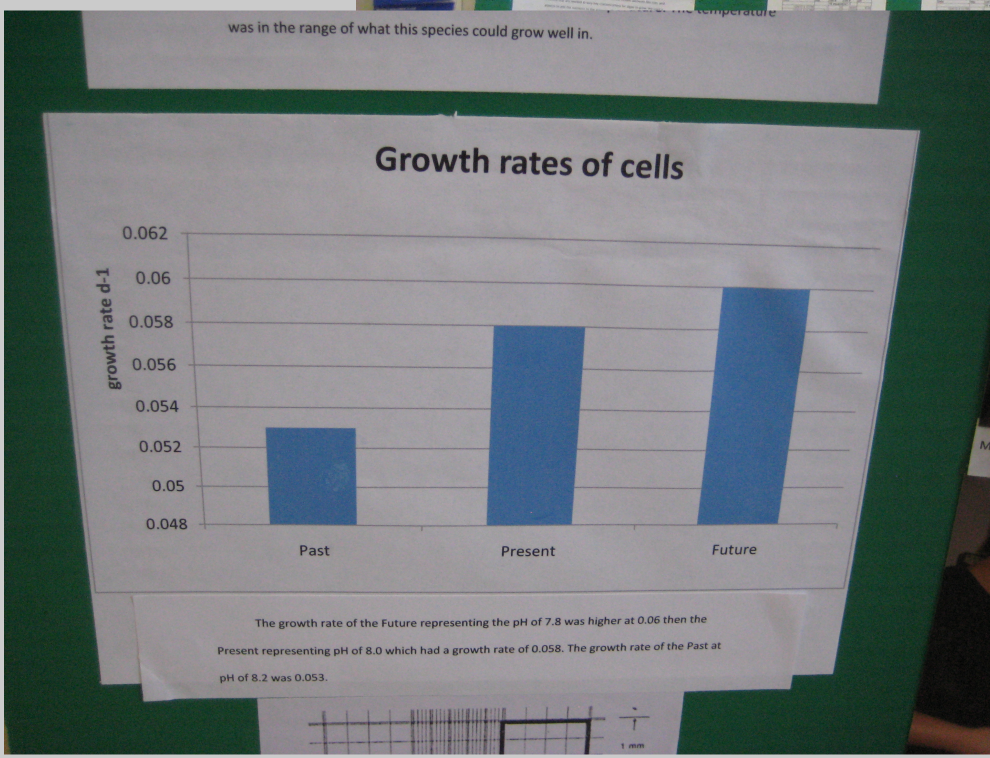
Photosynthesis increases!

Primary production increases

Not for all organisms!
Very temp. sensitive

Photosynthesis High School Science Project,: Impact of pH on growth of single celled algae

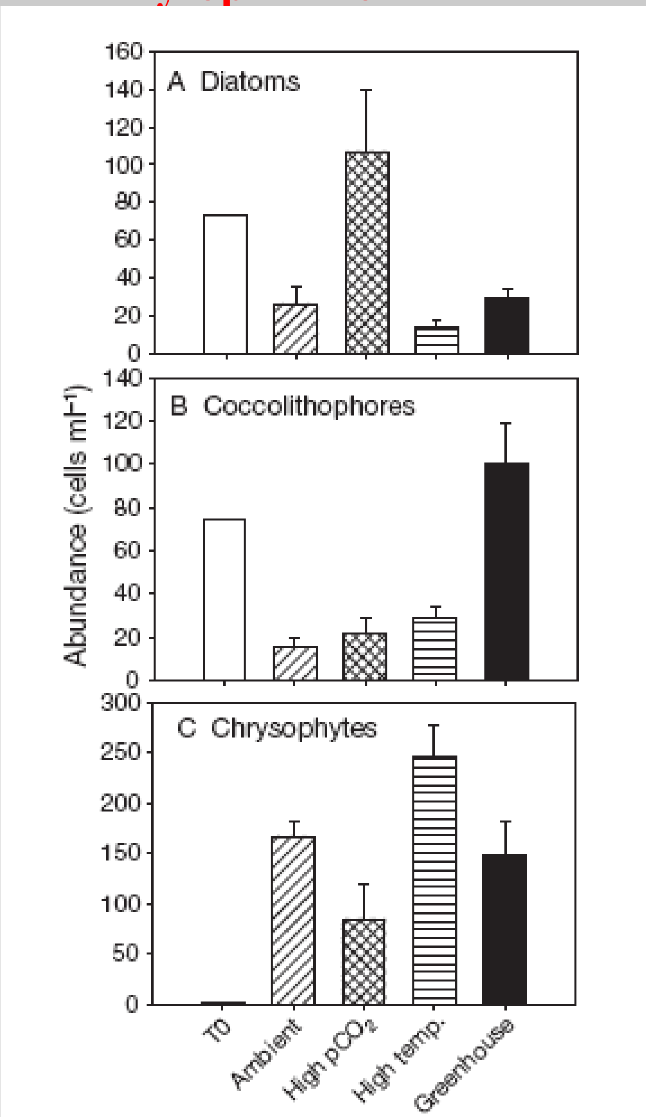




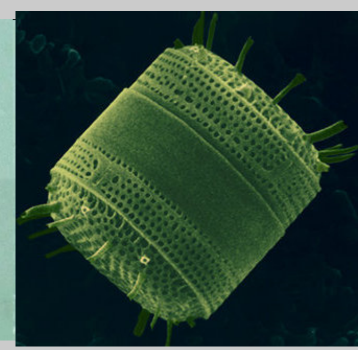
TJ, San Marcos High School

Photosynthesis

Phytoplankton



Species composition shifts!



Calcification

SHELLED ORGANISMS and crystal structure of $CaCO_3$

Calcite	Aragonite	Mg-Calcite
Coccolithophorids	Pteropods	Coraline Algae
Foraminifera	Corals	cold water Corals
some Bivalves	most Mollusks	
Sponges		
Ecinoderms		

Calcification

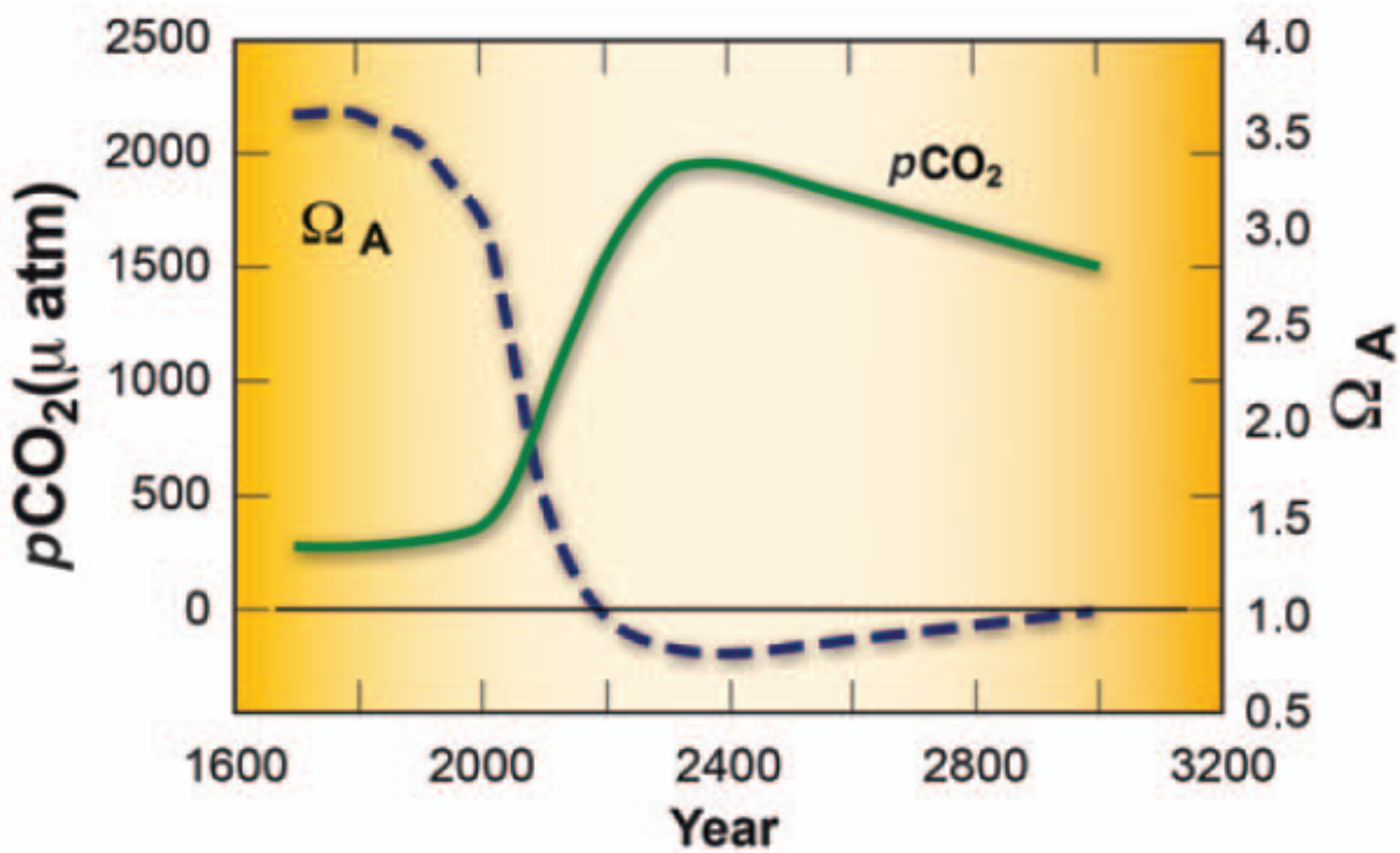


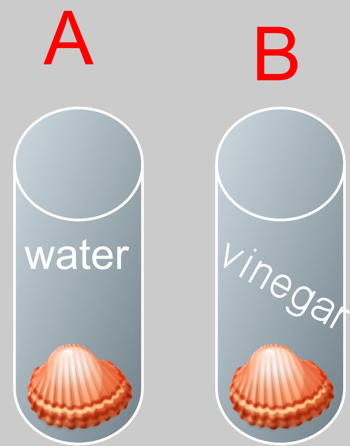
FIGURE 6 Estimated changes in pCO_2 and the saturation state of aragonite, Ω_A, as a function of time

Millero& DiTrollio 2010

Calcification

What happens when additional CO_2 enters the ocean?

Water + CO_2 makes the ocean more sauer (acidic) like vinegar or lemon juice



Any idea why that is a problem???????

Lets look at an experiment:

What happens to a

A sea shell in water

B sea shell in vinegar

Hint: remember what happened to your egg when you put it in vinegar!

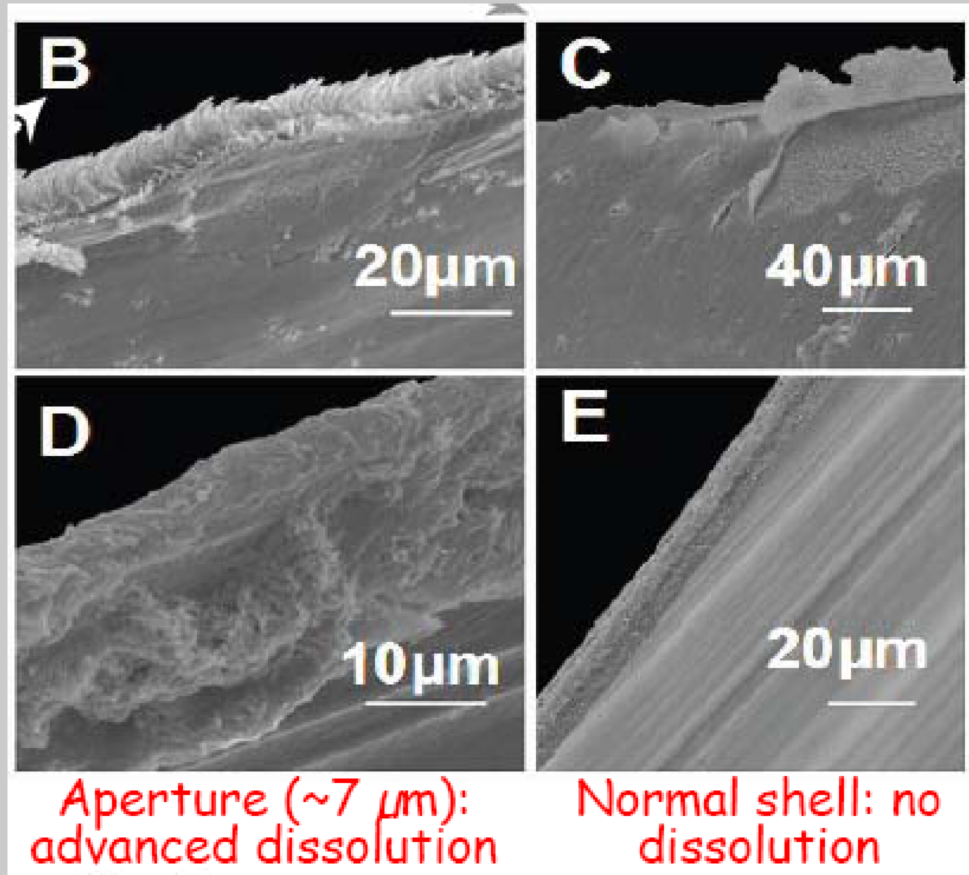
Calcification

Waters that are naturally acidic

FIGURE 14: *P. caerulea* and *H. truculus* showing severely eroded, pitted shells in naturally acidified areas of minimum pH 7.4. *Source: Hall-Spencer, 2008*[260].

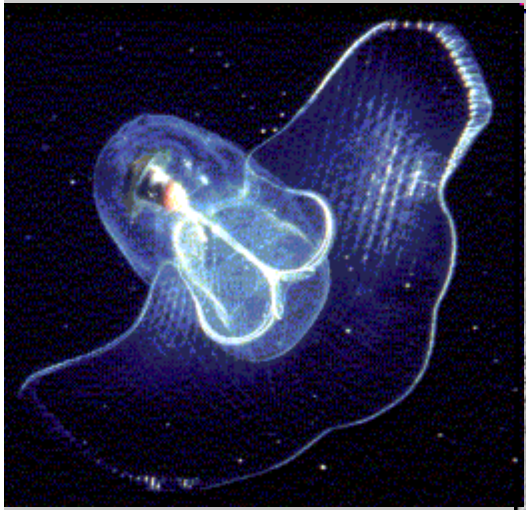
Calcification

Pteropods

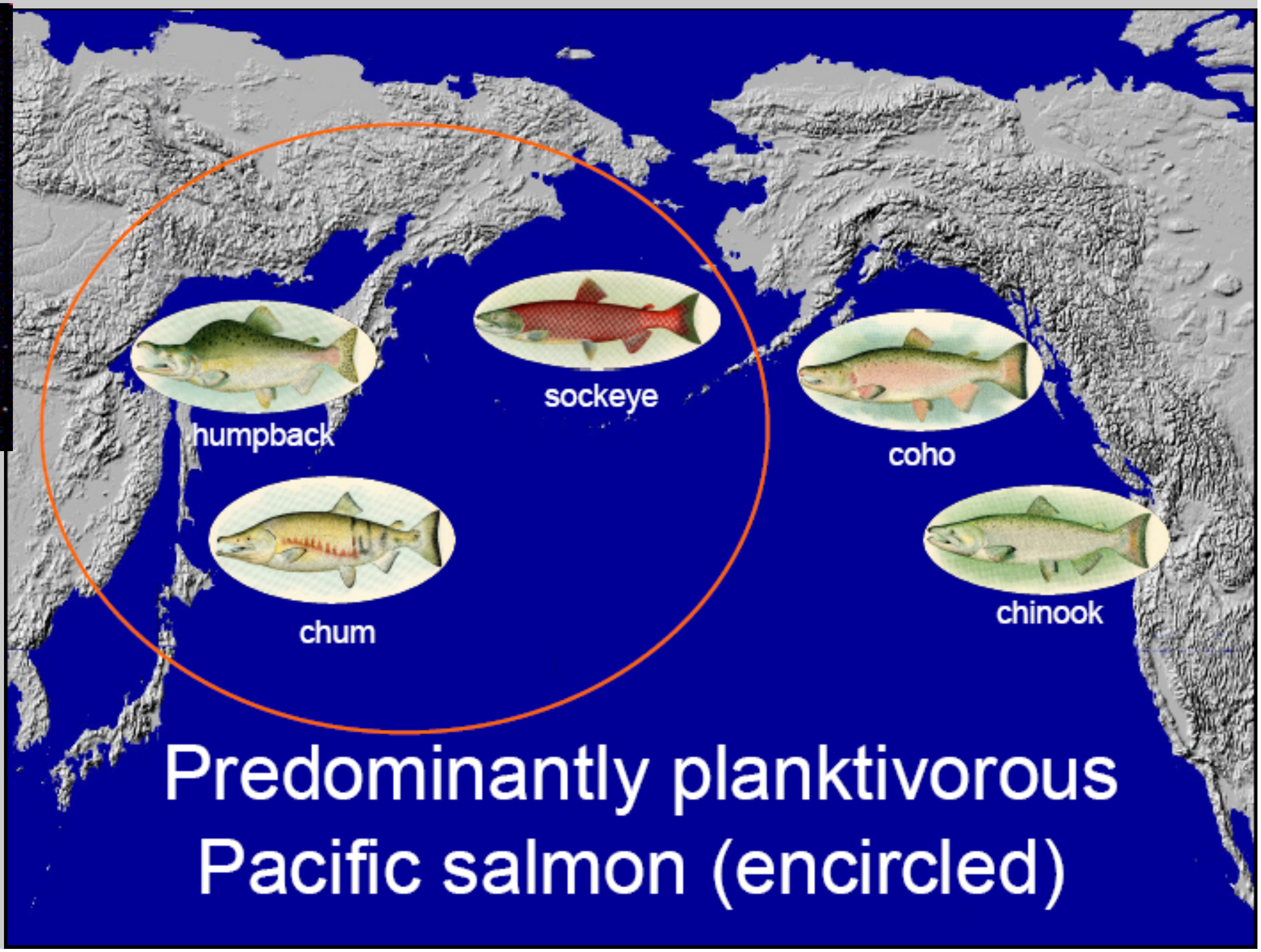


Fabry et al.

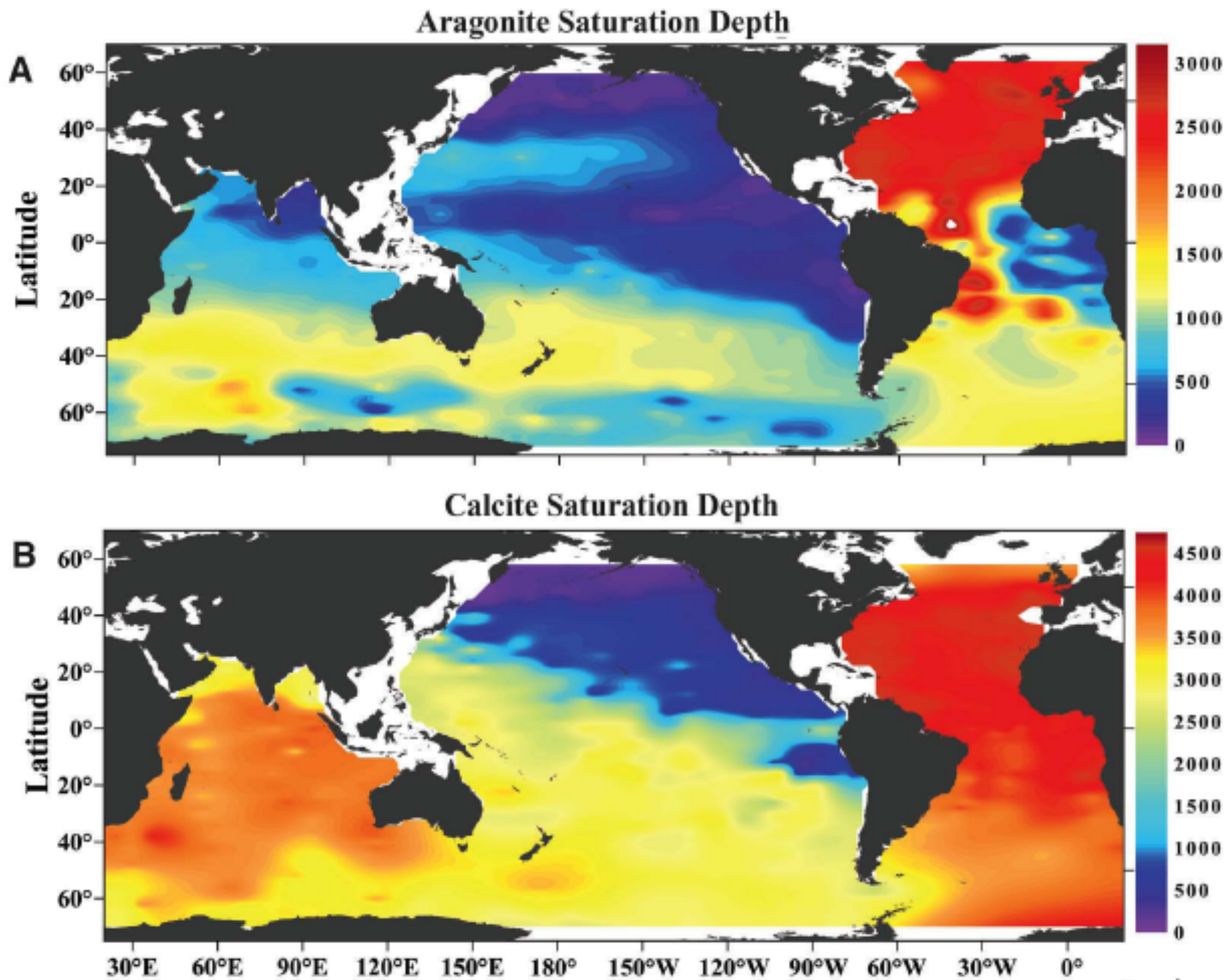
Calcification – potential consequences



A SWIMMING PTEROPOD, LIMACINA HELICINA



Calcification

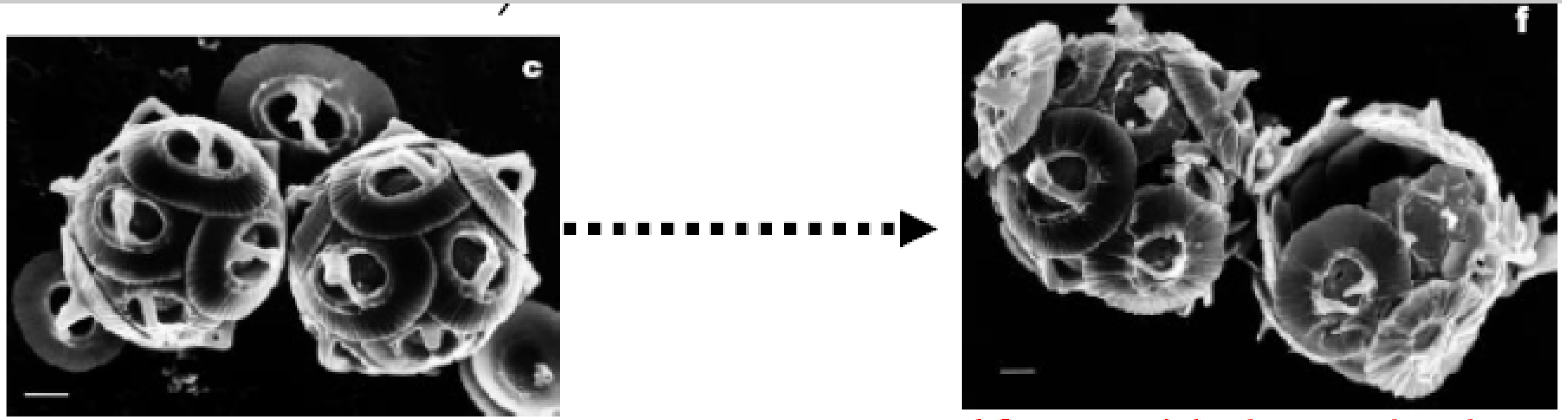


Feely et al. (2004)

Calcification

Calcification decreases
in many organisms

Coccolithophorids



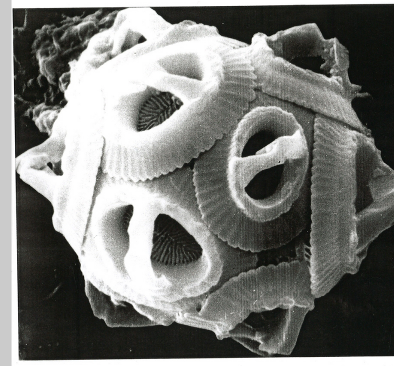
Gephyrocapsa oceanica

Malformed liths at high CO_2

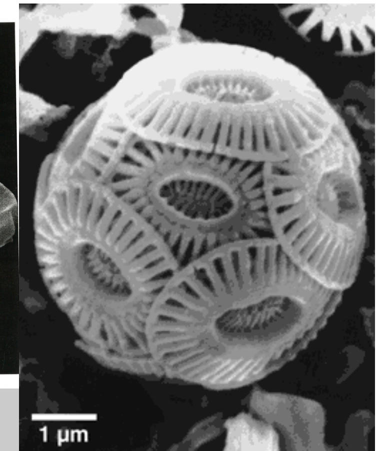
Calcification

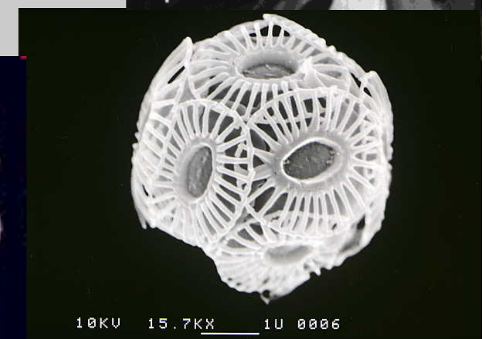
Phytoplankton

Coccolithophores

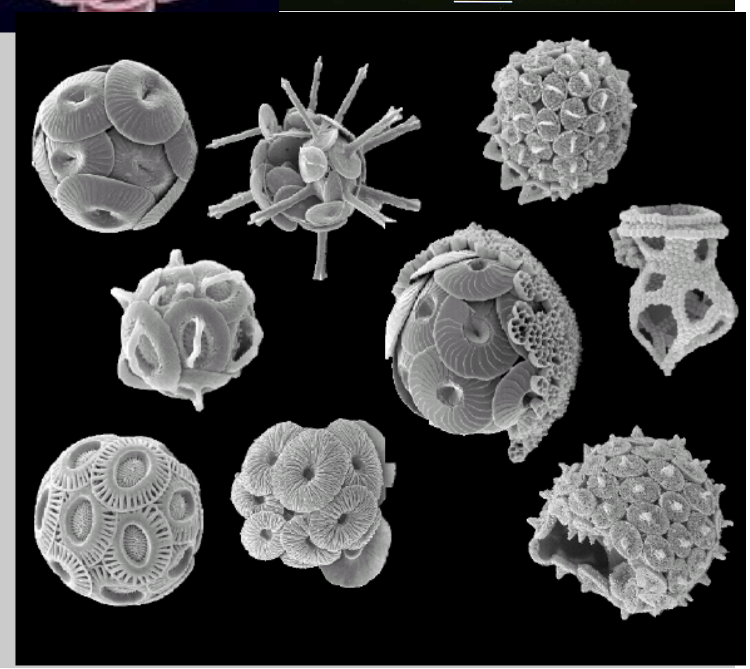


CaCO$_3$-plates





Huge blooms visible from space



Nitrogen Fixation

Nitrogen fixation: Biological process by which nitrogen (N_2) is converted into ammonia. This process is essential for life (amino acids, proteins) contain N.

Some bacteria, especially cyano-bacteria can fix nitrogen. Some plants have a symbiontic relationship with such bacteria (lupines, peanuts).

Cyanobacteria common in surface ocean.

Nitrogen Fixation

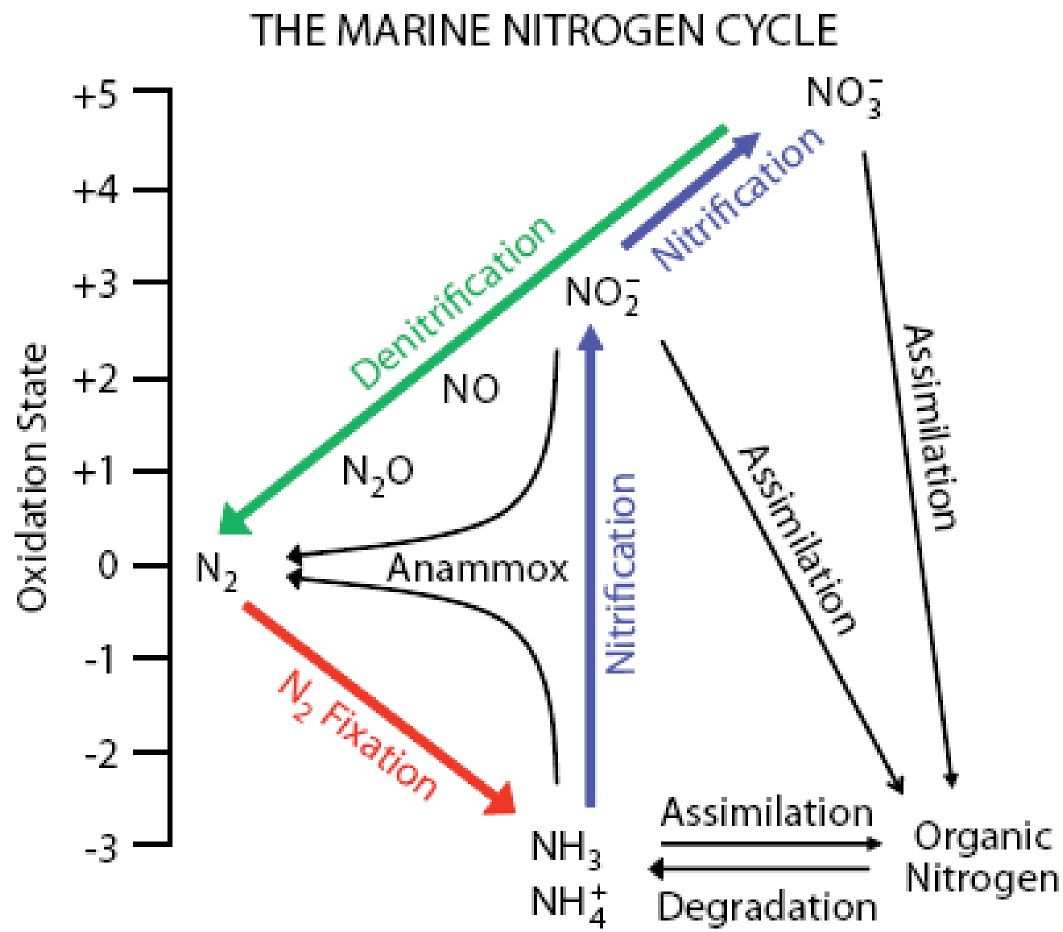
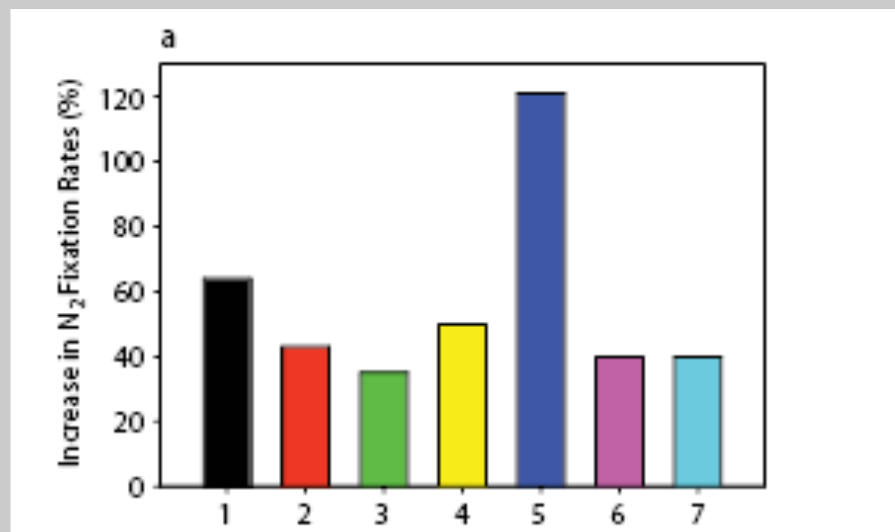


Figure 1. Major chemical forms and transformations of nitrogen in the ocean. The various chemical forms of nitrogen are plotted versus their oxidation states. Here, we consider the potential effects of increased ocean pCO_2 on three of the critical transformations within the N cycle: N_2 fixation (red arrow), nitrification (blue arrows), and denitrification (green arrow).

Nitrogen Fixation

N-Fixation:
Percent increase in N-fixation of 7 different strains of *Trichodesmium spp.* under at future (750 ppmV) vs. current CO_2 levels.

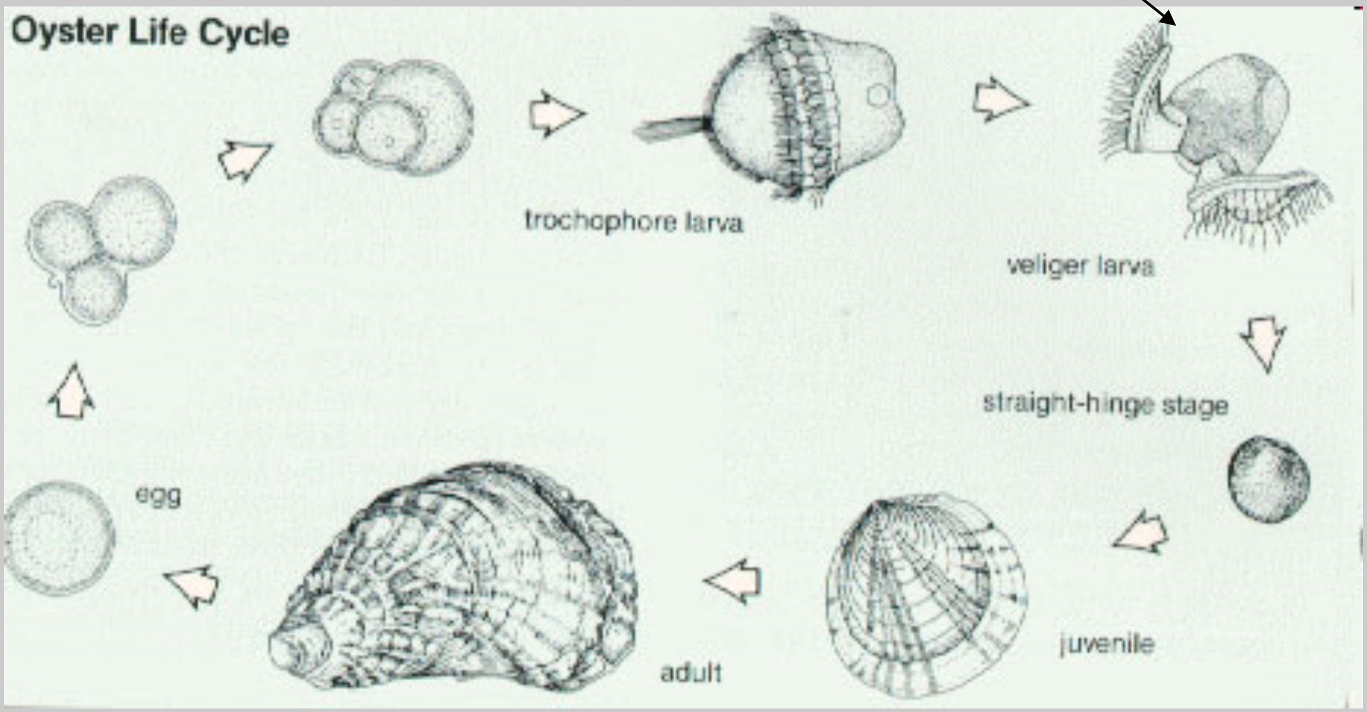


Calcification/ Reproduction

Oyster

3 weeks planktonic

Lifecycle



Hettinger

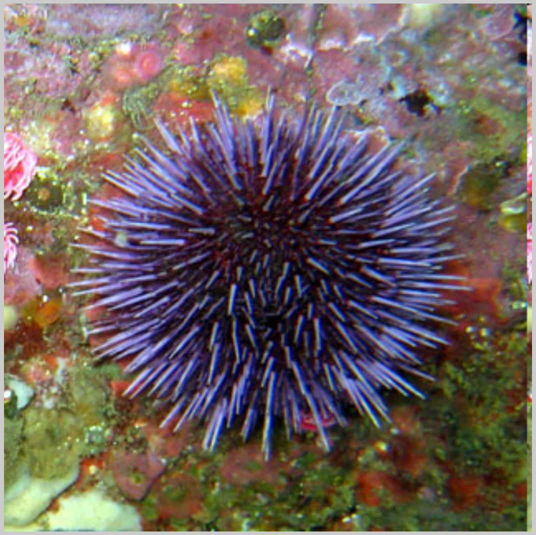
Calcification/ Reproduction

Precipitation of oyster shell after settlement (benthic)

	970 ppmV Vs 380	
Shell precipitated	16% less	
Size @ settelment	7% less	
Size after 4-5 days	42% less	

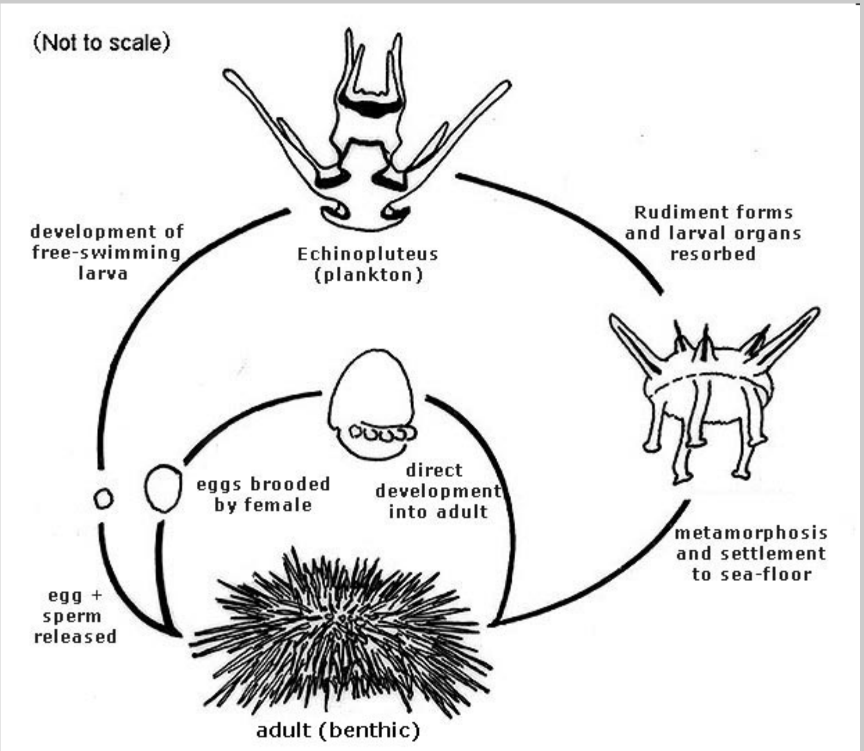
Reproductive problems at Oyster farms could be solved by adjusting carbonate system

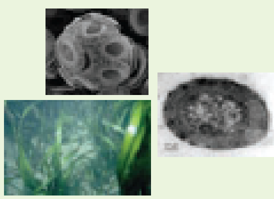
Calcification/ Reproduction

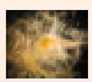


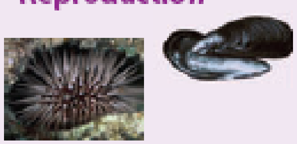
Sea Urchin

780 – 1200 ppmV vs. 380 ppmV
Calcification of larvae:
25% of ambient









Physiological response	Major group	Species studied	Response to increasing CO_2: a	b	c	d
Calcification						
	Coccolithophores[1]	4	2	1	1	1
	Planktonic Foraminifera	2	2	–	–	–
	Molluscs	4	4	–	–	–
	Echinoderms[1]	3	2	1	–	–
	Tropical corals	11	11	–	–	–
	Coralline red algae	1	1	–	–	–
Photosynthesis[2]						
	Coccolithophores[3]	2	–	2	2	–
	Prokaryotes	2	–	–	1	–
	Seagrasses	5	–	–	–	–
Nitrogen Fixation						
	Cyanobacteria	1	–	1	–	–
Reproduction						
	Molluscs	4	4	–	–	–
	Echinoderms	1	1	–	–	–

1) Increased calcification had substantial physiological cost; 2) Strong interactive effects with nutrient and trace metal availability, light, and temperature; 3) Under nutrient replete conditions.

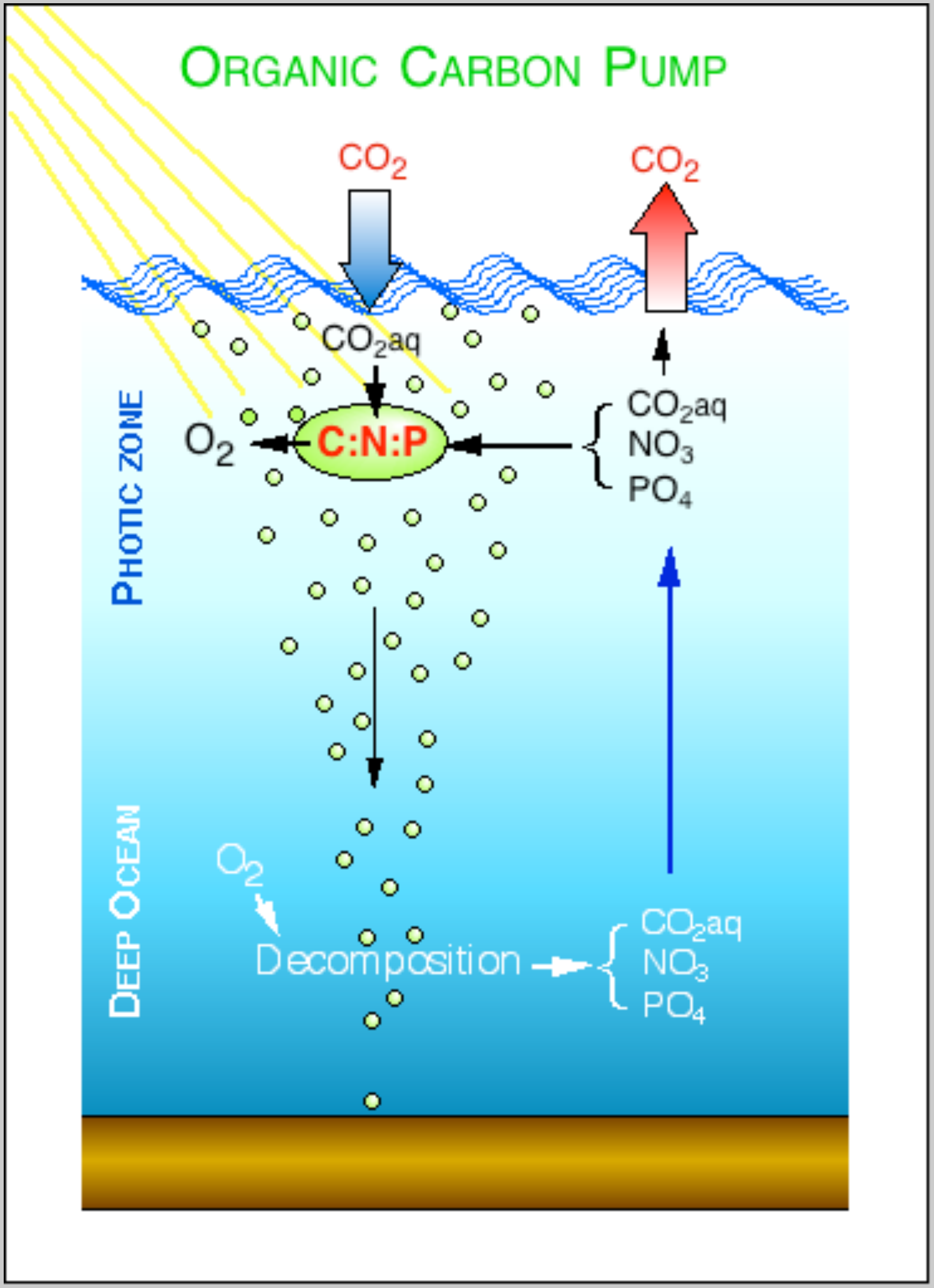
Calcification, Reproduction: decrease with higher CO2, Photosynthesis, N fixation increase, or remain constant

Marine Biological Carbon Pump!

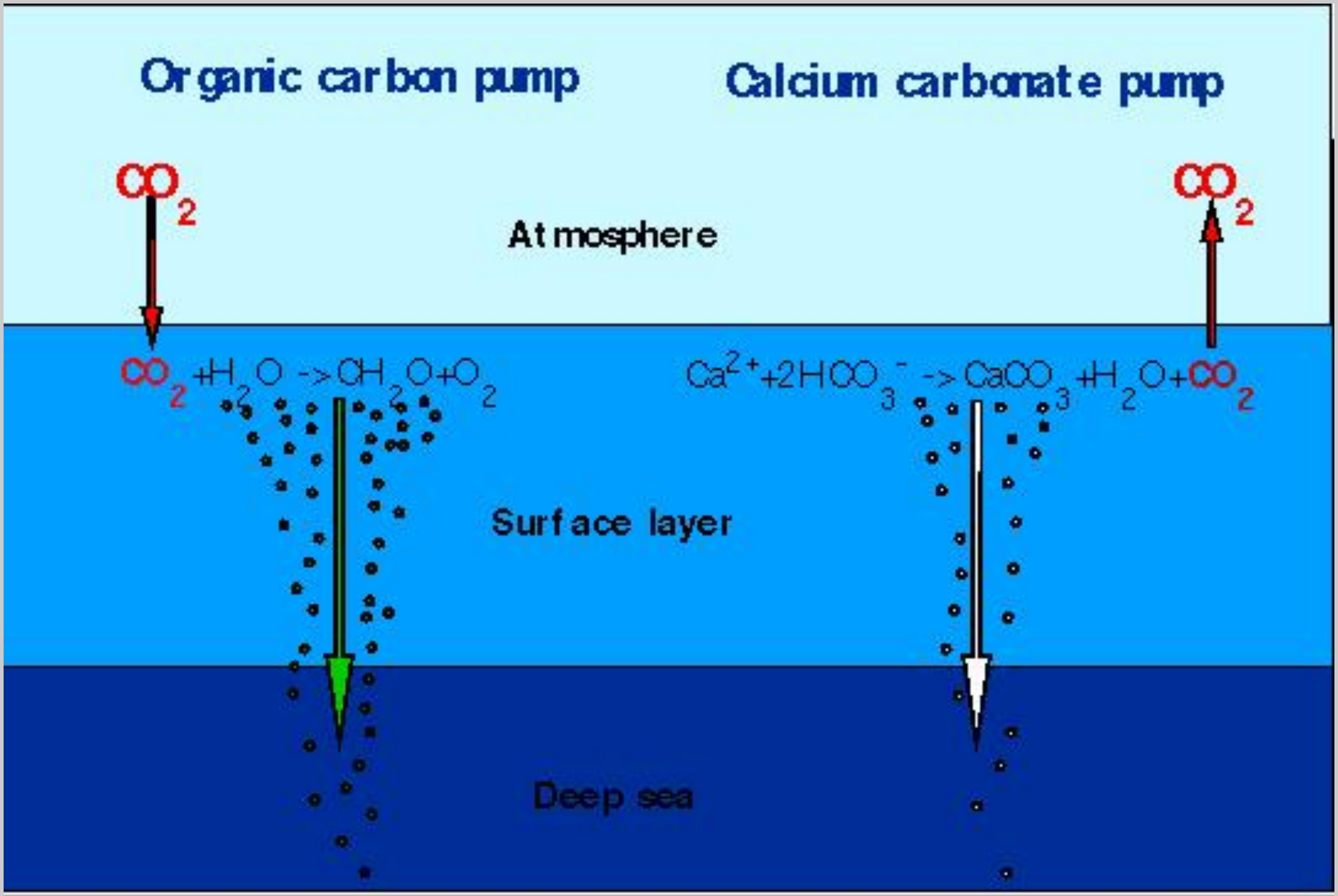
Particle Transport
via sinking of organic matter!

Carbon pumped against a gradient into deep ocean. Removed from atmosphere for around 1000 years till deep water comes up to the surface again

Strengthening the pump: more uptake of carbon by ocean



Marine Biological Carbon Pumps!

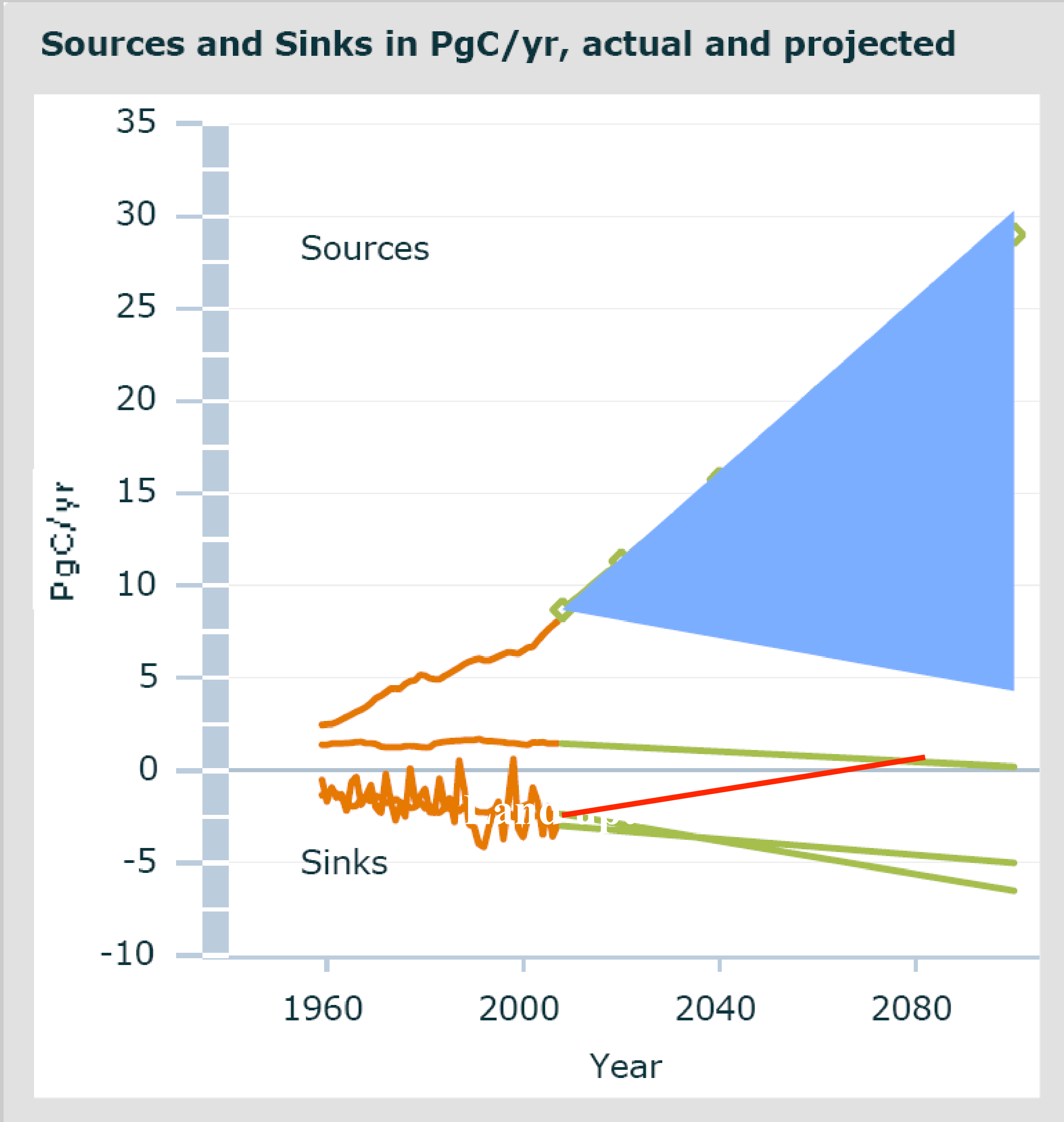


Calcium Carbonate or counter pump: counter intuitive


Phaeocystis
Diatoms:
Cyanobacteria
Phytoplankton
Coccolithophores
Dinoflagellates
20 μm

Atmospheric Carbon Concentration

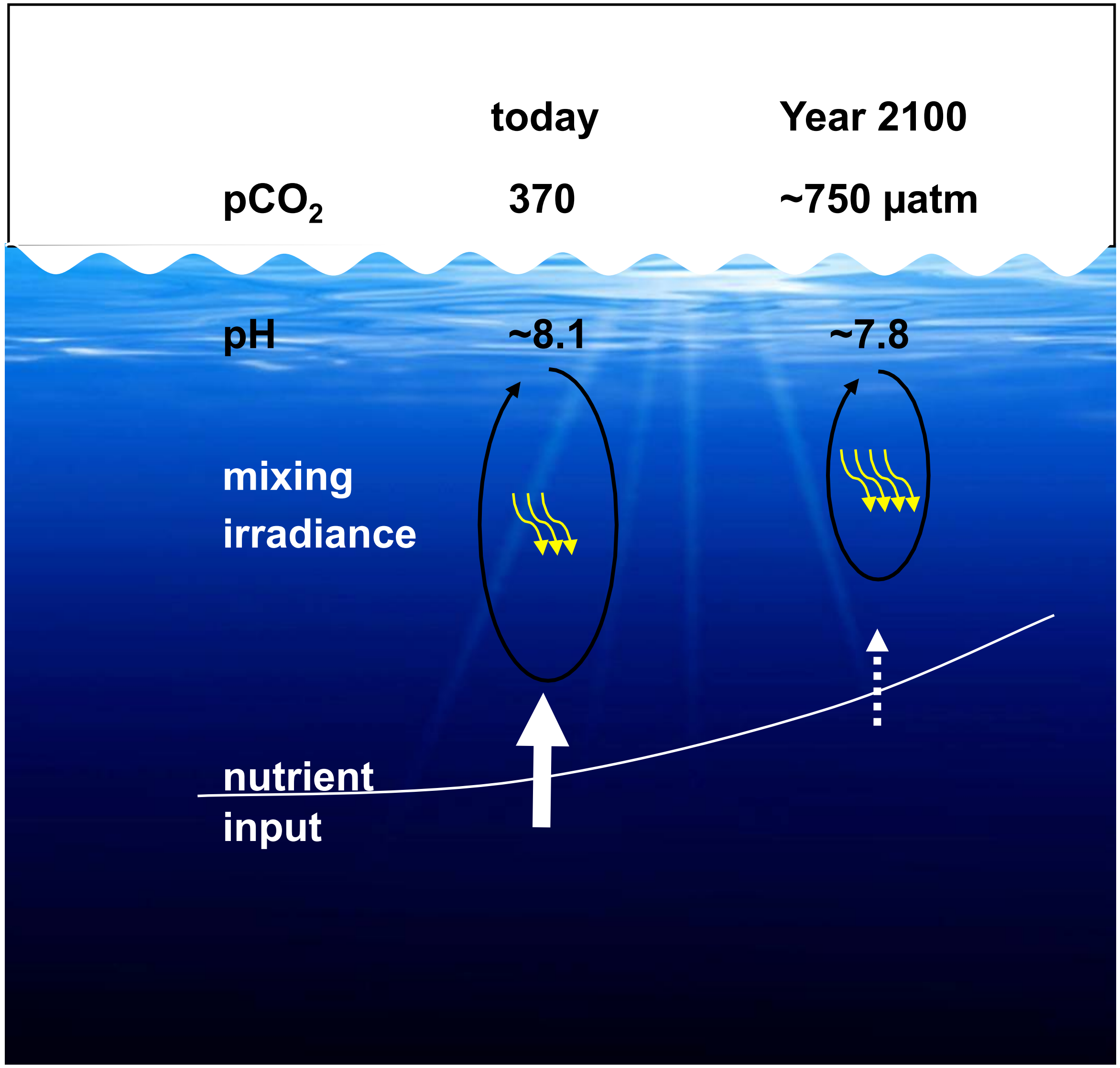
It is unclear if the efficiency of the biological pump will remain the same, increase or decrease.



http://carboncycle.aos.wisc.edu/index.php?page=carbon-budget-tool

Temperature & Stratification

- **Growth conditions**
  - $[CO_2]_{aq}$ / pH / Ω …
  - Temperature increase
  - light regimes
  - nutrient availability



Overall photosynthesis decrease observed. That could be a real problem as phytoplankton make up almost 50% of global photosynthesis.

Ocean Acidification

- is happening
- increase in DIC
- decrease in pH
- decrease in carbonate ions leads to more corrosive waters for calcification
- increase in CO_2 can positively effect photosynthesis

Biological Reactions to OA

Ocean acidification at the ***organism level*** tends to lead to

- increase in photosynthesis – but temperature effects change th
- increase in N-fixation – but iron availability important
- decrease in calcification – some species survive without shell
- decreased reproduction: benthic calcifiers (larvae vulnerable)

Variability is high

genetic variation

many interdependent processes

A challenge!

YES we CAN!

Think outside the box

Tipping points in society: smoking
Success stories: acid rain, DDT
Social sciences – cartoons
Religious leaders = steward ship of the earth

Useful Websites

http://carboncycle.aos.wisc.edu/carbon-budget-tool/

http://oceanacidification.nas.edu/

http://www.youtube.com/user/PMLAdministrator?feature=mhee#p/a/u/1/F5w_FgpZkVY

http://oceanacidification.wordpress.com/

http://www.youtube.com/user/PMLAdministrator?feature=mhee

http://cisanctuary.org/acidocean/

http://pmel.noaa.gov/co2/story/Education

http://www.epoca-project.eu/index.php/what-do-we-do/outreach/rug/oa-questions-answered.html

http://www.oceanacidification.org.uk/


Questions?

THANK YOU!

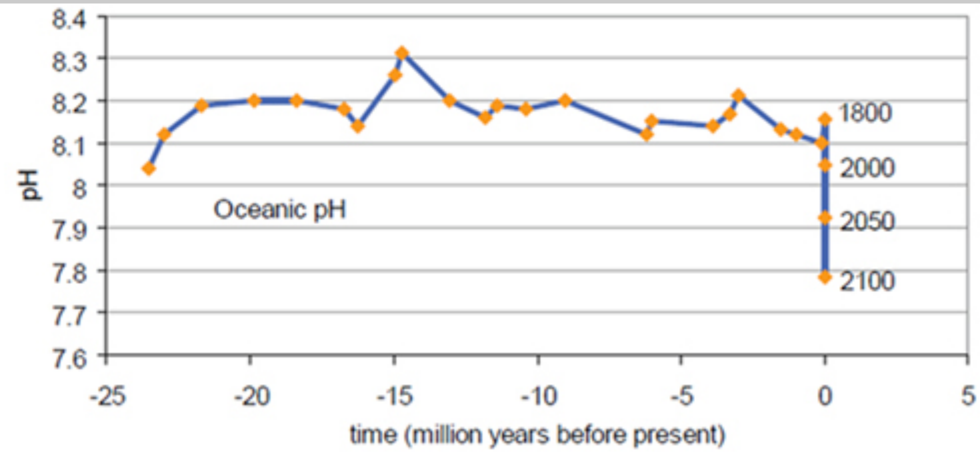
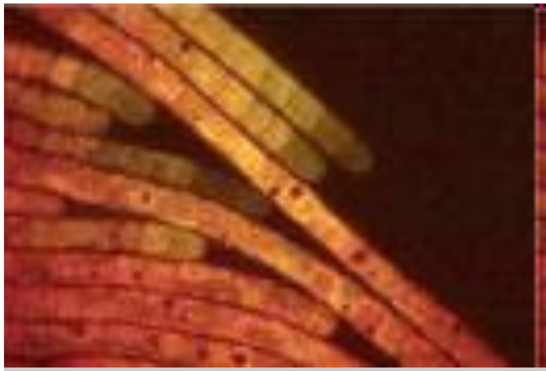


Figure 1. Past and contempory variability of marine pH. Future predictions are model derived values based on IPCC mean scenarios (from Turley *et al*, 2006. Cambridge University Press, 8, 65-70).



N-fixation by *Trichodesmium* sp.

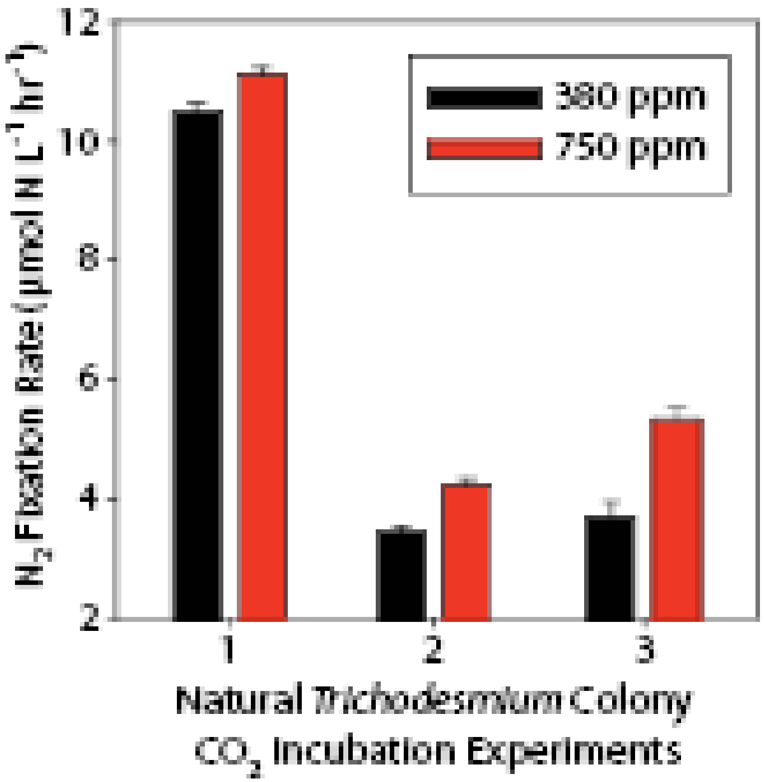
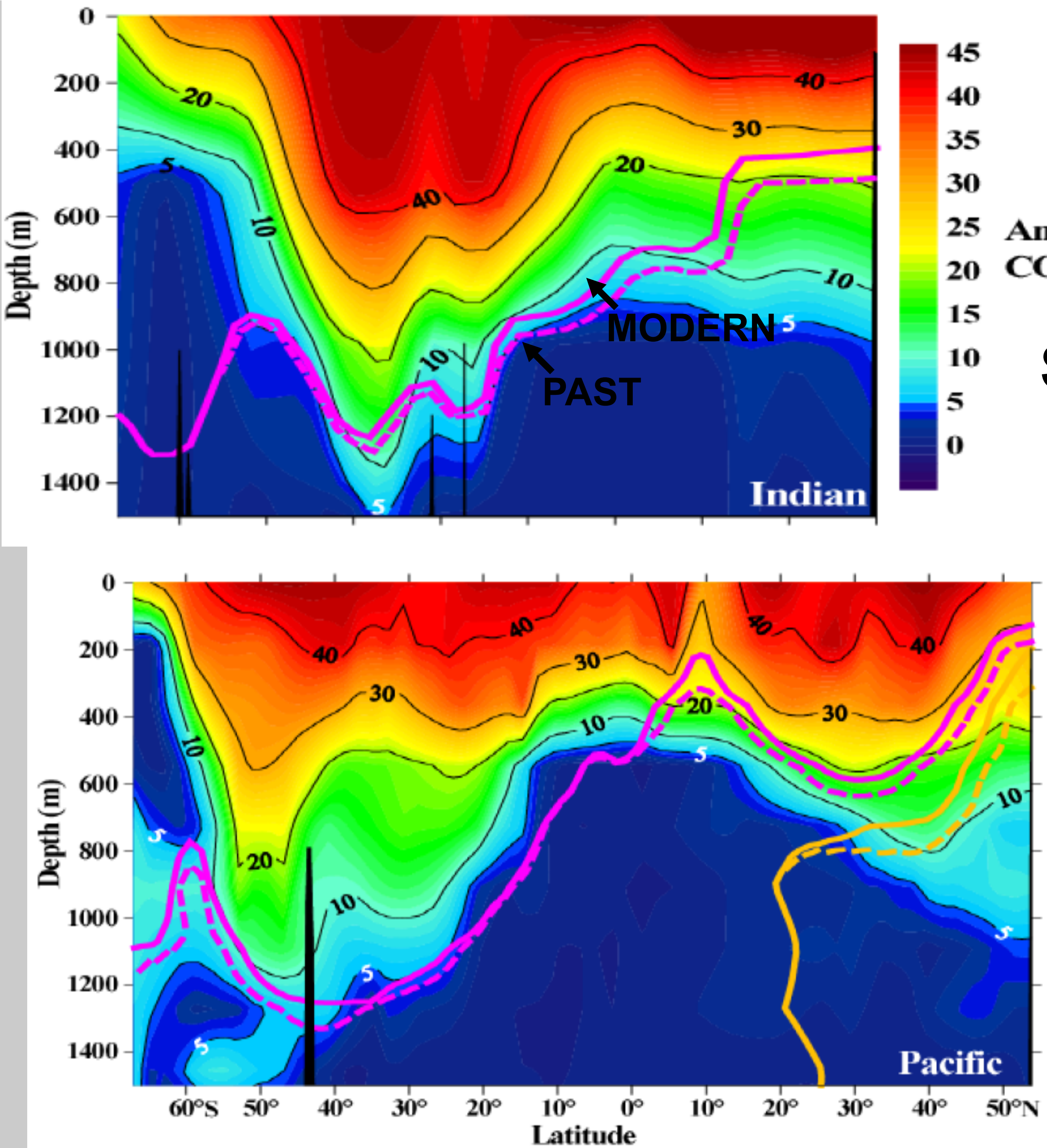


Figure 3. N_2 fixation rates of collected natural *Trichodesmium* spp. colonies from the Gulf of Mexico in three separate experiments, incubated for four to six hours at current pCO_2 (380 ppm, black) and projected year 2100 pCO_2 (750 ppm, red). Error bars are the standard deviations of triplicate bottles in each treatment. N_2 fixation rates at elevated pCO_2 in these three experiments were increased by 6%, 21%, and 41% above rates at ambient pCO_2.



Aragonite saturation Horizon

Saturation Horizons are shallowing

Calcite Saturation Horizon