# What's all this fuss (fizz?) about ocean acidification?



Contact kleypas@ucar.edu

# What's all this fuss (fizz?) about ocean acidification?

**Background**

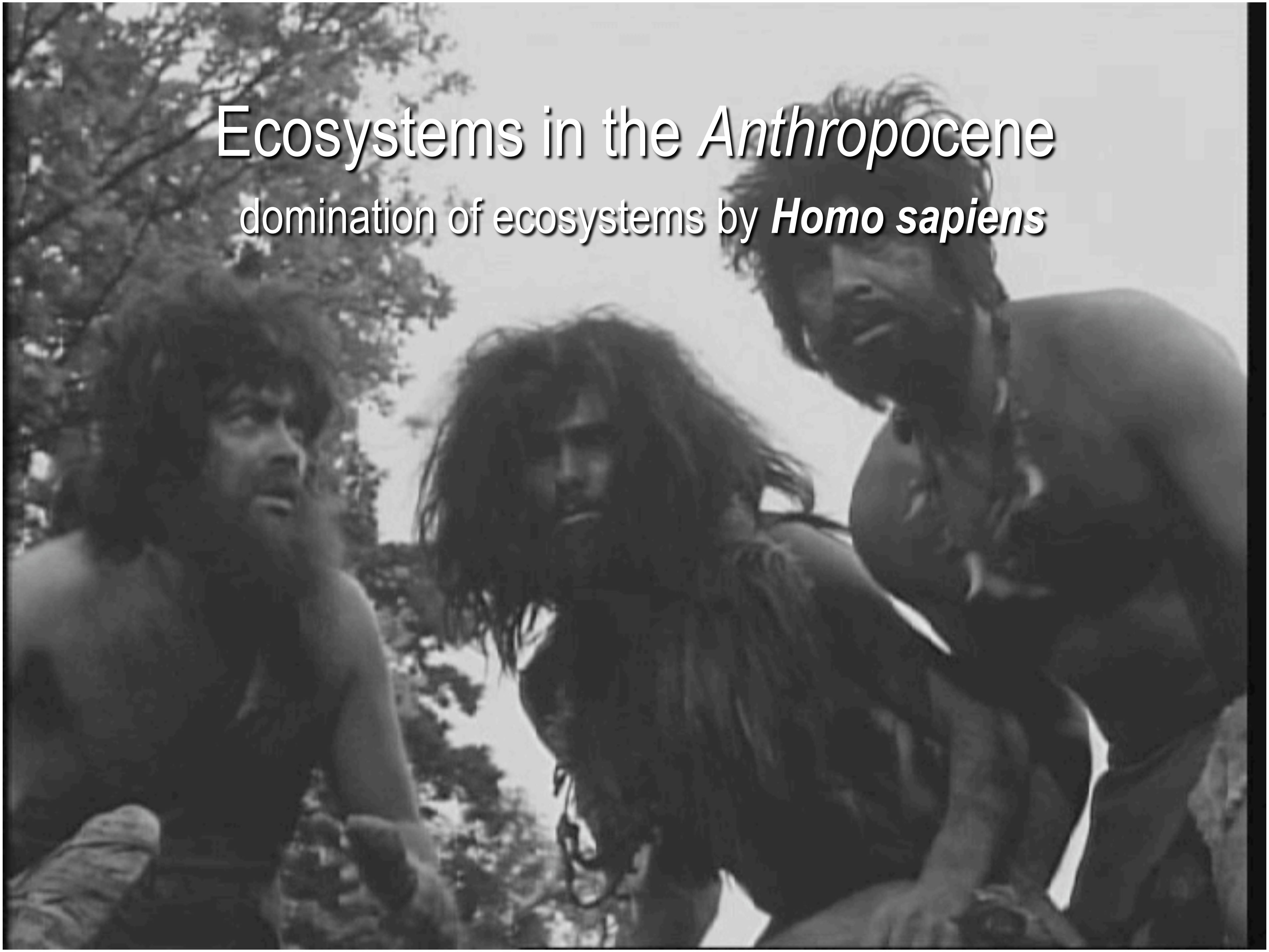
Impacts

Thresholds

Solutions?

NCAR

Colorado
University of Colorado at Boulder


Ecosystems in the *Anthropocene*
domination of ecosystems by ***Homo sapiens***

# Ecosystems in the *Anthropocene*

## domination of ecosystems by ***Homo sapiens***

### *H. sapiens* traits

- top competitor for space
- effective predator (hunting, overfishing)
- symbiotic relationships with other species (farming, ranching, also species protection)
- prolific chemical recycler (C, N, P, $H_20$ cycles)

### Ecosystem response

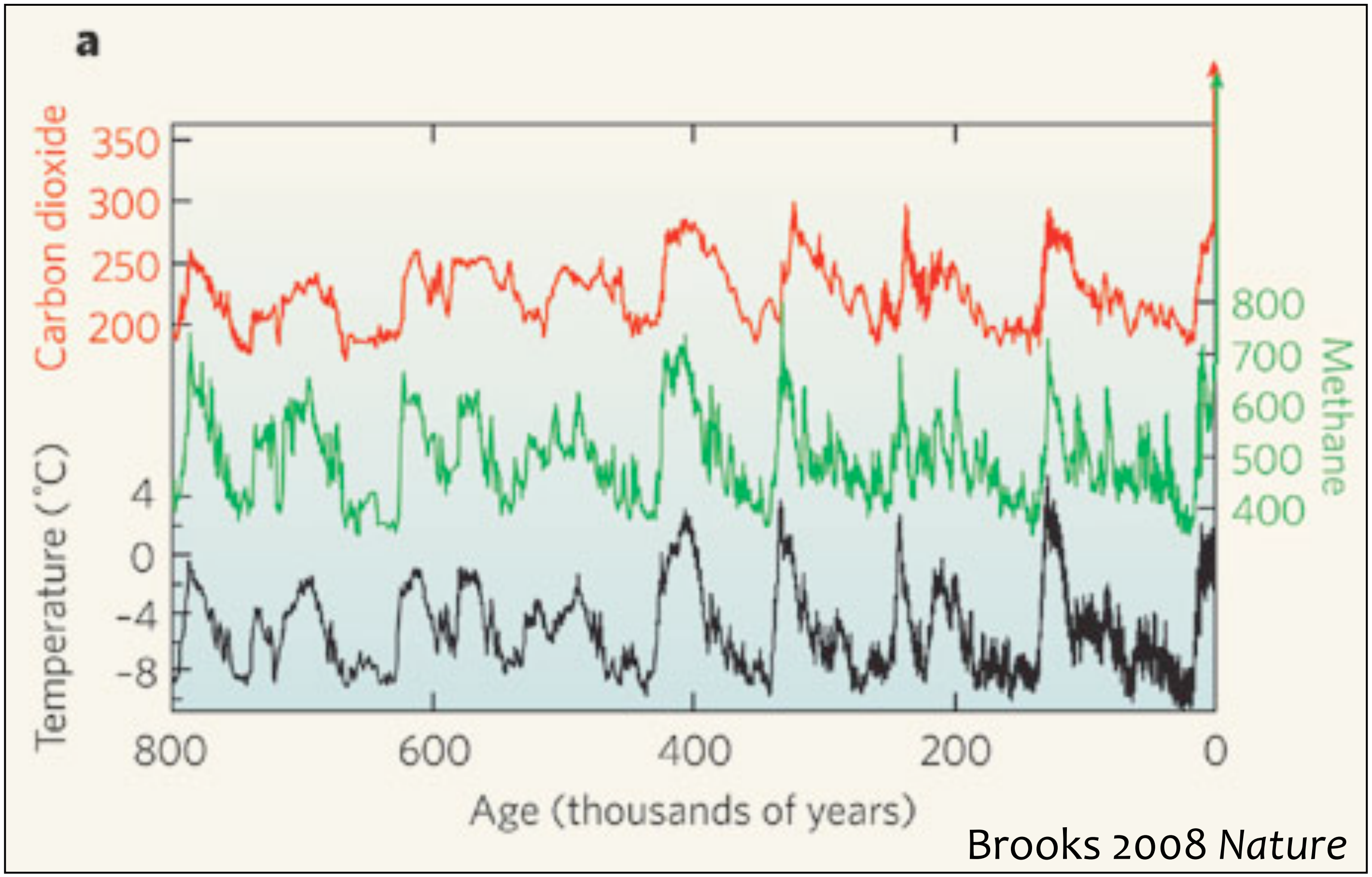
- habitat loss
- food web adjustment → ecosystem shift
- habitat gain/loss
- ecosystem shifts

*Homo sapiens* is much more sophisticated now…

# $CO_2$ Fluctuations over Different Time Scales

## Current $CO_2$ level exceeds the levels of …

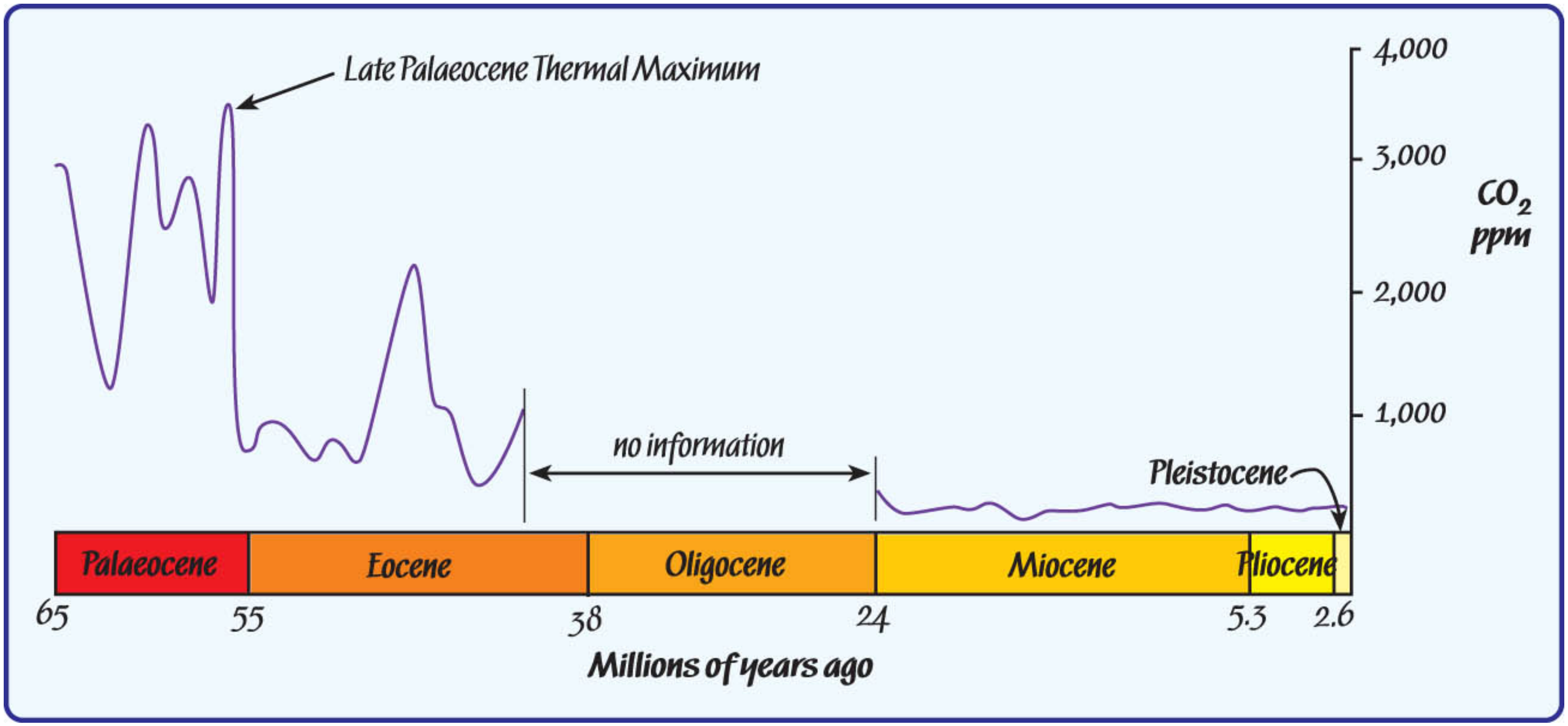
## … the past 800,000 years



# $CO_2$ Fluctuations over Different Time Scales

## Current $CO_2$ level exceeds the levels of …

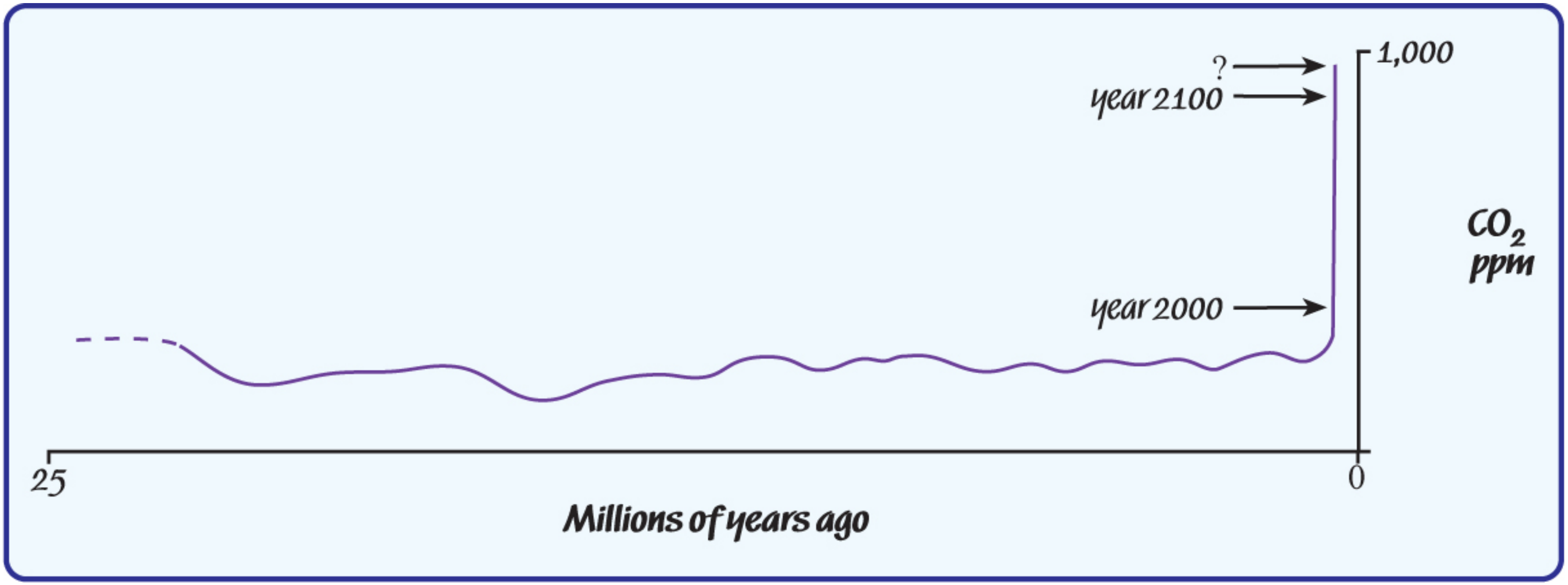
## … or even the past 24 million years




Veron 2008

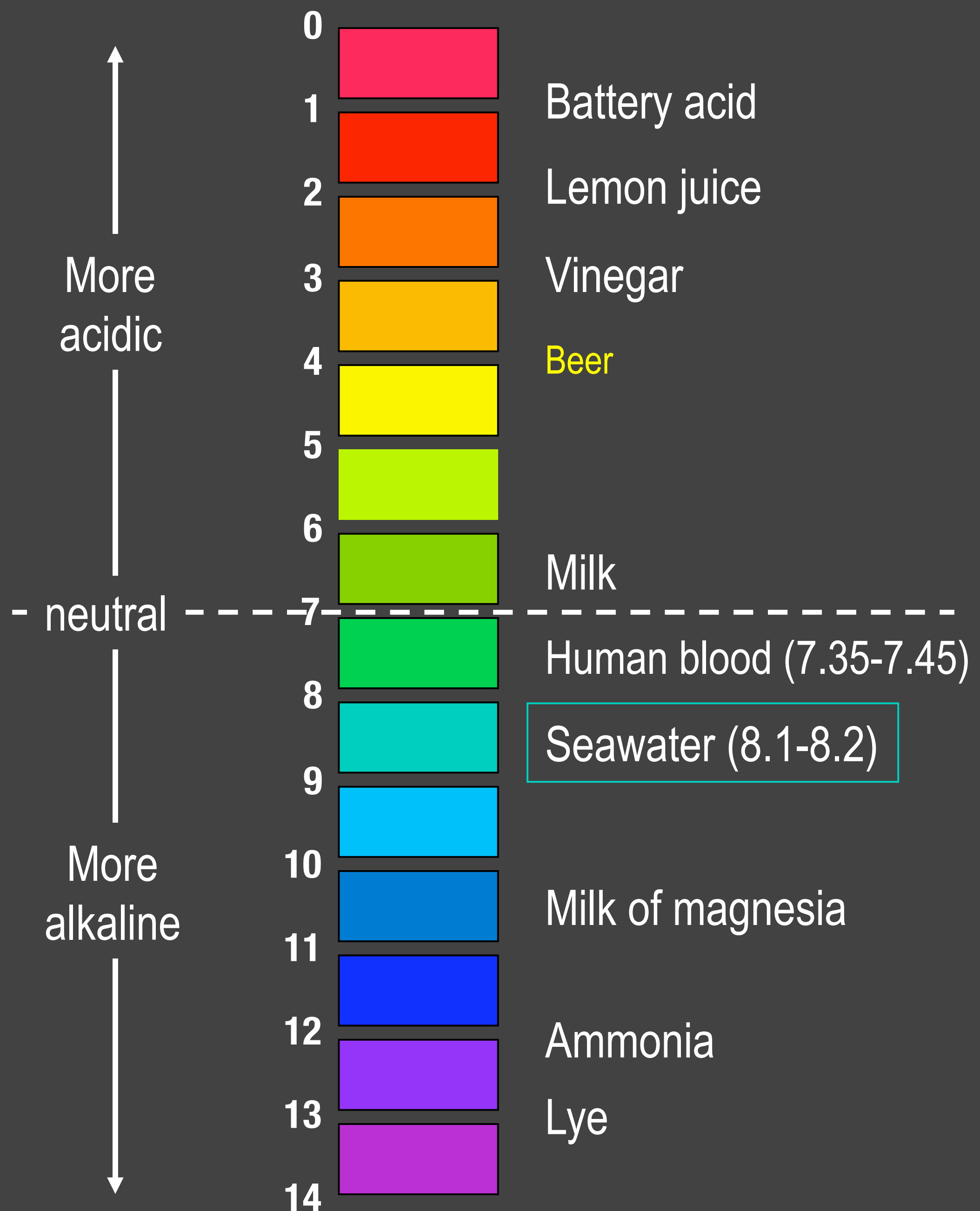
# $CO_2$ Fluctuations over Different Time Scales

But more important than the $CO_2$ increase is the **RATE** of the increase




Veron 2008

# The pH scale



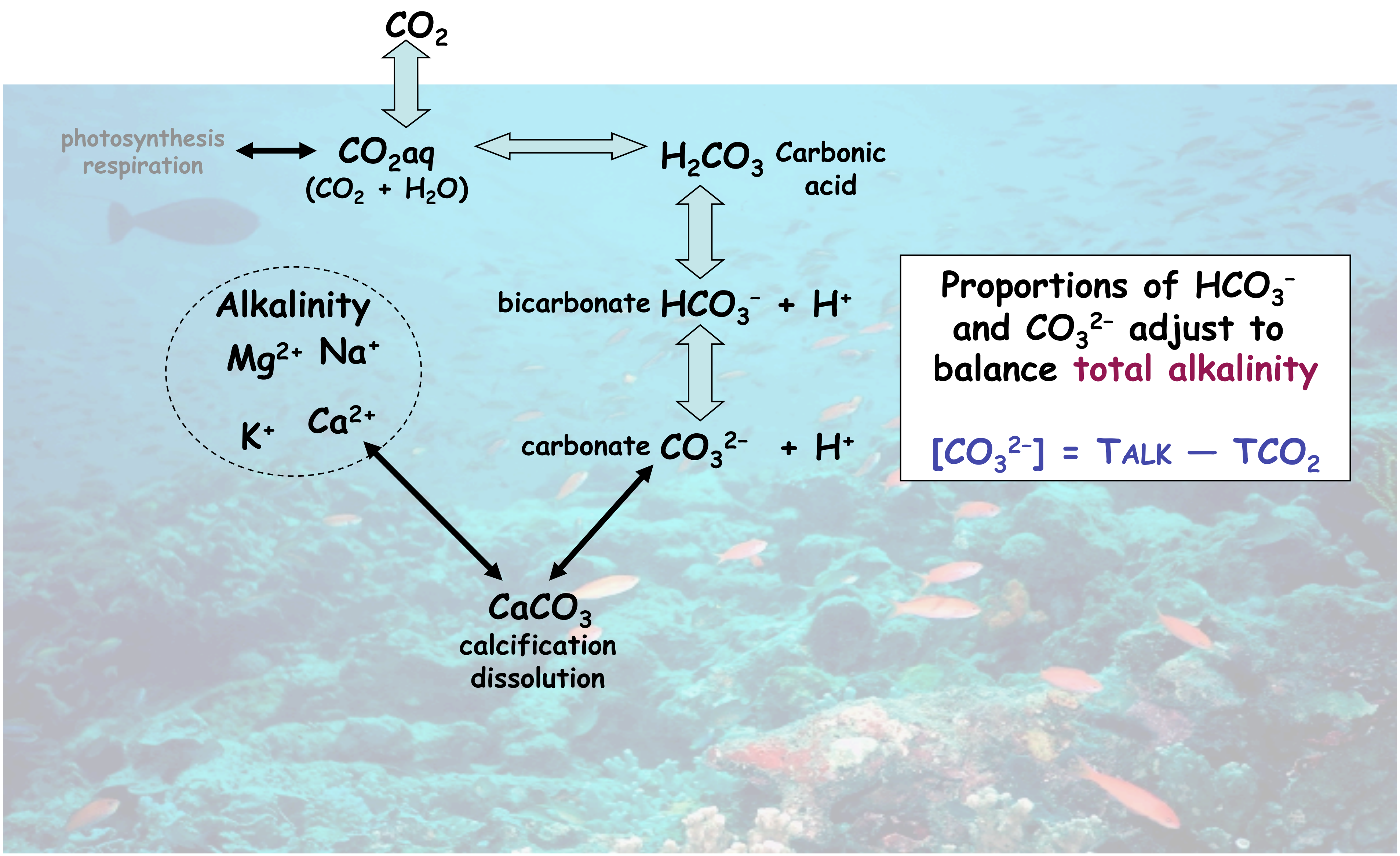

$$pH = -\log_{10} [H^+]$$

[H+] = 0.001
pH = 3

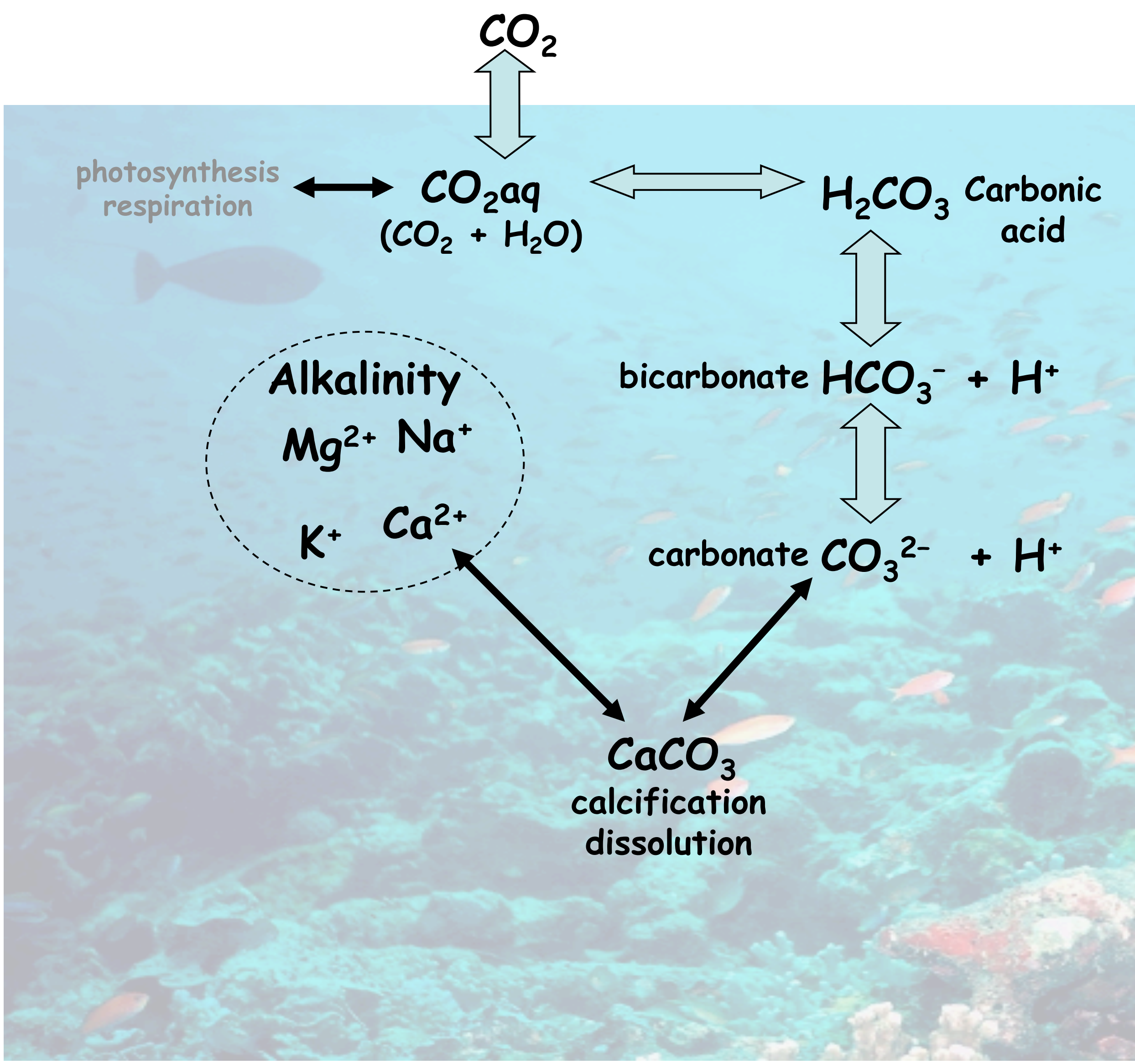
[H+] = 0.000001
pH = 6

[H+] = 0.000000001
pH = 9

# The $CO_2$ System in Seawater



# The $CO_2$ System in Seawater




| $1xCO_2$ | $2xCO_2$ | |
|---|---|---|
| 280 | 560 | |
| 8 | 16 | |
| 1635 | 1867 | |
| 272 | 177 | |
| 1915 | 2061 | $TCO_2$ / DIC |
| 8.17 | 7.93 | pH |
| 4.3 | 2.8 | Ω-arag |

# The $CO_2$ System in Seawater

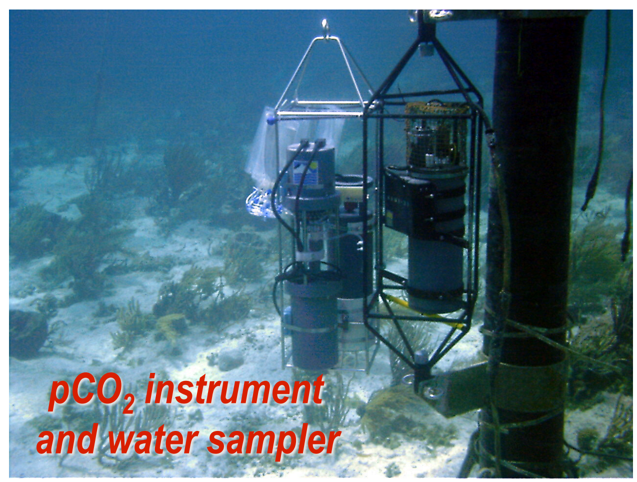
To characterize the entire $CO_2$ system in seawater, need to measure at least 2 of the 4 measureable $CO_2$ system parameters:

1. **Total Alkalinity**
2. **Total $CO_2$ (DIC)**
3. **$pCO_2$ in seawater**
4. **pH**

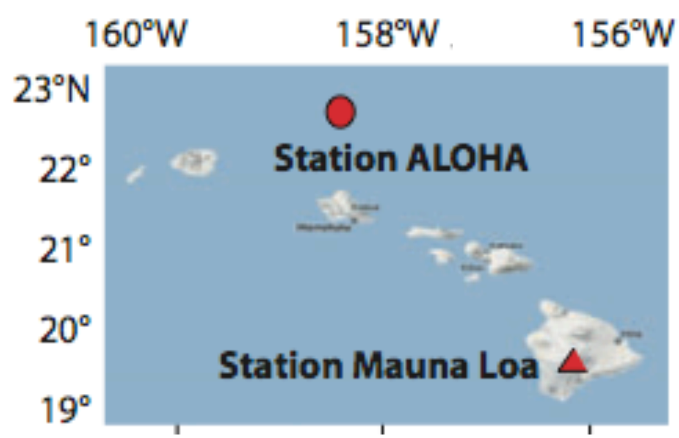
**+**

**Temperature**
**Salinity**
**Nutrients**
**Water Depth**

**A pH meter is not enough!**



# Observed decline in the surface ocean pH and $\Omega_{arag}$



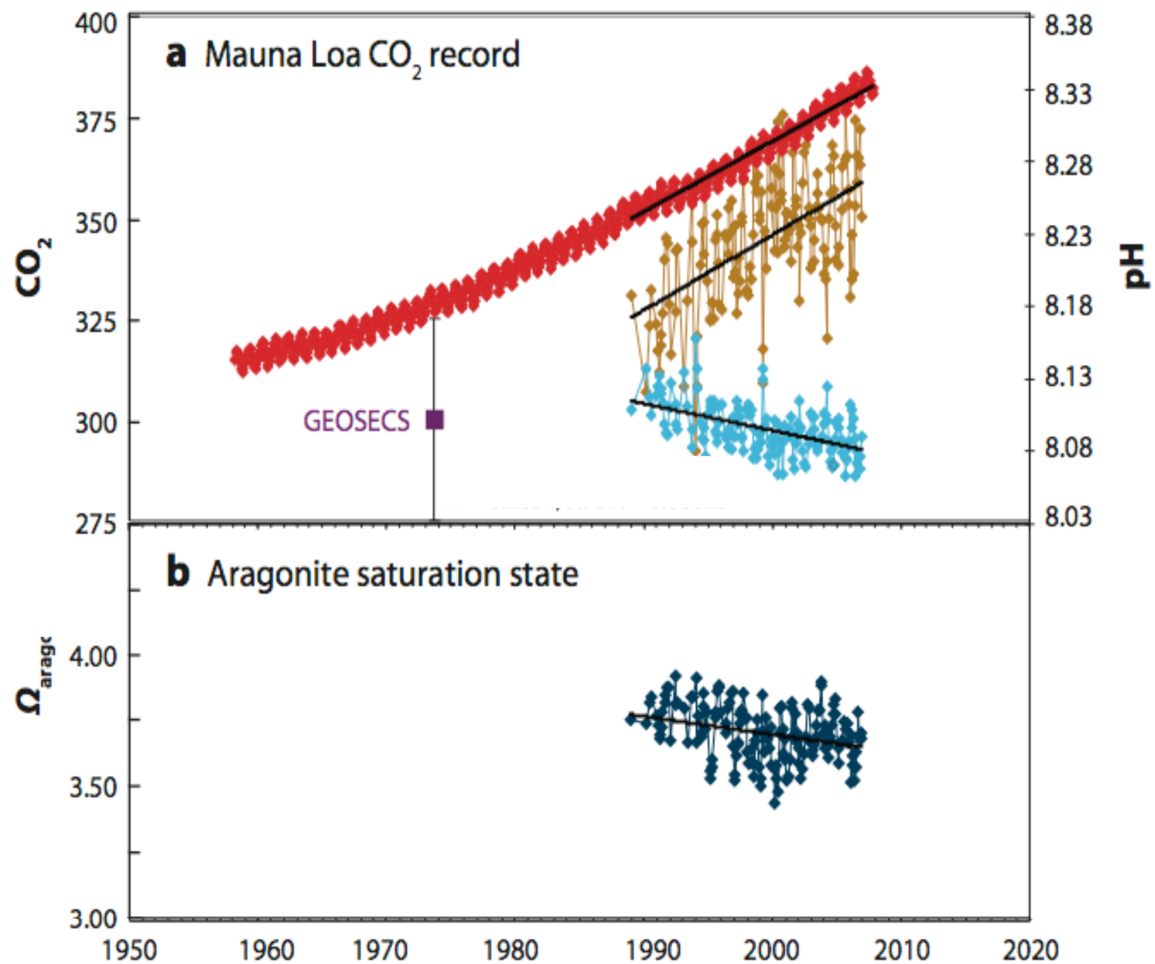
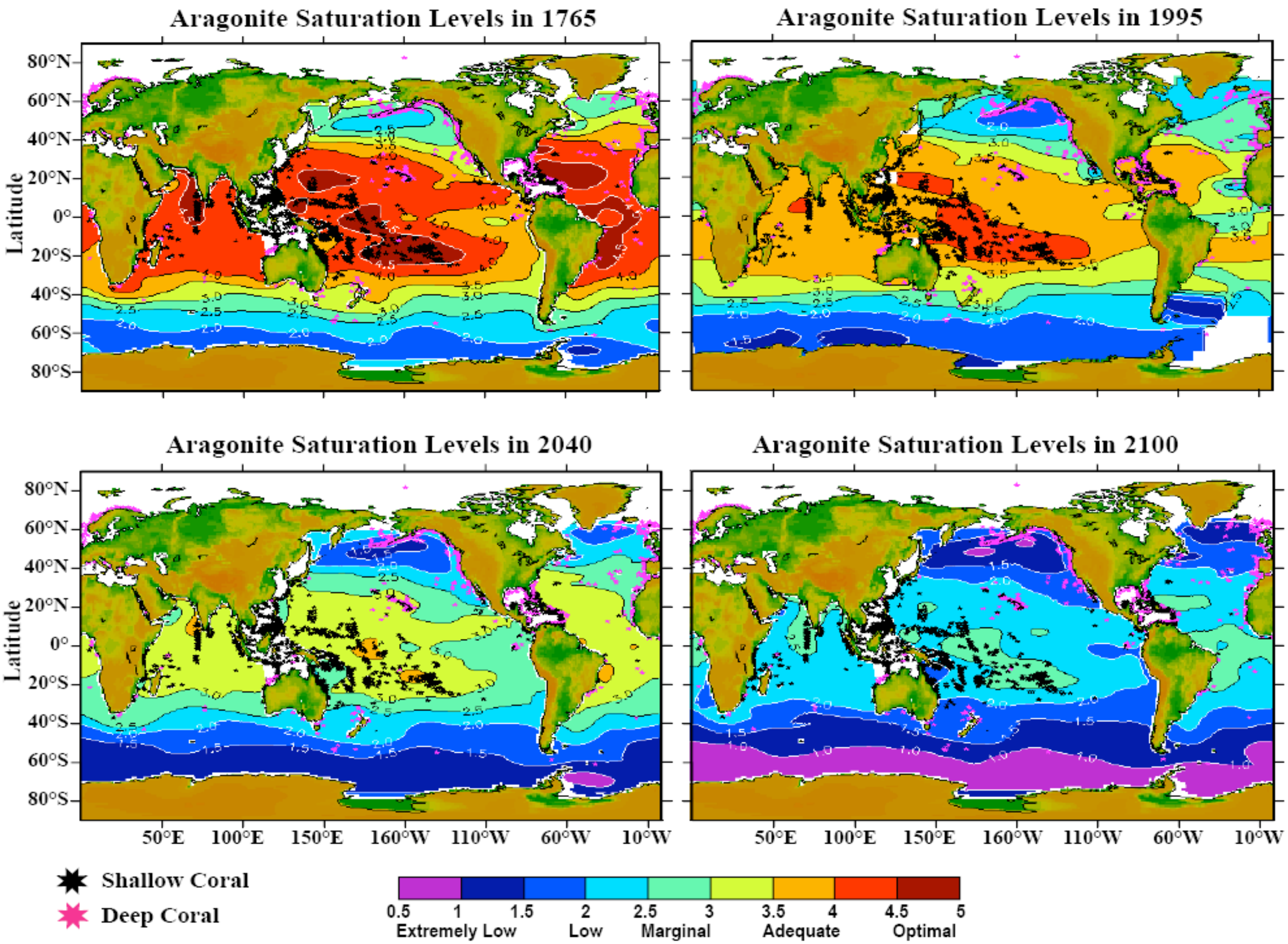




Figure from Dave Karl, in Doney et al. *Ann. Rev. Mar. Sci.* 2009

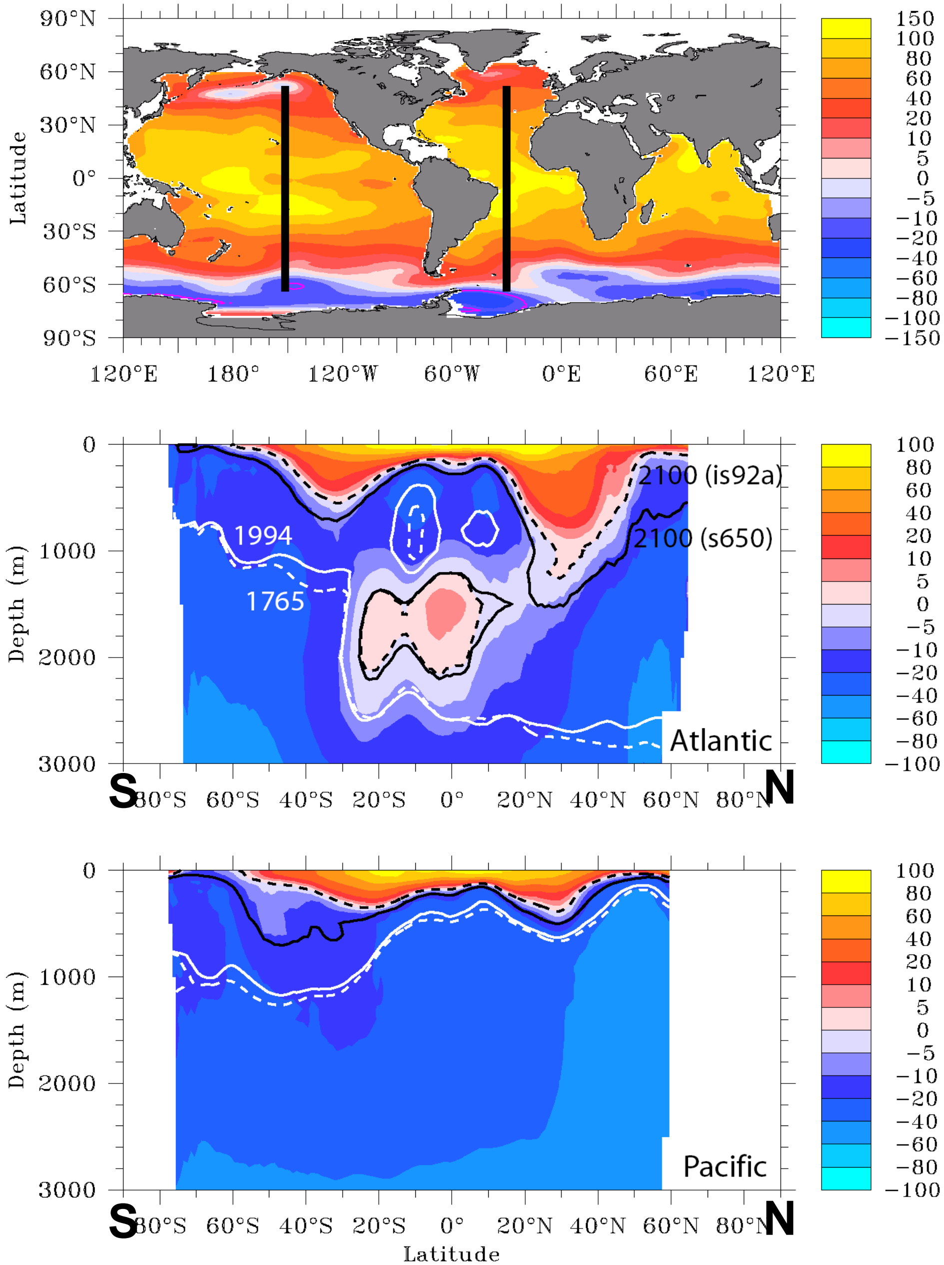
# Aragonite Saturation 1765-2100






After *Feely et al (in press)* with Modeled Saturation Levels from *Orr et al. 2005*

# Shoaling of the aragonite & calcite saturation horizons

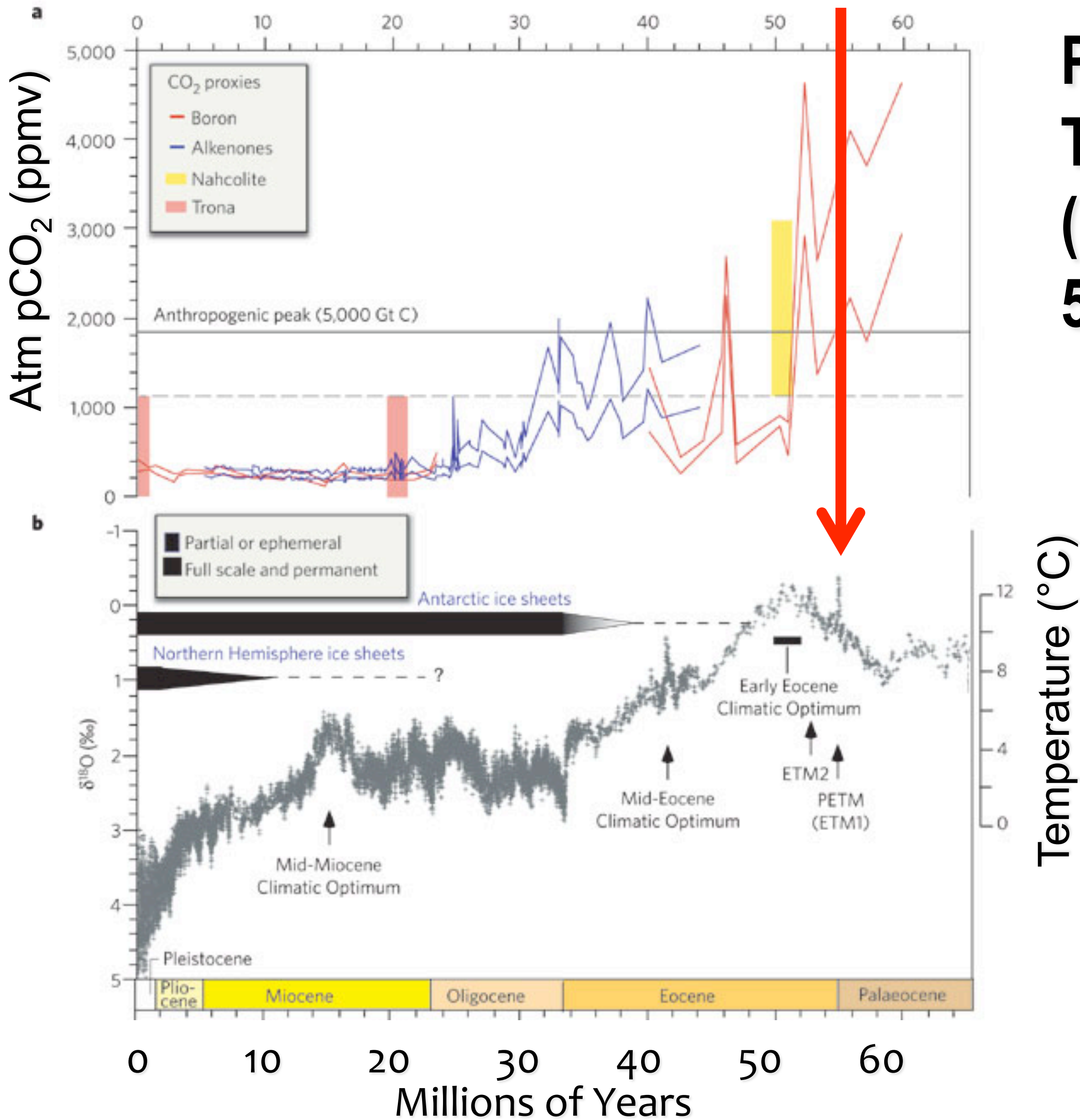



**Atlantic**

**Pacific**

Orr et al. 2005 *Nature*

CU S

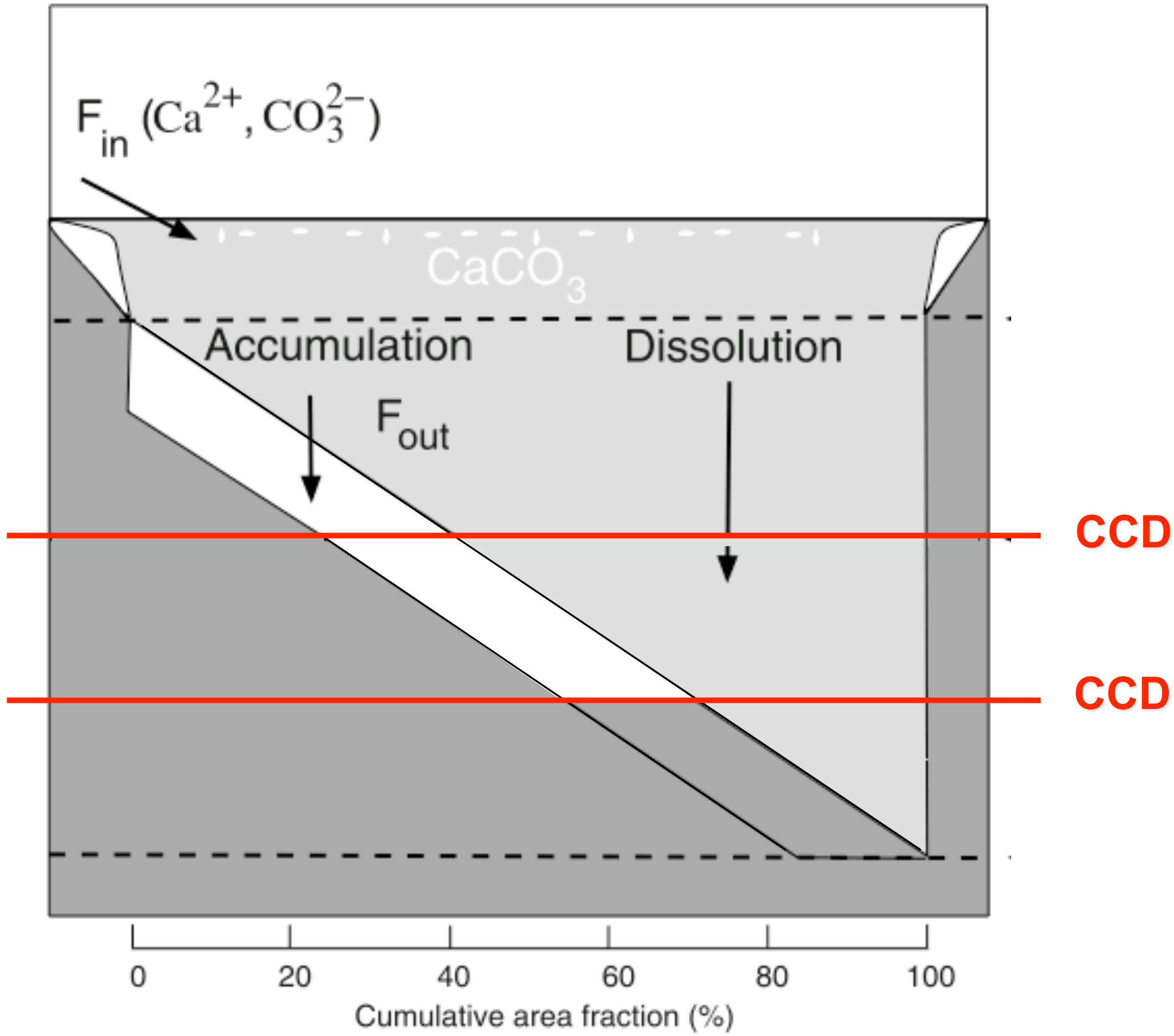



# Paleocene-Eocene Thermal Maximum (PETM)

# 55 my ago

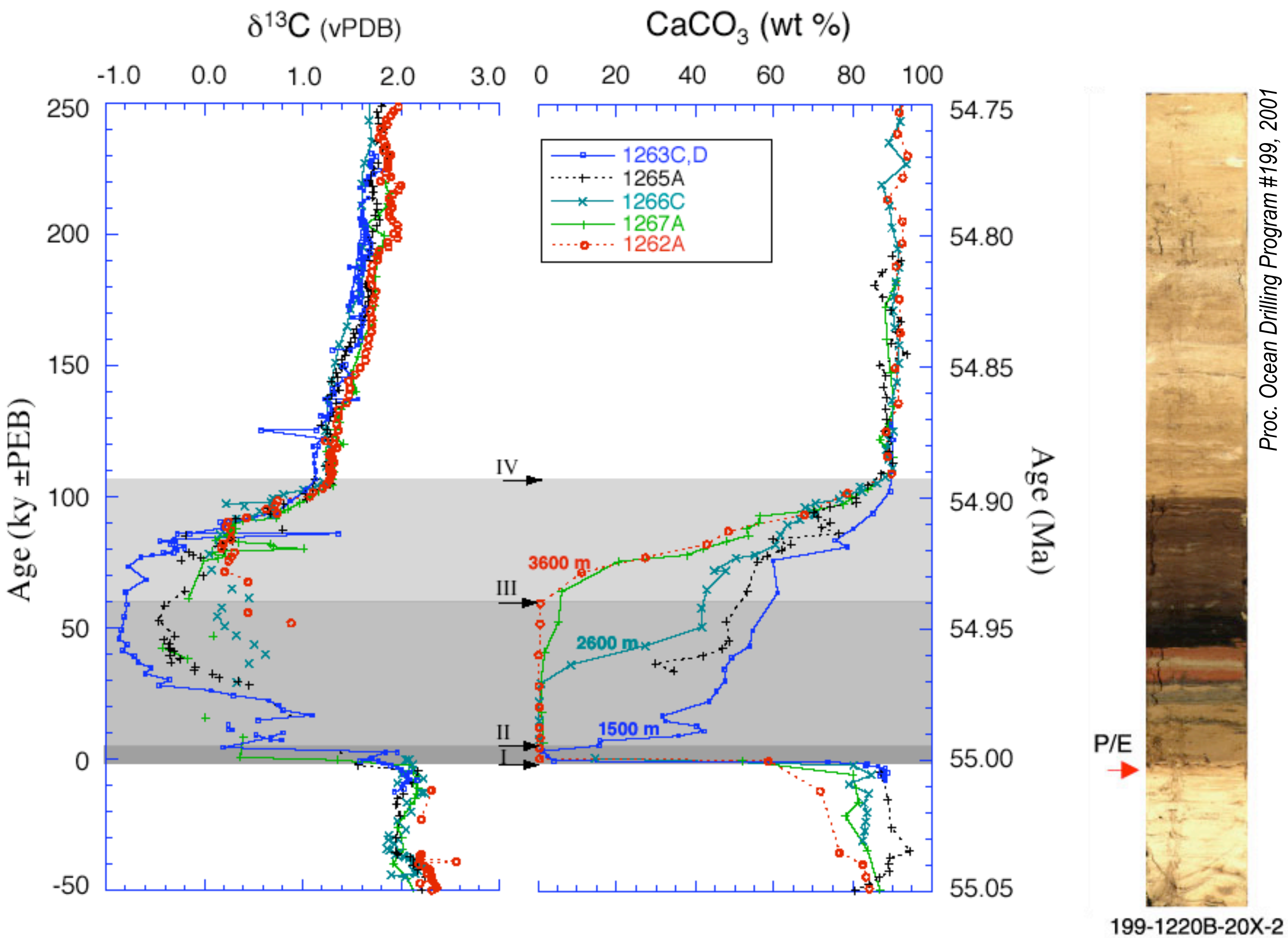
Zachos et al. 2008 *Nature*

# Evidence for Ocean Acidification in the Past




Modified from Zeebe 2003
*Geochem. Geophys. Geosys.*

# Paleocene-Eocene Thermal Maximum (55 Ma)




Zachos et al. 2005 *Science*

# What Happened in the PETM?

**Physical changes:**

- Increase in ocean temperature 5-8ºC
- Decrease in marine and terrestrial C isotopes 3-8‰
- Shoaling of the CCD up to 2 km

**Biological responses:**

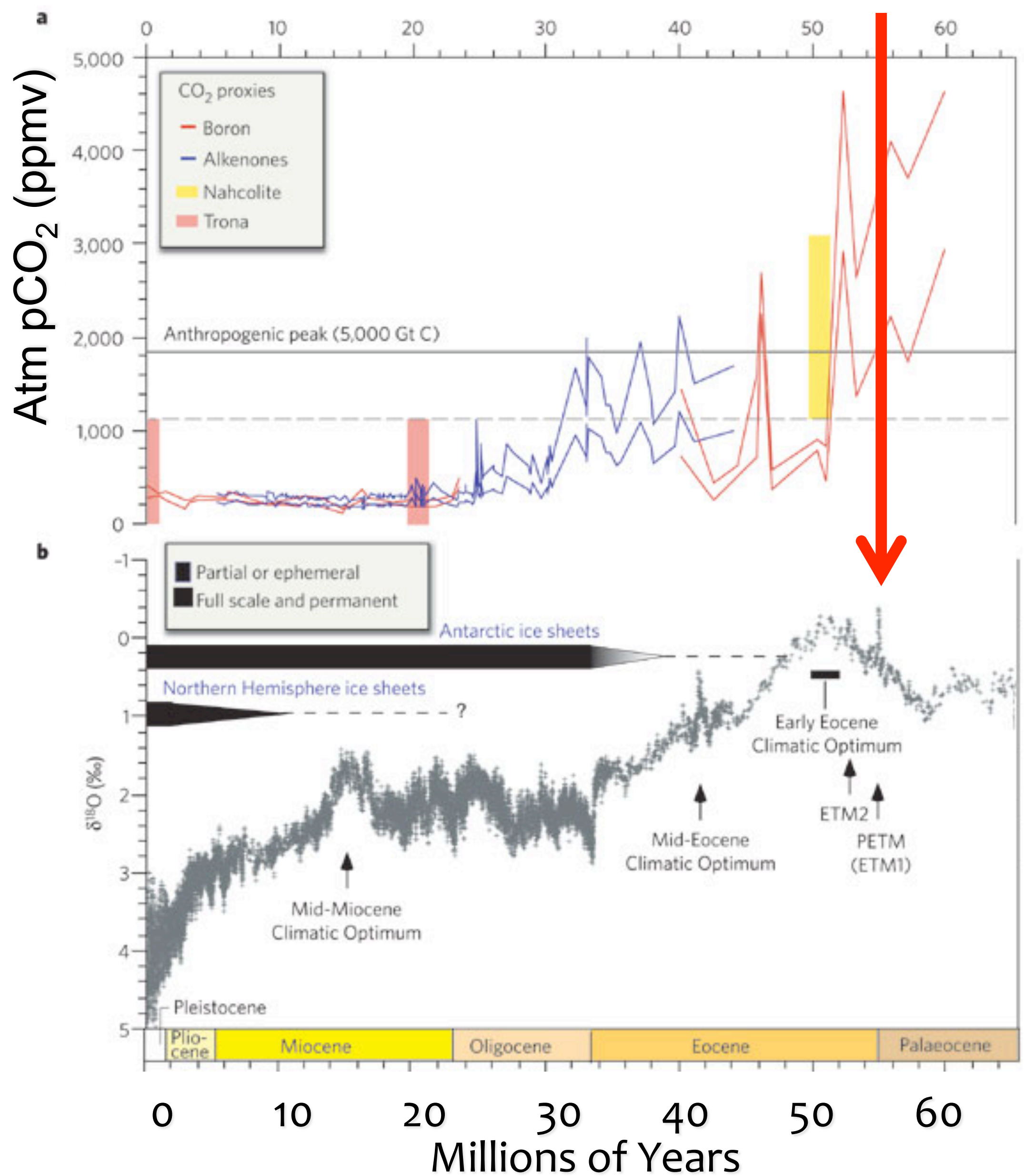
- Dramatic reorganization of marine and terrestrial ecosystems

marine: 35-50% of deep-water benthic foraminifera went extinct (Thomas 1998)

high species turnover of plankton (Gibbs et al 2006; Raffi et al 2009)

land: mammalian radiation

reorganization of terrestrial plant communities (Wing et al. 2005)




Zachos et al. 2008 *Nature*

# PETM
# A good analogue?

**$CO_2$ spike within an already high $CO_2$ environment**

*($CO_2$ = 2000-4000 ppm)*

**Rate of change uncertain**

*(time resolution = 1000 y)*

**Source of carbon is still debated**

**Different suite of organisms**

**Not just acidification in the oceans, but also:**

- **warming**
- **oxygen depletion**
- **changes in ocean circulation**

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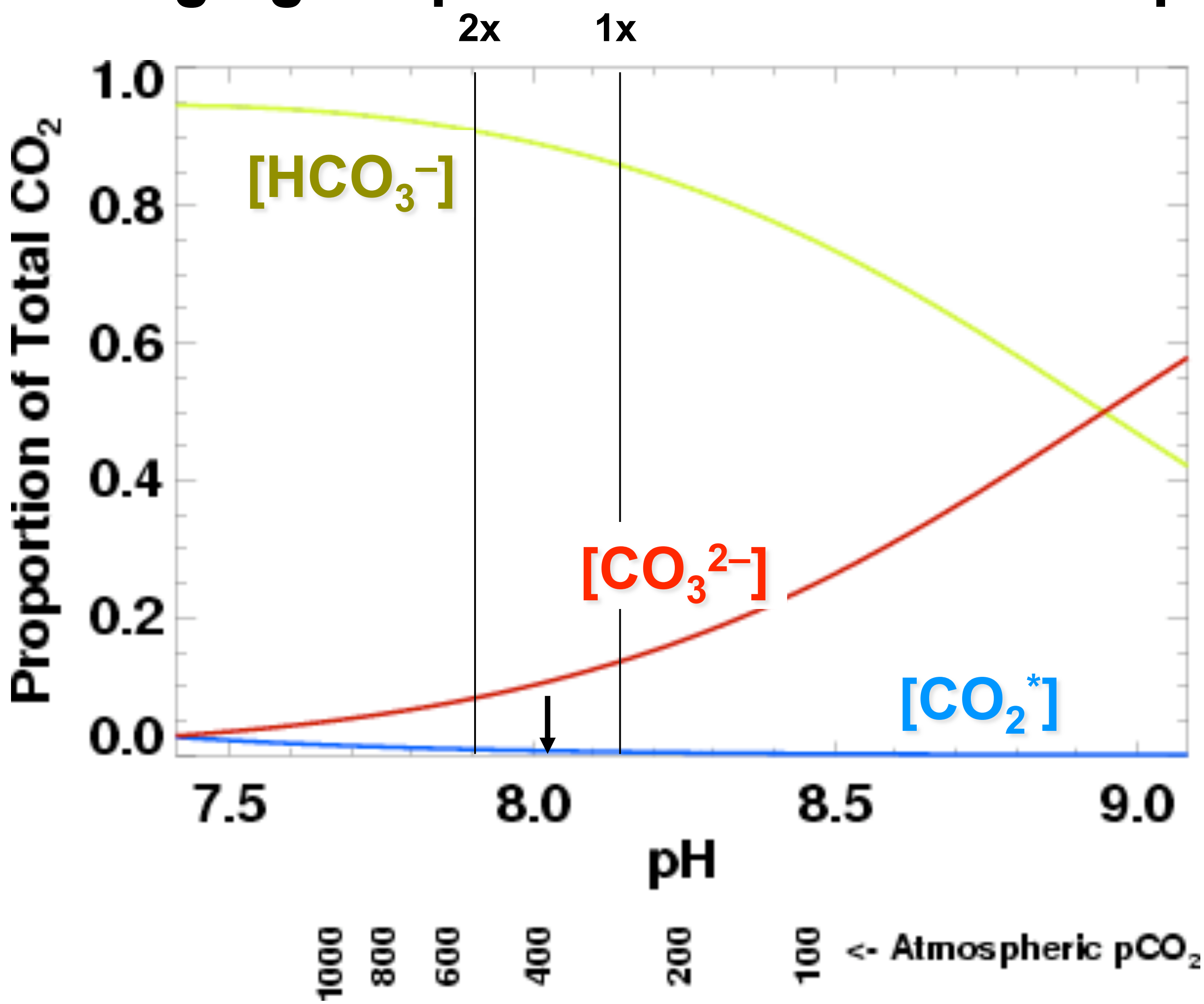
# Changing Proportions of Carbonate Species



# Effects of ocean acidification on marine life

| | | | |
|---|---|---|---|
| $CO_{2(aq)}$ | $HCO_3^-$ | ↑ | Increase in photosynthesis |
| $CO_3^{2-}$ | ↓ | | Decrease in calcification |
| pH | ↓ | | Physiological effects |

# Effects of ocean acidification on marine life

$CO_{2(aq)}$ | $HCO_3^-$ ↑

$CO_3^{2-}$ ↓

pH ↓

***Direct Effects***

Increase in photosynthesis

Decrease in calcification

Physiological effects

# Effects of ocean acidification on marine life

$CO_{2(aq)}$ | $HCO_3^-$ ↑

$CO_3^{2-}$ ↓

pH ↓

***Direct Effects***

Increase in photosynthesis

Decrease in calcification

Physiological effects

***Indirect Effects***

Chemical speciation

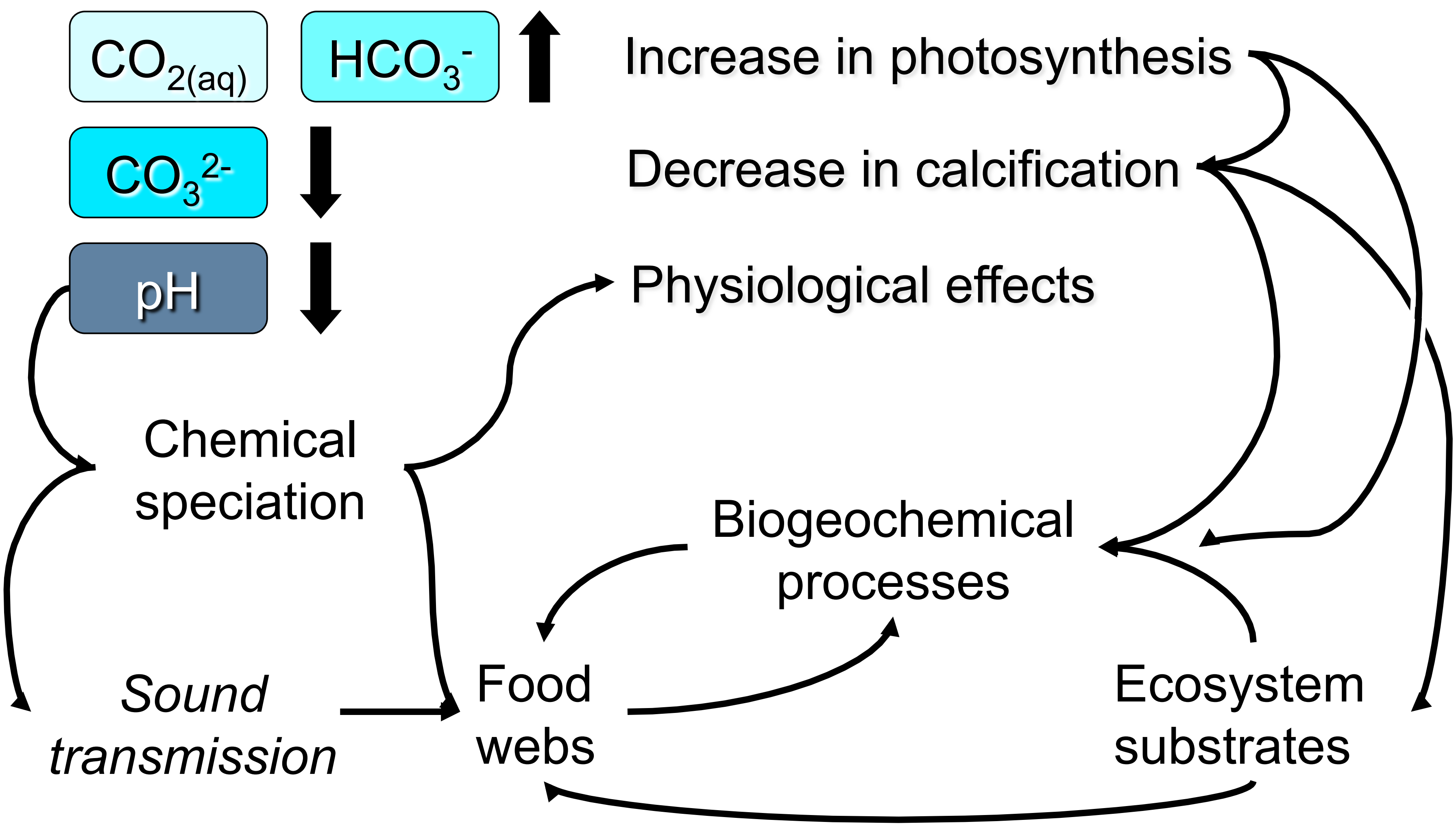
Biogeochemical processes

*Sound transmission*

Food webs

Ecosystem substrates

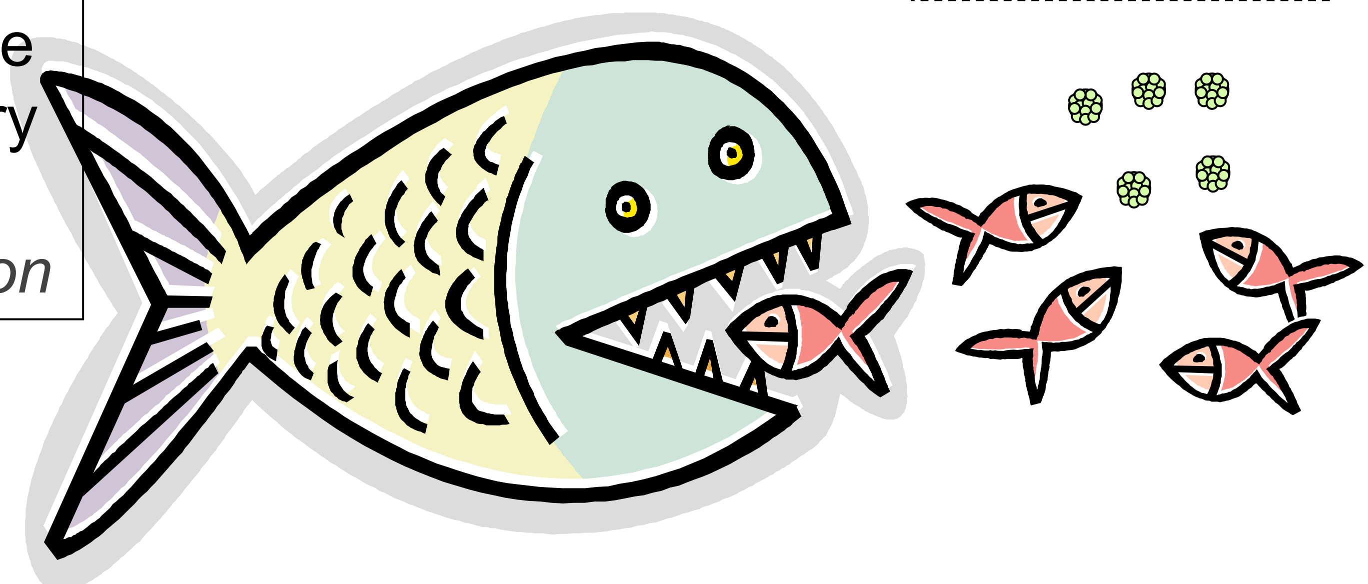
# Effects of ocean acidification on marine life



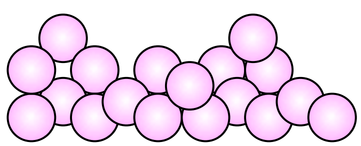
# Effects of Lowered pH on Organisms

**Physiology:**
Calcification rate
Respiration rate
Blood chemistry
Growth rate
*Chemoreception*

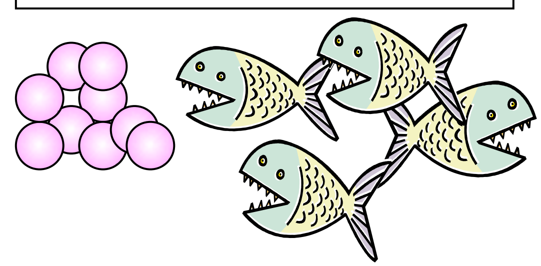
**Food Supply**

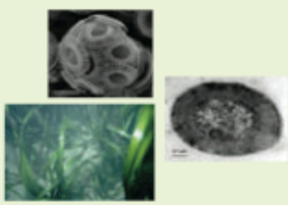


**Reproduction**



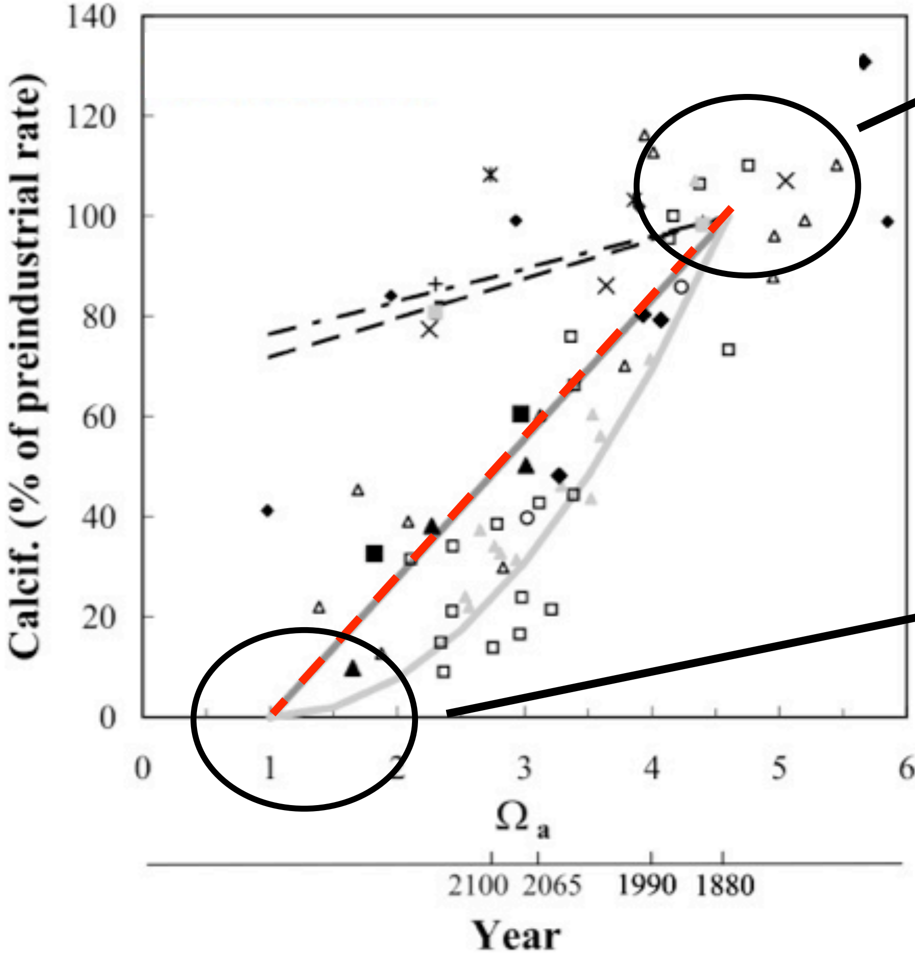
**Eggs or Larvae**



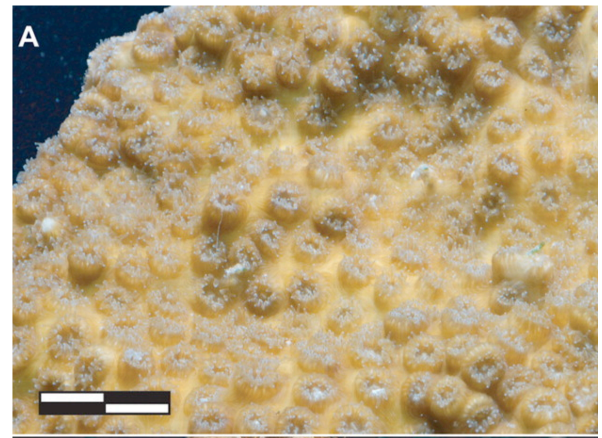
| Physiological response | Major group | Species studied | a | b | c | d |
|---|---|---|---|---|---|---|
| **Calcification**  | | | | | | |
| | Coccolithophores[1] | 4 | 2 | 1 | 1 | 1 |
| | Planktonic Foraminifera | 2 | 2 | – | – | – |
| | Molluscs | ~~4~~ 6 | 4 5 | – | –1 | – |
| | Echinoderms[1] | 3 | 2 | 1 | – | – |
| | Tropical corals | 11 | 11 | – | – | – |
| | Coralline red algae | ~~1~~ 4 | ~~1~~ 3 | – | –1 | – |
| **Photosynthesis[2]**  | | | | | | |
| | Coccolithophores[3] | 2 | – | 2 | 2 | – |
| | Prokaryotes | 2 | –1 | – | 1 | – |
| | Seagrasses | 5 | – | – | – | – |
| **Nitrogen Fixation**  | | | | | | |
| | Cyanobacteria | ~~1~~ 3 | – | ~~1~~ 3 | – | – |
| **Reproduction**  | | | | | | |
| | Molluscs | 4 | 4 | – | – | – |
| | Echinoderms | 1 | 1 | – | – | – |

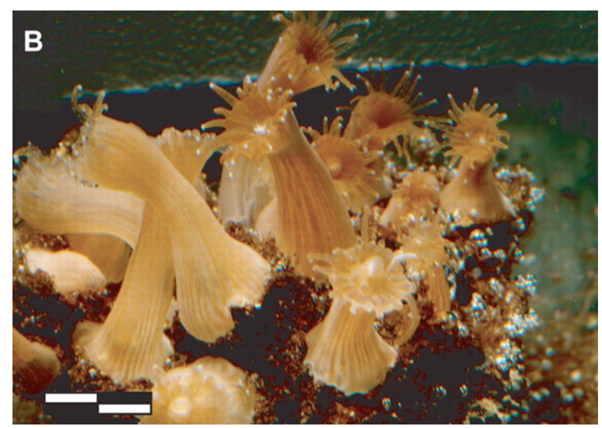
Doney et al. 2009

# Coral/Reef Calcification



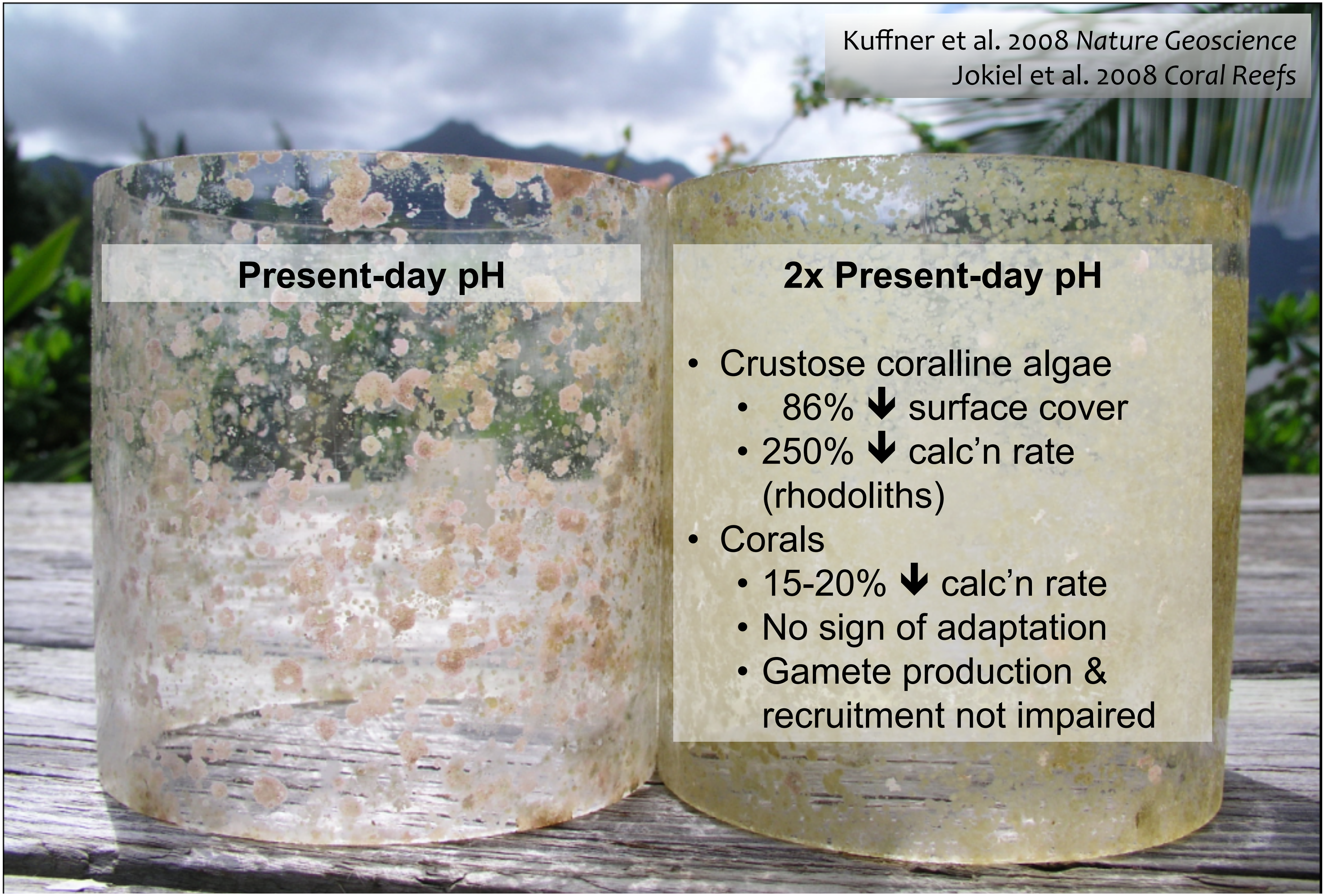

Langdon & Atkinson 2005 *JGR*



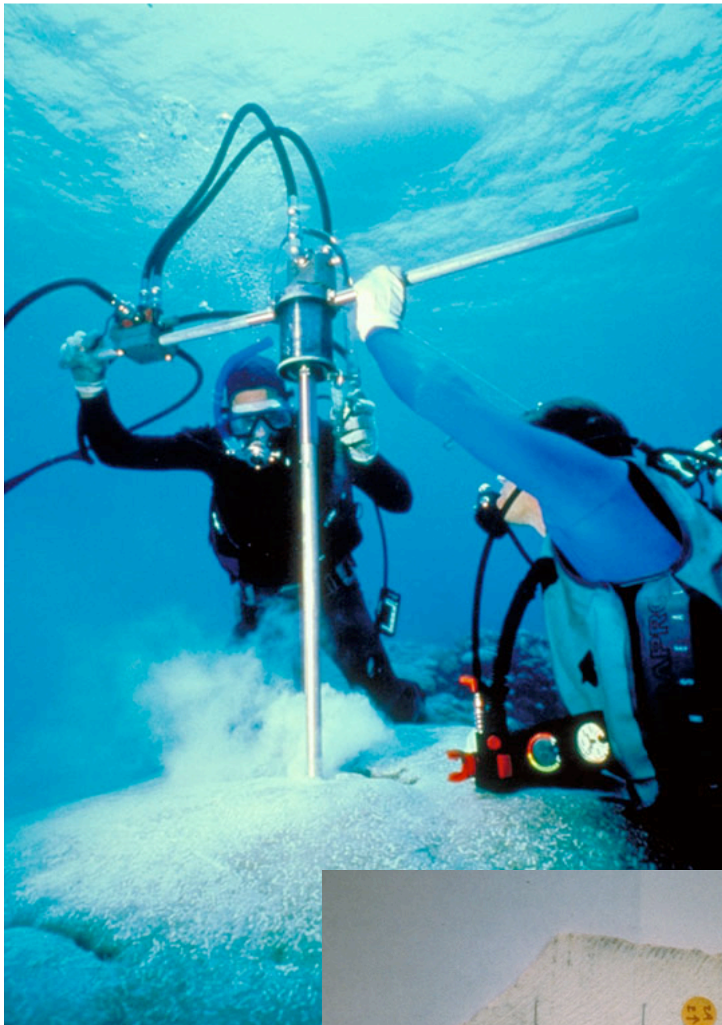

Fine & Tchernov 2007 *Science*

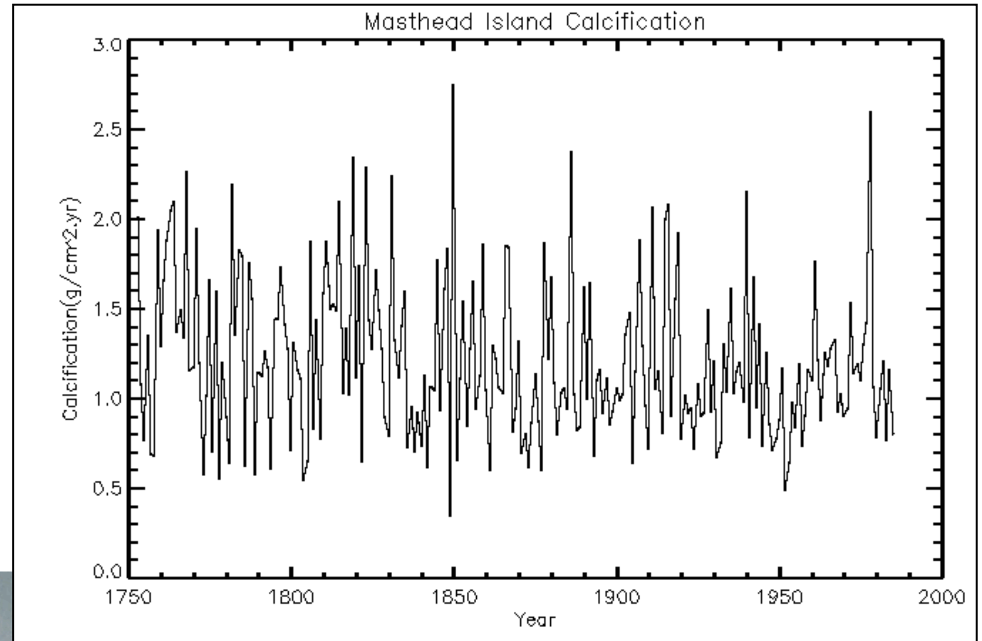
# Crustose Coralline Algae

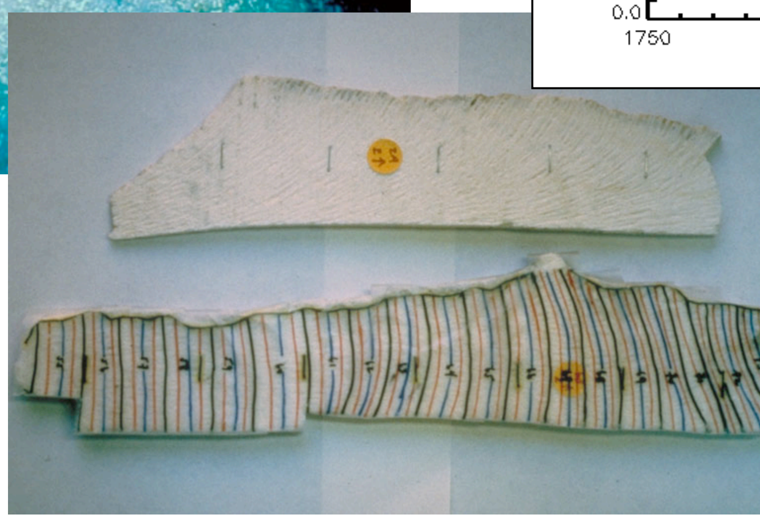


# Calcification Records from *Porites* corals

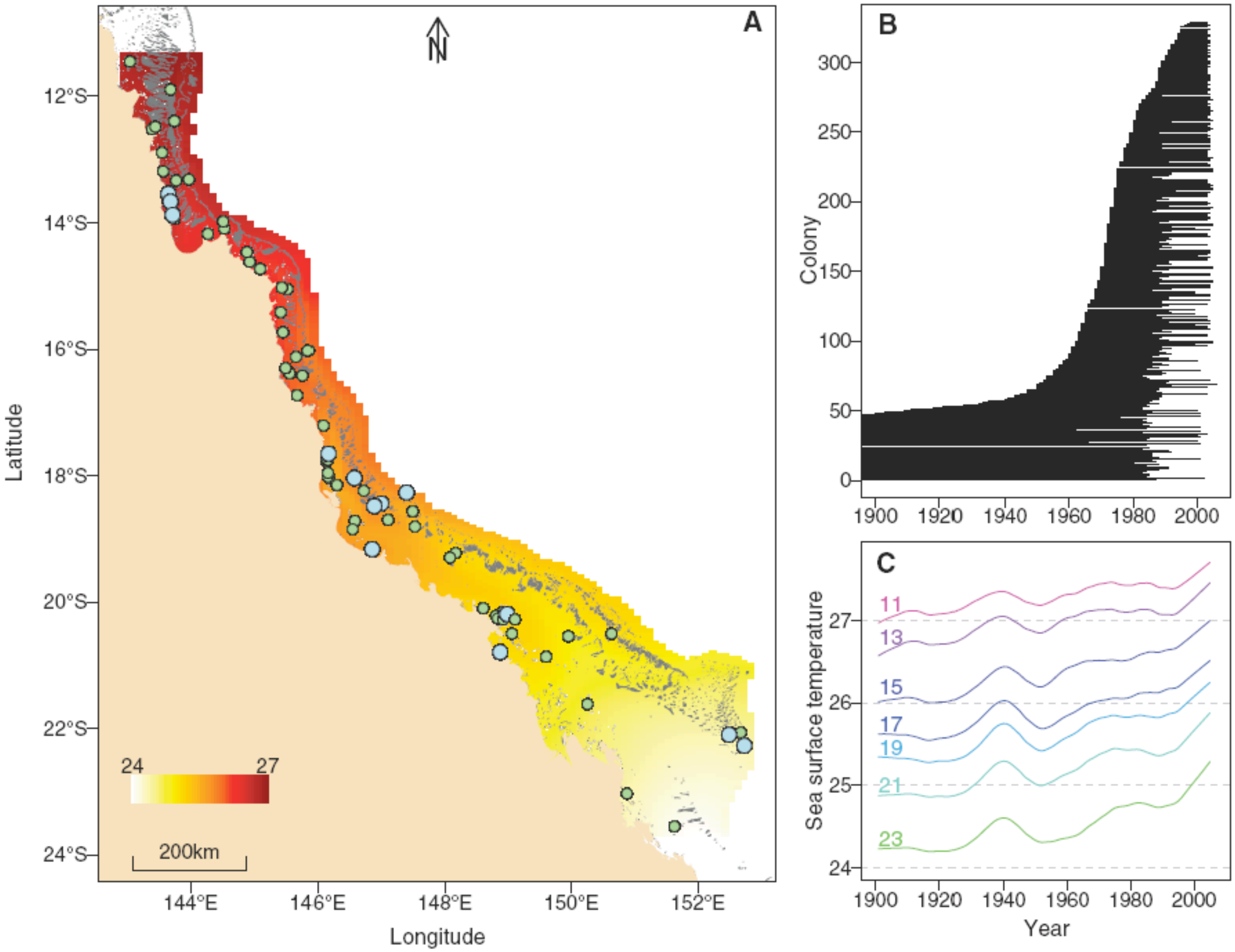
## (Lough & Barnes 2000)





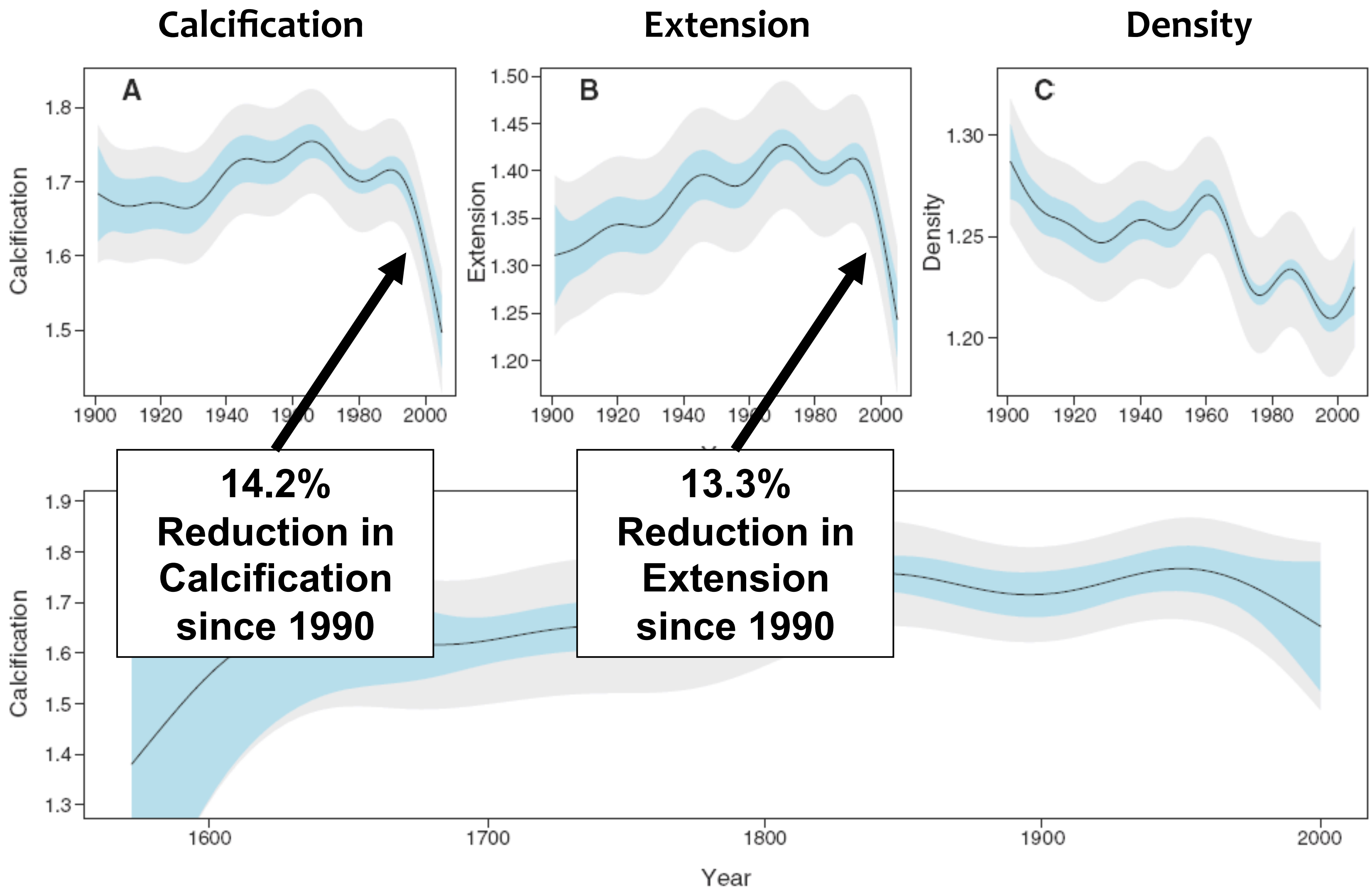
# Field Observations






De'ath et al (2009) *Science*

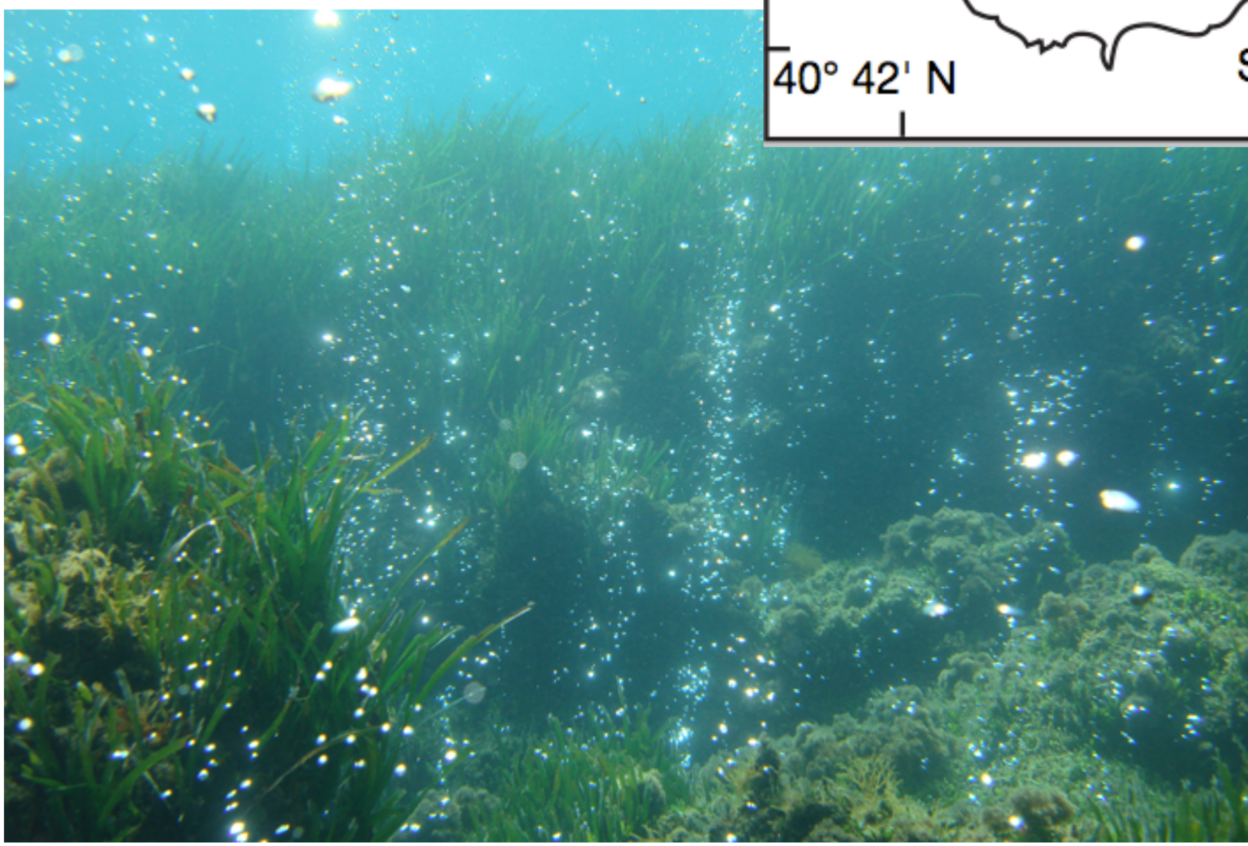
# Field Observations

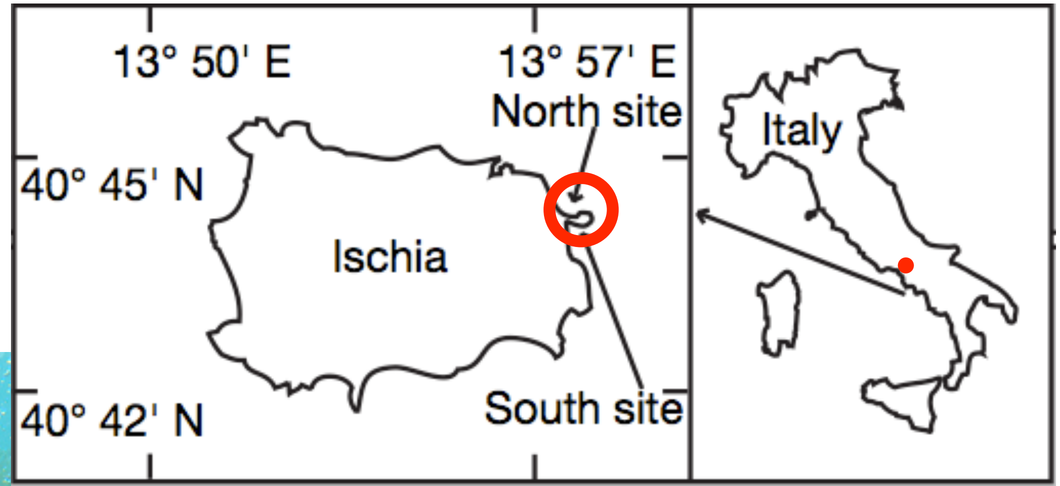



De’ath et al (2009) *Science*

# Natural undersea $CO_2$ fertilization

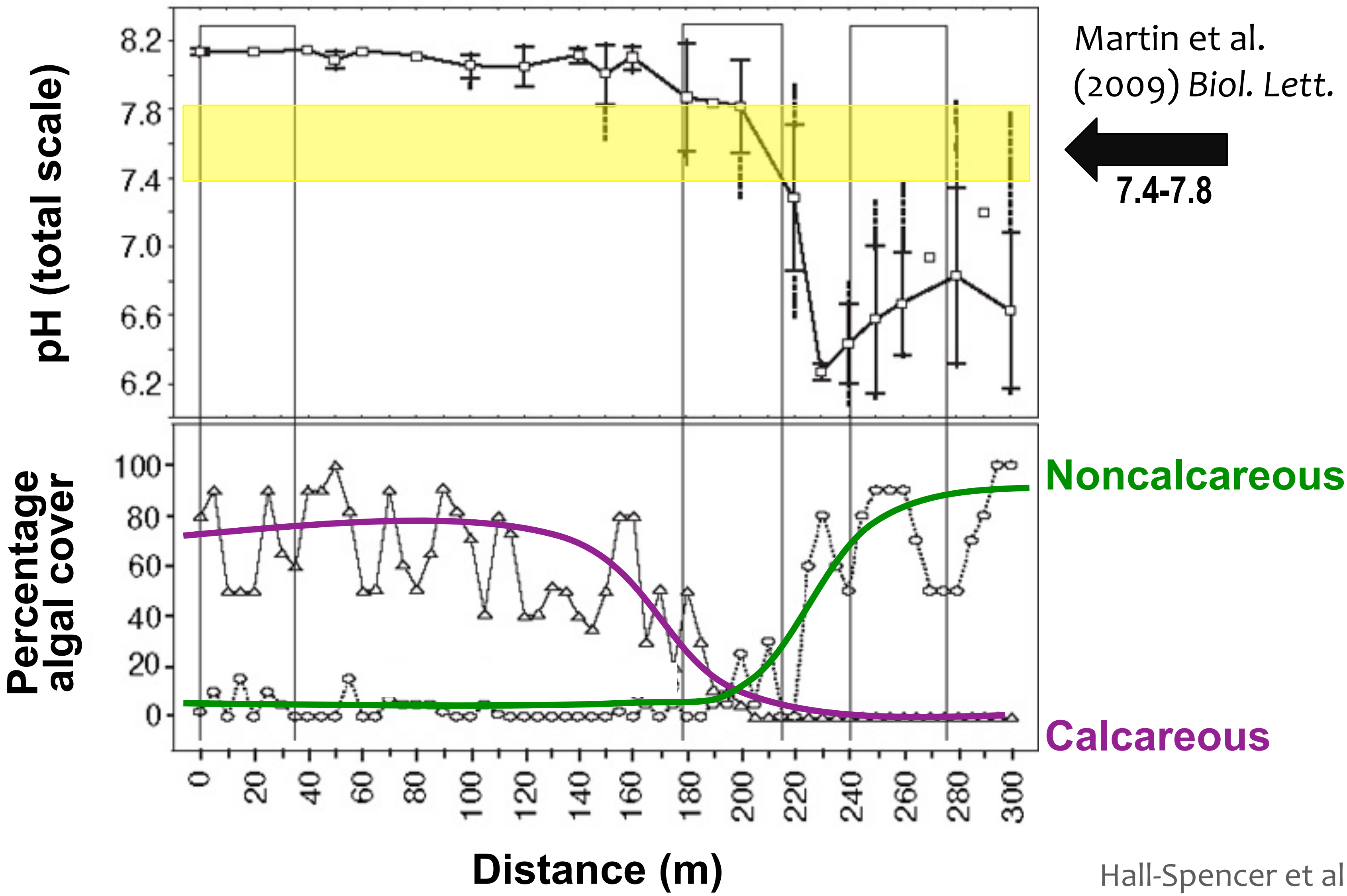
## Volcanic vents off Italy






Hall-Spencer et al.
(2008) *Nature*

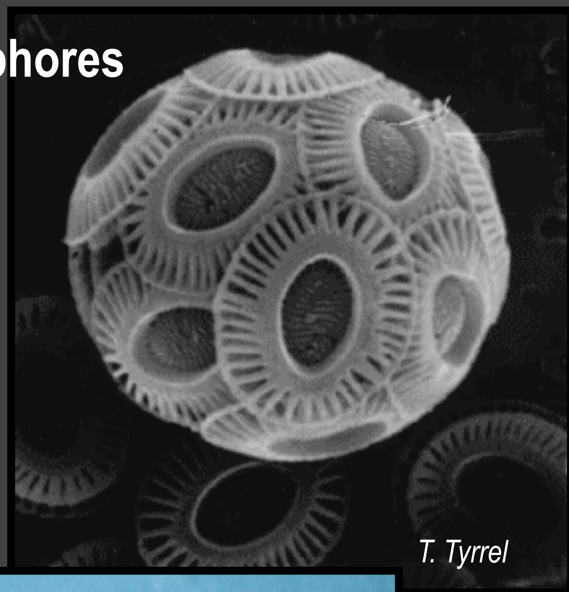
# Community Shifts with Decreasing pH

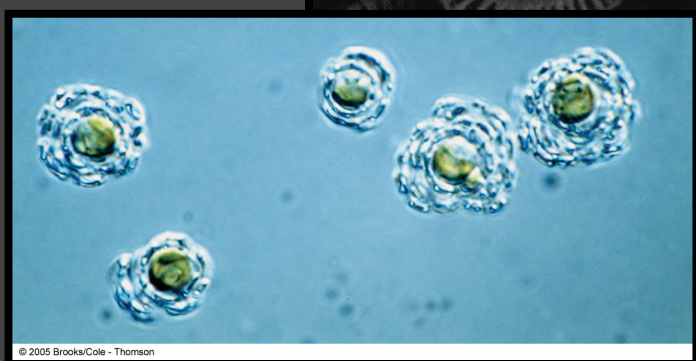



Hall-Spencer et al. (2008) *Nature*

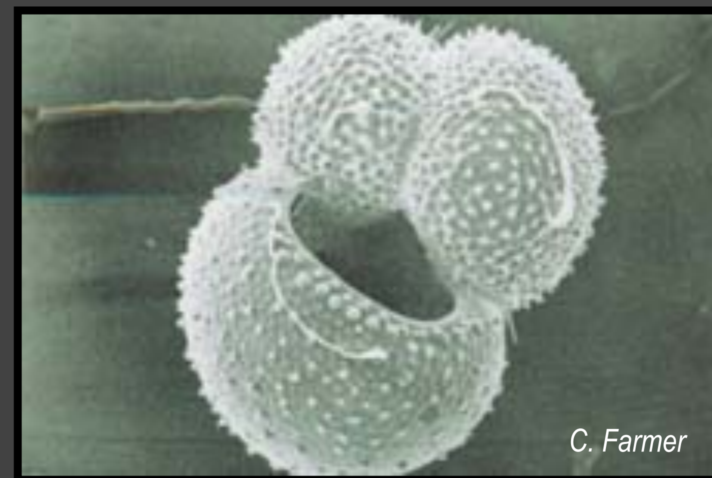
# Important Shell-forming Plankton

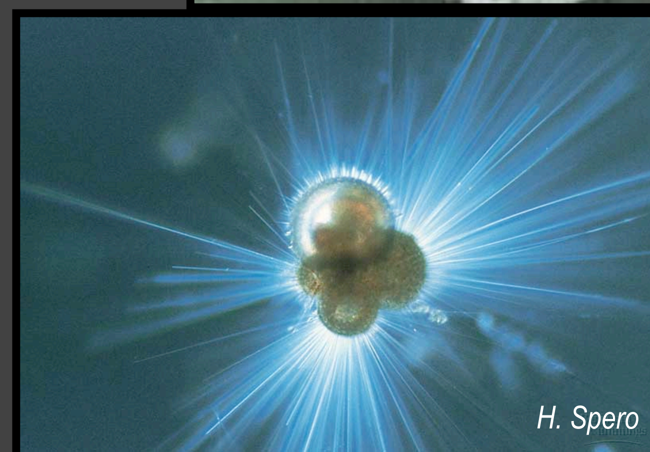
## Coccolithophores


T. Tyrrel

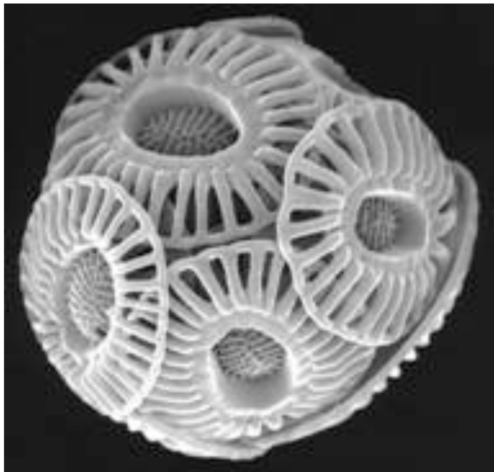

© 2005 Brooks/Cole - Thomson

## Forams


C. Farmer

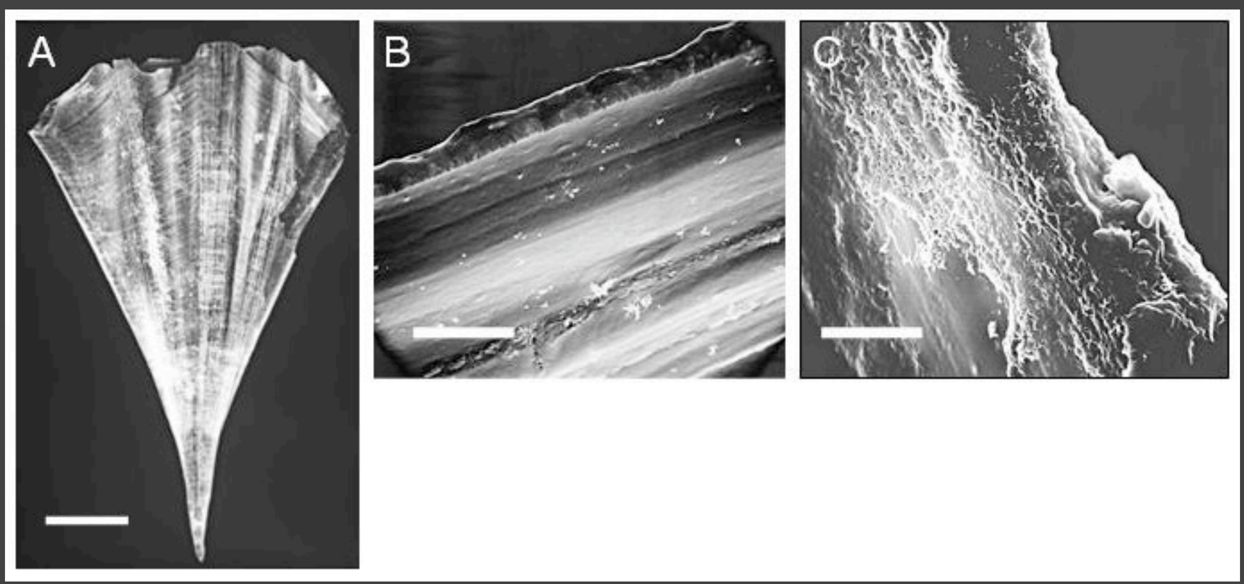

H. Spero

# Coccolithophores from Space



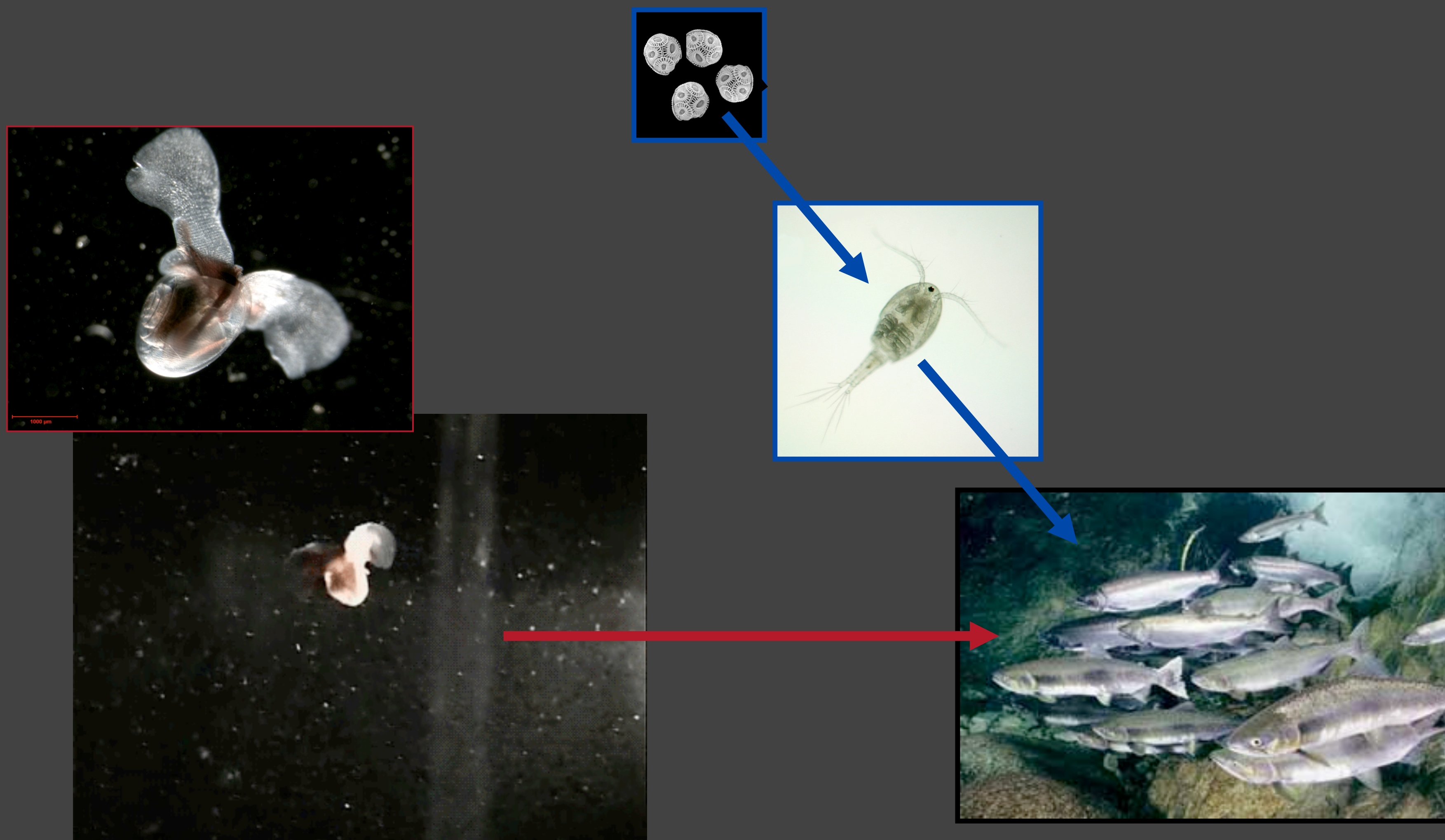
# "Pteropods"
# – planktonic marine snails

***Shells of living pteropods begin to dissolve at elevated $CO_2$ levels***




*Photos courtesy of Victoria Fabry*

# Effects on Open Ocean Food Webs



*Video courtesy of Brad Seibel*

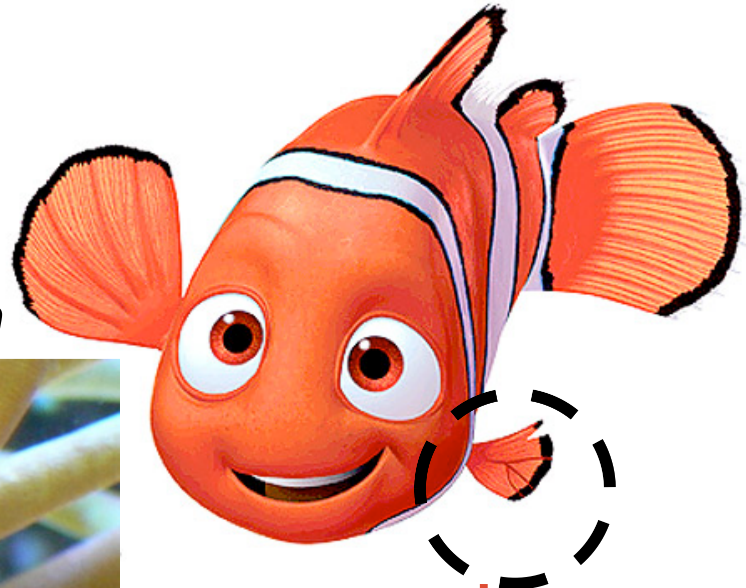
# Effects on Fisherman

Homer Alaska: commercial fishermen, mariners and others spelled out ‘SOS’ to protect jobs and fisheries from the threat of ocean acidification.

‘Voices for the Ocean’ hosted by the Alaska Marine Conservation Council (AMCC) and the Sustainable Fisheries Partnership (SFP).

# Homing Ability in Fish

**Larval Clownfish: *Amphiprion percula***

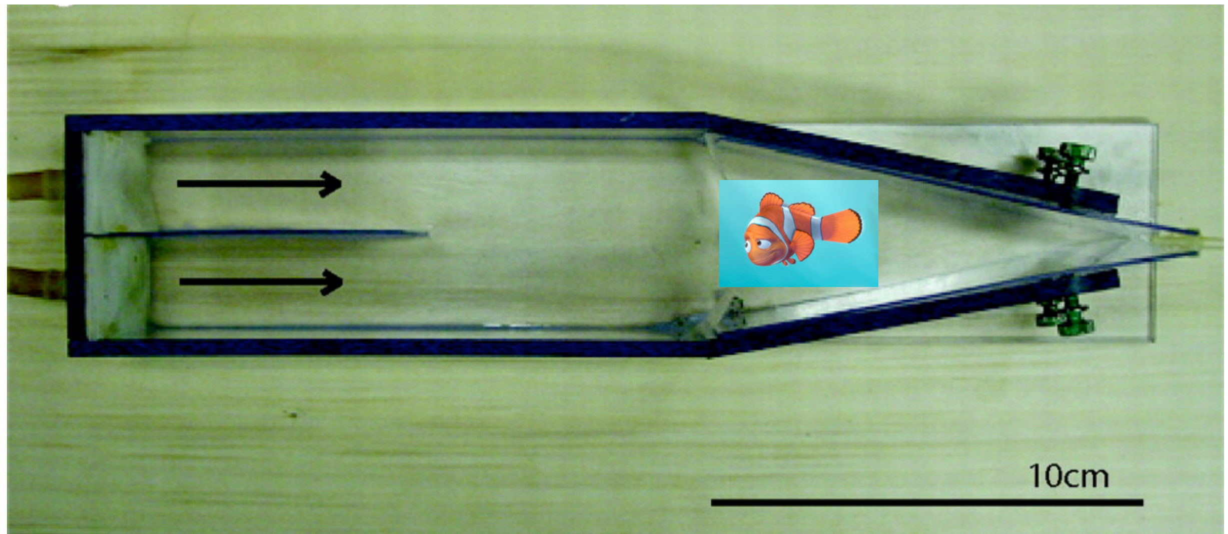


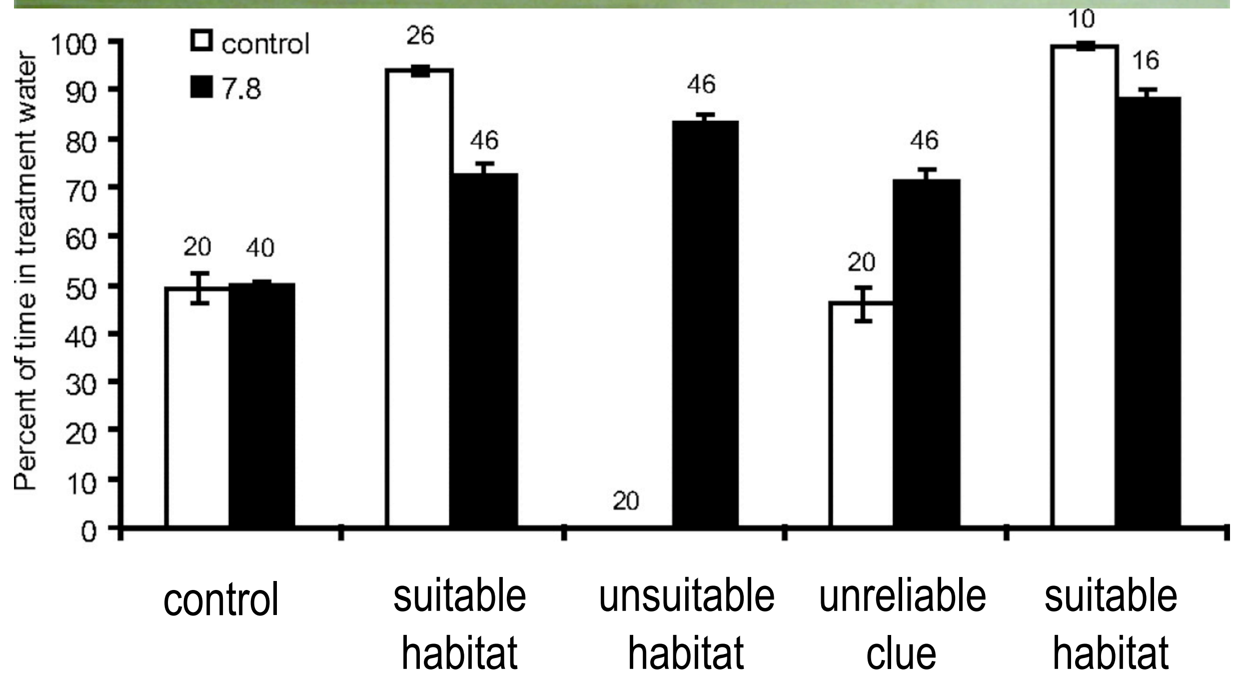
Probably NOT due to ocean acidification

# Homing Ability in Fish

Scent + Normal pH

Scent + Future pH



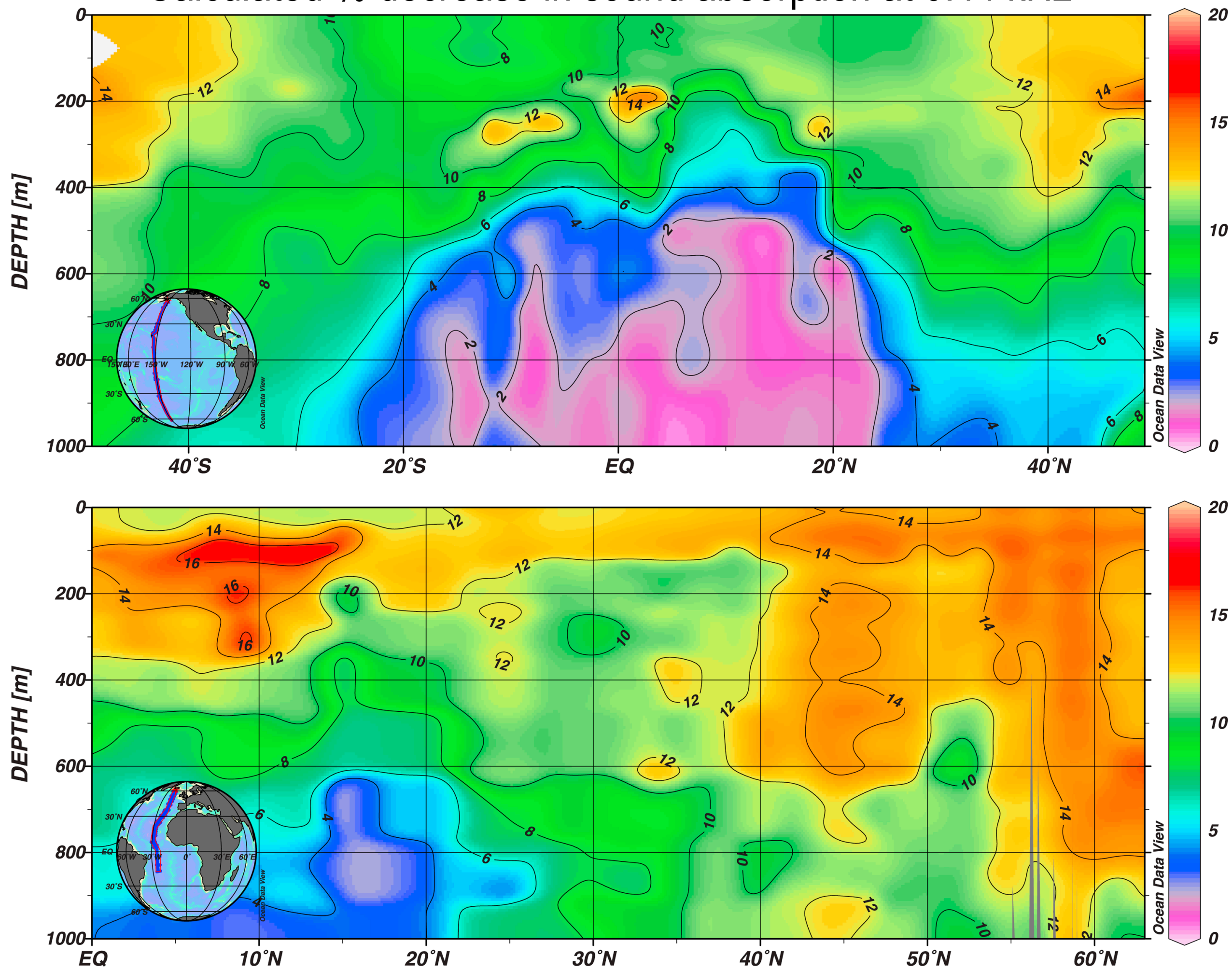

Munday et al. (2009) *PNAS*

# Sound ‘effects’

Calculated % decrease in sound absorption at 0.44 kHz

**Pacific**

**N Atlantic**

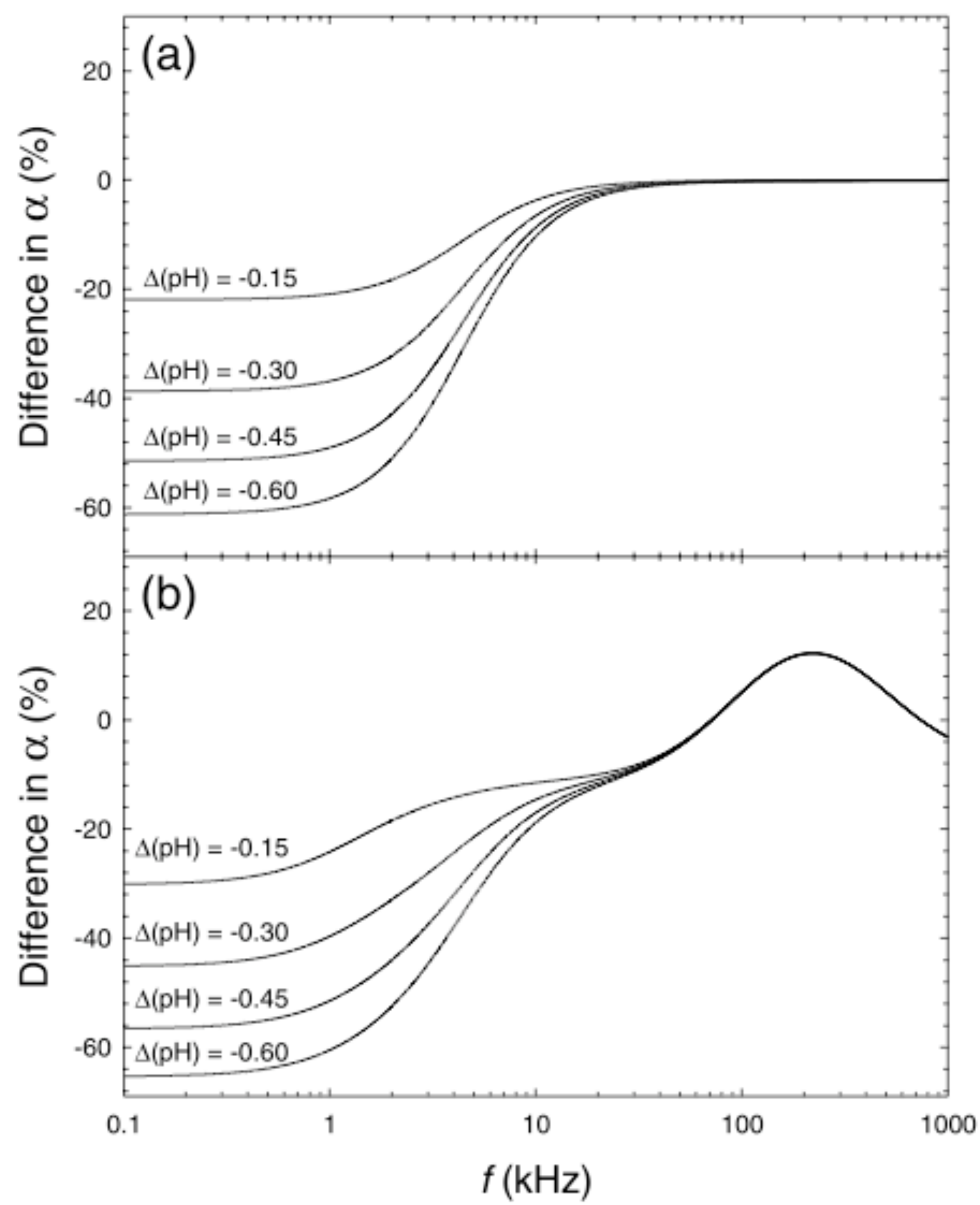



Hester et al 2008 *GRL*

# Sound 'effects'

pH change only

pH change + 3°C

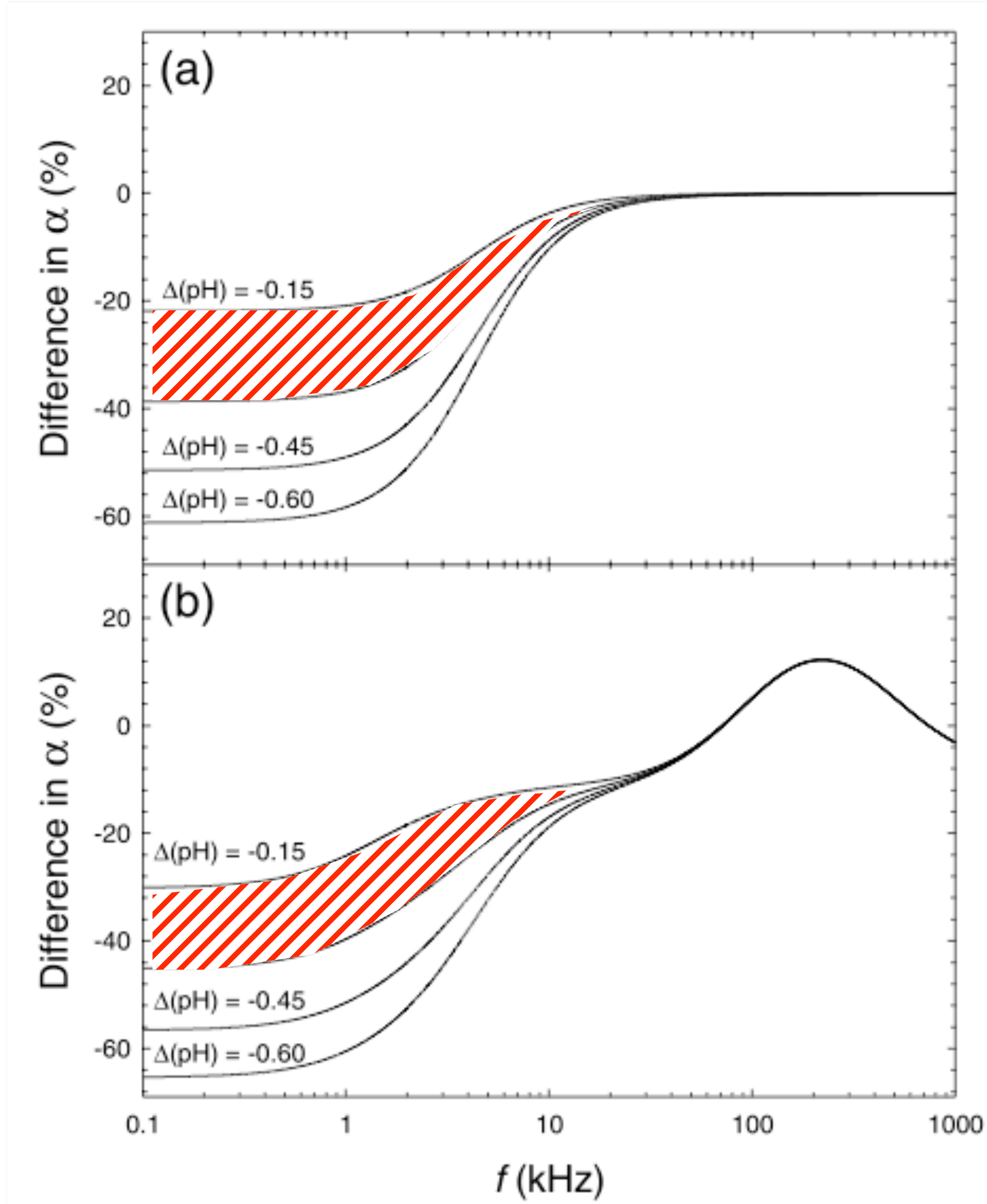



Hester et al 2008 *GRL*

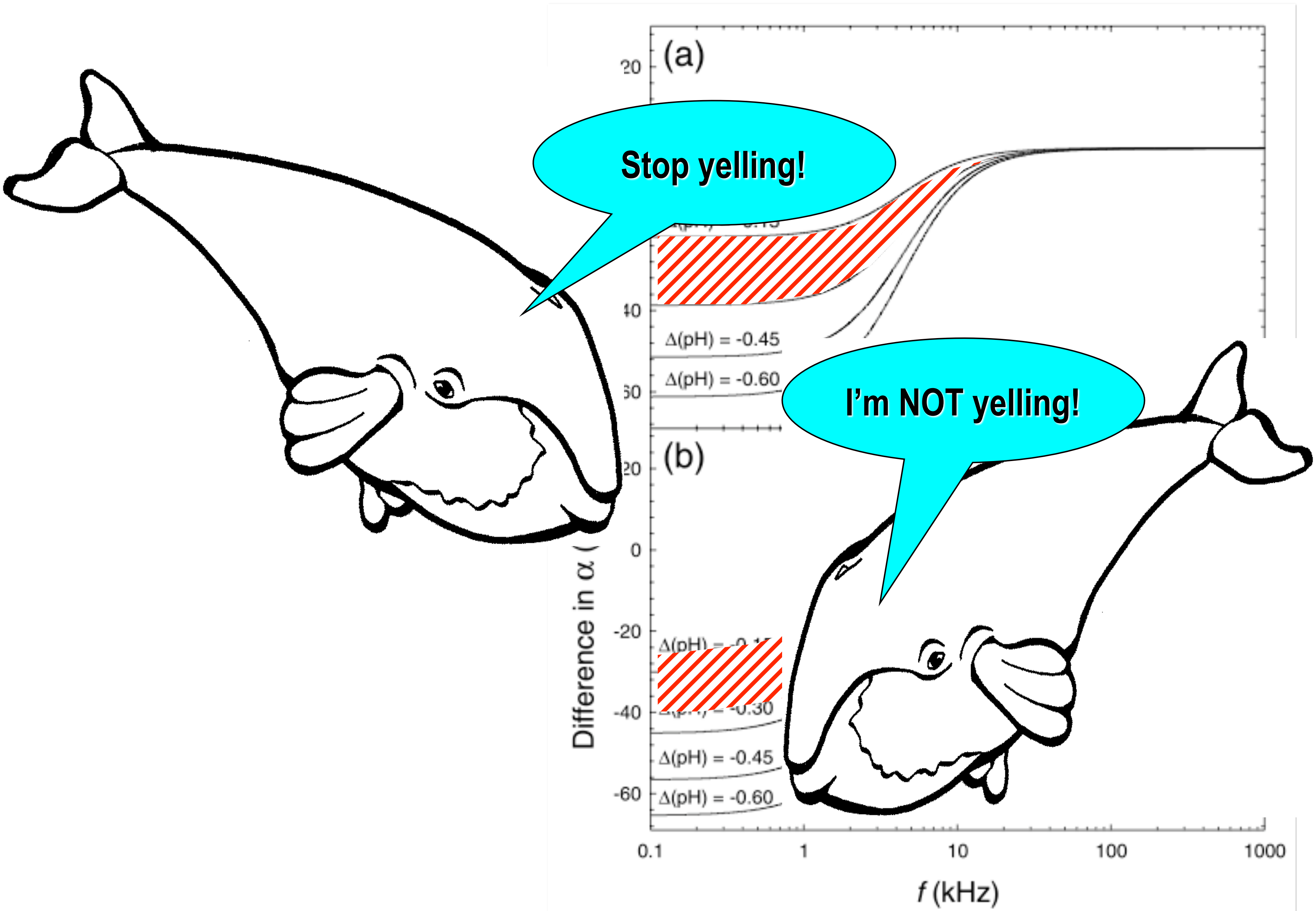
# Sound 'effects'

**pH change only**

**pH change + 3°C**



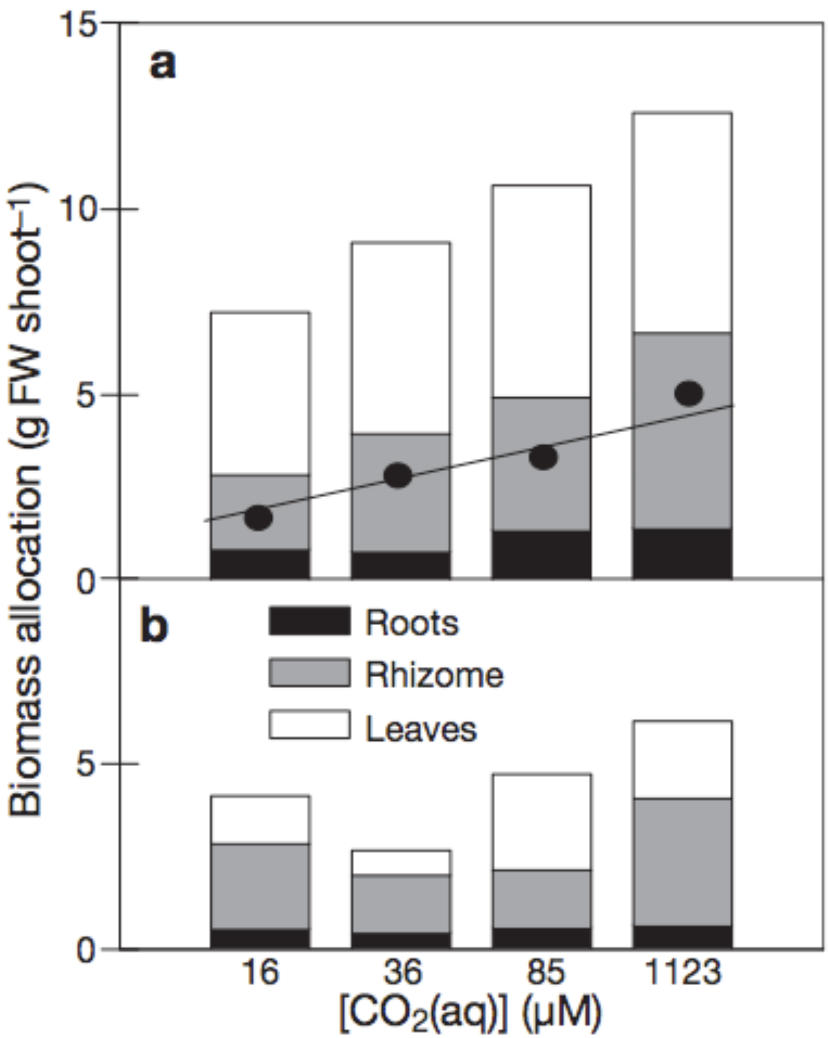

Hester et al 2008 *GRL*




Hester et al 2008 *GRL*

# Winners

## Seagrasses: *Zostera marina*




Light replete

Light limited


Palacios & Zimmerman (2007) MEPS

# Impacts on Communities

## Physical Environment

*determines which species CAN occur*

**"It's a nice place"**

## Biological Environment

*determines which species SUCCEED*

**"It's a jungle out there"**


**So far, few studies suggest that ocean acidification has directly eliminated reef species:**

•Hall-Spencer et al. & Martin et al.
•Guinotte et al. (cold-water corals)
•Recruitment rates

**Most studies have shown - or presumed - impacts on biological environment:**

- Increased vulnerability to predation
- Decreased recruitment success
- Reduced competition for space

# Impacts on Communities

## Predator-Prey

Weakened shells
Physiological compromises
(less energy for avoidance)
Phenology: Match-mismatch

## Competition

Lower growth rates
Overgrowth by ‘winners’
Physiological compromises
(less energy for competition)

**Biological Environment**

*determines which species SUCCEED*

“It’s a jungle out there”

Predator-Prey

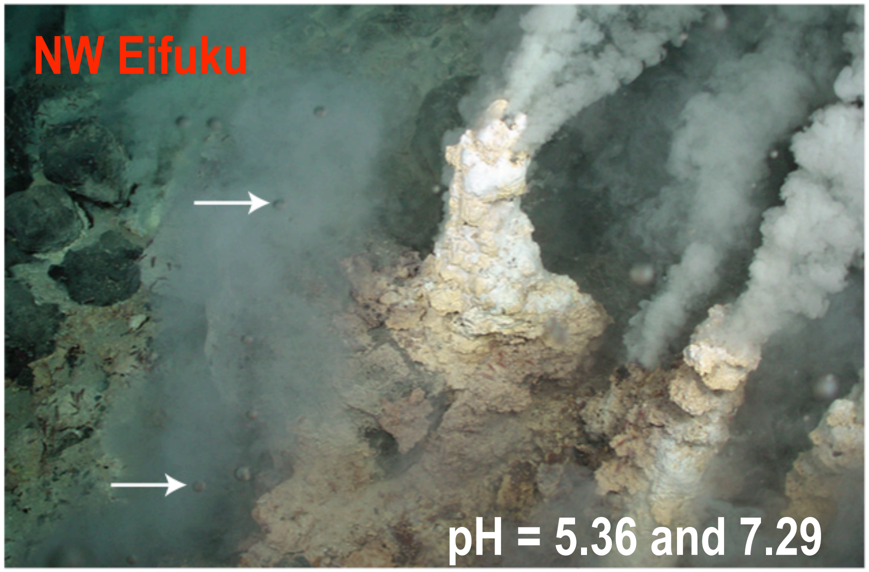
Competition

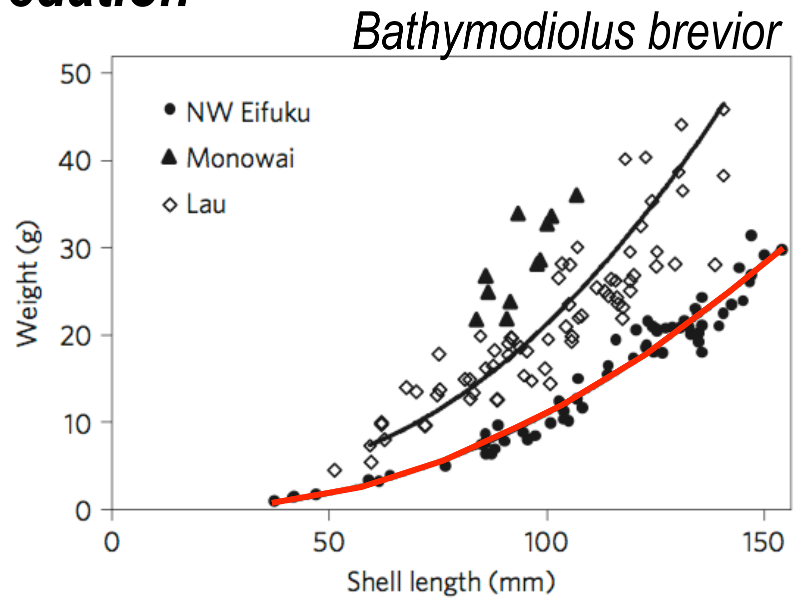
## Recruitment

Delayed reproduction
Low population density
Reduced settlement success

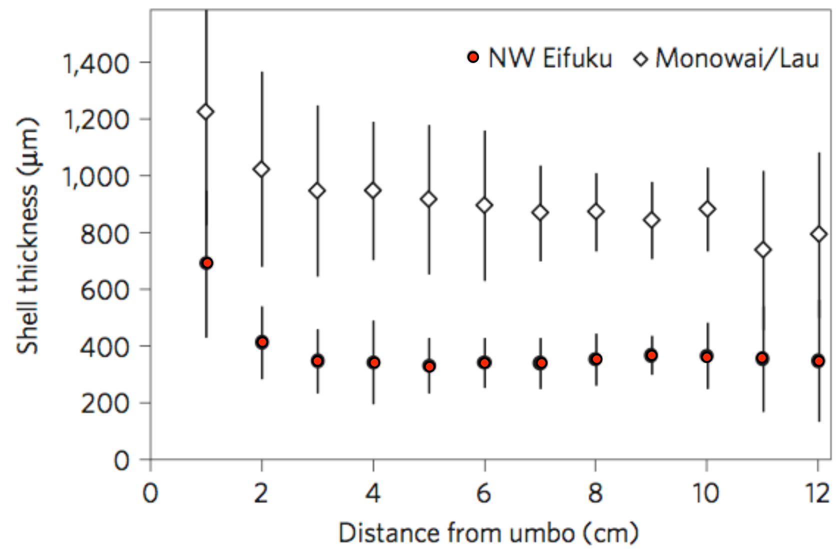
# Shell thinning

***but lack of predation***







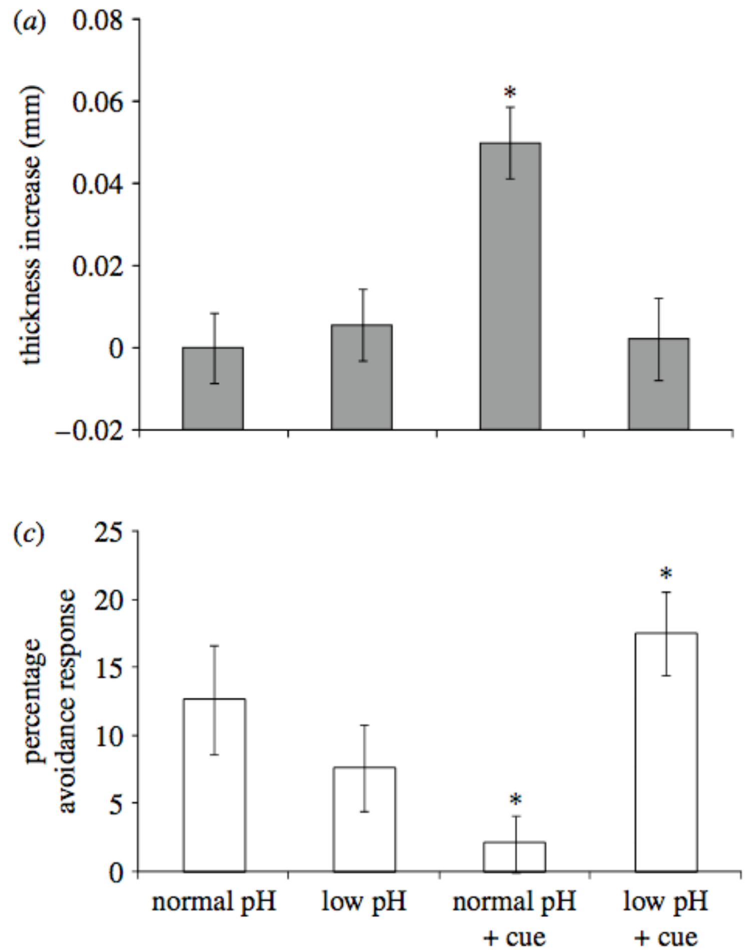

Tunnicliffe et al. (2009) *Nature Geosci.*

# Shell thinning

## *affects response to predators*

*Littorina littorea*

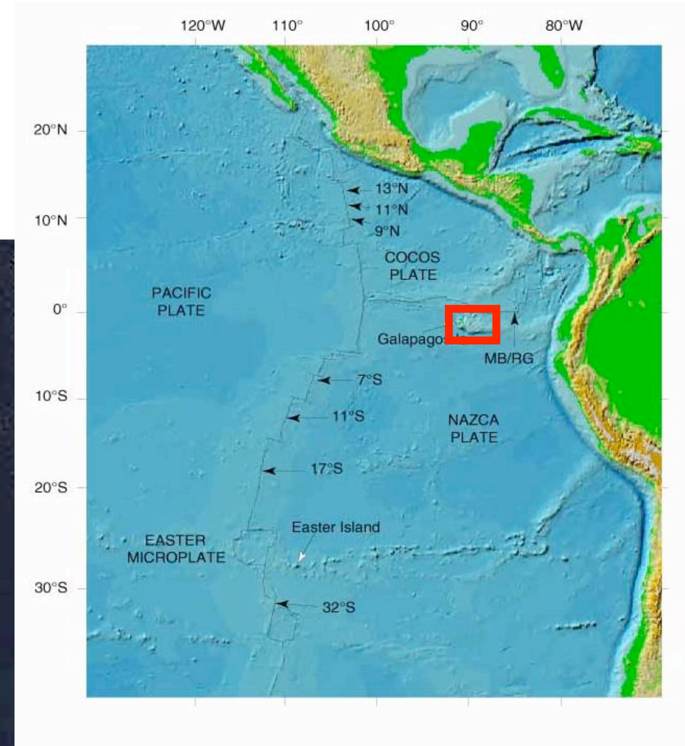

*Carcinus maenas*


Bibby et al. (2007)
*Biol. Lett.*

# Galápagos Coral Reefs

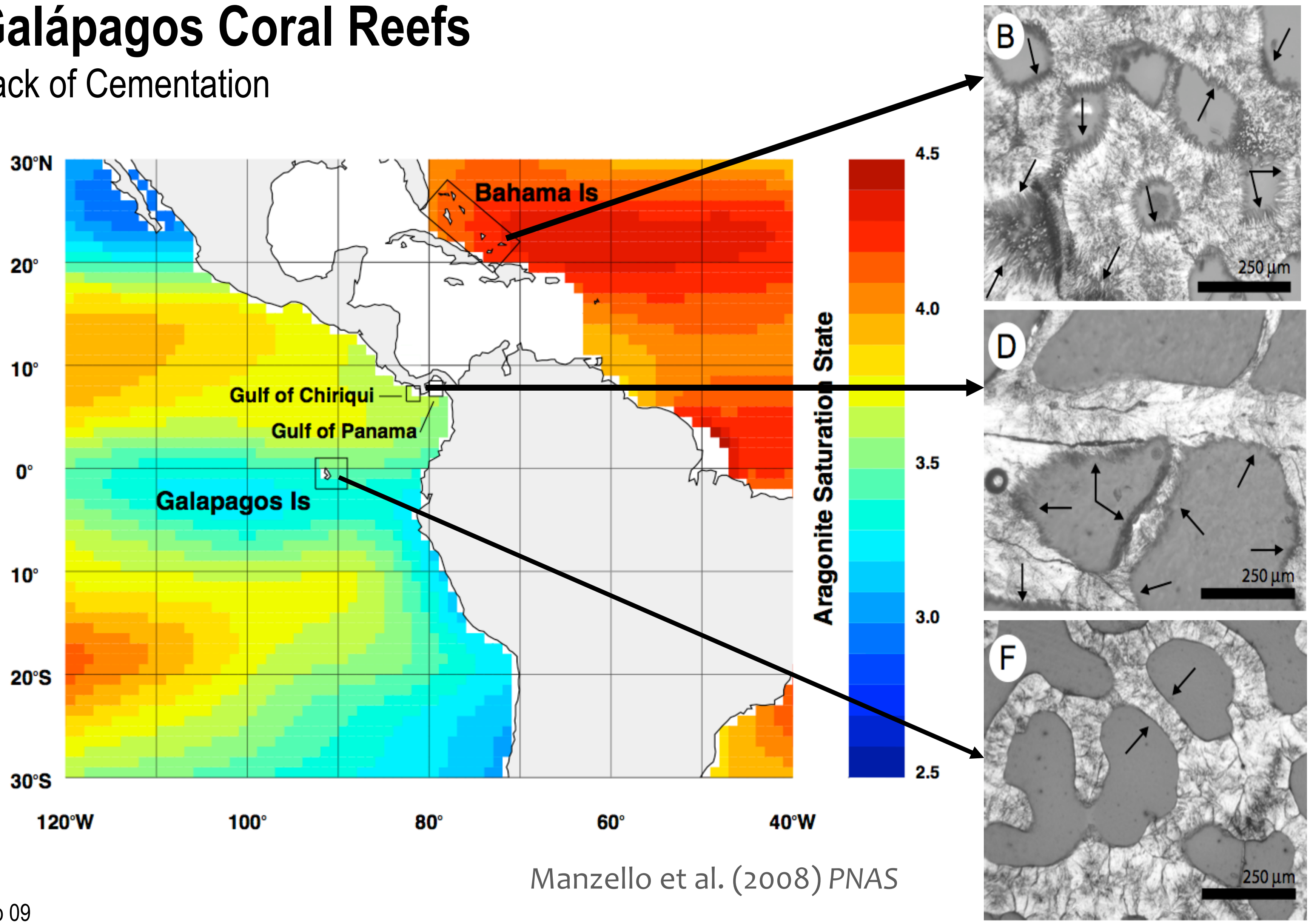
*dramatic erosion*




# Cementation

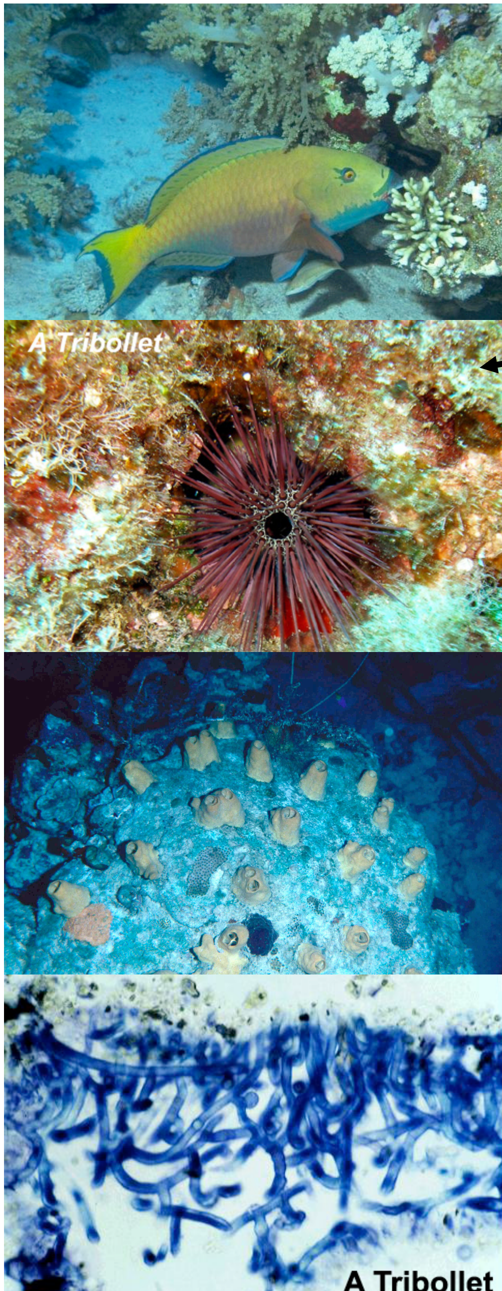
## Galápagos Coral Reefs

Lack of Cementation




Manzello et al. (2008) *PNAS*

# Does ocean acidification affect bioeroders?




Grazers

Macroborers

Microborers

**Changes in euendoliths at 750 vs 400 ppm $CO_2$**

- Deeper penetration of euendoliths
- 48% increase in carbonate dissolution rates

Tribollet et al. (2009)
*Global Biogeochem. Cycles*

# Slowing Down the Carbonate Factory

## Cascading effects to other ecosystems


THE WØRD
Threshold
COMEDY CENTRAL
hulu

# What's all this fuss (fizz?) about ocean acidification?

Background

Impacts

Thresholds

Solutions?

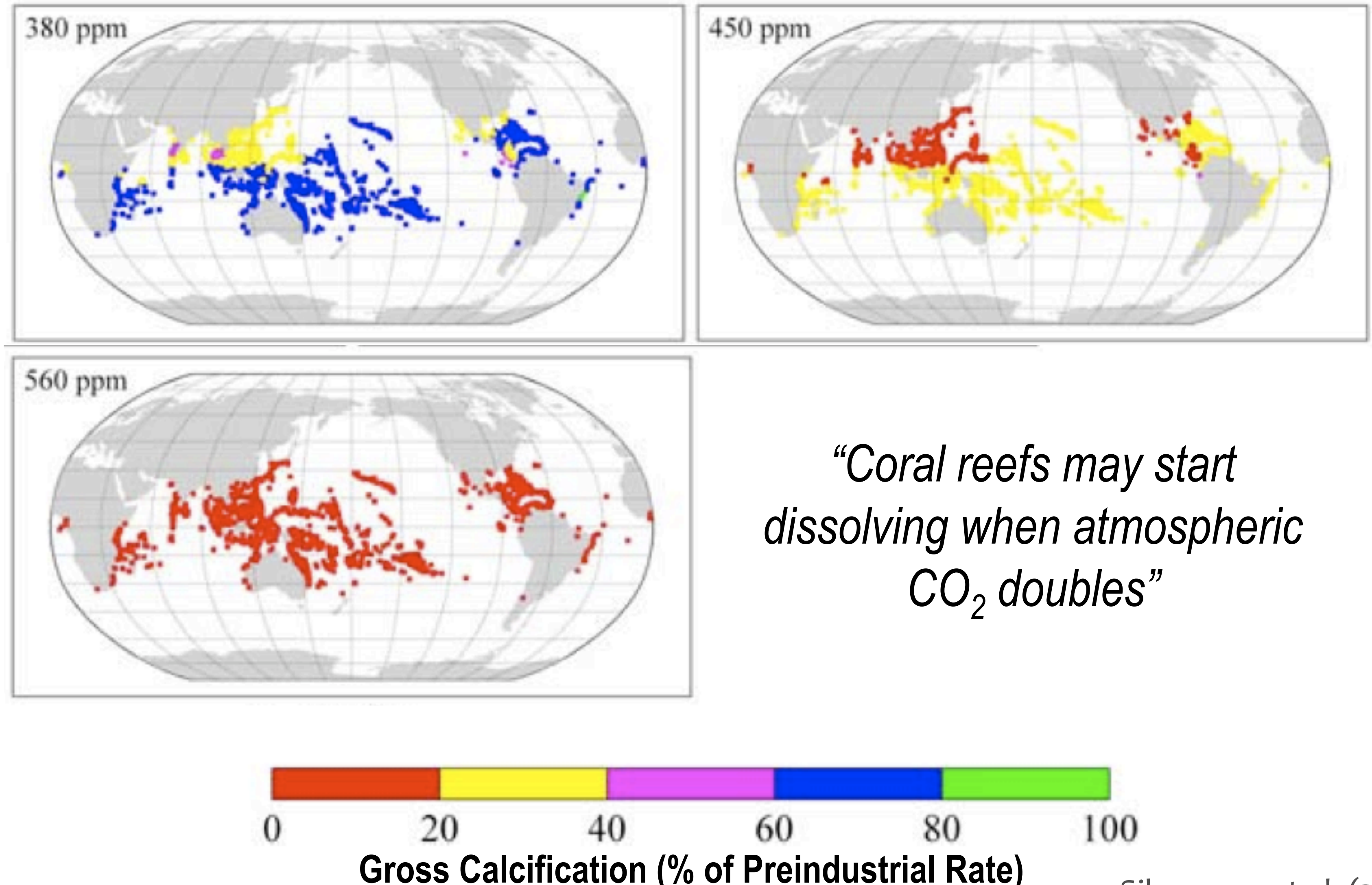
NCAR

Colorado
University of Colorado at Boulder

# THRESHOLDS

| | |
|---|---|
| **Geochemical** | calcium carbonate dissolves |
| **Physiological** | organisms are impacted physiologically<br>organisms cease to survive<br>organisms cease to function as before |
| **Population** | populations of organisms are not maintained |
| **Community/ Ecosystem** | ecosystem experiences a phase shift or regime shift |

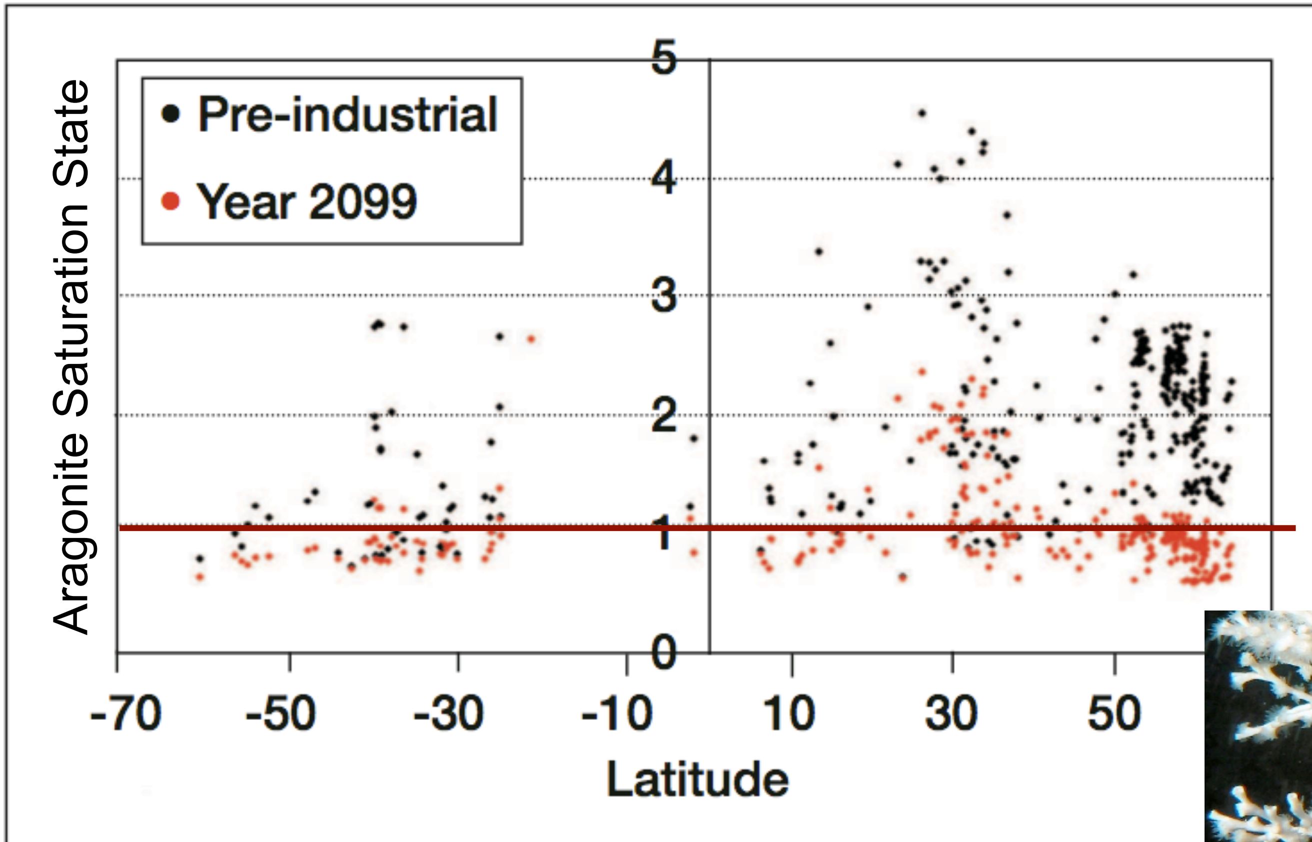
# Future Calcification
## - Combined T & Ω effects WITH bleaching -




*"Coral reefs may start dissolving when atmospheric $CO_2$ doubles"*

Silverman et al. (2009) *GRL*

# Cold-water Coral Communities

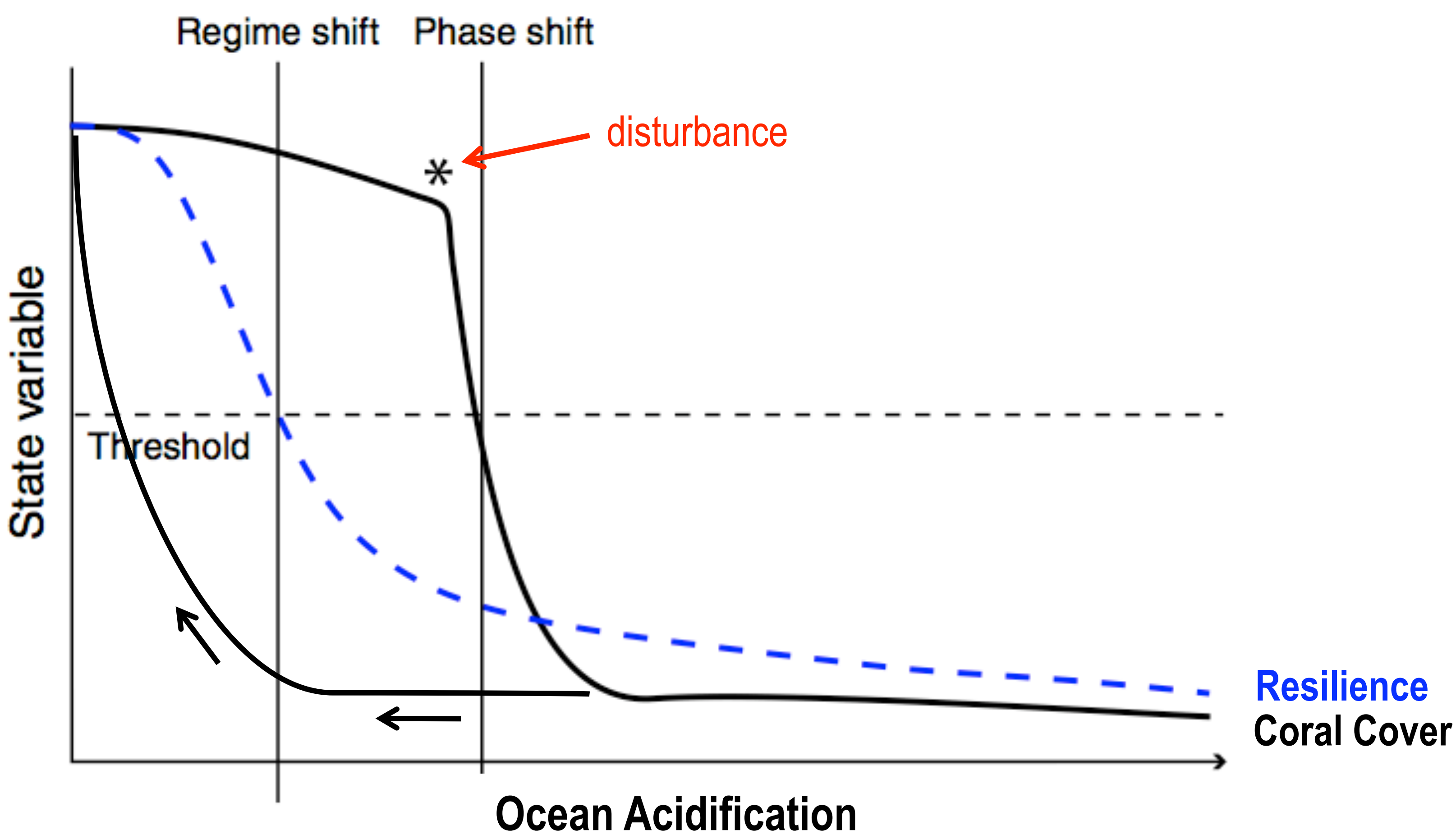



Geochemical Threshold

Guinotte et al. (2007) *Front. Ecol. Evol.*

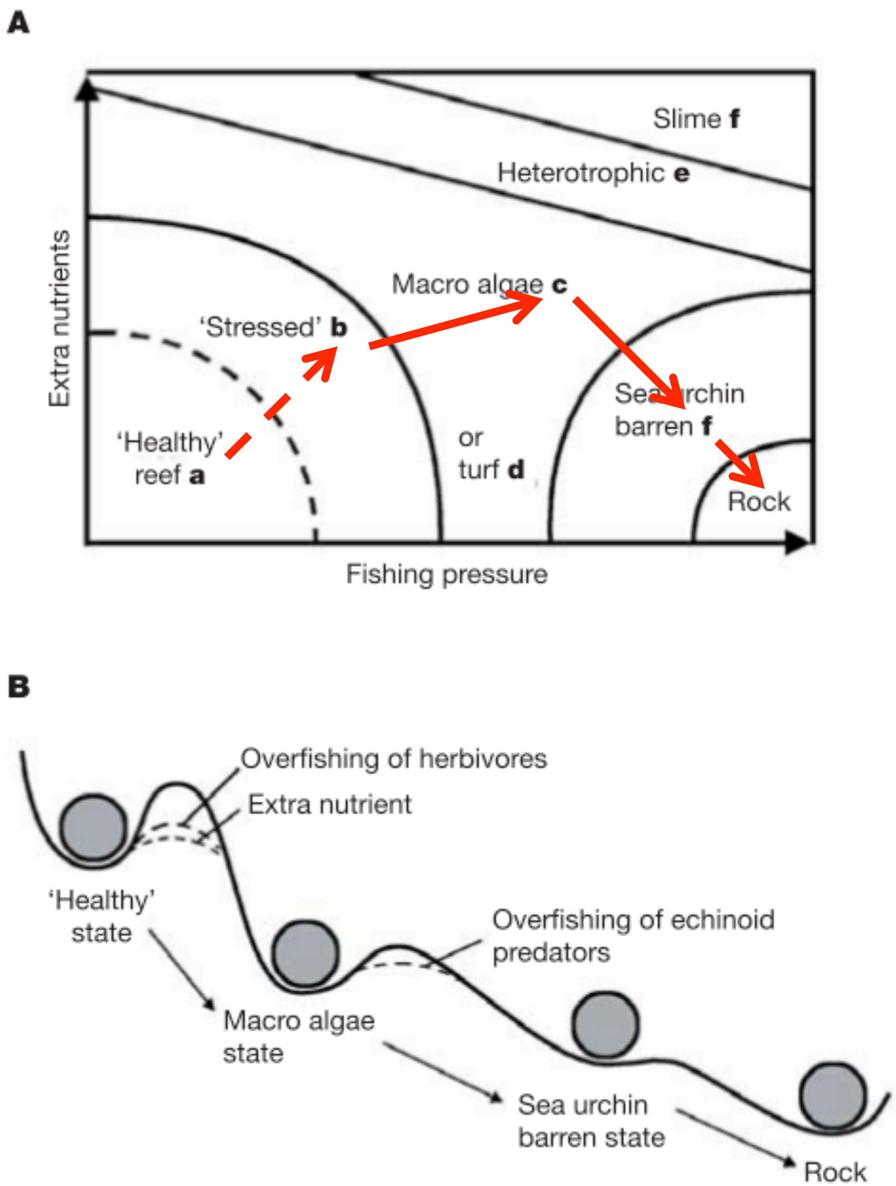
*Photo courtesy SW Ross*

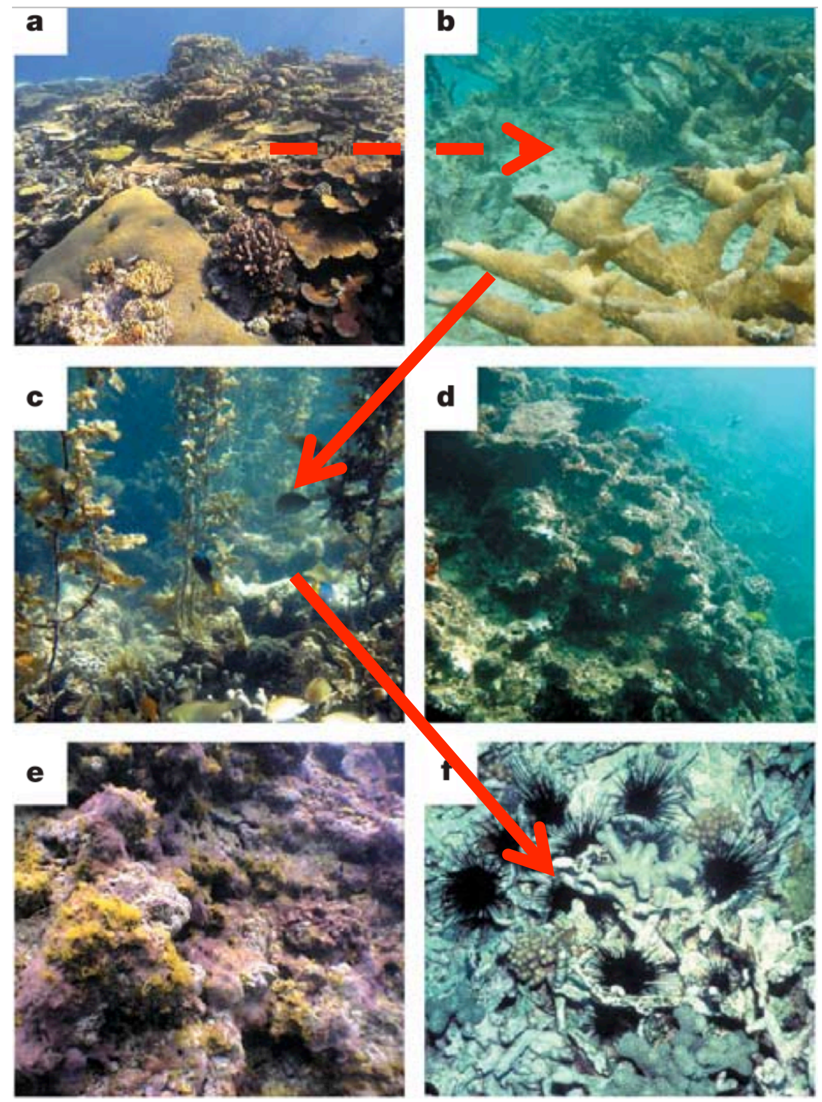
# Resilience, Thresholds
# Phase Shifts and Regime Shifts




Nyström et al. (2008)
*Coral Reefs*

# Alternative Stable States in Coral Reefs



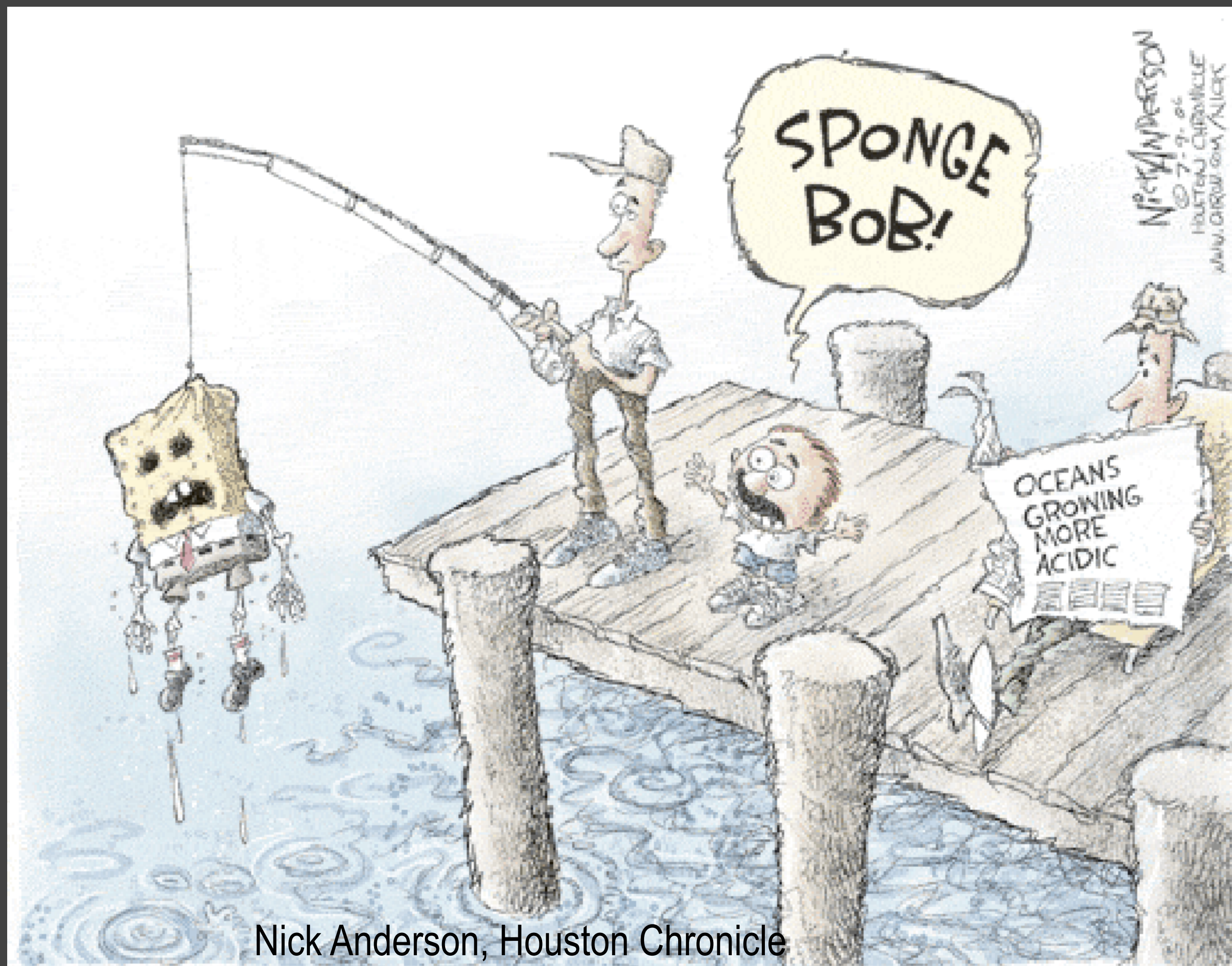

Bellwood et al. (2008)
*Nature*

# Can We See A Regime Shift Coming?
## DETECTION / PREDICTION

1. **Increased variance**
2. **Slower recovery following disturbance**
3. **Monitoring resilience:**
   a) **functional groups (e.g. grazers)**
   b) **demographic skewness in populations**
   c) **discontinuities (e.g. redundancy, diversity within body-size aggregates)**
4. **Indicators**
   **e.g. ratios of "good" colonizers versus "bad" colonizers**
5. **Tracking local phase shifts within a reef network**

Reviewed by
Nyström et al. (2008) *Coral Reefs*
Scheffer et al. (2009) *Nature*

# How Bad Will it Be?




Nick Anderson, Houston Chronicle

# Marine Ecosystem Response to Ocean Acidification

## High Uncertainty – High Risk

| | | |
|---|---|---|
| *Worst* | Widespread response of calcifiers & non-calcifiers | Major extinction event |
| | Widespread Response of Calcifiers & low response of non-calcifiers | Major ecosystem disruption |
| *Bad* | Selected Species Response | Significant ecosystem response |
| | Selected Species Response | Low ecosystem effects |
| *Good* | No effect | Selective extinction of some scientists! |

# What's all this fuss (fizz?) about ocean acidification?

Background

Impacts

Thresholds

**Solutions?**

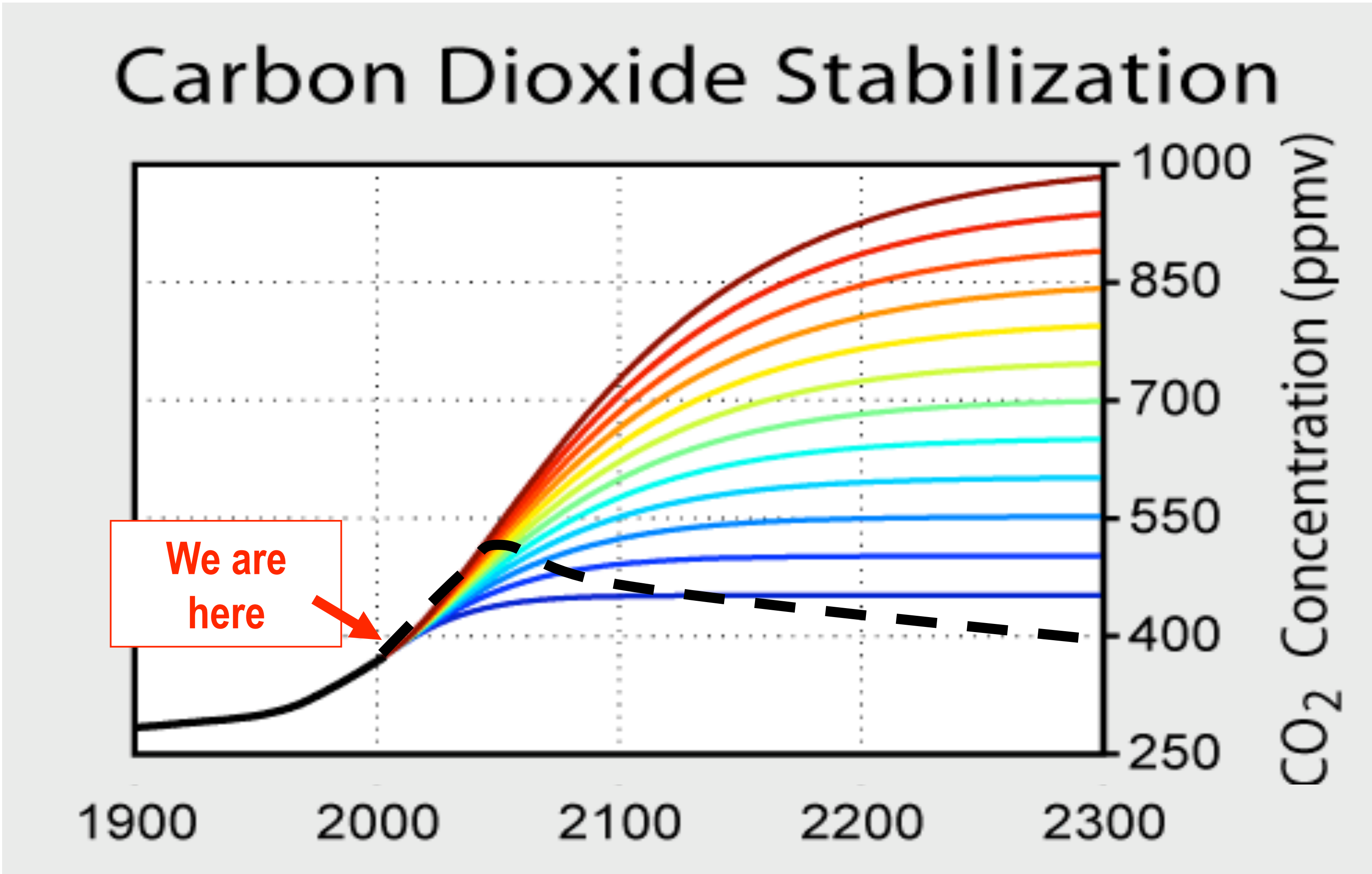
NCAR

Colorado
University of Colorado at Boulder

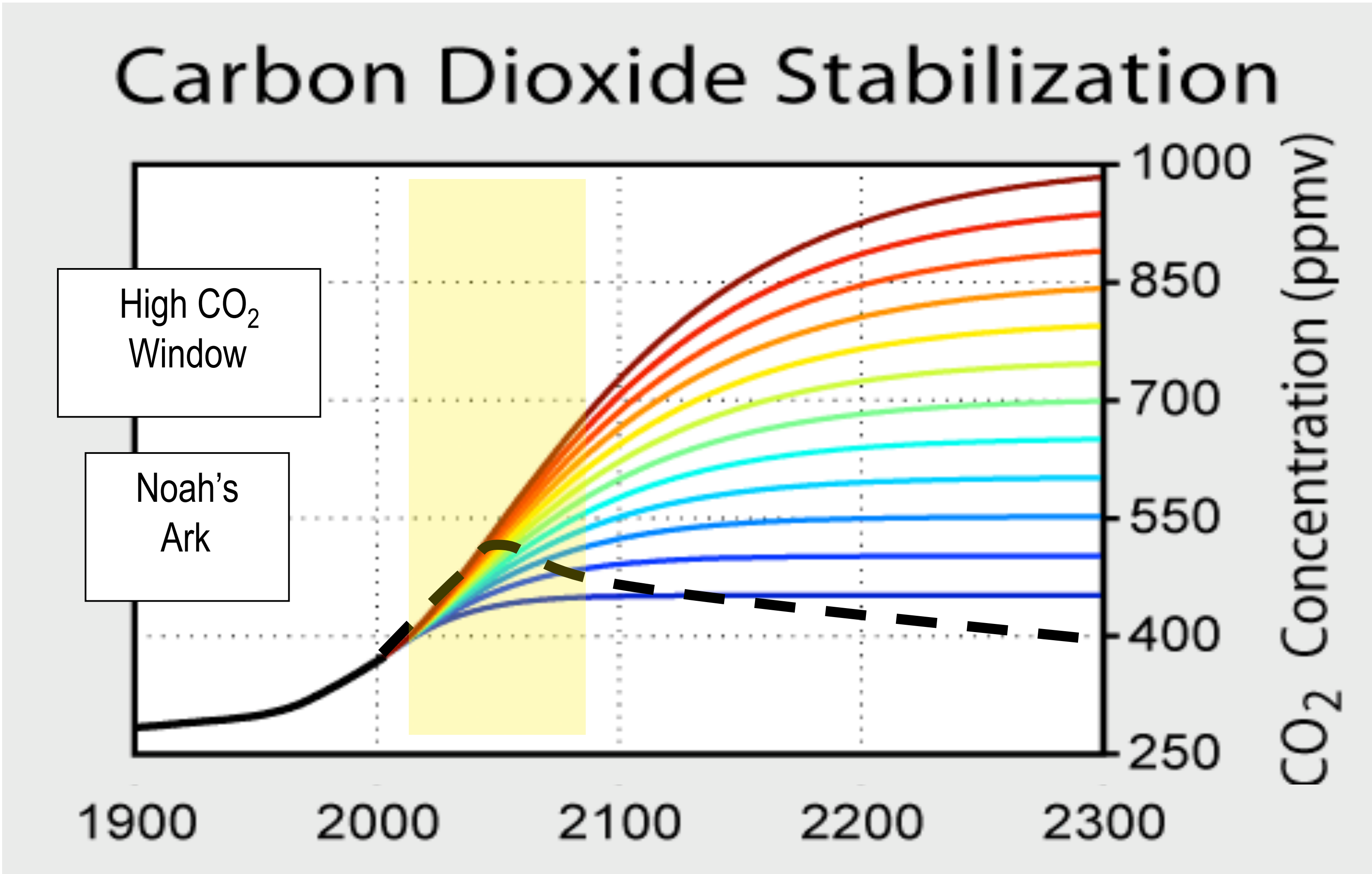
# Standard Recommendations to Protect Coral Reefs from Climate Change

1. Slow the growth of atmospheric $CO_2$
    - Engineering solutions
    - Human behavior changes
2. Local engineering solutions
3. Minimize other "controllable" stressors

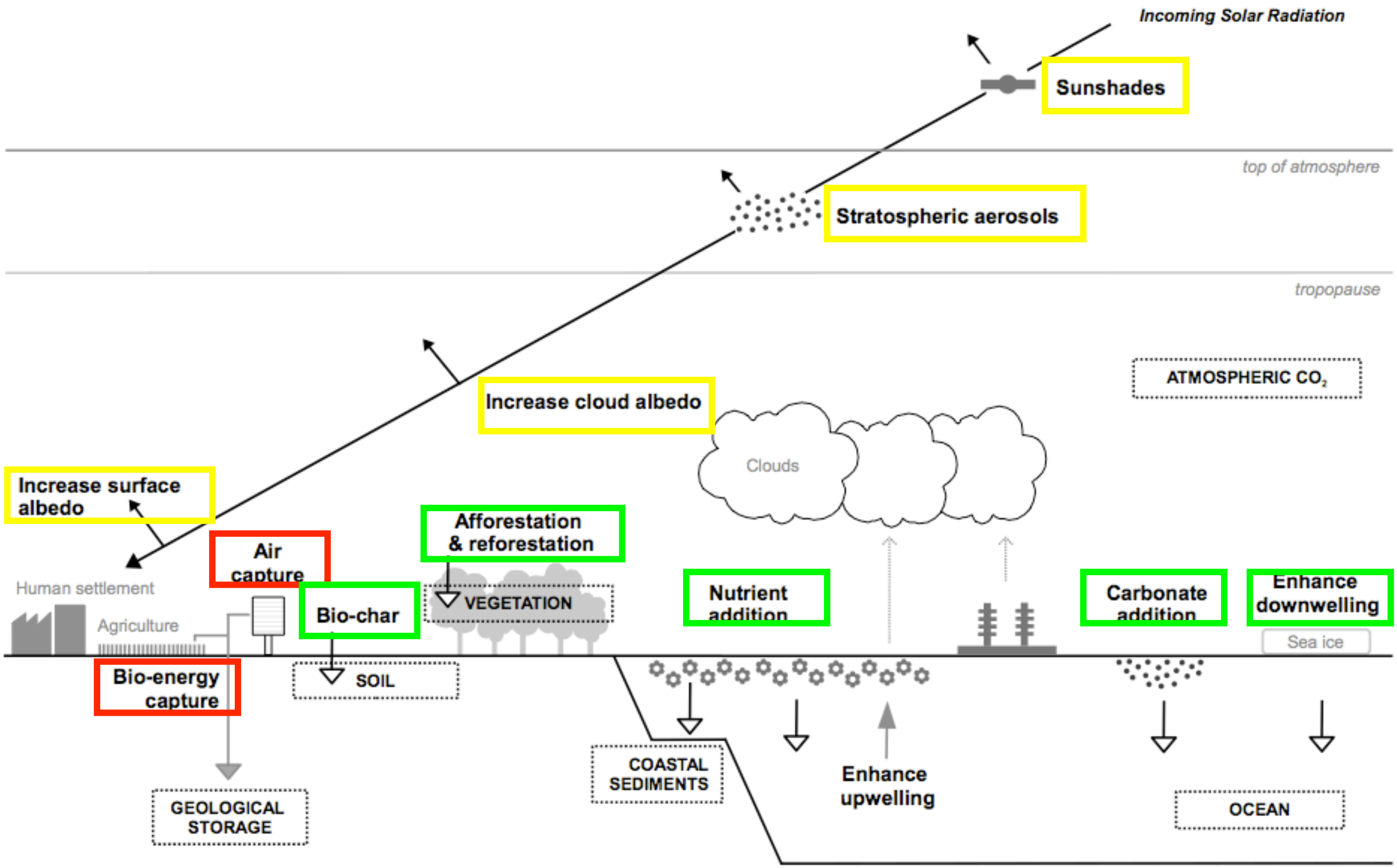
# A Different Way of Looking at It…



# A Different Way of Looking at It…



# Climate Geoengineering Options

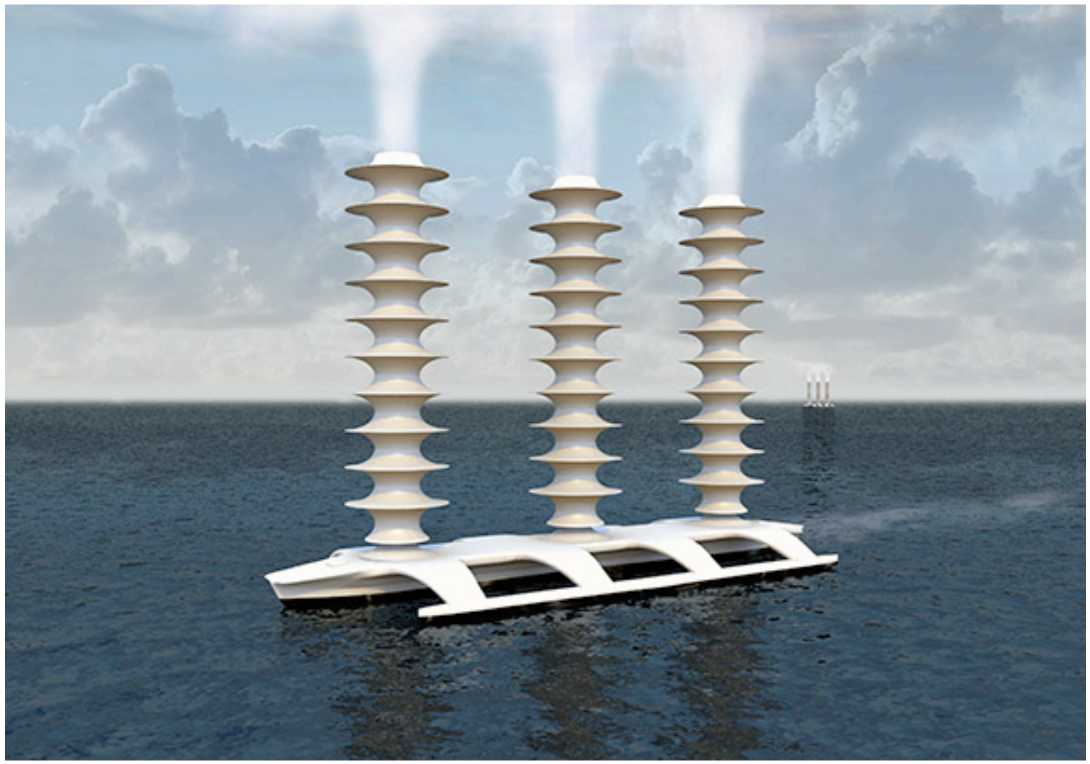





Lenton & Vaughan (2009) *Atm. Chem. Phys. Disc.*

# Climate Geoengineering Options

## Example: Cloud Formation

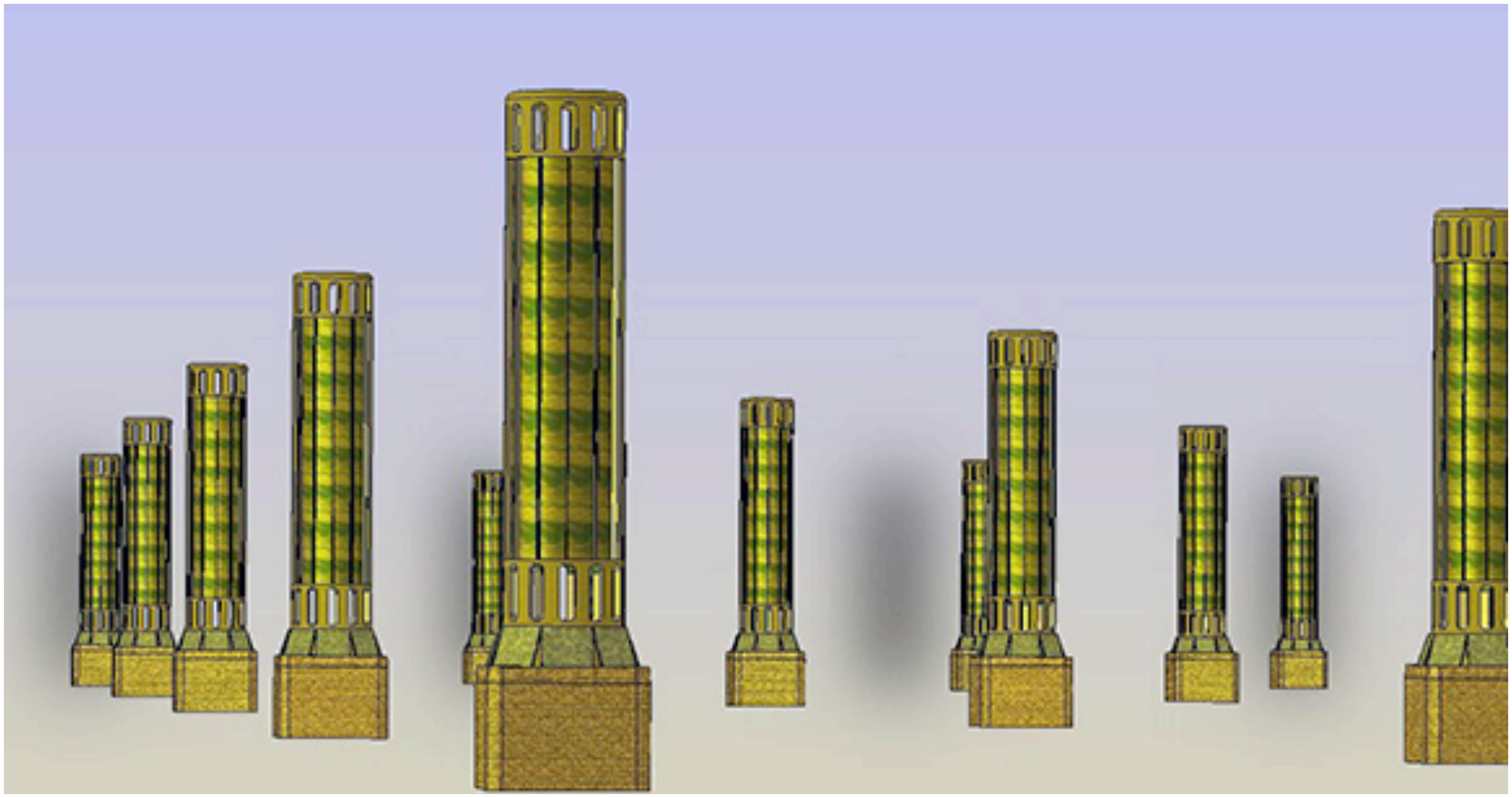


John Latham (NCAR) & Stephen Salter (Univ. Edinburgh)

Brandon Keim (Wired)
Illustration: *John MacNeill*

# Climate Geoengineering Options

**Example: Air Capture of $CO_2$ from Atmosphere**



Klaus Lackner - Direct removal of CO2 from the Atmosphere

Brandon Keim (Wired)
Illustration: *Global Research Technologies*

*Homo sapiens* is much more sophisticated now…

## CONCLUSIONS

Ocean acidification has many direct and indirect effects on marine ecosystems.

Effects of ocean acidification on marine ecosystems remain poorly known *…*
*the rate of ocean acidification is exceeding our rate of research!*
*…* but there will be winners and losers

Geochemical thresholds to ocean acidification are commonly used, but more subtle thresholds are probably more important

There are no solutions to ocean acidification, but dealing with it will be much easier once we set a maximum concentration for $CO2_{atm}$

# Thanks

To Baylor, to CU, and to you

For inviting me, for reading the article, and for enduring this long presentation!

NCAR