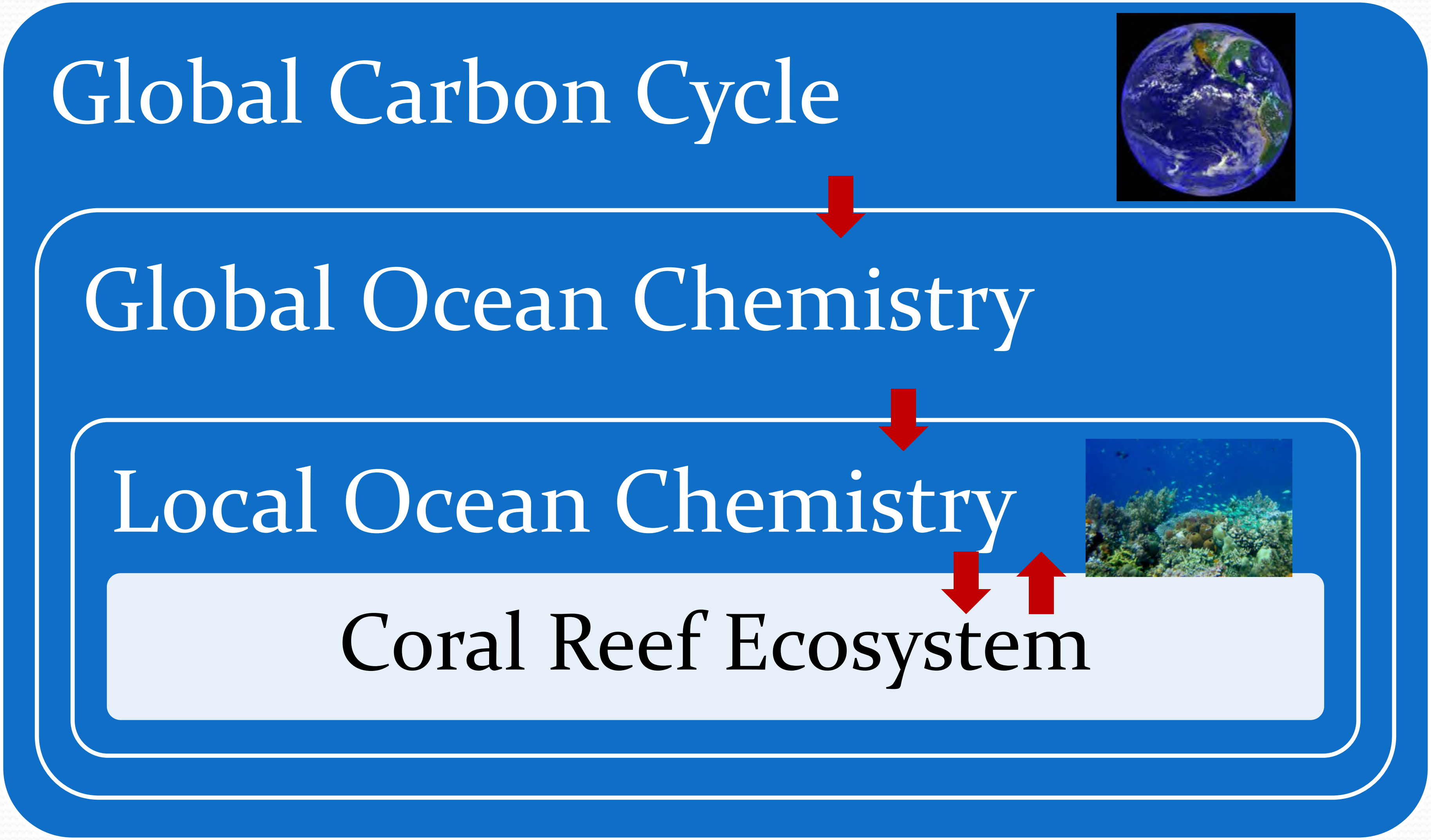
Ocean Acidification

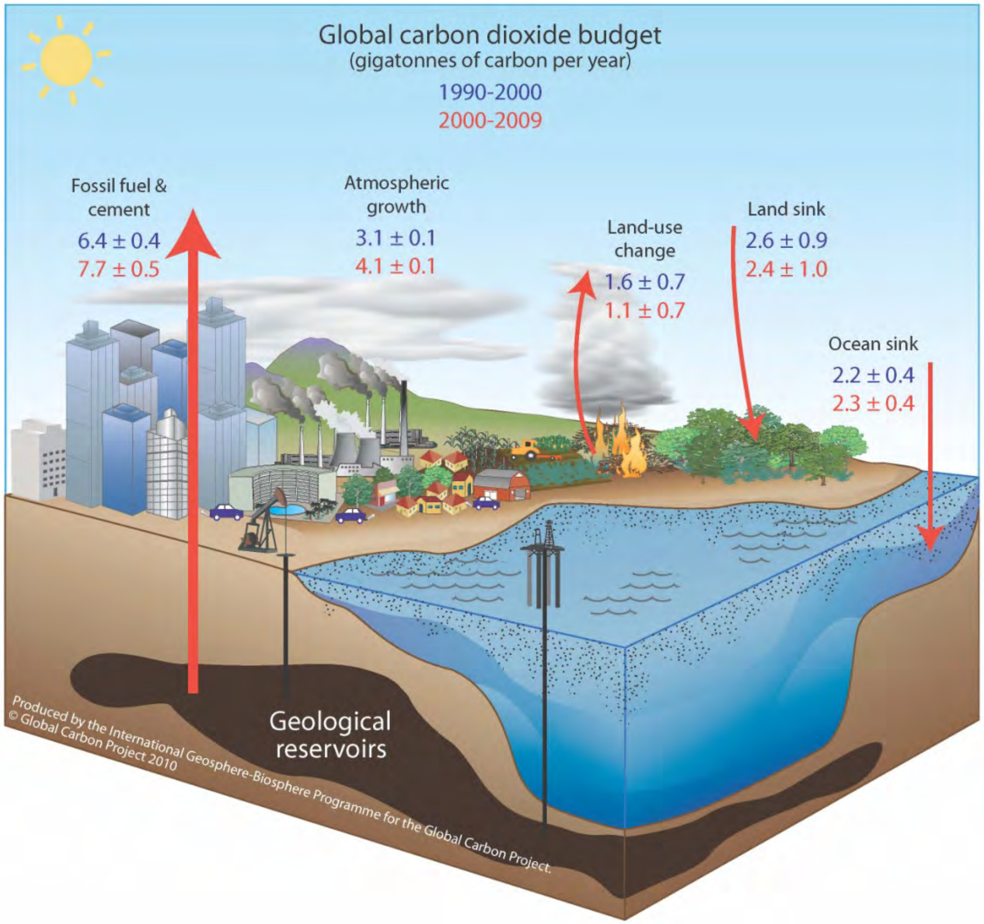
Coral Reefs in the Balance

Presented for:
The National Oceanic & Atmospheric Administration (NOAA)
Coral Reef Conservation Program (CRCP)
Education & Outreach Program

Presented by:
Dr. Dwight Gledhill
Atlantic Oceanographic and Meteorological Laboratory (AOML)
Cooperative Institute of Marine and Atmospheric Science (CIMAS)


Global Carbon Cycle
Global Ocean Chemistry
Local Ocean Chemistry
Coral Reef Ecosystem

Global Carbon Cycle



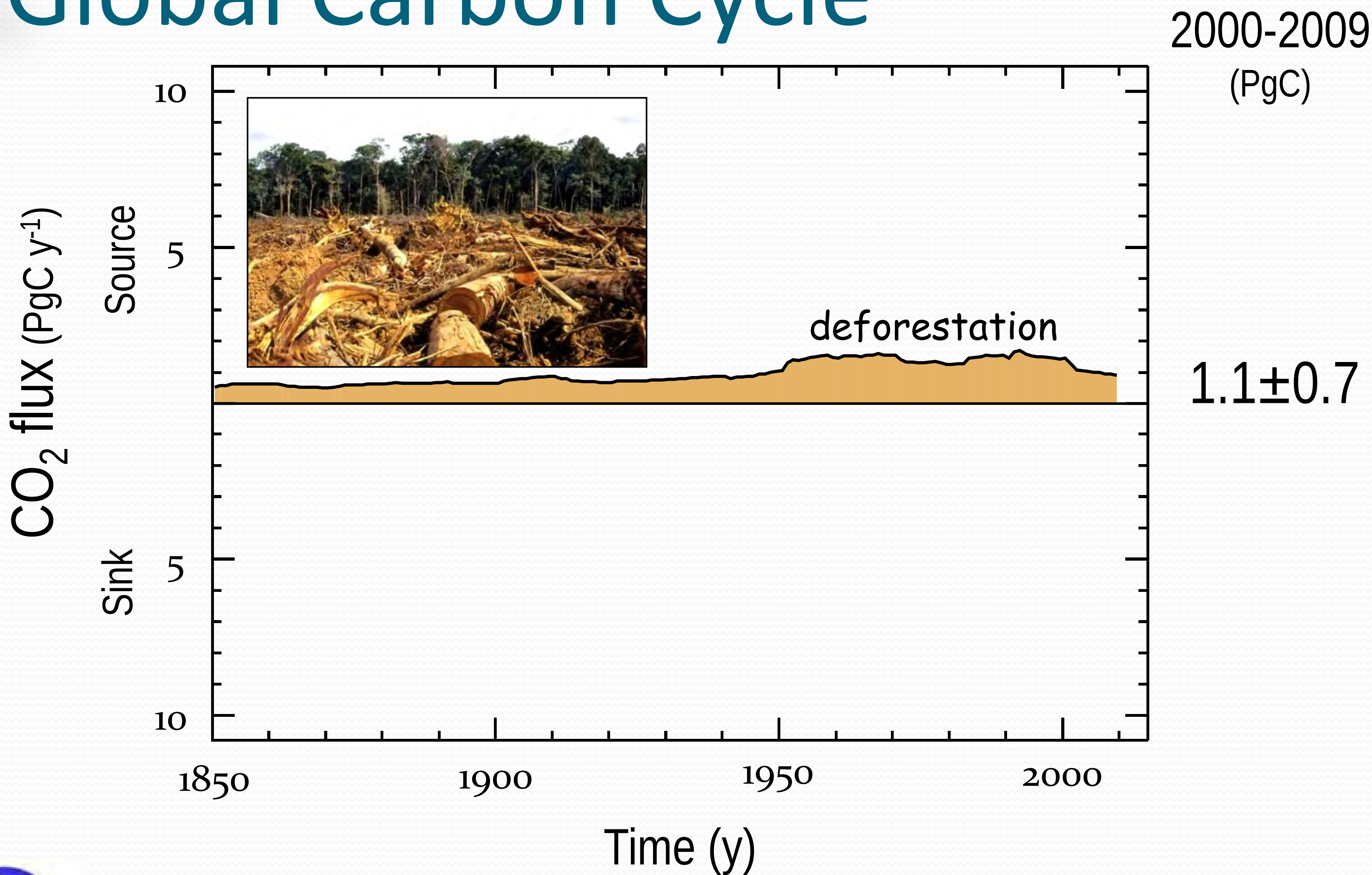
1 Petagram = 1 Gigatones = 10^{15}grams = 1 billion metric tonnes = 11 million Railroad hopper cars of Coal

- Chris Sabine (NOAA PMEL)

Global Carbon Project 2010; Updated from Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS

http://www.globalcarbonproject.org

Global Carbon Cycle



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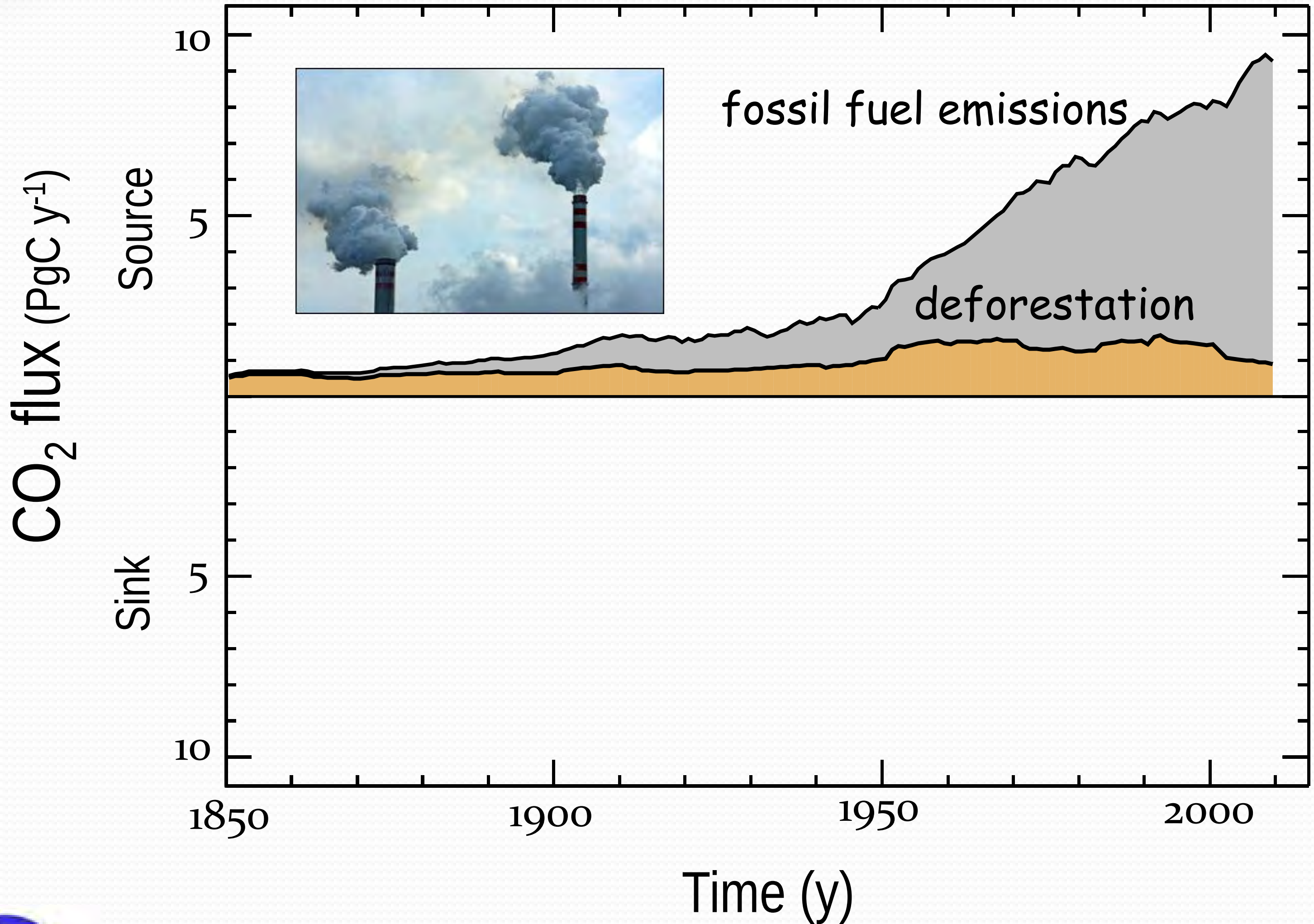
Global Carbon Cycle



2000-2009
(PgC)

7.7±0.5

1.1±0.7

Global Carbon Project 2010; Updated from Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS

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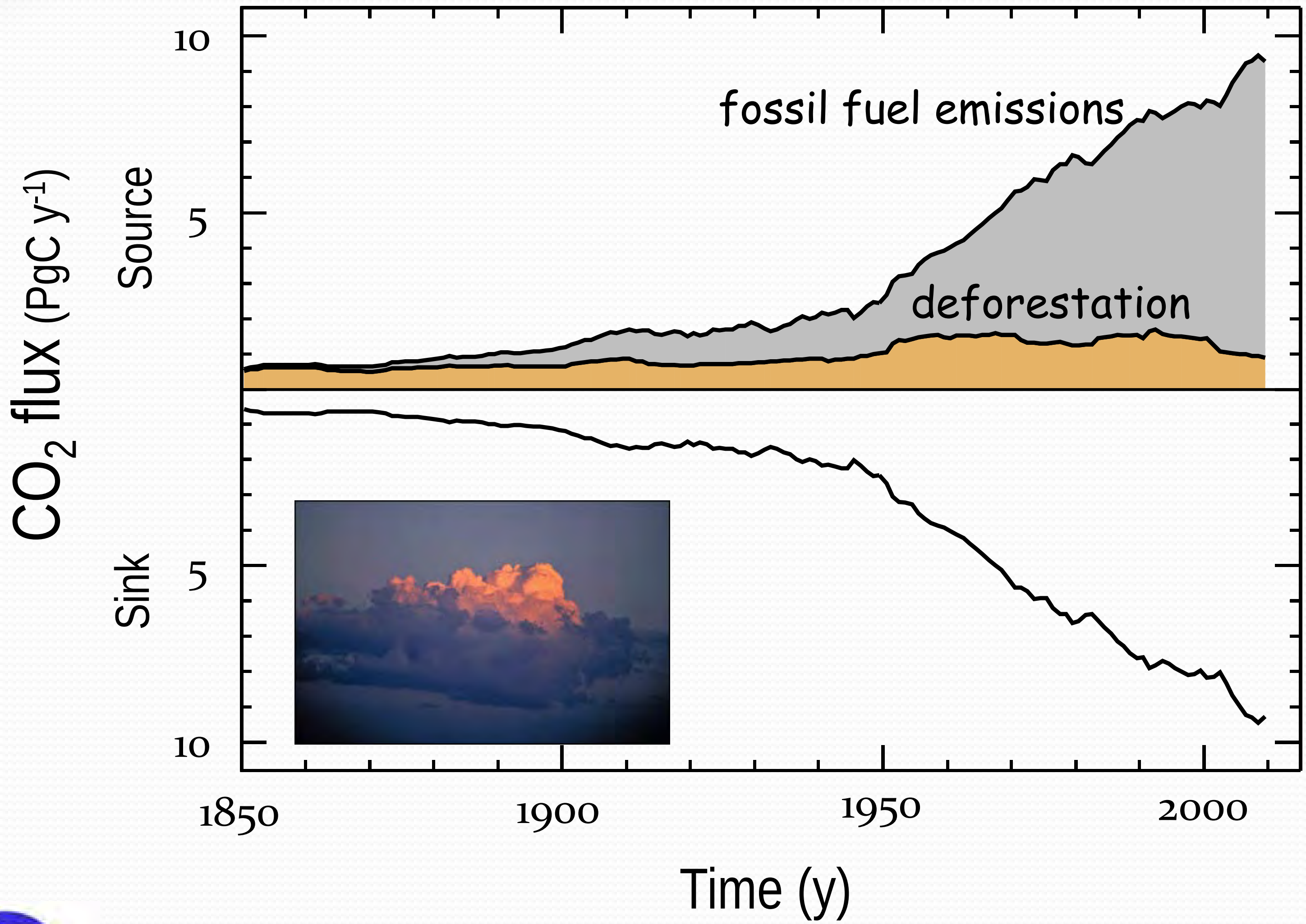
Global Carbon Cycle



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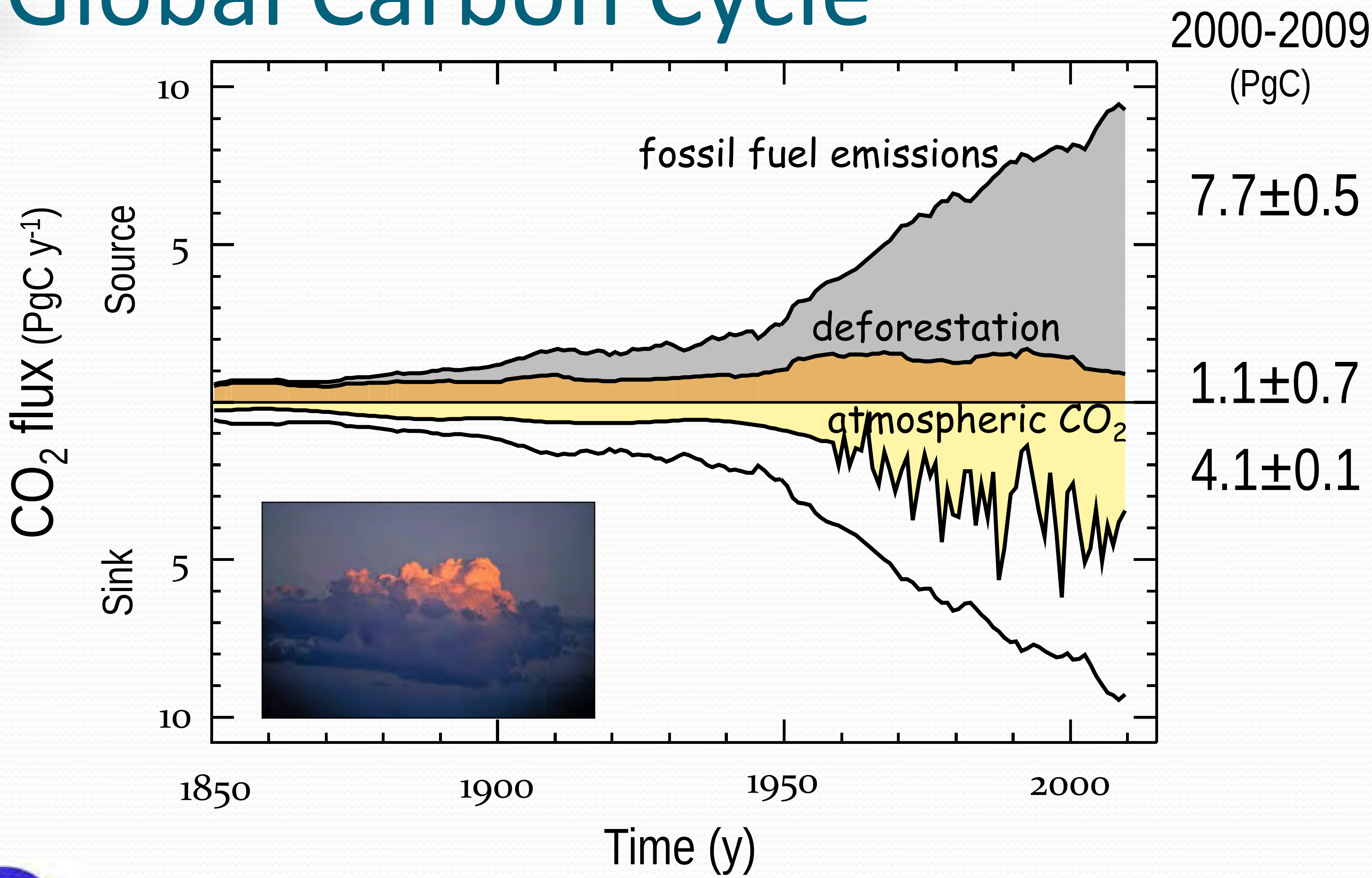

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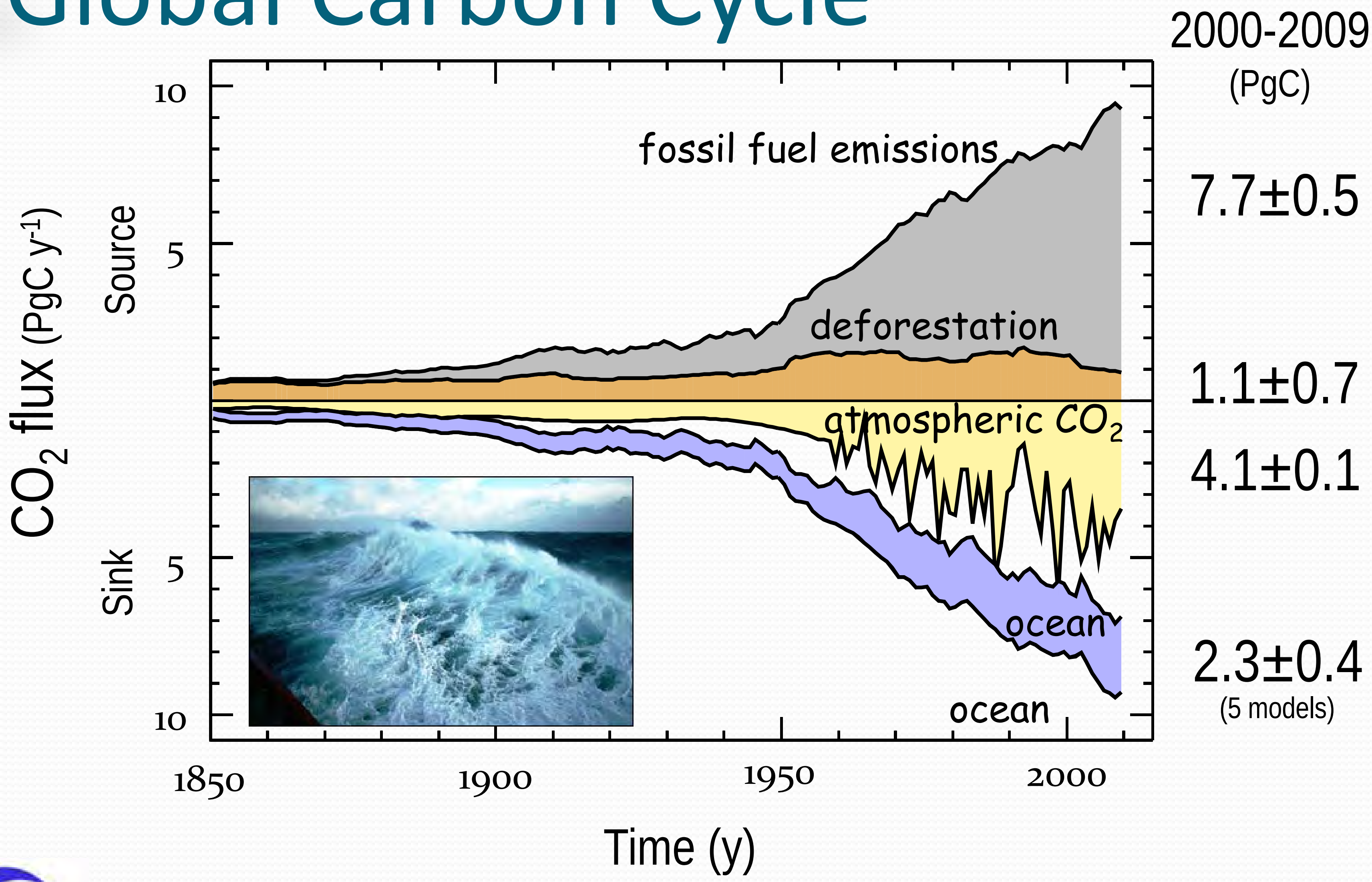

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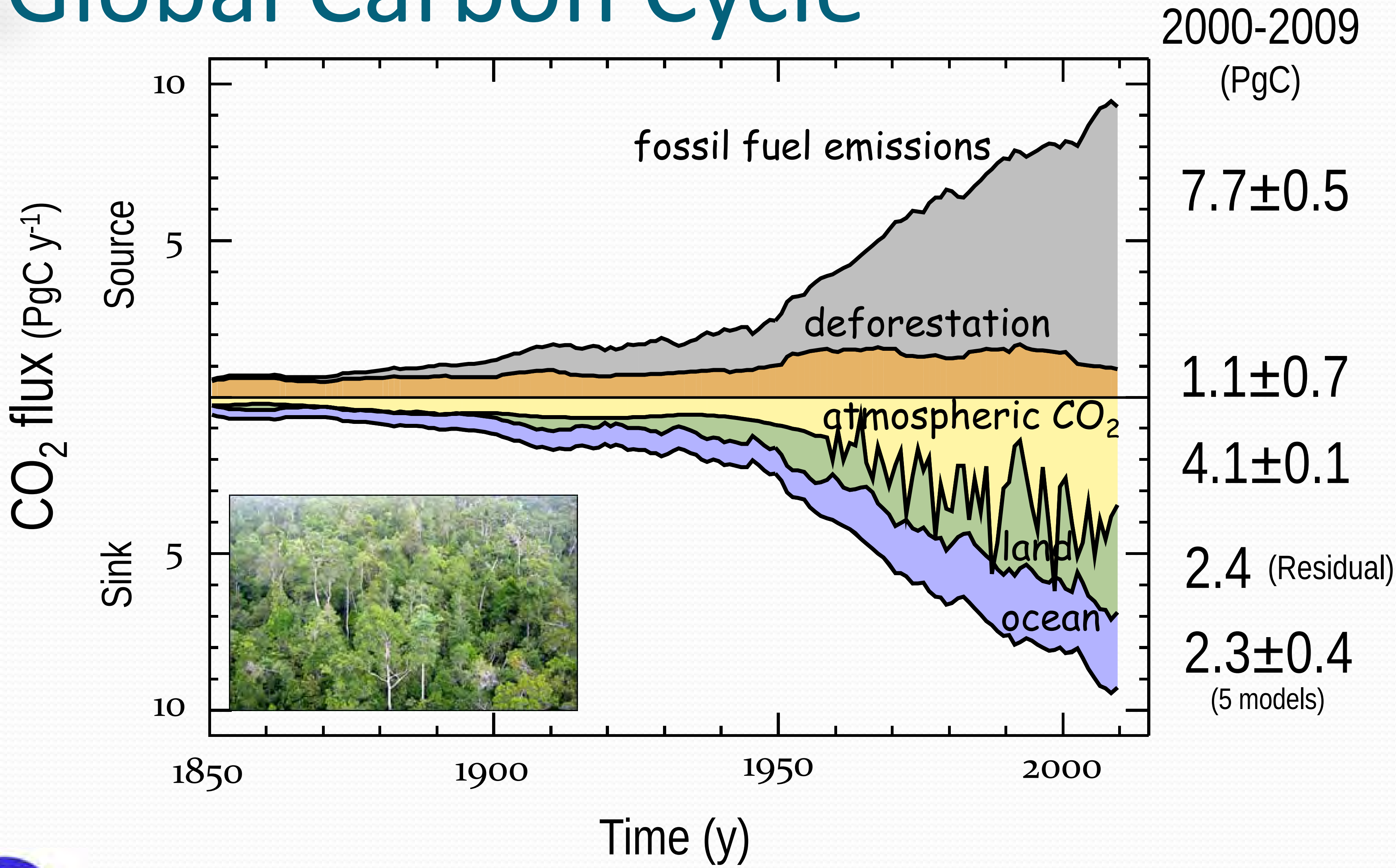
Global Carbon Cycle



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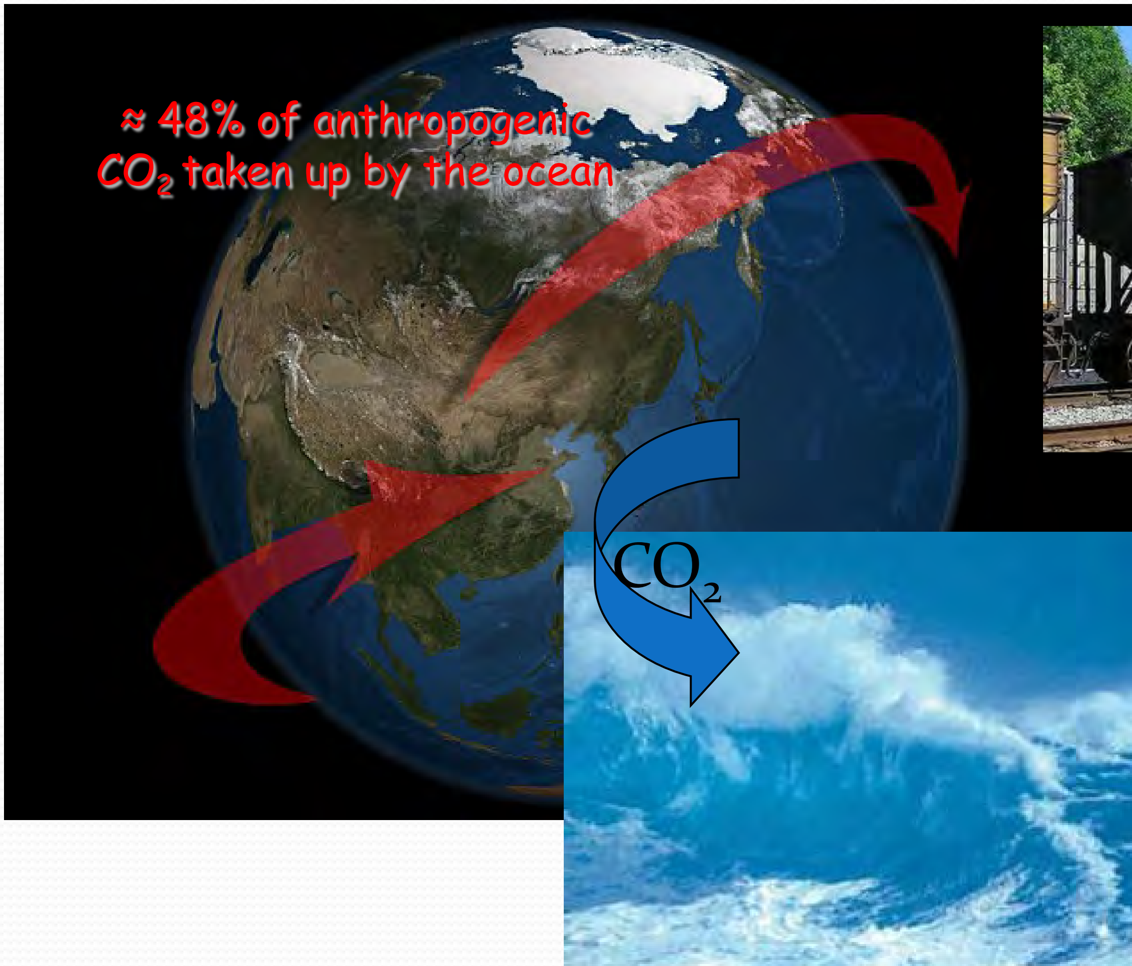
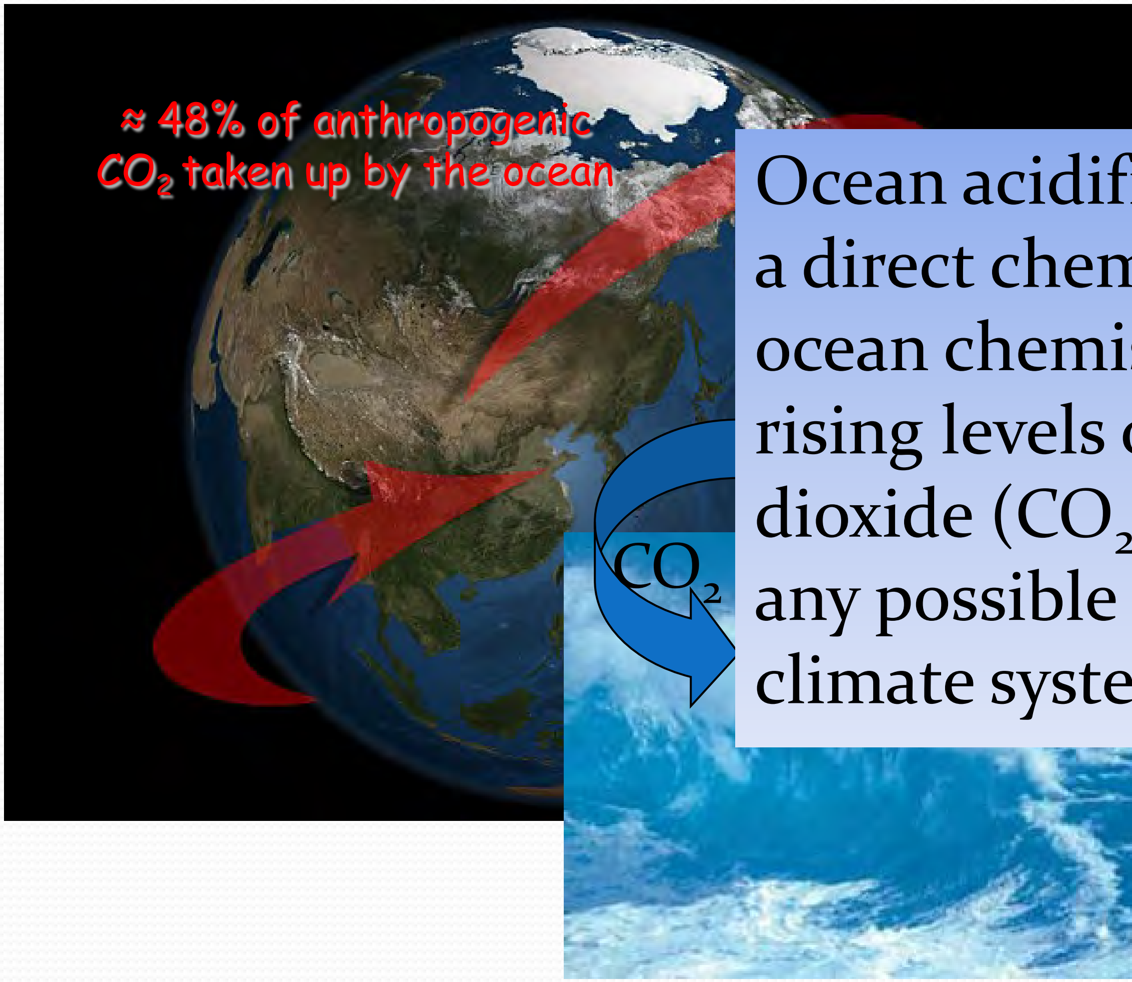
Global Ocean Chemistry
What is Ocean Acidification?



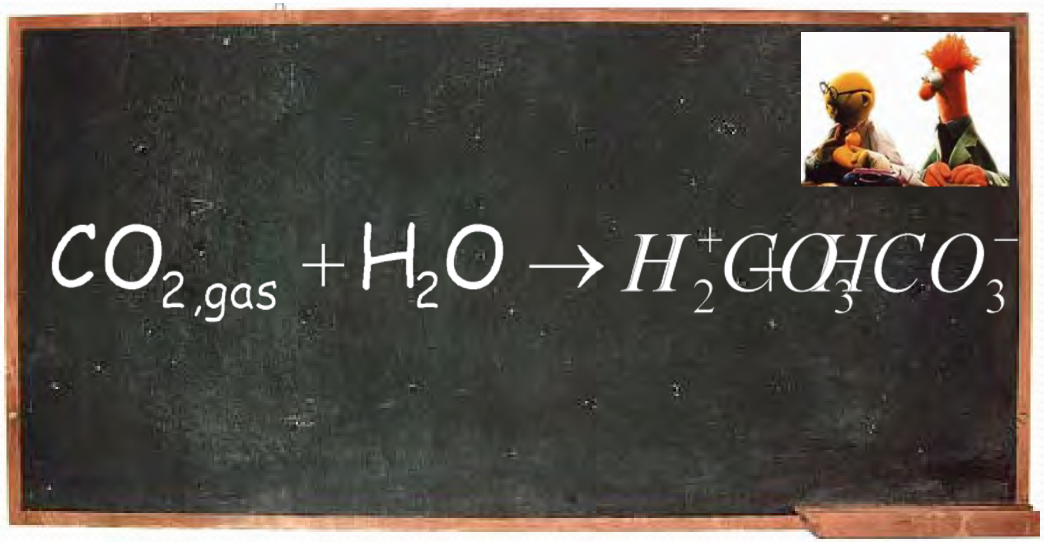
A railroad train carrying 2.3 Pg of carbon would stretch around the Earth 14 times! – Chris Sabine (NOAA PMEL)

Global Ocean Chemistry
What is Ocean Acidification?



Ocean acidification (OA) represents a direct chemical change to global ocean chemistry in response to rising levels of atmospheric carbon dioxide (CO_2) and is in addition to any possible effects of CO_2 on the climate system.

Global Ocean Chemistry
What is Ocean Acidification?



"Ocean Acidification" refers to the reduction in seawater pH resulting from the reaction of $CO_{2,gas}$ with water.

$$pH \approx -Log_{10}[a_{H^+}]$$

pH is a measure of hydrogen concentration in a solution:

Concentrations of Hydrogen Ions compared to distilled water (pH)		Examples of solutions and their respective pH
10,000,000	0	Battery Acid
1,000,000	1	Hydrochloric Acid
100,000	2	Lemon Juice, Vinegar
10,000	3	Orange Juice, Soda
1,000	4	Tomato Juice
100	5	Black Coffee, Acid Rain
10	6	Urine, Saliva
1	7	"Pure" Water
1/10	8	Sea Water
1/100	9	Baking Soda, Toothpaste
1/1,000	10	Milk of Magnesium
1/10,000	11	Household Ammonia
1/100,000	12	Soapy Water
1/1,000,000	13	Bleach, Oven Cleaner
1/10,000,000	14	Liquid Drain Cleaner

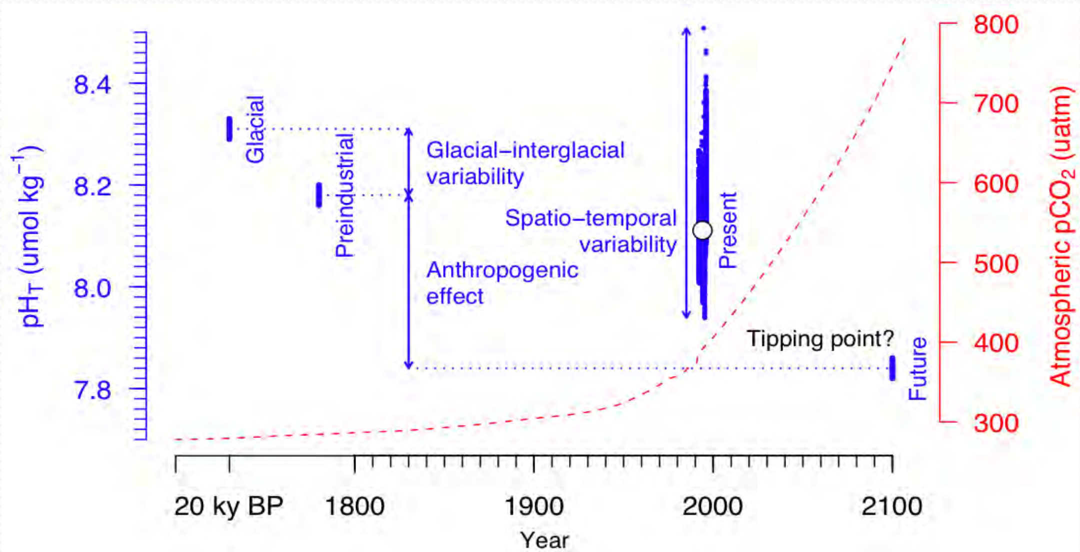
pH scale figure modified from http:EPOCA-Project.eu

Global Ocean Chemistry
What is Ocean Acidification?

“To put the possible environmental changes facing us into some perspective, one would have to turn the clock back at least 100 million years to find analogous surface ocean pH conditions.” – *Ridgwell and Zeebe (2005)*

Two Major Misconceptions:

1) The oceans are turning to *battery acid*!
2) The changes are *insignificant*!



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1	7	"Pure" Water
1/10	8	Sea Water
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1/1,000	10	Milk of Magnesium
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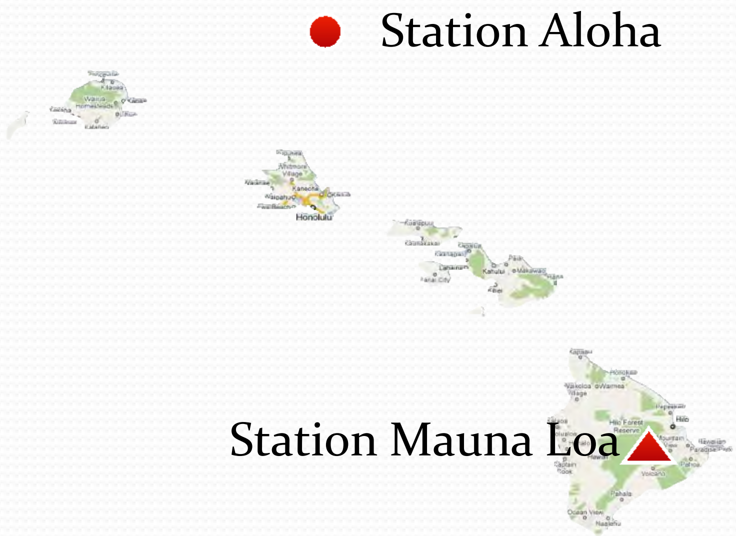
Figures from http:EPOCA-Project.eu

Global Ocean Chemistry Observing Ocean Acidification



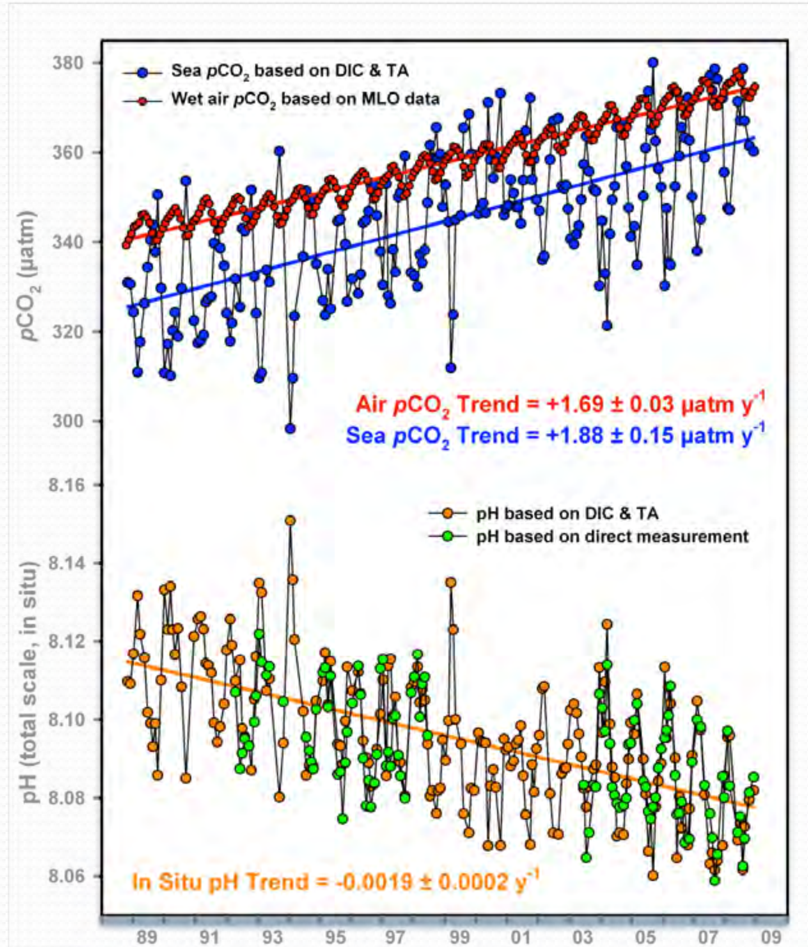


Figure courtesy of Richard Feely (NOAA PMEL) reproduced from Doney, *Science* (2010) and Dore et al., *PNAS* (2009)

Coral Reef Ecosystems What is a Coral Reef?

- Composed predominantly of scleractinian corals
- High biodiversity (600,000 to 9 million reef species)
- Structural complexity drives biodiversity

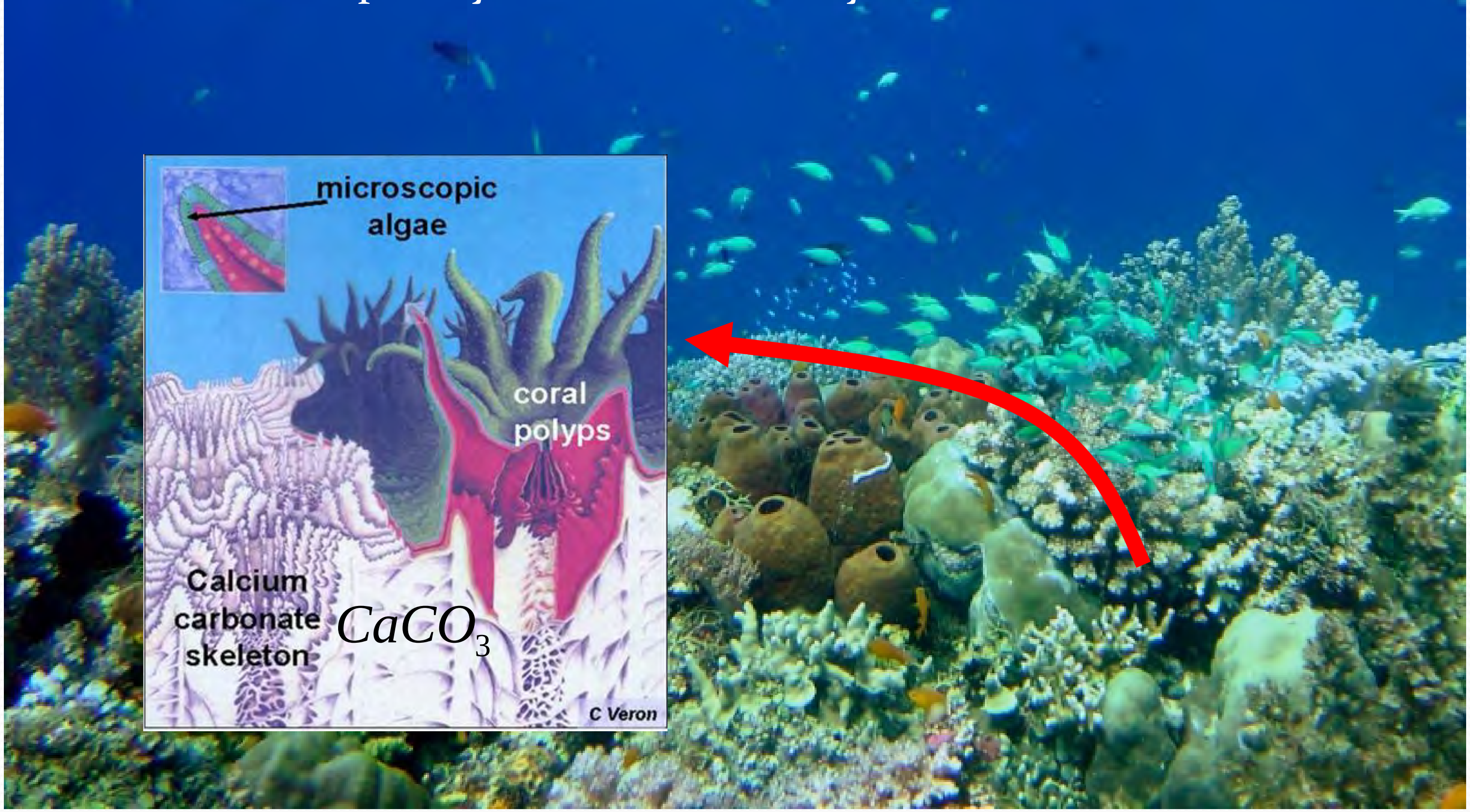


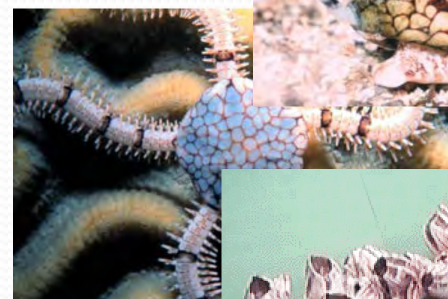
Figure from NOAA CRCP http:/http://coralreef.noaa.gov

Joanie Kleypas (Lead Author);Jean-Pierre Gattuso (Topic Editor) "Coral reef". In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment).

Coral Reef Ecosystems

What is a Coral Reef?

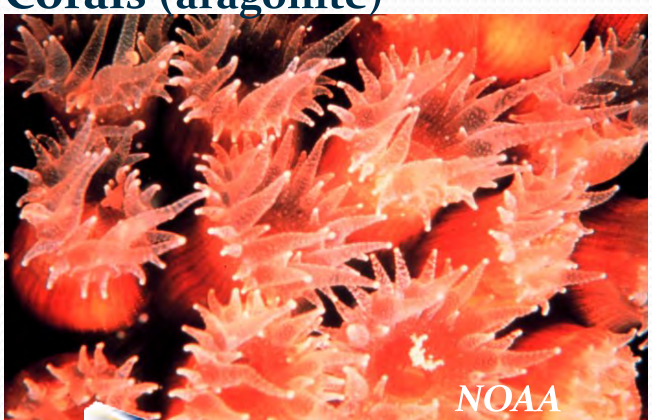
Mollusks



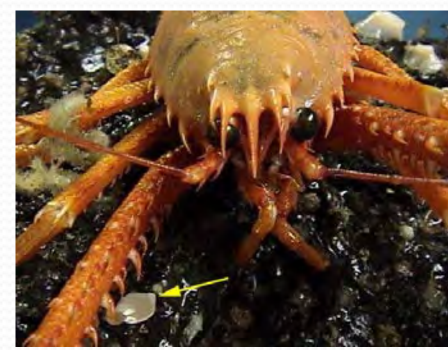
Coralline Algae (hi-mag calcite)

***Halimeda* (aragonite)**

Corals (aragonite)



Benthic Forams
Calcite + hi-mag calcite



NCAR Figures provided courtesy of Joanie Kleypas (National Center for Atmospheric Research)

Coral Reef Ecosystems
Reef’s in the Balance

Coral Reef $CaCO_3$ Budget

Production

Loss

Mechanical erosion

Calcification

bioerosion

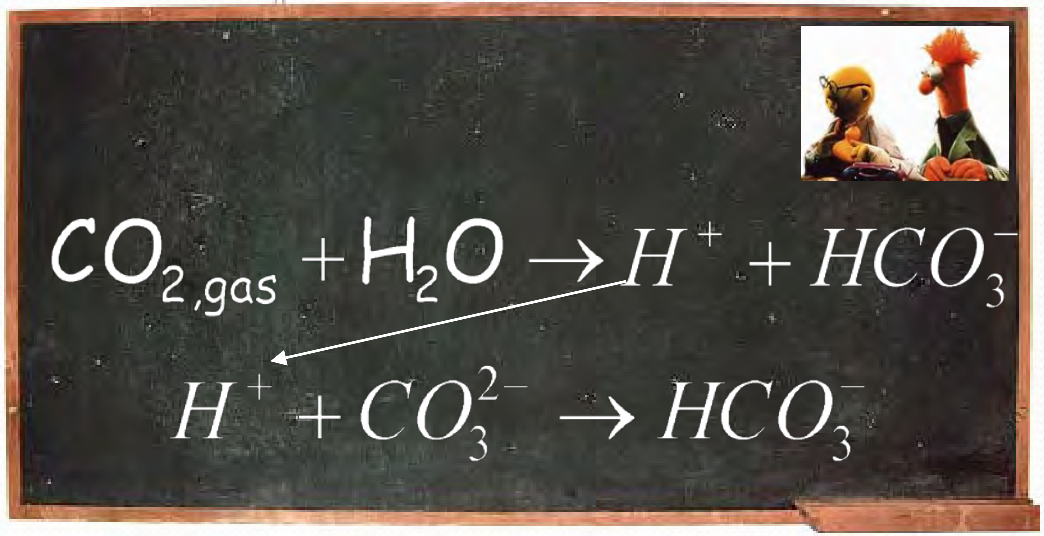
Precipitation

Dissolution

The more technical definition of "coral reef" includes an additional geological requirement that the reef organisms produce enough calcium carbonate to build the physical reef structure. – J. Kleypas

Coral Reef Ecosystems

$CaCO_3$ Saturation State (Ω_{arg})



Coral Reef Ecosystems
$CaCO_3$ Saturation State (Ω_{arg})

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

$$CO_{2,gas} + H_2O \rightarrow H^+ + HCO_3^-$$

$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

Coral Reef Ecosystems
$CaCO_3$ Saturation State (Ω_{arg})

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

$$\Omega_{phase} = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp,phase}}$$

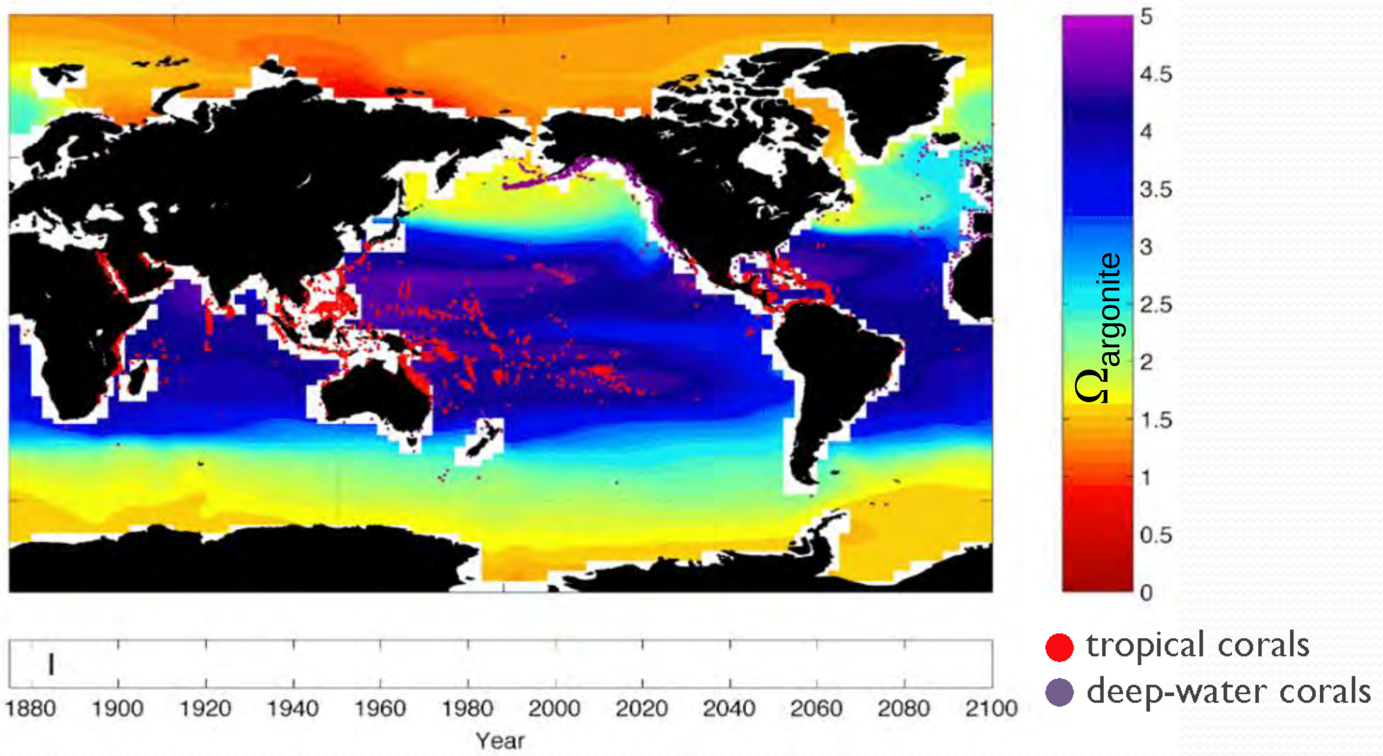
"Since the time of the HMS Challenger expeditions in the late 19th century, it has been recognized that that the **saturation state** of seawater overlying sediments in the deep ocean exerts a major influence on the distribution and abundance of calcium carbonate in these sediments" – J. Morse

"Saturation State"

$\Omega > 1 =$ *precipitation*

$\Omega < 1 =$ *dissolution*

Global Ocean Chemistry $CaCO_3$ Saturation State (Ω_{arg})

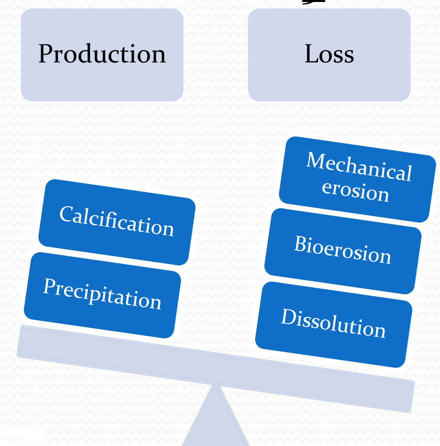


Animation courtesy of Richard Feely (PMEL)
after Feely et al (2009) with Modeled Saturation Levels using NCAR CCSM3 model

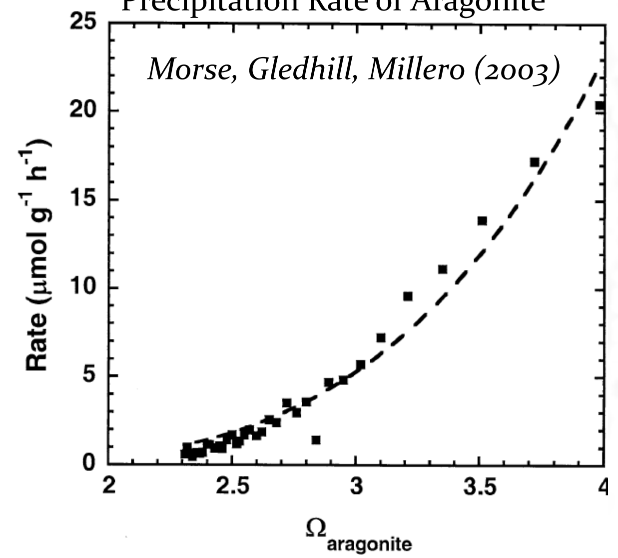
Coral Reef Ecosystems Production

Both inorganic precipitation and biologically mediated calcification are affected by the degree to which seawater is supersaturated Ω.

Coral Reef $CaCO_3$ Budget

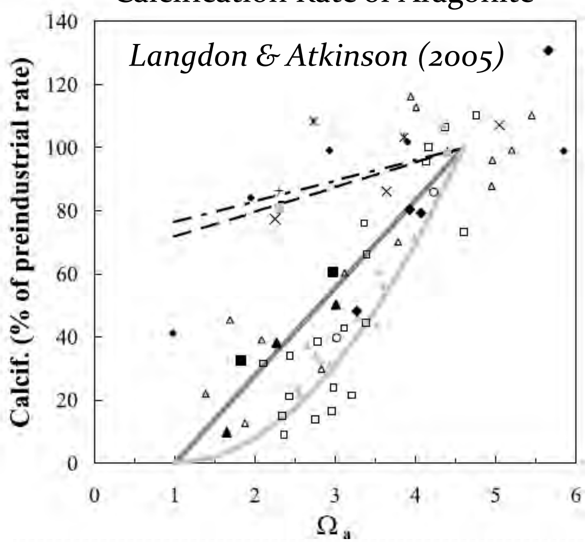


Precipitation Rate of Aragonite



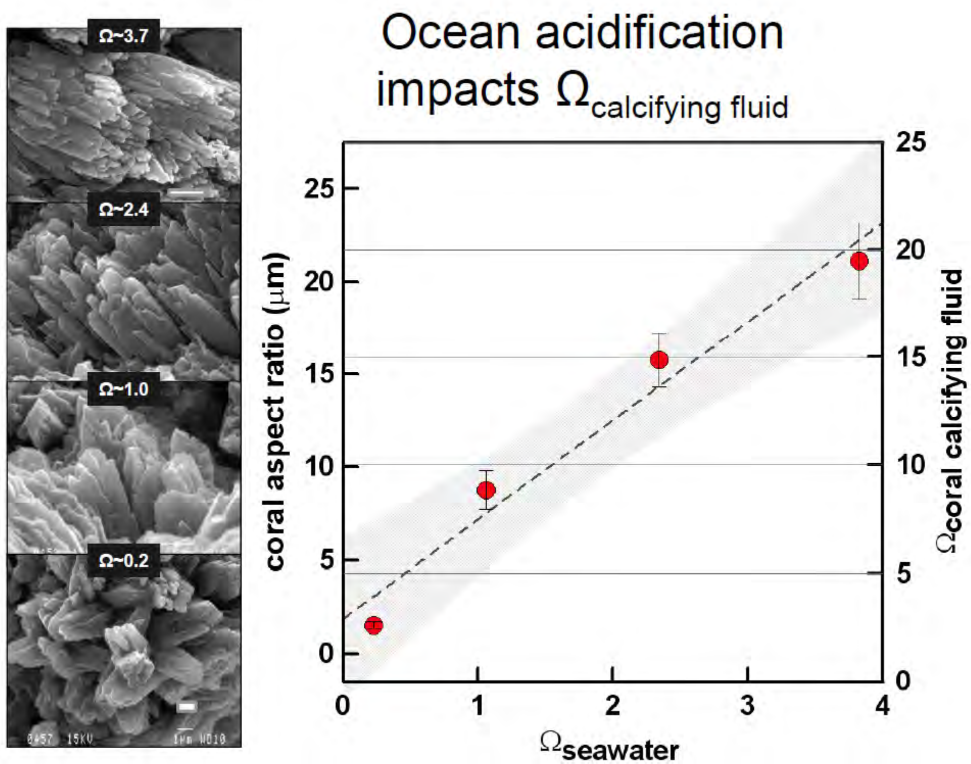
Inorganic

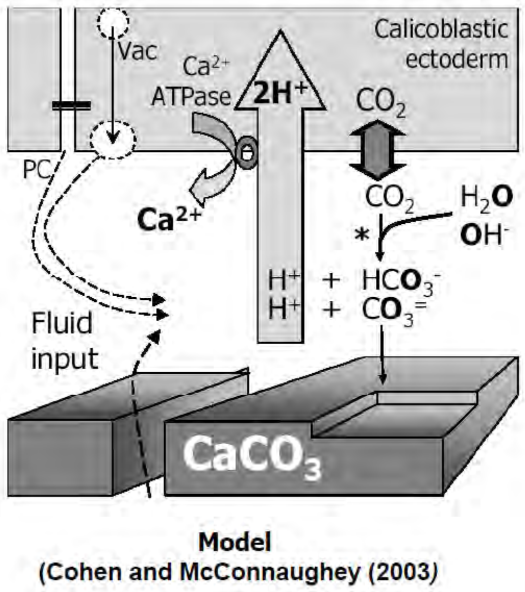
Calcification Rate of Aragonite



Biological

Coral Reef Ecosystems
Calcification

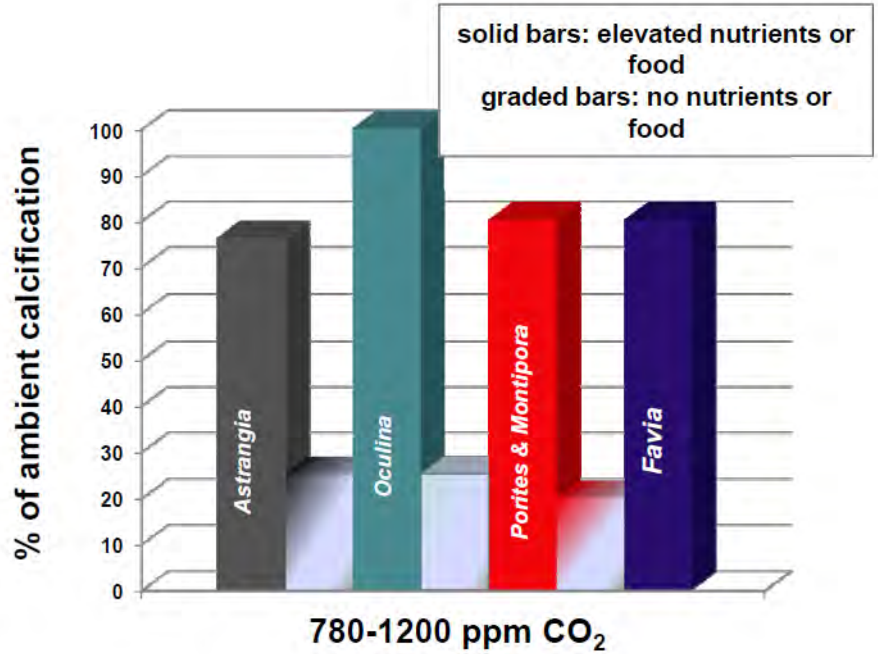




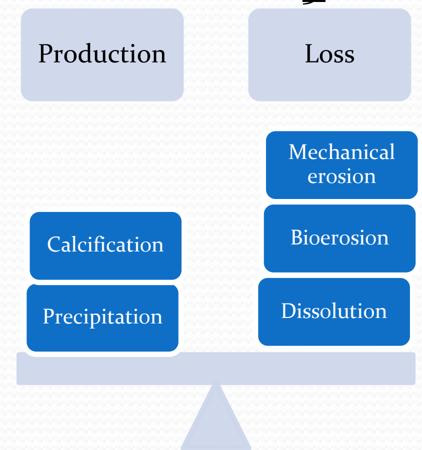
Slide courtesy of Anne Cohen Woods Hole Oceanographic Institution, Woods Hole, MA

Coral Reef Ecosystems Calcification

Feeding can modulate coral response to ocean acidification



Coral Reef $CaCO_3$ Budget



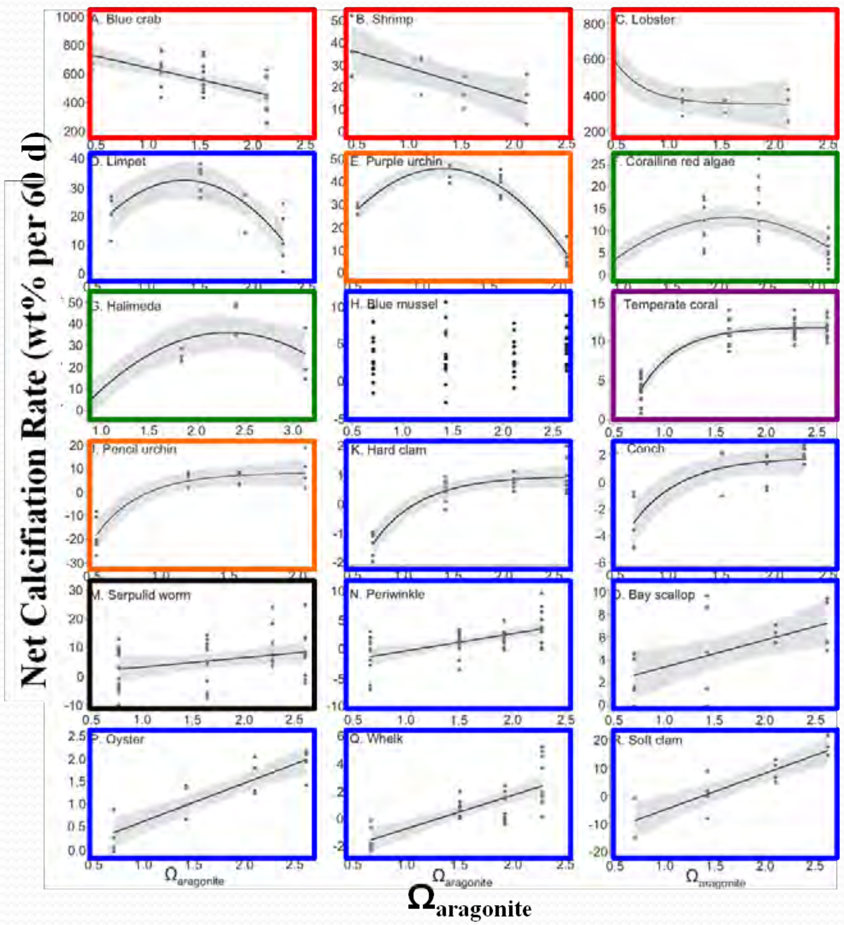
"In corals (and possibly in other organisms, energetic cost associated with raising fluid saturation state limits growth rate" but "The response to OA can be modulated by nutritional status" – A. Cohen

Slide courtesy of Anne Cohen Woods Hole Oceanographic Institution, Woods Hole, MA

Coral Reef Ecosystems Calcification

Calcification response varies

Ries 2009 *Geology*



Decapod Crustacean

Molluscs

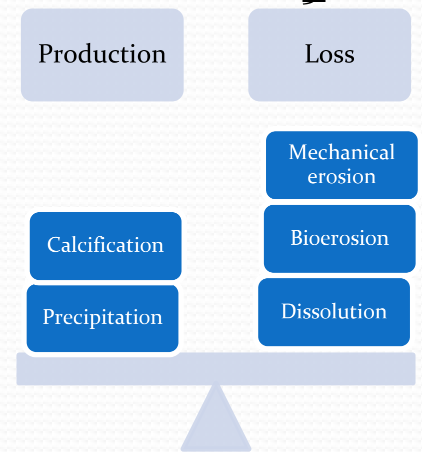
Algae

Temperate Coral

Echinoderms

Serpulid Worm

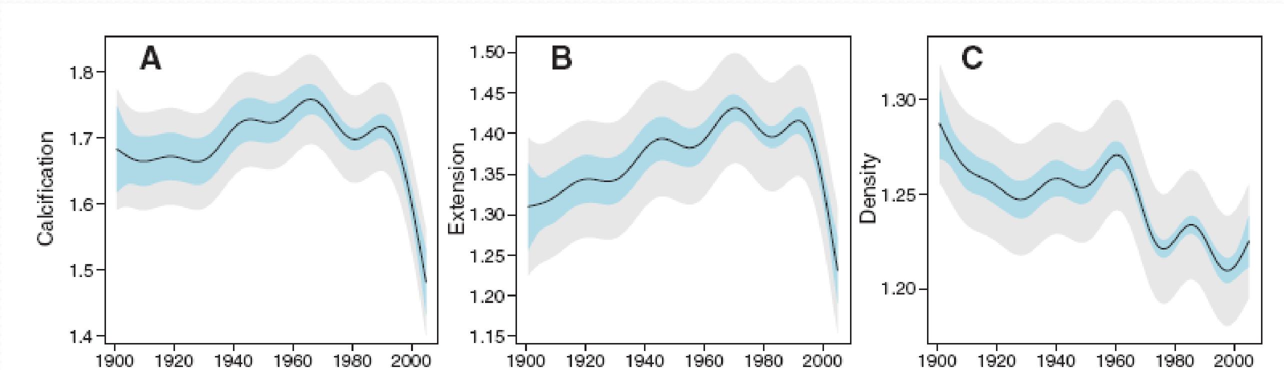
Coral Reef $CaCO_3$ Budget



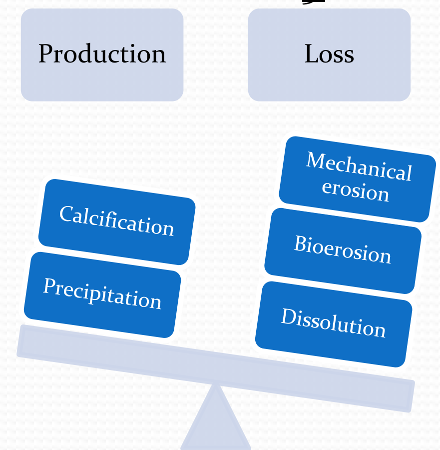
In terms of calcification rates, a range of sensitivities and responses to OA have been experimentally determined precluding a simple narrative

Figures provided courtesy of Joanie Kleypas (National Center for Atmospheric Research)

Coral Reef Ecosystems Calcification



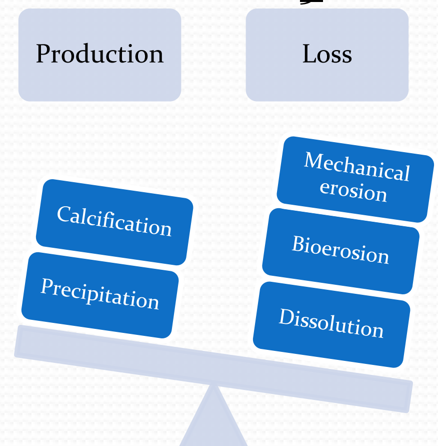
Coral Reef $CaCO_3$ Budget

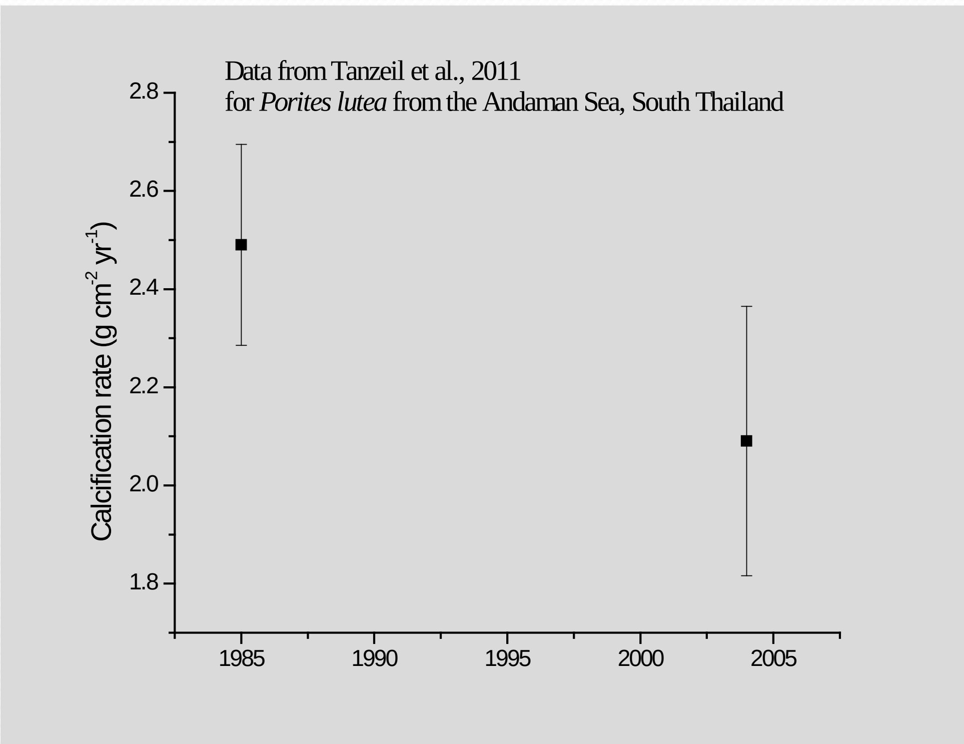


"Skeletal records show that throughout the Great Barrier Reef (Australia), calcification has declined by 14.2% since 1990, predominantly because extension (linear growth) has declined….the causes of the decline remain unknown.." - De'ath et al., *Science* (2009)

Coral Reef Ecosystems
Calcification

<u>Coral Reef $CaCO_3$ Budget</u>





"There was a significant decrease in coral calcification (23.5%) and linear extension rates (19.4 – 23.4%) between the two sampling periods…while skeletal bulk density remained unchanged" – Tanzil et al., (2009)

Coral Reef Ecosystems Calcification

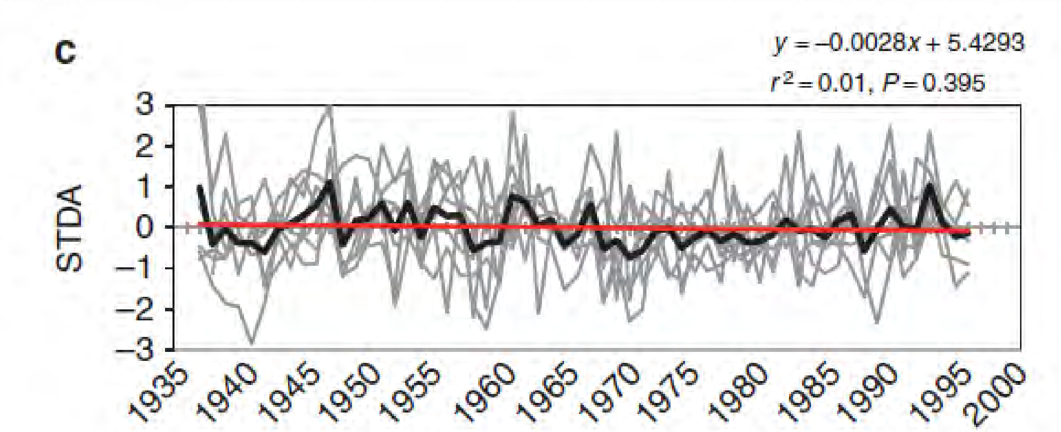
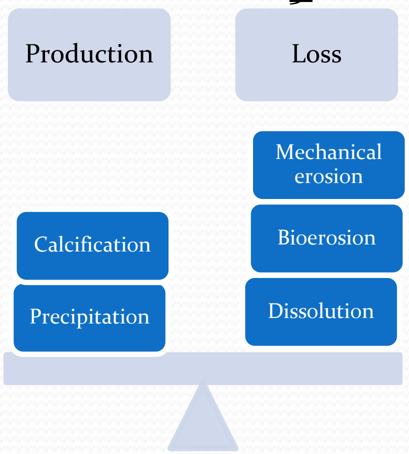


Figure 1 | Coral growth master chronologies 1937-1996. Master chronologies (*n* = 7 corals) are presented in standardized anomaly (STDA)

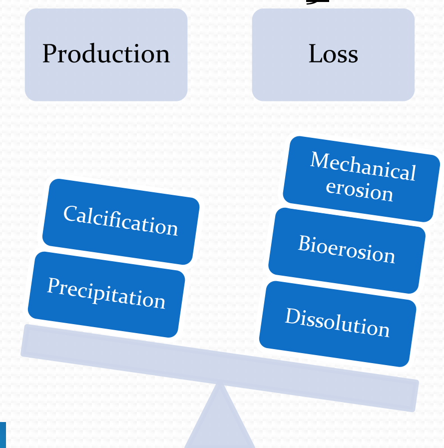
Coral Reef $CaCO_3$ Budget



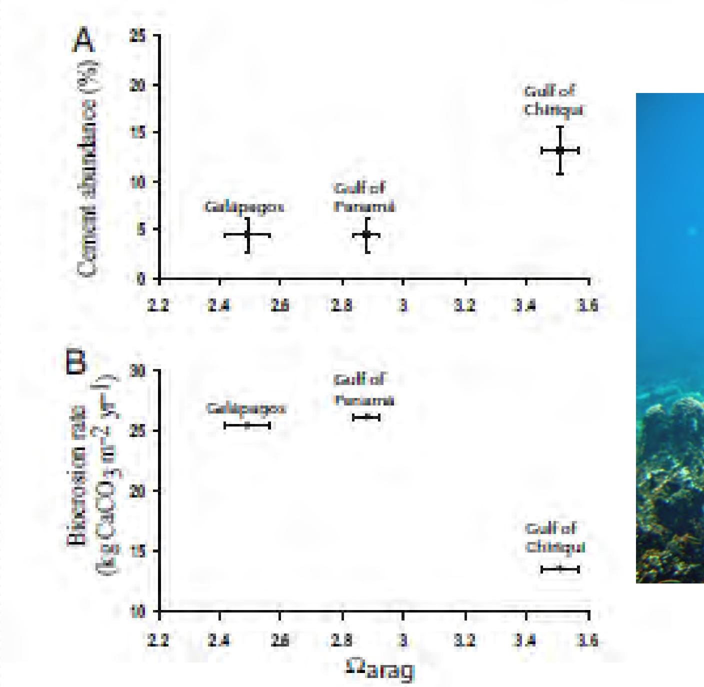
“Linear trends indicate that extension increased, density decreased and calcification remained stable while the most recent decade was not significantly different than decadal averages over the preceding 50 years for extension and calcification. The results suggest that growth rates in this species of subtropical coral have been tolerant to recent climatic changes up to the time of collection (1996).” - Helmle et al., *Nature Com.* (2011)

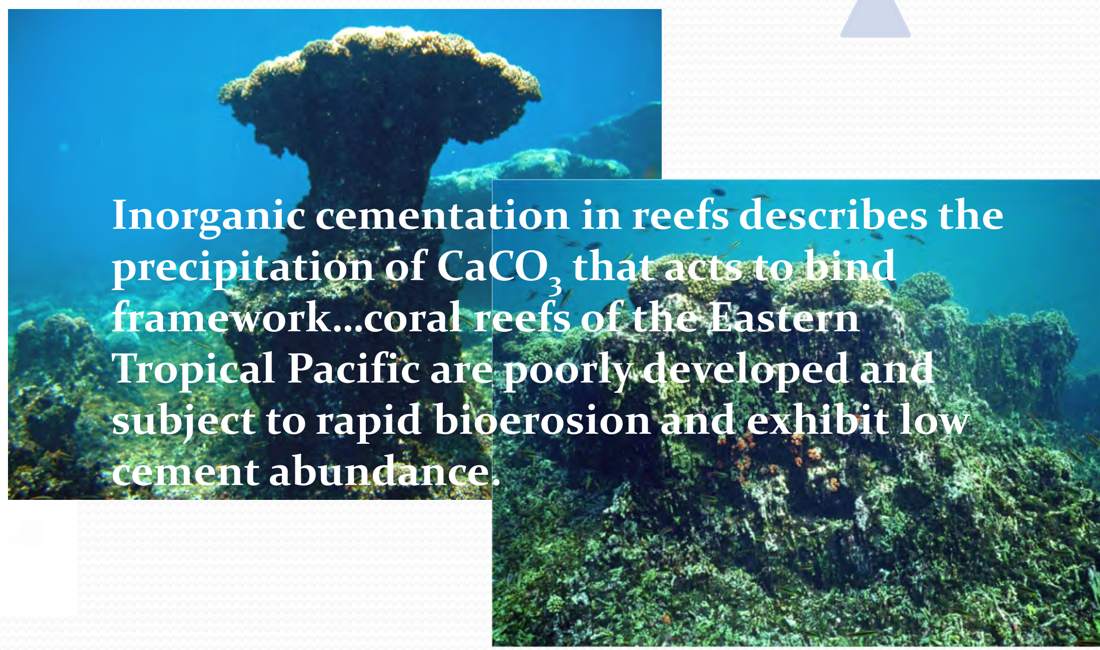
Coral Reef Ecosystems Mechanical/Bioerosion

Coral Reef $CaCO_3$ Budget



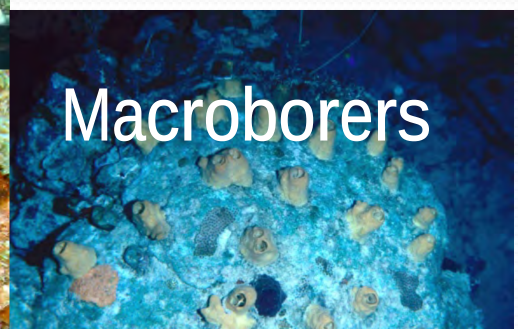
“Eastern Tropical Pacific (ETP) reefs represent a real-world example of coral reef growth in low-Ω waters that provide insights into how the biological-geological interface of coral reef ecosystems will change in a high-CO_2 world”. – *Manzello et al., PNAS (2008)*



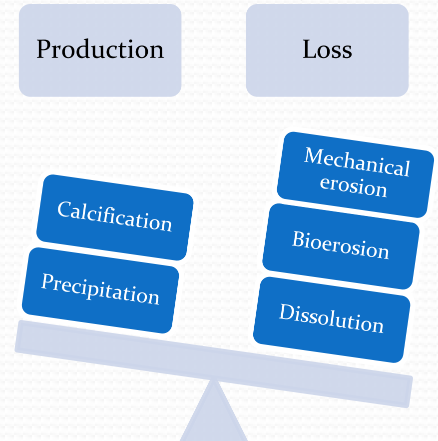


Inorganic cementation in reefs describes the precipitation of $CaCO_3$ that acts to bind framework…coral reefs of the Eastern Tropical Pacific are poorly developed and subject to rapid bioerosion and exhibit low cement abundance.

Coral Reef Ecosystems
Bioerosion



Coral Reef $CaCO_3$ Budget

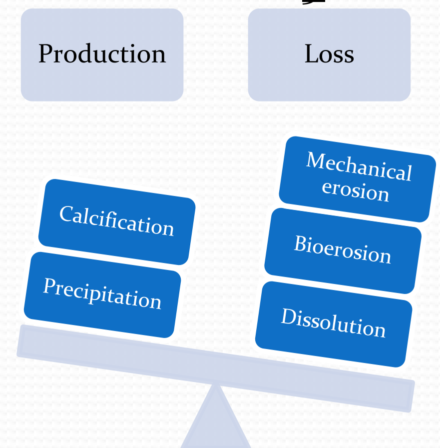


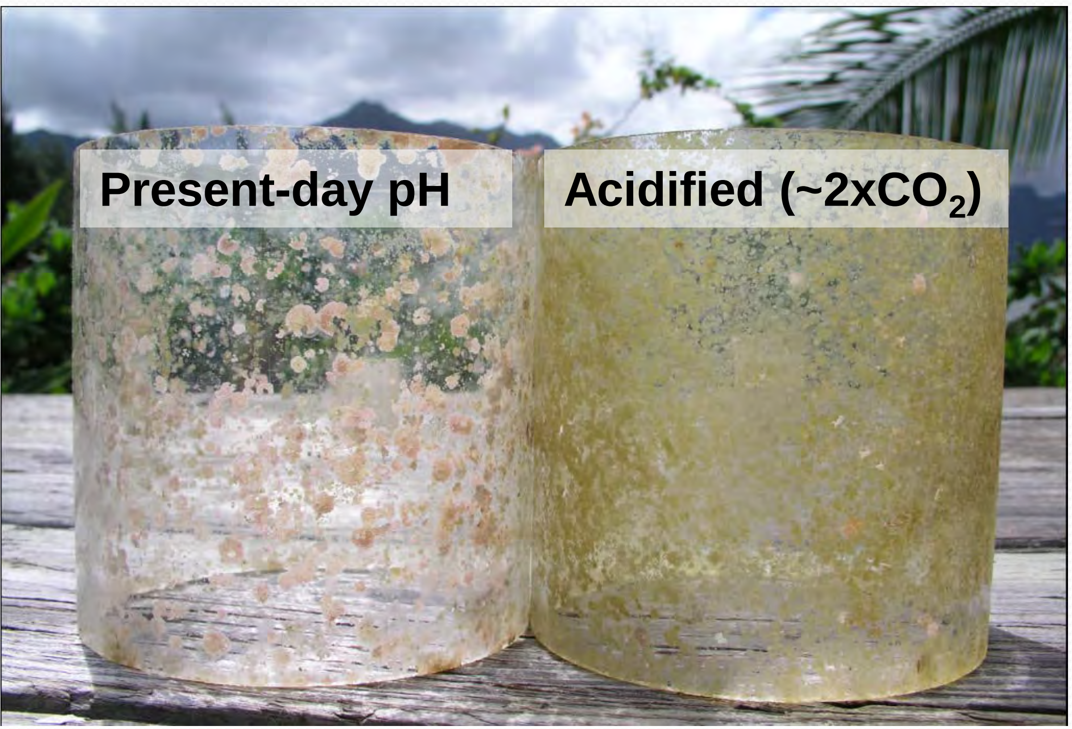
At elevated pCO_2 (750 ppm) the depth of penetration of Euendolithic bioeroders increased increasing dissolution rates by 48% - Tribollet et al., *Global Biogeochem. Cycles* (2009)

NCAR Slide modified courtesy of Joanie Kleypas (National Center for Atmospheric Research)

Coral Reef Ecosystems
Mechanical erosion

Coral Reef $CaCO_3$ Budget





"Crustose coralline algae (CCA) play an important role in the growth and stabilization of carbonate reefs. Under present day pH, CCA had developed 25% cover in the control mesocosms and only 4% under the acidified mesocosms". – *Jokiel et al., Coral Reefs (2008)*

Kuffner et al., *Nature Geoscience* (2008)
Jokiel et al. *Coral Reefs* (2008)

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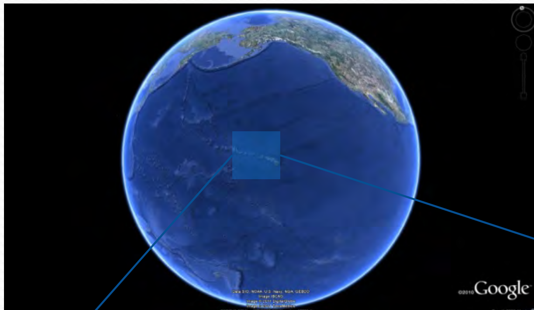
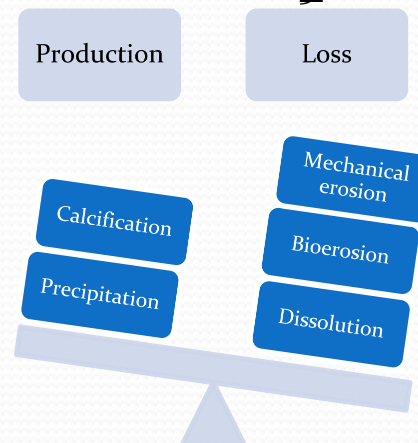
Local Ocean Chemistry Dissolution



Under current conditions, the Molokai reef flat exhibits net dissolution 13% of the time.

Coral Reef $CaCO_3$ Budget



Photosynthesis / Respiration

$$CO_2 + H_2O \leftrightarrow CH_2O + O_2$$

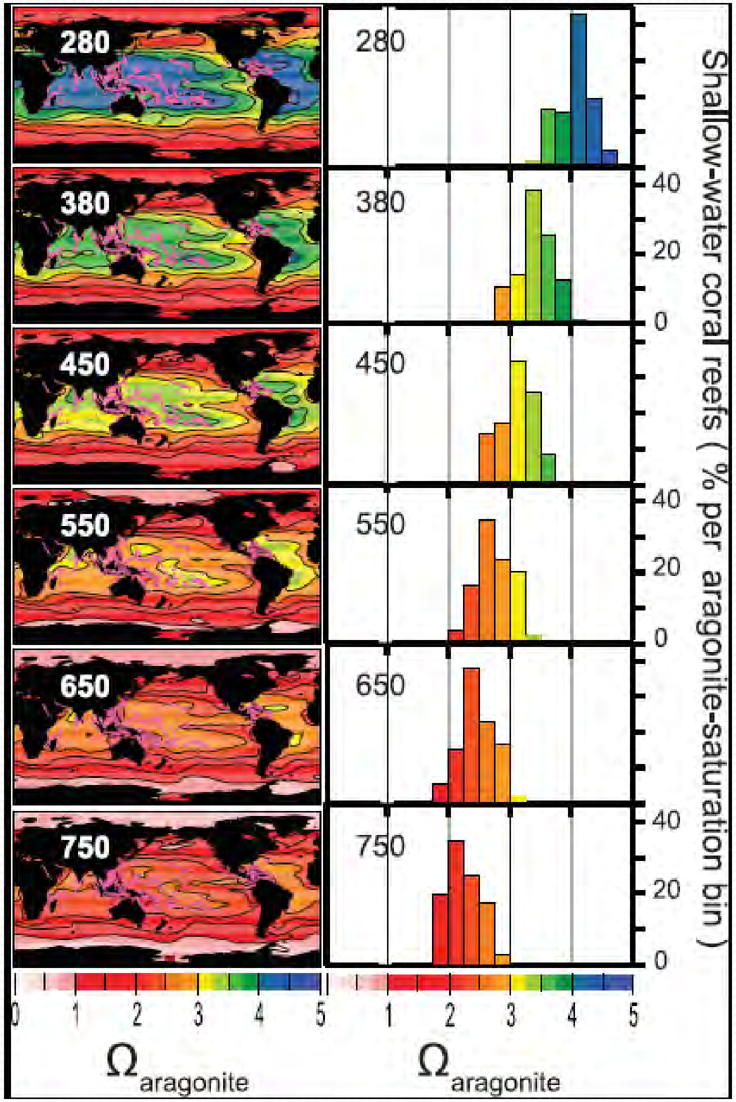
Calcification / Dissolution

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

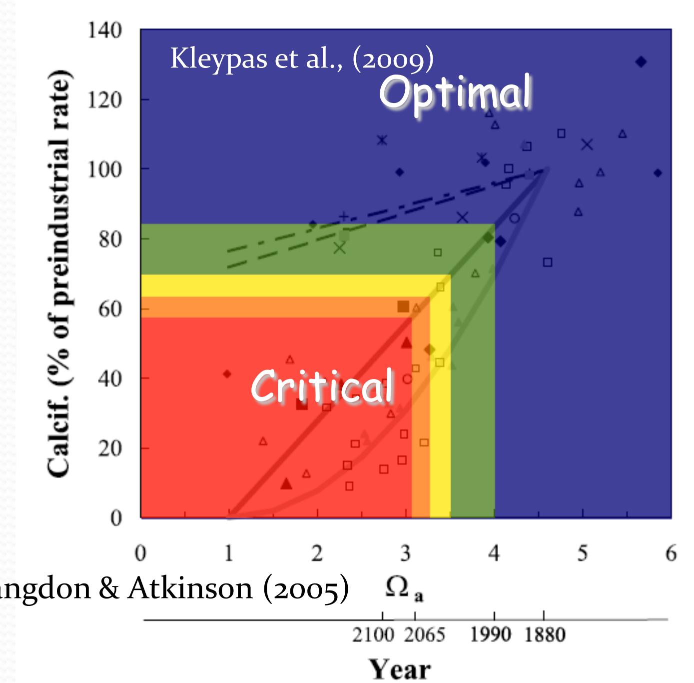
"It is predicted that atmospheric pCO_2 will exceed the average pCO_2 threshold value for calcification and dissolution on the Molokai reef flat by the year 2100." – Yates & Halley (2006)

Image of "SHARQ" available from http://soundwaves.usgs.gov/2007/01/

Global Ocean Chemistry



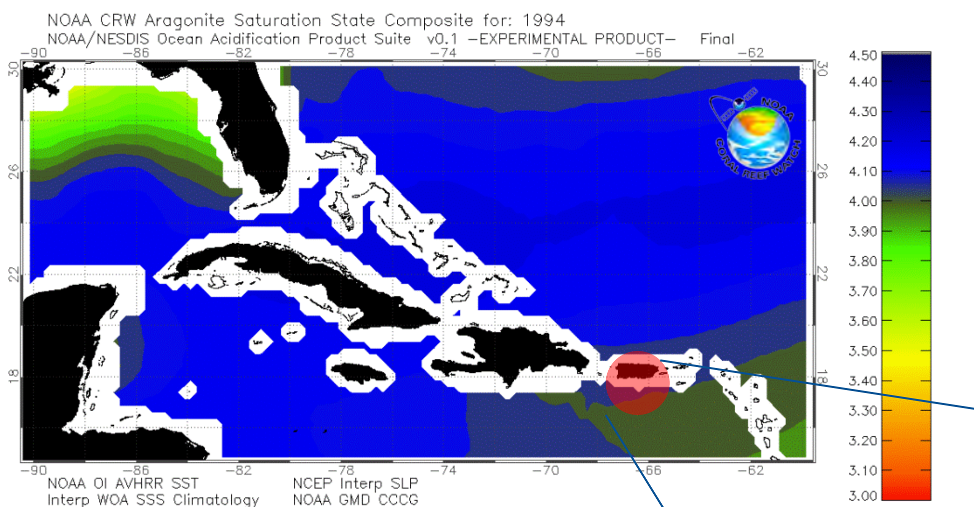
Cao and Calderia, GRL (2008)



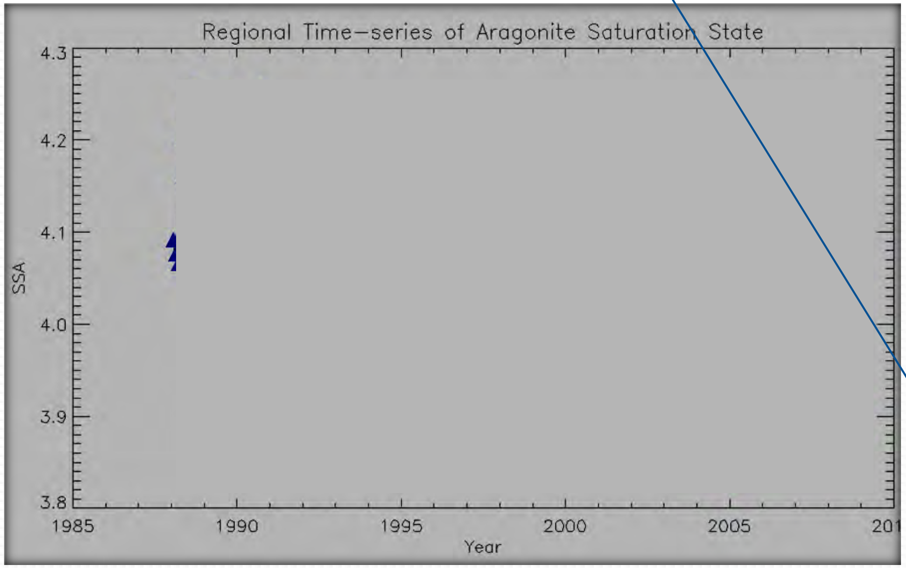
Is there a geochemical threshold?

"Before the industrial revolution, more than 98% of corals reefs were surrounded by waters that were >3.5 times saturated with respect to their skeleton materials (aragonite). If atmospheric CO2 is stabilized at 450 ppm only 8% of existing coral reefs will be surrounded by water with this saturation level.– *Cao and Calderia (2008)*

Local Ocean Chemistry

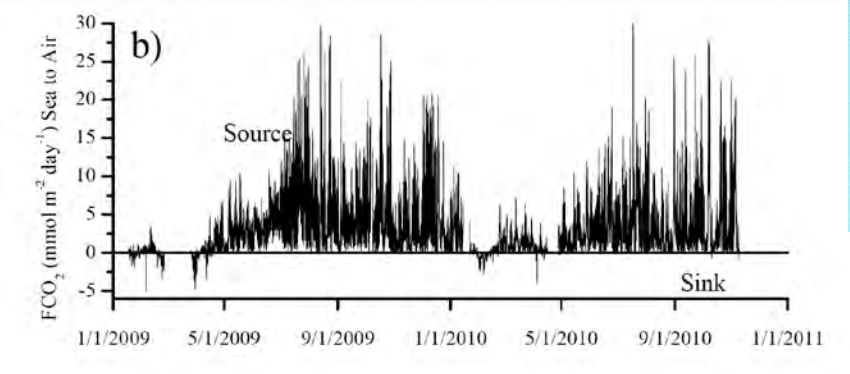


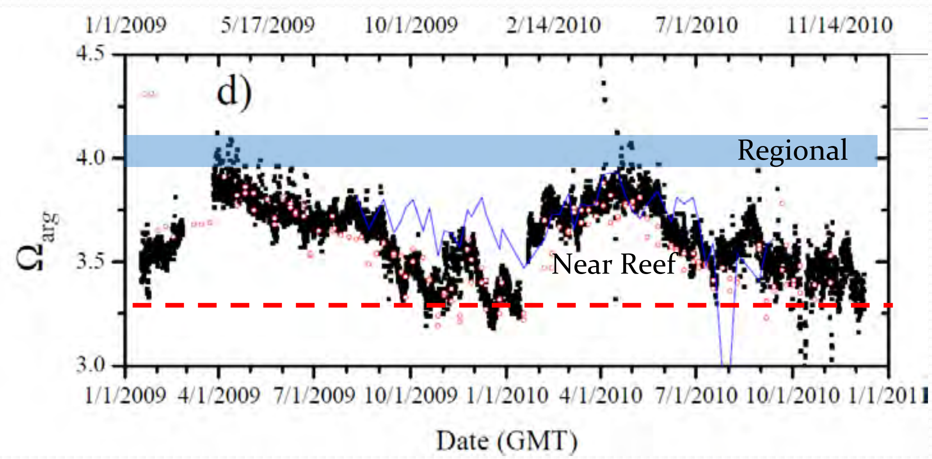
- Saturation State is controlled by more than pCO_2!
- Locally and on short time-scales, Ω can be dominated by temperature and salinity changes.



Gledhill et al., (2008)

Local Ocean Chemistry





Photosynthesis / Respiration

$$CO_2 + H_2O \leftrightarrow CH_2O + O_2$$

Calcification / Dissolution

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

NOAA coral reef CONSERVATION PROGRAM

RSMAS

Marine Sciences, UPRM

Lamont-Doherty Earth Observatory

COLUMBIA UNIVERSITY | EARTH INSTITUTE

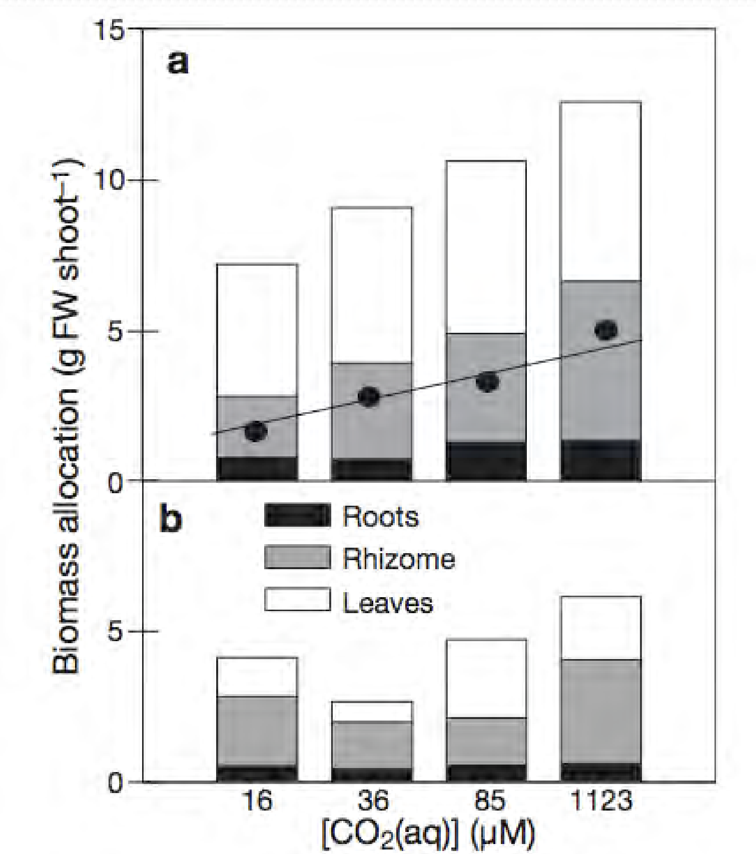
USGS science for a changing world

Coral Reef Ecosystems Non-carbonate Factors

Larval Clownfish: *Amphiprion percula*

Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. -Munday et al. *PNAS* (2009.)

Coral Reef Ecosystems Non-carbonate Factors



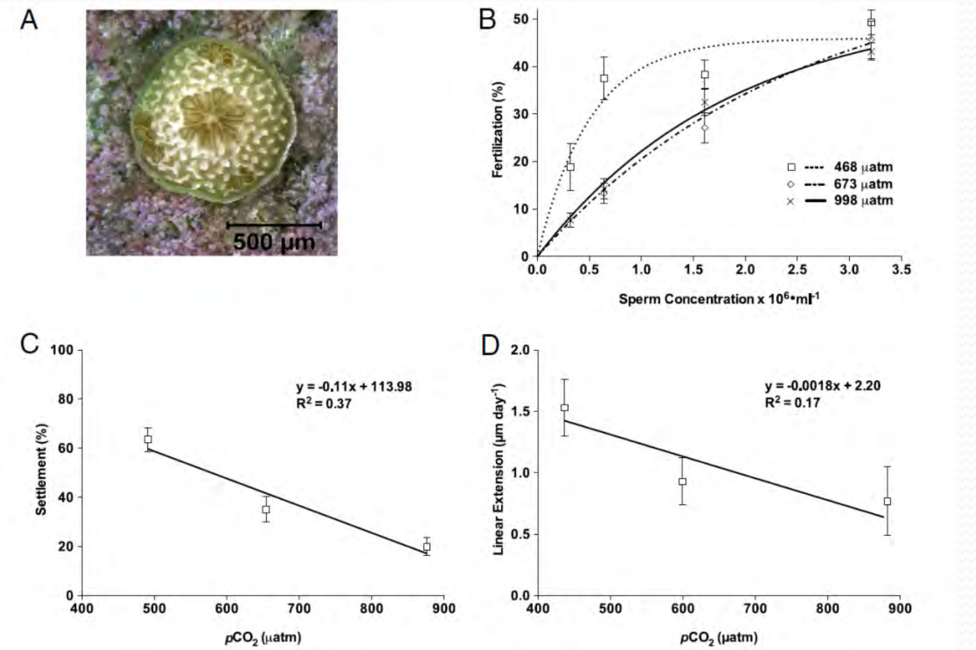
Seagrass may be enhanced by OA. – Palacios & Zimmerman, *MEPS* (2007)

Coral Reef Ecosystems Non-carbonate Factors

"Coral recruitment, which necessitates successful fertilization, larval settlement, and postsettlement growth and survivorship, is critical to the persistence and resilience of coral reefs.....

The cumulative impact of OA on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO2 conditions projected for the middle and the end of this century, respectively...

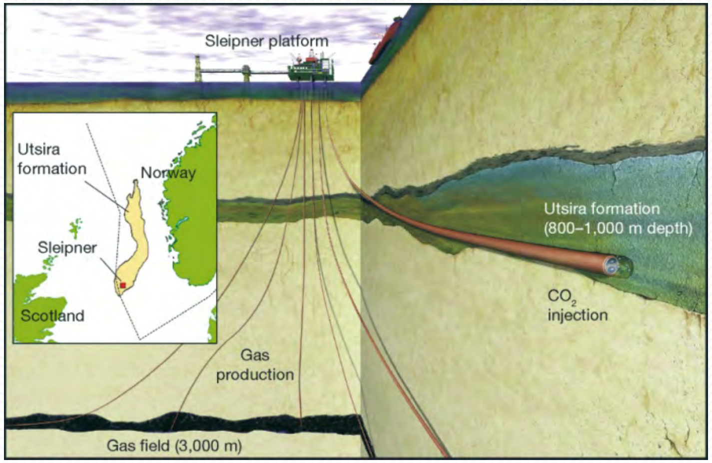
Additional declines of 39% (mid-CO2) and 50% (hig CO2) were observed in postsettlement linear extensi rates relative to controls...



These results suggest that OA has the potential to impact multiple, sequential early life history stages, thereby severely compromising sexual recruitment and the ability of coral reefs to recover from disturbance..."

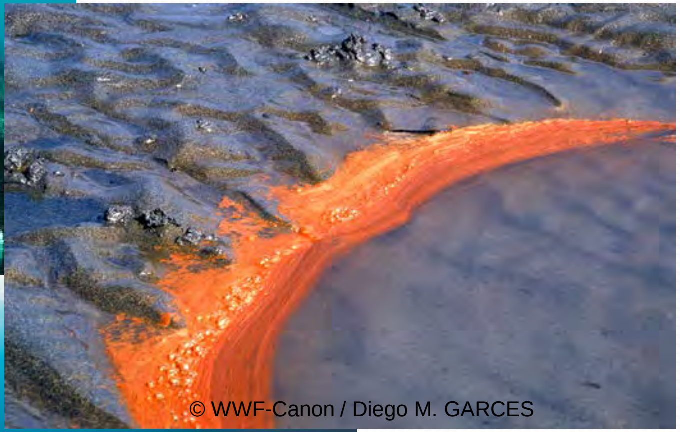
- Albright et al., *PNAS* (2010)

The Ultimate Solution… A Balanced Budget



The Interim Solution…
Foster Reef Resilience

Multiple, Synergistic Stresses on both
Global & Local Scales



Concluding Remarks

- Ocean Acidification represents a global scale change in ocean chemistry in direct response to rising atmospheric CO_2.
- These changes represent perhaps the most rapid shift in ocean chemistry in millions of years.
- Coral Reef Ecosystems may prove vulnerable to such changes due to several factors including reduced carbonate production (precipitation, calcification), enhanced mechanical erosion, enhanced bioerosion, and enhanced dissolution.
- The precise ecological implications remains uncertain given the range of calcification response thus far observed.
- Additional factors beyond carbonate budget considerations may represent the greatest concern for coral reefs.
- Coral reef are under threat from a number of global and local factors demanding improved management which better foster resilience.

Special Thanks to Contributors to this Talk

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The Global Carbon Project

EPOCA

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Select data, images and figures from:

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The Global Carbon Project: http://www.globalcarbonproject.org

The National Center for Atmospheric Research: http://ncar.ucar.edu/

NOAA Pacific Marine Environmental Laboratory (PMEL): http://www.pmel.noaa.gov/

NOAA Coral Reef Conservation Program: http://coralreef.noaa.gov/

Woods Hole Oceanographic Institute: http://www.whoi.edu