Ocean Acidification and other Climate Change Implications

A deeper look at the effects of growing CO_2 and climate change on the ocean

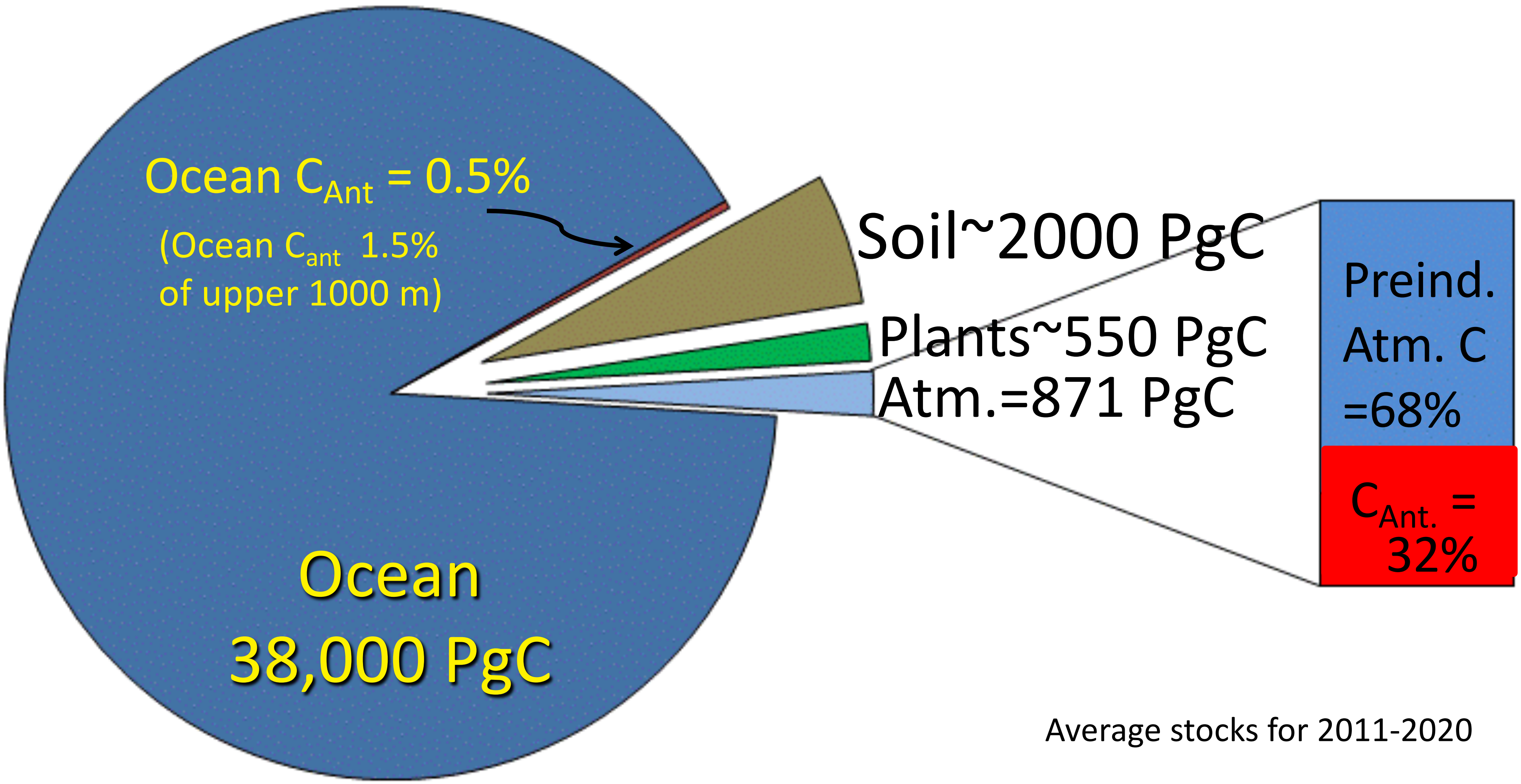
OCN 623 – Chemical Oceanography

Student Learning Outcomes (SLOs)

At the completion of today's section, students should be able to:

1. Know the basic definition of Revelle Factor and how it will change with rising CO_2
2. Describe the impact of rising CO_2 on calcifying organisms
3. List some of the concerns for OA on marine ecosystems
4. Understand how IPCC views risk for climate change and OA

Carbon Inventories of Reservoirs that Naturally Exchange Carbon on Time Scales of Decades to Centuries



Average stocks for 2011-2020

- Oceans contain ~90% of carbon in this 4 component system
- anthropogenic component is difficult to detect in the ocean

Ocean Carbon Chemistry Review

$CO_{2(gas)}$

$CO_2 + H_2O \leftrightarrow H_2CO_3$

Carbonic acid

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$

Bicarbonate

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

Carbonate

$pCO_2 = xCO_2 \cdot P$

$TCO_2 = [CO_2^*]+[HCO_3^-]+[CO_3^{2-}]$

$TA = [HCO_3^-]+2[CO_3^{2-}]+[B(OH)_4^-]+\ldots- [H^+]$

$pH = -\log\{H^+\}$

Ocean Carbon Chemistry Review

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Bicarbonate

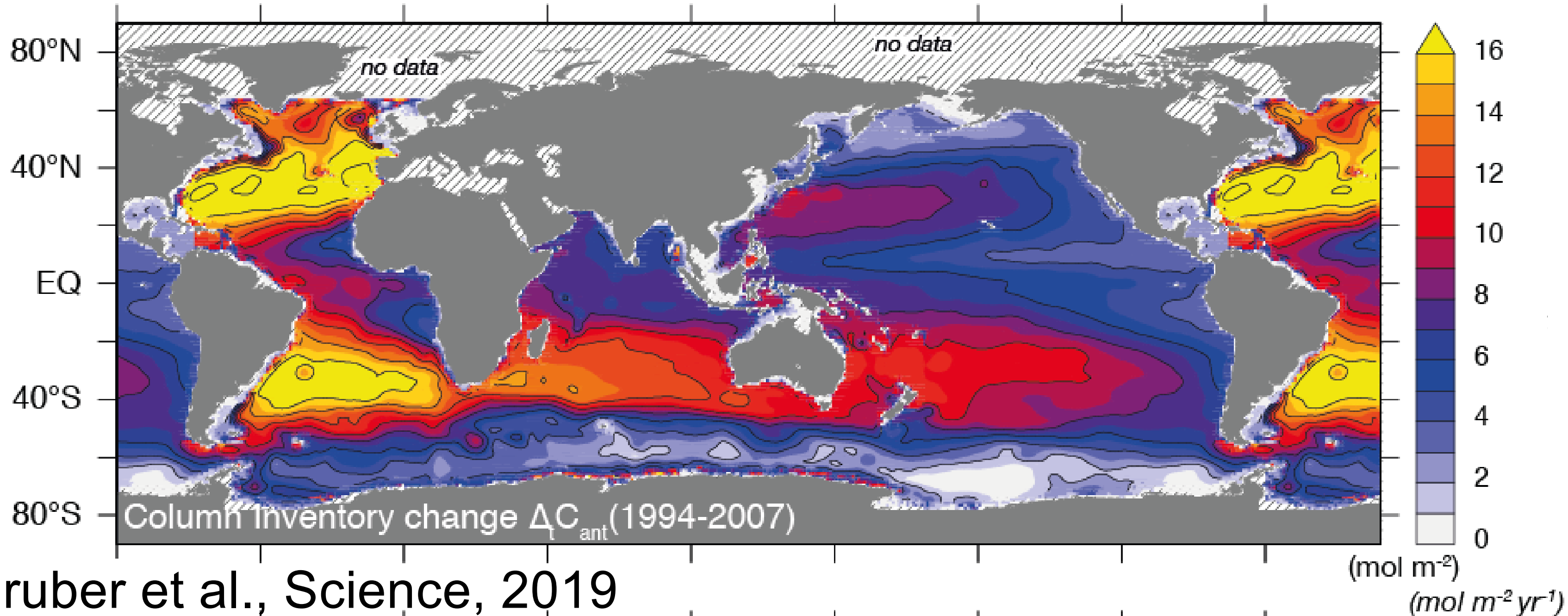
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$
Carbonate

280 µatm	560 µatm
8 µmol kg^{-1}	15 µmol kg^{-1}
1617 µmol kg^{-1}	1850 µmol kg^{-1}
268 µmol kg^{-1}	176 µmol kg^{-1}
1893 µmol kg^{-1}	2040 µmol kg^{-1}

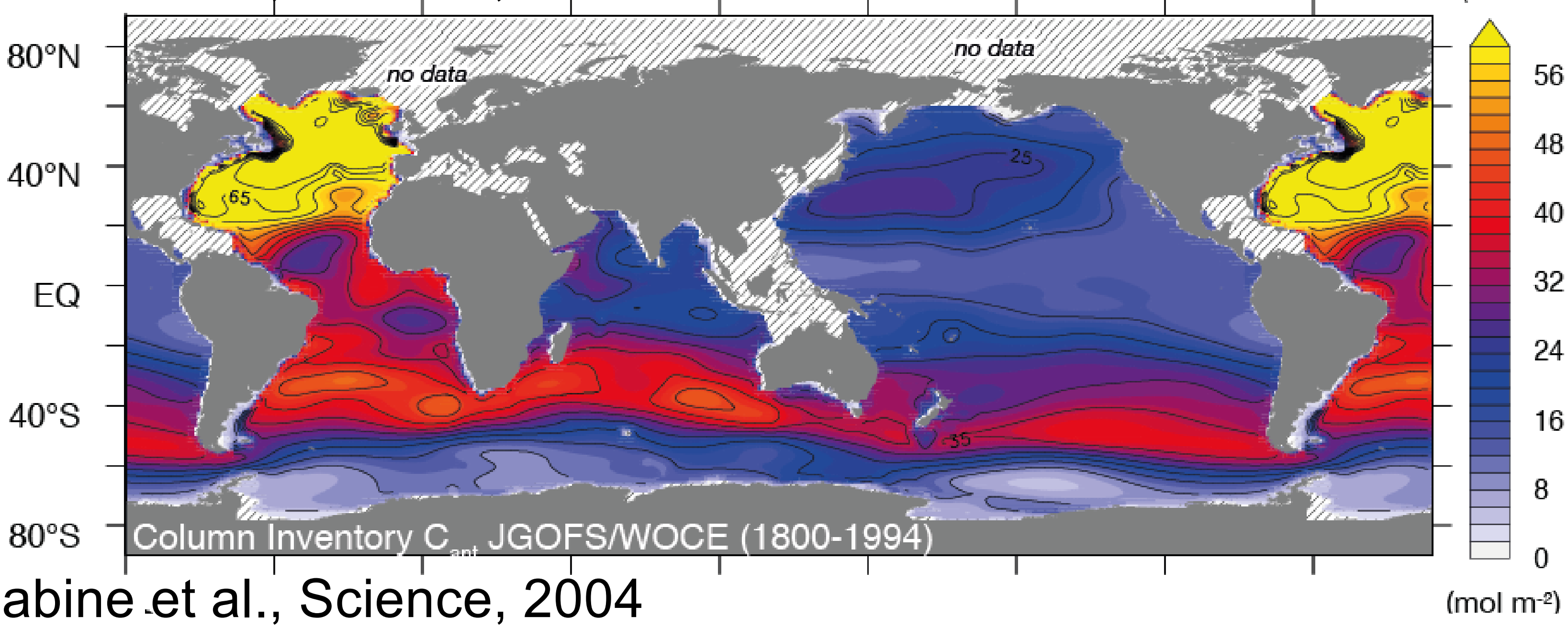
100% $\Delta pCO_2 \rightarrow$ 8% ΔTCO_2

Taken from Feely et al. (2001)

Measurement-Based Inventory Change Estimates Confirm An Average Global Uptake Rate of 2.6+/-0.3 PgC/yr between 1994 and 2007



Gruber et al., Science, 2019



Sabine et al., Science, 2004

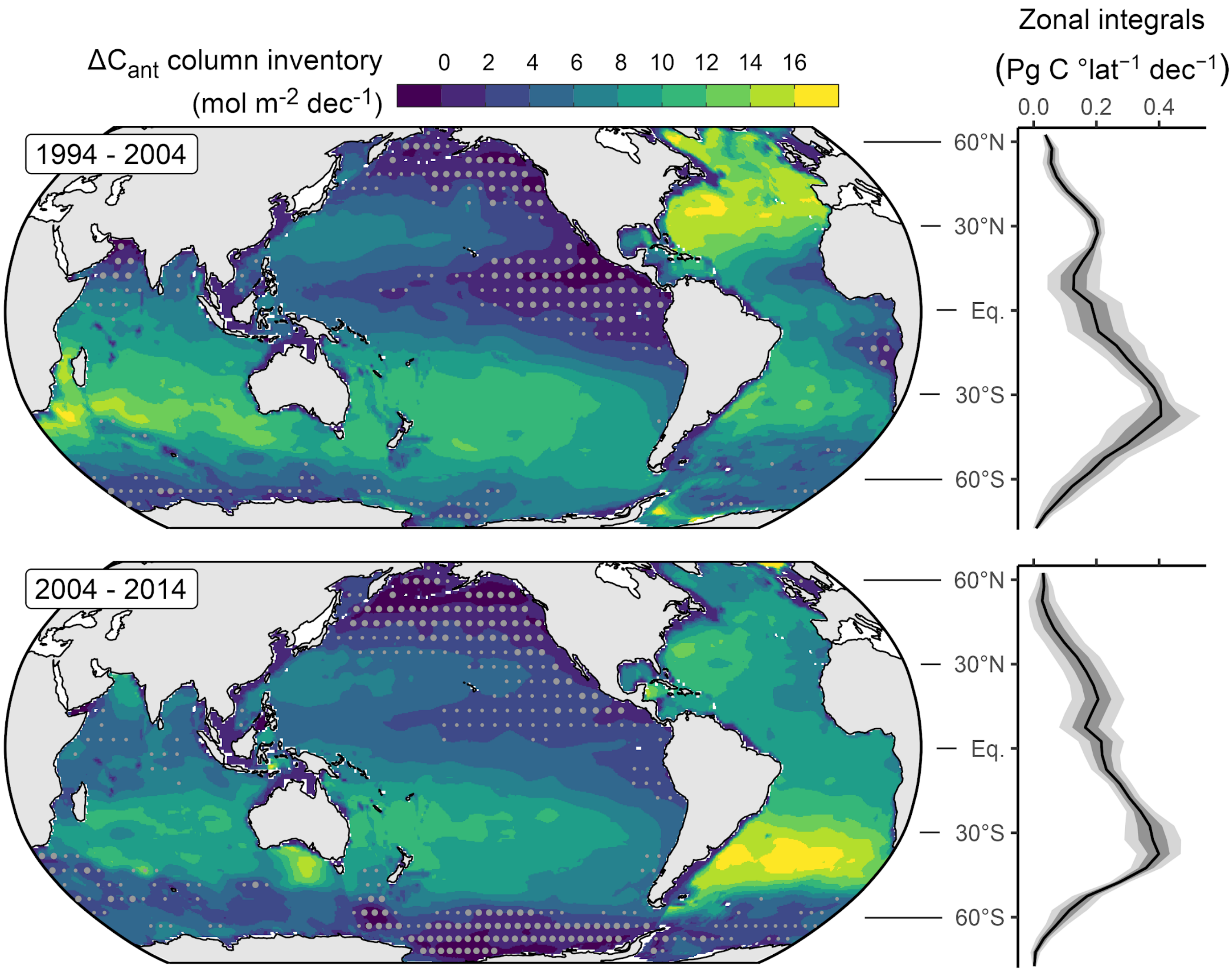
Total <u>Inventory</u>

2007:
154 PgC

24% increase in 13 years

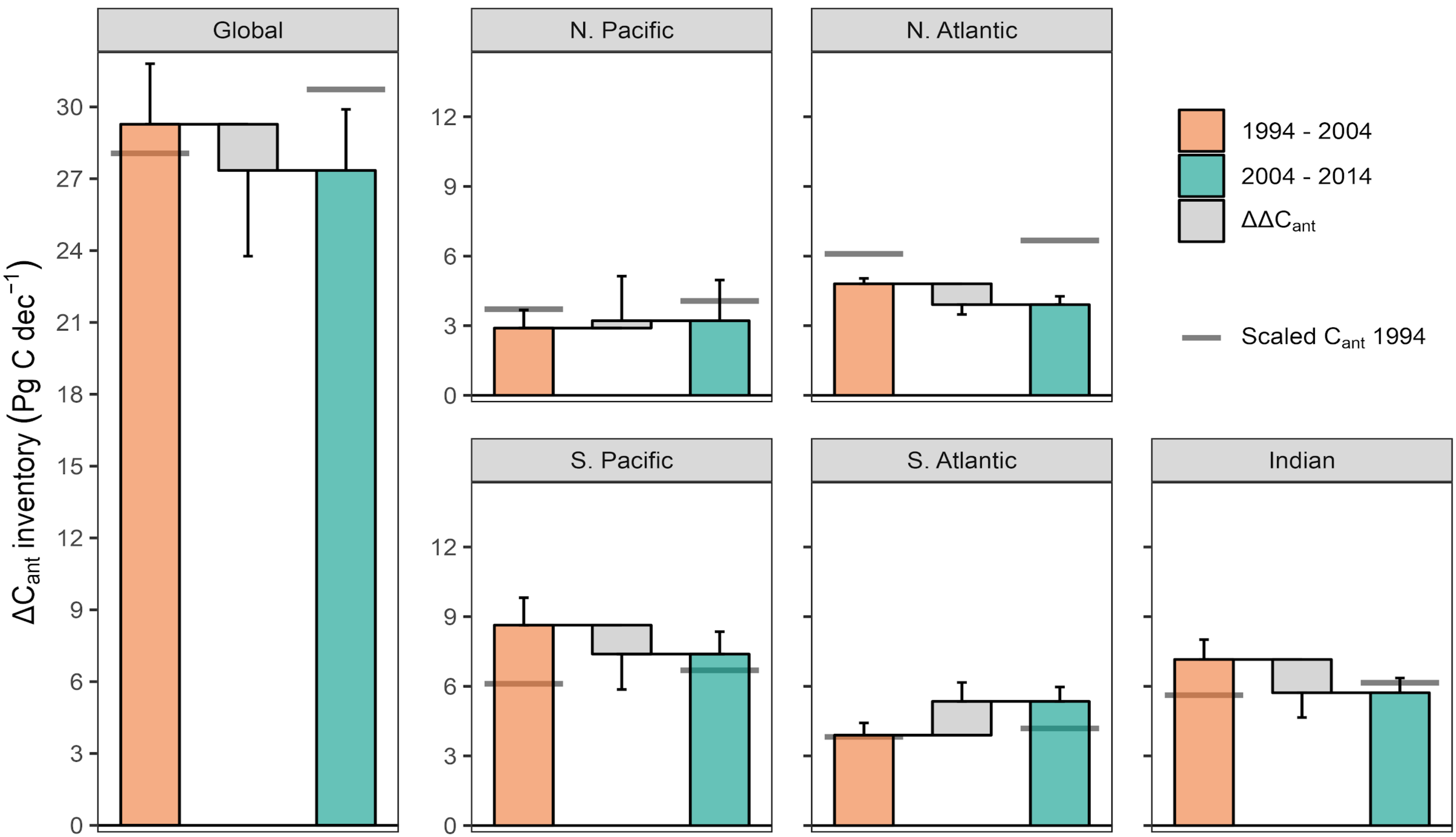
1994:
118 PgC

Column Inventory Maps and Zonal Integrals of Anthropogenic Carbon



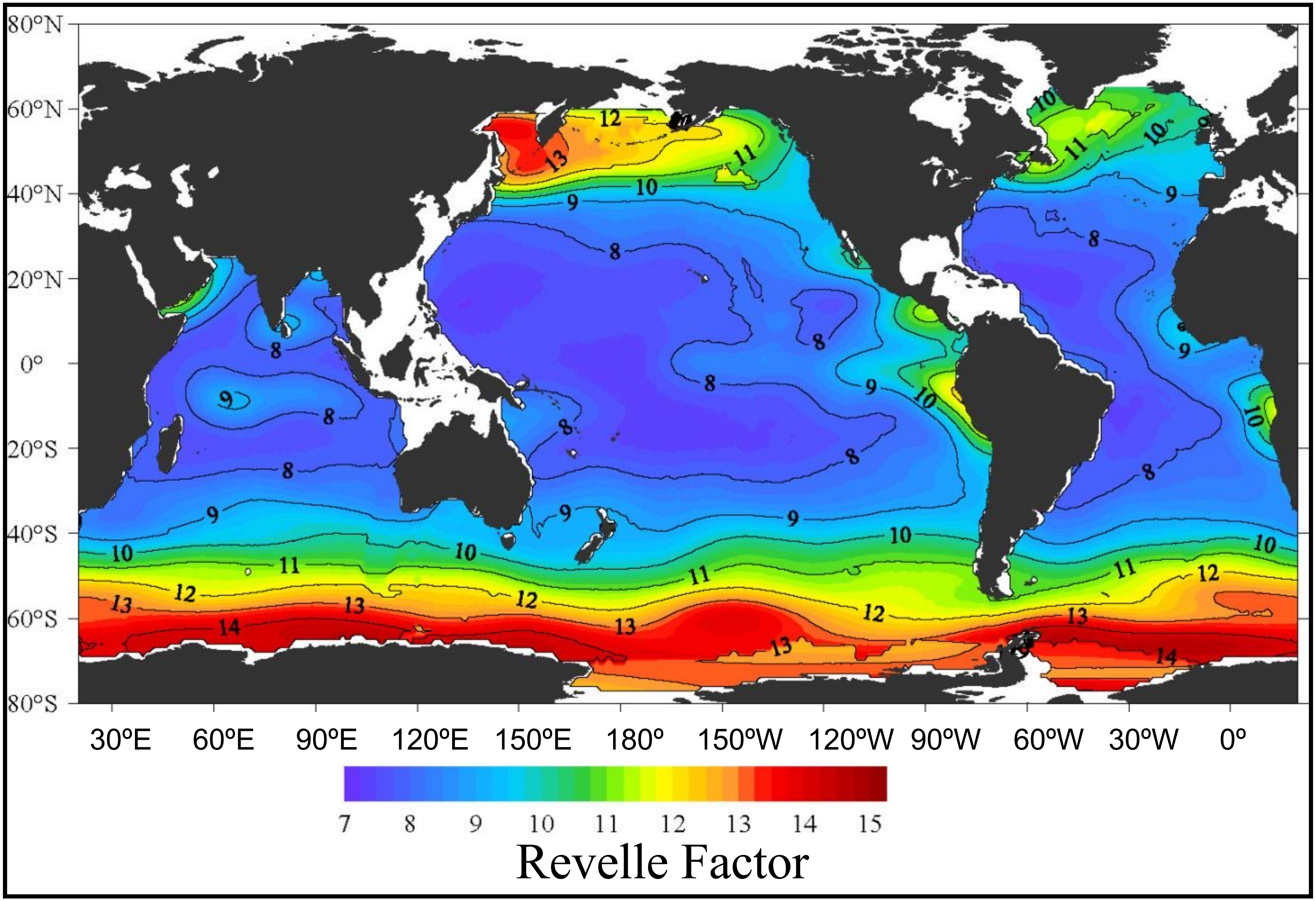
Müller et al. (2023)

Change in Anthropogenic Carbon Storage Over Two Decades



Müller et al. (2023)

Global Distribution of Surface Revelle Factor



R. Revelle, H.,E. Suess, Tellus 9, 18 (1957)

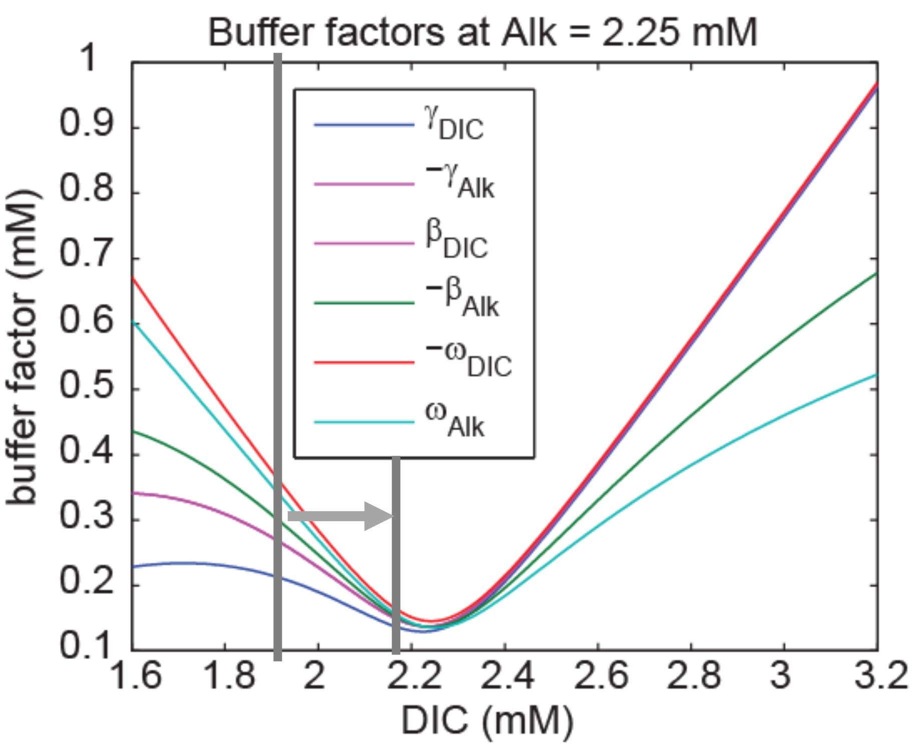
$$\frac{(\Delta fCO_2/\Delta DIC)}{(fCO_2/\ DIC)}$$

Egleston et al. (GBC, 2010) define six new buffer factors, each of which can be explicitly calculated:

$$\gamma_{DIC} = \left(\frac{\partial \ln[CO_2]}{\partial DIC} \right)^{-1} = DIC - \frac{Alk_C^2}{S} \qquad S = [HCO_3^-] + 4[CO_3^{2-}] + \frac{[H^+][B(OH)_4^-]}{K_{hb} + [H^+]} + [H^+] - [OH^-]$$

Revelle Factor = DIC/γ_{DIC}

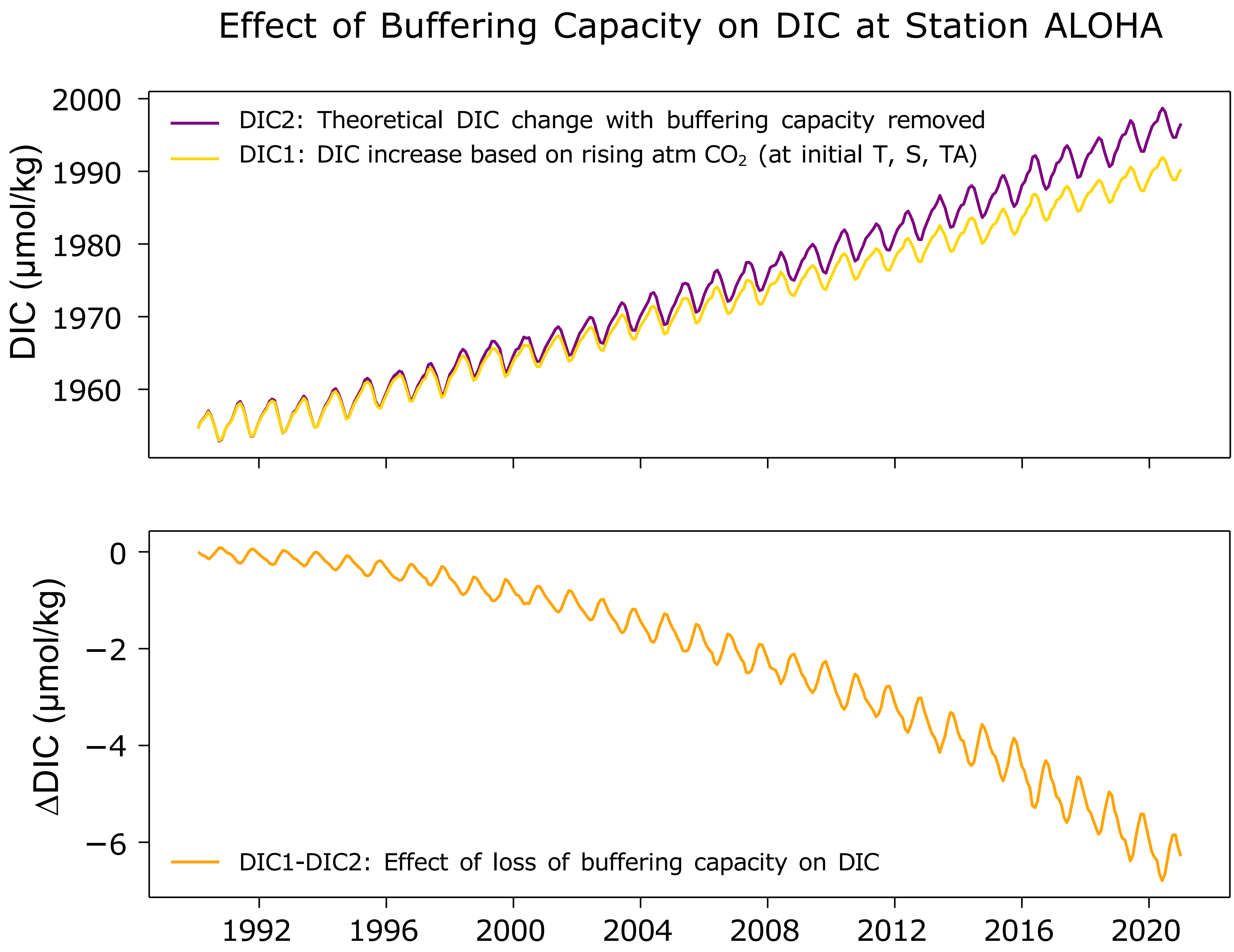
equivalent to traditional Revelle Factor that can be used to determine the efficiency of the ocean sink as CO_2 rises



Between the preindustrial and 2000 we expect to see a 25% decrease in uptake efficiency

A doubling of CO_2 (560 ppm) results in a 60% decrease in uptake efficiency

A tripling of CO_2 (840 ppm) results in a 75% decrease in uptake efficiency



Effect of Buffering Capacity on DIC at Station ALOHA
DIC2: Theoretical DIC change with buffering capacity removed
DIC1: DIC increase based on rising atm CO₂ (at initial T, S, TA)
DIC (µmol/kg)
2000
1990
1980
1970
1960
DIC1-DIC2: Effect of loss of buffering capacity on DIC
ΔDIC (µmol/kg)
0
−2
−4
−6
1992
1996
2000
2004
2008
2012
2016
2020

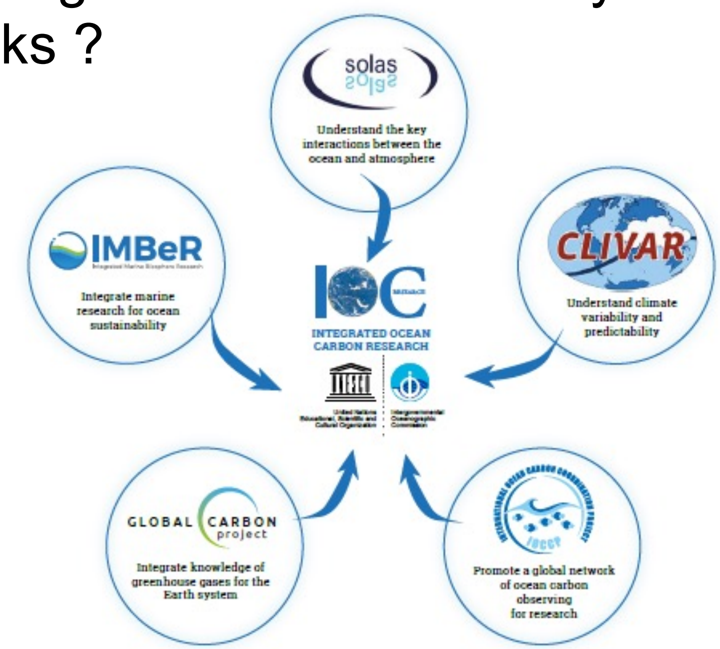
Fundamental and Emerging Research Questions

Will the ocean uptake of anthropogenic carbon dioxide continue as primarily an abiotic process ?

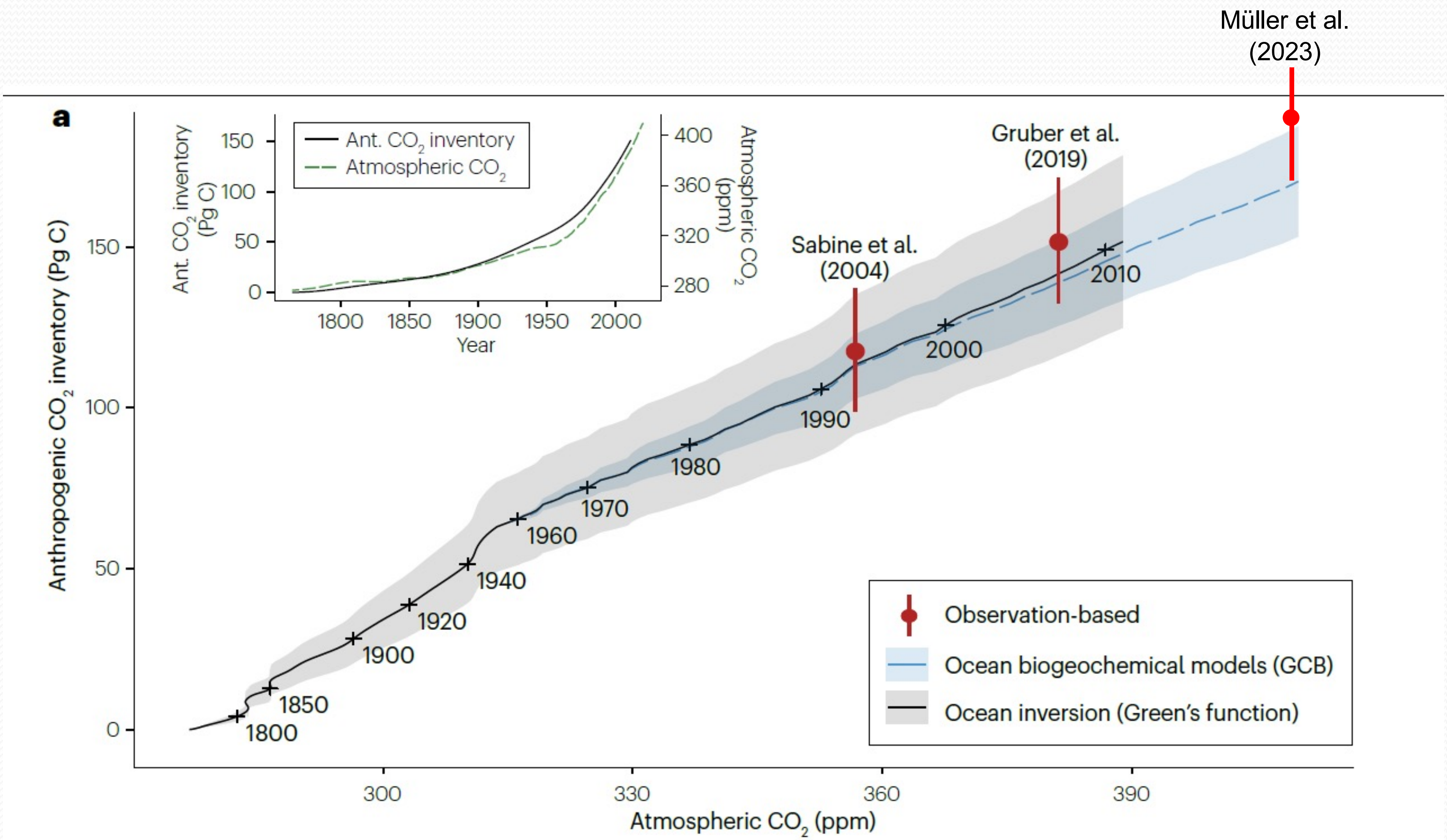
What is the role of biology in the ocean carbon cycle and how is it changing ?

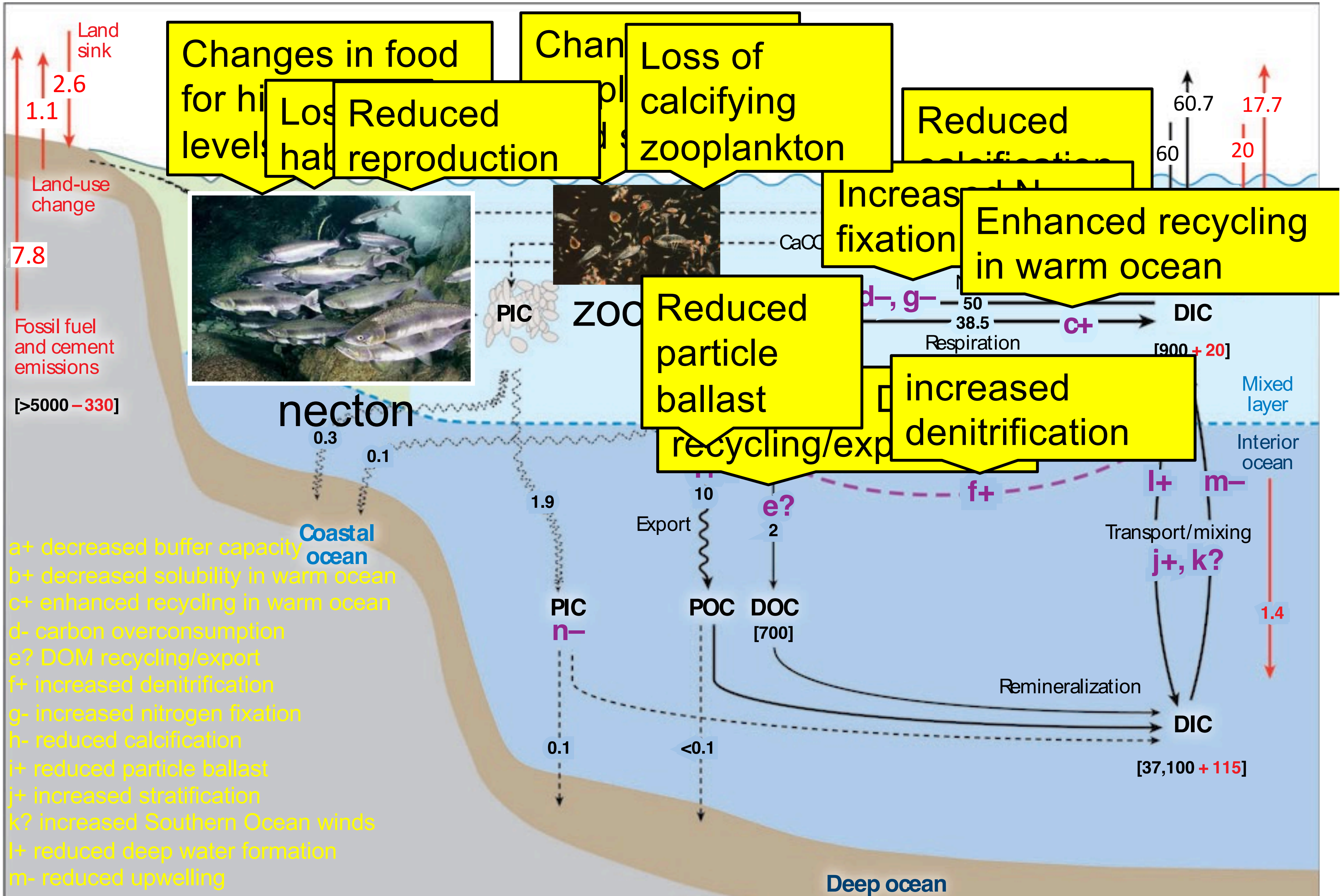
What are the exchanges of carbon between the land-ocean-ice continuum ?

How are humans altering the ocean carbon cycle and resulting feedbacks ?



Anthropogenic CO_2 Inventory Increase Follows Atmospheric Trend

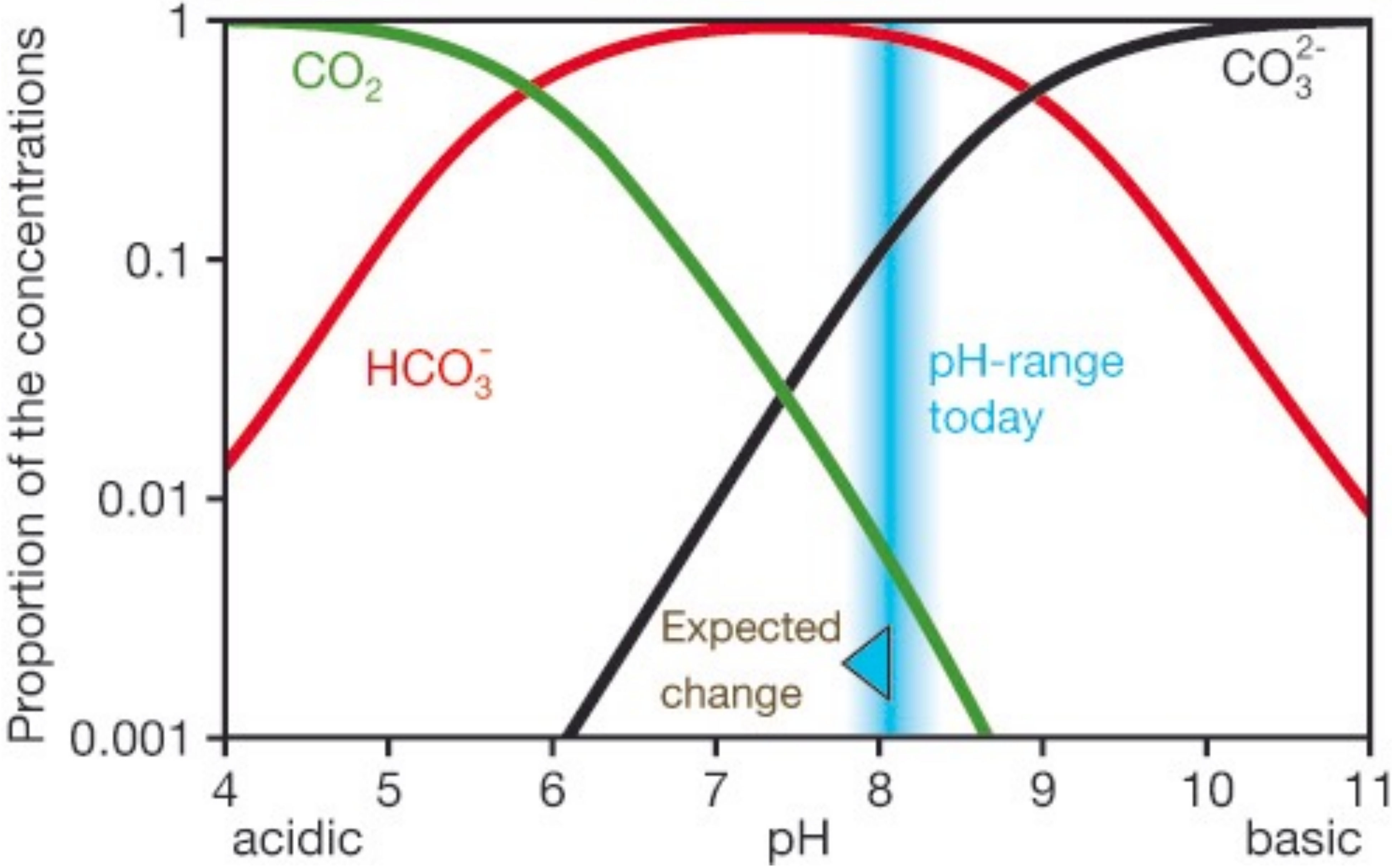




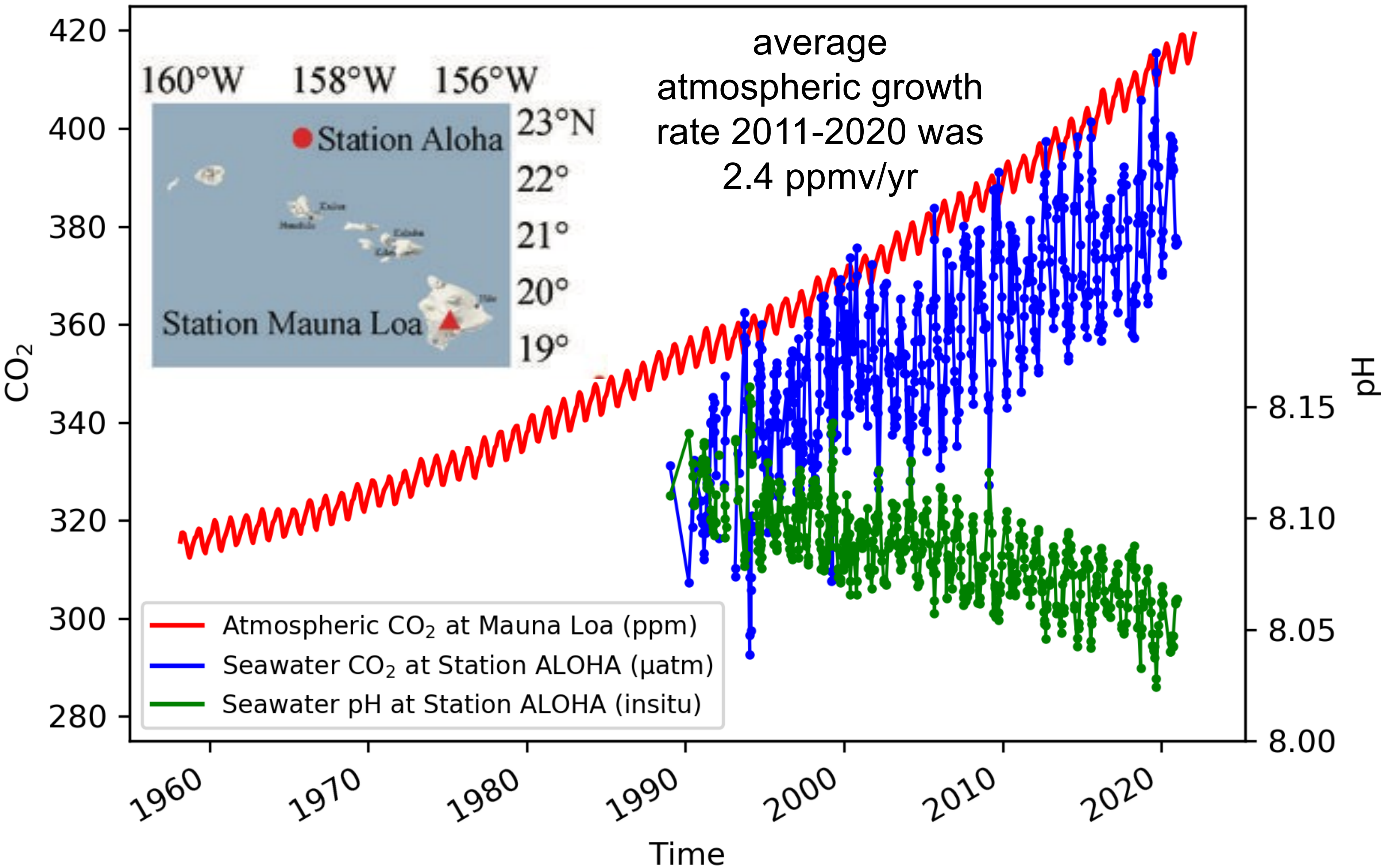
Adapted from Sabine and Tanhua 2009

$$CO_{2(aq)} + H_2O + CO_3^{2-} \longleftrightarrow 2HCO_3^-$$

$$CO_{2(aq)} + H_2O \longleftrightarrow HCO_3^- + H^+$$

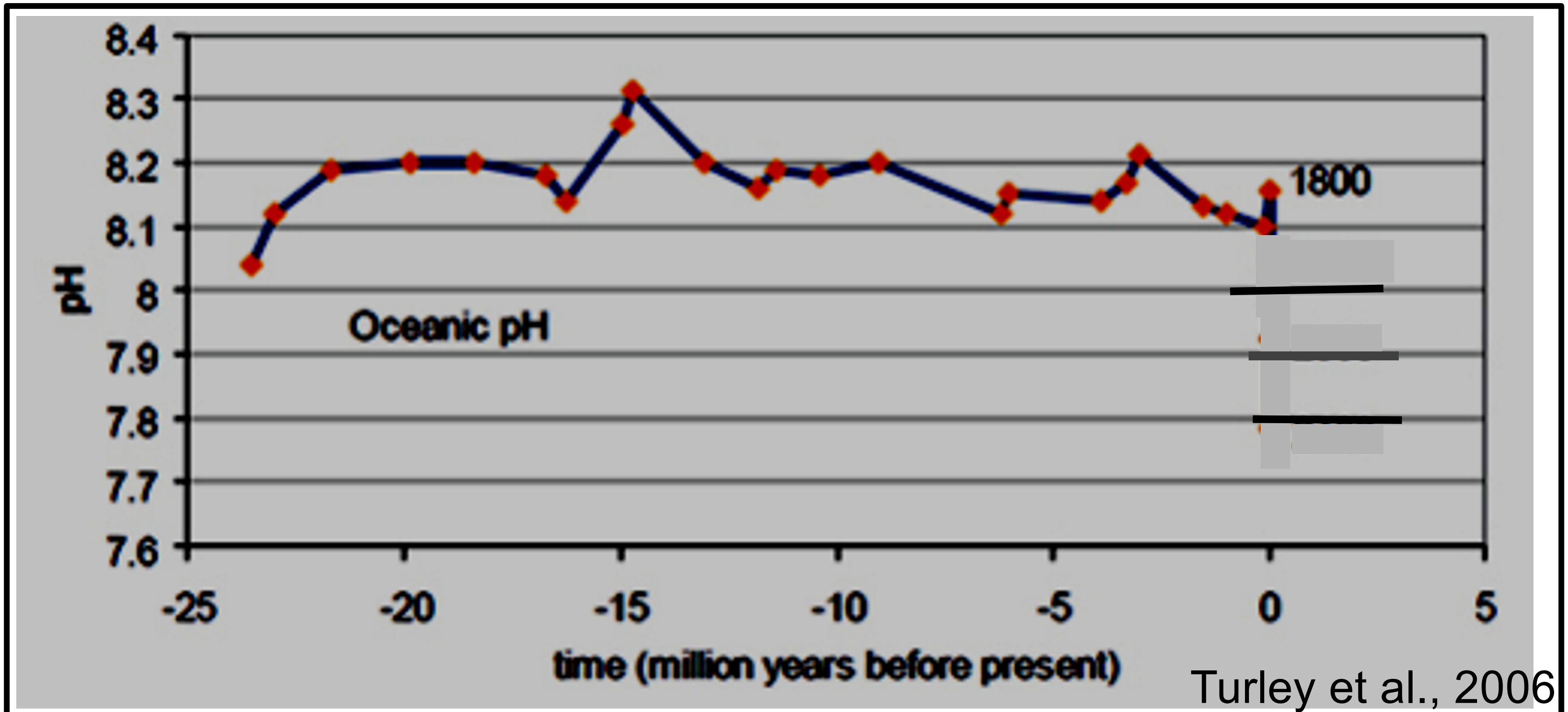


Surface Ocean pH Decreases as CO_2 Increases



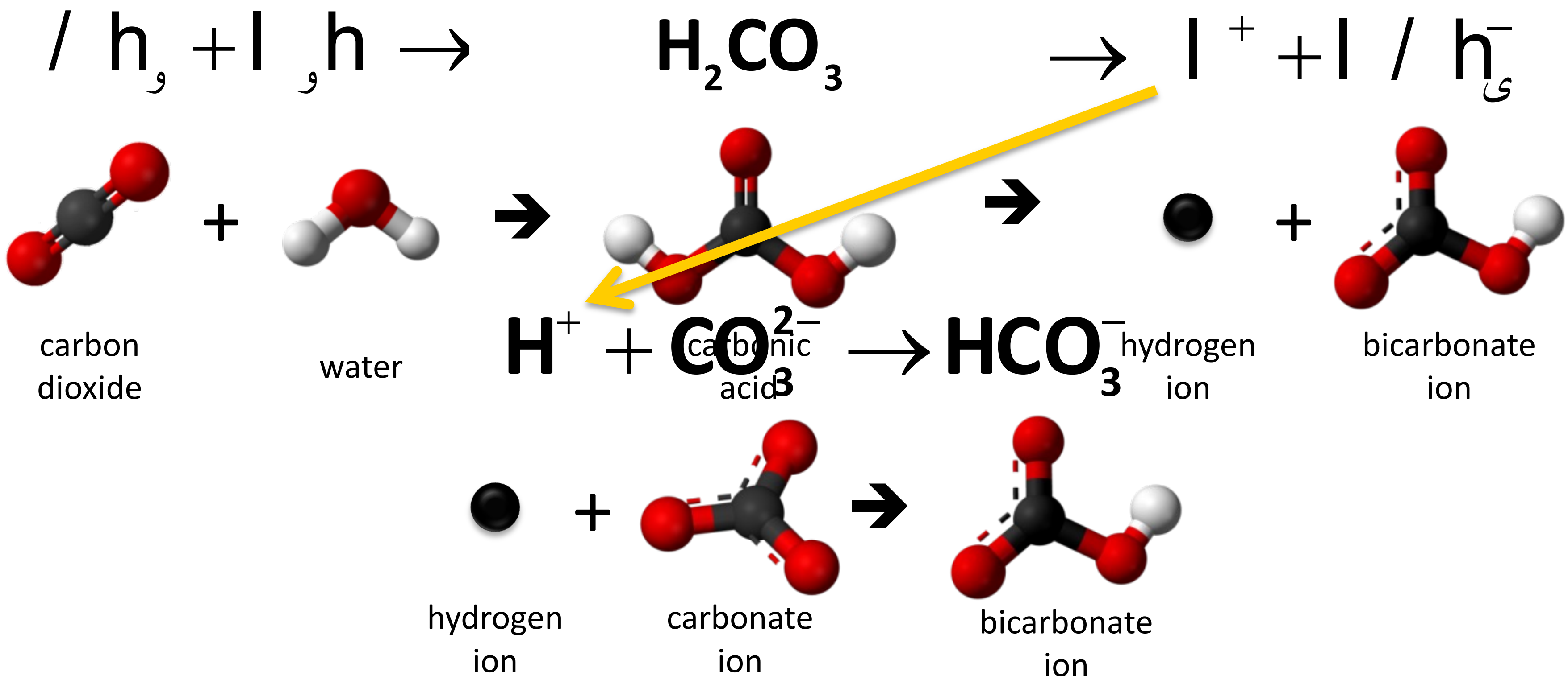
Ocean Acidification: Historical Perspective

- For the last 20 Million years the pH of the ocean has remained relatively stable between approximately 8.1 and 8.2
- The uptake of anthropogenic CO_2 has lowered ocean pH by 0.1, representing a 28% increase in acidity over the last 200 years.
- The estimated drop in pH by the end of the century is not only larger than seen over the last 20 million years, but is also at least 100 times faster than in the past.



Turley et al., 2006

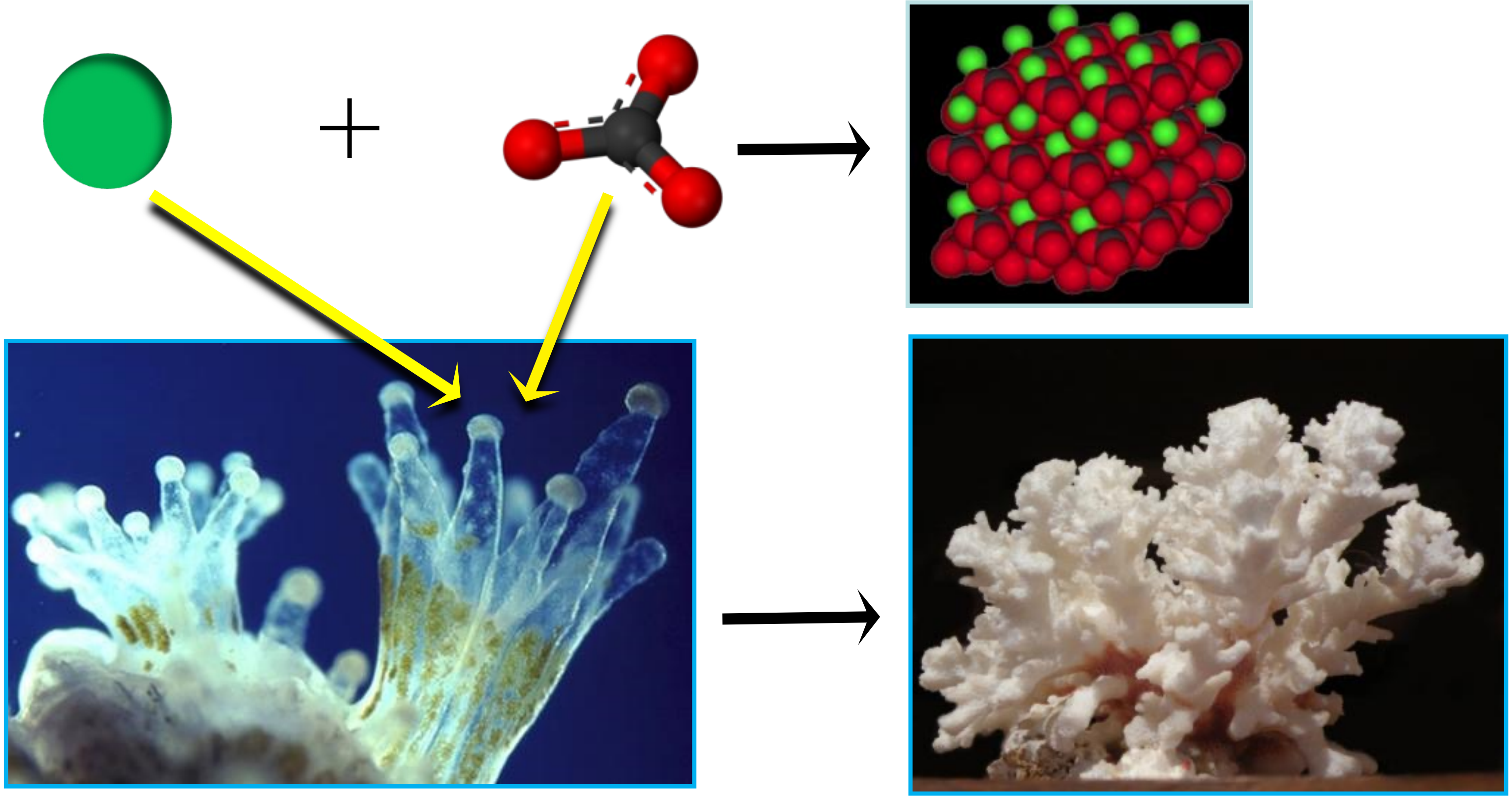
Ocean Acidification: Fundamental Chemistry



- More than 99% of the H^+ formed consume CO_3^{2-} to form HCO_3^- making it more difficult for organisms to form their shells.

Ocean Acidification: Fundamental Chemistry

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



Calcification Index

Saturation State

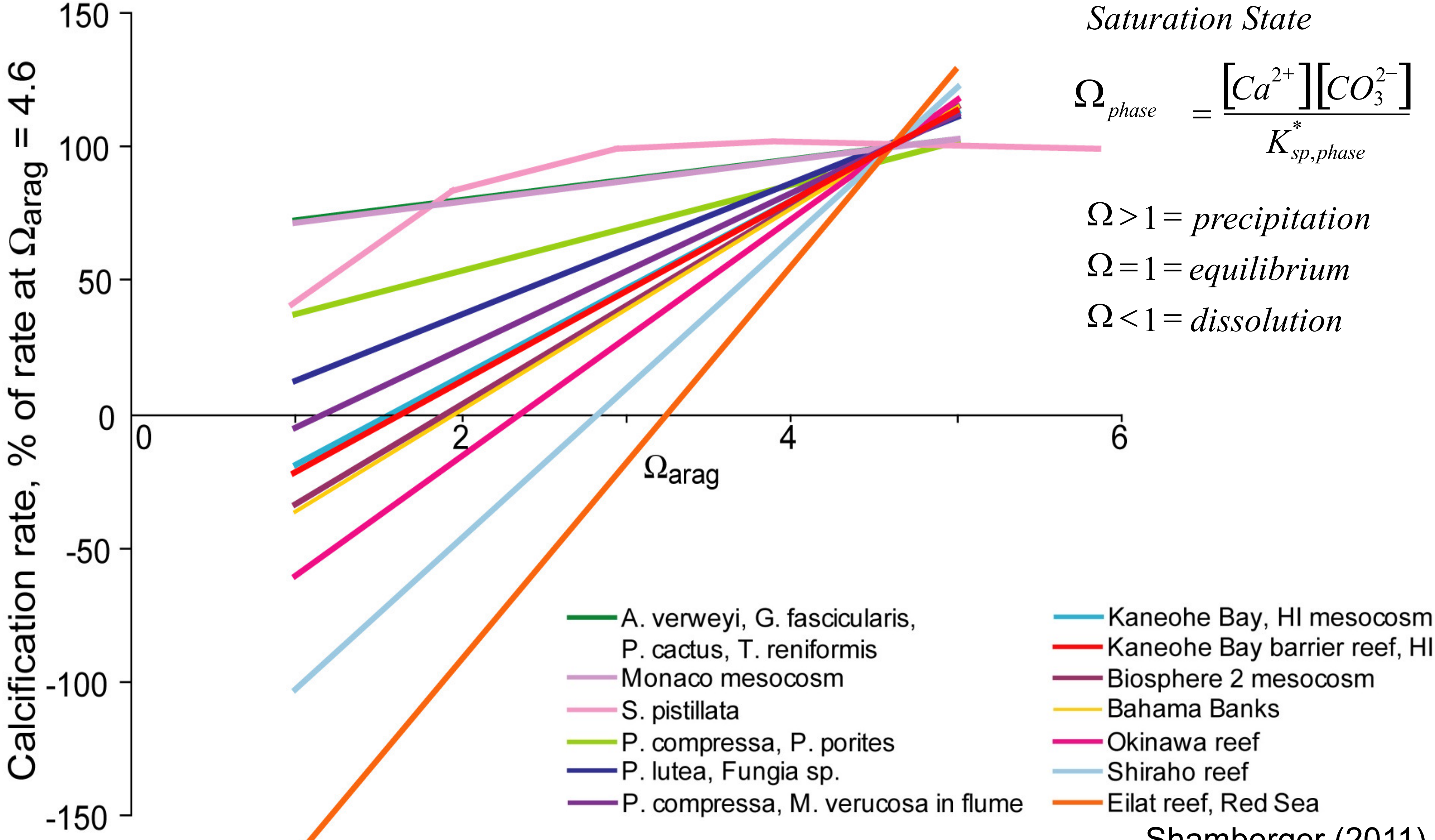
$$\Omega_{phase} = \frac{[Ca^{2+}][CO_3^{2-}]}{K^*_{sp,phase}}$$

$\Omega > 1$ $CaCO_3$ stable

$\Omega = 1$ equilibrium

$\Omega < 1$ $CaCO_3$ dissolves

Corals show a strong response to high CO_2/ low saturation state



Saturation State

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

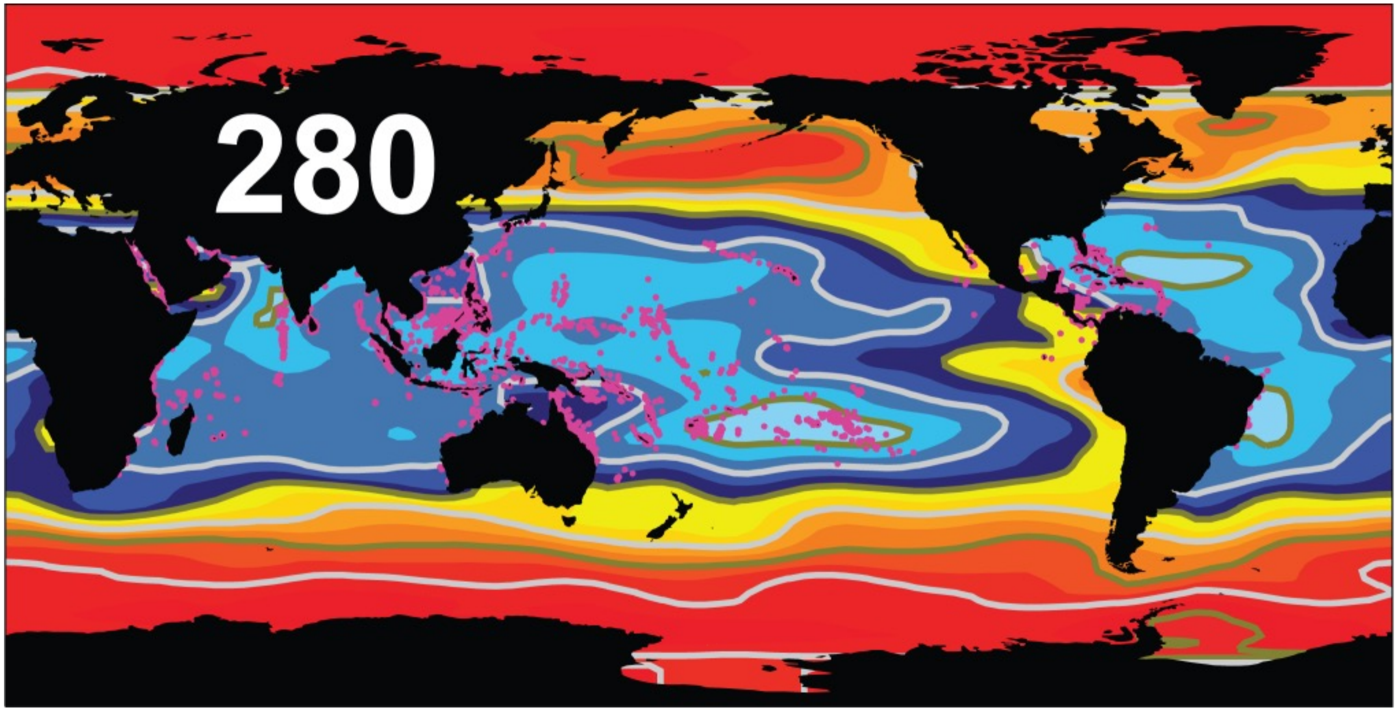
$\Omega > 1 = precipitation$

$\Omega = 1 = equilibrium$

$\Omega < 1 = dissolution$

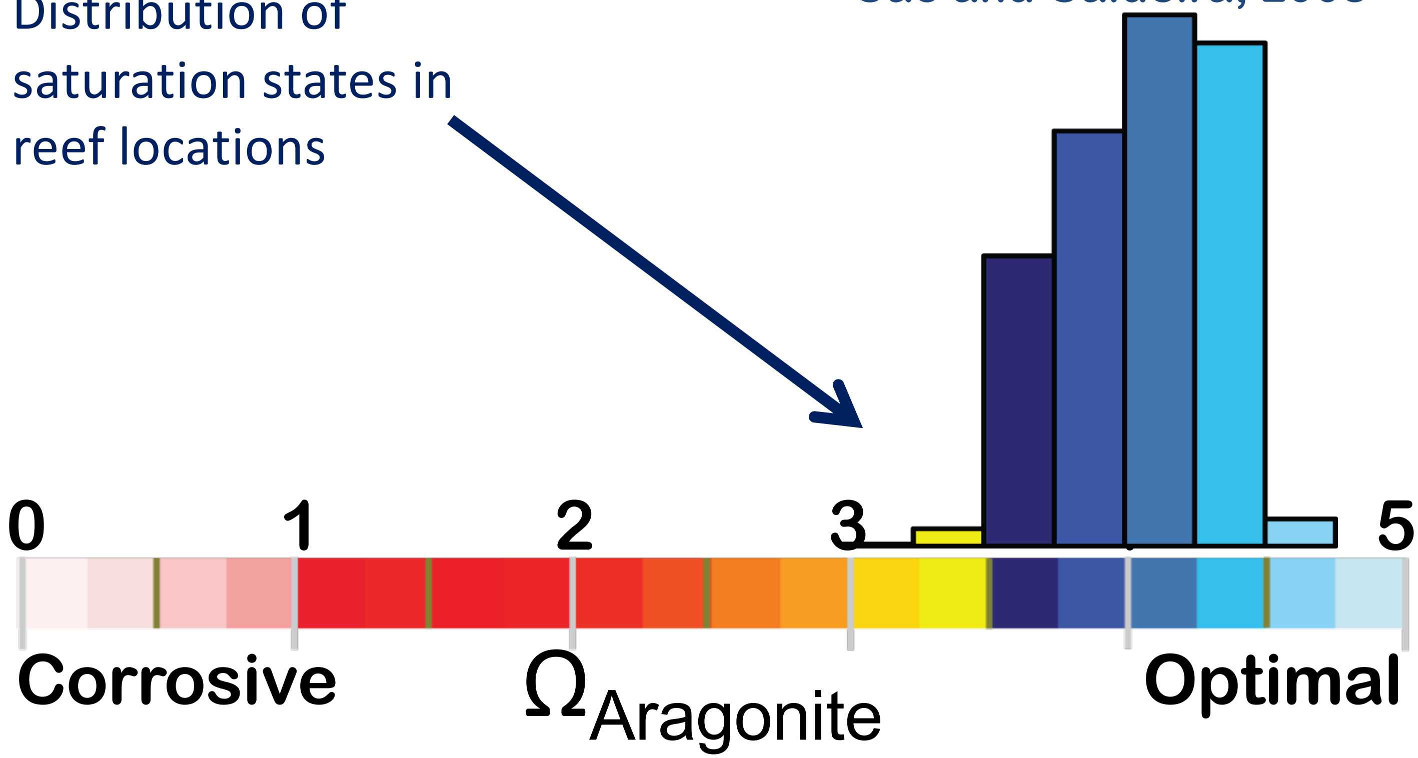
Shamberger (2011)

Surface Water Aragonite Saturation States in Preindustrial Times

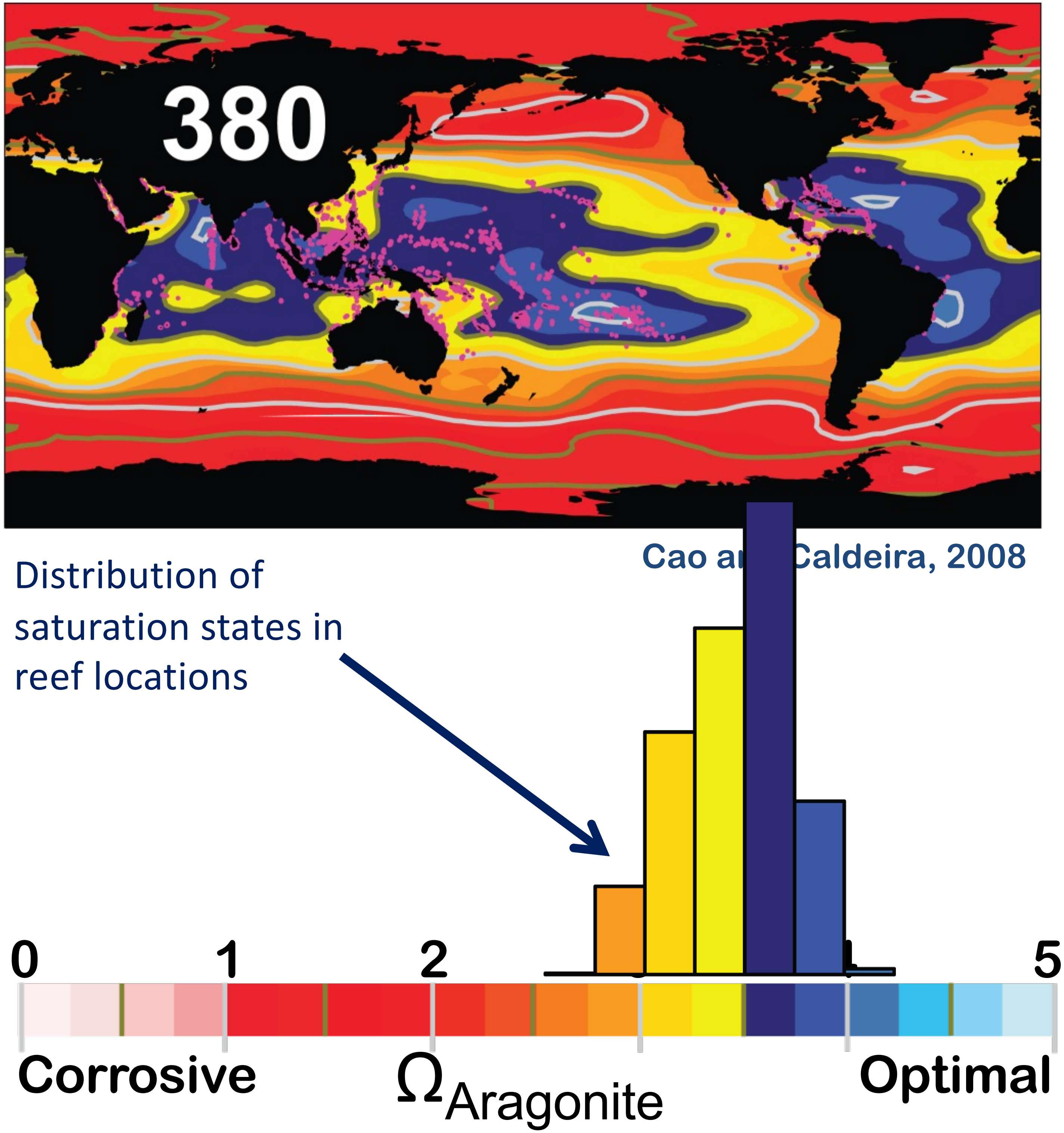


Cao and Caldeira, 2008

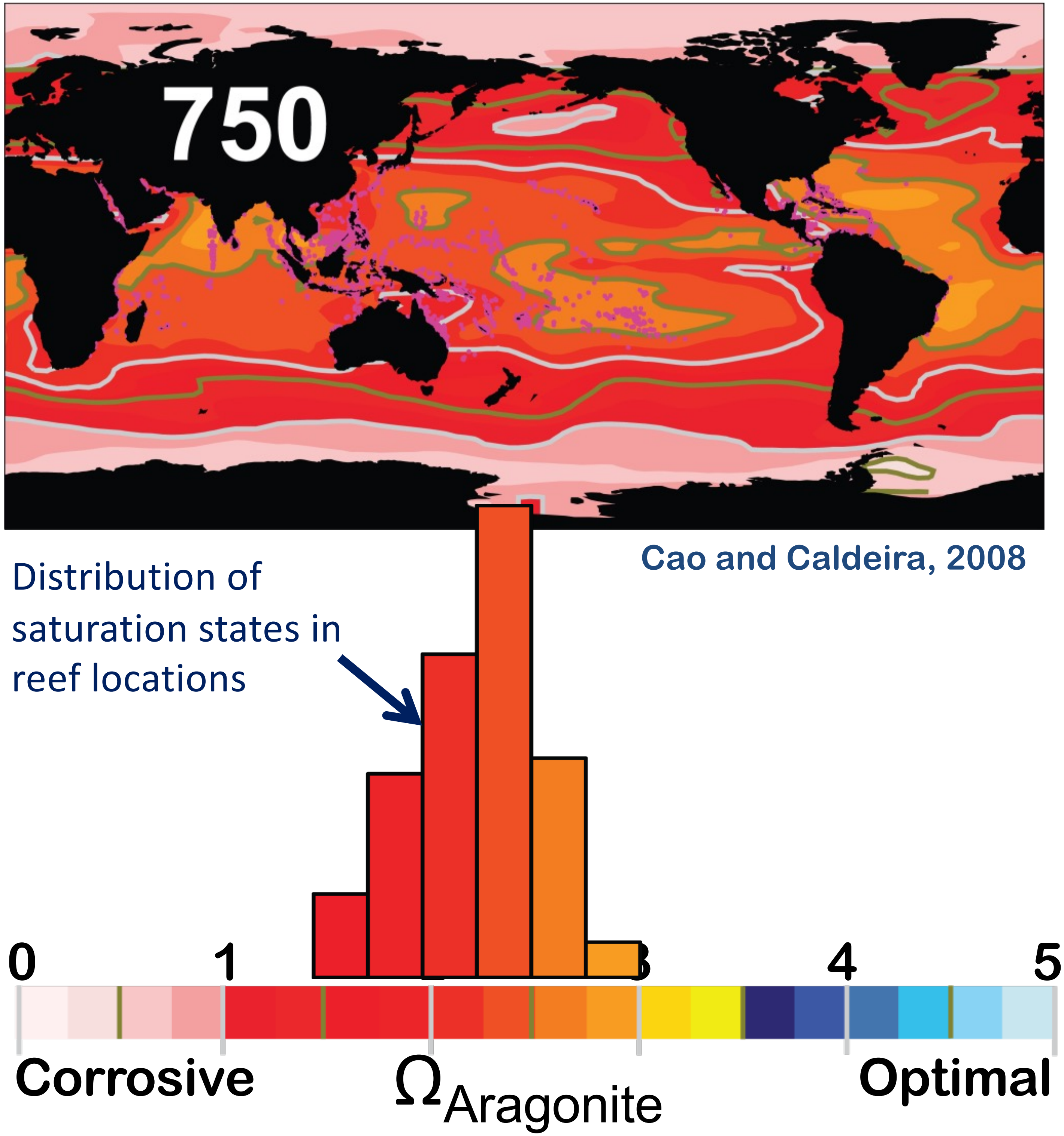
Distribution of saturation states in reef locations



Surface Water Aragonite Saturation States Circa 2000

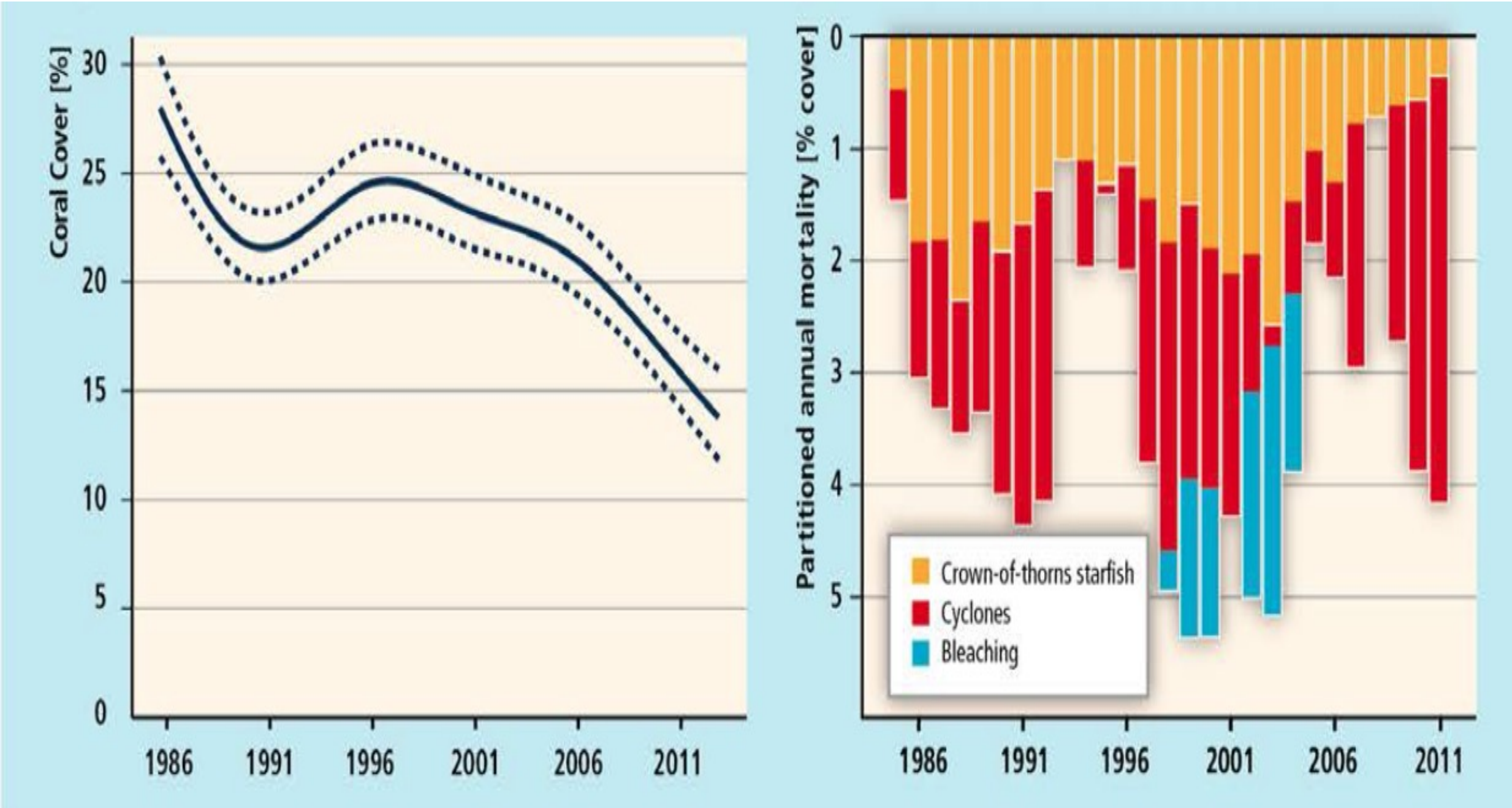


Surface Water Aragonite Saturation States Possible by 2100 or Earlier



Cao and Caldeira, 2008

Multiple Stressors on the Great Barrier Reef

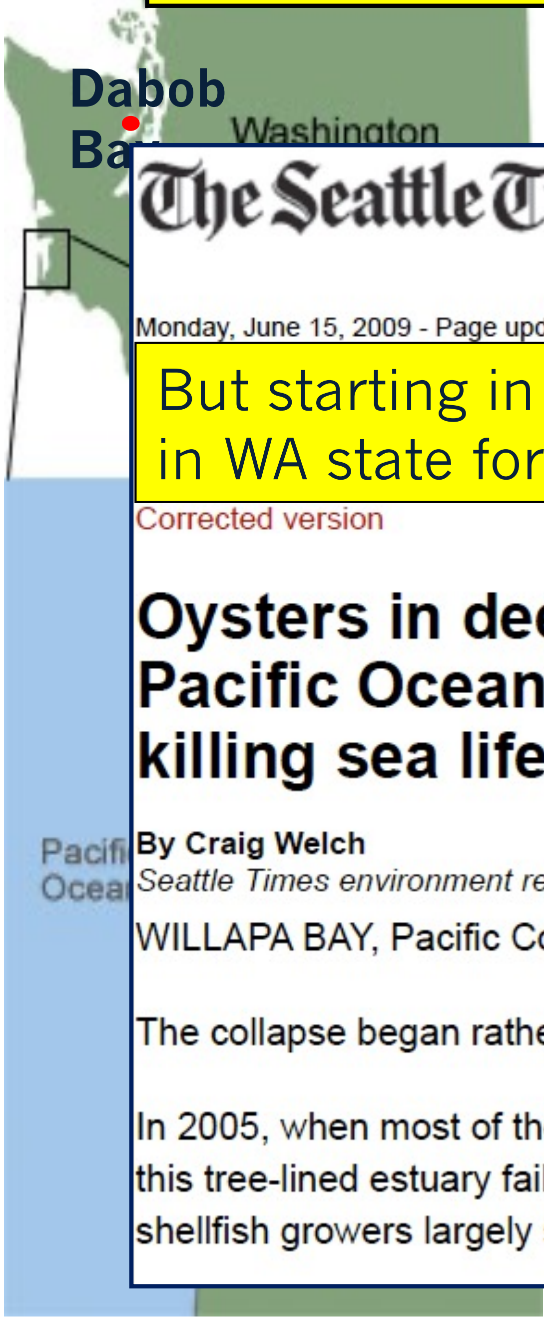


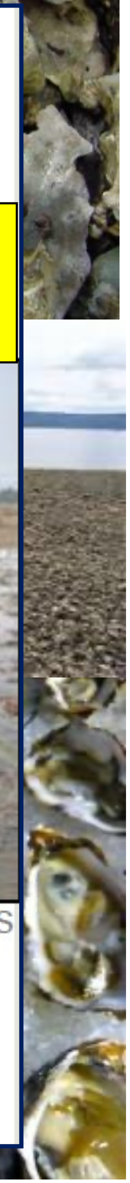
The Great Barrier Reef has seen a 50% reduction in coral cover over the last three decades

INTERGOVERNMENTAL PANEL ON climate change

Shellfish are a big business along the US West Coast

Commercial oyster Industry is $100M/yr in Pacific NW (3000 Jobs)





The Seattle Times

Monday, June 15, 2009 - Page updated at 11:38 AM

But starting in 2005 there was no natural recruitment of oysters in WA state for a decade in part due to ocean acidification…

Corrected version

Oysters in deep trouble: Is Pacific Ocean's chemistry killing sea life?

By Craig Welch
Seattle Times environment reporter

WILLAPA BAY, Pacific County â€”

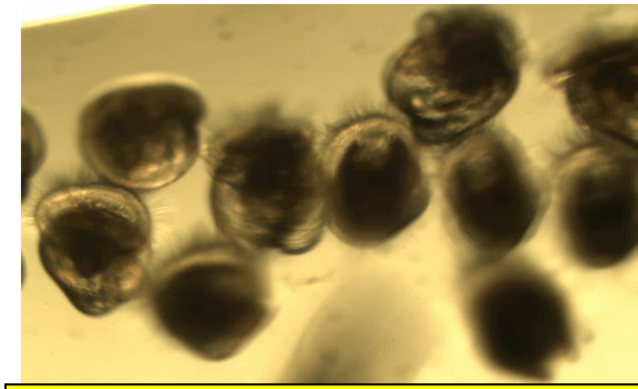
The collapse began rather unspectacularly.

In 2005, when most of the millions of Pacific oysters in this tree-lined estuary failed to reproduce, Washington's shellfish growers largely shrugged it off.

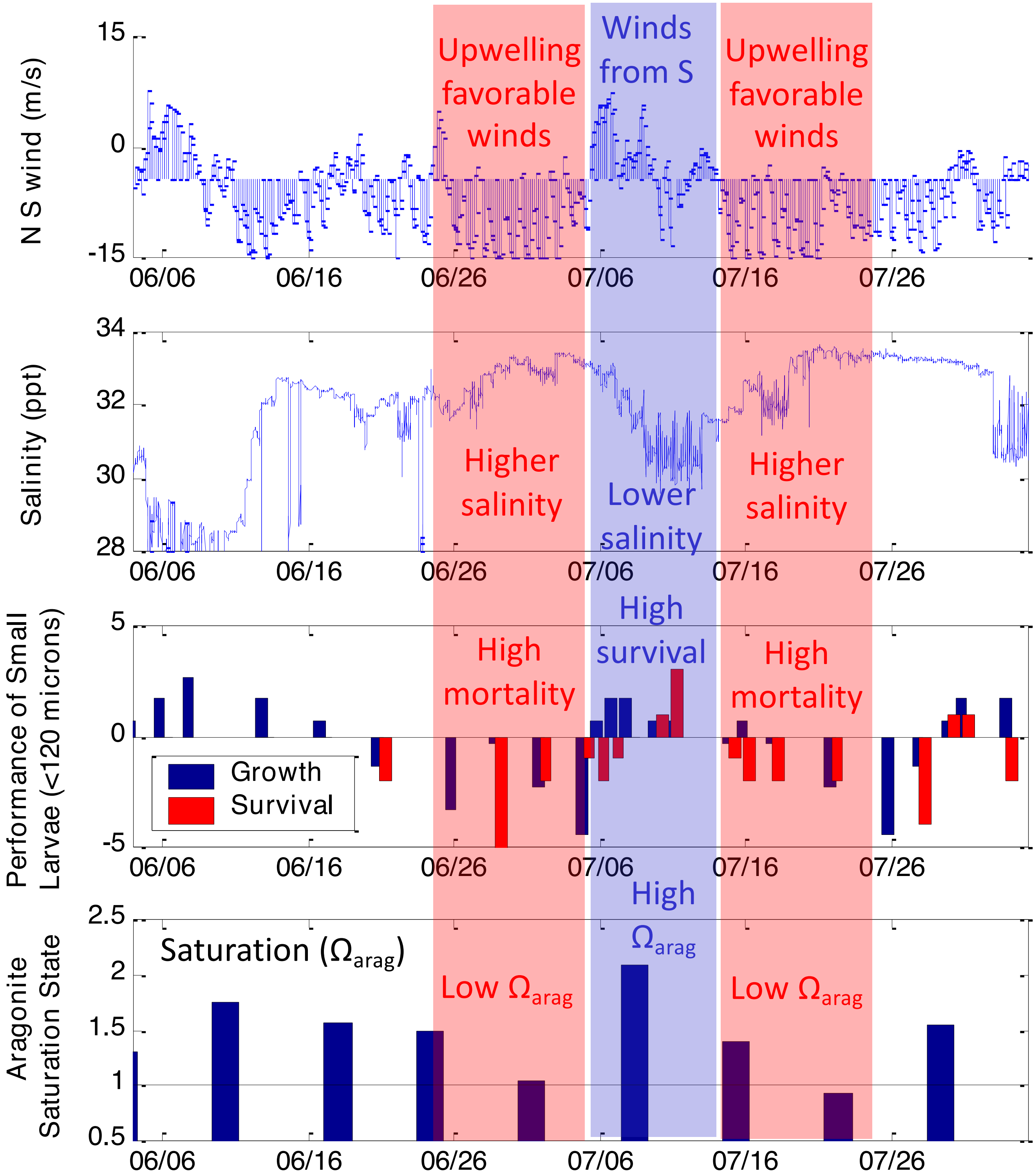
STEVE RINGMAN / THE SEATTLE TIMES

Oysters' failure to reproduce will lead workers like Northern Oyster Co.'s Gildardo Mendoza to collect far more of their product from a state "oyster preserve" in Willapa Bay. Pacific oysters haven't successfully reproduced in the wild since 2004.

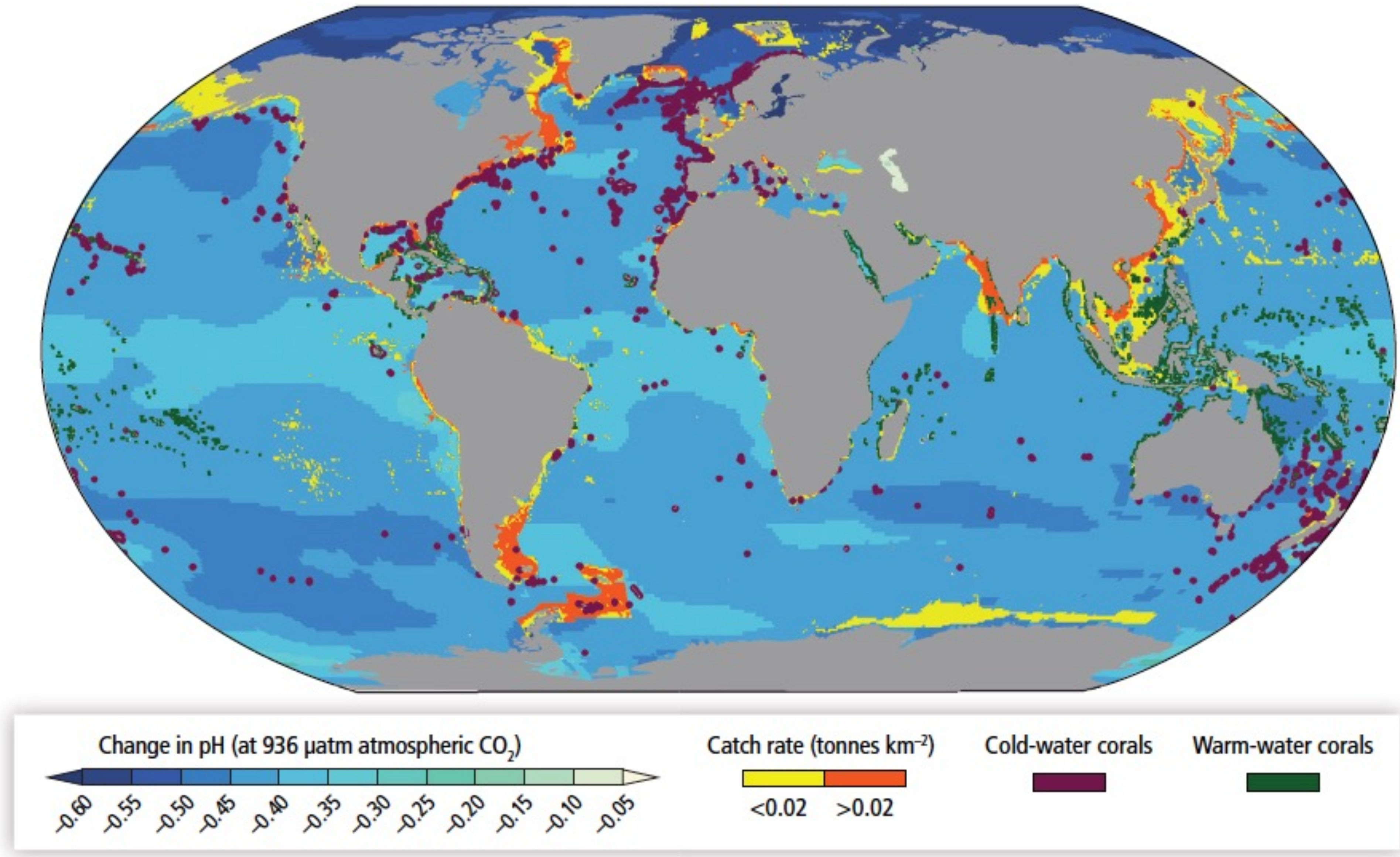
Seawater conditions linked to low recruitment



By turning off the water flow when the water showed low pH values, the hatcheries had their best year since the collapse saving the industry ~$35M in 2010.



Distribution of Societally Important Calcium Carbonate Species



INTERGOVERNMENTAL PANEL ON climate change

Concern for Marine Organisms and Ecosystems

- Reduced calcification rates
- Increased photosynthesis and nitrogen fixation
- Reduced growth, production and life span of adults, juveniles & larvae
- Reduced tolerance to other environmental fluctuations
- Significant shift in key nutrient and trace element speciation

Changes to:

- Fitness and survival
- Species biogeography
- Key biogeochemical cycles
- Food webs

Reduced:

- Sound Absorption
- Homing Ability
- Recruitment and Settlement