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

19 April 2018

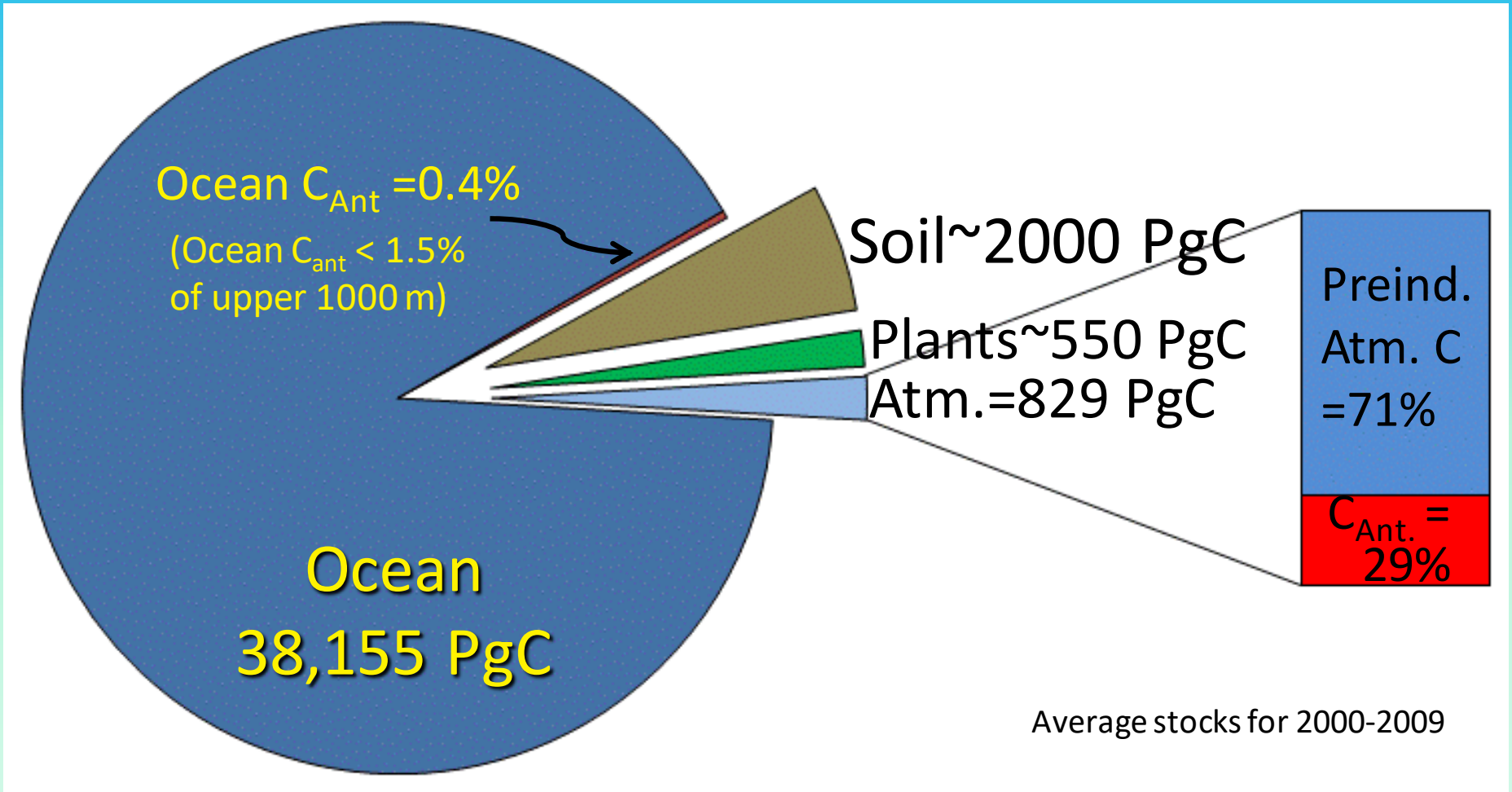
Reading: Libes, Chapter 25

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



- 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

$H_3CO_2 \leftrightarrow H^+ + HCO_3^-$

Bicarbonate

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

Carbonate

$pCO_2 = xCO_2 \cdot P$

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

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

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

$CO_2 + CO_3^{2-} \leftrightarrow 2\,HCO_3^-$

Ocean Carbon Chemistry Review

$CO_{2(gas)}$

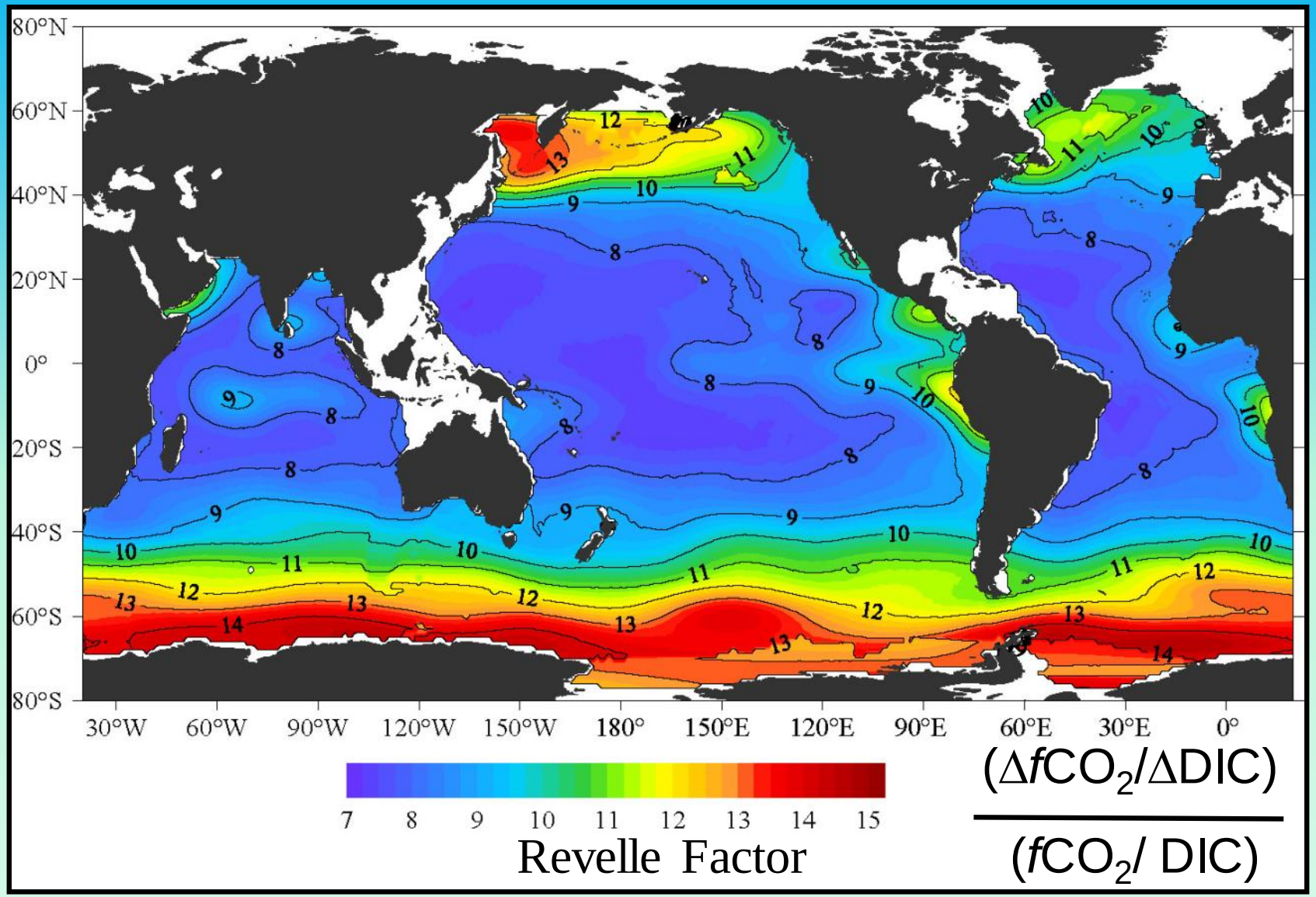
	280 μatm	560 μatm
$CO_2 + H_2O \leftrightarrow H_2CO_3$ Carbonic acid	8 μmol kg^{-1}	15 μmol kg^{-1}
$H_3CO_2 \leftrightarrow H^+ + HCO_3^-$ Bicarbonate	1617 μmol kg^{-1}	1850 μmol kg^{-1}
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$ Carbonate	268 μmol kg^{-1}	176 μmol kg^{-1}
	1893 μmol kg^{-1}	2040 μmol kg^{-1}

$CO_2 + CO_3^{2-} \leftrightarrow 2\,HCO_3^-$

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

Taken from Feely et al. (2001)

Global Distribution of Surface Revelle Factor



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

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

$$\gamma_{\mathrm{DIC}} = \left(\frac{\partial \ln[\mathrm{CO_2}]}{\partial \mathrm{DIC}}\right)^{-1} = \mathrm{DIC} - \frac{\mathrm{Alk_C^2}}{S}$$

equivalent to traditional Revelle Factor that can be used to determine the efficiency of the ocean sink as CO_2 rises Revelle Factor = DIC/γ_{DIC}

$$\gamma_{\mathrm{Alk}} = \left(\frac{\partial \ln[\mathrm{CO_2}]}{\partial \mathrm{Alk}}\right)^{-1} = \frac{\mathrm{Alk_C^2} - \mathrm{DIC} \times S}{\mathrm{Alk_C}}$$

similar to Revelle Factor but looks at the impact of changing alkalinity on CO_2

$$\beta_{\mathrm{Alk}} = \left(\frac{\partial \ln[\mathrm{H^+}]}{\partial \mathrm{Alk}}\right)^{-1} = \frac{\mathrm{Alk_C^2}}{\mathrm{DIC}} - S$$

general buffer capacity – resistance of pH to addition of acid/base

$$\beta_{\mathrm{DIC}} = \left(\frac{\partial \ln[\mathrm{H^+}]}{\partial \mathrm{DIC}}\right)^{-1} = \frac{\mathrm{DIC} \times S - \mathrm{Alk_C^2}}{\mathrm{Alk_C}}$$

in practice this is equivalent to - γ_{Alk}

$$\omega_{\mathrm{DIC}} = \left(\frac{\partial \ln \Omega}{\partial \mathrm{DIC}}\right)^{-1} = \mathrm{DIC} - \frac{\mathrm{Alk_C} \times P}{[\mathrm{HCO_3^-}]}$$

a measure of the impact of DIC changes on saturation state

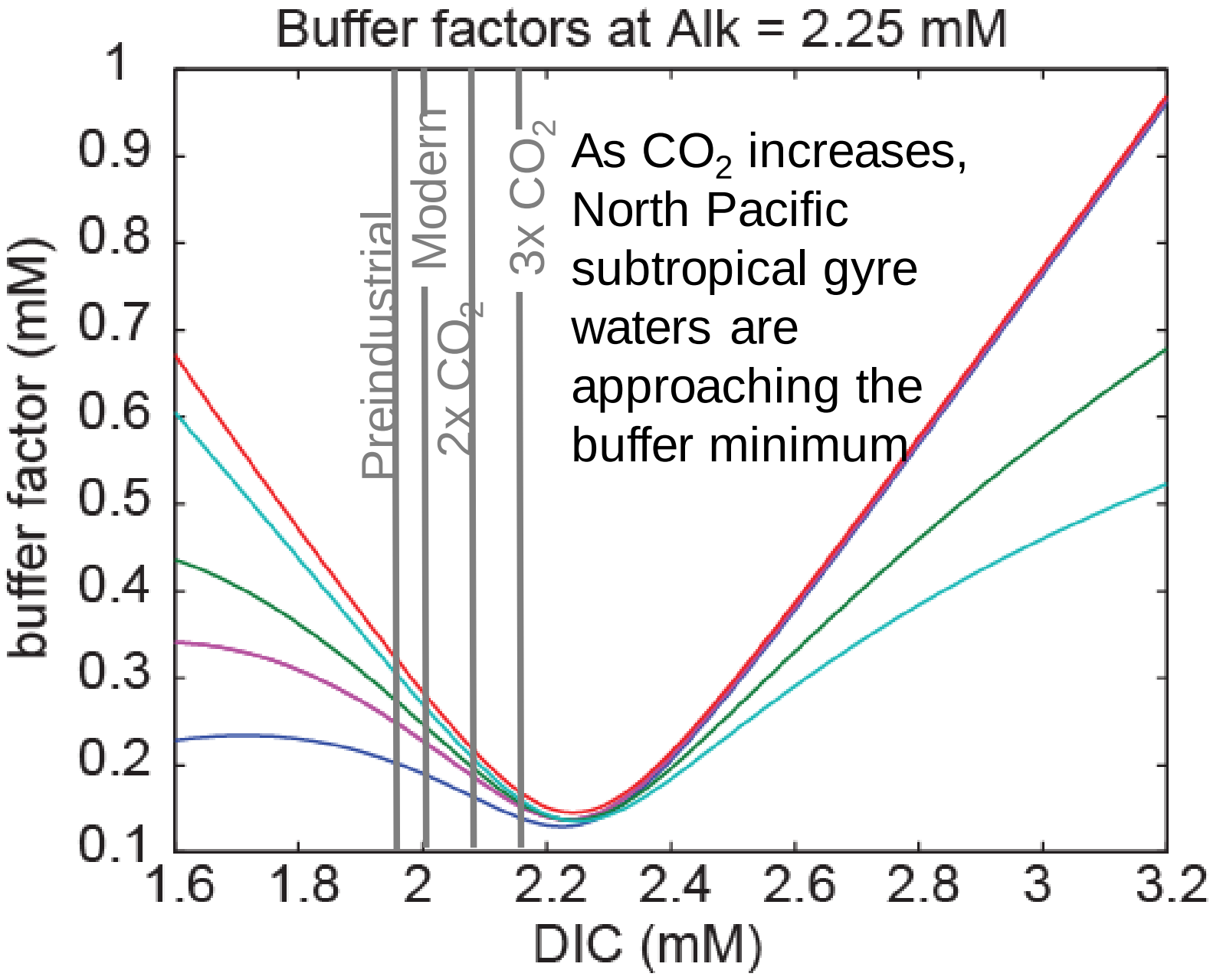
$$\omega_{\mathrm{Alk}} = \left(\frac{\partial \ln \Omega}{\partial \mathrm{Alk}}\right)^{-1} = \mathrm{Alk_C} - \frac{\mathrm{DIC}[\mathrm{HCO_3^-}]}{P}$$

a measure of the impact of alkalinity changes on saturation state

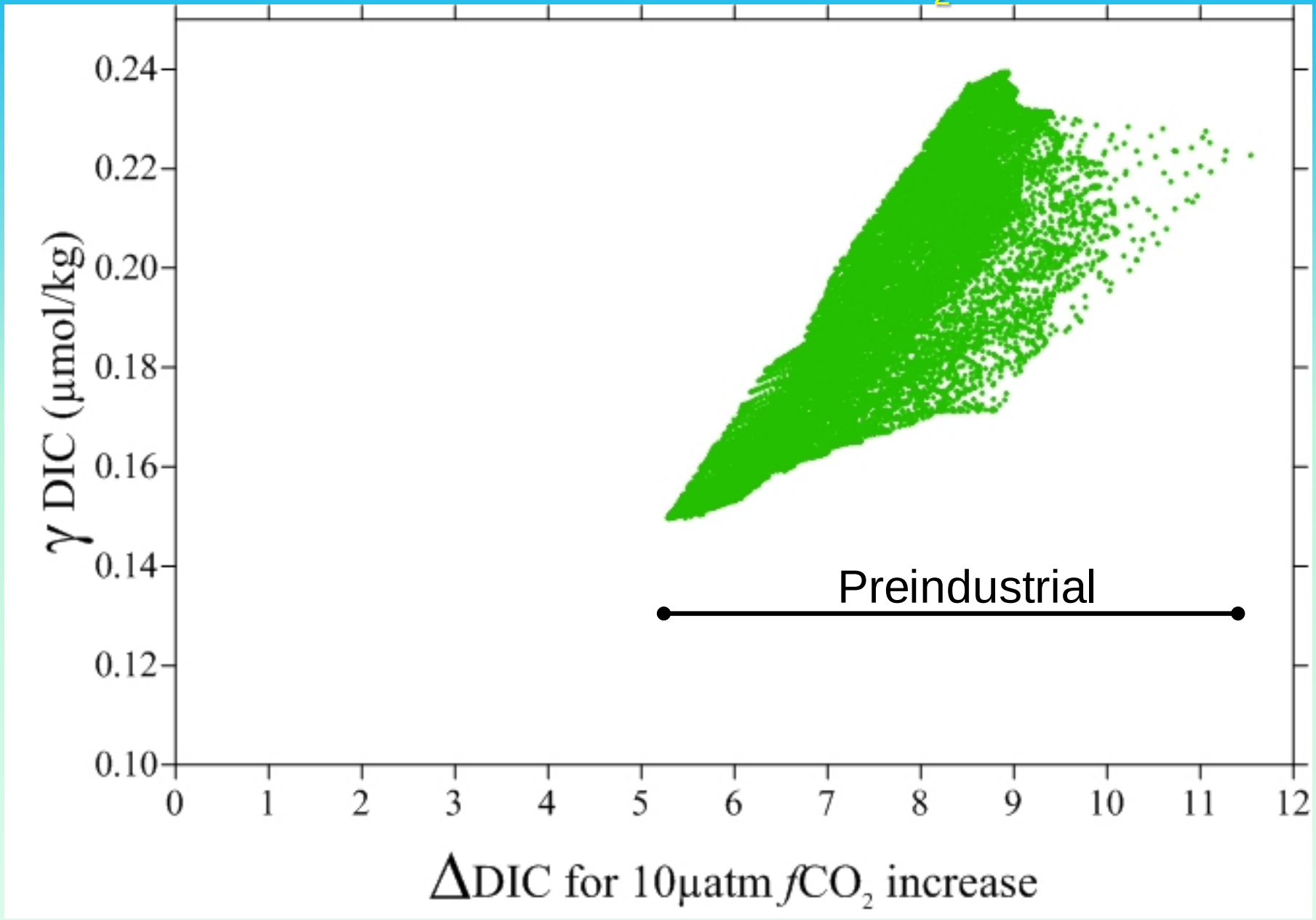
$$S = [\mathrm{HCO_3^-}] + 4[\mathrm{CO_3^{2-}}] + \frac{[\mathrm{H^+}][\mathrm{B(OH)_4^-}]}{K_{hb} + [\mathrm{H^+}]} + [\mathrm{H^+}] - [\mathrm{OH^-}]$$

$$P = 2[\mathrm{CO_2}] + [\mathrm{HCO_3^-}]$$

All Buffer Factors show a minimum where DIC=Alk



Higher buffer factor means larger DIC increase for the same amount of CO_2 rise



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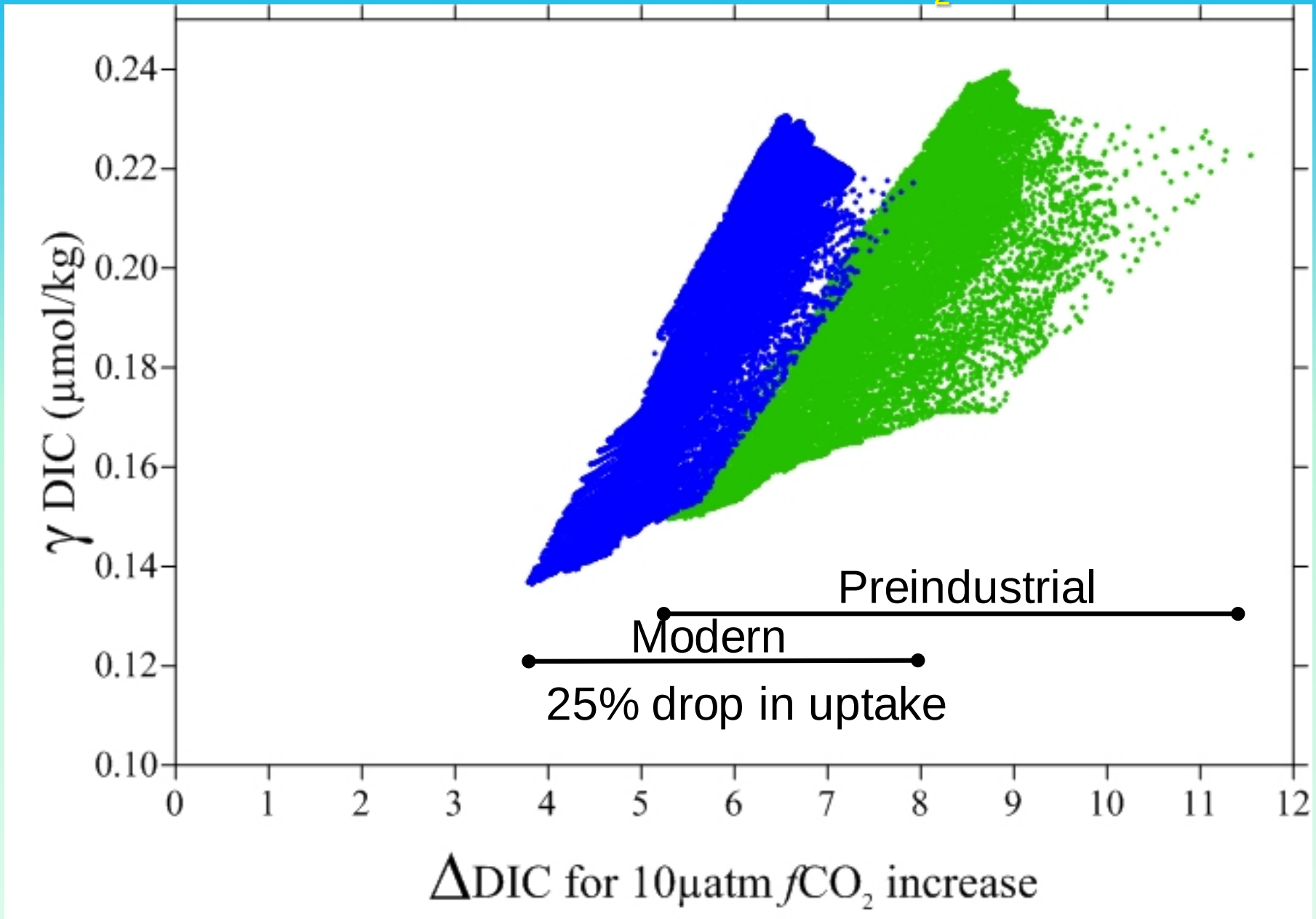

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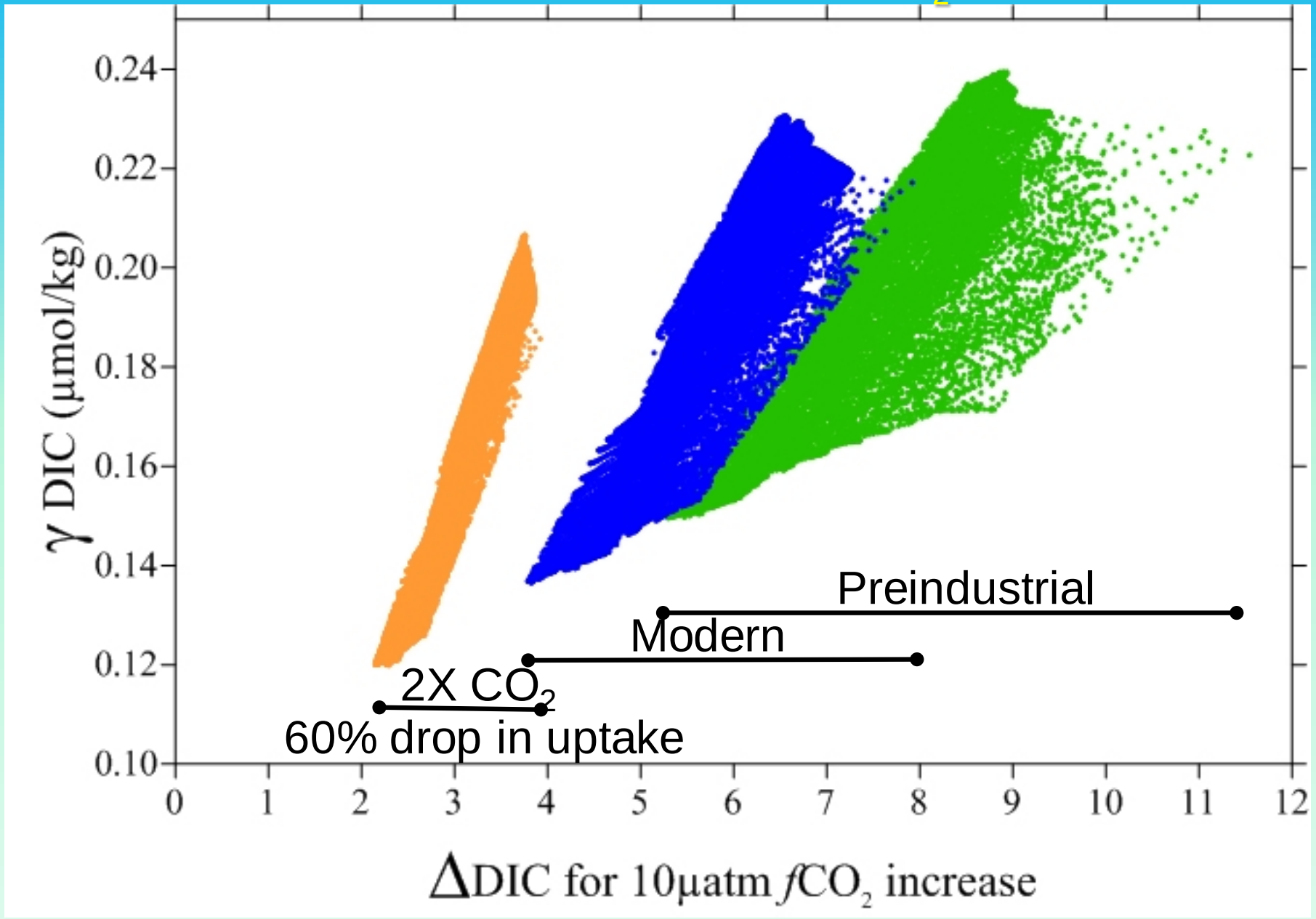

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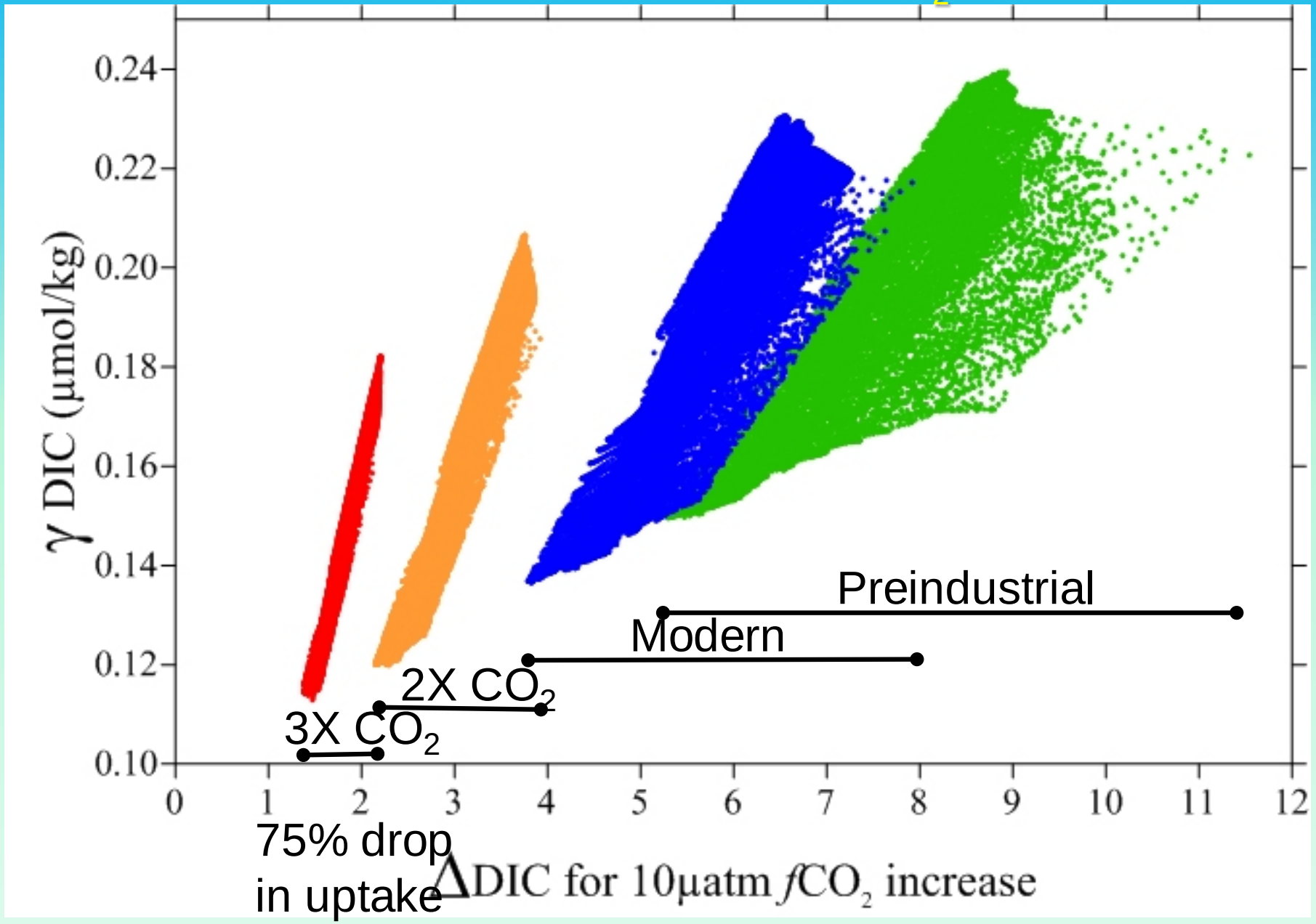


Ocean Acidification: Fundamental Chemistry

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

carbon dioxide | water | carbonic acid | hydrogen ion | bicarbonate ion

CO_2 is an acid gas so the addition of 26 million tonnes of carbon dioxide to the ocean every day is acidifying the seawater…we call this process "ocean acidification"

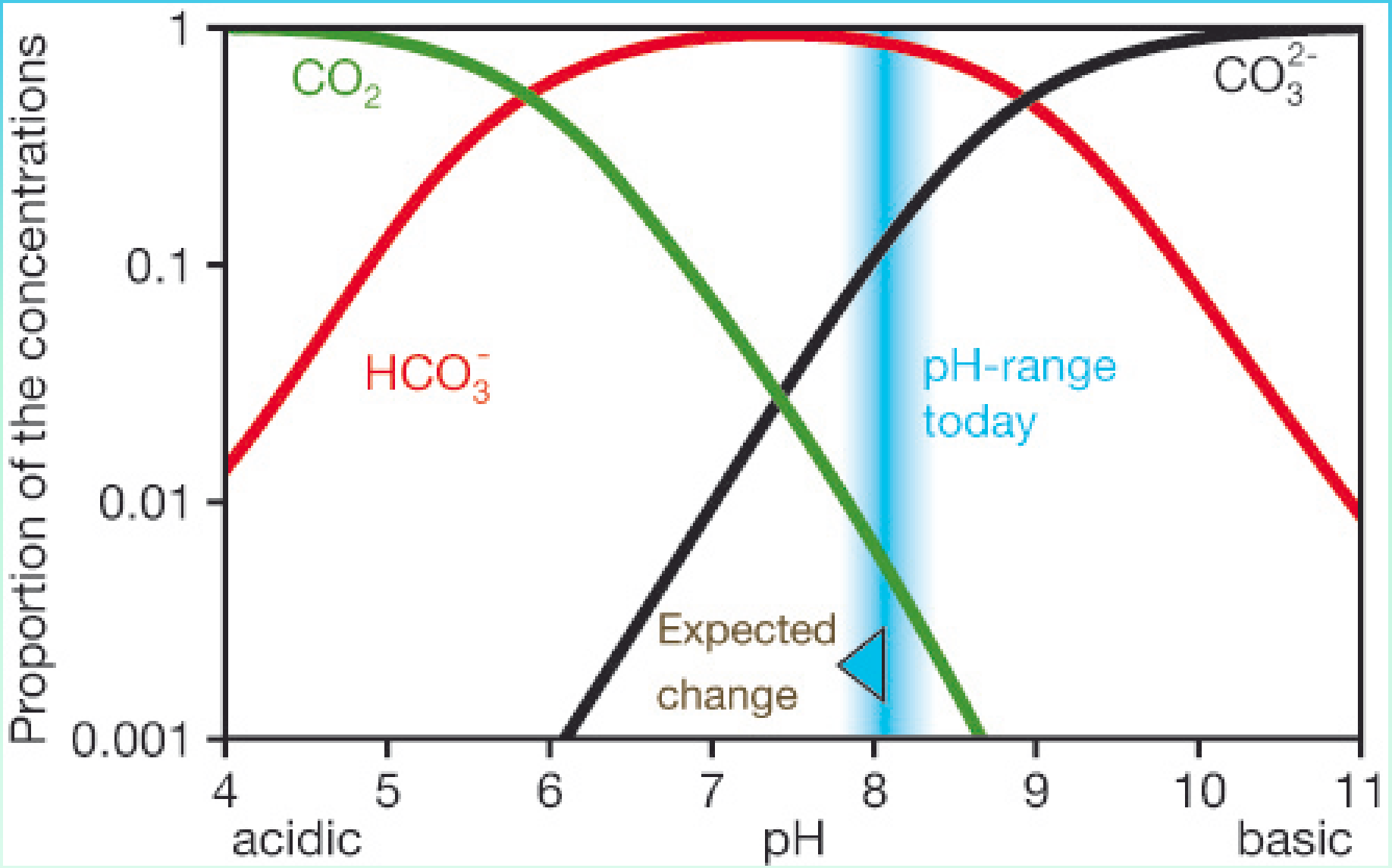
Phenol Red is a pH sensitive Dye

Q: How would the color change if someone breathed into water with Phenol Red dye in it?

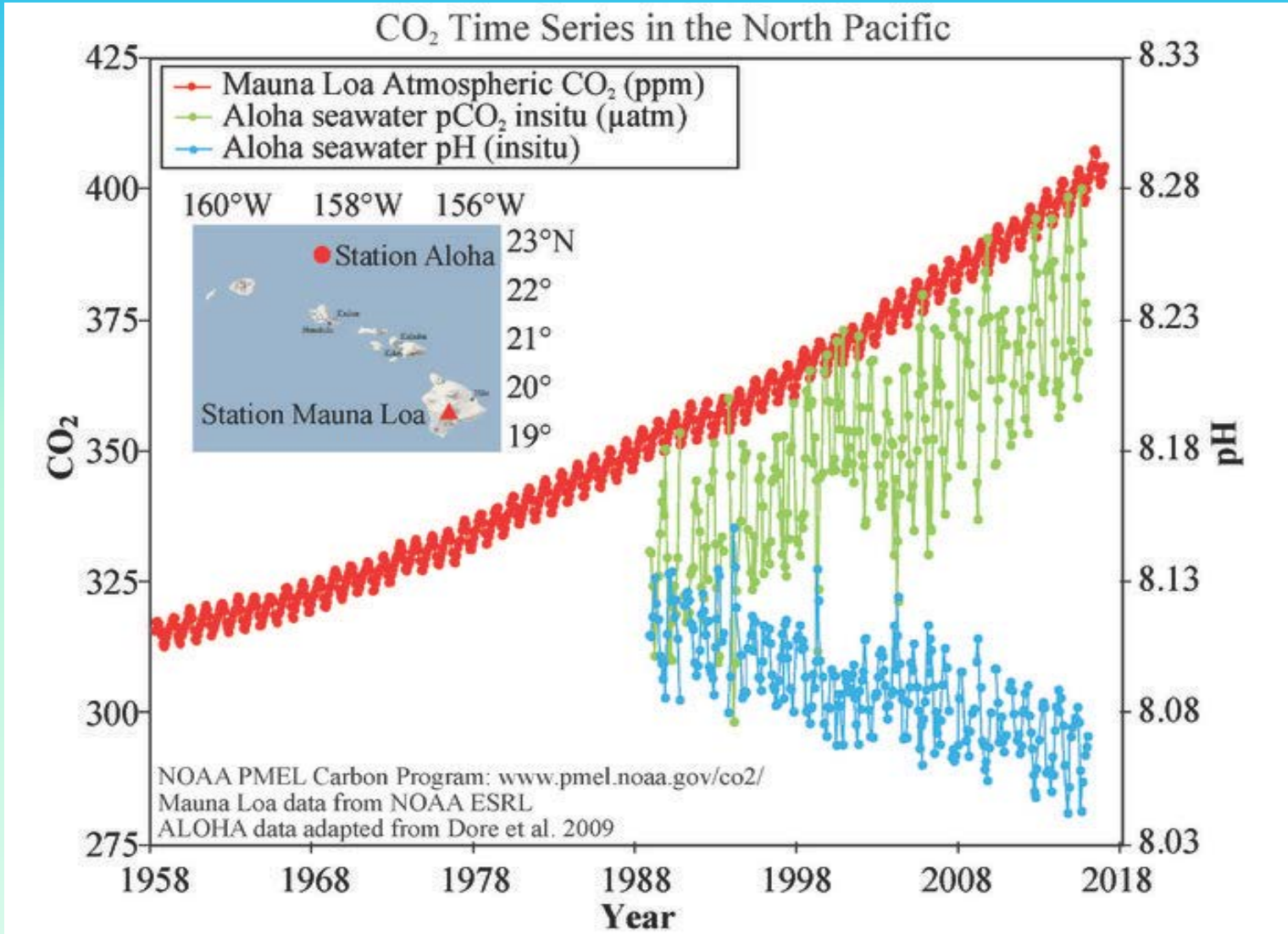
Q2: Would fresh water and seawater react the same way?

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

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



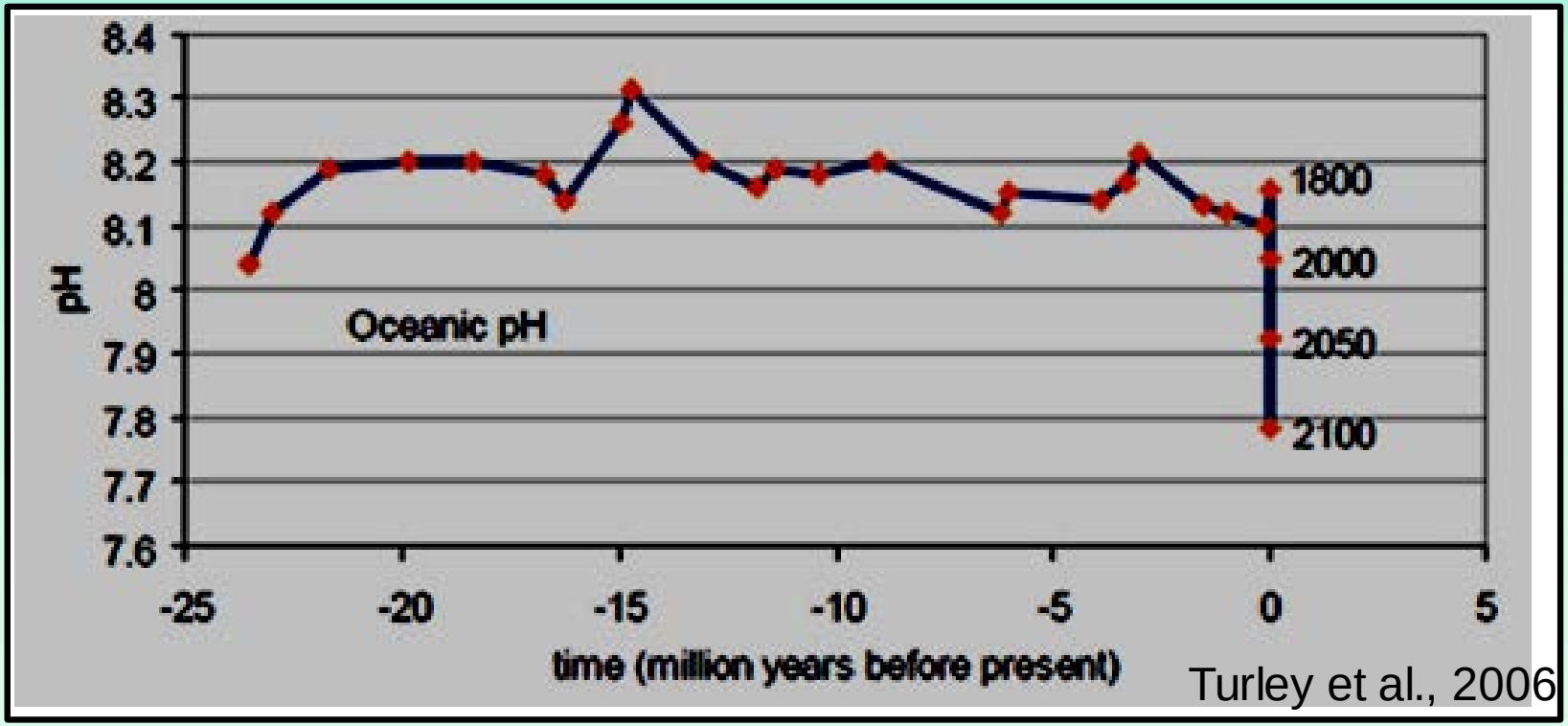
Rising Ocean CO_2 = Decreasing Oceanic pH



Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt)
Ref: J.E. Dore et al, 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc Natl Acad Sci USA* **106**:12235-12240.

Ocean Acidification: Historical Perspective

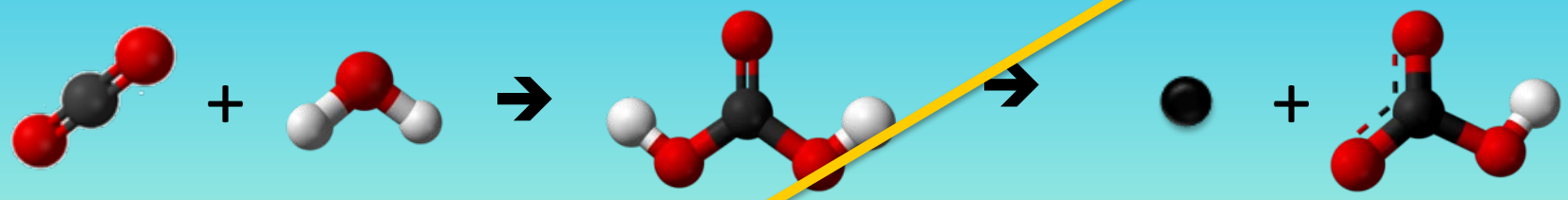
- For the last 20 Million years the pH of the ocean has remained relatively stable between approximately 8.1 and 8.2
- The uptake of anthropogenic CO_2 has lowered ocean pH by 0.1, representing a 28% increase in acidity over the last 200 years.
- The estimated drop in pH by the end of the century is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



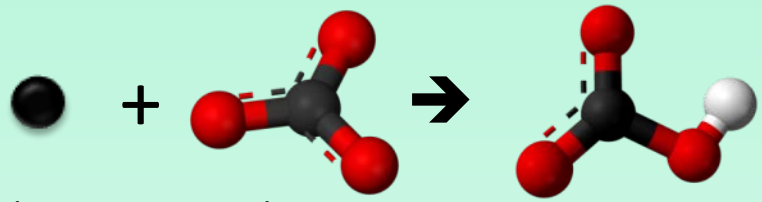
Turley et al., 2006

Ocean Acidification: Fundamental Chemistry

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$



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

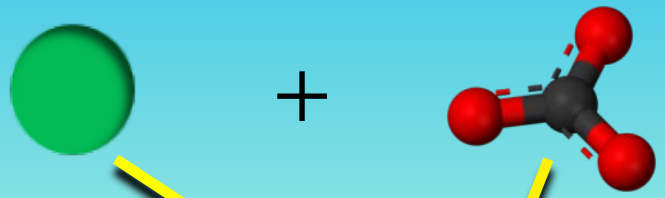


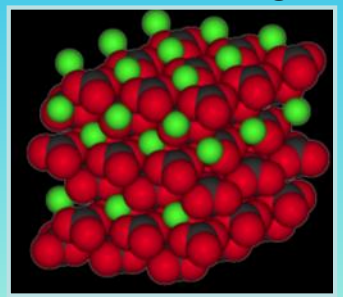
hydrogen ion | carbonate ion | bicarbonate ion

- 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

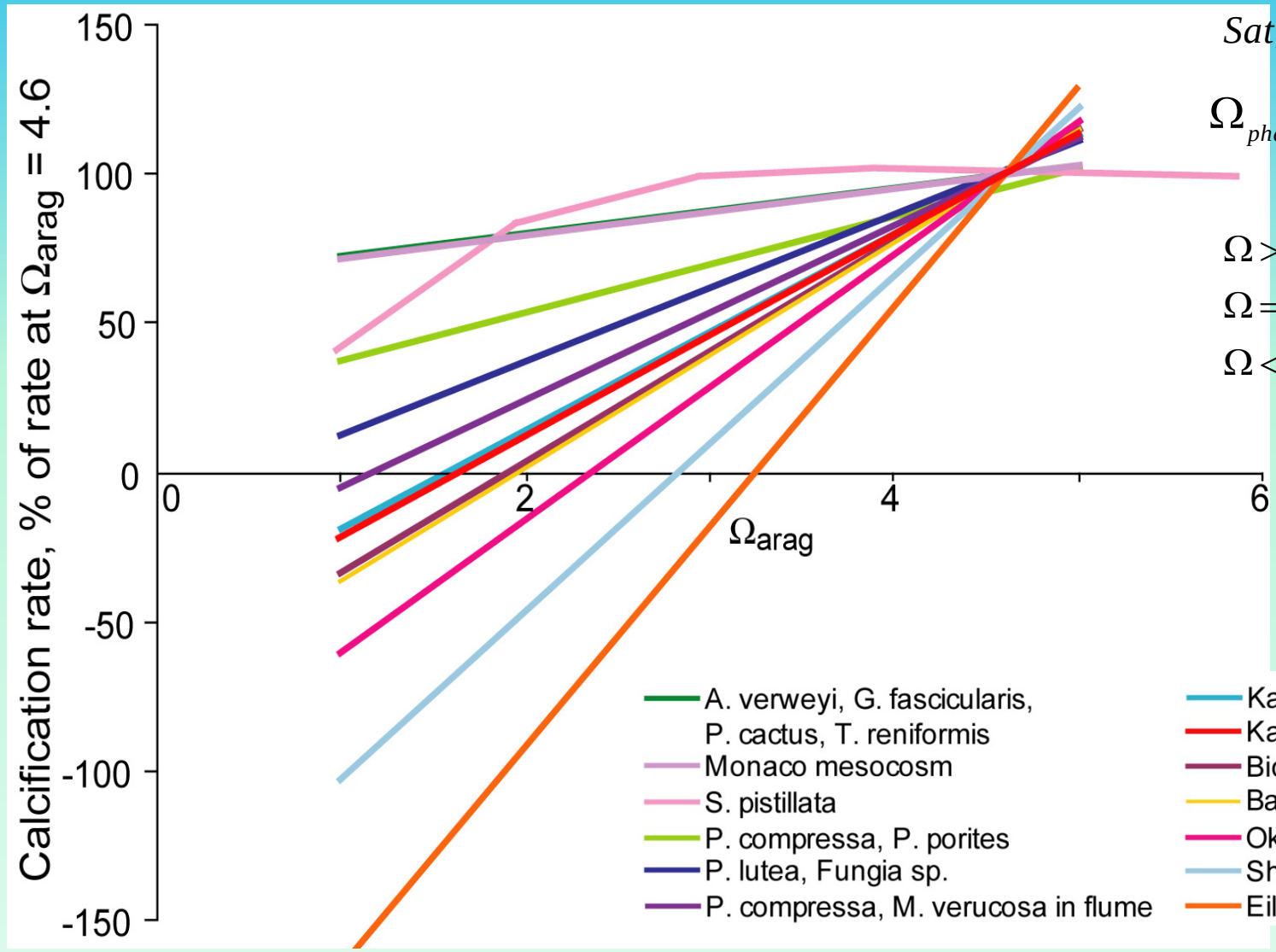
$$\Omega_{phase} = \frac{[Ca^{2+}][CO_3^{2-}]}{K^*_{sp,phase}}$$

$\Omega > 1$ $CaCO_3$ stable

$\Omega = 1$ equilibrium

$\Omega < 1$ $CaCO_3$ dissolves

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



Saturation State

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

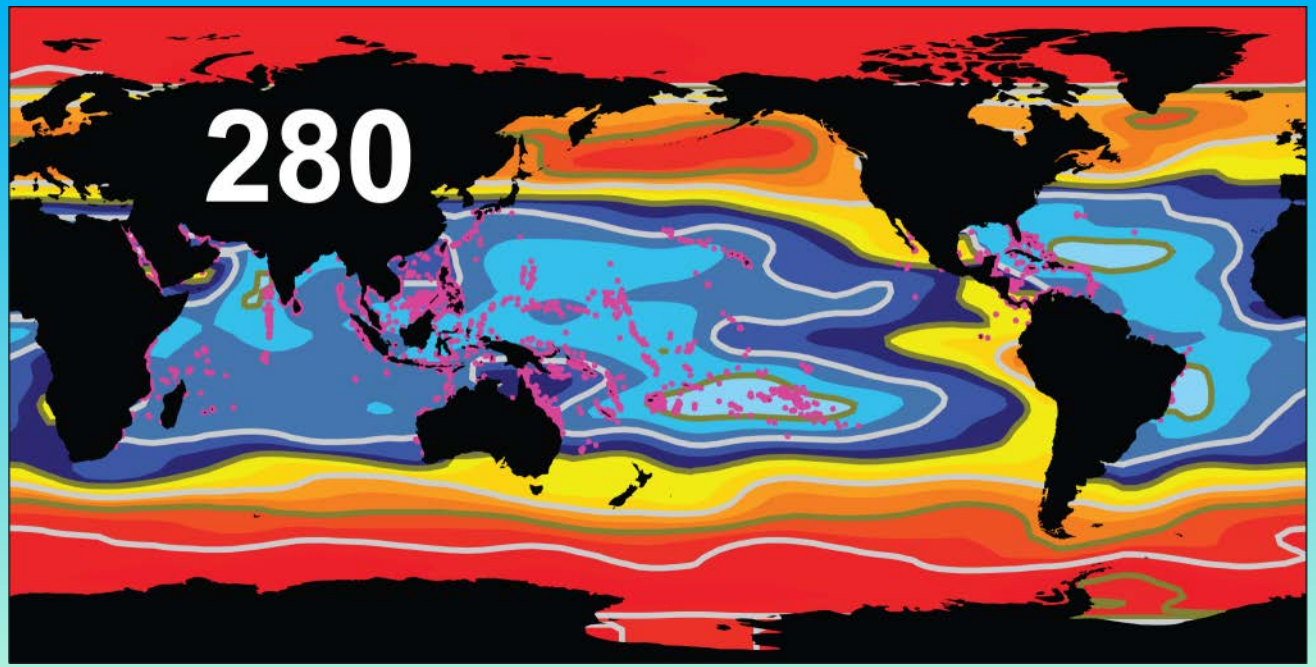
$\Omega > 1 = precipitation$

$\Omega = 1 = equilibrium$

$\Omega < 1 = dissolution$

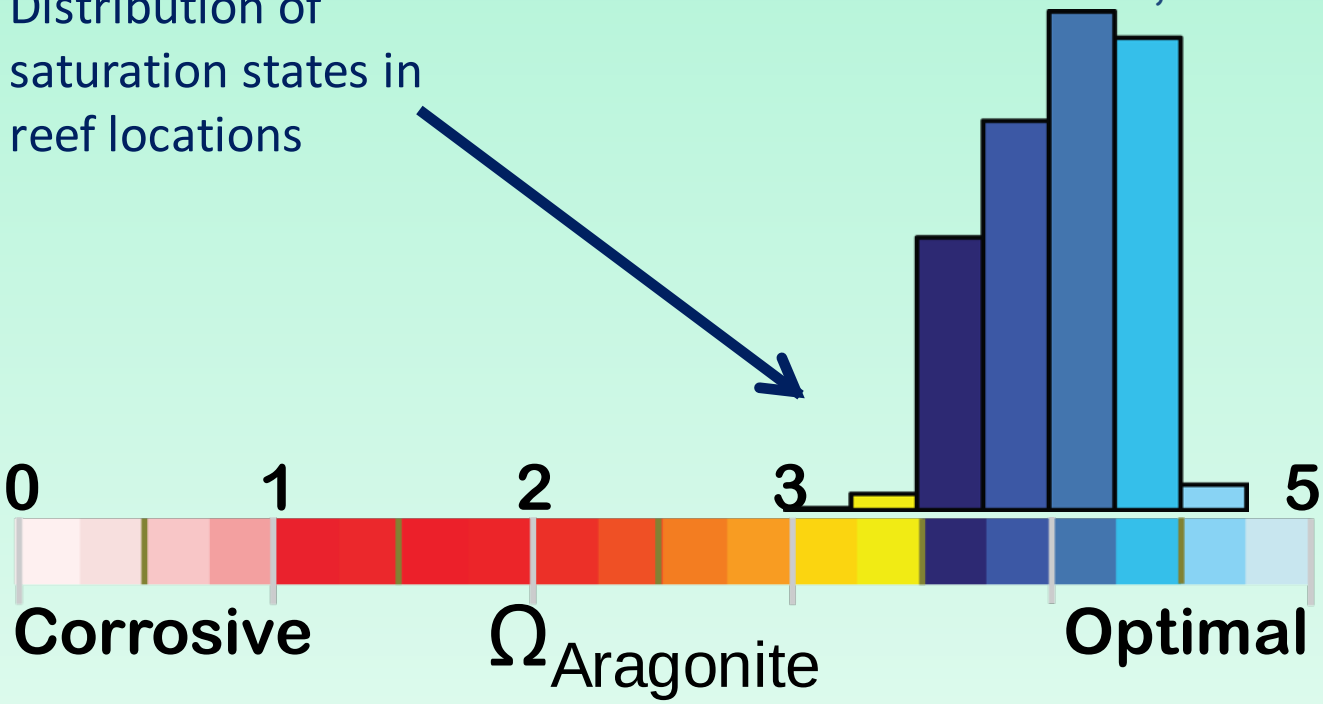
Shamberger (2011)

Surface Water Aragonite Saturation States in Preindustrial Times

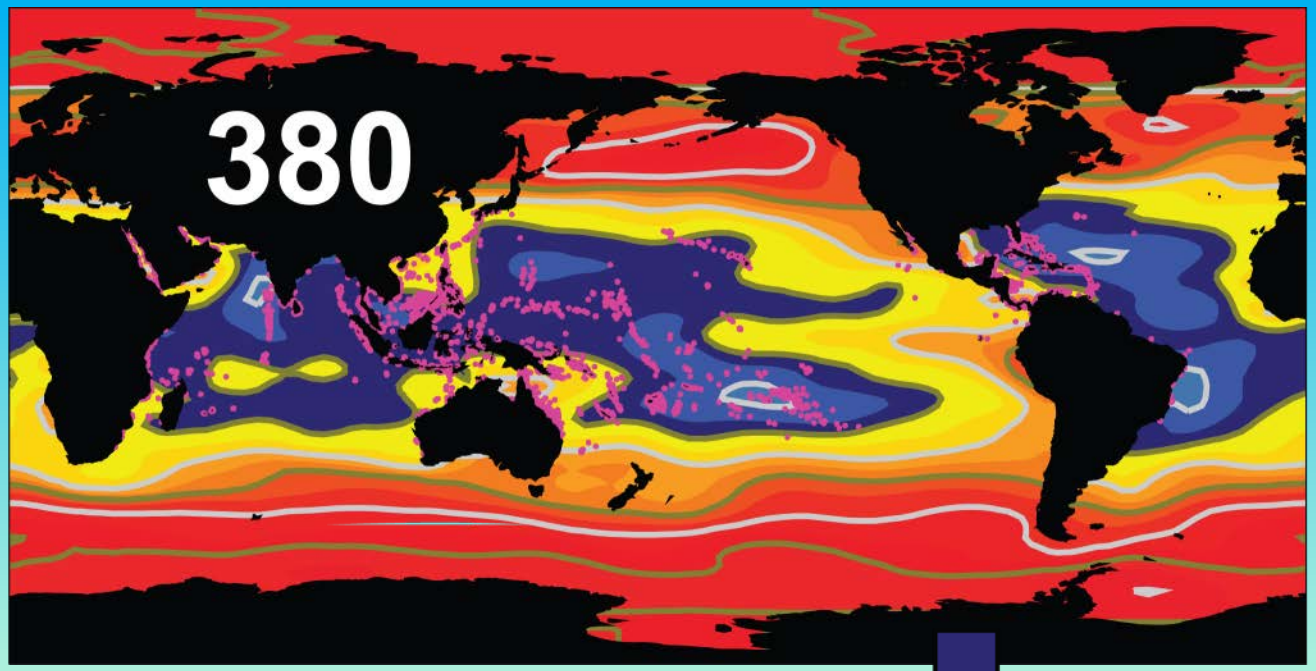


Cao and Caldeira, 2008

Distribution of saturation states in reef locations

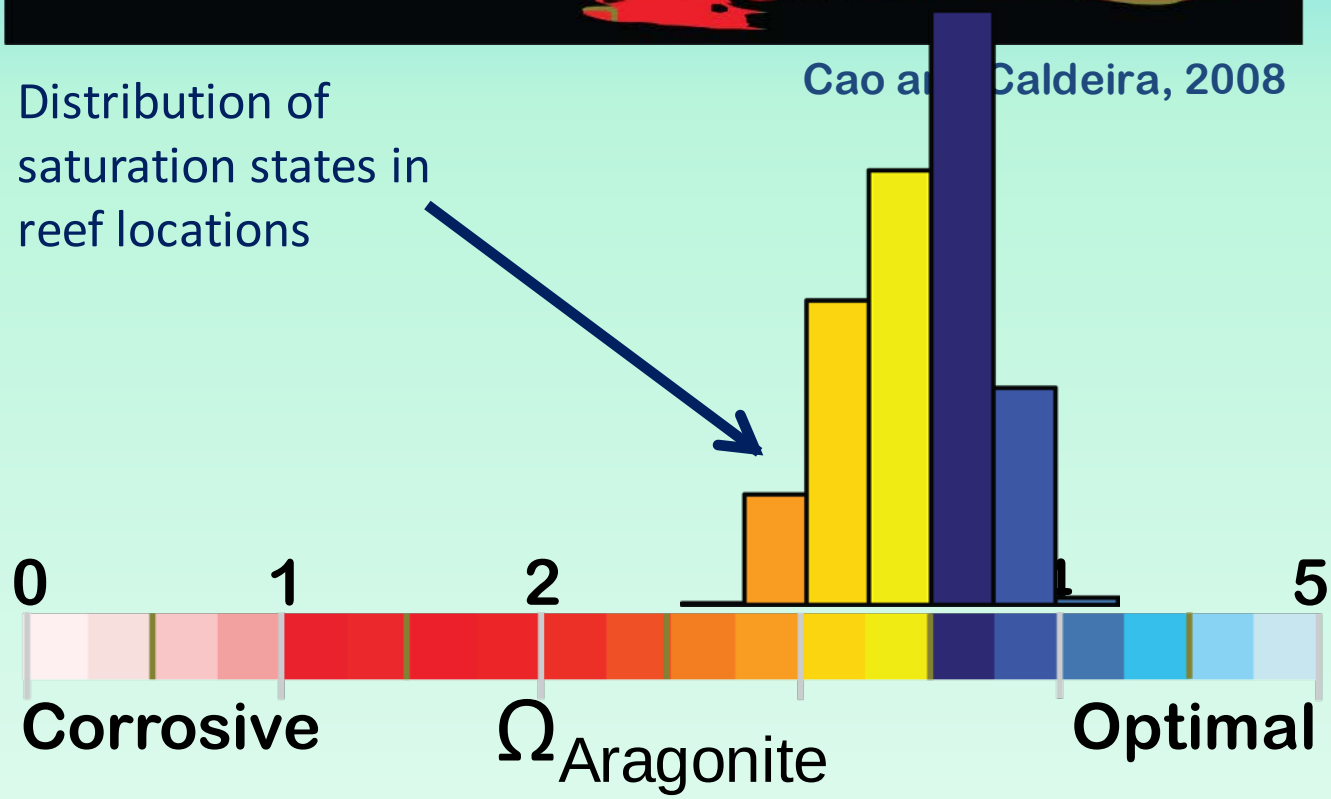


Surface Water Aragonite Saturation States Circa 2000

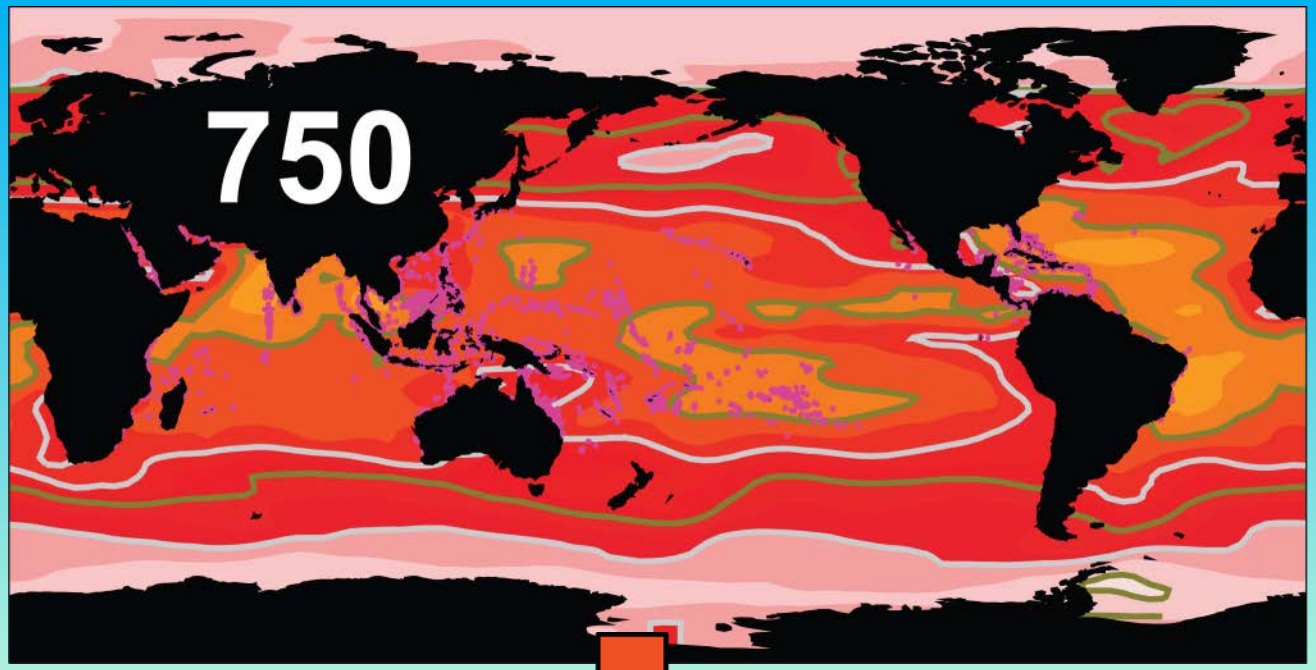


Cao a Caldeira, 2008

Distribution of saturation states in reef locations



Surface Water Aragonite Saturation States Possible by 2100 or Earlier



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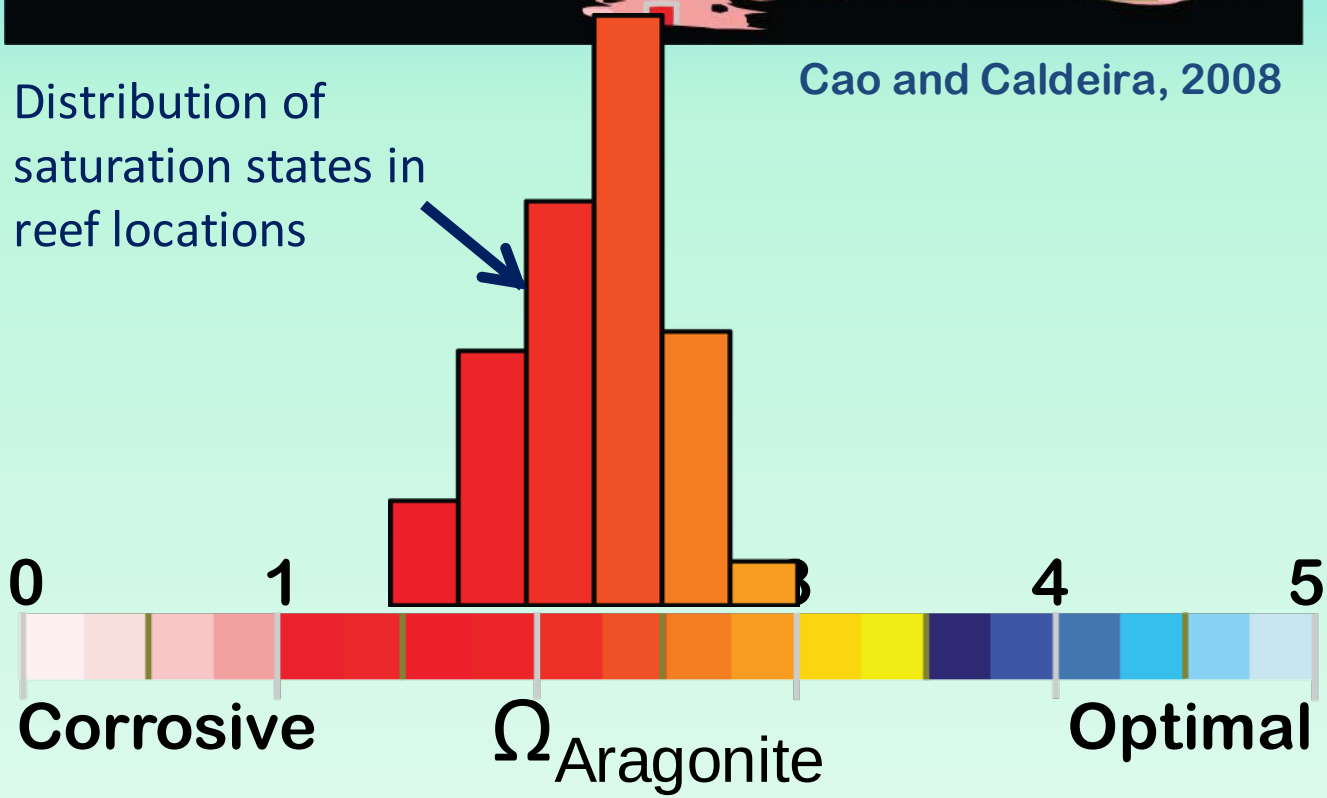
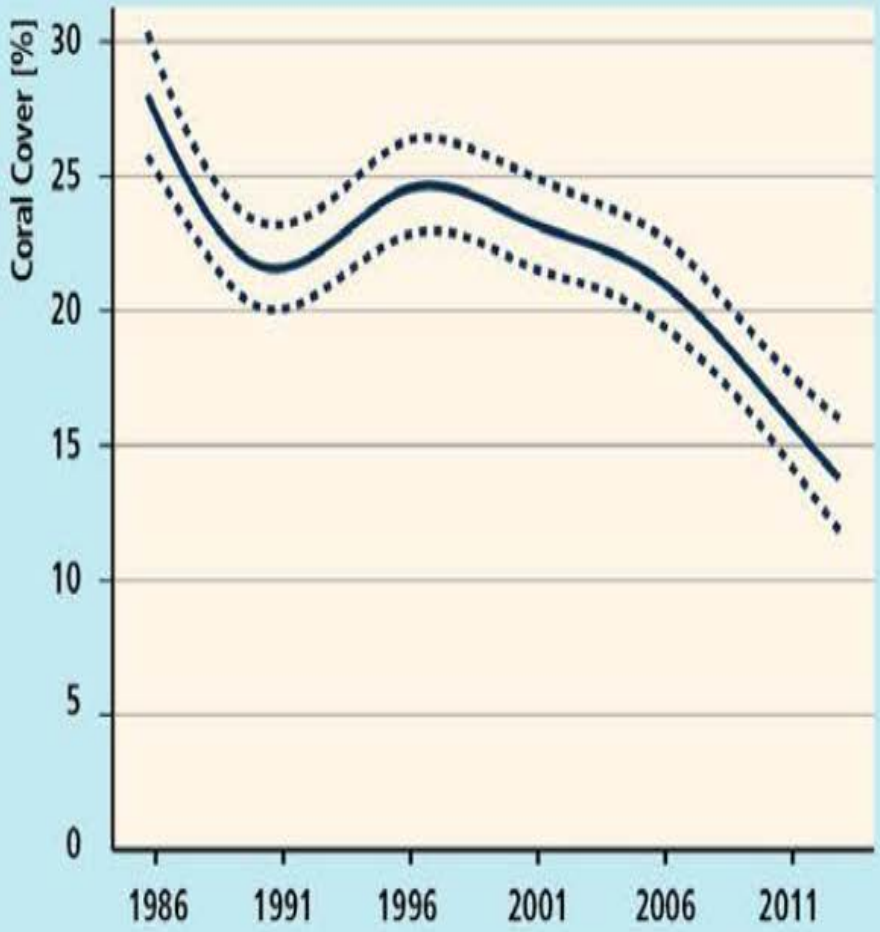
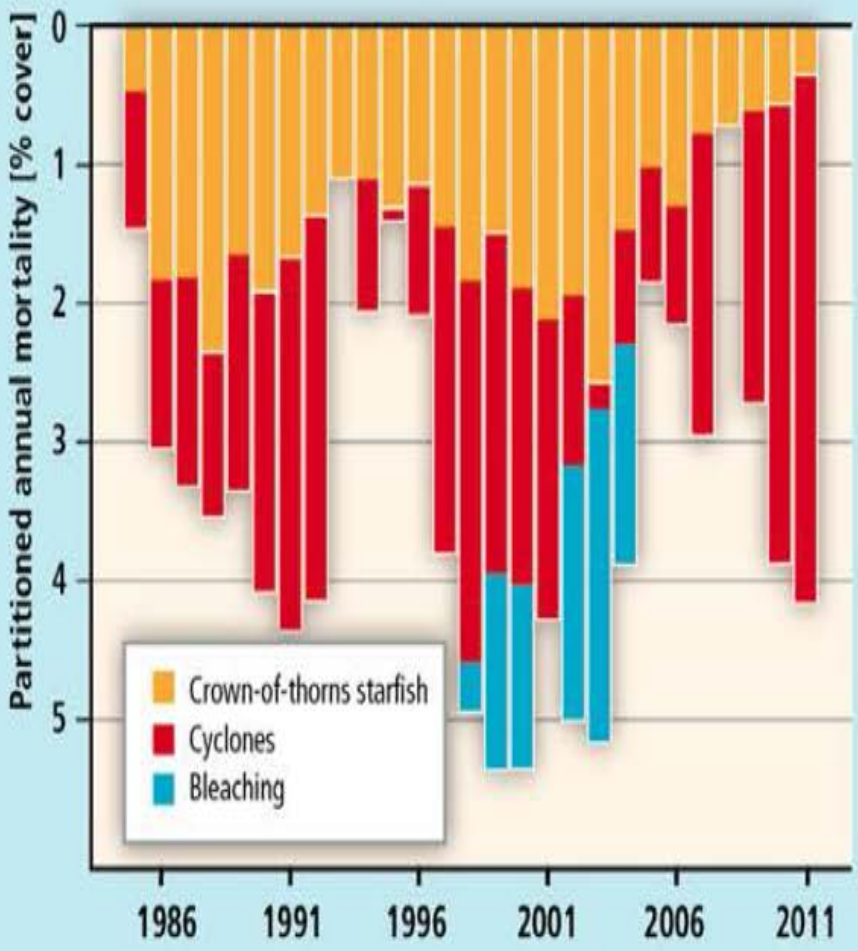
Distribution of saturation states in reef locations



Multiple Stressors on the Great Barrier Reef





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

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Shellfish are a big business along the US West Coast

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.

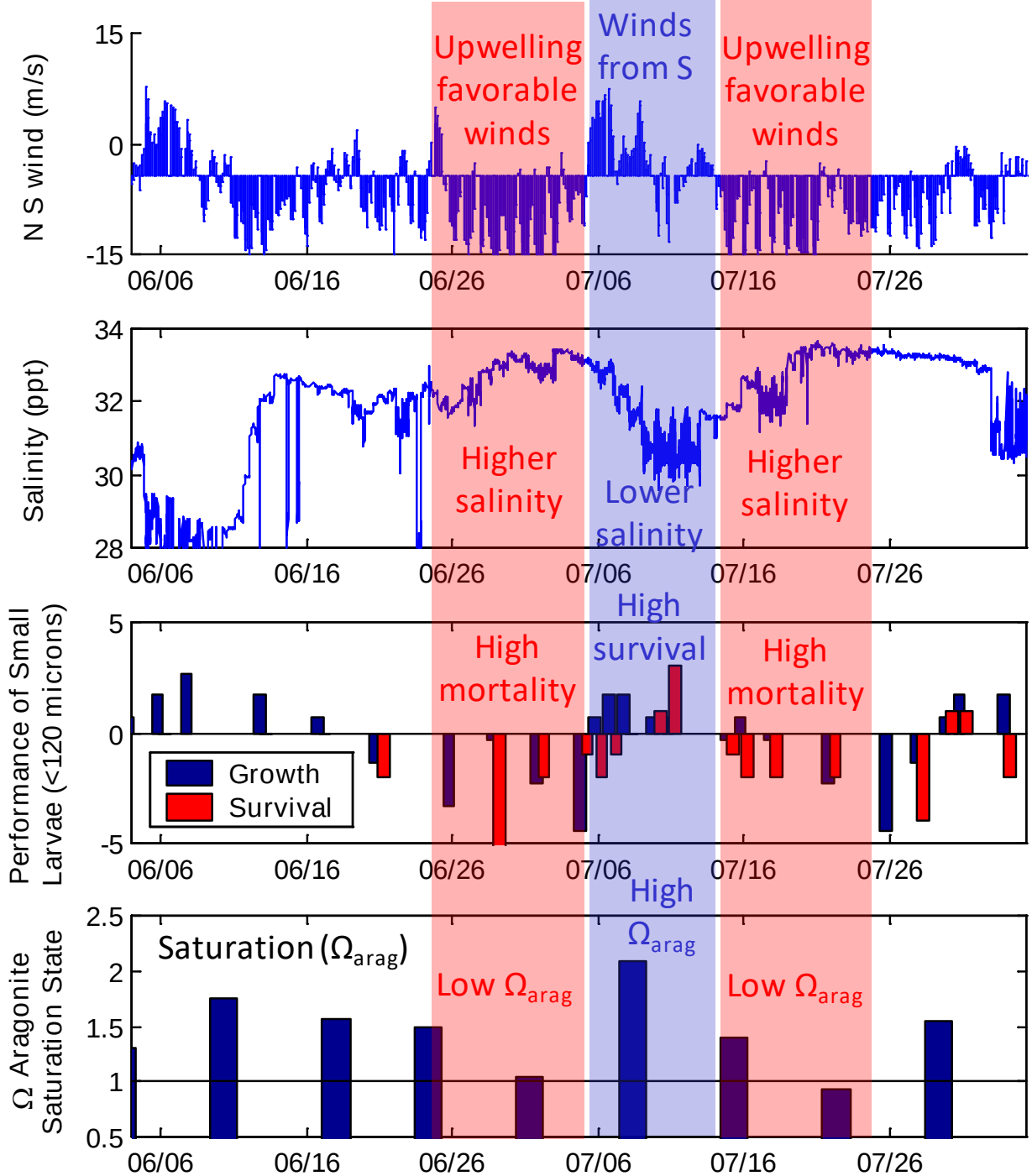
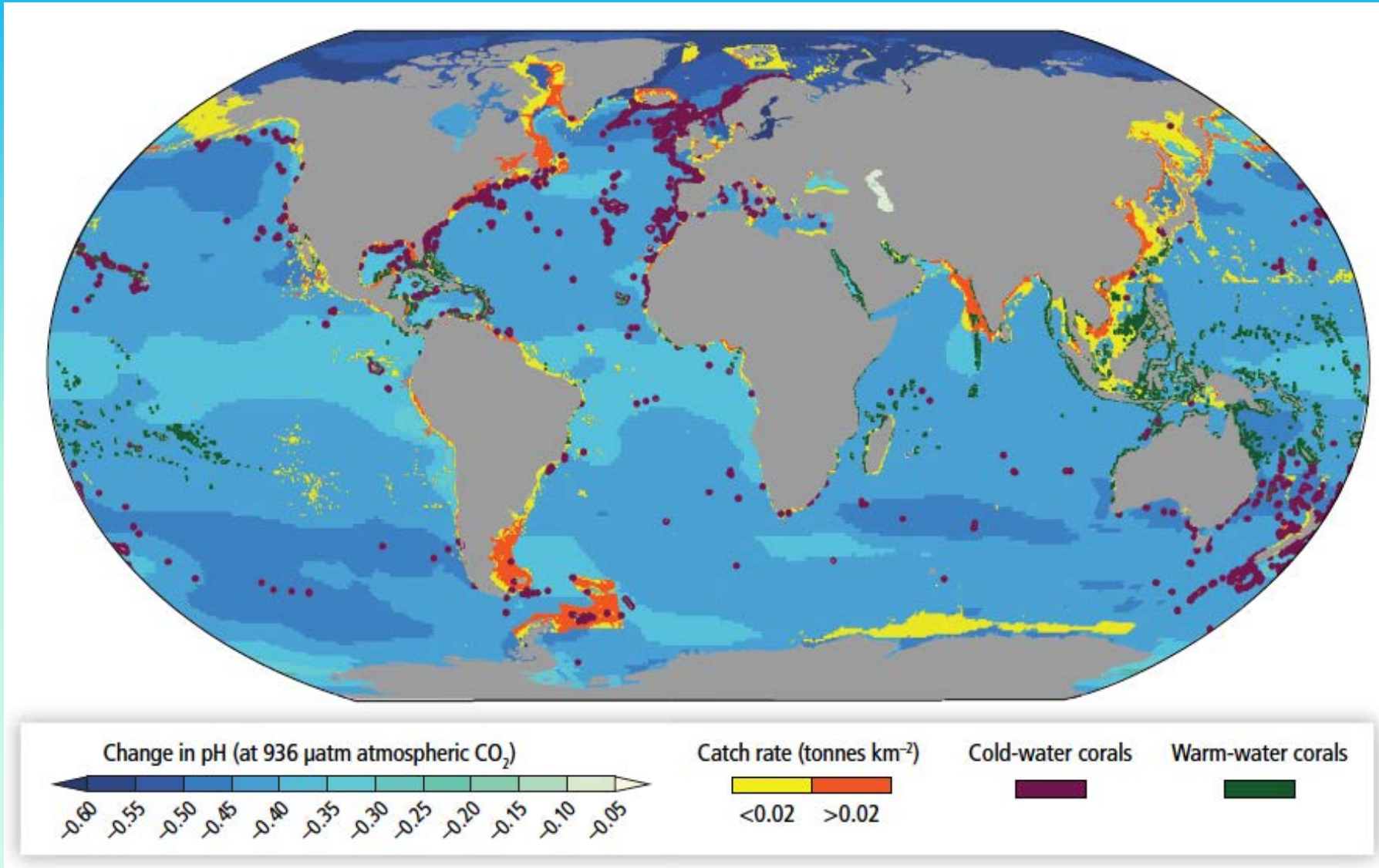


Figure courtesy of Alan Barton

Distribution of Societally Important Calcium Carbonate Species



Concern for Marine Organisms and Ecosystems

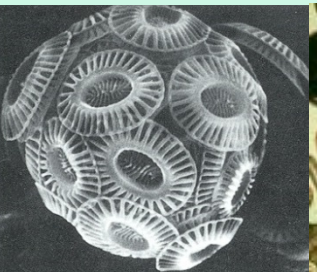
- Reduced calcification rates
- Increased photosynthesis and nitrogen fixation
- Reduced growth, production and life span of adults, juveniles & larvae
- Reduced tolerance to other environmental fluctuations
- Significant shift in key nutrient and trace element speciation

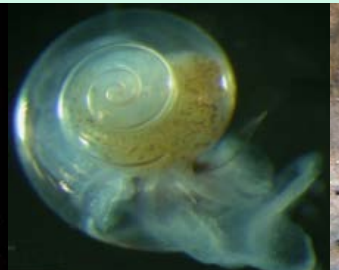
Changes to:

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

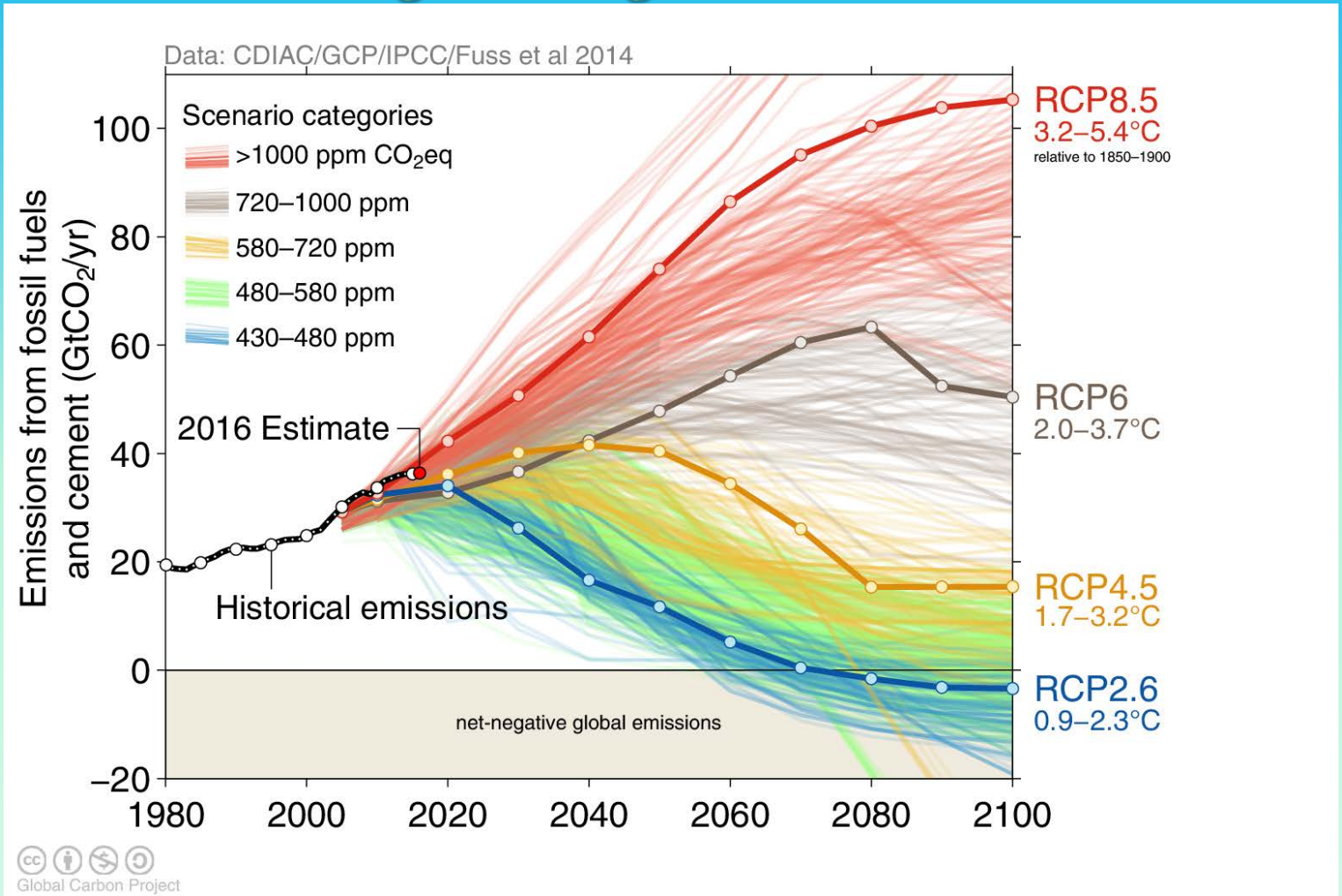
Reduced:

- Sound Absorption
- Homing Ability
- Recruitment and Settlement





How does IPCC evaluate how things might change in the future?



- The IPCC has been associated with four generations of emission scenarios
- Main periods of use: SA90 (1990–1992, not shown), IS92 (1992–2000), SRES (2000–2012), RCPs (2012+)
- Source: Peters et al. 2012a; CDIAC Data; Global Carbon Project 2013

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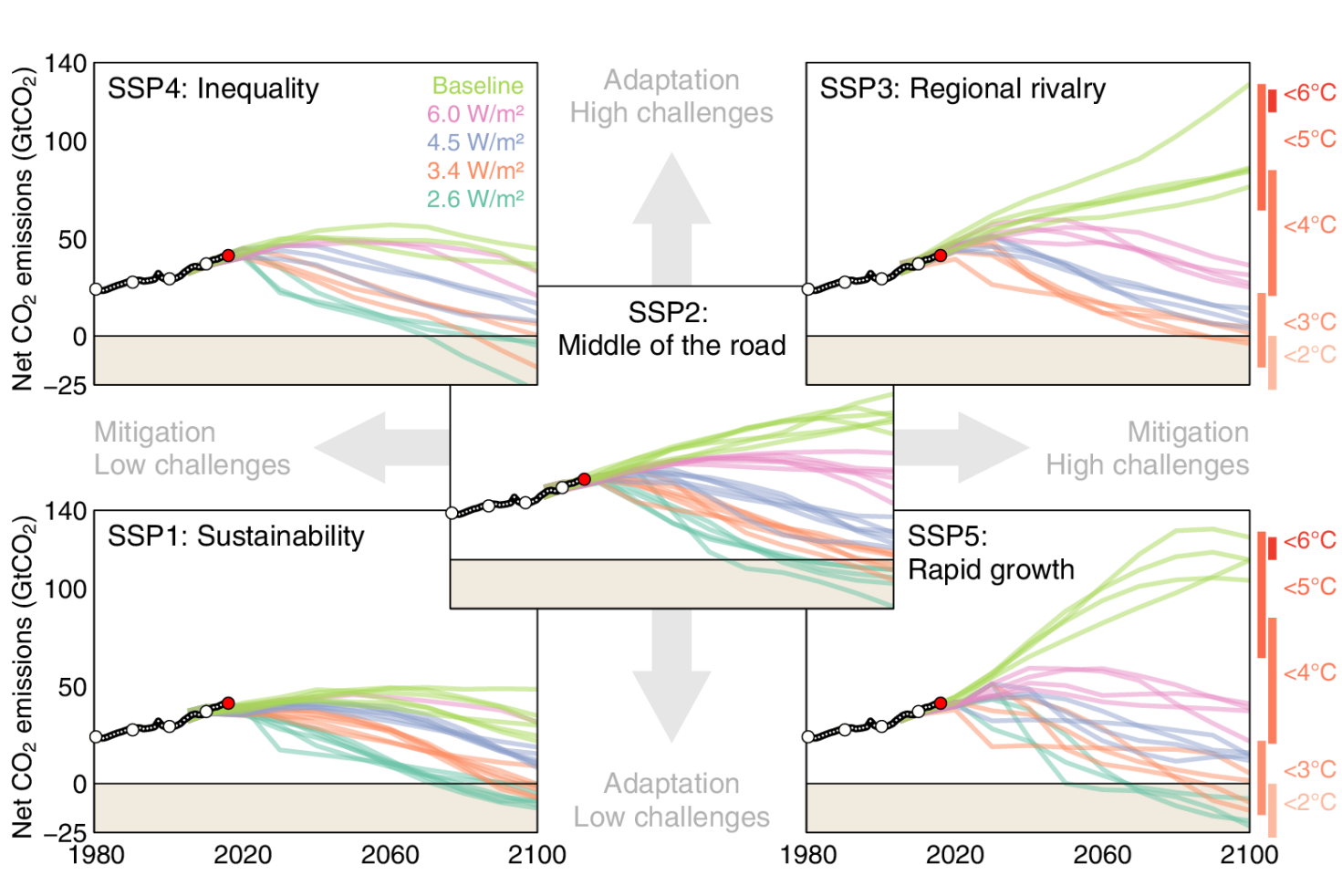
New generation of scenarios

In the lead up to the IPCC's Sixth Assessment Report new scenarios have been developed to more systematically explore key uncertainties in future socioeconomic developments



Five Shared Socioeconomic Pathways (SSPs) have been developed to explore challenges to adaptation and mitigation. Shared Policy Assumptions (SPAs) are used to achieve target forcing levels (W/m^2).

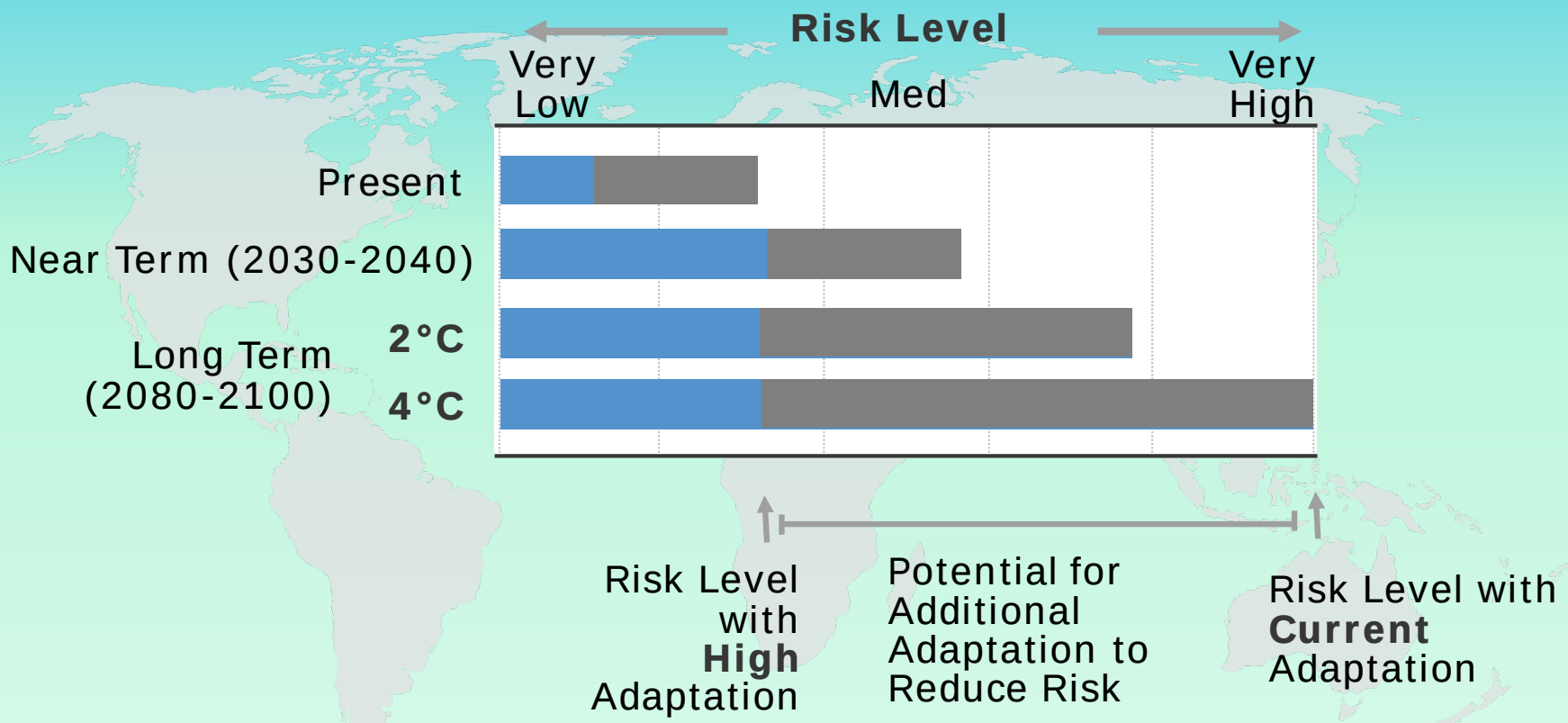
Source: Riahi et al. 2016; IIASA SSP Database; Global Carbon Budget 2016

Assessing Risk in AR5

key risks are those relevant to article 2, UNFCCC

" dangerous anthropogenic interference with the climate system"

PRINCIPLES



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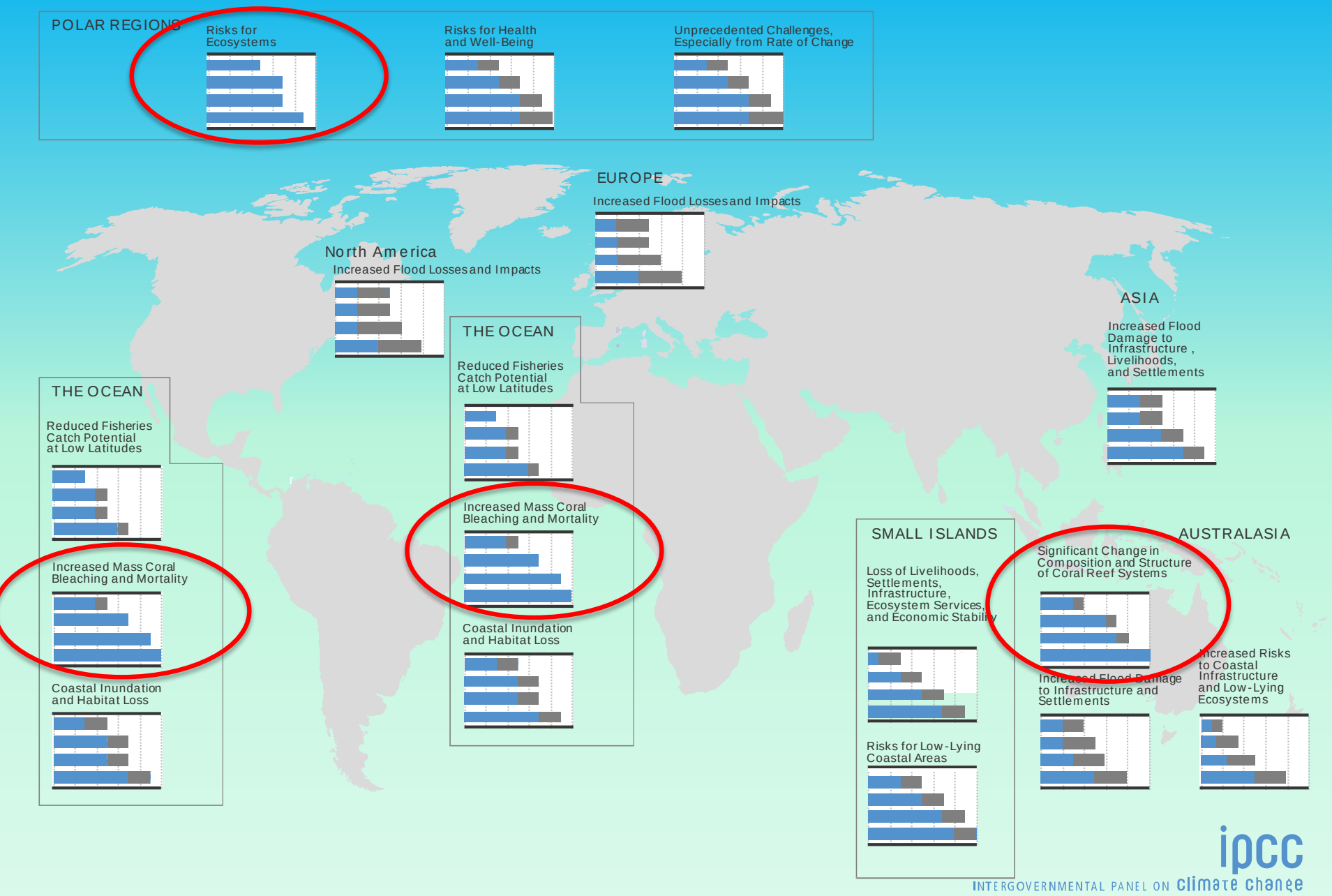
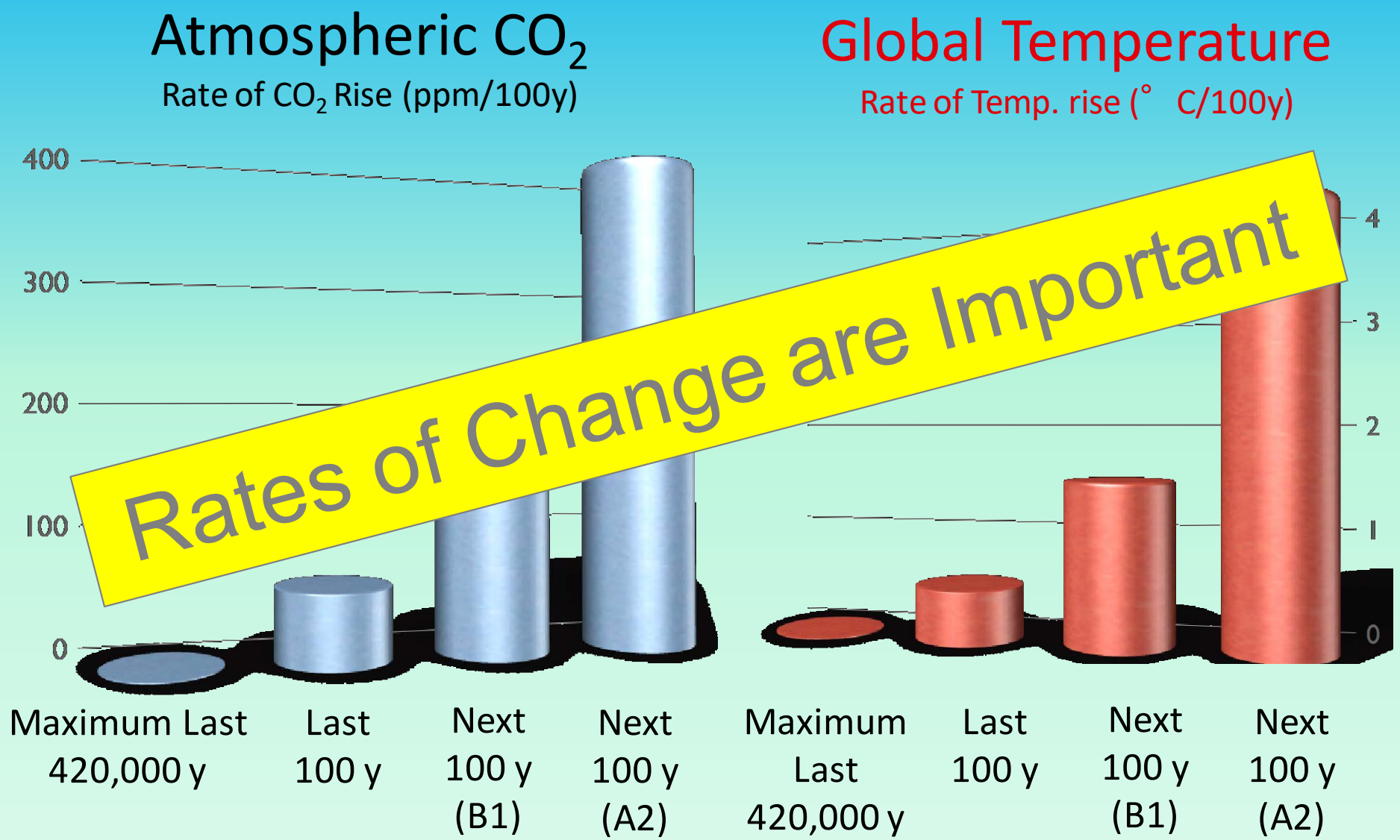
Risks involving the oceans, a global perspective:...is there risk reduction by adaptation?



Where do we go from here?



Hoegh-Guldberg et al. 2007, Science