Biogeochemistry Counts!: Implications of Ocean Acidification for Marine Ecosystems

- Predictions concerning the level and distribution of declining oceanic pH

- Research Strategies for Understanding Impacts of OA on Ocean Ecosystems

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Background -

- Average pH of the world's oceans is about 8.2, which is moderately alkaline, and is buffered by a calcium carbonate equilibrium system $CO_2 + CO_3^{-2} + H_20 <-> 2HCO_3^-$; $Ca^{2+} + CO_3^{2-} -> CaCO_3$
- Increases in CO_2 concentration in the atmosphere are highly correlated with declining pH of the ocean's surface waters – About 0.1 pH unit decline since late 1980s – predicted to be ~ -0.3 to -0.5 units by 2100 (wide error bounds)
- Can calculate the pH at which calcium carbonate precipitates vs. dissolves – called the "saturation state" (generally closer to dissolution with increasing depth). Saturation depth much shallower in the North Pacific vs. North Atlantic
- Because the ocean mixes slowly, ½ of anthropogenic CO_2 is stored in the upper 10% of the world's oceans

What we know
about ocean CO_2 chemistry
...saturation state

$$CO_2 + CO_3^{2-} + H_2O \Leftrightarrow 2HCO_3^-$$

Saturation State

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

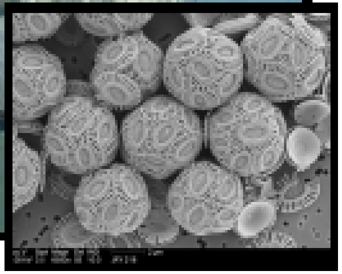
$$Ca^{2+} \quad + \quad CO_3^{2-} \rightarrow \quad CaCO_3$$

calcium carbonate calcium carbonate

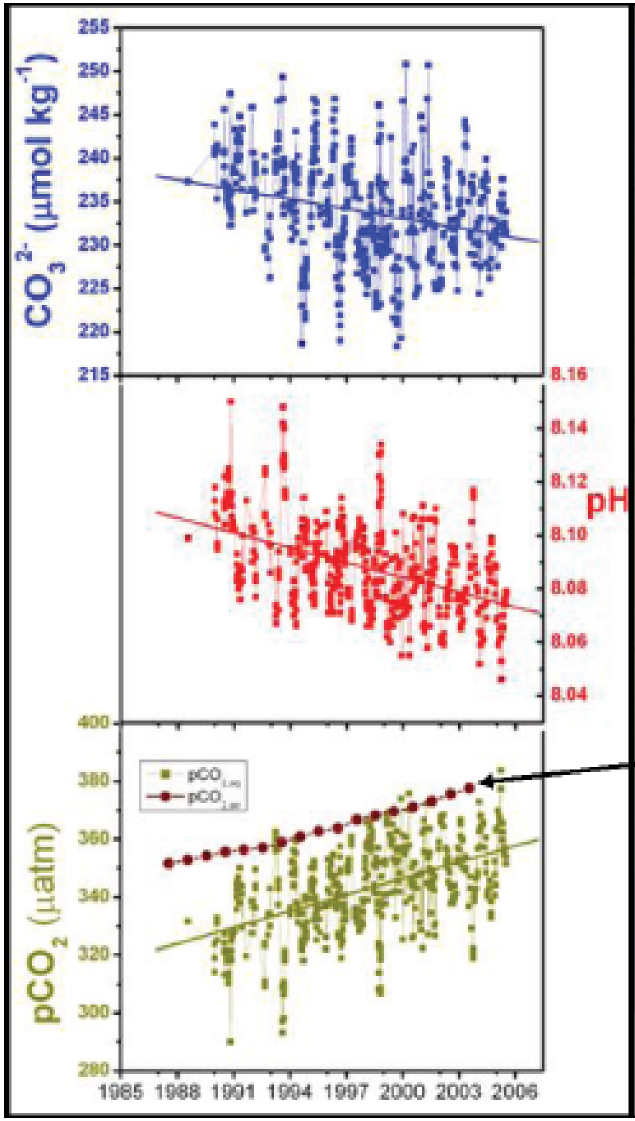
$\Omega > 1 = precipitation$

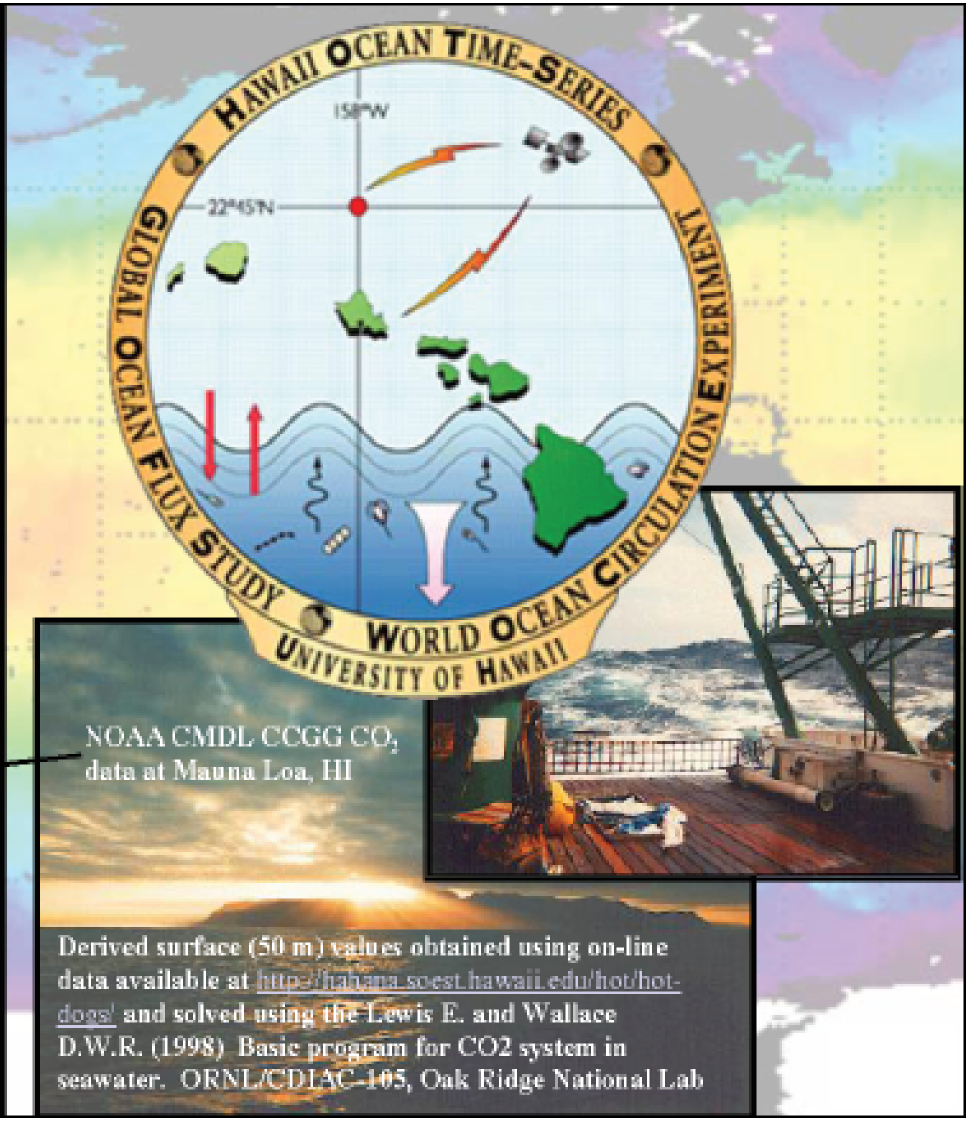
$\Omega = 1 = equilibrium$

$\Omega < 1 = dissolution$



What we know
about ocean CO_2 chemistry
…from time series observations

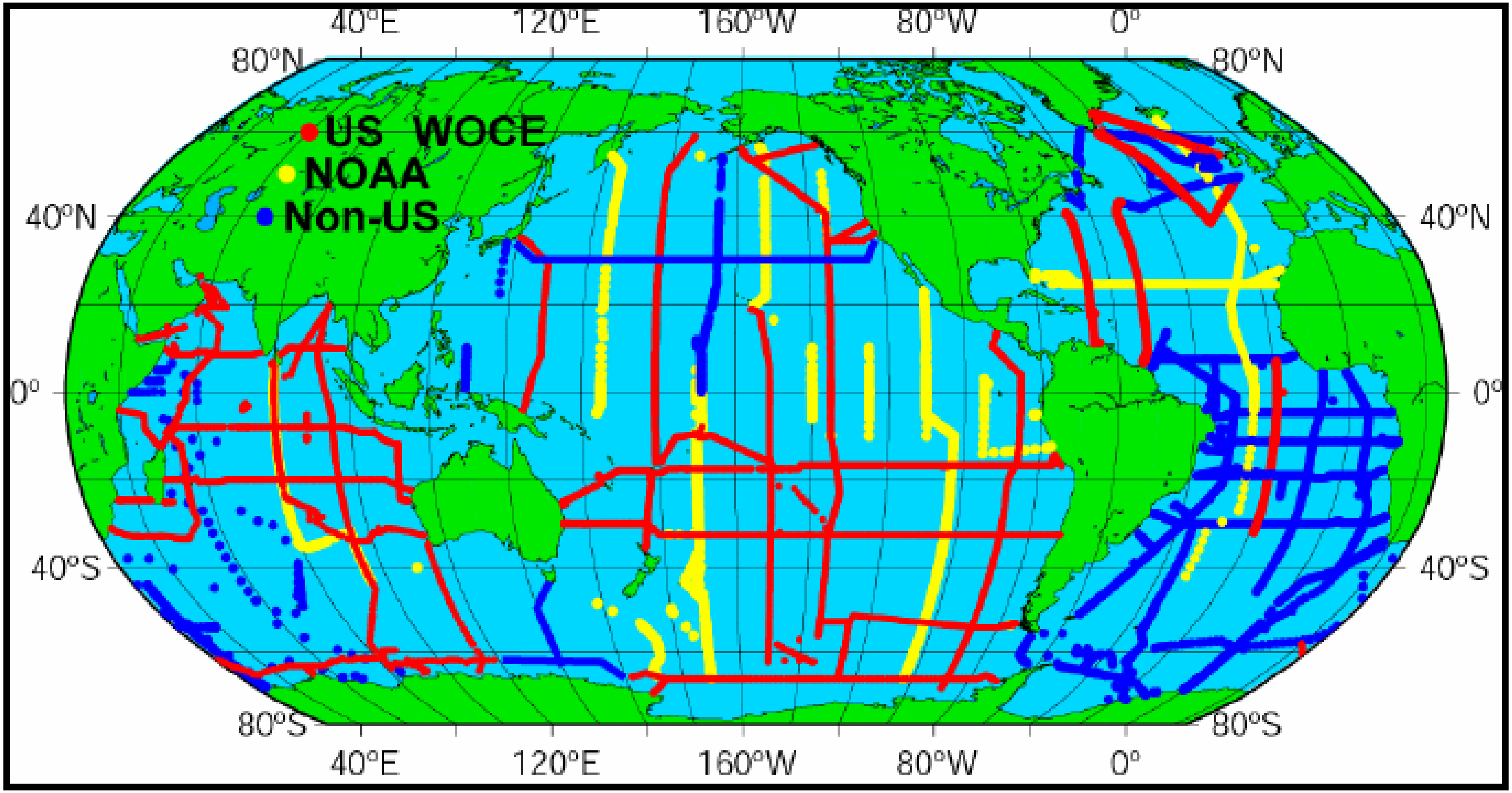




NOAA CMDL CCGG CO_2 data at Mauna Loa, HI

Derived surface (50 m) values obtained using on-line data available at http://hahana.soest.hawaii.edu/hot/hot-dogs/ and solved using the Lewis E. and Wallace D.W.R. (1998) Basic program for CO2 system in seawater. ORNL/CDIAC-105, Oak Ridge National Lab

What we know
about ocean CO_2 chemistry
...from field observations



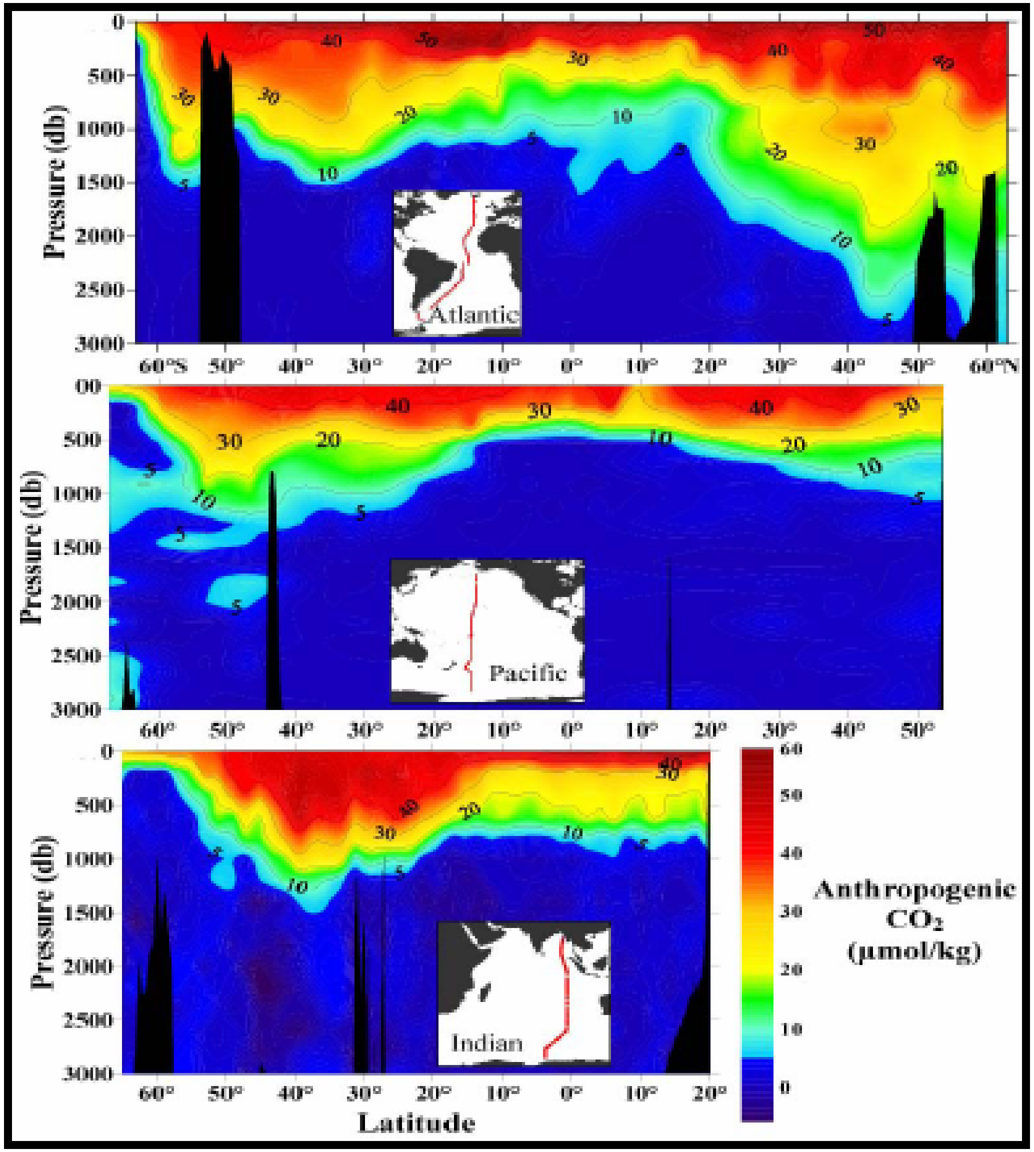
WOCE/JGOFS/OACES Global CO_2 Survey

~72,000 sample locations
collected in the 1990s

DIC ± 2 μmol kg^{-1}
TA ± 4 μmol kg^{-1}

Sabine et al (2004)

What we know
about ocean CO_2 chemistry
...about human impacts on ocean CO_2 chemistry

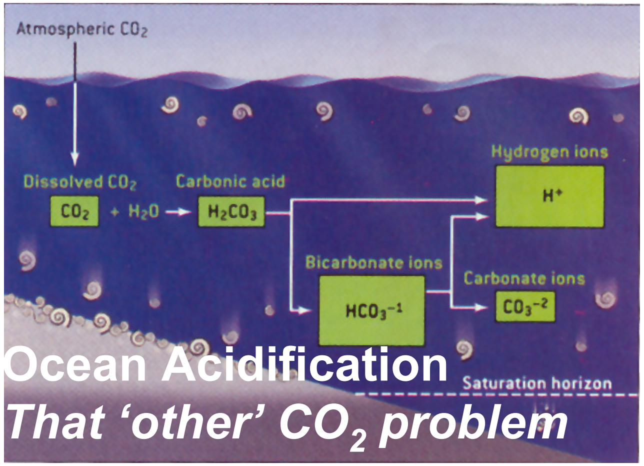


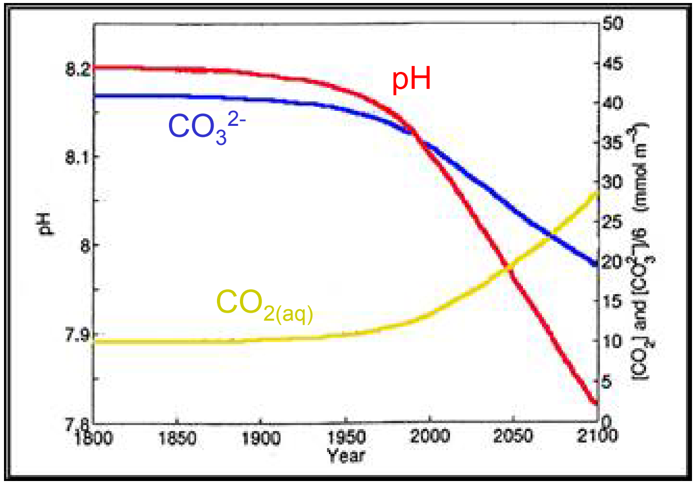
- ➢From the WOCE/JGOFS global CO2 survey, the observed anthropogenic CO_2 inventory through 1994 is calculated to be 118±19 Pg C.
- ➢Because the ocean mixes slowly, half of the anthropogenic CO_2 stored in the oceans is found in the upper 10% of the ocean

Sabine et al. Science (2004)

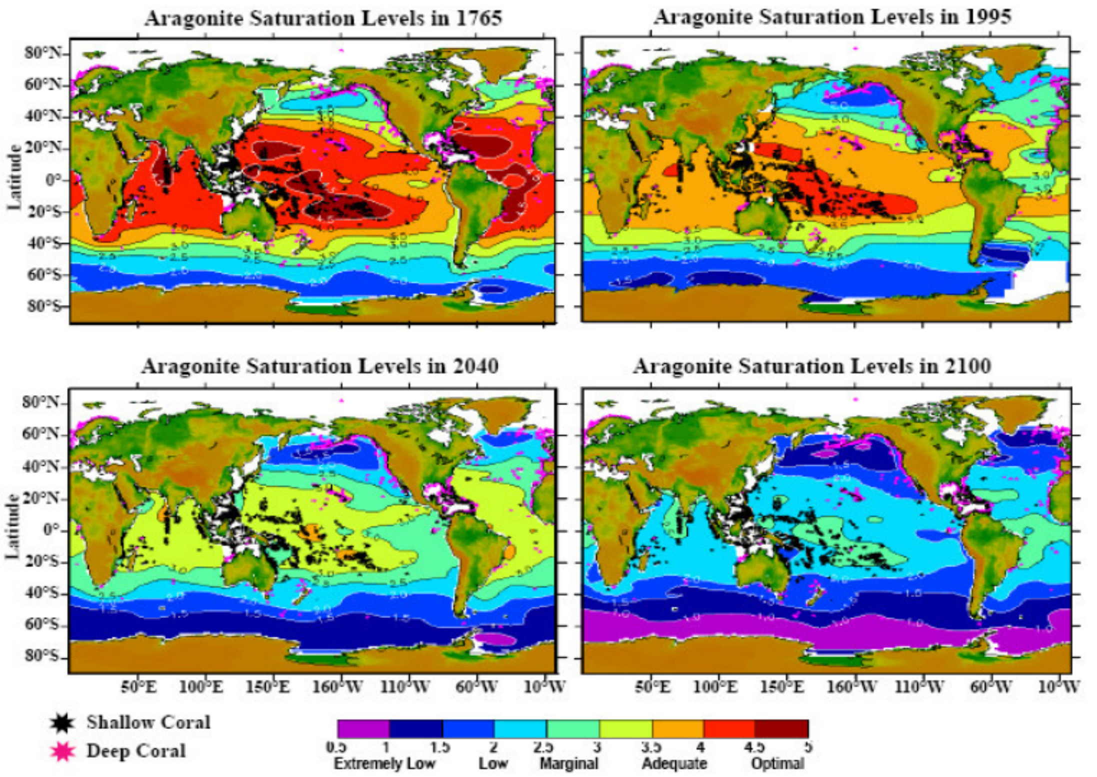
Ocean Acidification

That ‘other’ CO_2 problem





Wolf-Gladrow et al., 1999

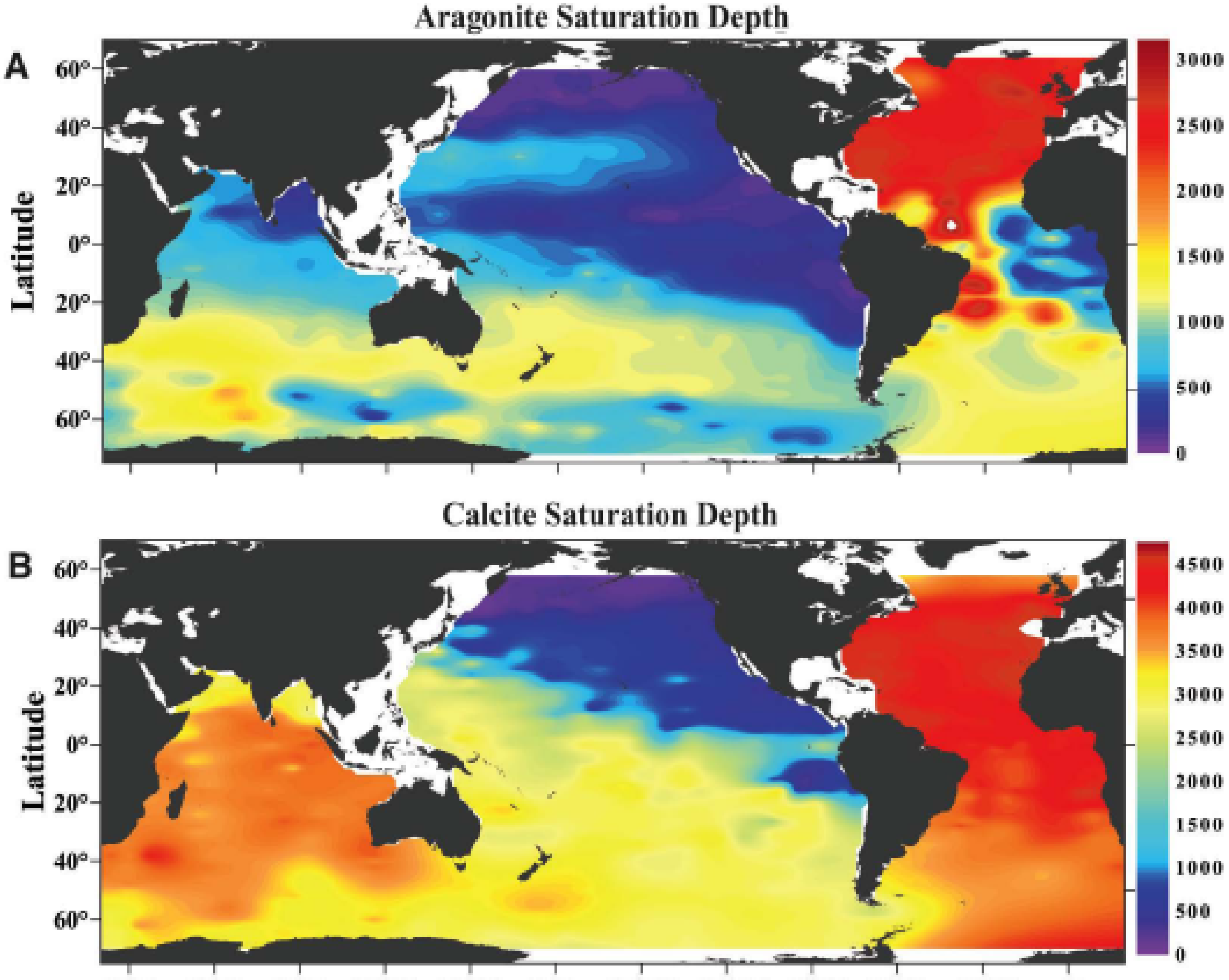


Estimated aragonite saturation states of the surface ocean for the years 1765, 1995, 2040, and 2100 (Feely et al., submitted), based on the modeling results of Orr et al. (2005) and a business-as-usual CO_2 emissions scenario.

As ocean calcium carbonate saturation state decreases, a concomitant reduction in calcification rates by marine organisms can occur.

- reduced extension rates
- weaker skeletons/shells

What we know about ocean CO_2 chemistry *…from observed aragonite and calcite saturation depths in the global oceans*



Aragonite Saturation Depth

Calcite Saturation Depth

Feely et al. (2004)

What we know about ocean CO_2 chemistry *...from cumulative carbon sources and sinks over the last two centuries*

Sources

Land-use change
200 Pg C
(42%)

Fossil emission
280 Pg C
(58%)

Sinks

Atmospheric accumulation
190 Pg C
(40%)

Terrestrial sink
166 Pg C
(35%)

Ocean sink
124 Pg C
(26%)

House et al. (2002) GCB

The Impact of Ocean Acidification on Fisheries & Ecosystems

(1) Background and Potentially Significant Issues

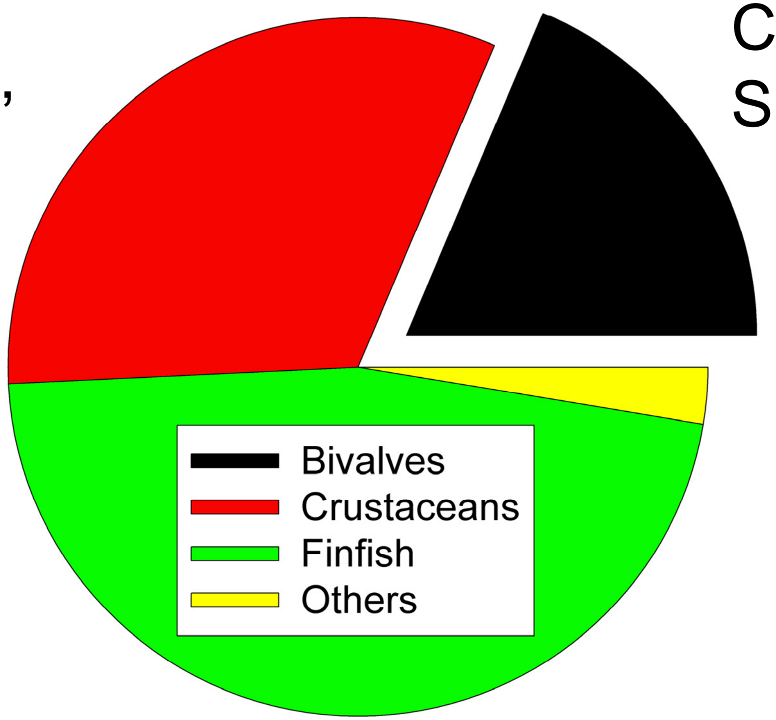
(2) Economic and Ecological Consequences of Ocean Acidification on Fisheries – First Order Effects

(3) Key Unknowns & Priorities

2005 Fishery Landings Value = $3.933 Billion
(First Sale)

Lobsters, Crabs,
Shrimp

Clams, Oysters,
Scallops, mussels



$ 60 billion/yr
Seafood Industry

Value:

Bivalves: $732M ex-vessel commercial value

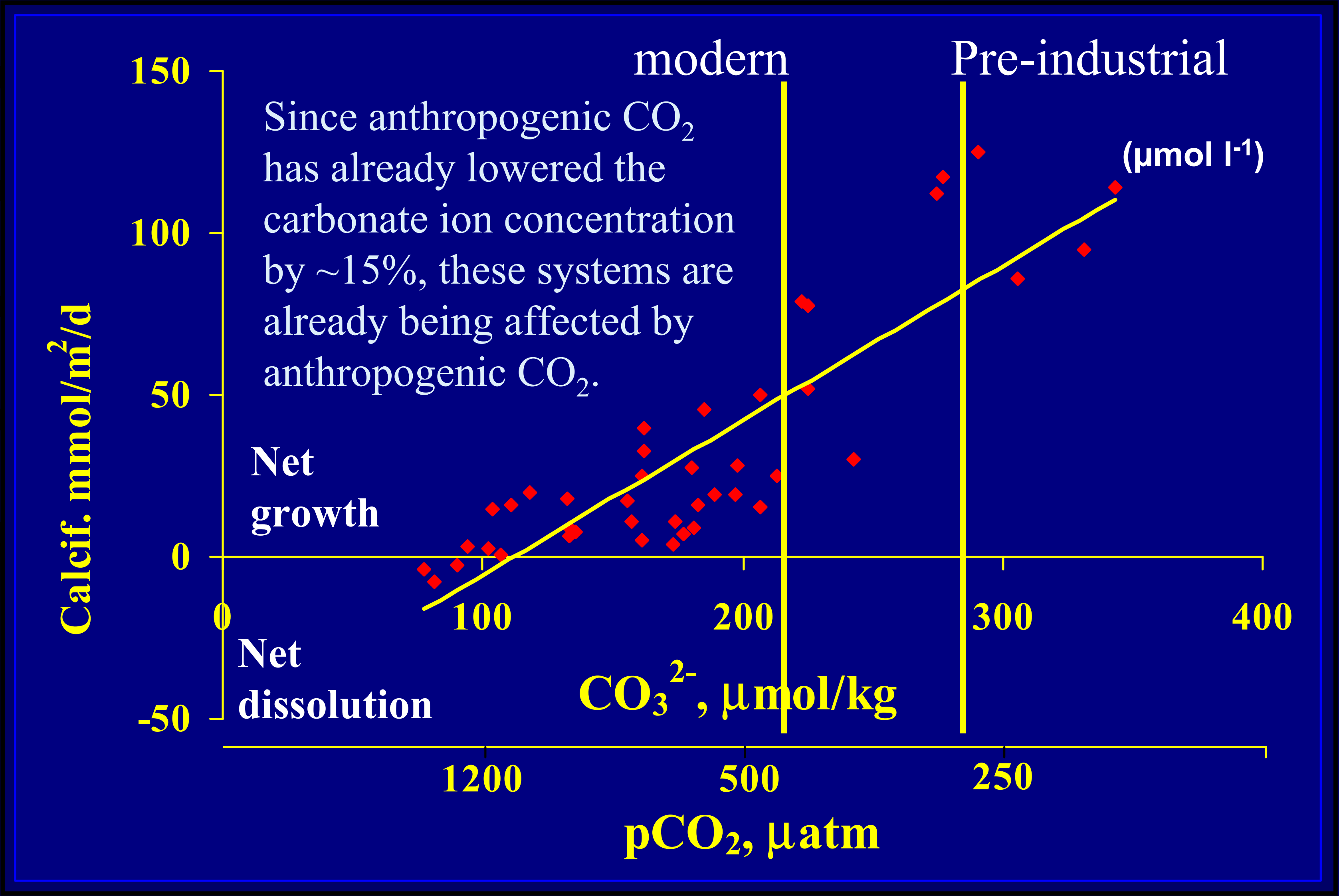
Crustaceans: $1,265M ex-vessel commercial value

Combined : $1,997M ex-vessel commercial value (51% of commercial catch by $)

Some Observed & Potential Impacts of OA on Calcifying Biota

- Coral Reefs
  - shallow (tropical) corals
  - deep corals
- Plankton (shelled & non)
- Bivalves
- Crustaceans

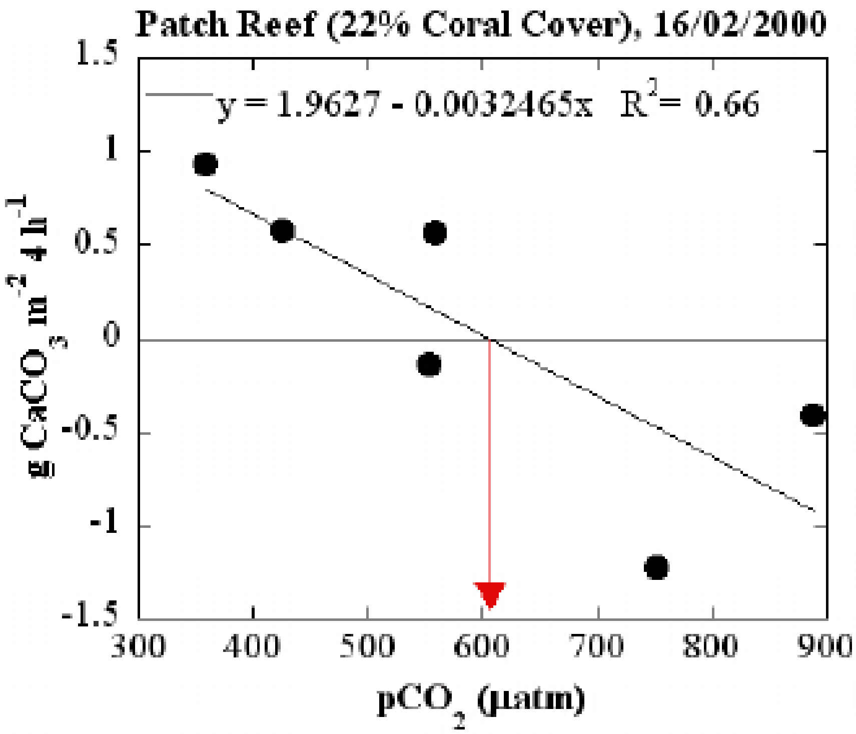
There appears to be a linear decrease in the calcification rate of coral reef systems with decreasing carbonate ion concentrations.



Since anthropogenic CO_2 has already lowered the carbonate ion concentration by ~15%, these systems are already being affected by anthropogenic CO_2.

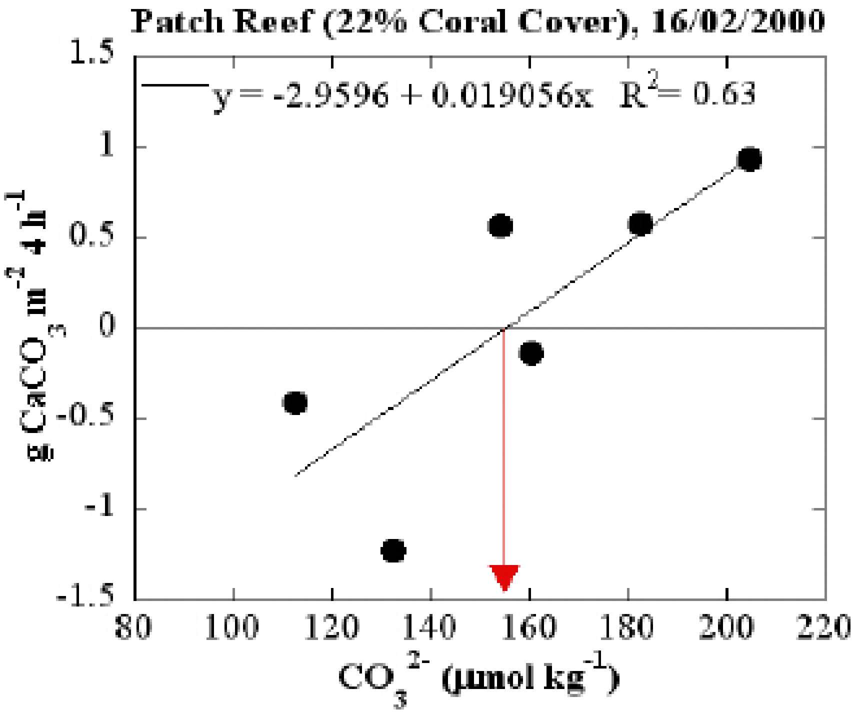
What we know
about the biological impacts of ocean acidification
...on tropical corals

Yates and Haley,
Biogeosciences (2006)



Dissolution occurs above pCO_2 threshold of 654 µatm.

Dissolution occurs below CO_3^{2-} threshold of 152 µmol kg^{-1}.



Some evidence that shallow corals can survive in polyp form w/o caclified structure

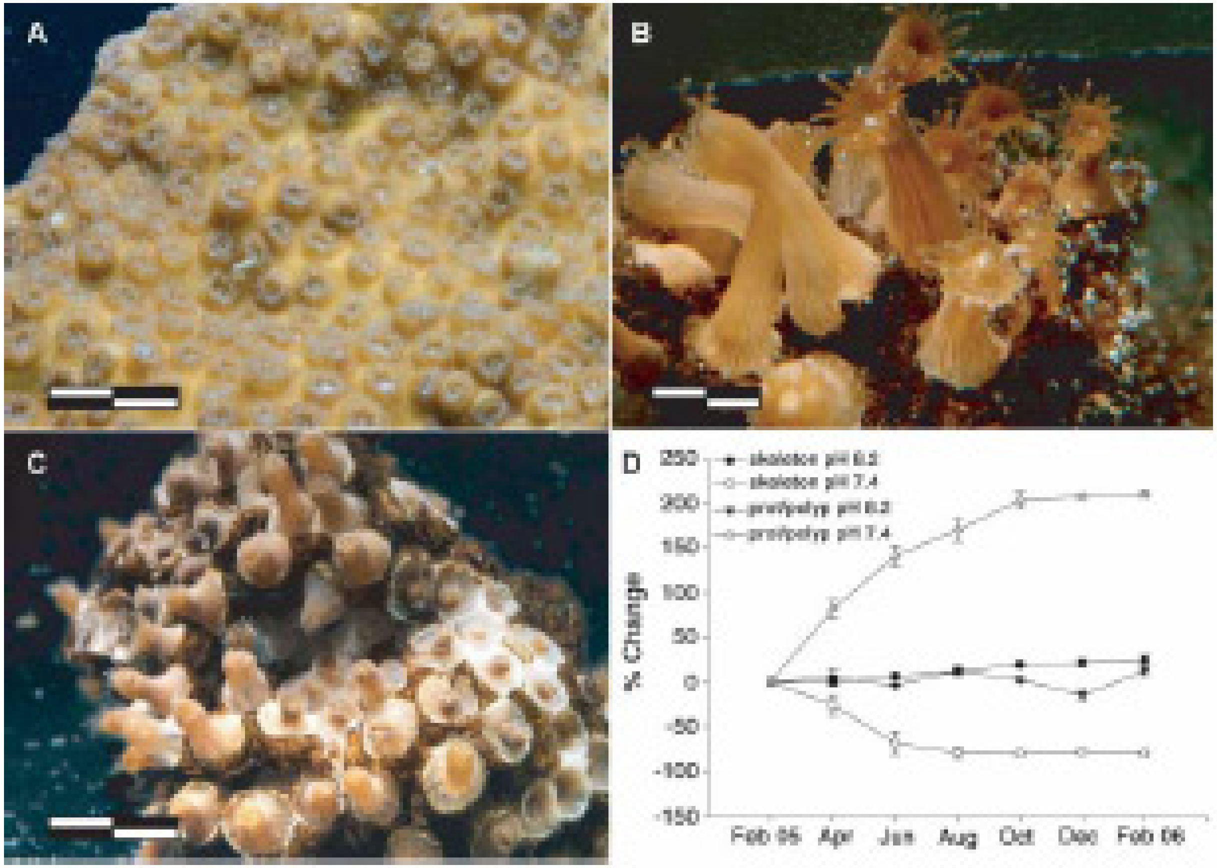


Fig. 1. Photographs of *O. patagonica*. Scale bars indicate 2 mm. **(A)** Control colony. **(B)** Sea anemone–like coral polyps following skeleton dissolution in low-pH conditions. **(C)** Solitary polyps reforming a colony and calcifying after being transferred back to normal seawater following 12 months as soft-bodied polyps in low-pH conditions. **(D)** Time series illustrating percent change (average ± SE) in protein per polyp (biomass) and total buoyant weight over 12 months in experimental (pH = 7.4) and control (pH = 8.2) seawater (*N* = 20). A two-way analysis of variance (time × pH) revealed significant changes ($P < 0.001$) between treatments over time.

(Fine & Tchernov 2006)

Coral Reef-Dependent Fisheries

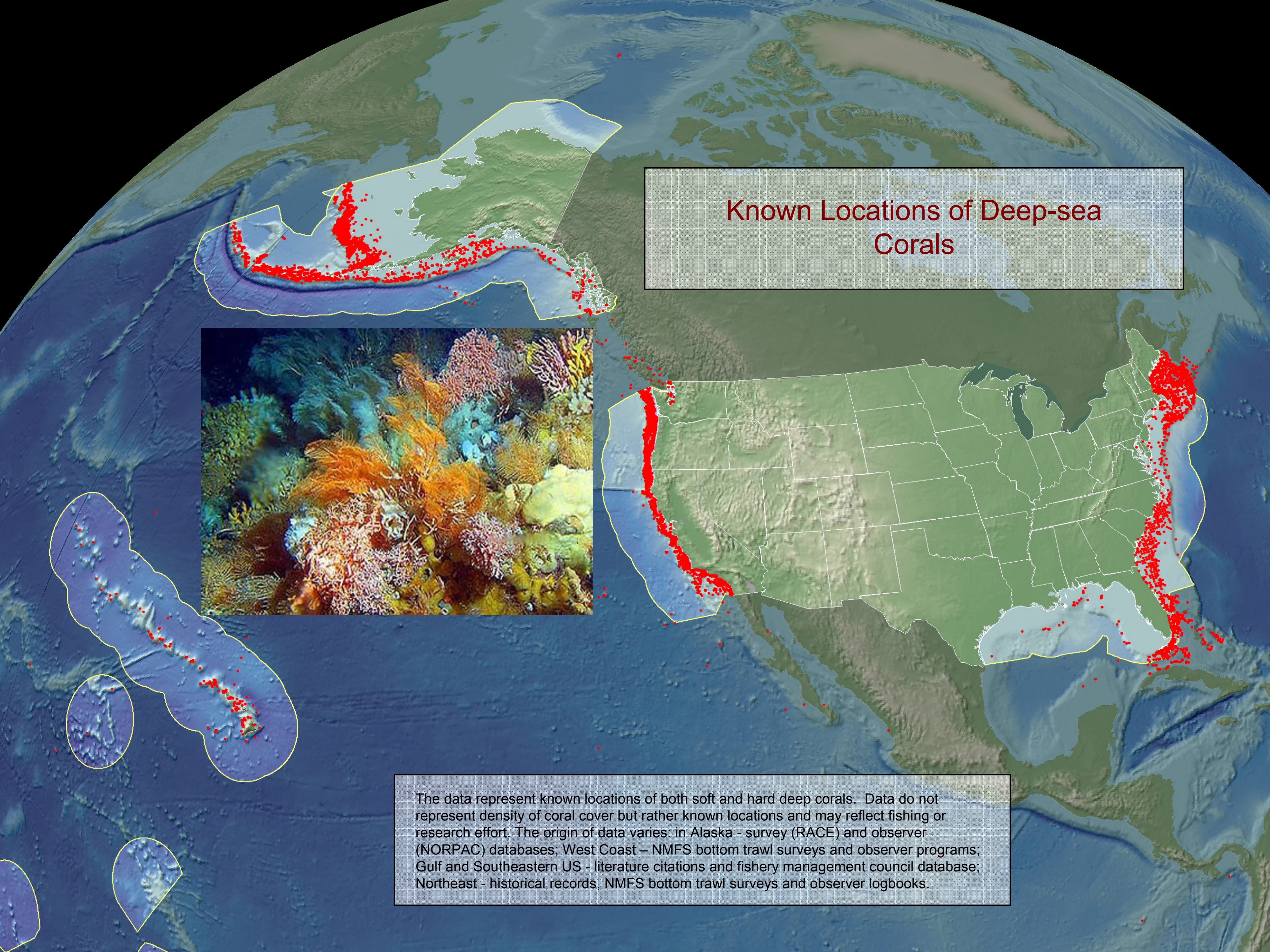
Value:

- Value to U.S. fish stocks estimated at over $100M
- Non-consumptive value of tropical coral ecosystems in $billions

Vulnerability:

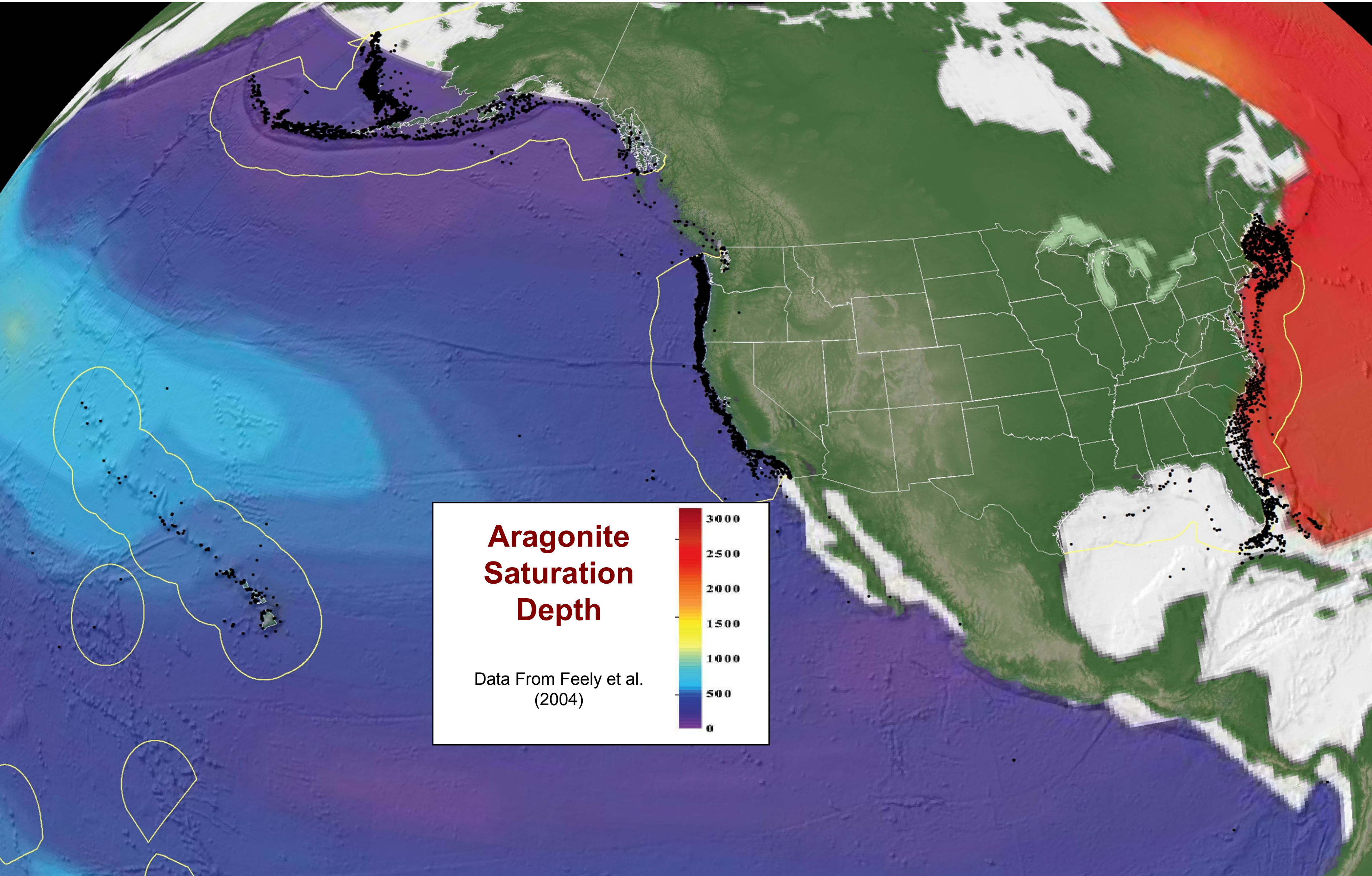
- Corals build their skeletons out of aragonite and are therefore directly susceptible to ocean acidification. The many fisheries dependent upon coral reef habitat are consequently at risk.

Known Locations of Deep-sea Corals



The data represent known locations of both soft and hard deep corals. Data do not represent density of coral cover but rather known locations and may reflect fishing or research effort. The origin of data varies: in Alaska - survey (RACE) and observer (NORPAC) databases; West Coast – NMFS bottom trawl surveys and observer programs; Gulf and Southeastern US - literature citations and fishery management council database; Northeast - historical records, NMFS bottom trawl surveys and observer logbooks.

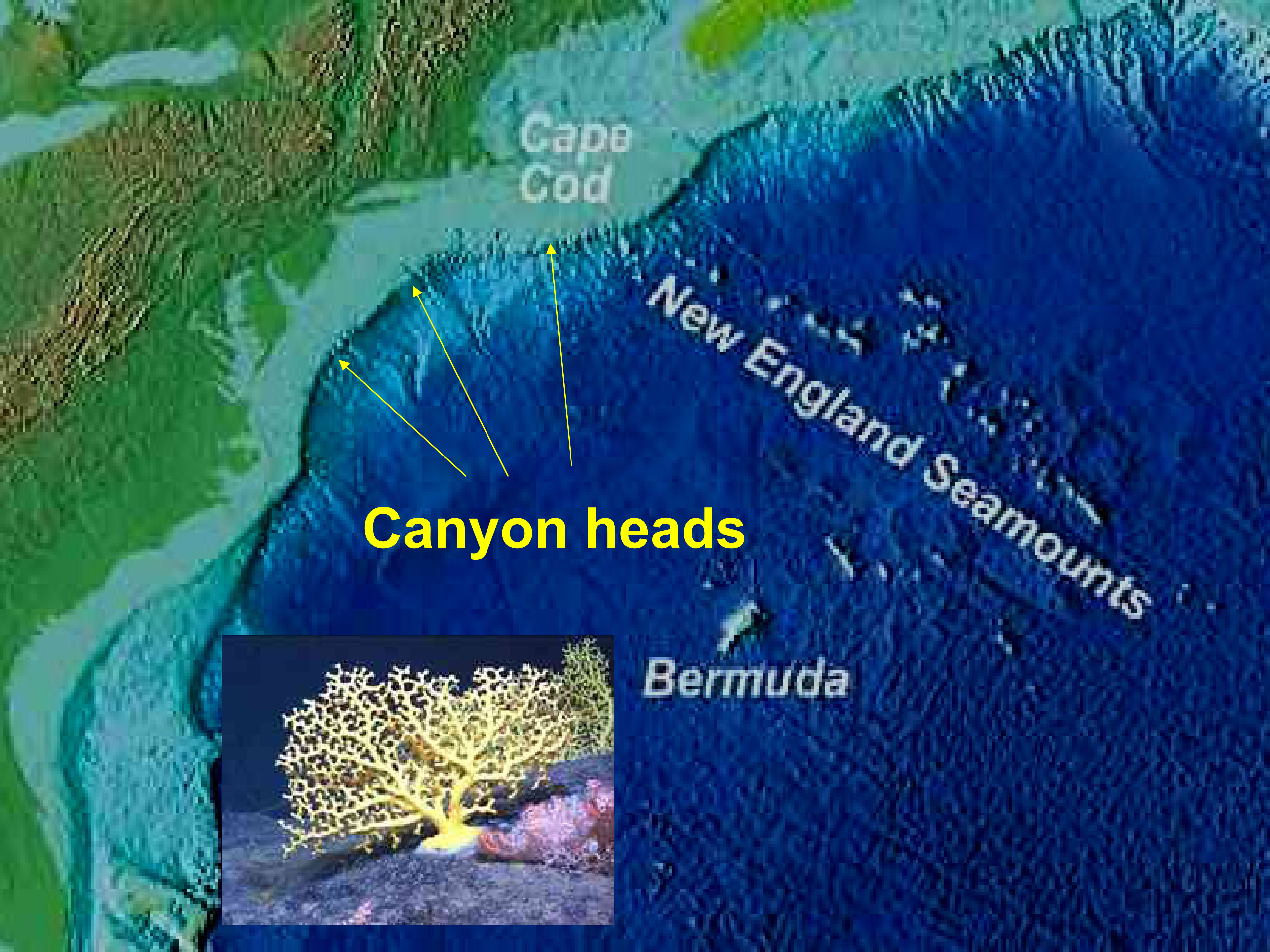
Known Locations of Deep Corals and Observed Aragonite Saturation Depths



Data From Feely et al. (2004)

Alaska - Known Locations of Deep-sea Corals

The data represent known locations of both soft and hard deep corals. Data do not represent density of coral cover but rather known locations and may reflect fishing or research effort. The origin of data in Alaska includes Resource Assessment and Conservation Engineering Division (RACE) Groundfish Survey data and the northern pacific (NORPAC) observer database.



Canyon heads

Pelagic ecosystems at risk

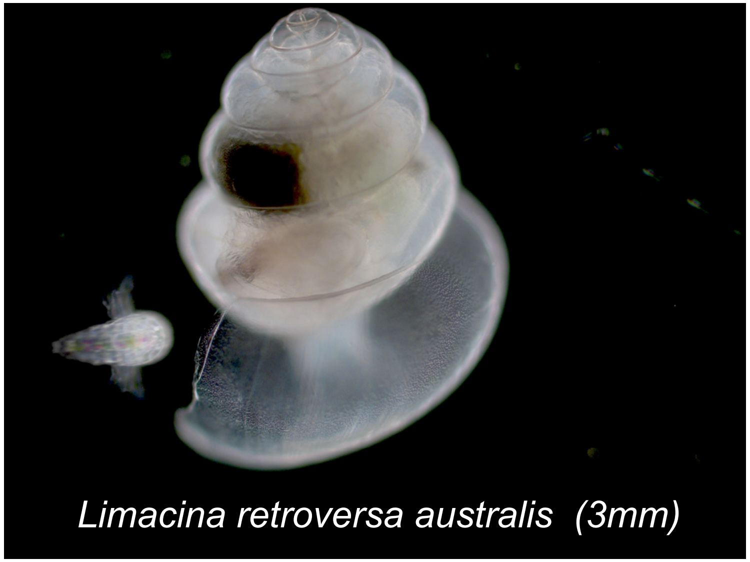
Regions where Ω is already low

i.e. high latitudes,

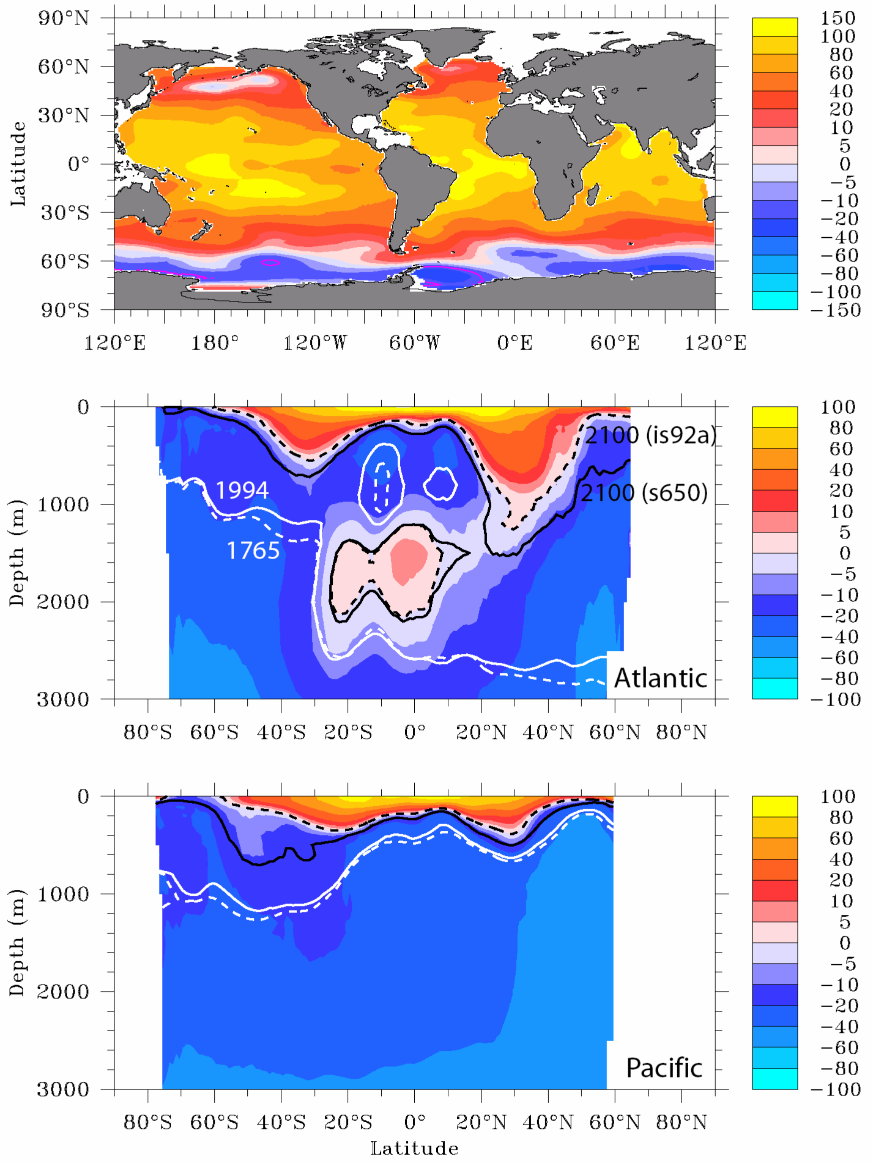
particularly Southern Ocean

Ecosystems dominated by aragonite-producers

e.g. pteropods in Southern Ocean



Limacina retroversa australis (3mm)



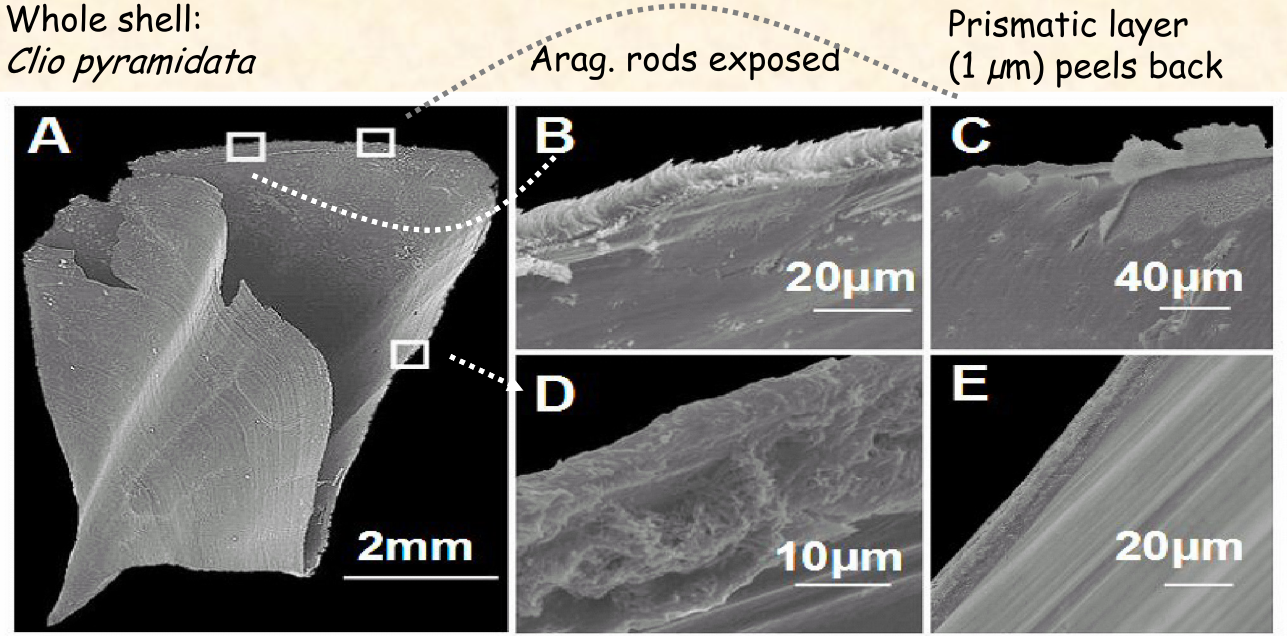
Orr et al. (2005)

Studies have shown that the shells of living pteropods begin to dissolve at elevated CO_2 levels

Whole shell:
Clio pyramidata

Arag. rods exposed

Prismatic layer
(1 μm) peels back



Aperture (~7 μm):
advanced dissolution

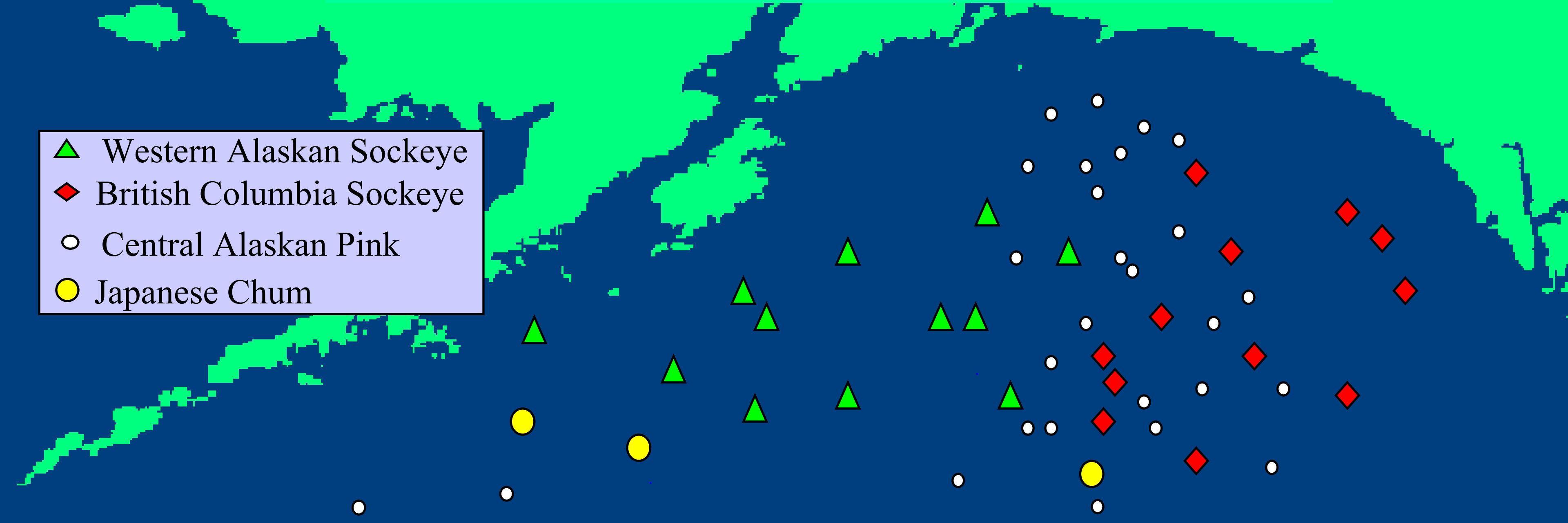
Normal shell: unexposed
to undersaturated water

Limacina helicina

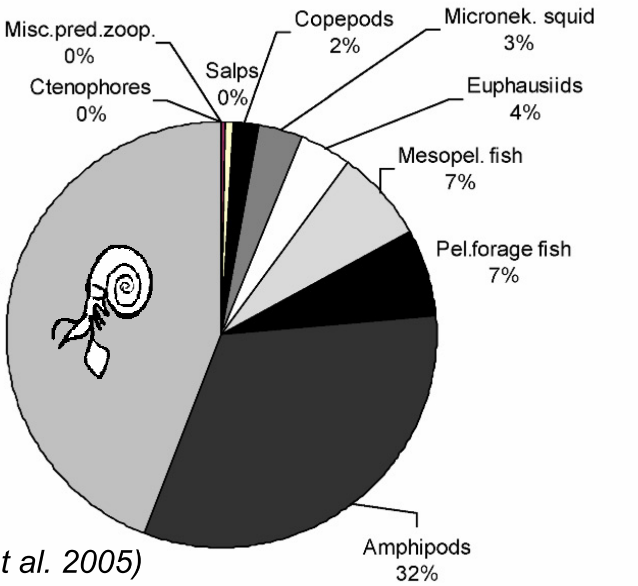
C. pyramidata

Orr et al., (2005)

Research on Impacts of OA on Pacific Salmon



Pink salmon diet



(Aydin et al. 2005)

Predicted effect of climate change on pink salmon growth:

- 10% increase in water temperature leads to 3% drop in mature salmon body weight (physiological effect).

- 10% decrease in pteropod production leads to 20% drop in mature salmon body weight (prey limitation).

Phytoplankton Response Studies Conducted by NMFS for Aquaculture Food

- Possible fertilization effect of increased CO_2 (carbon) as phytoplankton nutrient
- Studies with some phytoplankton indicate that reductions of 0.3-0.5 pH units have little impact on productivity, but may differentially impact species dominance
- Variety of lab studies

Some Physiological Research on Bivalves

- Study in the Netherlands indicates that for Pacific oyster and blue mussel, calcification rates decline linearly with increasing partial CO_2 concentration (both are major aquaculture species and support wild fisheries)
- Unknown if larval and juvenile stages are more susceptible than adults
- Should be straight forward to study but acclimation and complex physiological mechanisms may buffer response

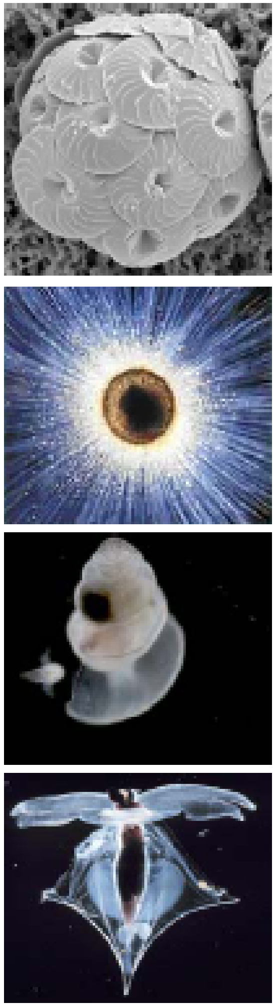
Potential OA Impacts on Crustaceans

- Larval blue king crab, Kodiak Alaska, pilot experiment, 2006
- Tested range of projected global ocean pH change over the current century.
- ~15% reduction in growth and ~67% reduction in survival when pH was reduced 0.5 units.
- Expansion to red, brown and blue king crab planned for 2007.

M. Litzow and J. Short, NOAA Alaska Fisheries Science Center

What we know
about the biological impacts of ocean acidification
...effects

- Adverse effects
  - biogenic calcification
  - hypercapnia (accumulation of CO_2 in tissues)
  - life cycle (hatching success, larval development, recruitment)
  - mortality (grazing, programmed cell death, viral infection)



- Stimulating effects
  - phytoplankton carbon fixation
  - production of climate relevant trace gases
  - diazotrophic nitrogen fixation
- Transfer of effects through the ecosystem via
  - competitive interaction
  - predator-prey interaction
  - symbiotic/parasitic relationships
- Acclimation (gene expression, physiological)

  Adaptation (genetic diversity, micro-evolution)

What we know about the biological impacts of ocean acidification ...and sensitivity to CO_2/pH perturbation

Much of our present knowledge stems from

- abrupt CO_2/pH perturbation experiments
- with single species/strains
- under short-term incubations
- with often extreme pH changes

Hence, we know little about

- responses of genetically diverse populations
- synergistic effects with other stress factors
- physiological and micro-evolutionary adaptations
- species replacements
- community to ecosystem responses
- impacts on global climate change

Scientific questions

- What are the temporal and spatial changes of the carbon system in the global oceans and their impacts on biological communities and ecosystems?

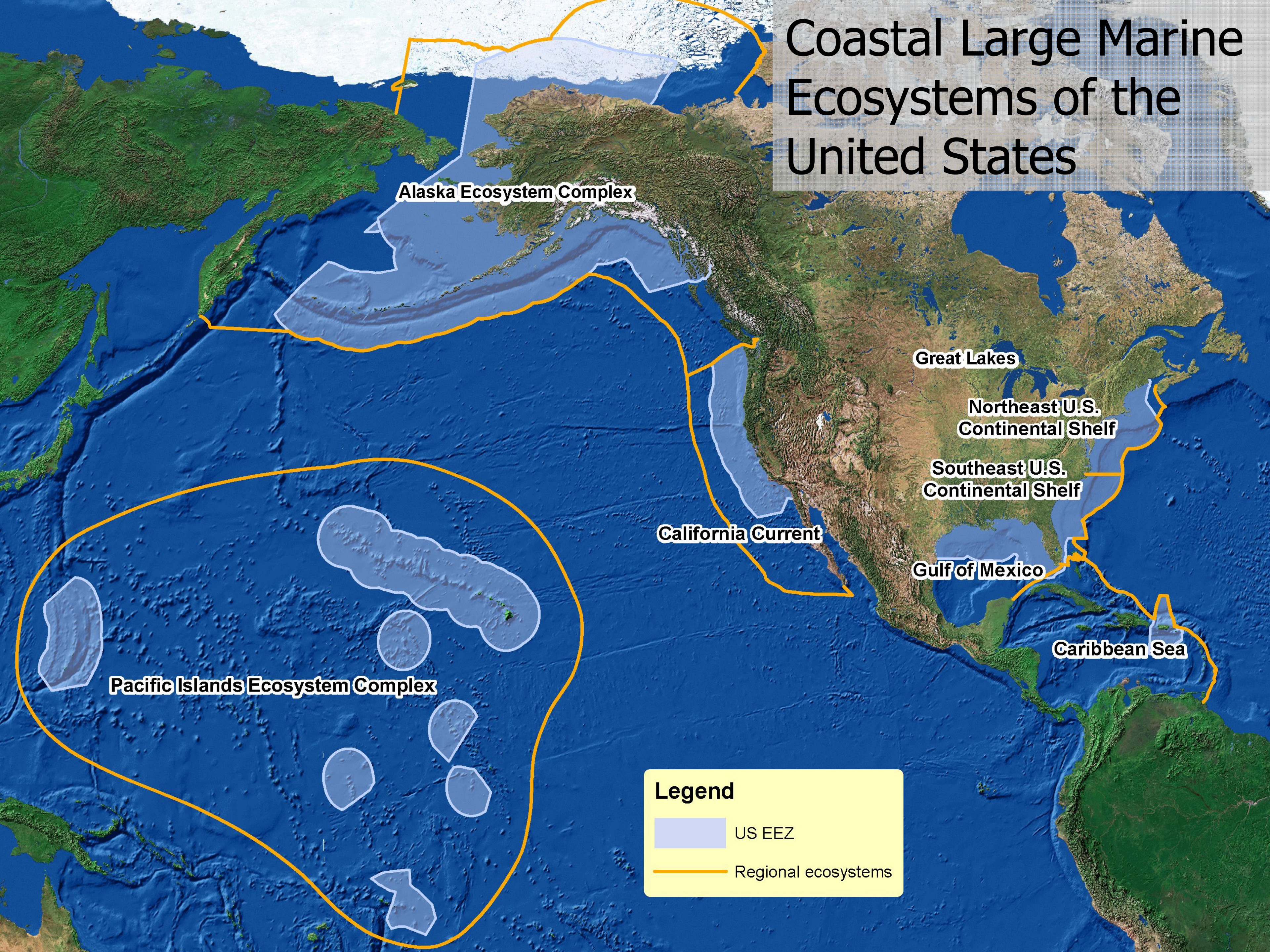
- Will marine calcifying organisms be able to acclimate to elevated CO_2 and/or temperature if given sufficient time?

- How are certain species able to adapt to life in low saturation state water?

- What are the impacts of high CO_2 on calcification, respiration, reproduction, settlement and remineralization?

- What are the effects of high CO_2 on the processes that affect ecosystem responses and global feedbacks?

Coastal Large Marine Ecosystems of the United States



Highest Priority Fishery Research on OA

Priorities for Fisheries & Ecosystems

- Exposure studies on bivalve mollusks (especially larval bivalves), crustaceans, and phytoplankton
- Chronic exposure studies, using factoral design with temperature, CO_2 and pH stress (+ other factors)
- *In situ* exposure studies (mesocosms) of shallow and cold coral ecosystems
- Analysis of archival samples of plankton and chemistry (e.g., CALCOFI, Antarctica)

Priorities for Monitoring

- Development of precise & rugged instrumentation
- Shallow water monitoring sites for bigeochemistry & physiology
- Monitoring of oceanic pH, carbon parameters & carbon budget – 1st OA Mooring Station Papa