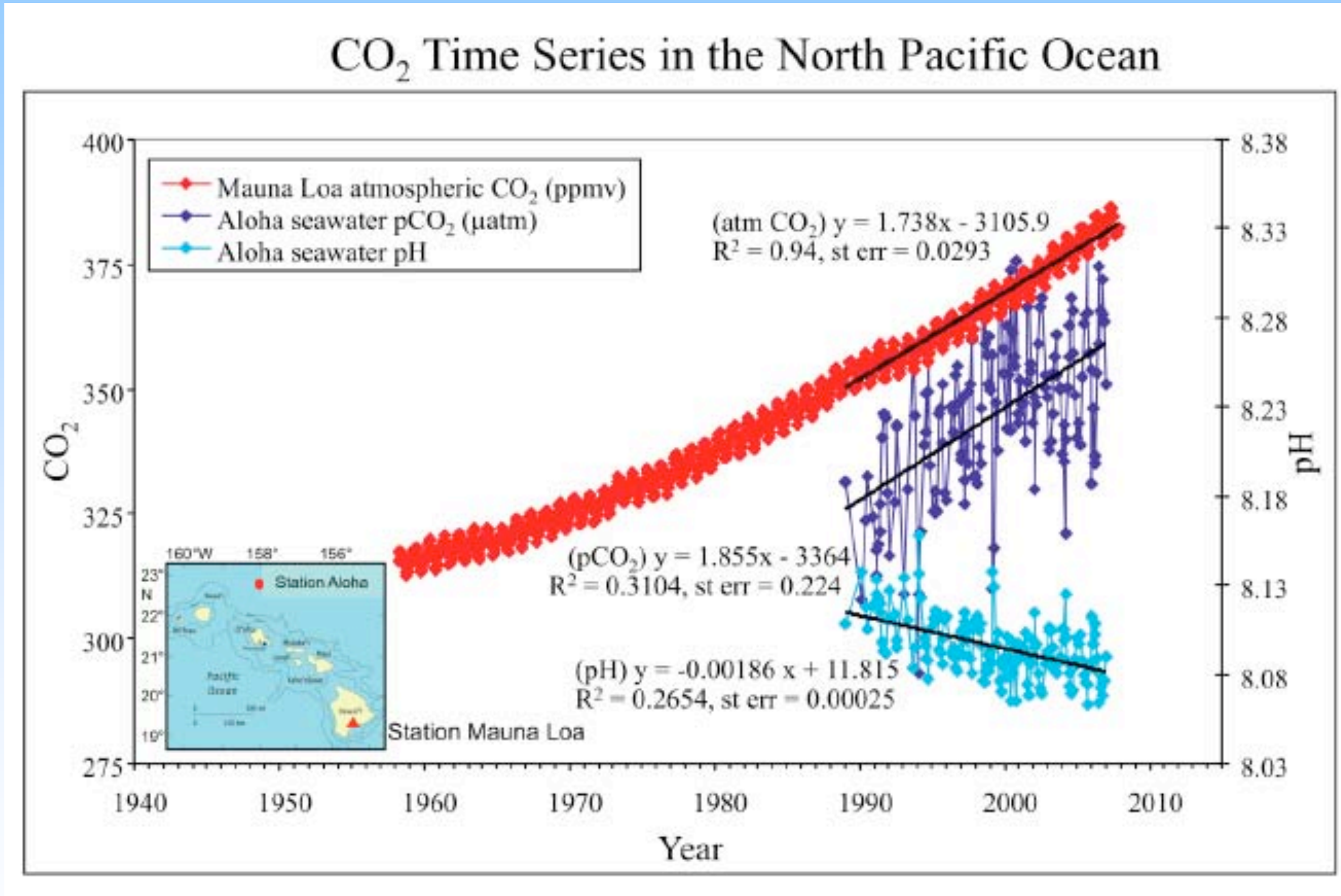
Climate Change & Ocean Acidification

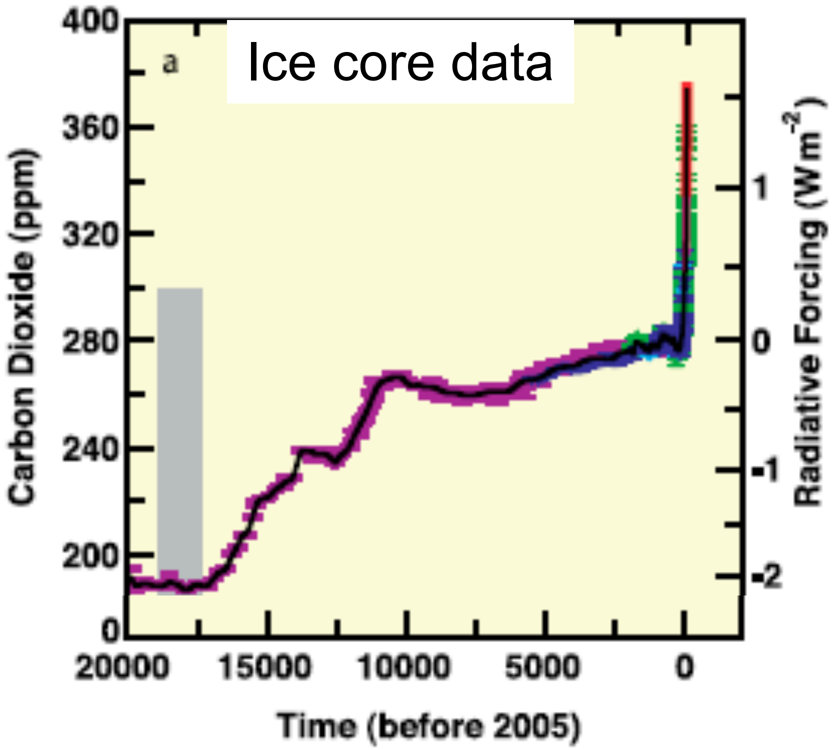
Scott Doney Woods Hole Oceanographic Institution

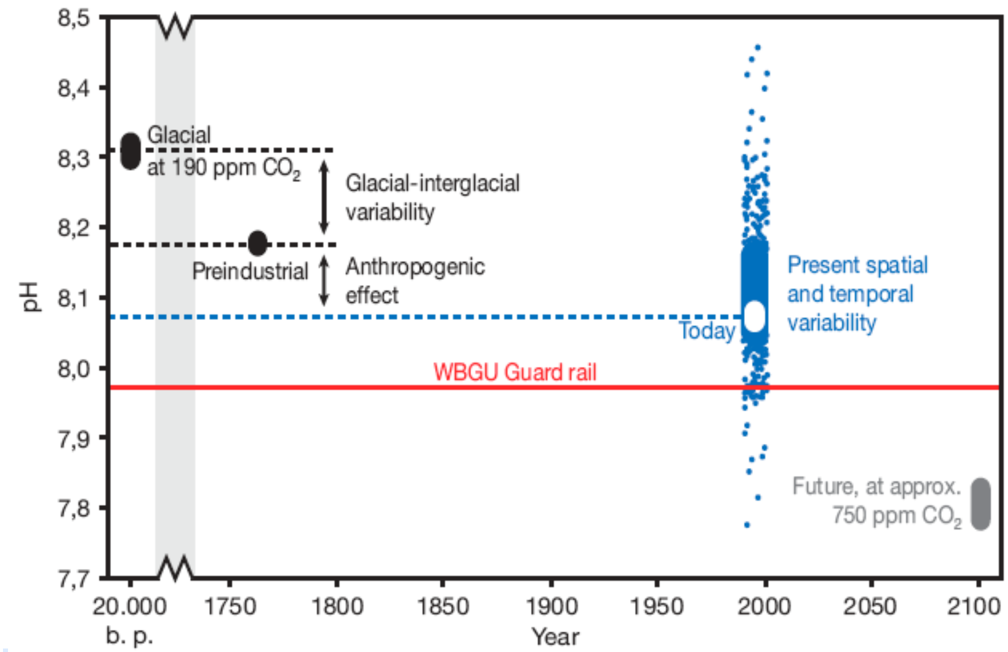


"Thus human beings are now carrying out a large scale geophysical experiment…"

Revelle and Suess, Tellus, 1957

Rising Atmospheric CO_2





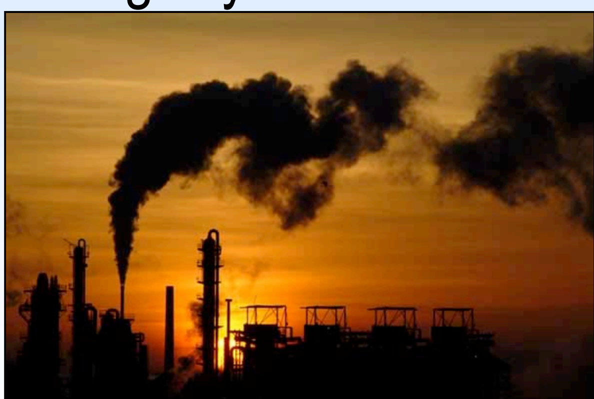
-rate of CO_2 rise and pH decrease unprecedented in recent geological record (~30 faster than natural rates)
-highest atmospheric CO_2 level in at least last million years

Fate of Anthropogenic CO_2 Emissions (2000-2007)

1.5 Pg C y^{-1}

+

7.5 Pg C y^{-1}



4.2 Pg y^{-1}

Atmosphere

46%

2.6 Pg y^{-1}

Land

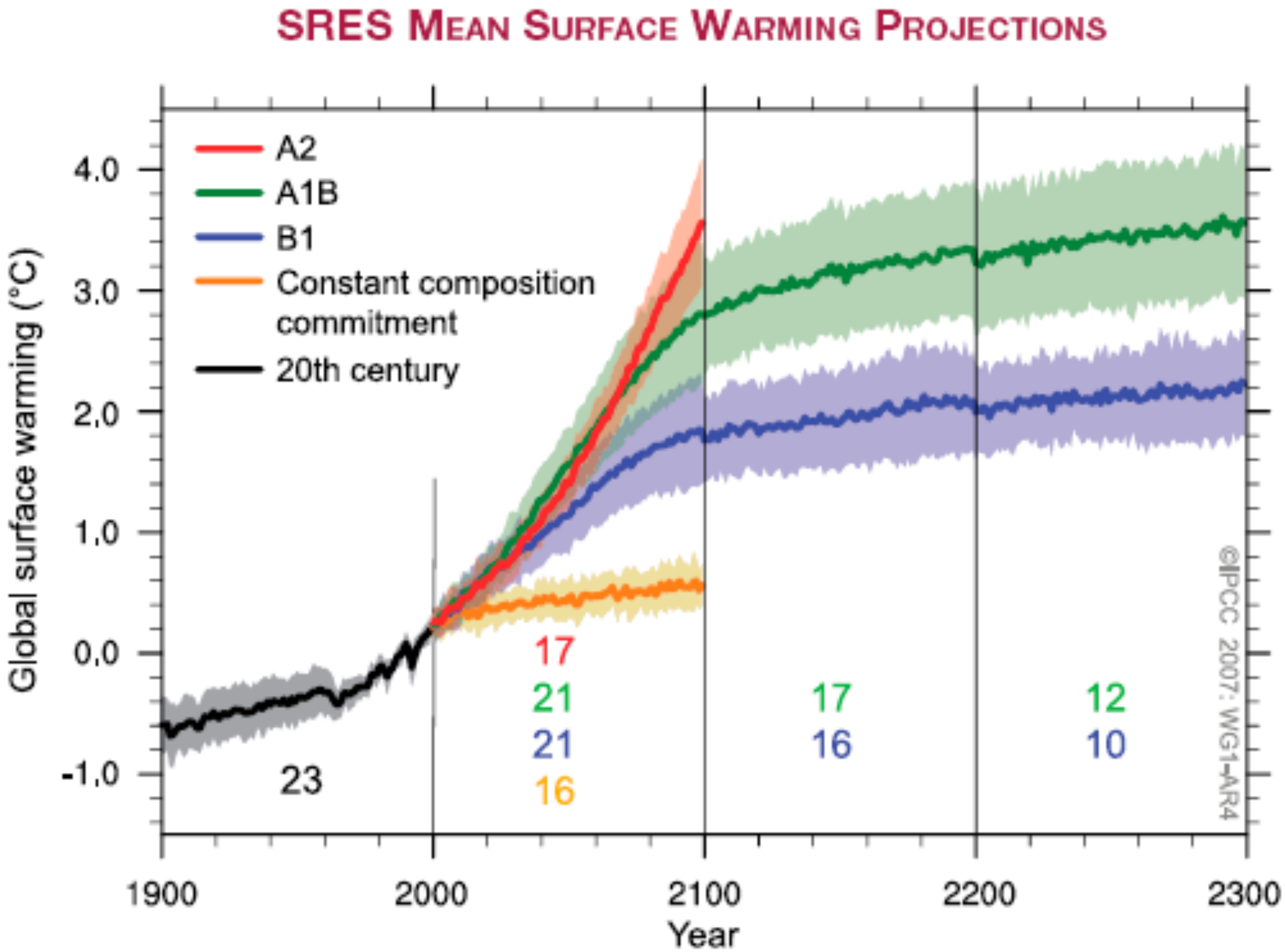
29%

2.3 Pg y^{-1}

Oceans

26%

Canadell et al. 2007, PNAS (updated); http://www.globalcarbonproject.org/



Future Climate Projections

IPCC (2007)

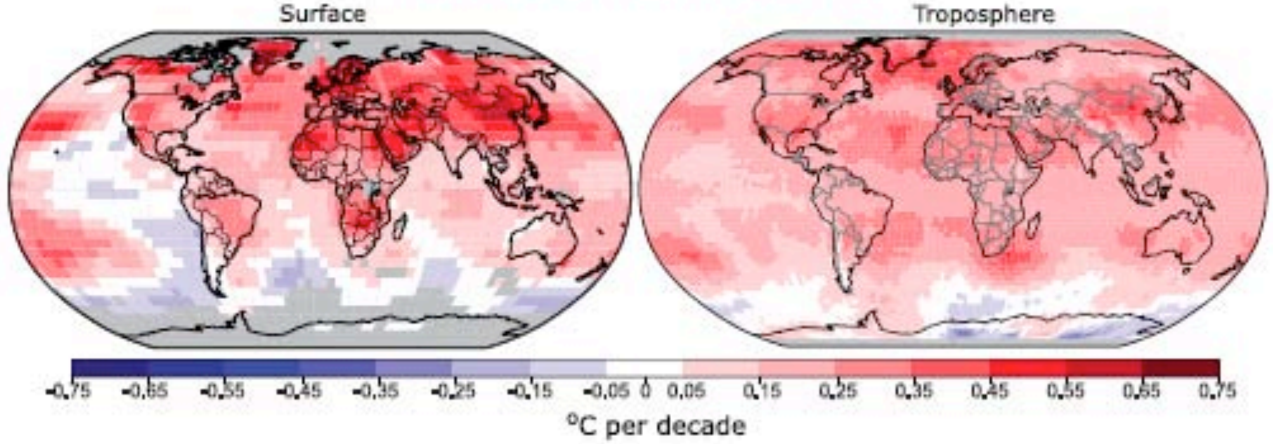
Major uncertainties:

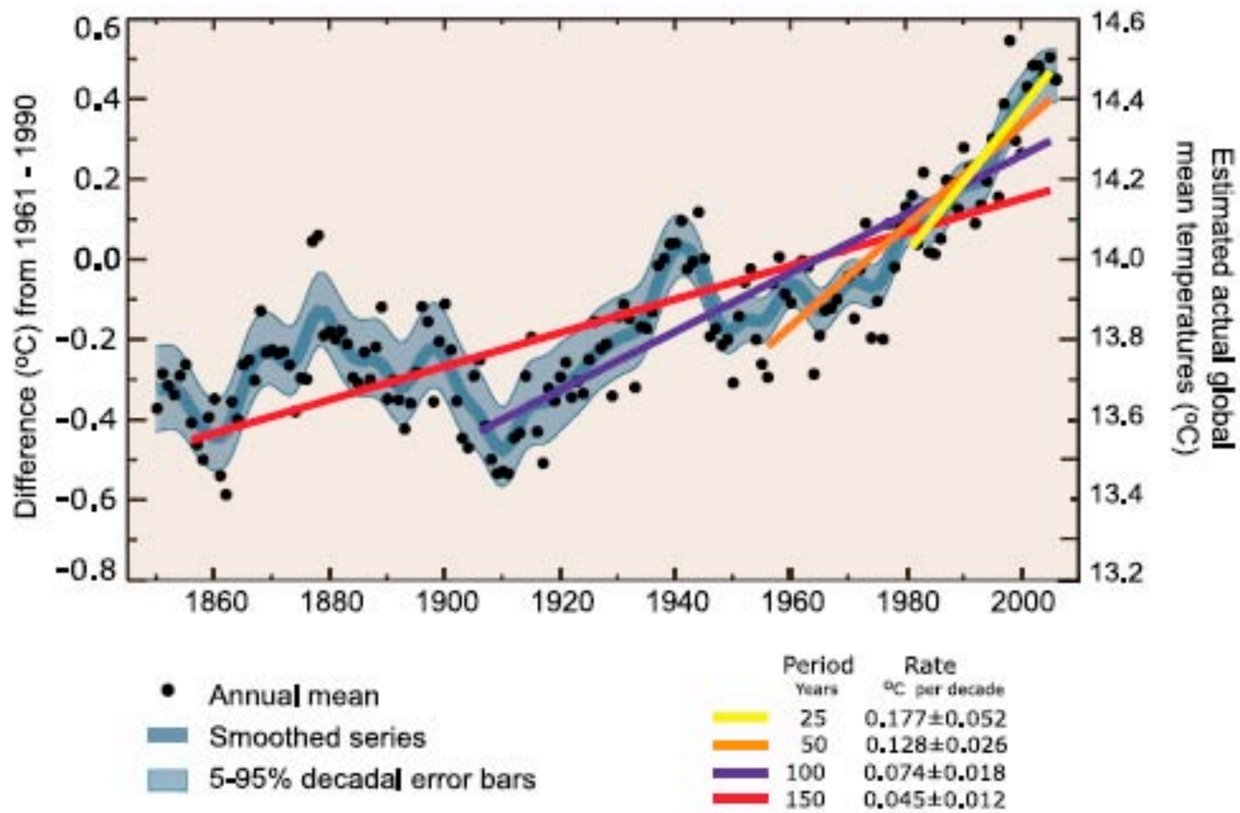
-CO_2 emissions (social, political, economic, geological)

-atmospheric CO_2 (carbon sinks, climate-carbon feedbacks)

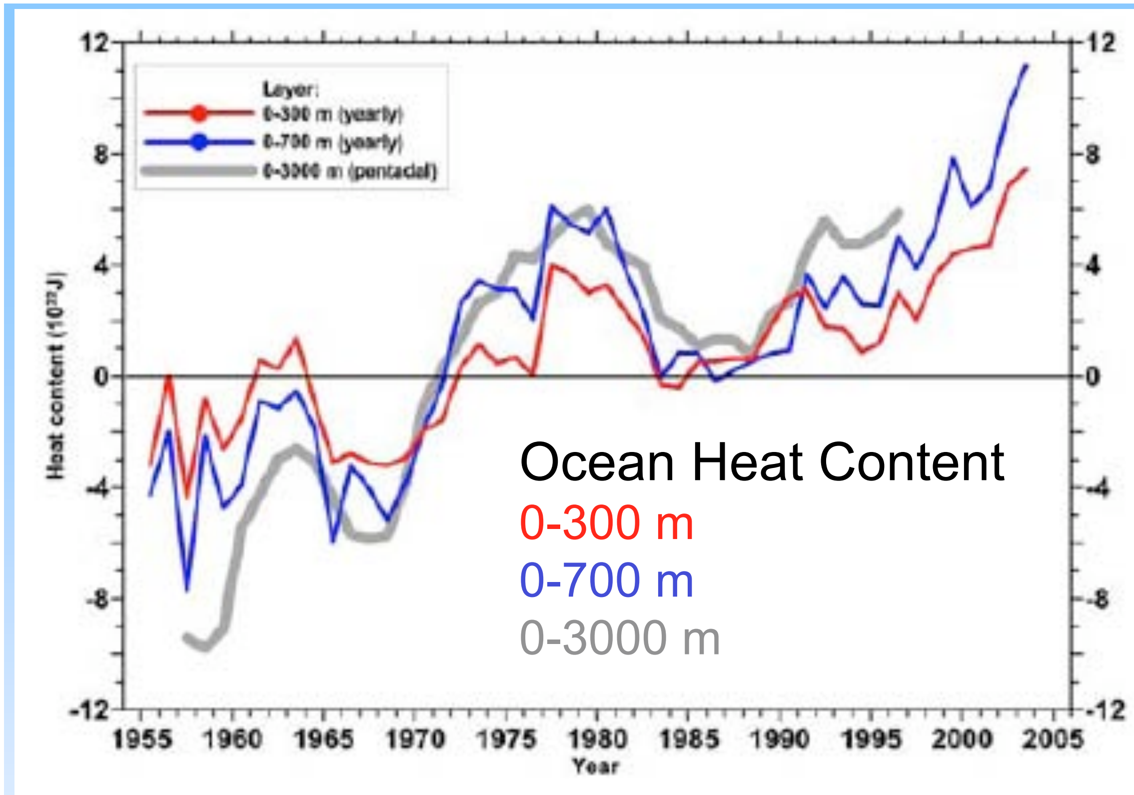
-climate sensitivities (clouds, water vapor)

Global Temperature Trends





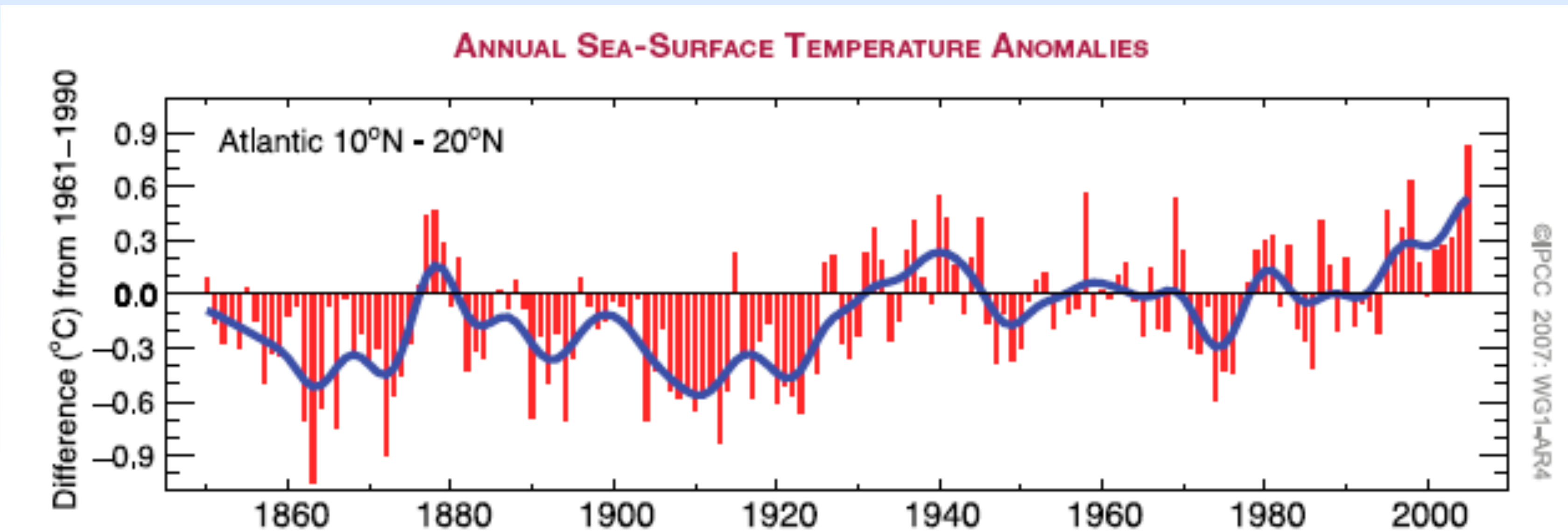
Ocean Warming



-anthropogenic warming & decadal variability signatures

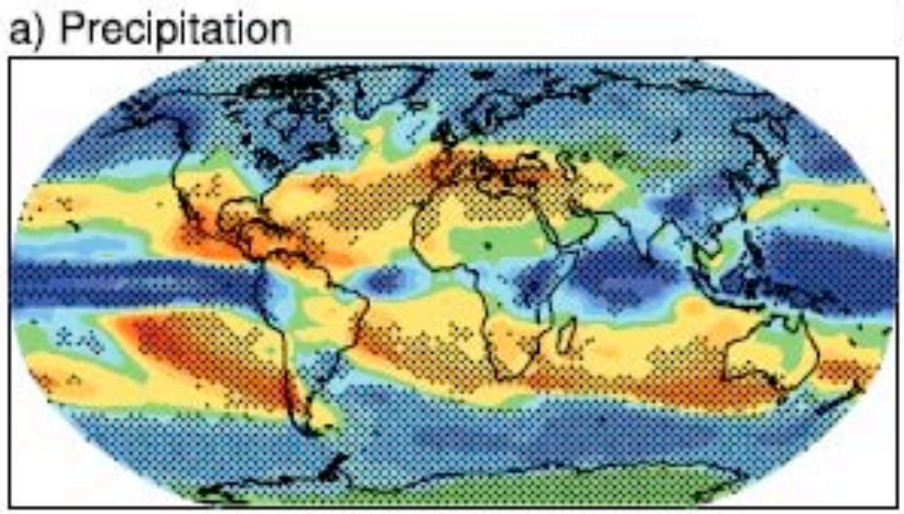
-80% of excess heat in climate system is in the oceans

Levitus et al. Geophys. Res. Lett.(2005)



IPCC (2007)

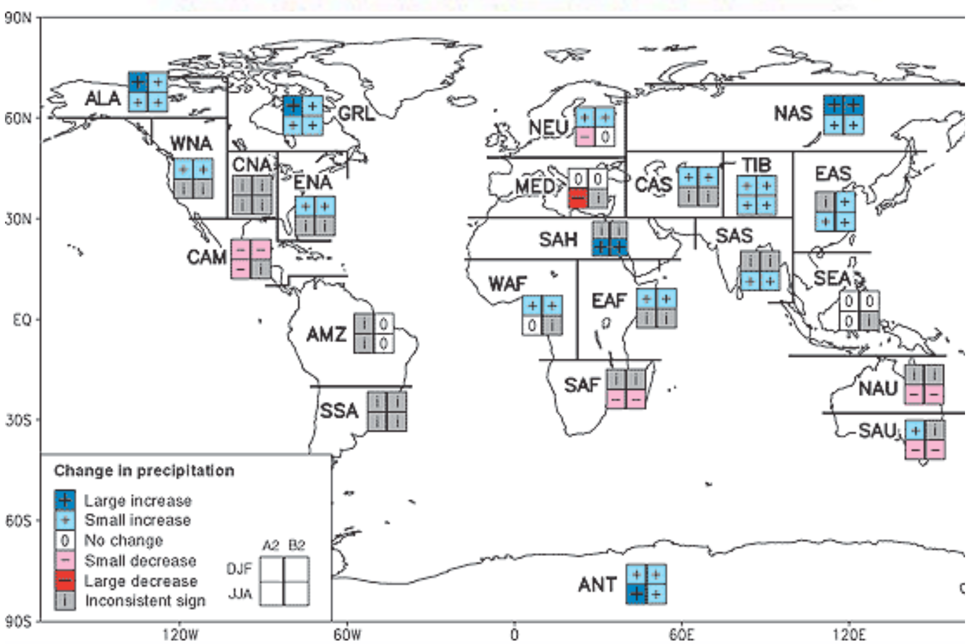
Stronger Water Cycle (Flooding & Droughts)

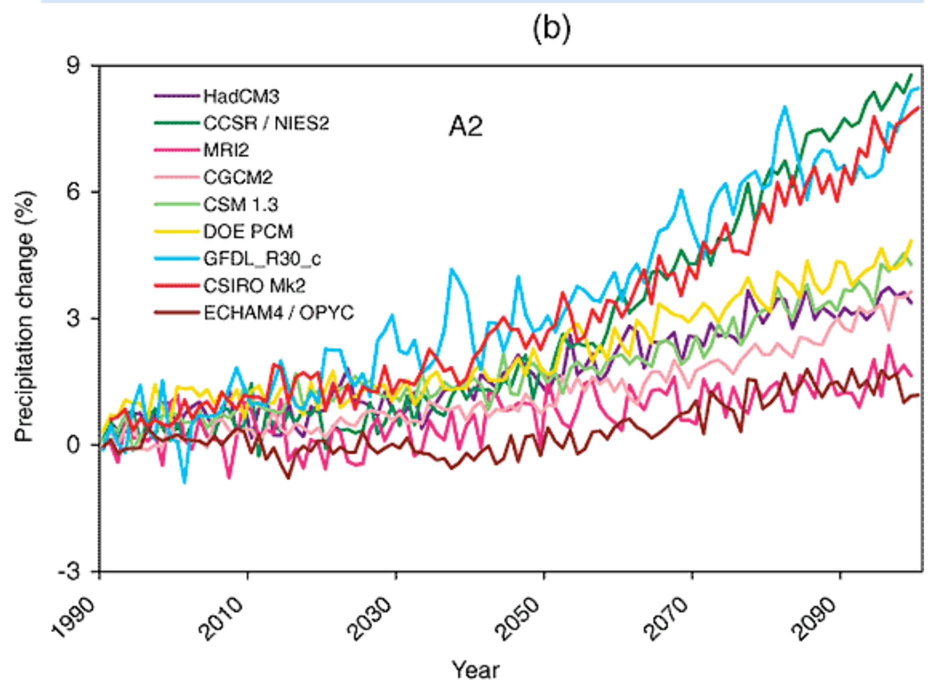


Accelerated water cycle

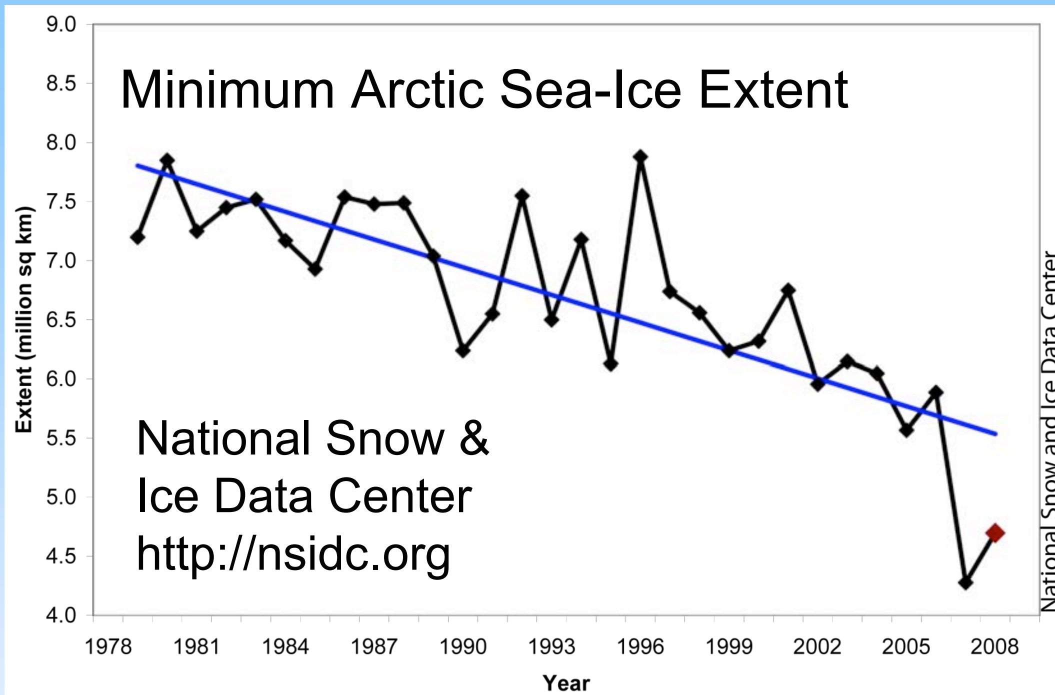
Wetter locations become wetter

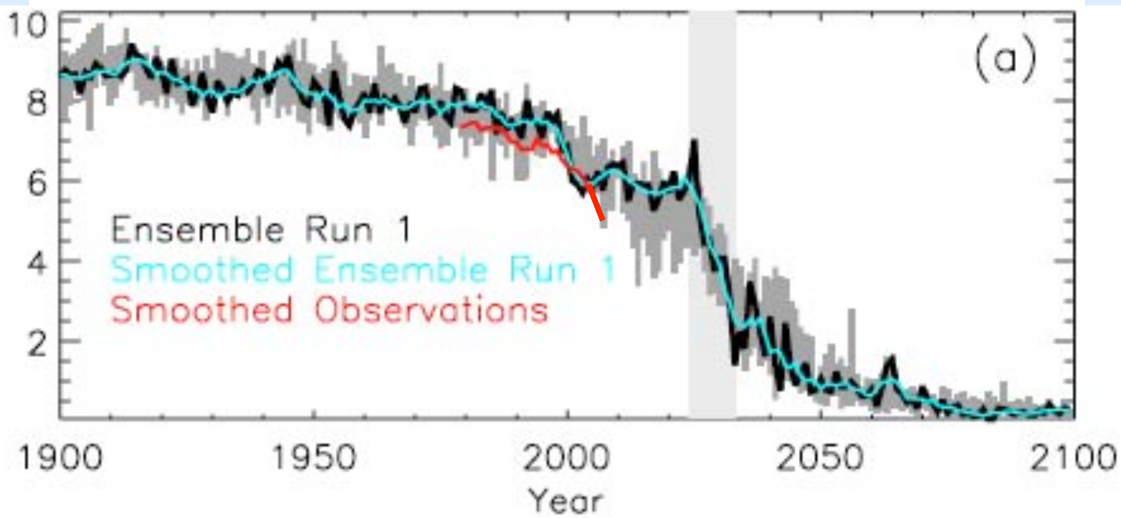
Drier locations become drier

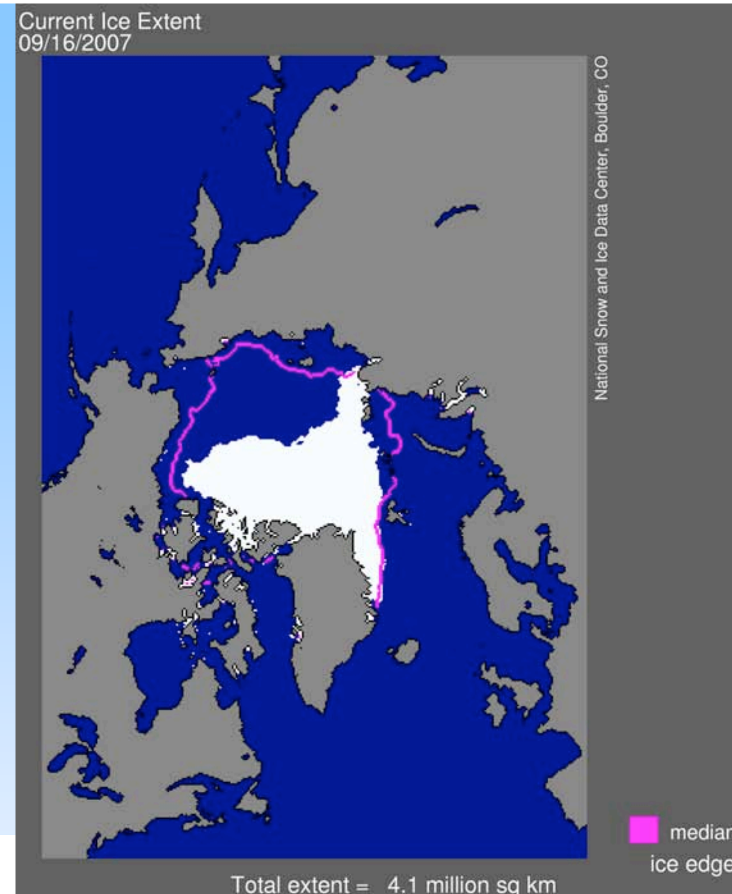


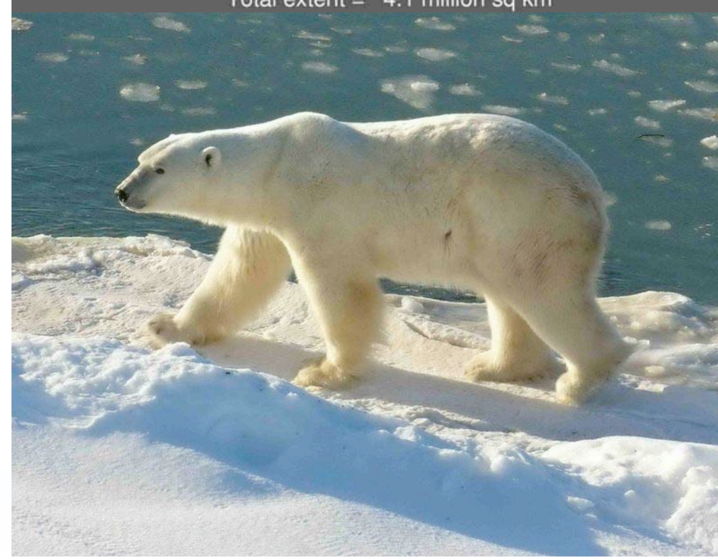


Shrinking Sea-Ice



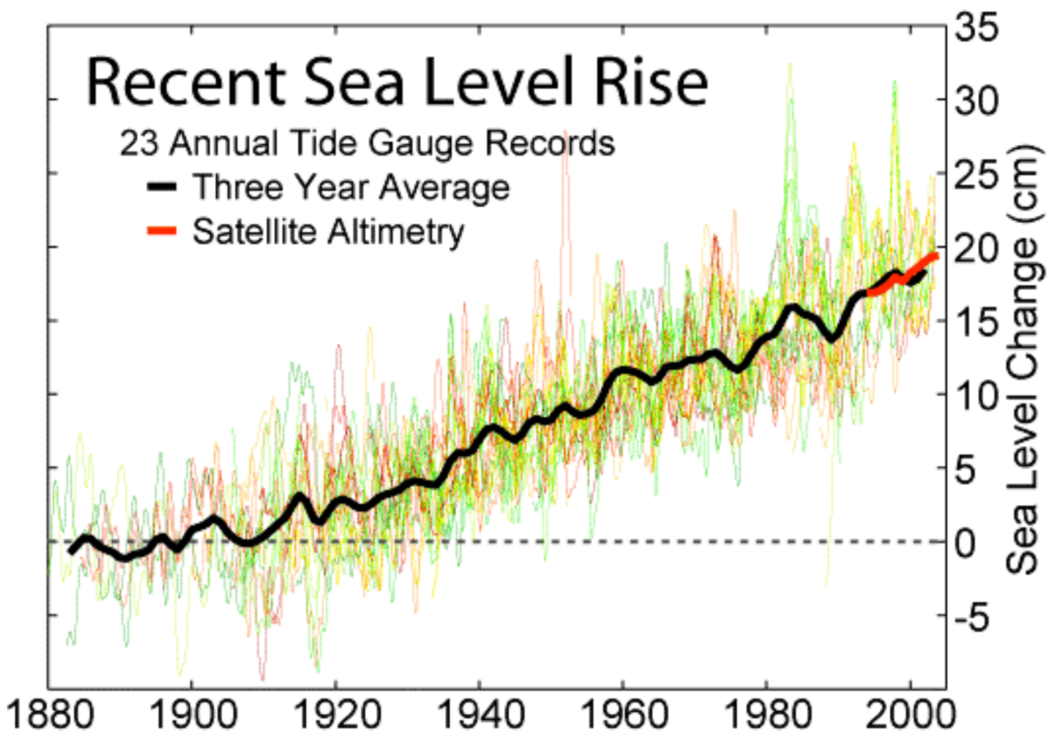


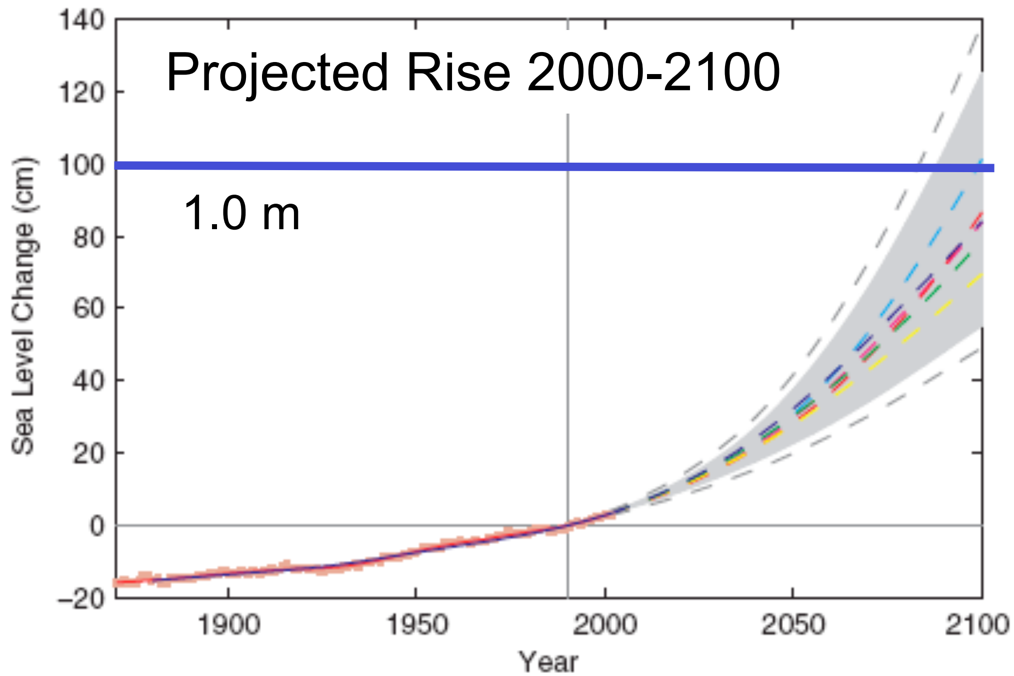


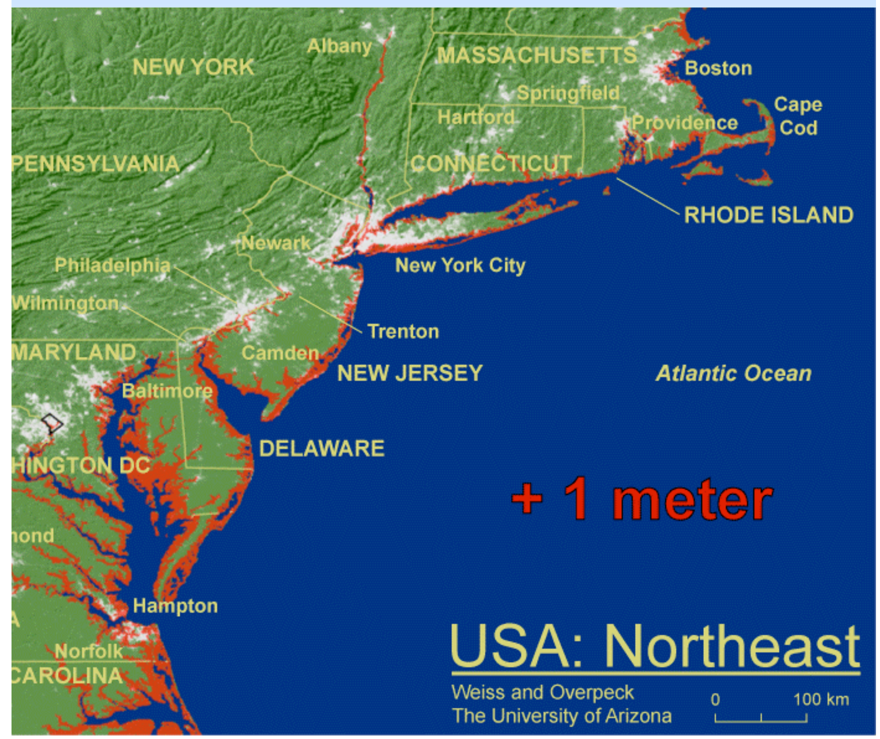


Sea-Level Rise

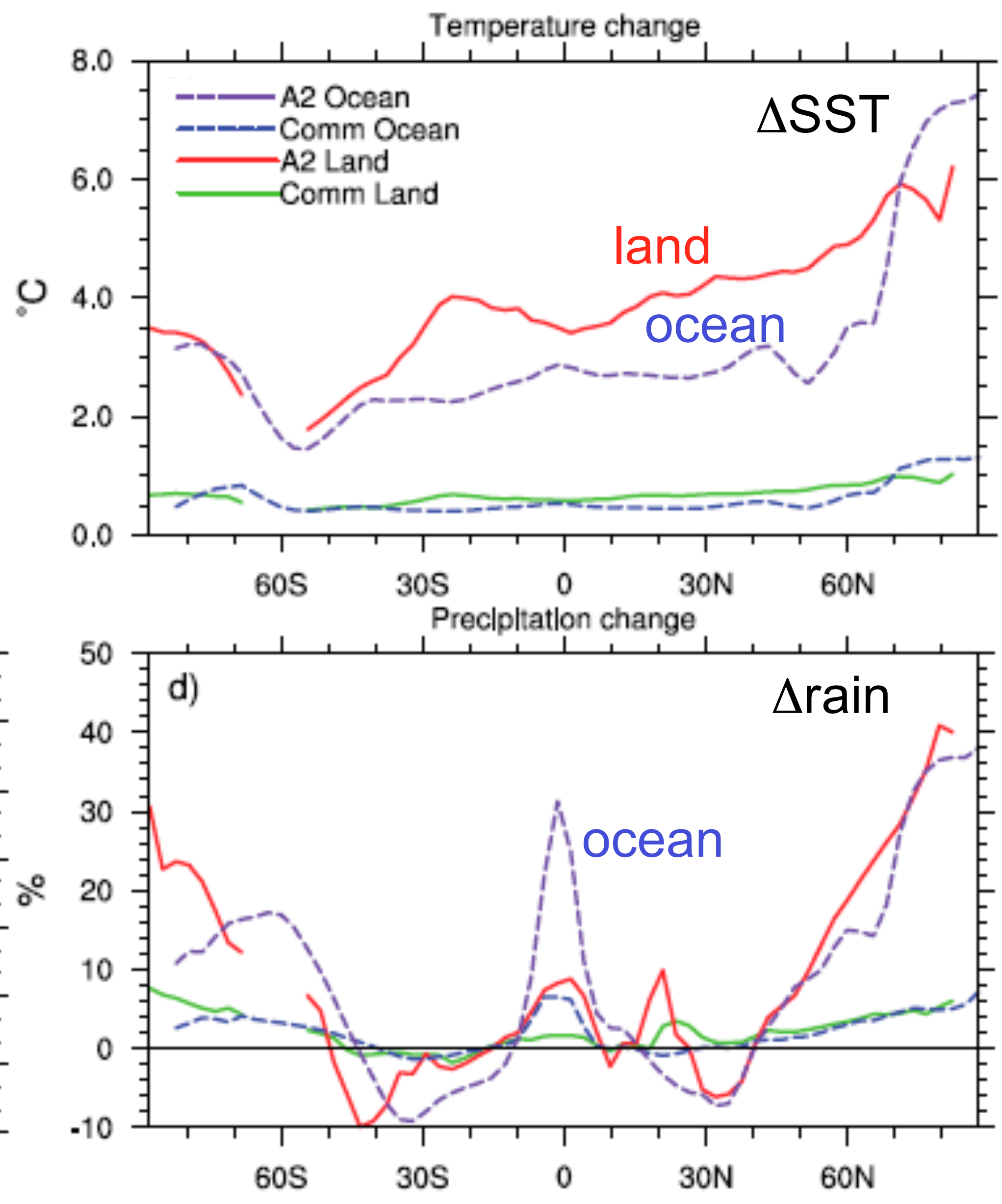
- Warming seawater & melting land-ice
- More coastal erosion & loss of wetlands
- Storm surge damage







zonal means; 2080-2099 minus 1980-1999

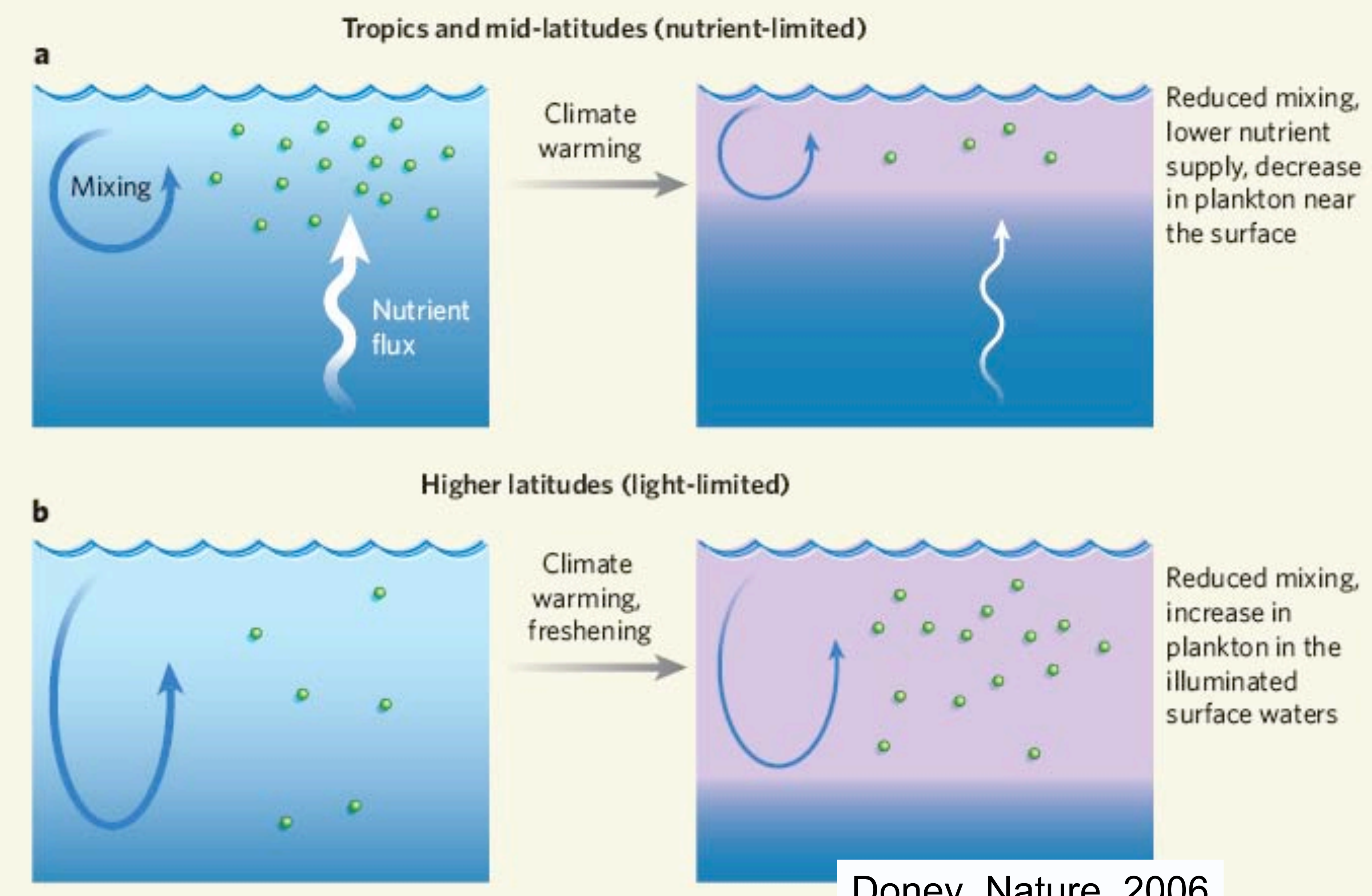


Spatial Patterns of Climate Change

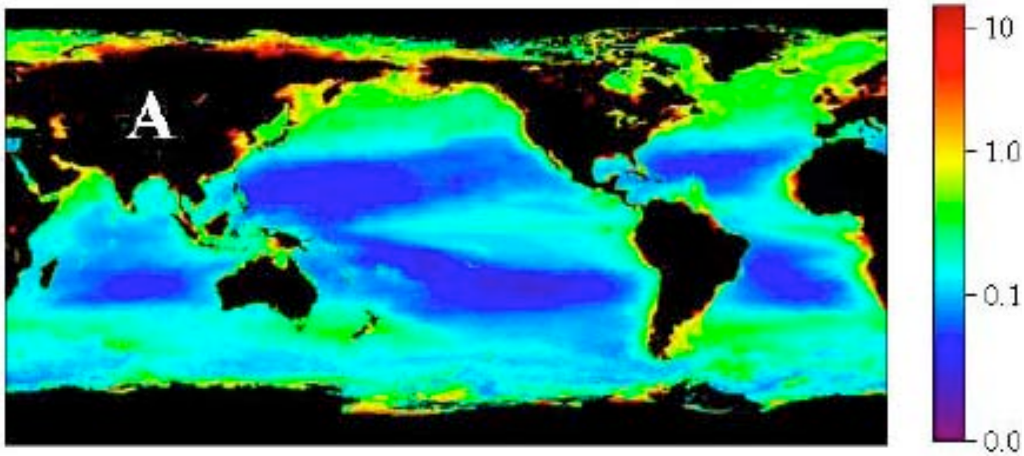
- poles warm faster than tropics
- freshening in tropics & poles from more rain and sea-ice melt
- increased surface stratification
- sea-level rise

IPCC (2007)

Biological Responses to Increased Stratification



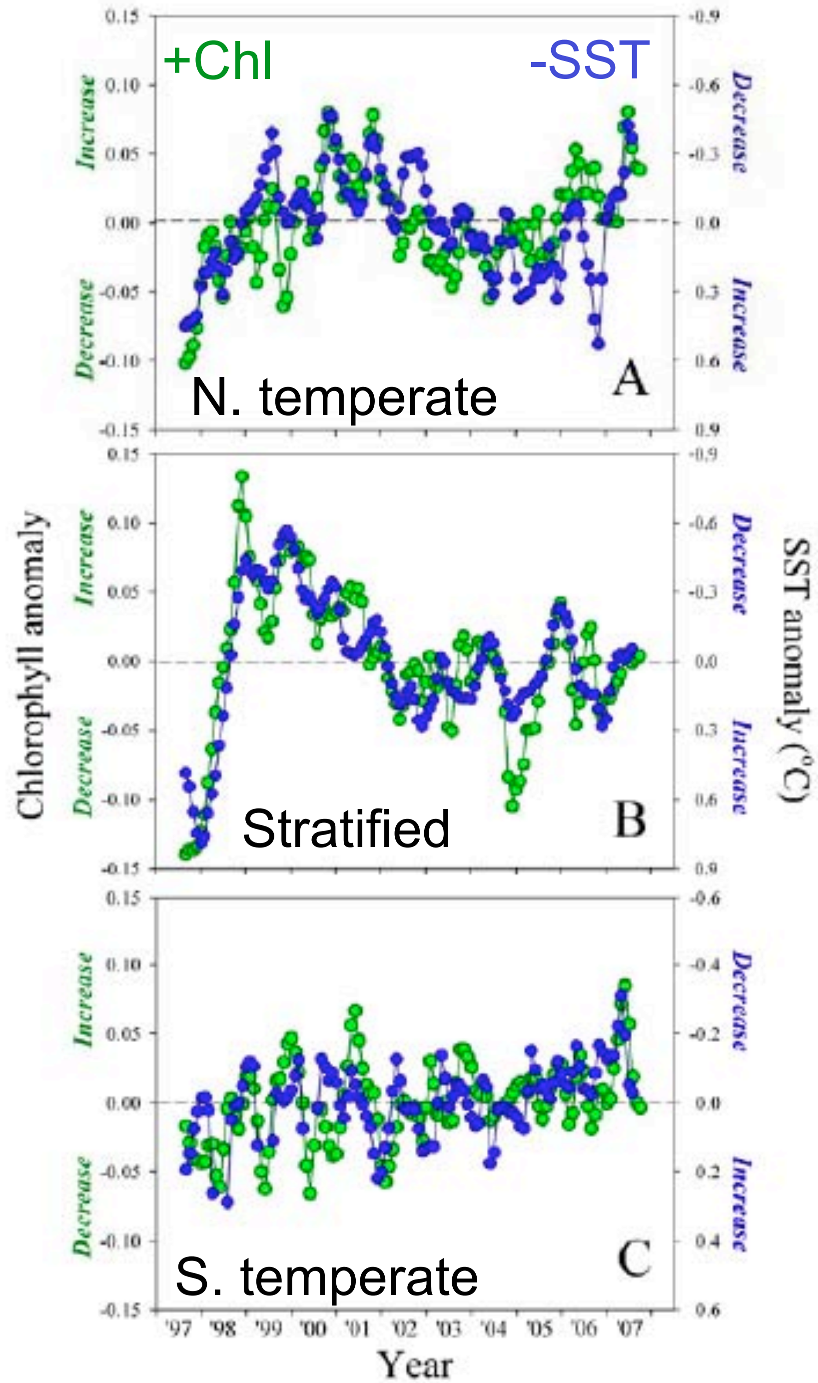
Doney, Nature, 2006



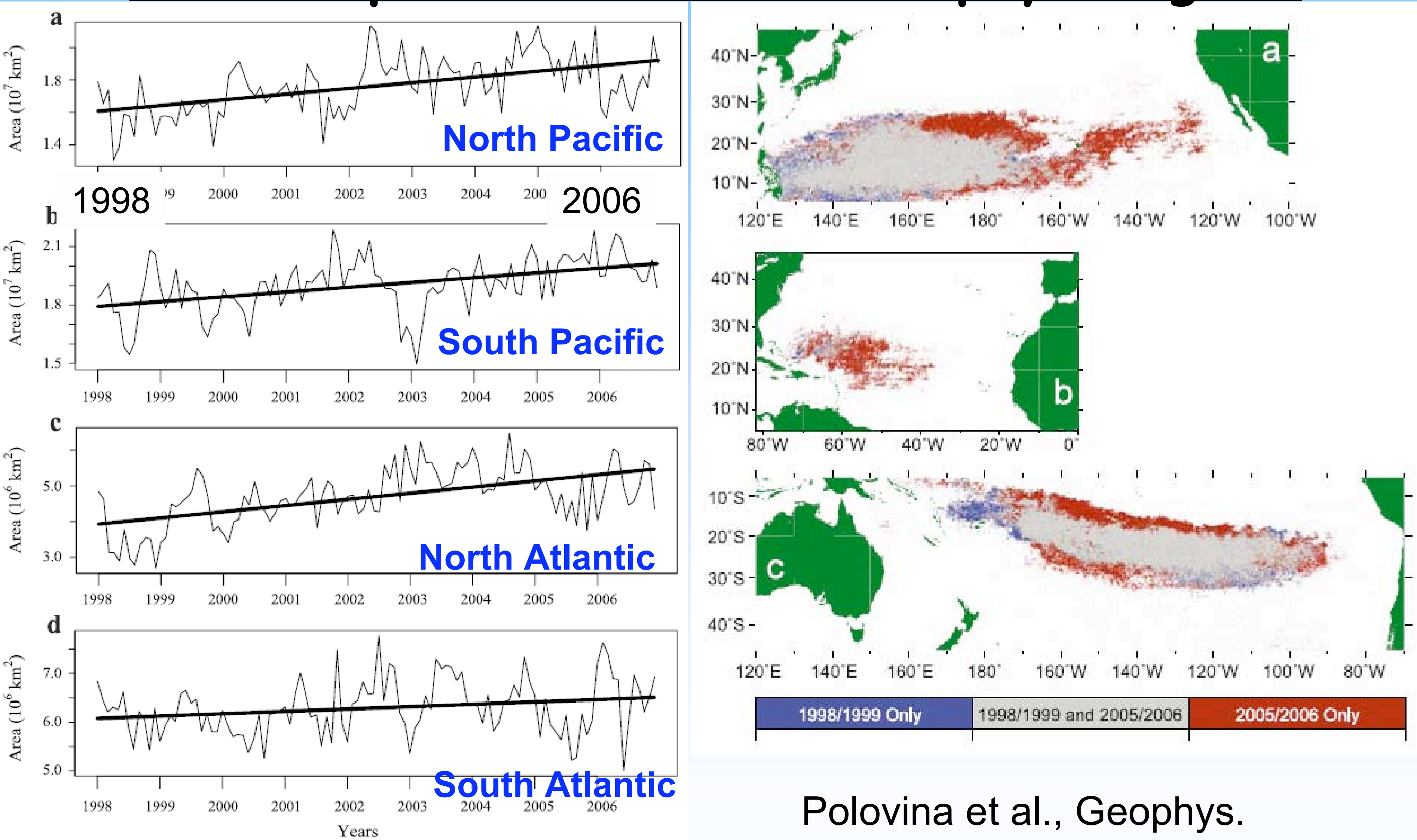
Satellite observations to date show that phytoplankton chlorophyll (biomass proxy) decreases when SST increases:

- •tropics/subtropics (agree with models)
- •temperate/polar (contradict models)

Behrenfeld et al. (2006; in prep.)

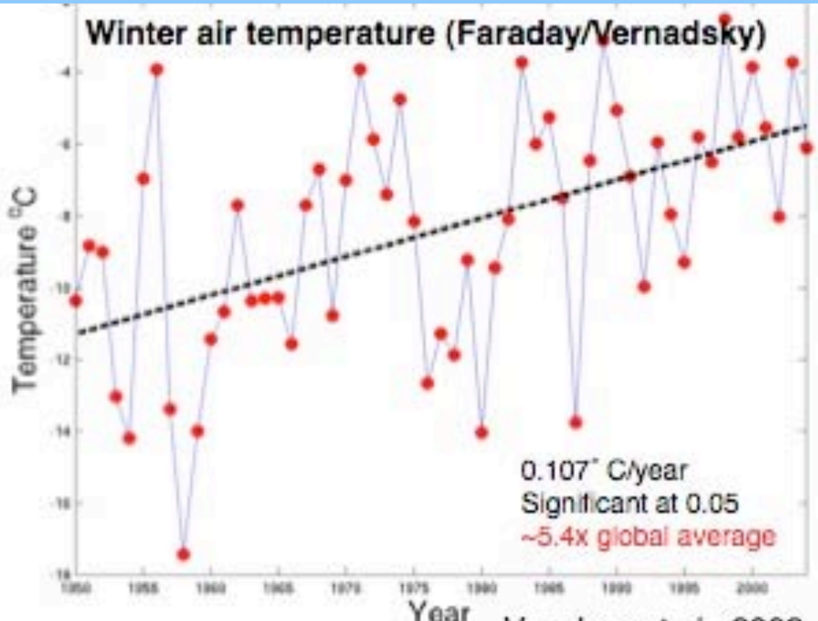


Areal Expansion of Low Chlorophyll Regions

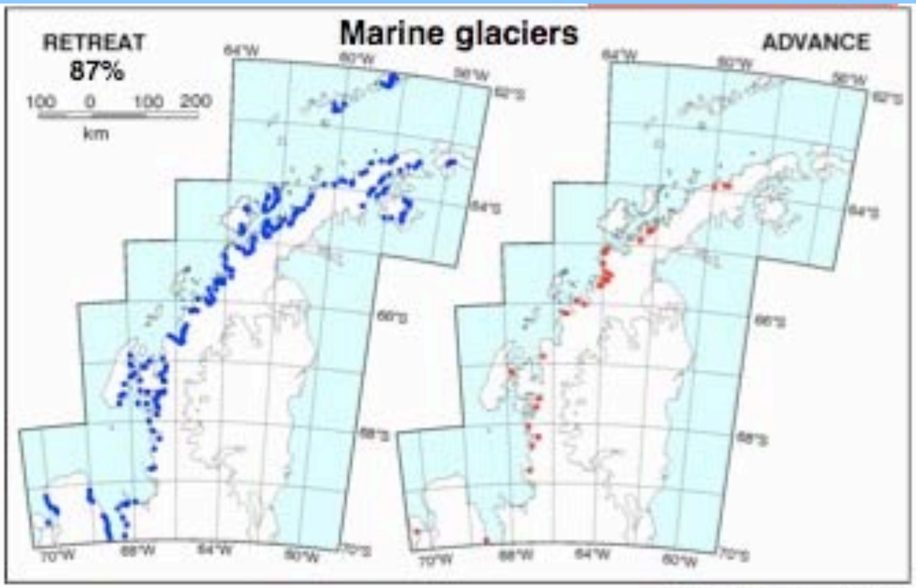


Polovina et al., Geophys. Res. Lett., 2008

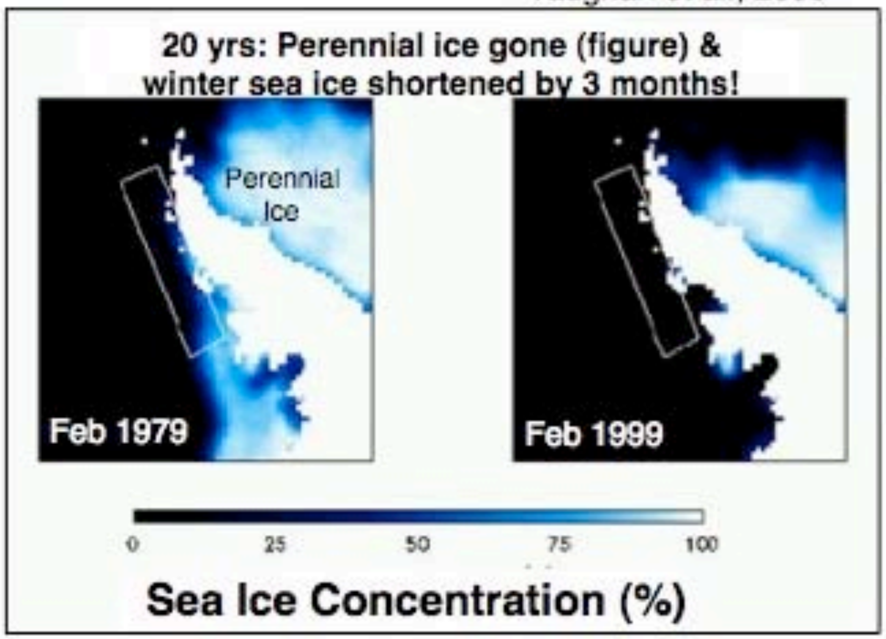
Rapid Climate Shift on West Antarctic Peninsula



Vaughan et al., 2003

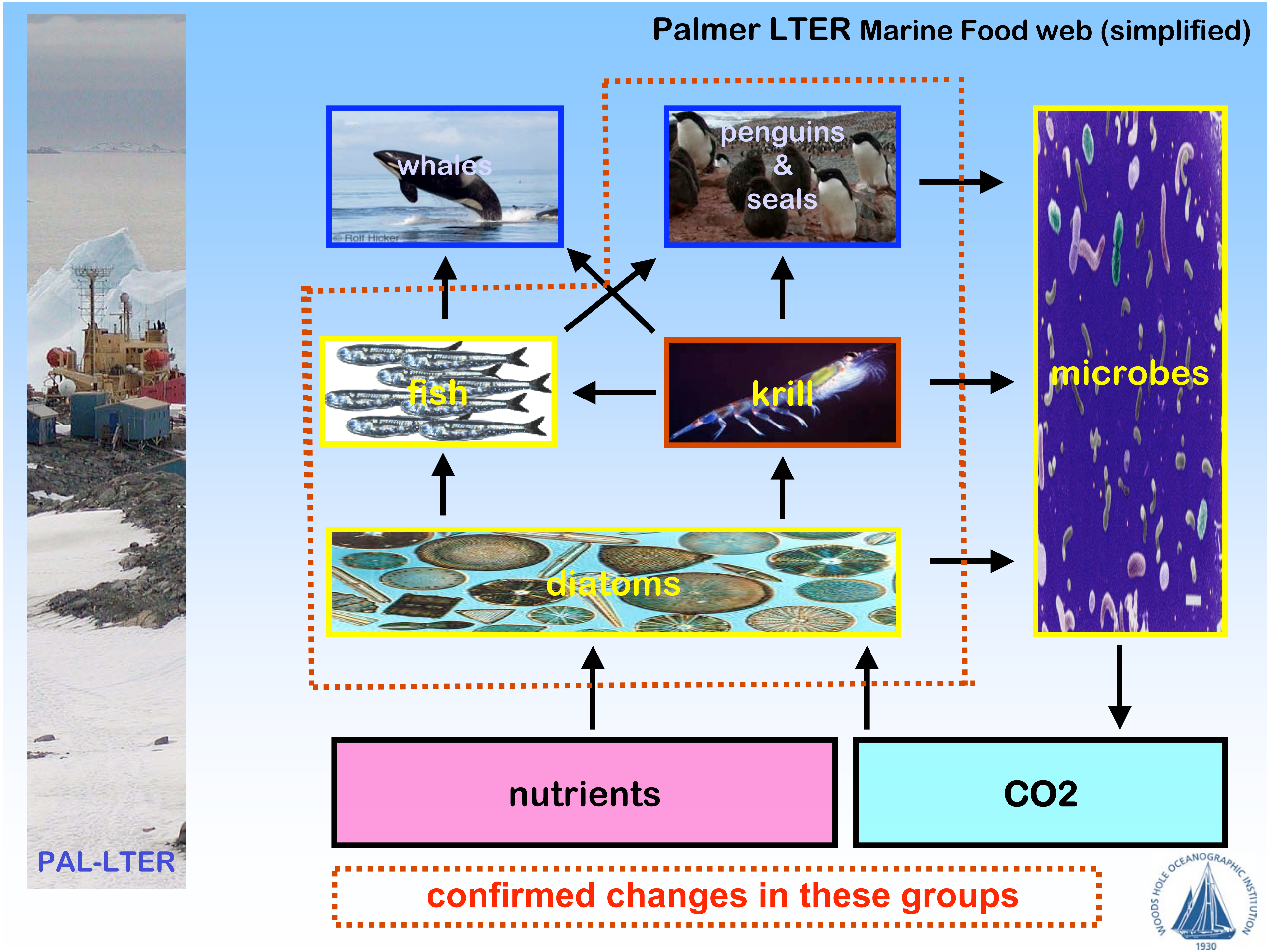


Cook et al., 2005

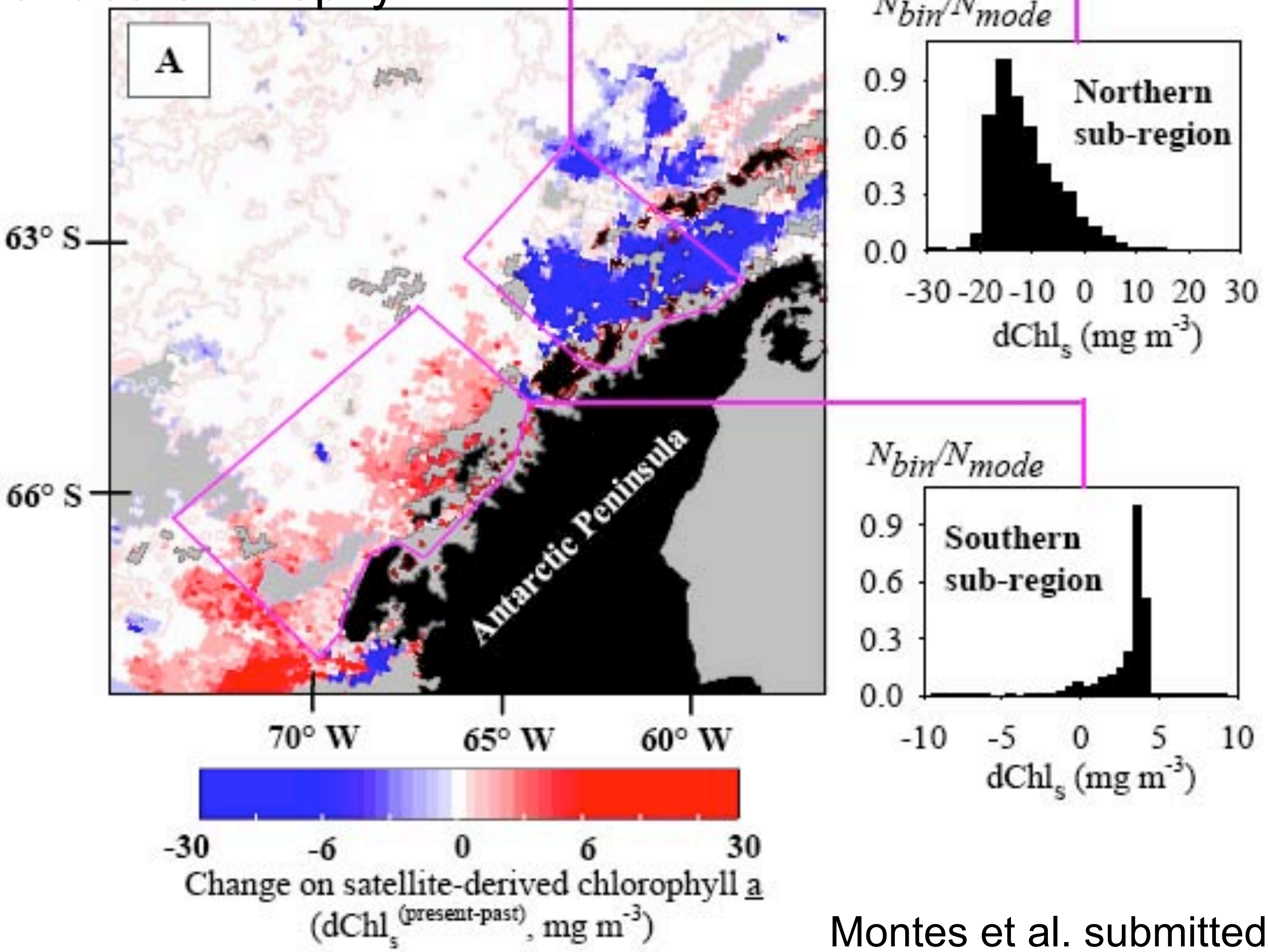


Stammerjohn et al., 2007

Fraser et al., 2008


Palmer LTER Marine Food web (simplified)
whales
© Rolf Hicker
penguins & seals
fish
krill
diatoms
microbes
nutrients
CO2
confirmed changes in these groups
PAL-LTER
WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

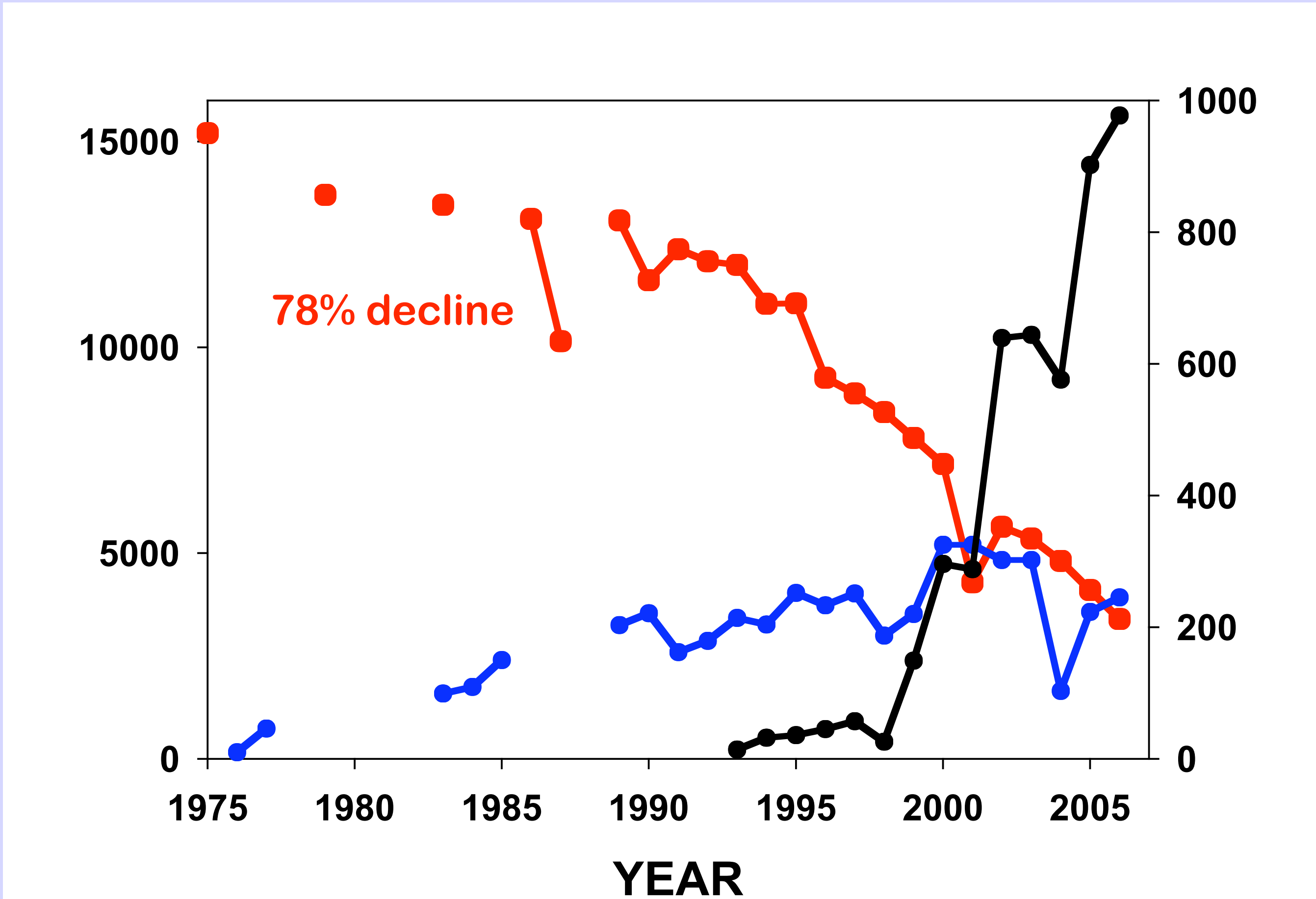
Decadal Change in Surface Chlorophyll



Montes et al. submitted

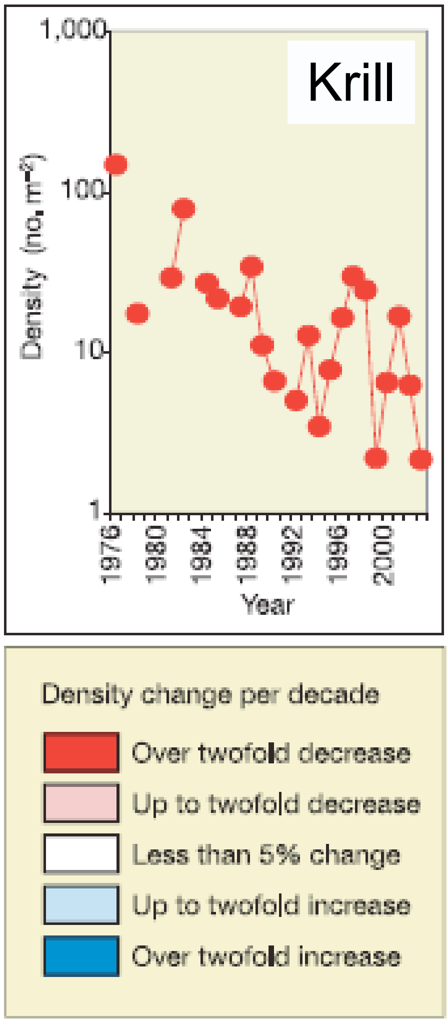
PENGUIN POPULATIONS NEAR PALMER STATION

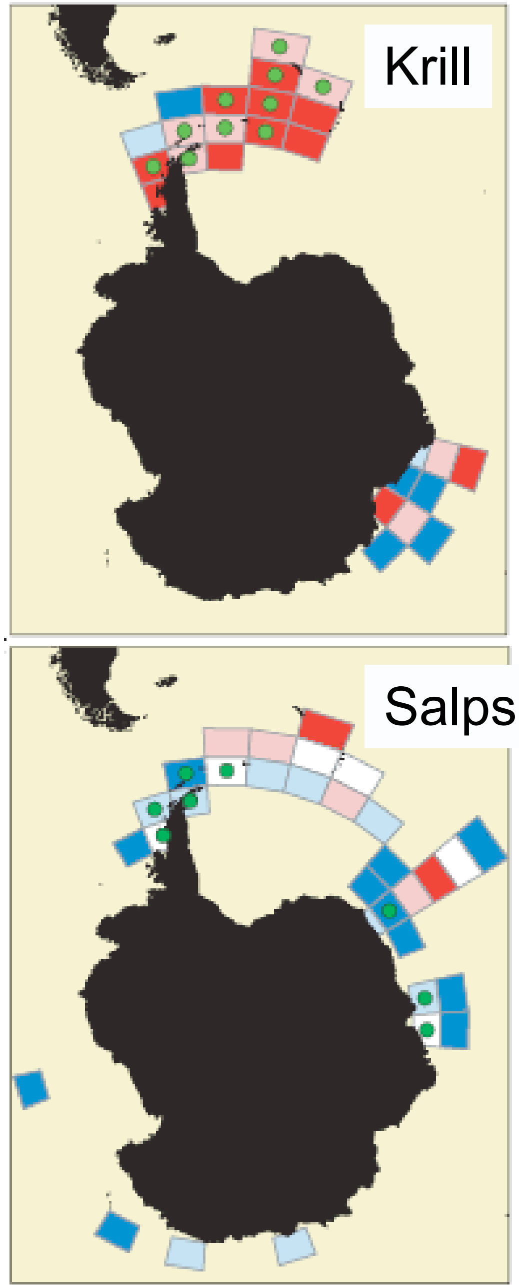
Adélies declining, Gentoos and Chinstraps invading and increasing



BIODIVERSITY IS INCREASING IN RESPONSE TO CLIMATE WARMING

Bill Fraser





Atkinson et al., Nature (2004);

Possible Ecological Regime Shifts

-Krill distributions:

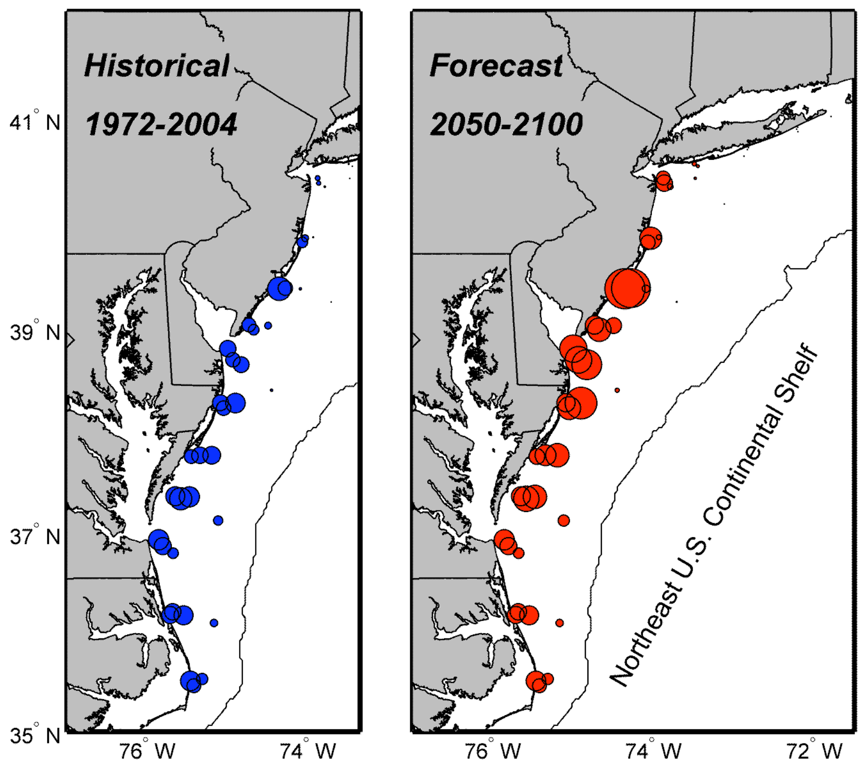
•spatial correlation with chlorophyll;

•temporal correlation with winter sea-ice extent

-May see future shift from krill dominated to salp dominated system

Shifting Fish Distributions

- Poleward shift in species ranges
- Replacement of “cool-water” species by “warm-water” species will likely increase



Atlantic croaker – Hare et al. submitted

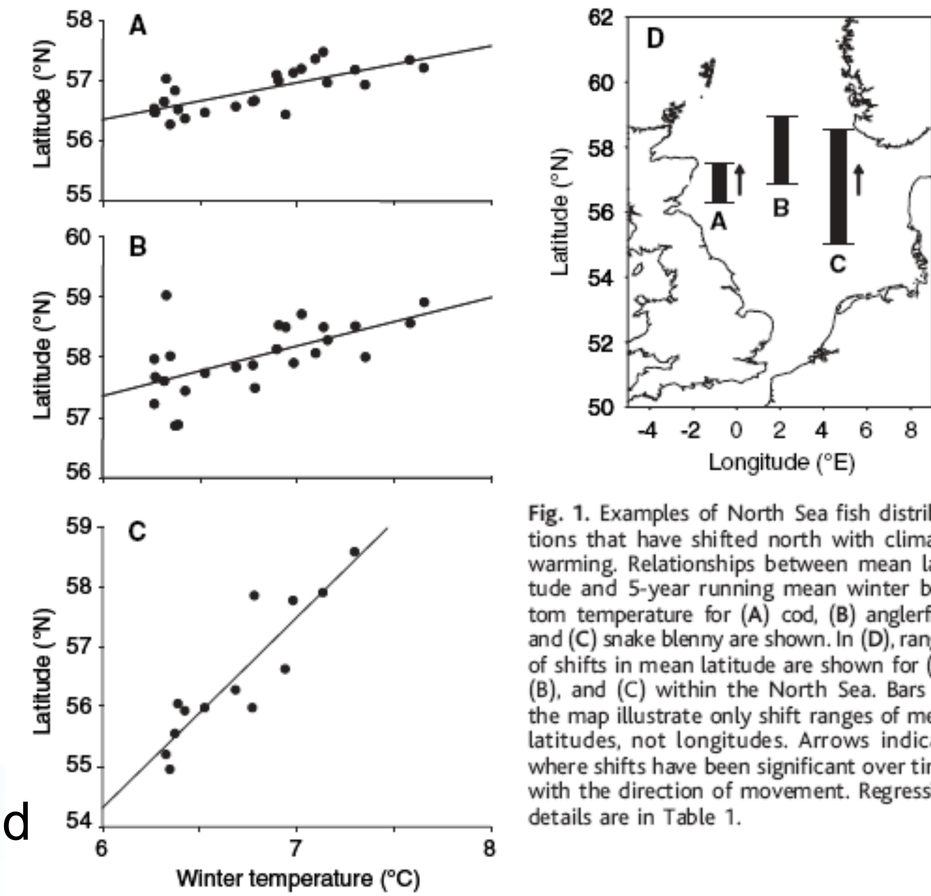
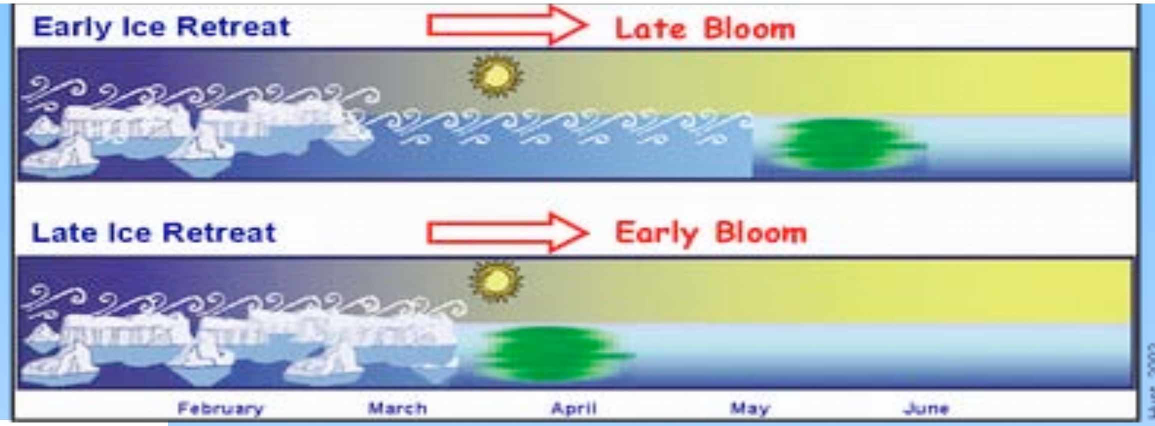
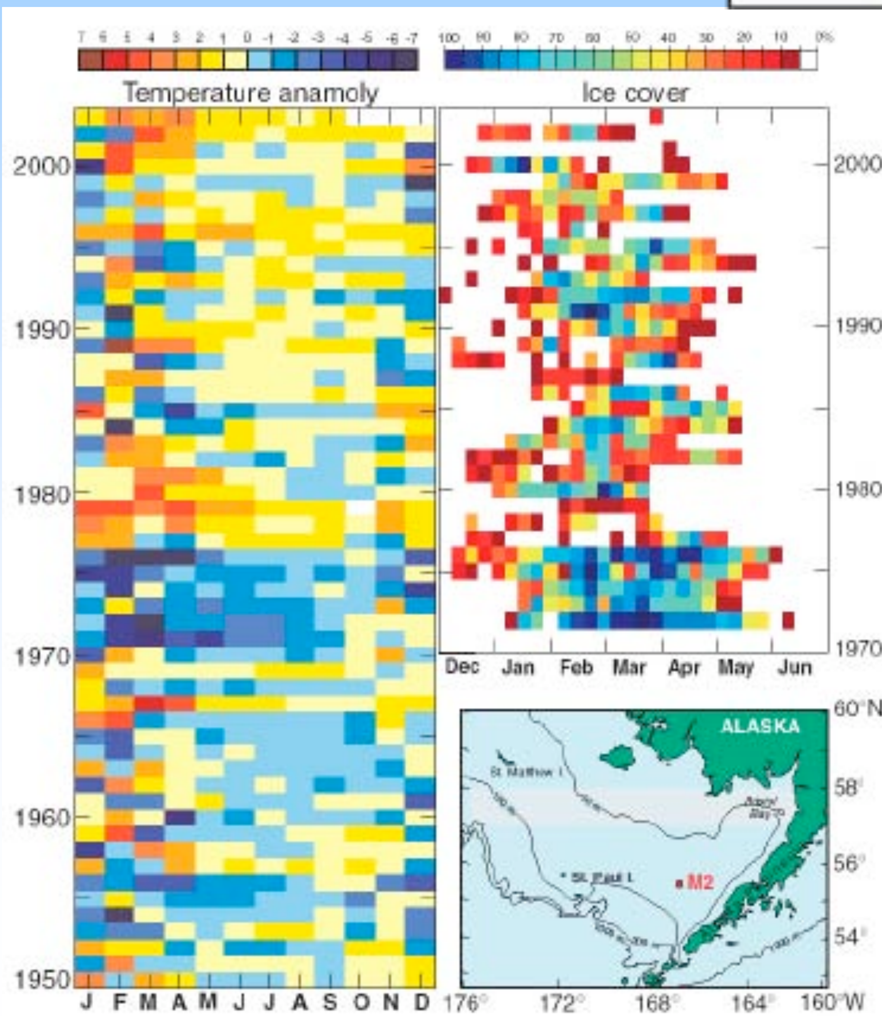


Fig. 1. Examples of North Sea fish distributions that have shifted north with climatic warming. Relationships between mean latitude and 5-year running mean winter bottom temperature for (A) cod, (B) anglerfish, and (C) snake blenny are shown. In (D), ranges of shifts in mean latitude are shown for (A), (B), and (C) within the North Sea. Bars on the map illustrate only shift ranges of mean latitudes, not longitudes. Arrows indicate where shifts have been significant over time, with the direction of movement. Regression details are in Table 1.

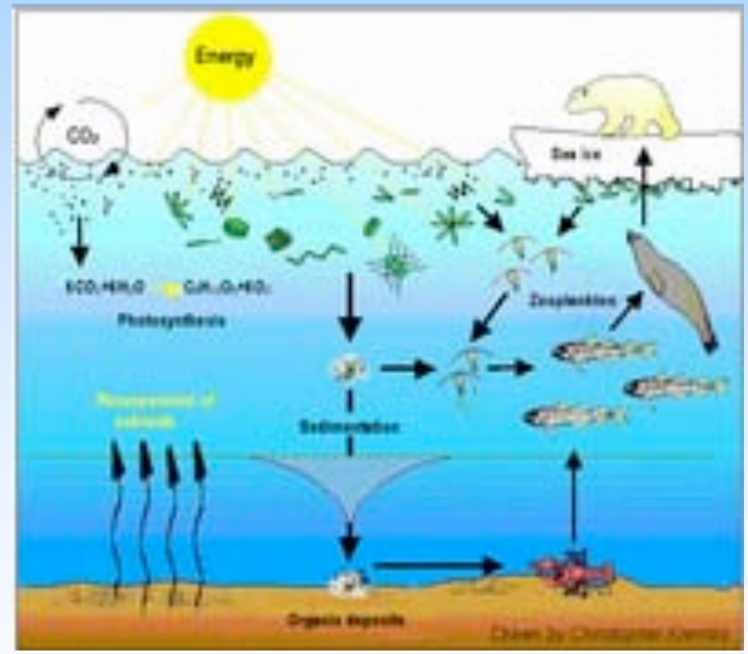
Perry et al. Science 2005

Bering Sea Ecosystem & Climate



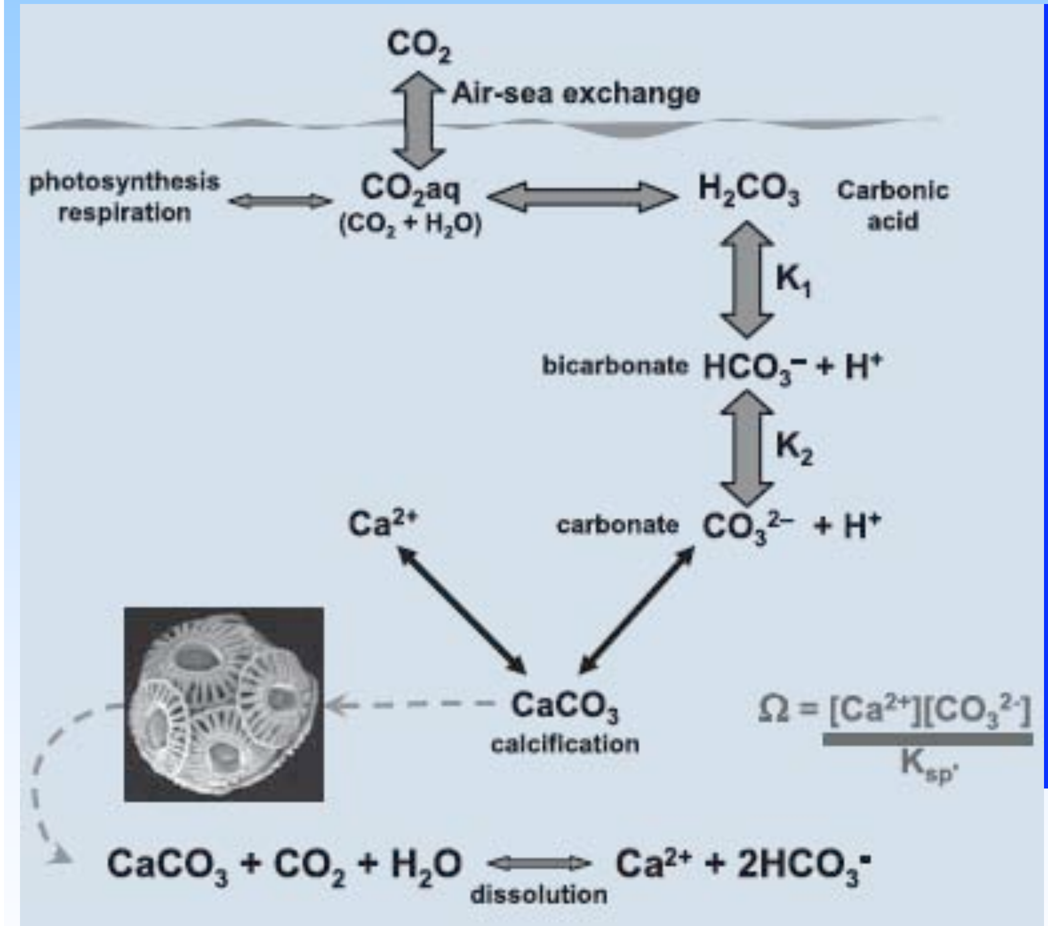


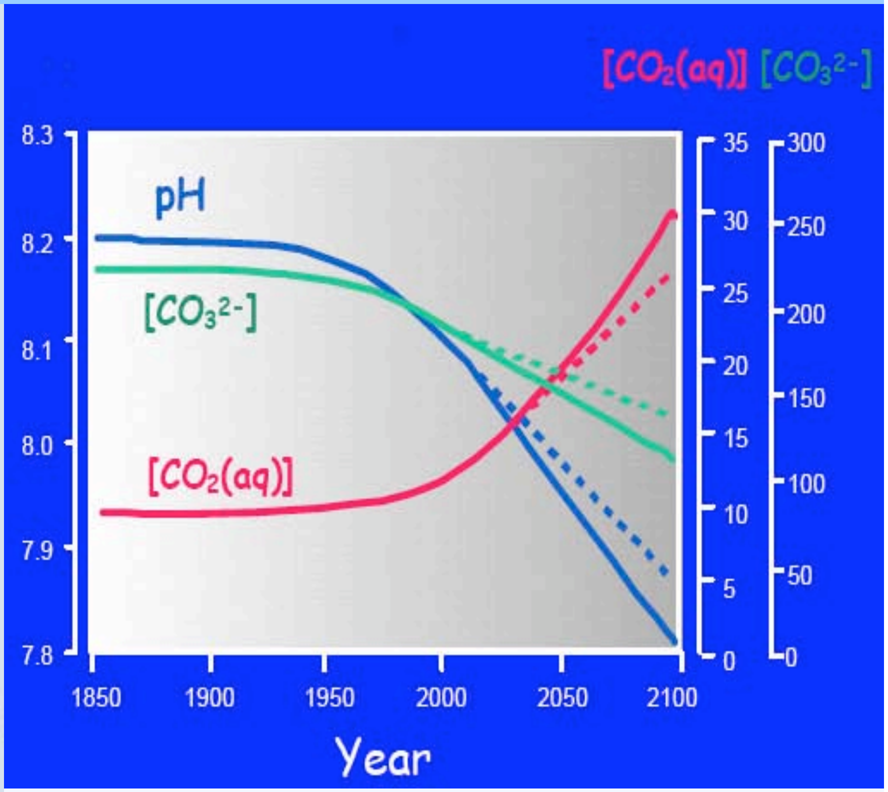
Arctic marine food web



-Predator-prey mismatch leads to ecosystem disruption

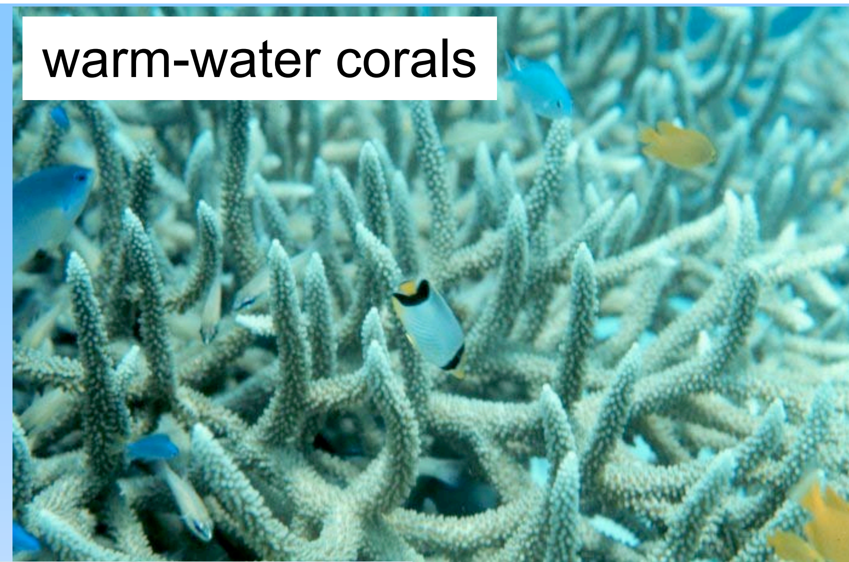
Rising CO_2 also leads to ocean acidification threatening shell-forming plants and animals



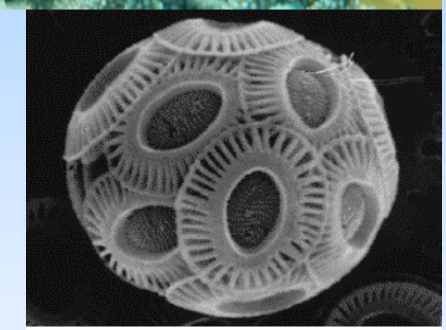


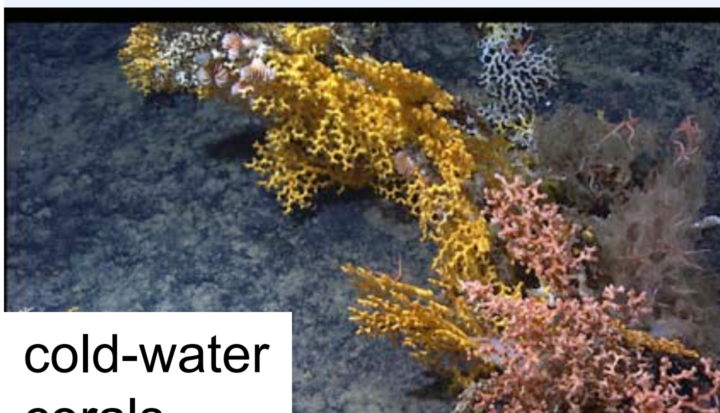
Biological Impacts

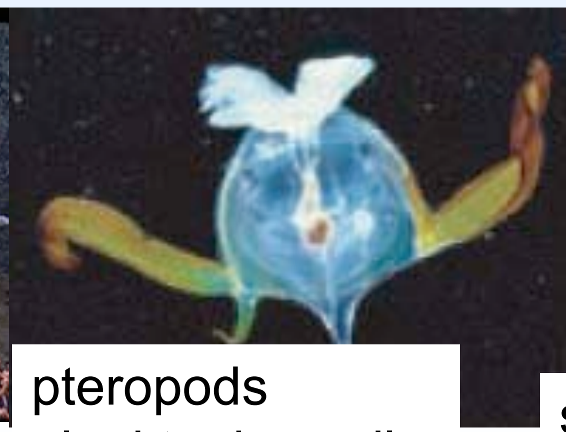
- Shell forming plants & animals
  - reduced shell formation (calcification)
  - lower reproduction & growth rates
- Habitat loss (reefs)
- Less food for predators
  - humans, fish, whales
- Possible negative effects on larvae

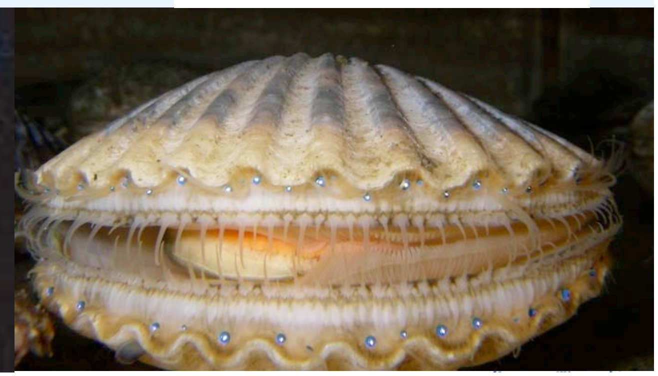

warm-water corals


lobsters, crabs

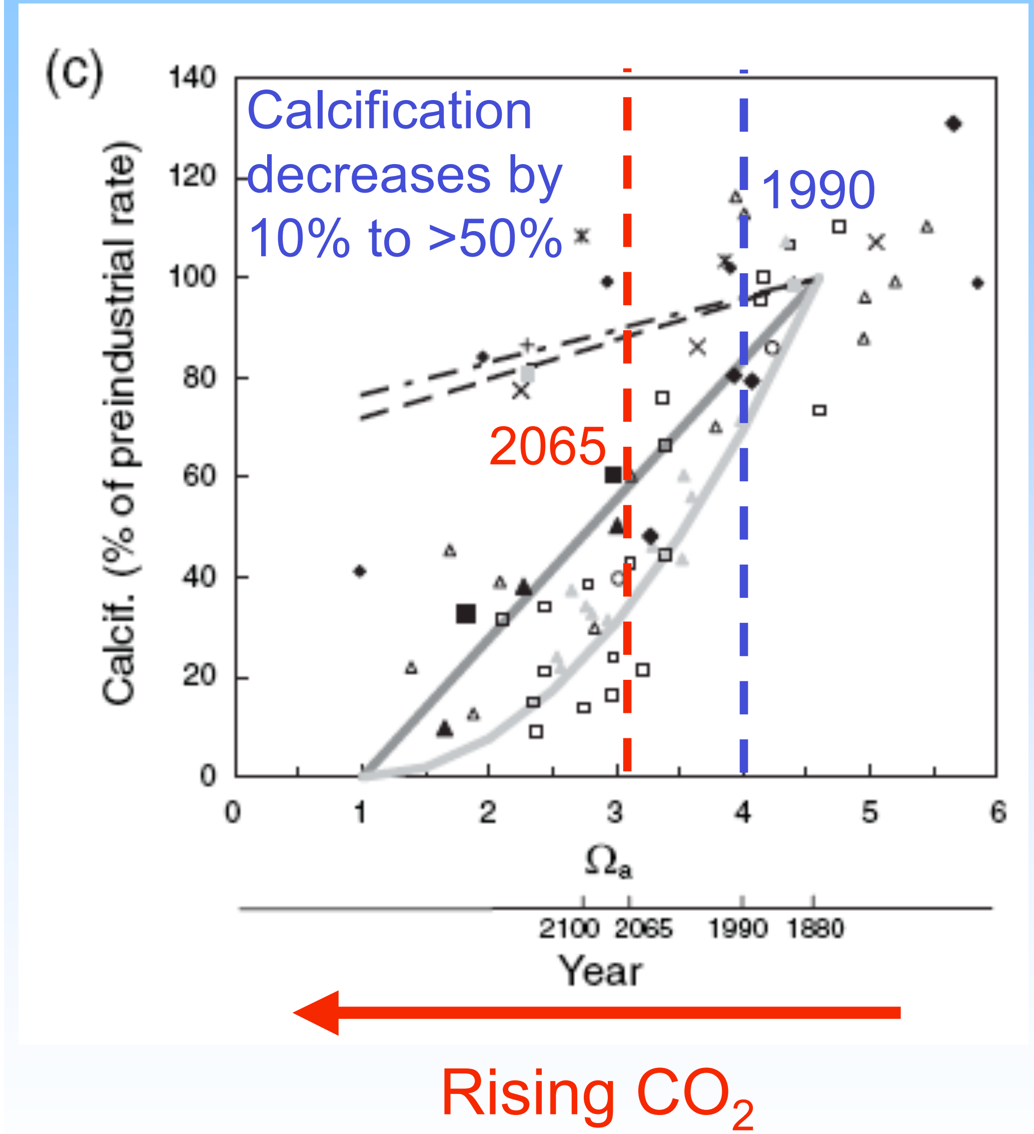

some plankton


cold-water corals


pteropods planktonic snails


scallops, clams, oysters

Tropical Corals

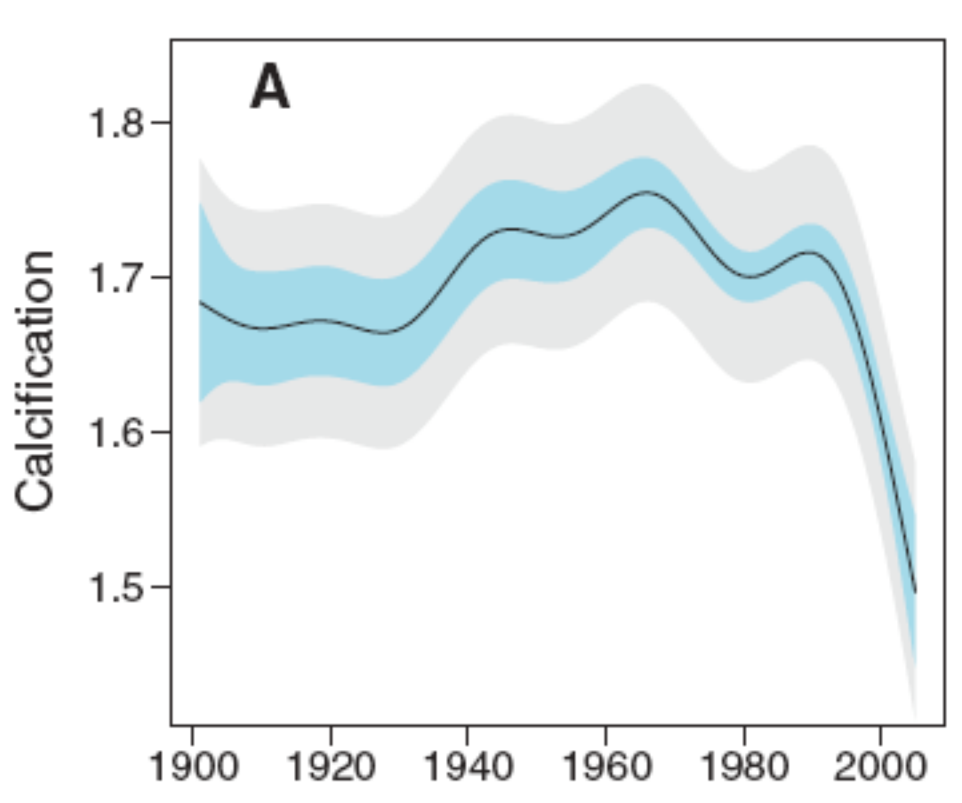


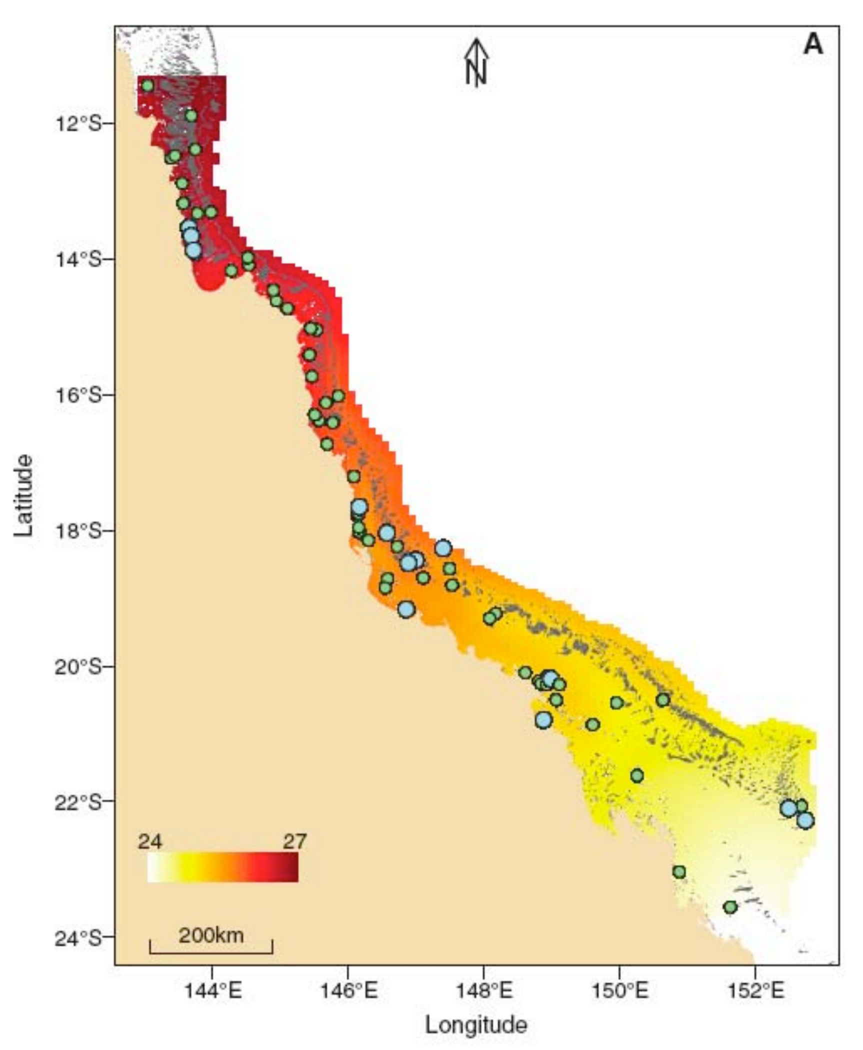
-Acidification reduces coral calcification & growth

-Tropical reefs key habitats

-Corals threatened also by warming, over-fishing & pollution

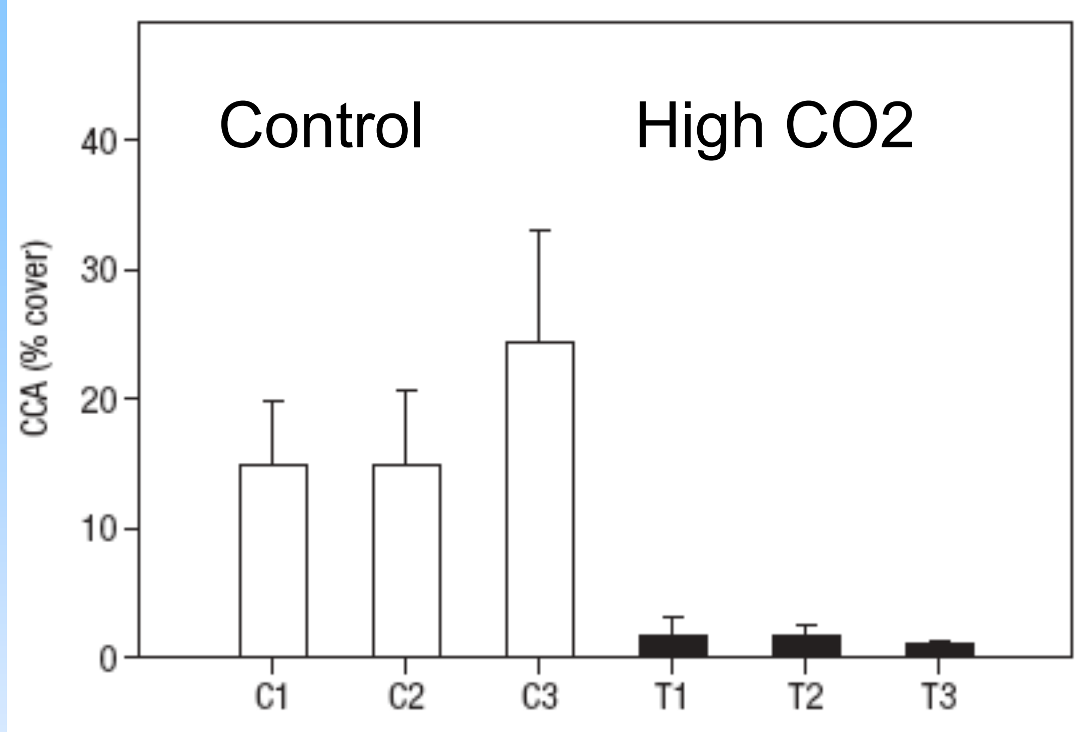
Declining Corals on Great Barrier Reef, Australia





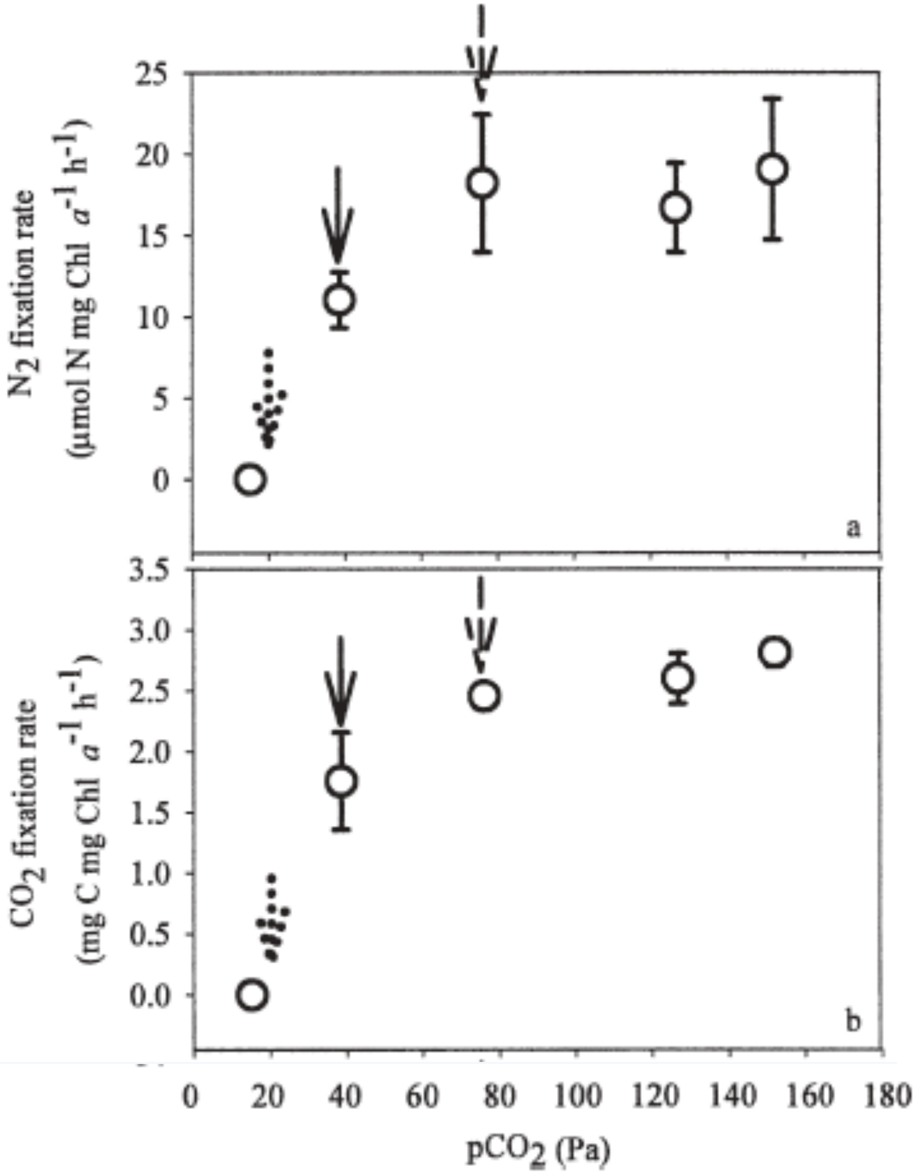
De'ath et al., Science, 2009

Crustal Coralline Algae



Coralline algae is replaced by non-calcifying algae

Kuffner et al. Nat. Geosci. 2007



Hutchins et al. L&O 2007

Fu et al. J. Phycol. 2007

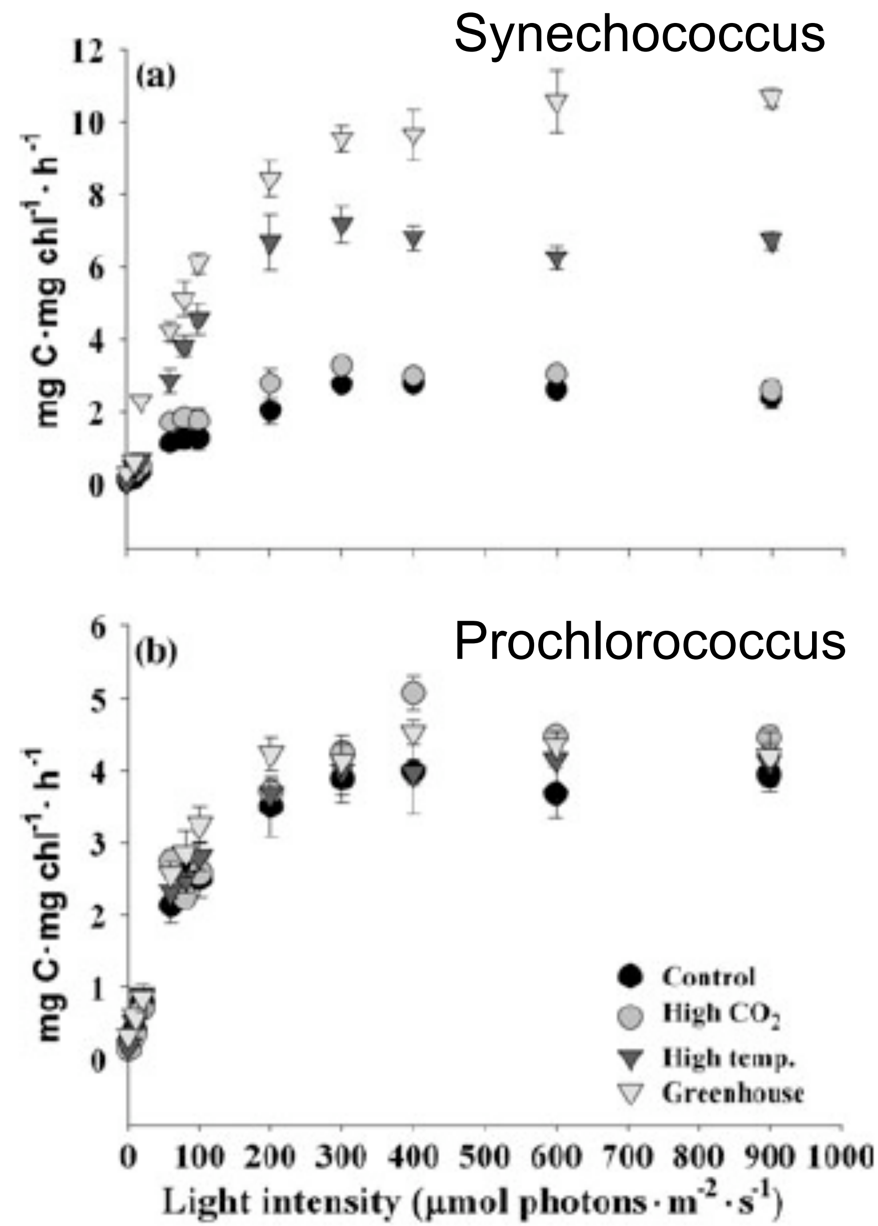
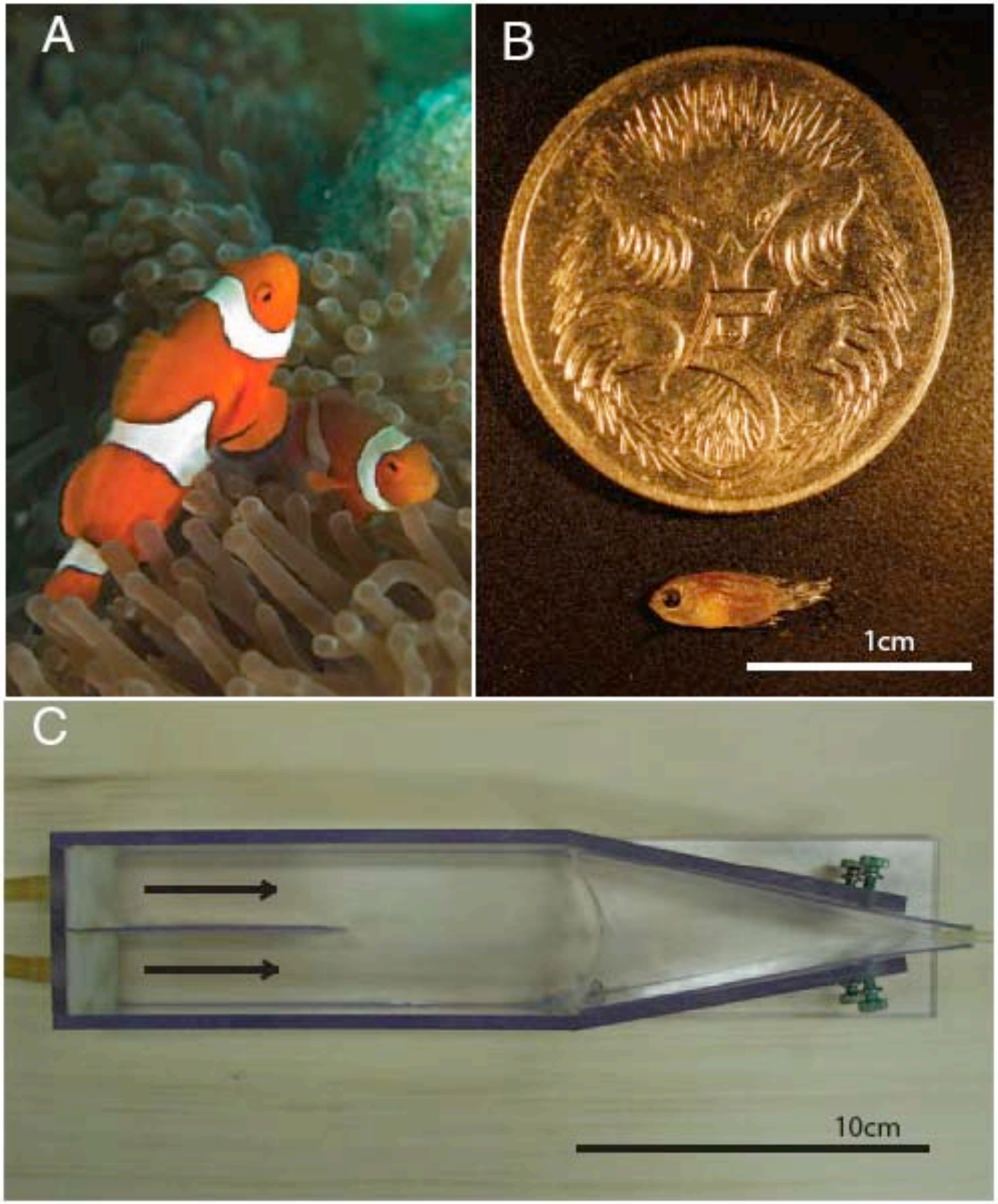


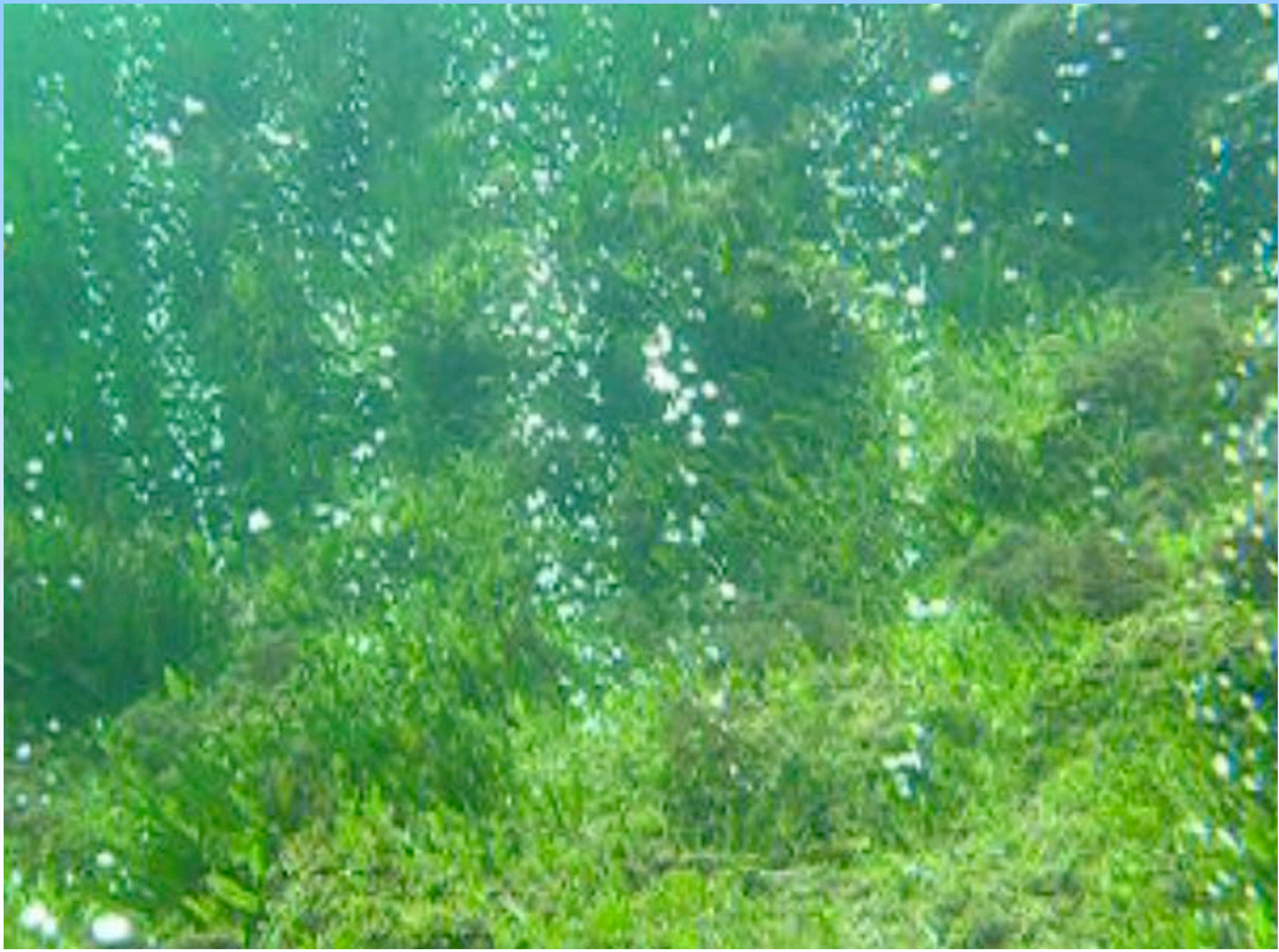
FIG. 2. P–E curves (photosynthesis vs. irradiance curves) for *Synechococcus* (a) and *Prochlorococcus* (b) under the four temperature and CO_2 treatments. Errors denote the standard deviations of triplicate samples.



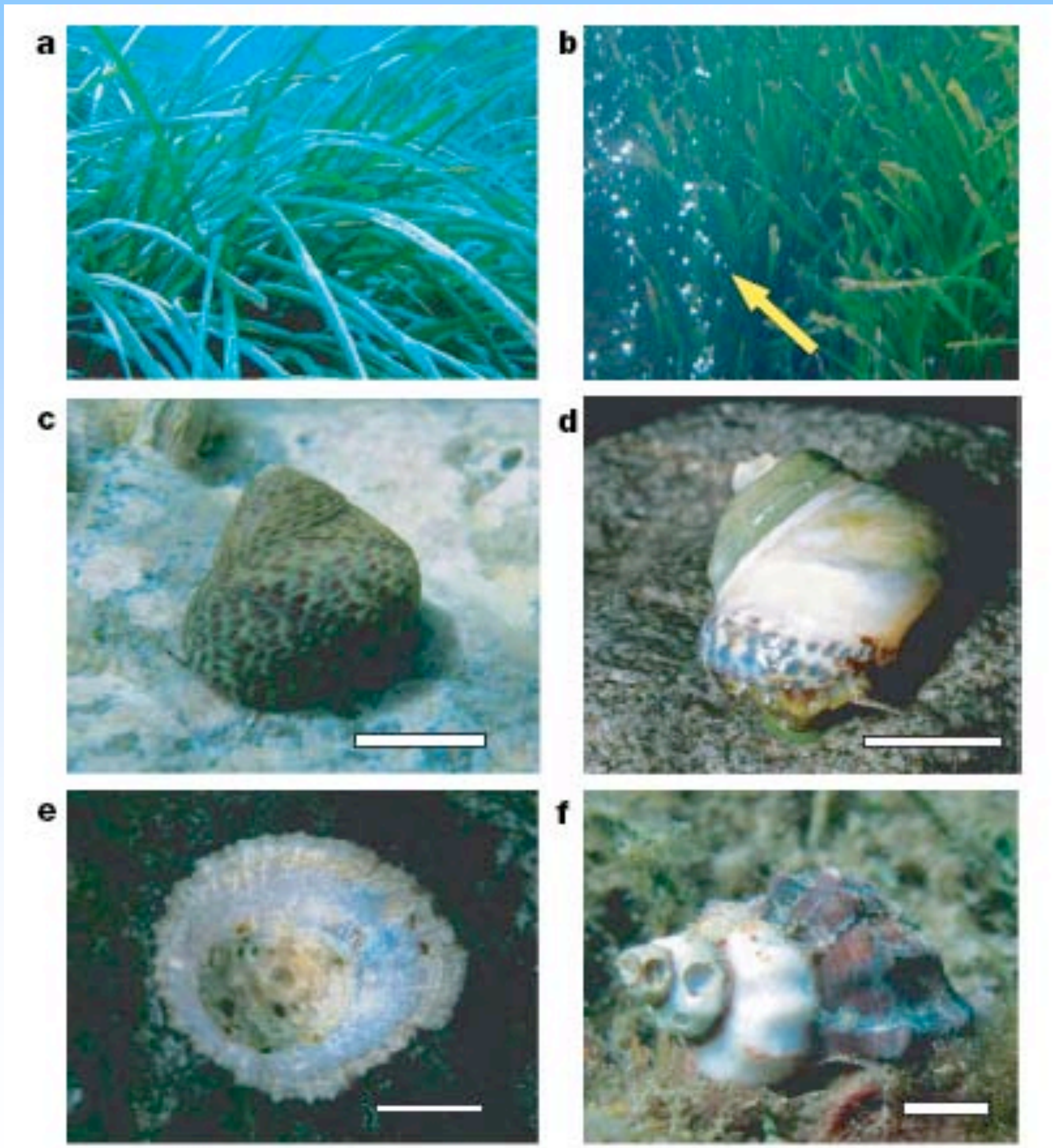
Reduced pH interferes with fish sense of smell

Munday et al. 2000

Natural CO_2 Vents



"normal" volcanic CO_2 vents



Biological Consequences

-laboratory "fish tank" experiments

-natural habitats with high CO_2

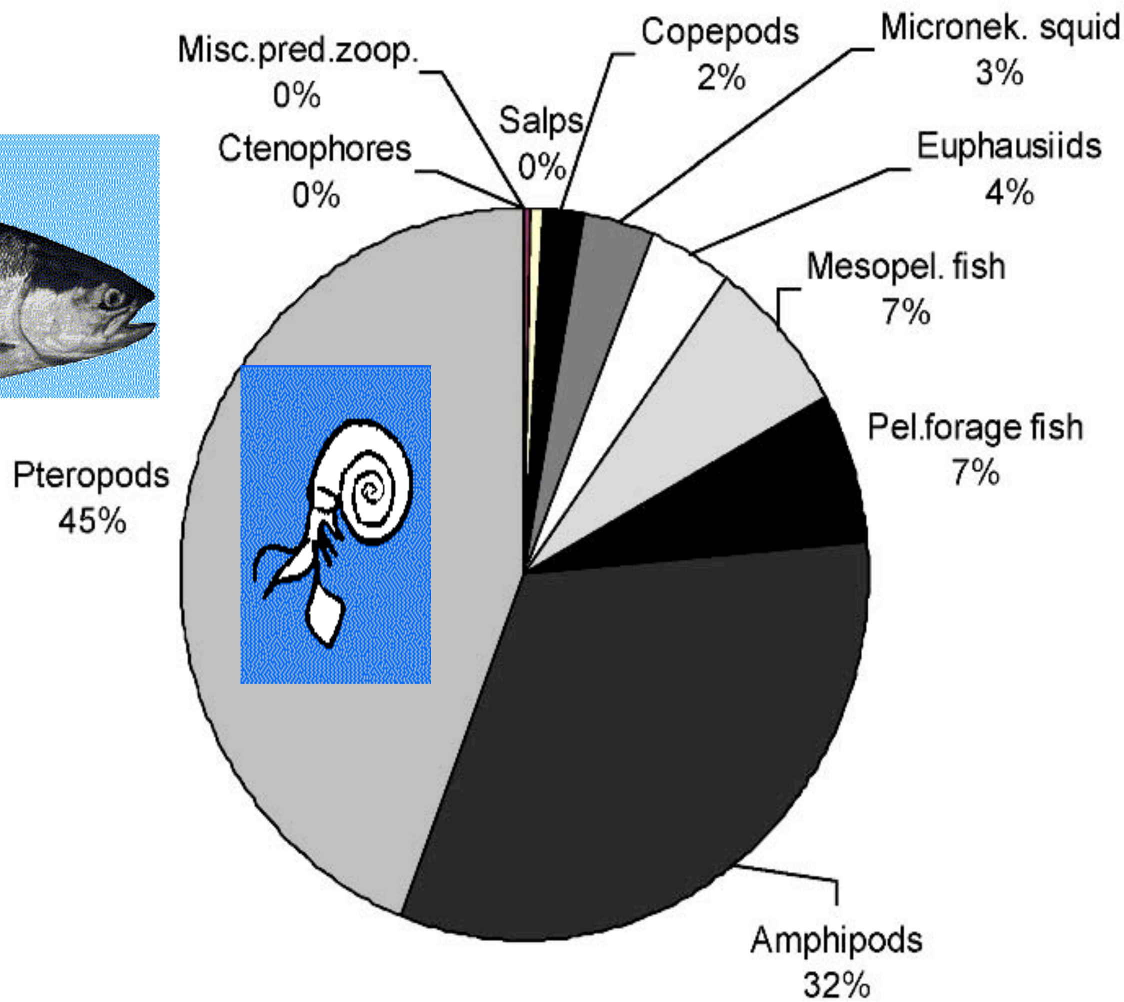
- No corals, corraline algae, juvenile mollusks & unhealthy adults

Hall-Spenser et al. 2008

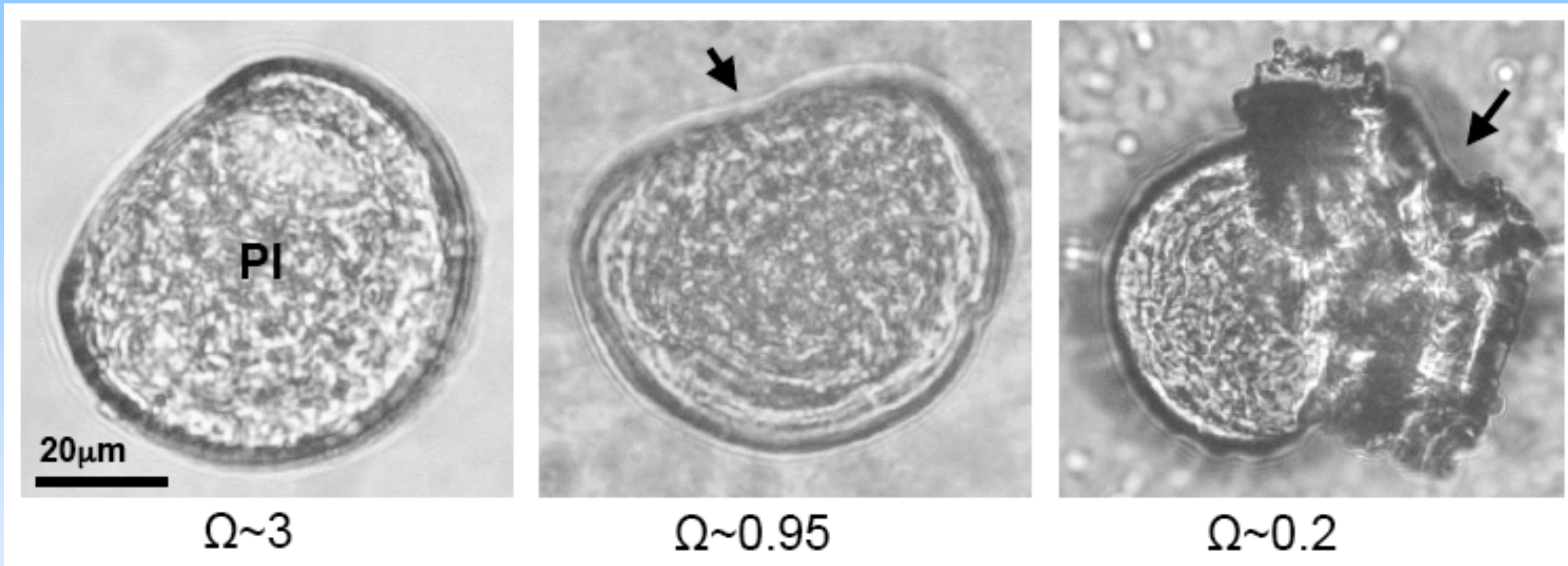
Effects Will Cascade Through Food Webs

Pink salmon diet

Pteropods are prey for many fish, whales: "ocean popcorn"



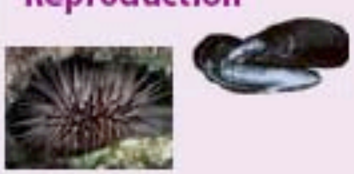
Larval Eastern Oyster (*Crassostrea virginica*)



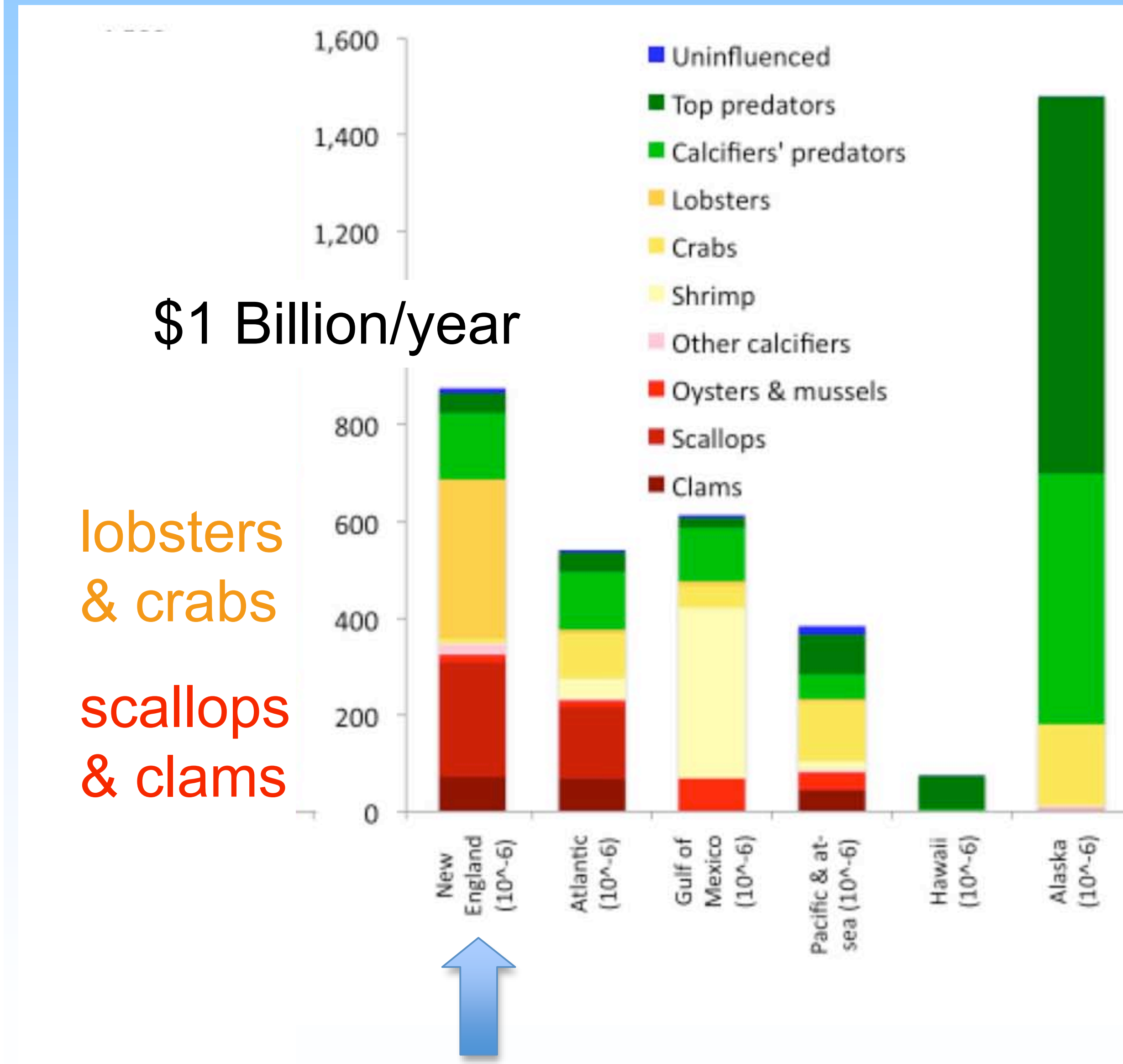
Increasing Acidity →

Larval shellfish grow with more soluble shells and more be more sensitive to acidification

Anne Cohen and Dan McCorkle, WHOI, 2007

Physiological response	Major group	Species studied	Response to increasing CO_2			
			a	b	c	d
Calcification 						
	Coccolithophores[1]	4	2	1	1	1
	Planktonic Foraminifera	2	2	–	–	–
	Molluscs	4	4	–	–	–
	Echinoderms[1]	3	2	1	–	–
	Tropical corals	11	11	–	–	–
	Coralline red algae	1	1	–	–	–
Photosynthesis[2] 						
	Coccolithophores[3]	2	–	2	2	–
	Prokaryotes	2	–	–	1	–
	Seagrasses	5	–	–	–	–
Nitrogen Fixation 						
	Cyanobacteria	1	–	1	–	–
Reproduction 						
	Molluscs	4	4	–	–	–
	Echinoderms	1	1	–	–	–

New England commercial fisheries depend on species at risk

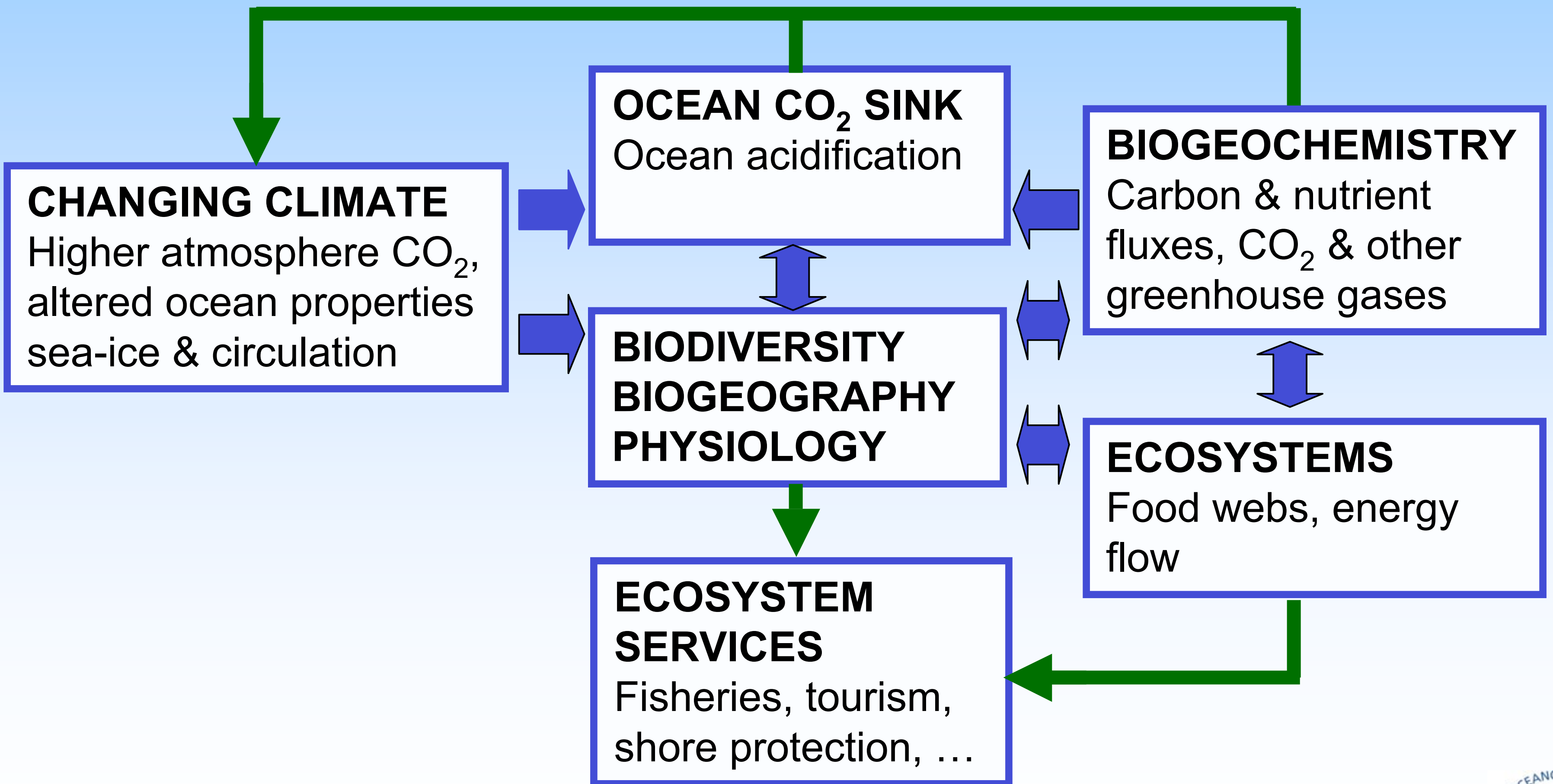


New England primary fishery revenue ~$850 million/year ~80% are from shellfish

For whole U.S.:
$4 billion revenue =>
$70 billion industry &
$35 billion net GNP

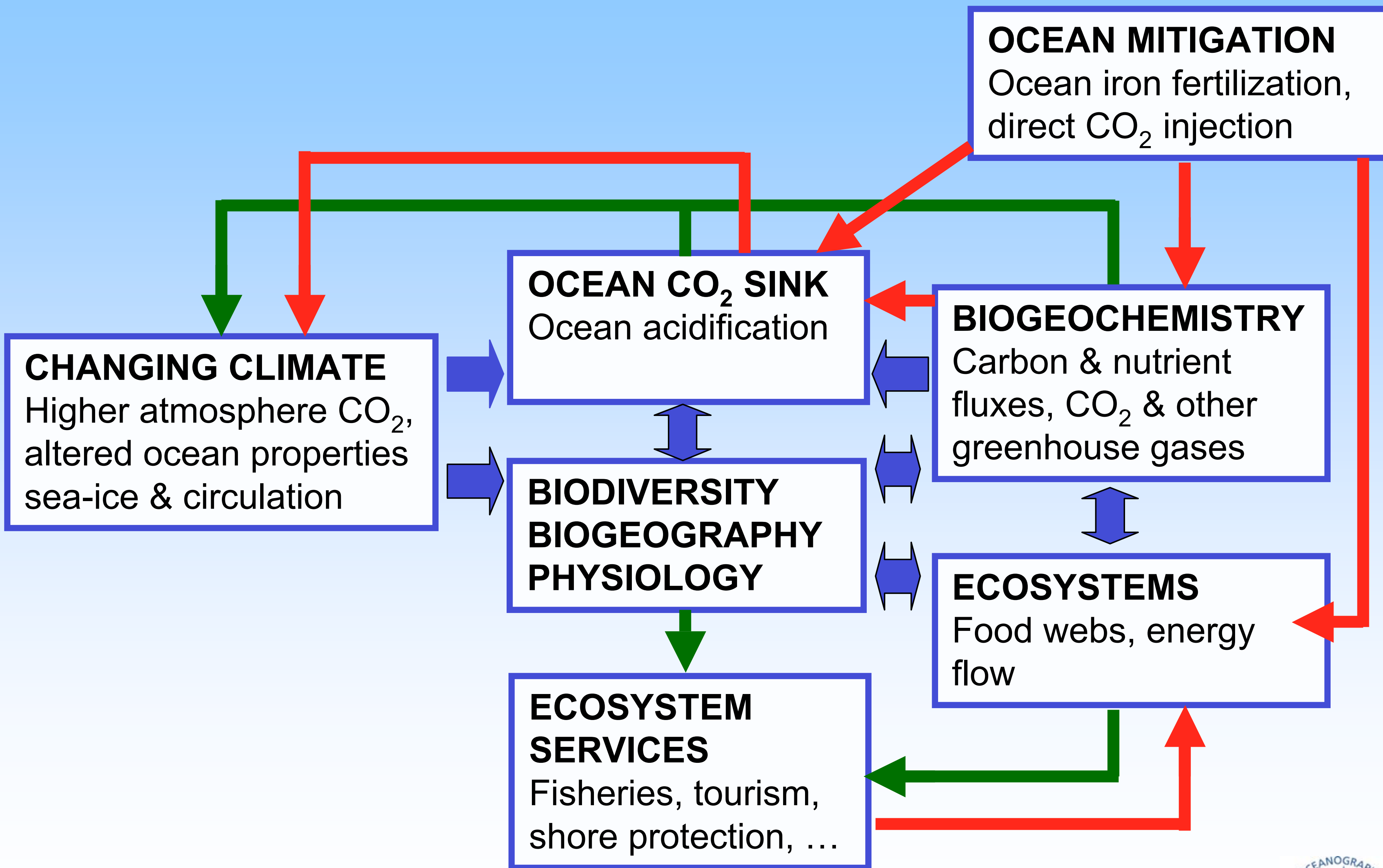
Woods Hole Oceanographic Institution 1930

Ocean Climate Responses & Feedbacks



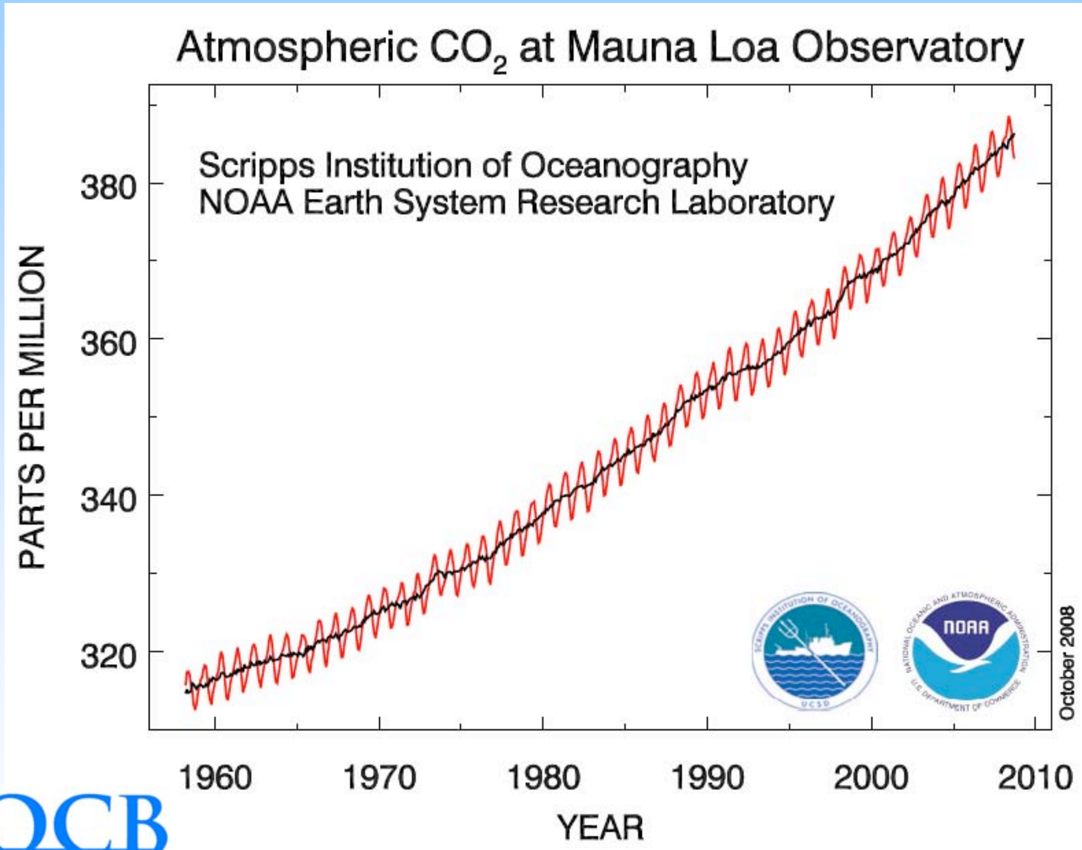
WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Ocean Climate Responses & Feedbacks

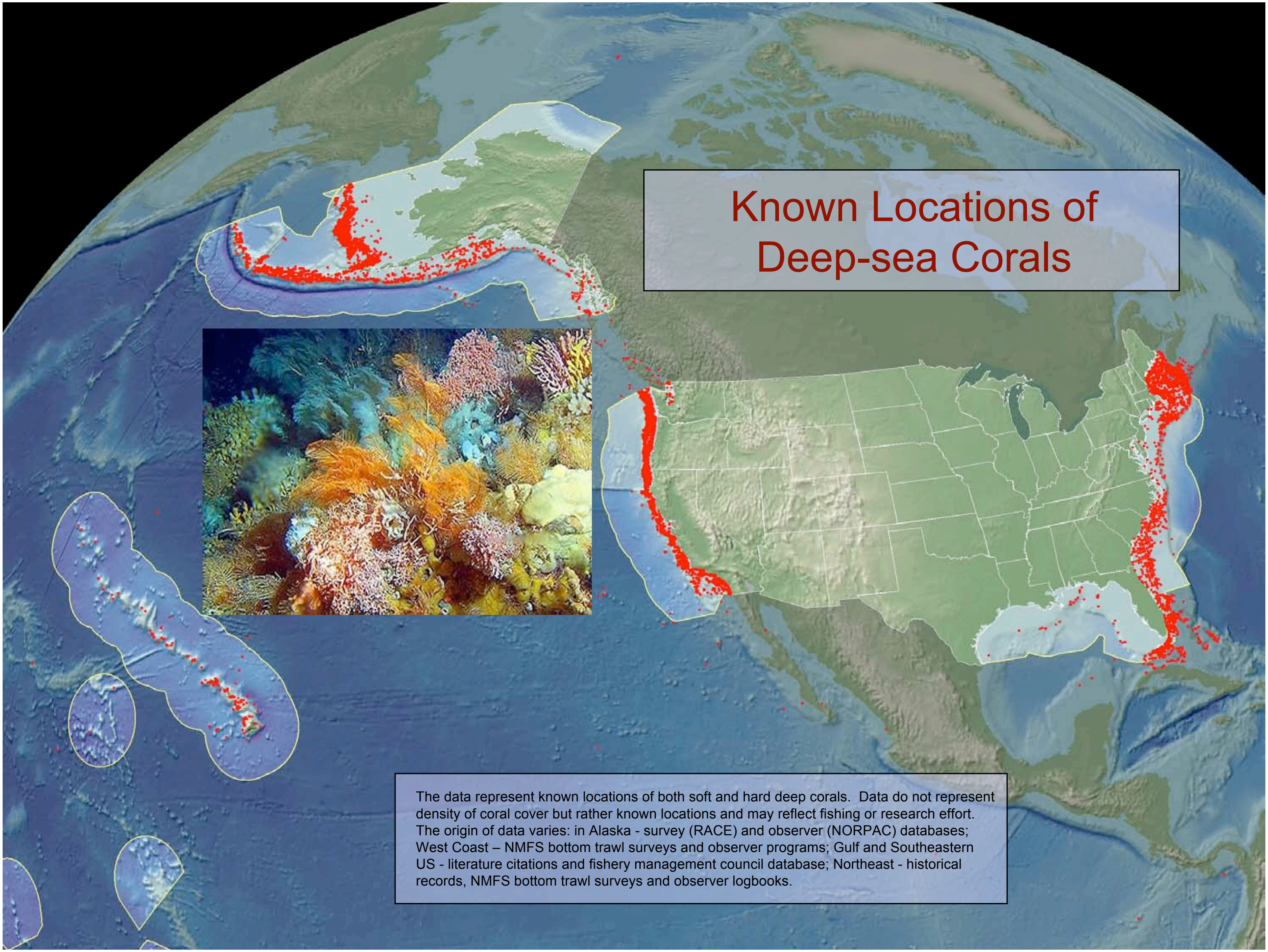


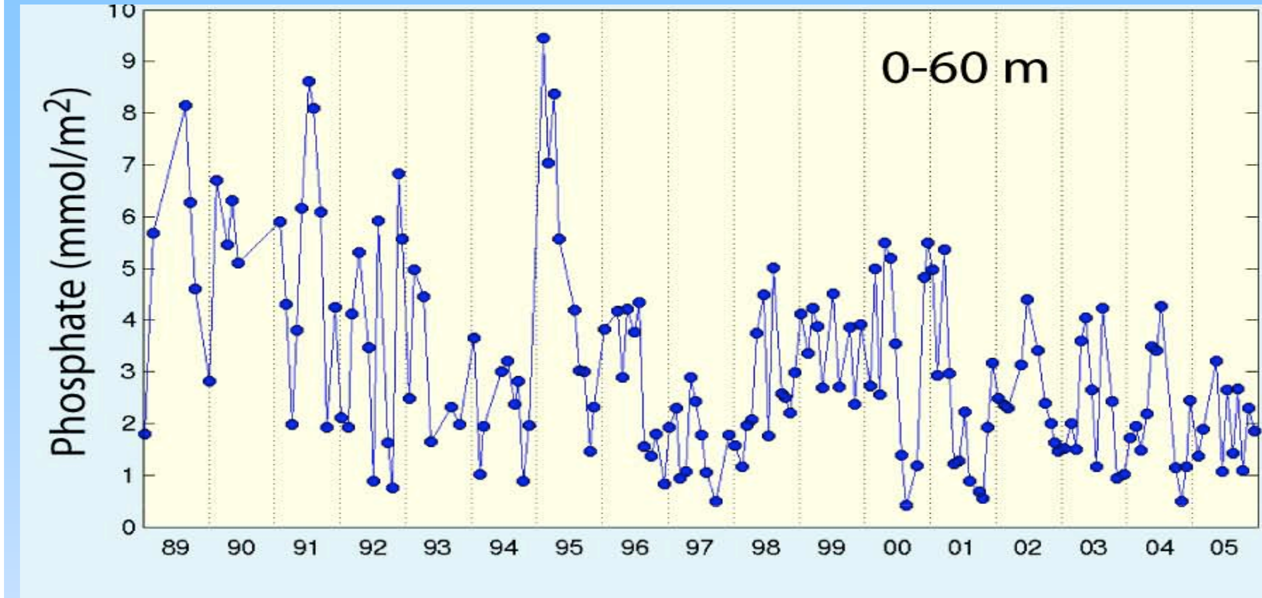
"to manage the unavoidable & avoid the unmanageable"

Thomas Friedman 2008



Ocean Carbon & Biogeochemistry

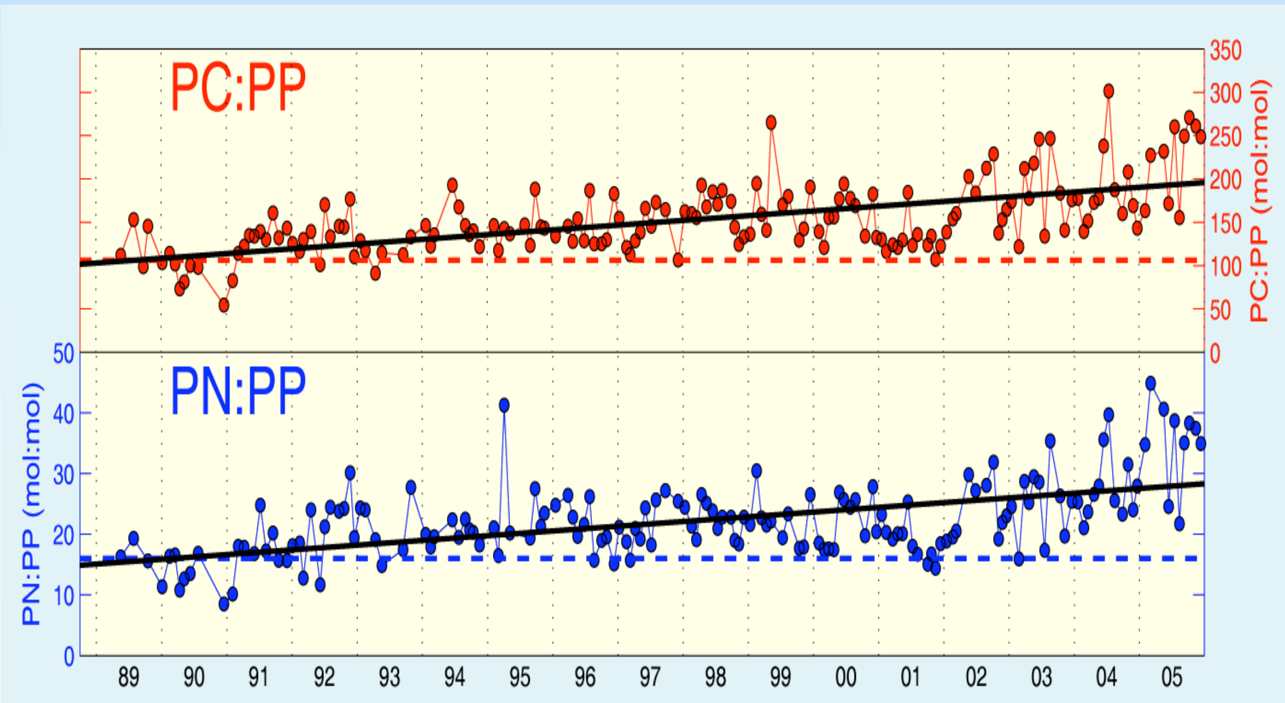

Known Locations of Deep-sea Corals
The data represent known locations of both soft and hard deep corals. Data do not represent density of coral cover but rather known locations and may reflect fishing or research effort. The origin of data varies: in Alaska - survey (RACE) and observer (NORPAC) databases; 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.



Altered Biogeochemistry

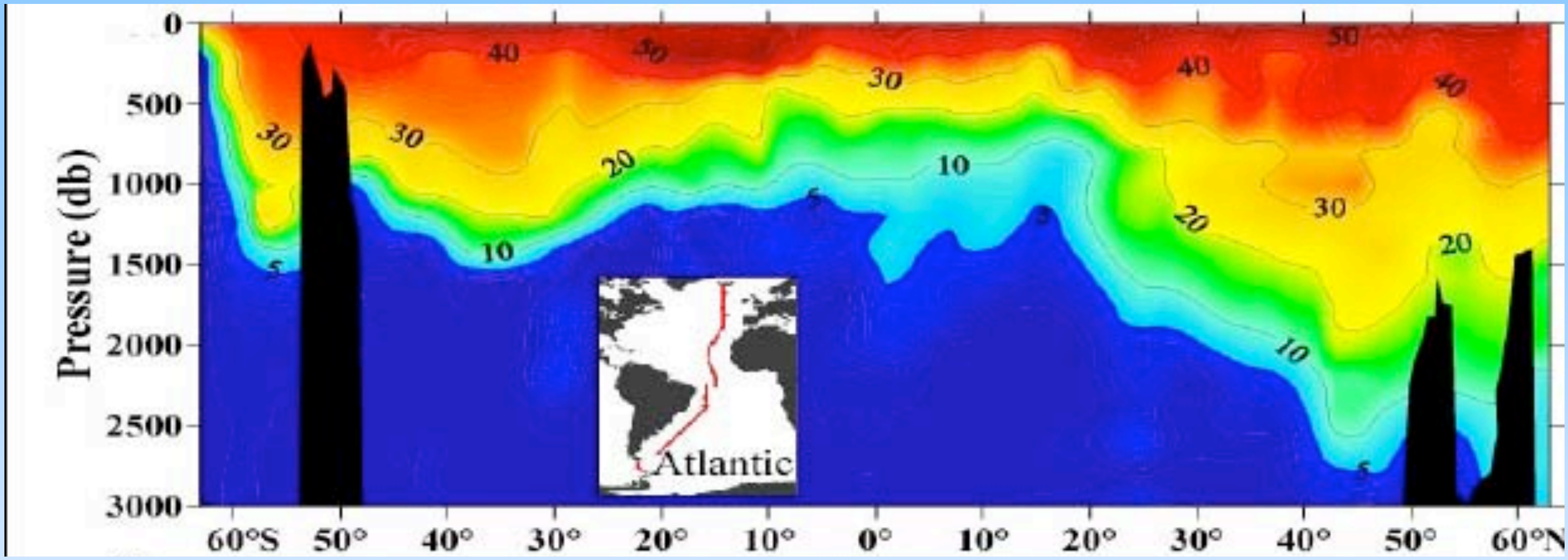
At Hawaii seeing:

- sharp drawdown in phosphorus pool
- shift in elemental composition
- Sign of increased N_2 fixation?



D. Karl (unpubl.)

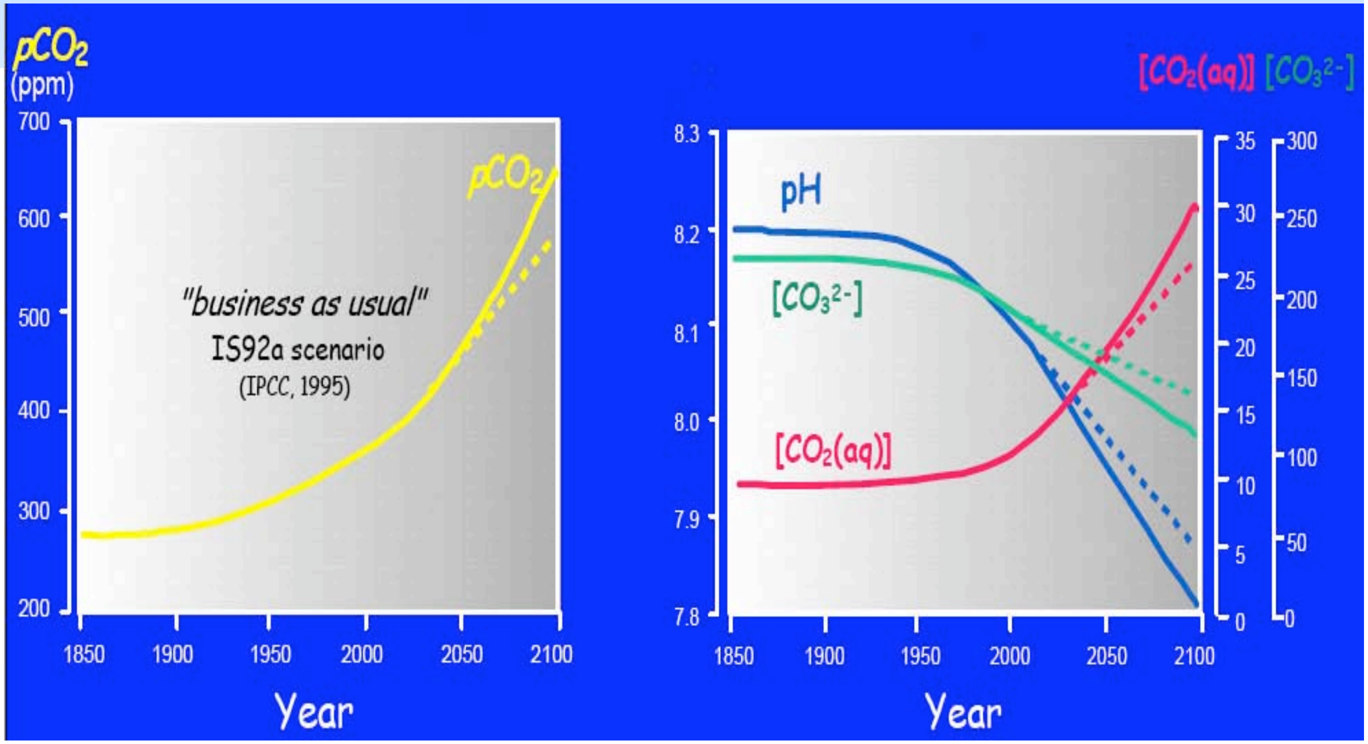
Ocean Acidification



-Oceans are sink for 1/3 to 1/2 of all fossil fuel carbon

-CO_2 combines with water to form carbonic acid

-surface pH will drop by another ~0.3 by 2100



Currently on Bleak CO2 Trajectory