50th Anniversary of the Global Carbon Dioxide Record Symposium and Celebration
November 28-30, 2007 ~ Kona, Hawaii

Global Warming and Ocean Acidification: Double Trouble for Ocean Ecosystems

Dr. Richard A. Feely
Supervisory Oceanographer
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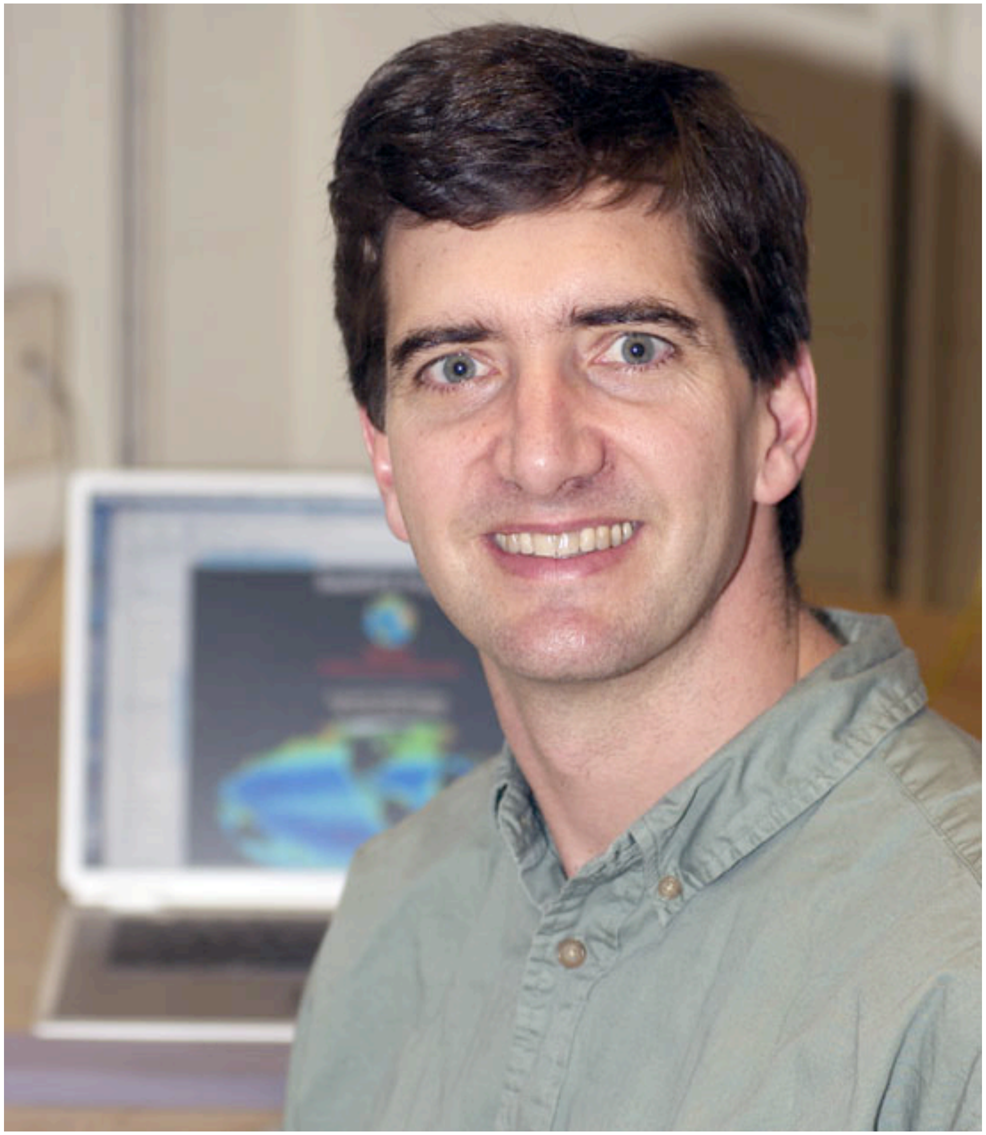
November 29, 2007

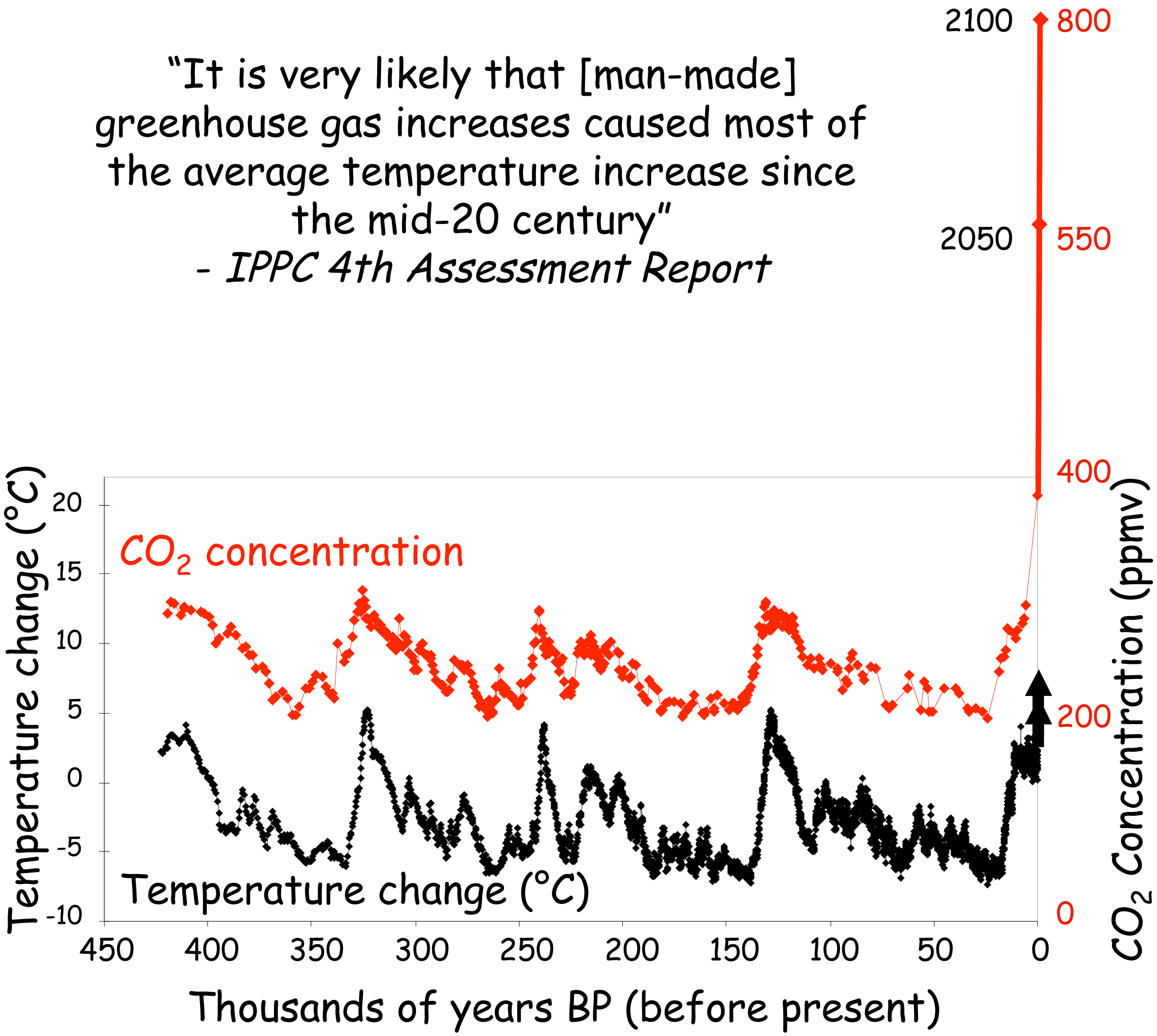
Dr. Scott Doney



Dr. Victoria Fabry

Antarctic Ice Core Record

"It is very likely that [man-made] greenhouse gas increases caused most of the average temperature increase since the mid-20 century"
- *IPPC 4th Assessment Report*



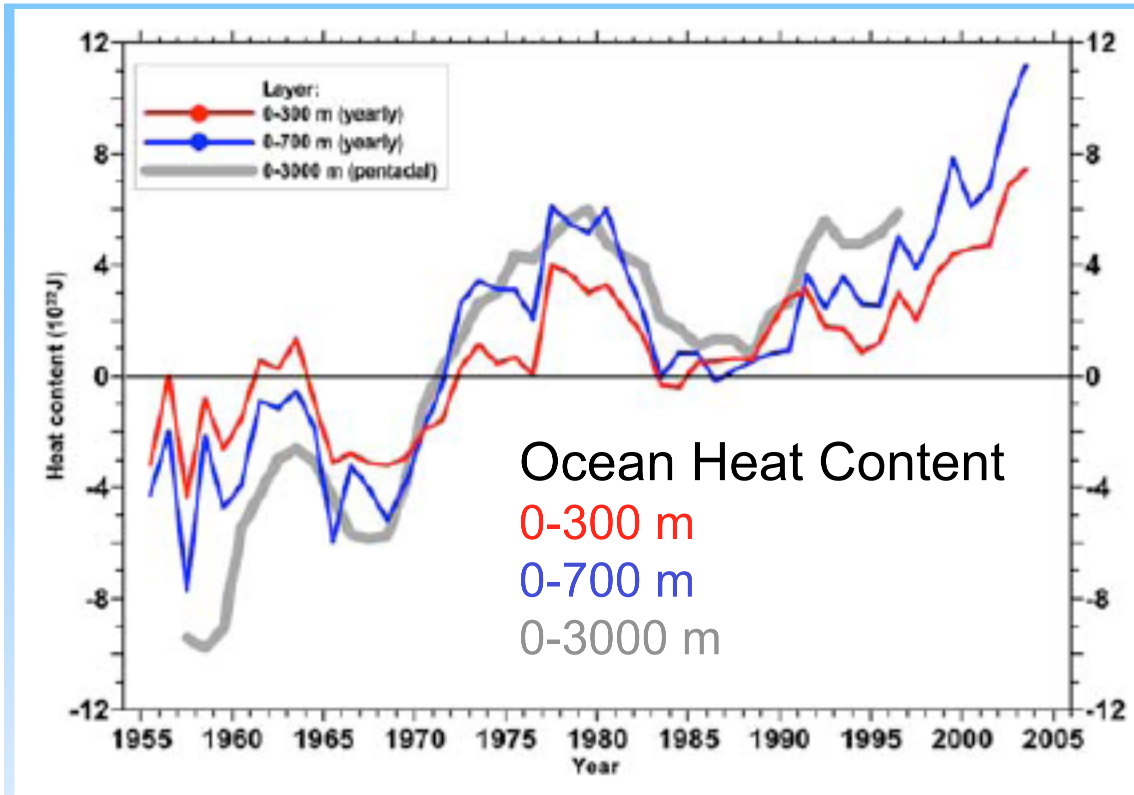
➢ Global Climate Change Processes are Real

- Greenhouse gases including CO_2
- Increased global temperatures
- Sea level rise
- Loss of sea ice
- Loss of biodiversity
- Ocean acidification

➢ Foreknowledge is Power

For policy creation and mitigation
Complex systems require predictive models

Predictive models require…
- Process identification
- Parameterization
- Testing and verification

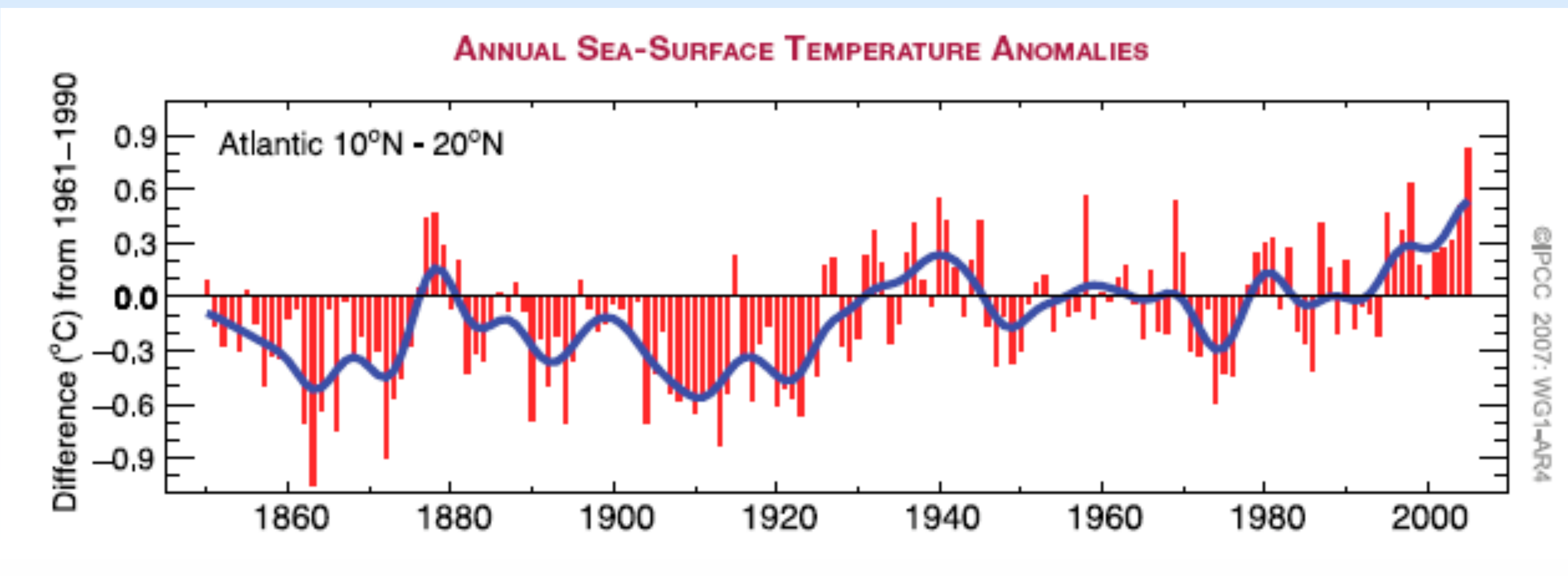


Ocean Warming

-anthropogenic warming & decadal variability signatures

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

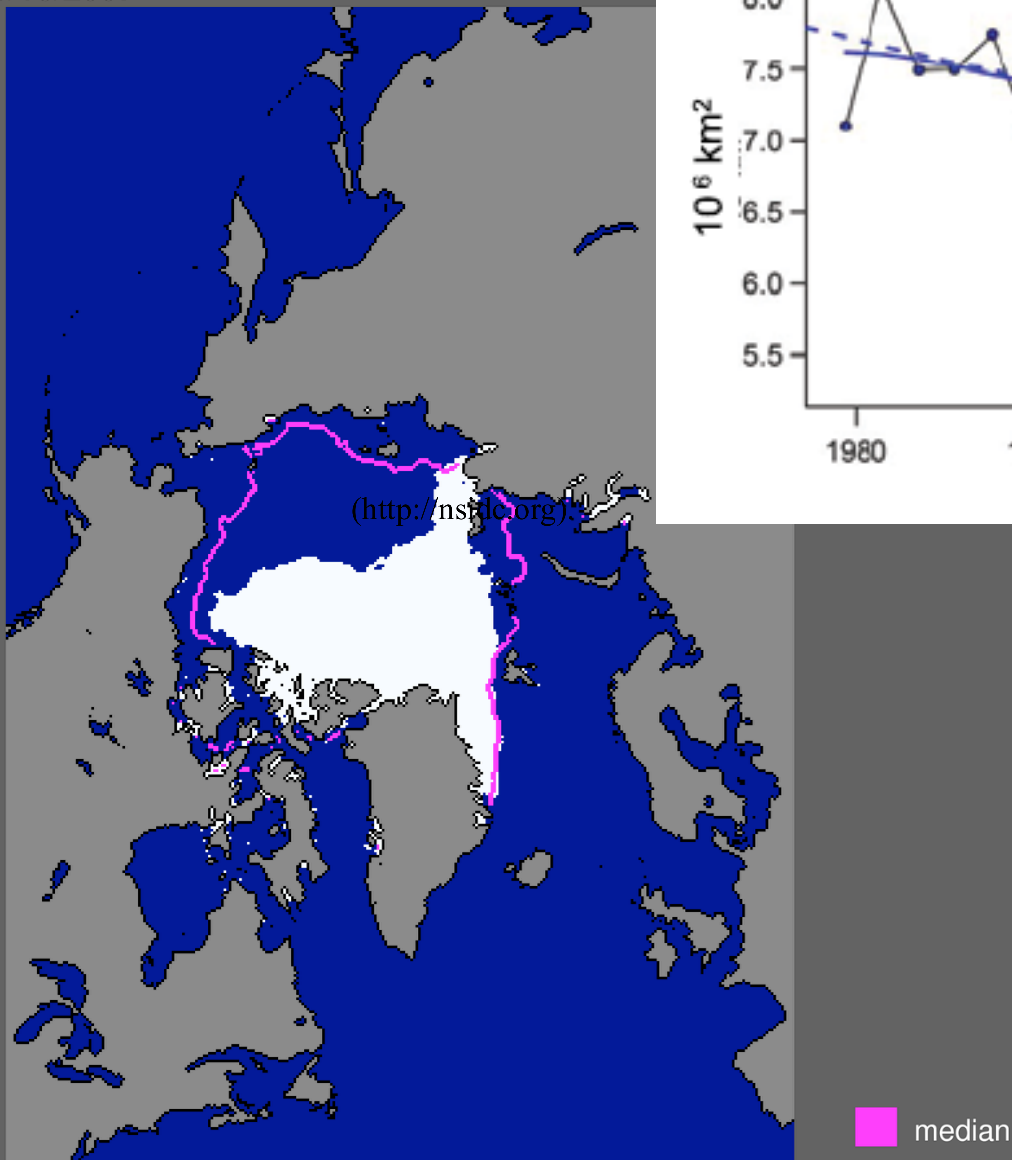
Levitus et al. Geophys. Res. Lett.(2005)



IPCC (2007)

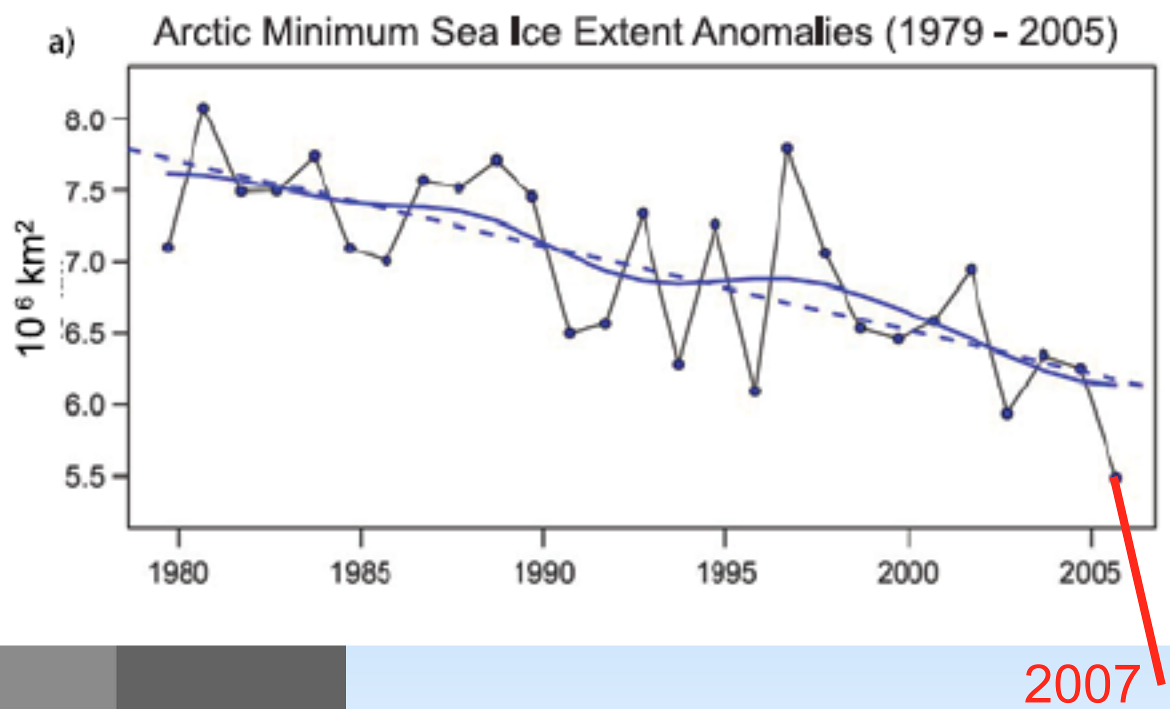
Sea-Ice Trends

Current Ice Extent
09/16/2007



Total extent = 4.1 million sq km

Changes in Sea Ice Extent

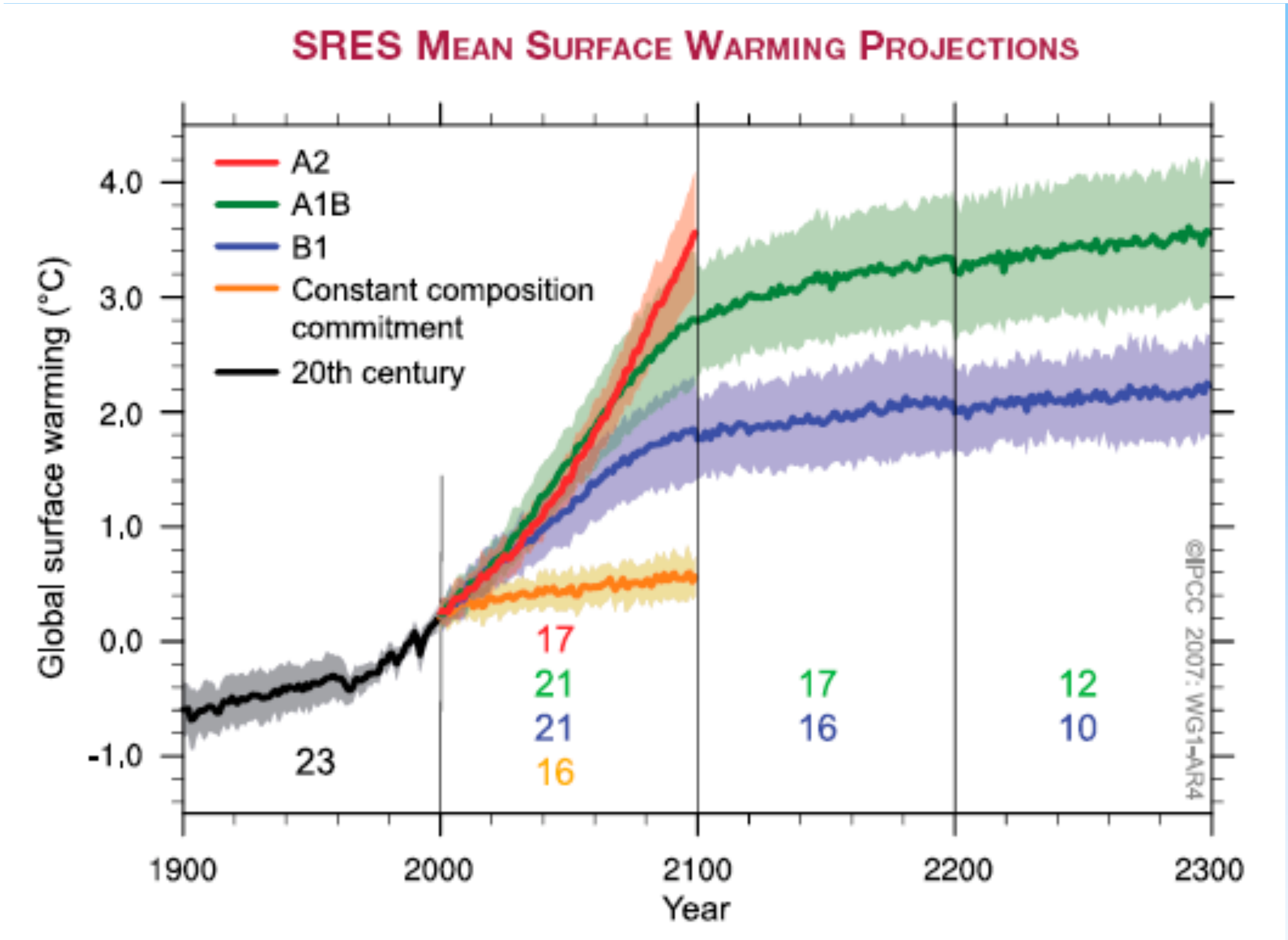


-Dramatic decreases in Arctic sea-ice extent and thickness

-Antarctic sea-ice flat or small increase

National Snow & Ice Data Center (http://nsidc.org).

Future Climate Projections



IPCC (2007)

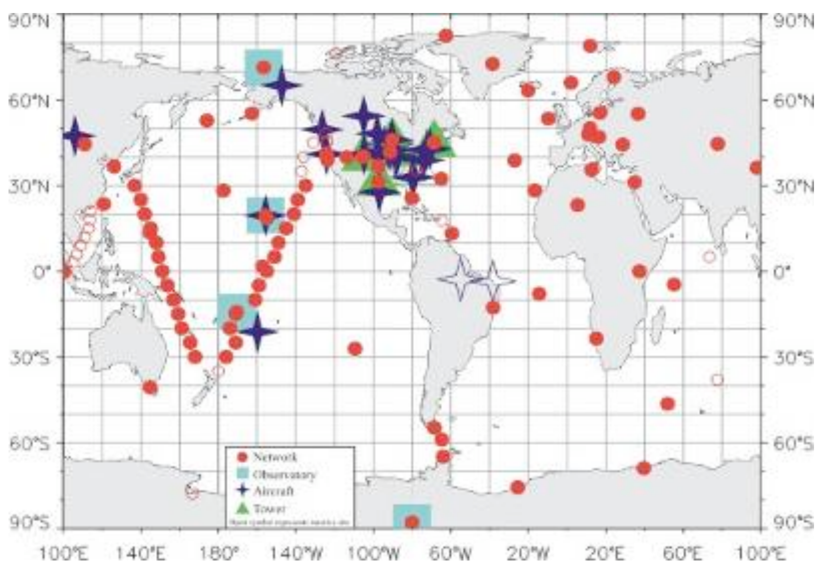
Major uncertainties:

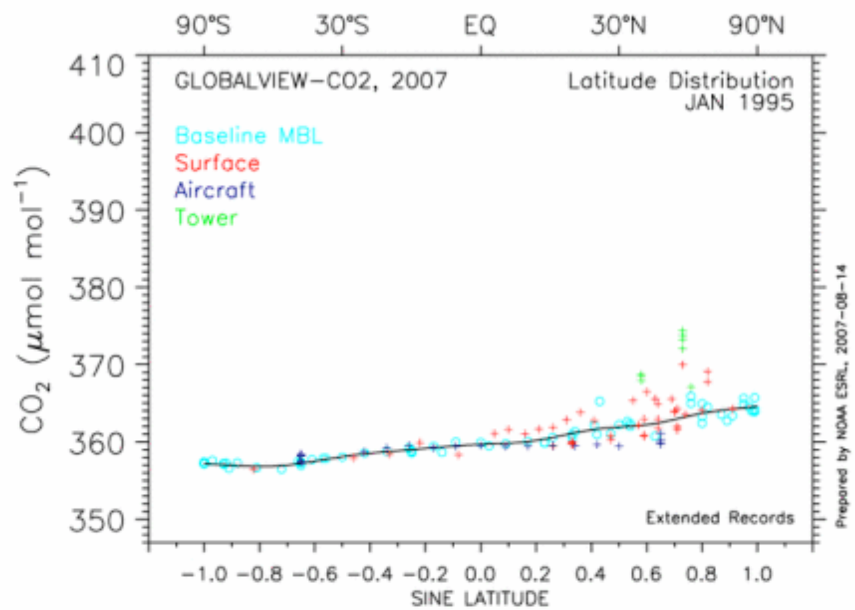
-CO_2 emissions (social, political, economic)

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

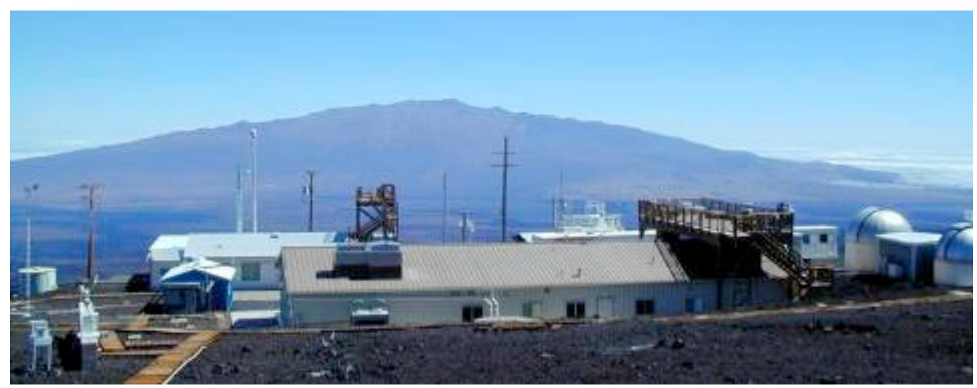
-climate sensitivities (clouds, water vapor)

Atmospheric CO_2 Record





NOAA Earth Systems Research Laboratory, Global Monitoring Division Global CO_2 Monitoring Network
Mouna Loa Observatory, Hawaii



Partition of Anthropogenic Carbon Emissions into Sinks

45% of all CO_2 emissions accumulated in the atmosphere

Atmosphere

The Airborne Fraction

The fraction of the annual anthropogenic emissions that remains in the atmosphere

55% were removed by natural sinks

Ocean removes ~25%

Land removes ~30%

Canadell et al. 2007, PNAS

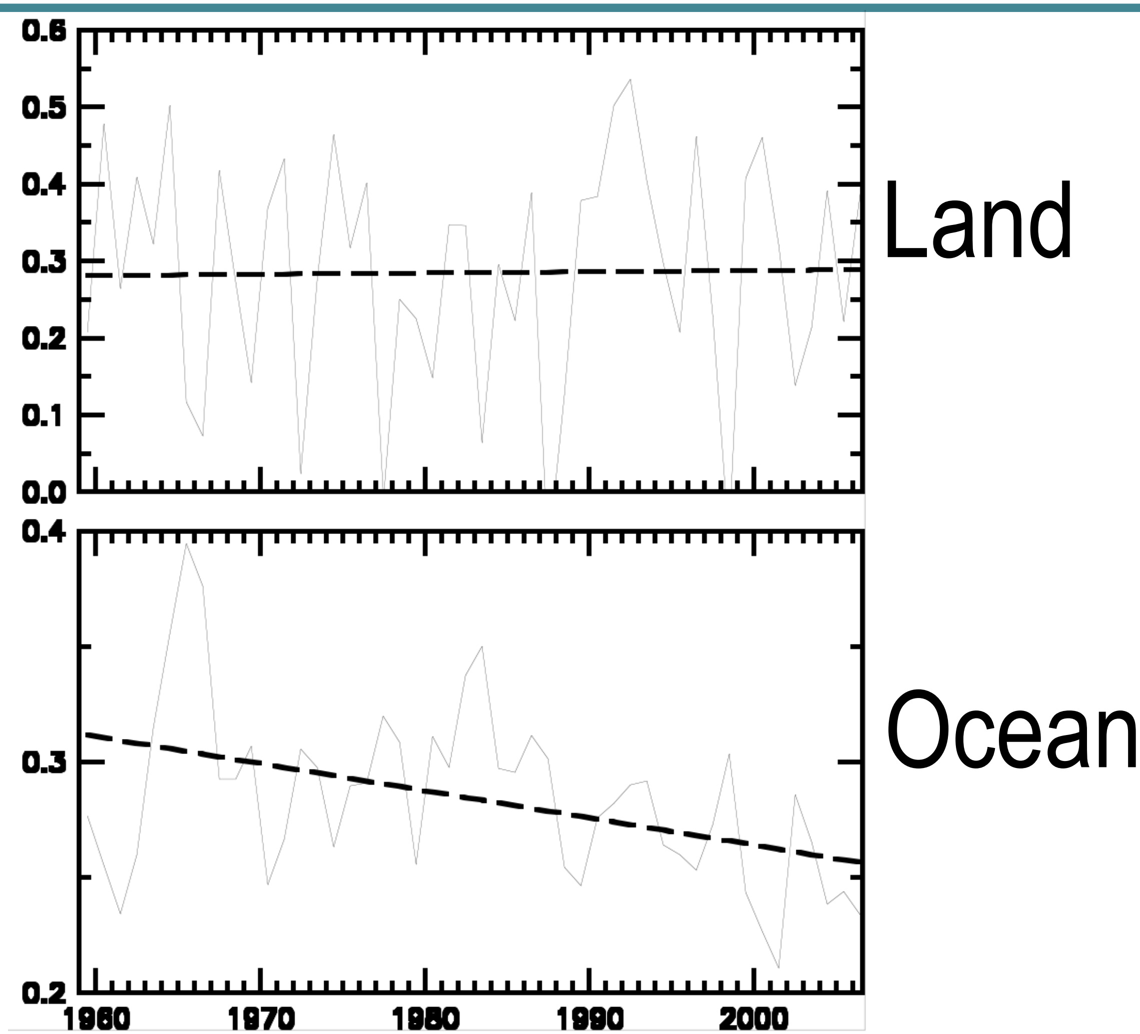
Factors that Influence the Airborne Fraction

1. The rate of CO_2 emissions.

2. The rate of CO_2 uptake and ultimately the total amount of C that can be stored by land and oceans:
   - Land: CO_2 fertilization effect, soil respiration, N deposition fertilization, forest regrowth, woody encroachment, …
   - Oceans: CO_2 solubility (temperature, salinity), ocean currents, stratification, winds, biological activity, acidification, …

Canadell et al. 2007, Springer; Gruber et al. 2004, Island Press

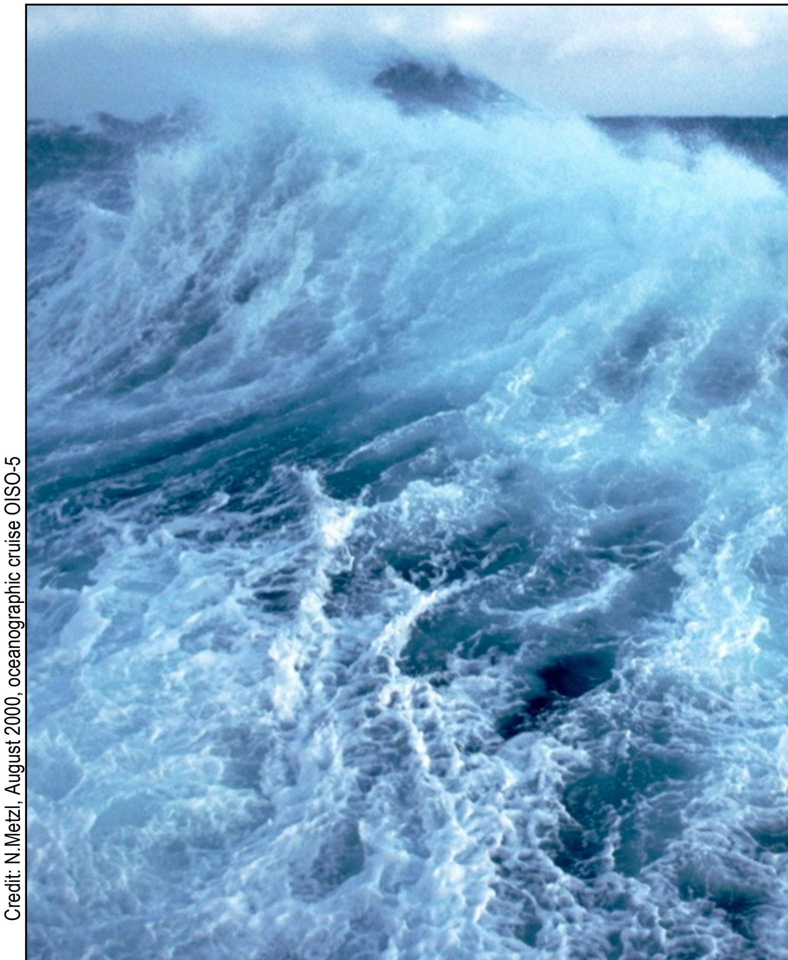
The Efficiency of Natural Sinks: Land and Ocean Fractions



The efficiency of the ocean carbon sink has decreased ~16% in the last 50 years

Canadell et al. 2007, PNAS

Causes of the Declined in the Efficiency of the Ocean Sink



Credit: N.Metzl, August 2000, oceanographic cruise OISO-5

- Part of the decline is attributed to up to a 30% decrease in the efficiency of the Southern Ocean sink over the last 20 years.
- This sink removes annually 0.7 Pg of anthropogenic carbon.
- The decline is attributed to the strengthening of the winds around Antarctica which enhances ventilation of natural carbon-rich deep waters.
- The strengthening of the winds is attributed to global warming and the ozone hole.

Le Quéré et al. 2007, Science

Ocean Acidification

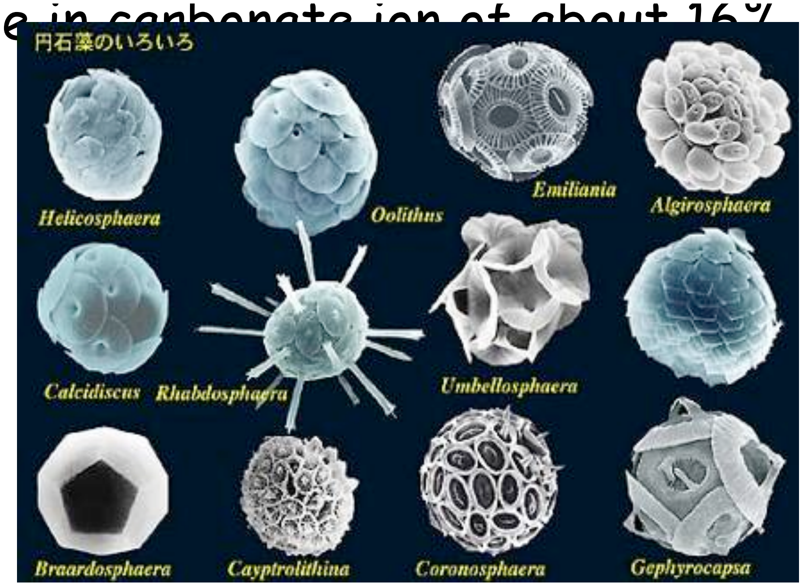
50 YEARS Recording the Past Informing the Future

Since the beginning of the industrial age, the pH and CO_2 chemistry of the oceans (ocean acidification) have been changing because of the uptake of anthropogenic CO_2 by the oceans.

- These changes in pH and carbonate chemistry may have serious impacts on open ocean and coastal marine ecosystems.
- 30% increase in acidity; decrease in carbonate ion of about 16%

Photo: Missouri Botanical Gardens

Corals



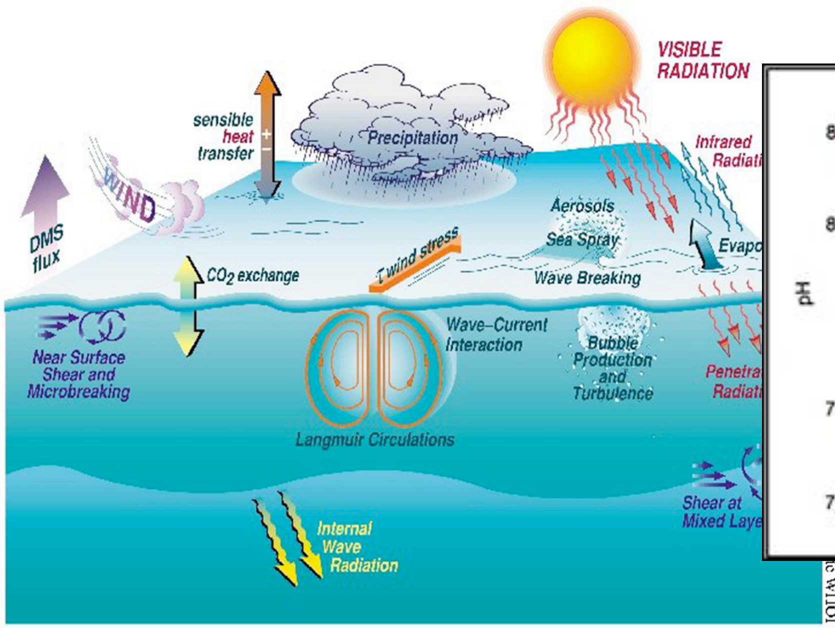
http://www.biol.tsukuba.ac.jp/~inouye

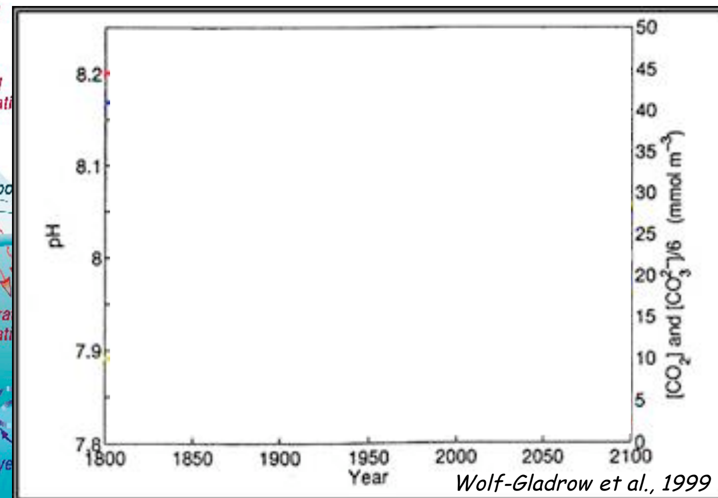
Calcareous Plankton

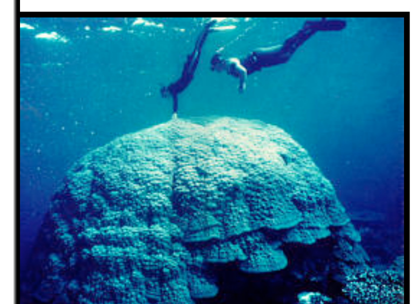
What we know about the chemistry of ...ocean acidification

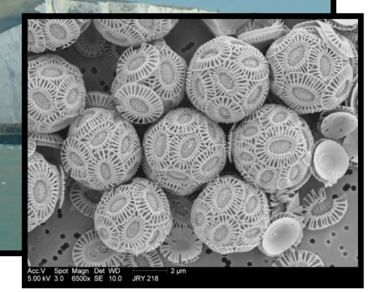
$$CO_2 + H_2O \rightarrow H^+ + HCO_3^- \qquad H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

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









What we know about the ocean chemistry of
...saturation state

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

Saturation State

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

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

calcium + carbonate → calcium carbonate

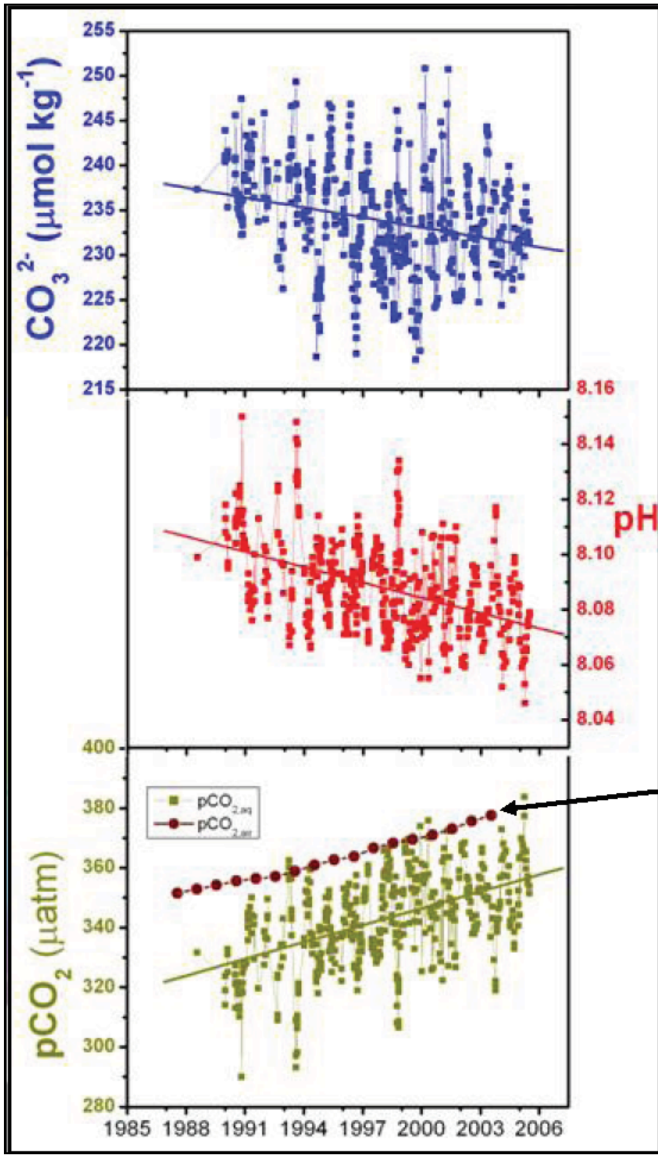
$\Omega > 1 = precipitation$

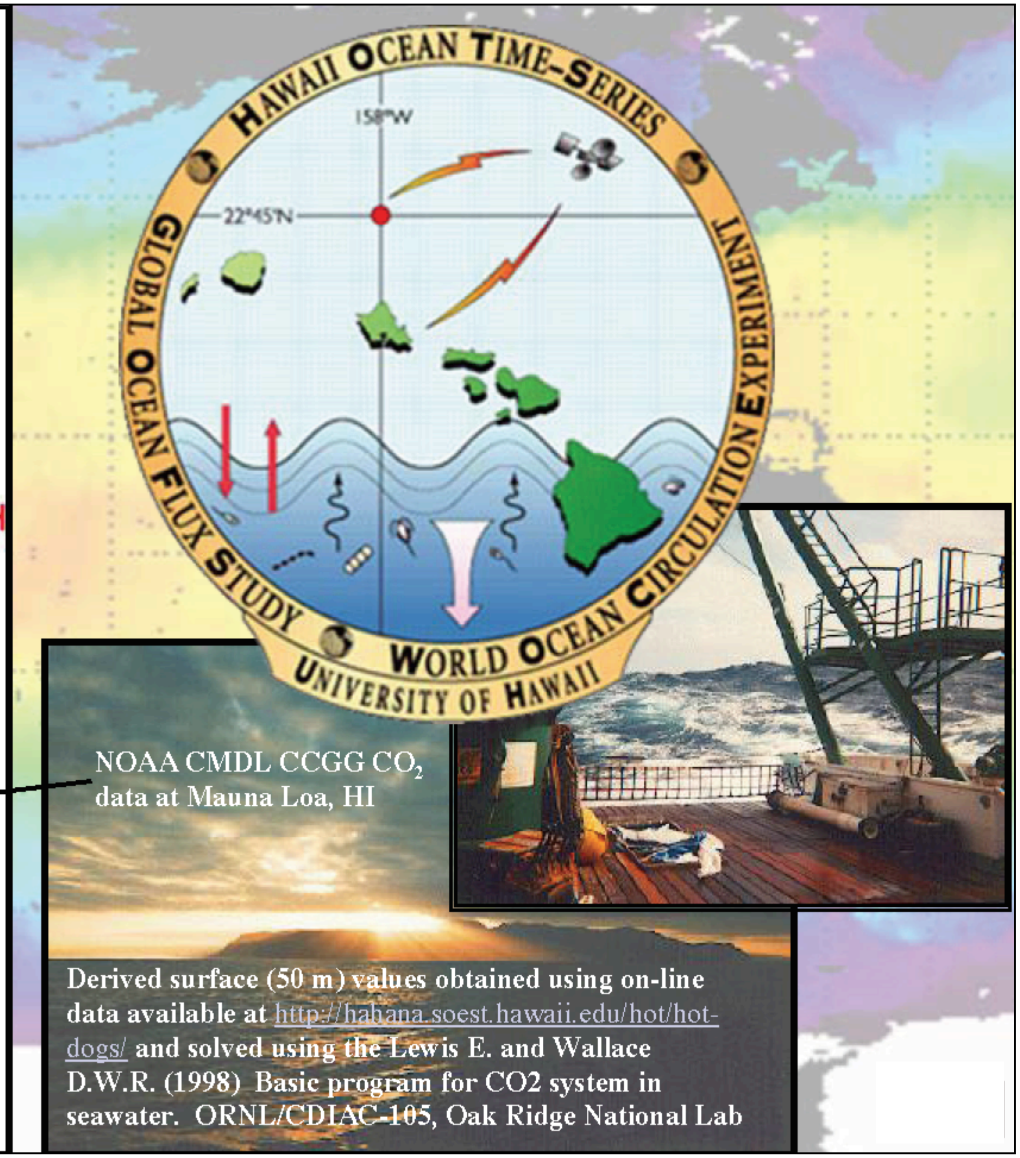
$\Omega = 1 = equilibrium$

$\Omega < 1 = dissolution$

What we know about ocean CO_2 chemistry

...from time series observations

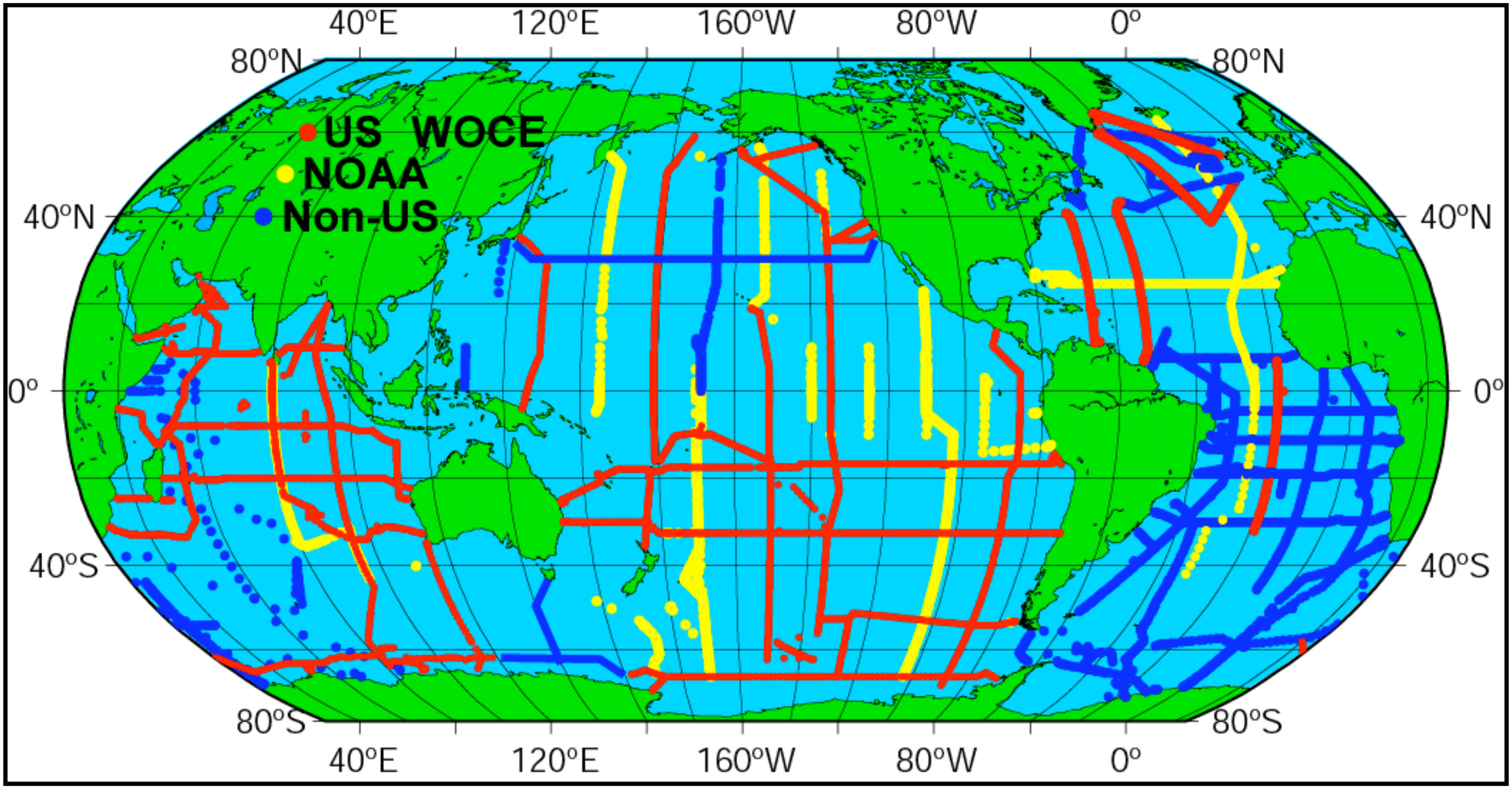




What we know about ocean CO_2 chemistry

…from field observations

Recording the Past
Informing the Future



WOCE/JGOFS/OACES Global CO_2 Survey

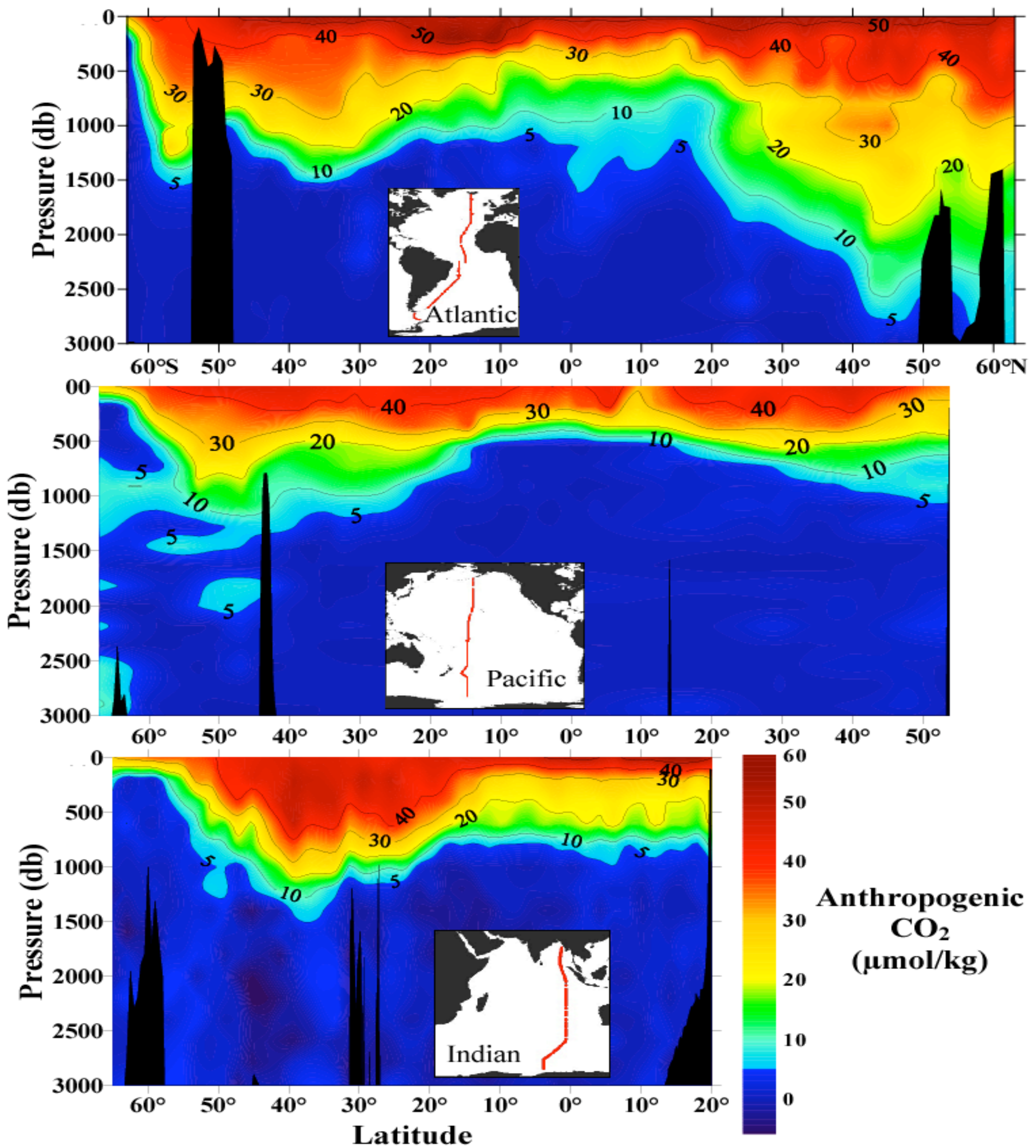
~72,000 sample locations
collected in the 1990s

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

Sabine et al (2004)

What we know about ocean CO_2 chemistry

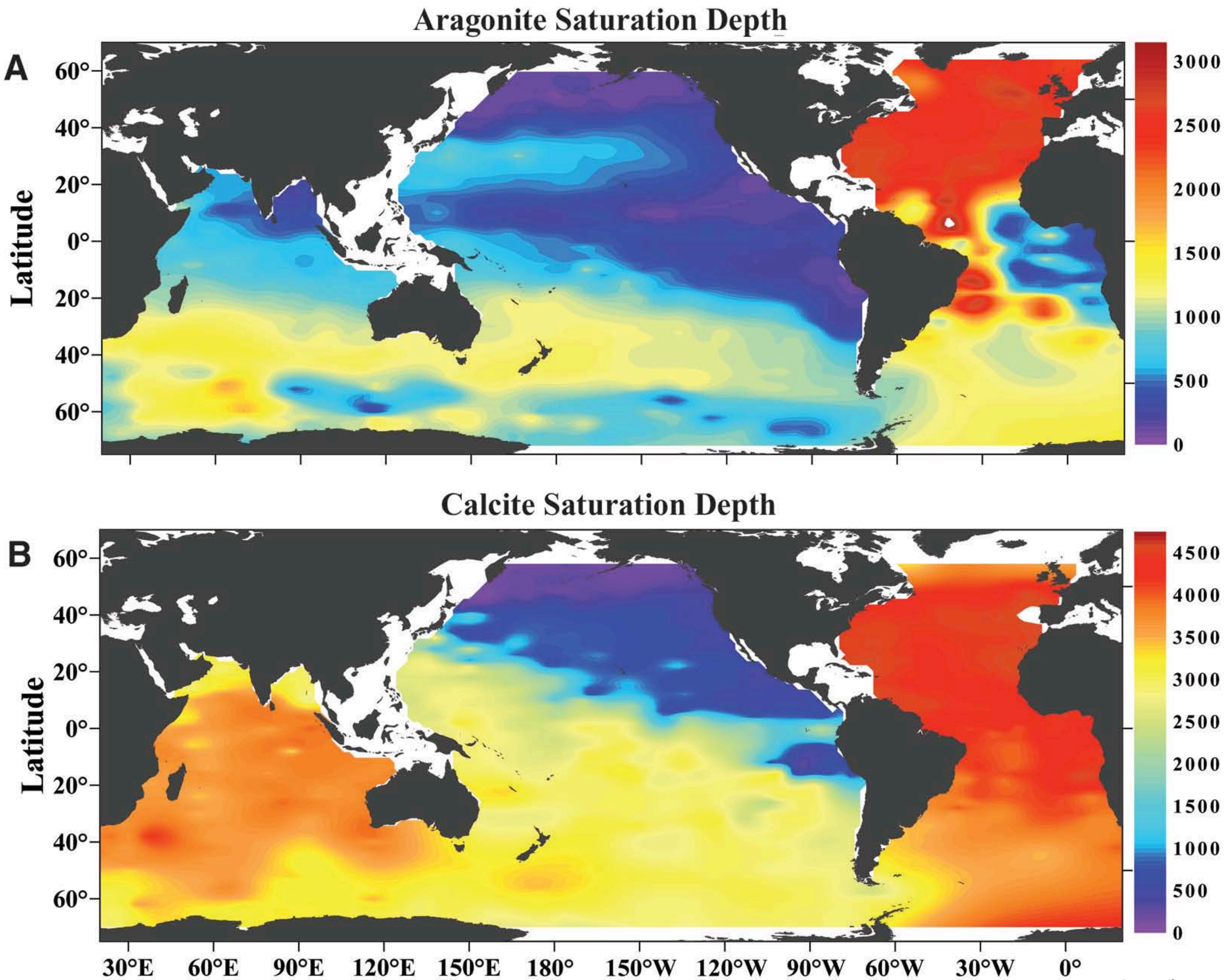
…about human impacts on ocean CO_2 chemistry



- From the WOCE/JGOFS global CO_2 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
- What are the impacts of increased CO_2 on marine ecosystems?

Sabine et al. Science (2004)

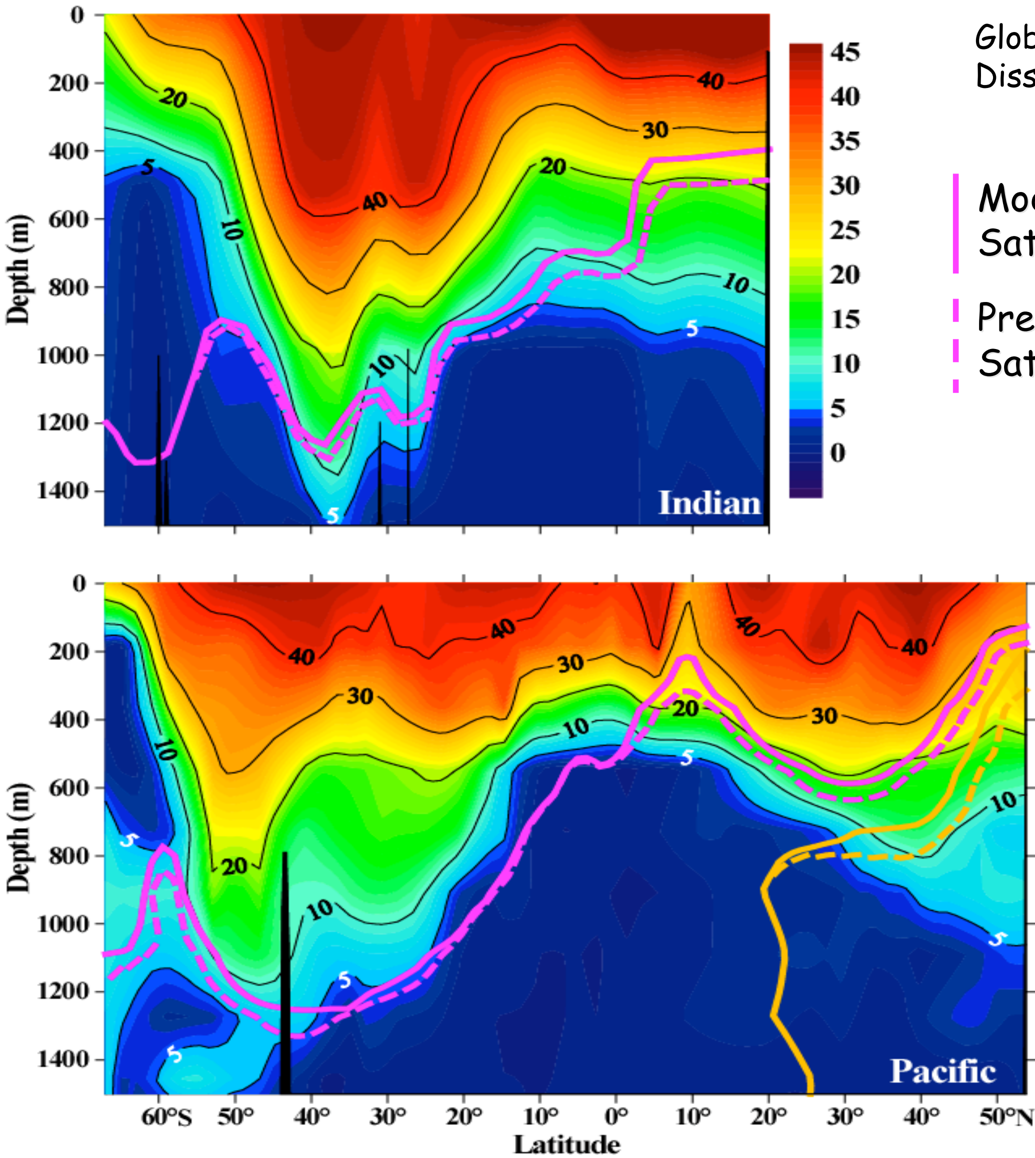
What we know
about ocean CO_2 chemistry
…from observed aragonite and calcite saturation depths in the global oceans



Feely et al. (2004)

What we know
about ocean CO_2 chemistry
…from observed shoaling saturation horizons

Recording the Past
Informing the Future



Global Water-column Dissolution = 0.5 Pg C yr^{-1}

Modern Aragonite Saturation Horizon

Preindustrial Aragonite Saturation Horizon

Modern Calcite Saturation Horizon

Preindustrial Calcite Saturation Horizon

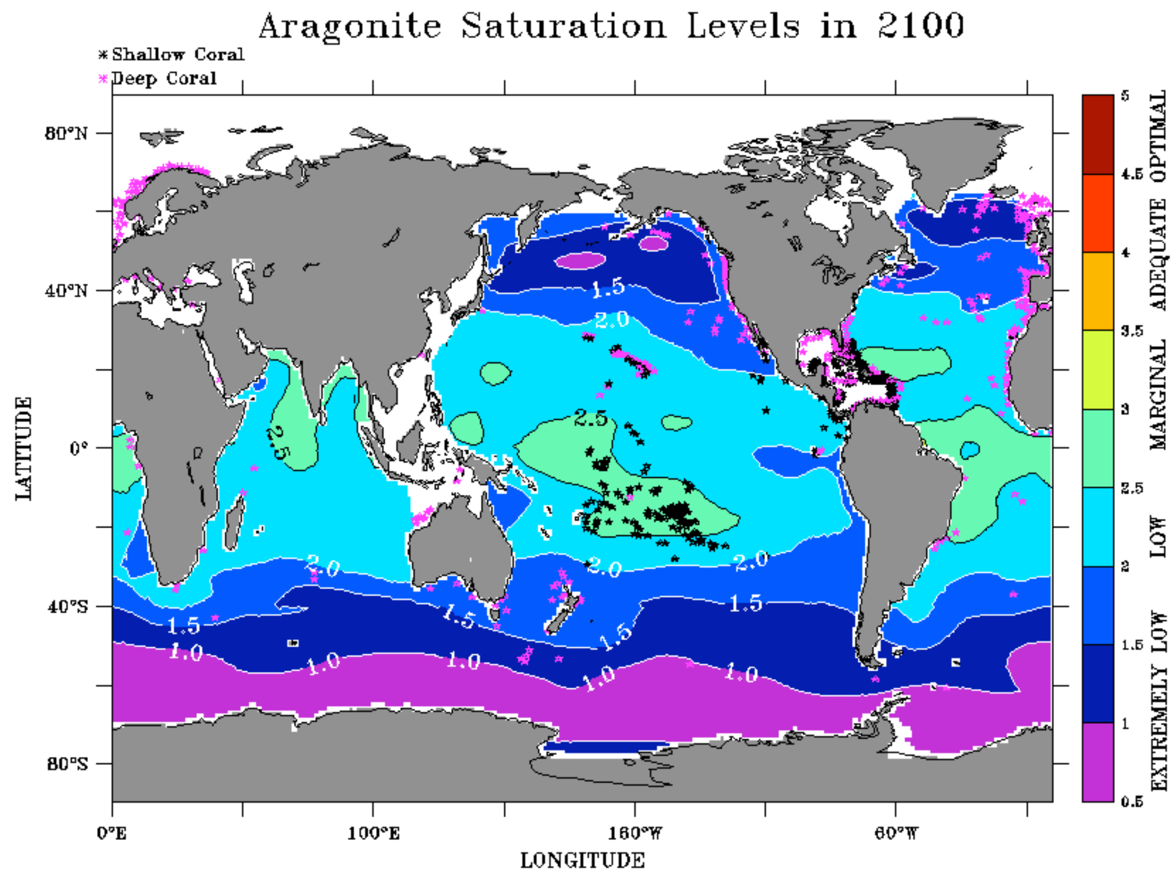
The aragonite and calcite saturation horizons have shoaled towards the surface of the oceans due to the penetration of anthropogenic CO_2 into the oceans.

Feely et al. (2004)

Model projections of aragonite saturation levels through time

Coral Reef calcification
- 1765 **Adequate**
- 2000 **Marginal**
- 2100 **Low**

Calcification rates in the tropics may decrease by 30% over the next century



Aragonite Saturation from Orr et al 2005

After Feely et al (in press) with Modeled Saturation Levels from Orr et al (2005)

Questions to be Discussed in our Mini-Panel

1. What CO_2 and pH changes should we strive to avoid in the oceans?

2. What mitigation and adaptation strategies can be applied to reduce the most severe impacts in the oceans?