PMEL $CO_2$ Program

NOAA

# Carbon Program Overview

1. Introduction and Motivation for Research
2. An Observational Program for Evolving Science Questions
3. New and Future Challenges


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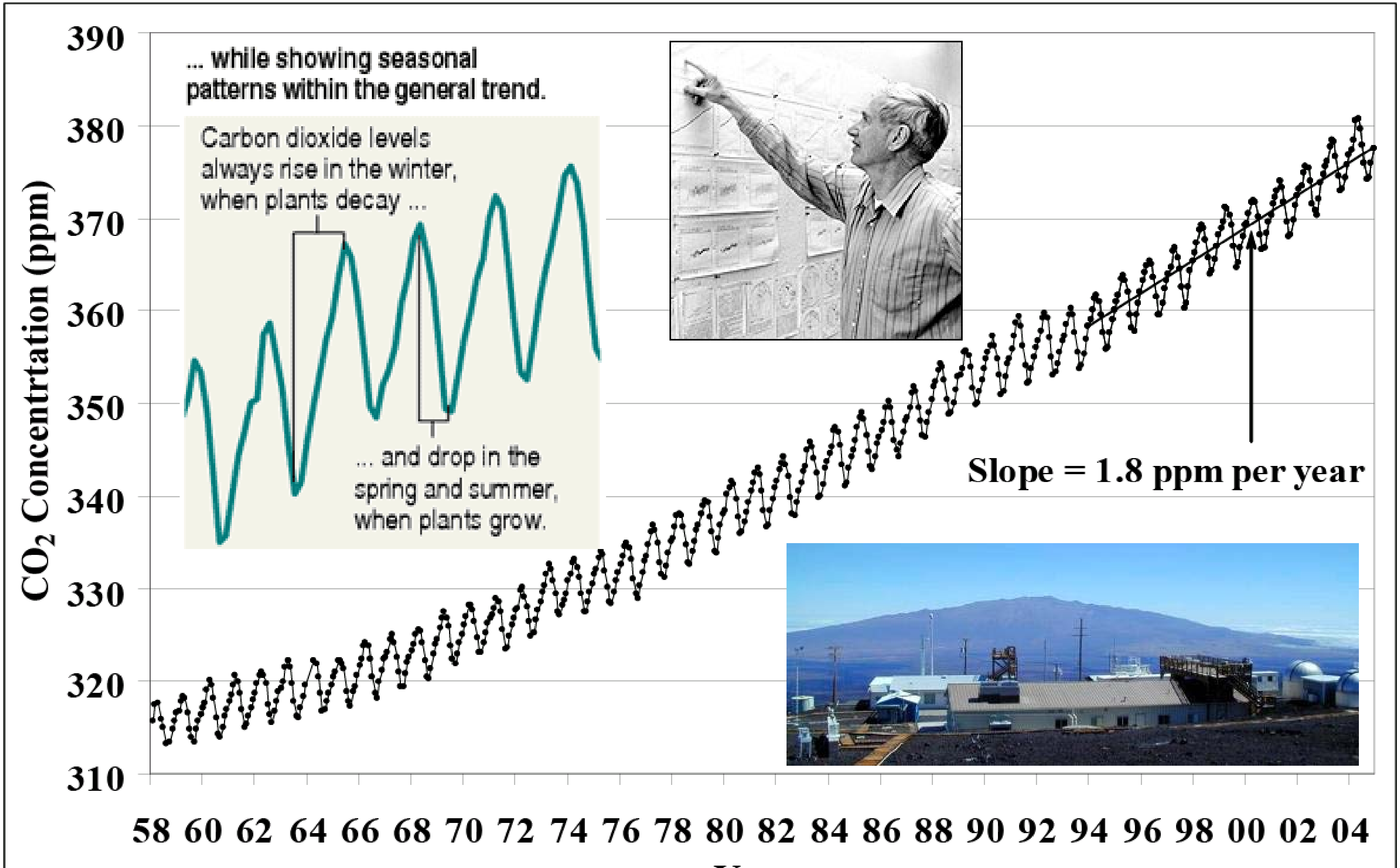
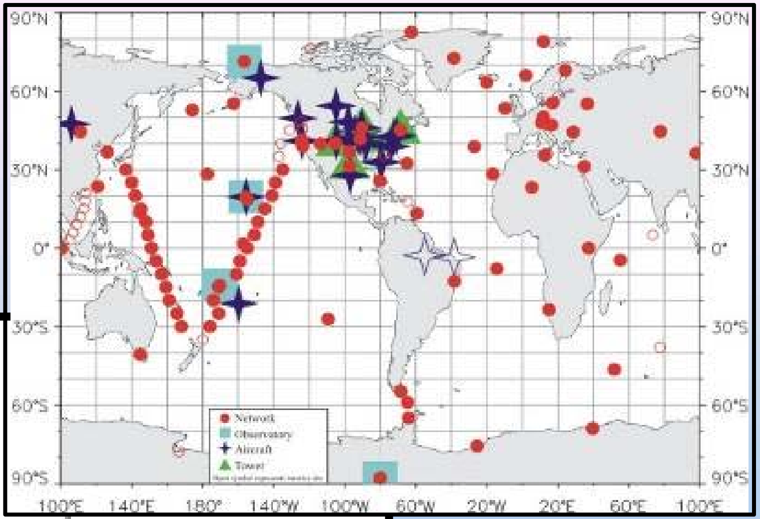
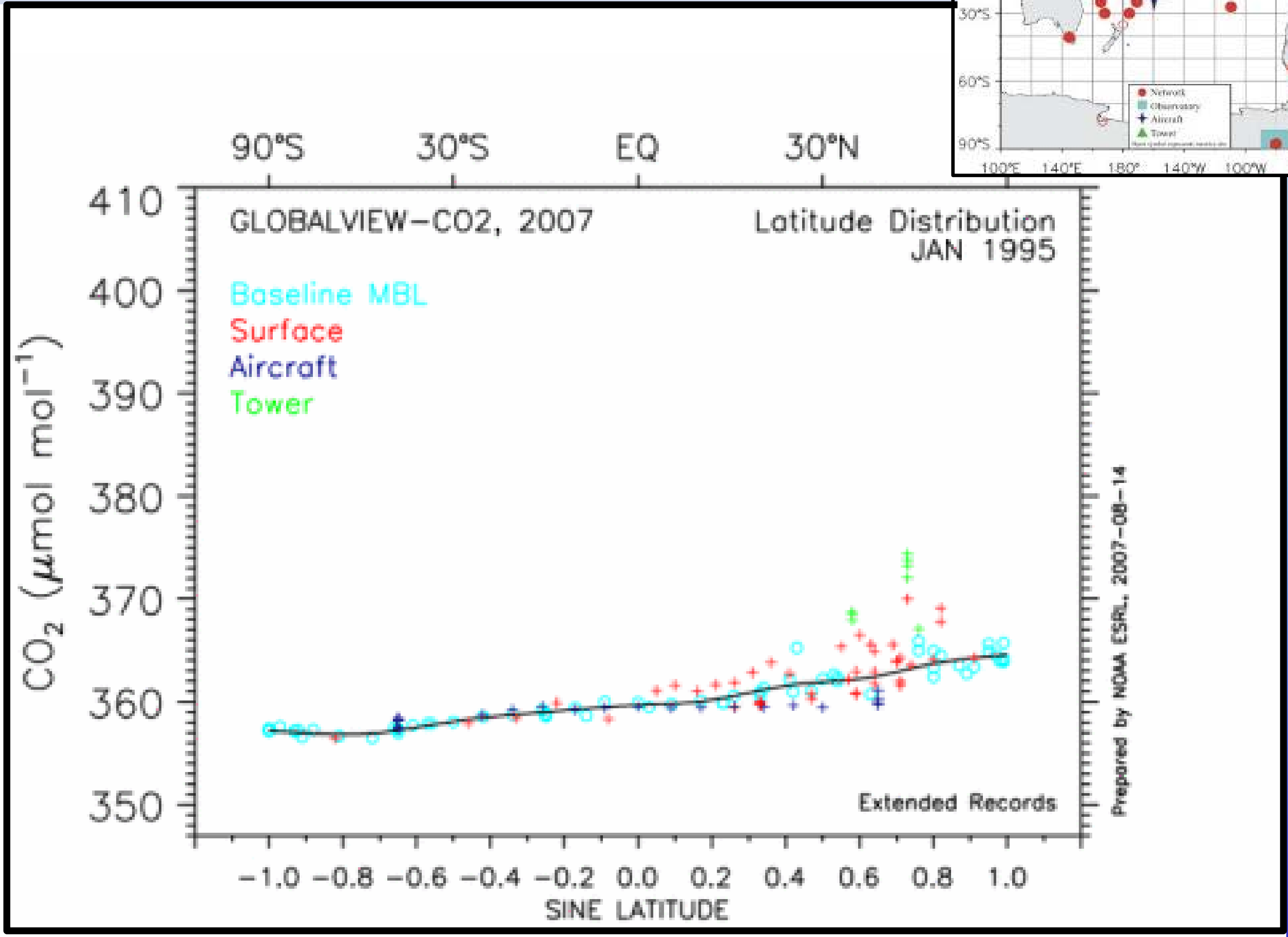
# Rising Atmospheric $CO_2$ was first discovered by Dr. David Keeling in the mid 1900s.




Data from Keeling and Whorf, 2004

# Globalview Atmospheric $CO_2$ Network




Atmospheric $CO_2$ levels are rising everywhere in the world. This can easily be seen even with the natural variability.

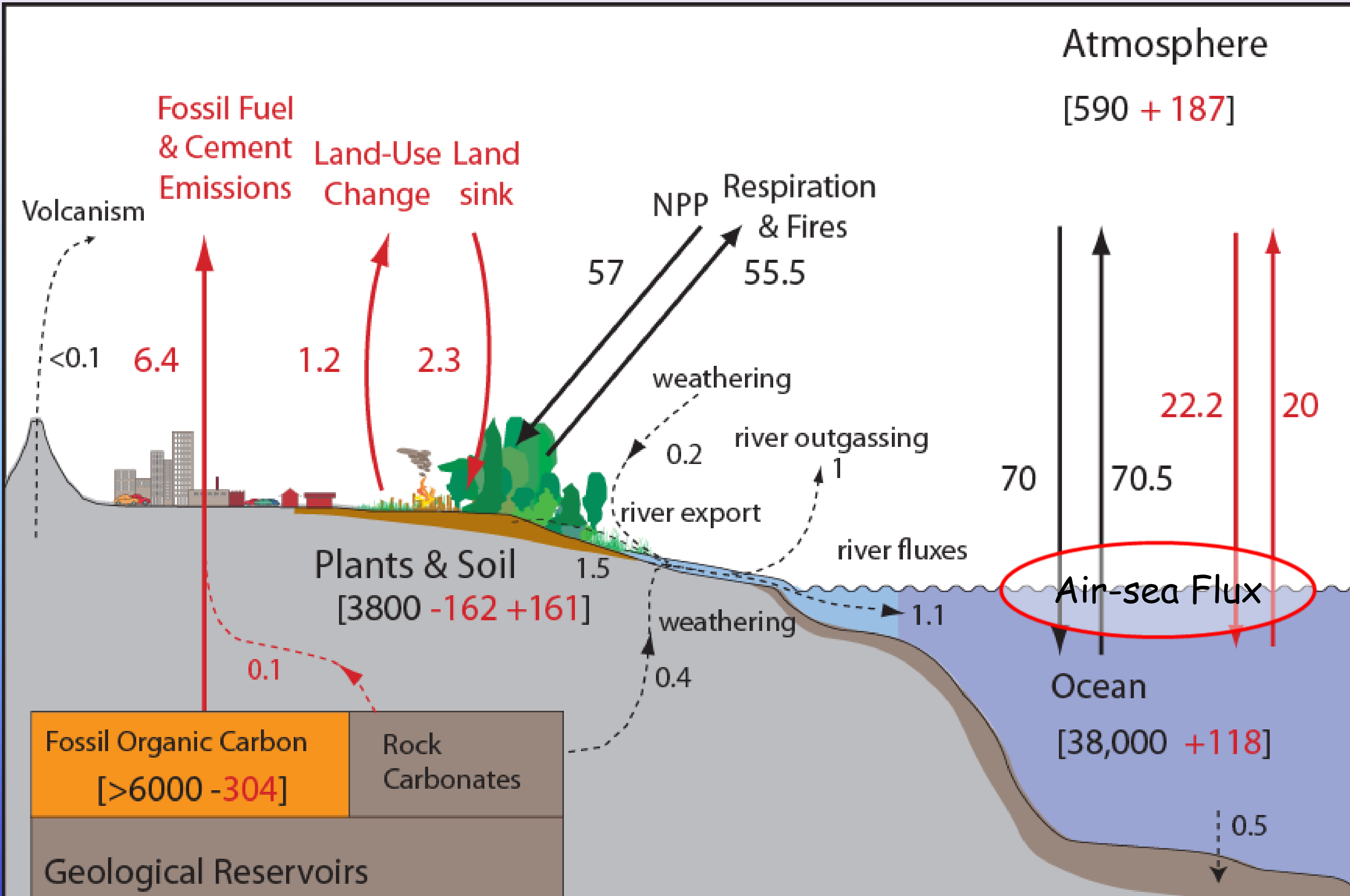
# Motivation for the PMEL $CO_2$ Program

The NOAA's Climate Mission Goal -- To understand climate variability and change to enhance society's ability to plan and respond.

Research Area: Develop an Integrated Global Observation and Data Management System for routine delivery of information, including attribution of the state of the climate.

Performance Objective: Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship.

# Global Carbon Budget for 1990s published in the Nov. 2007 First State of the Carbon Cycle Report (SOCCR)




*adapted from Sabine et al., 2004*

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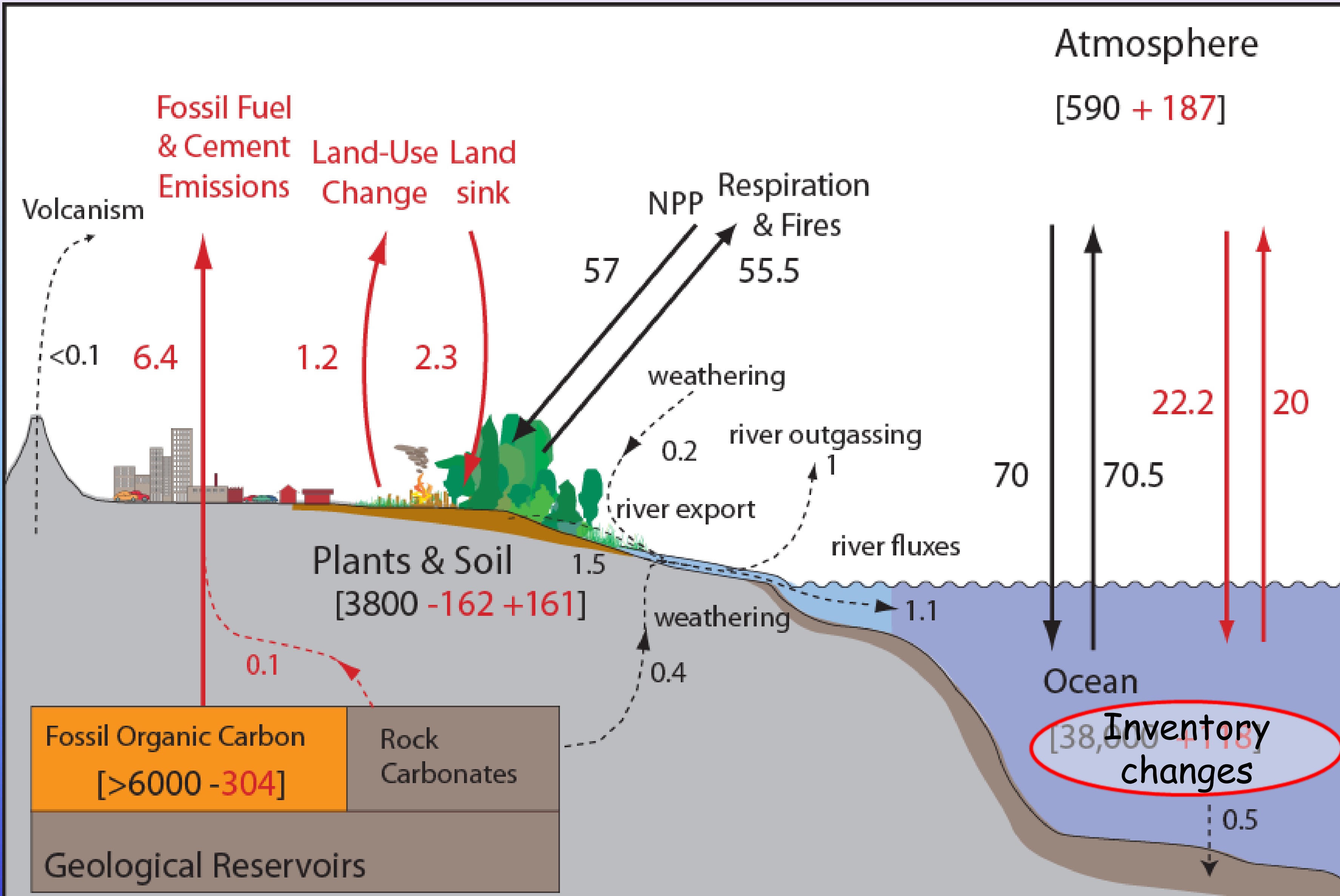
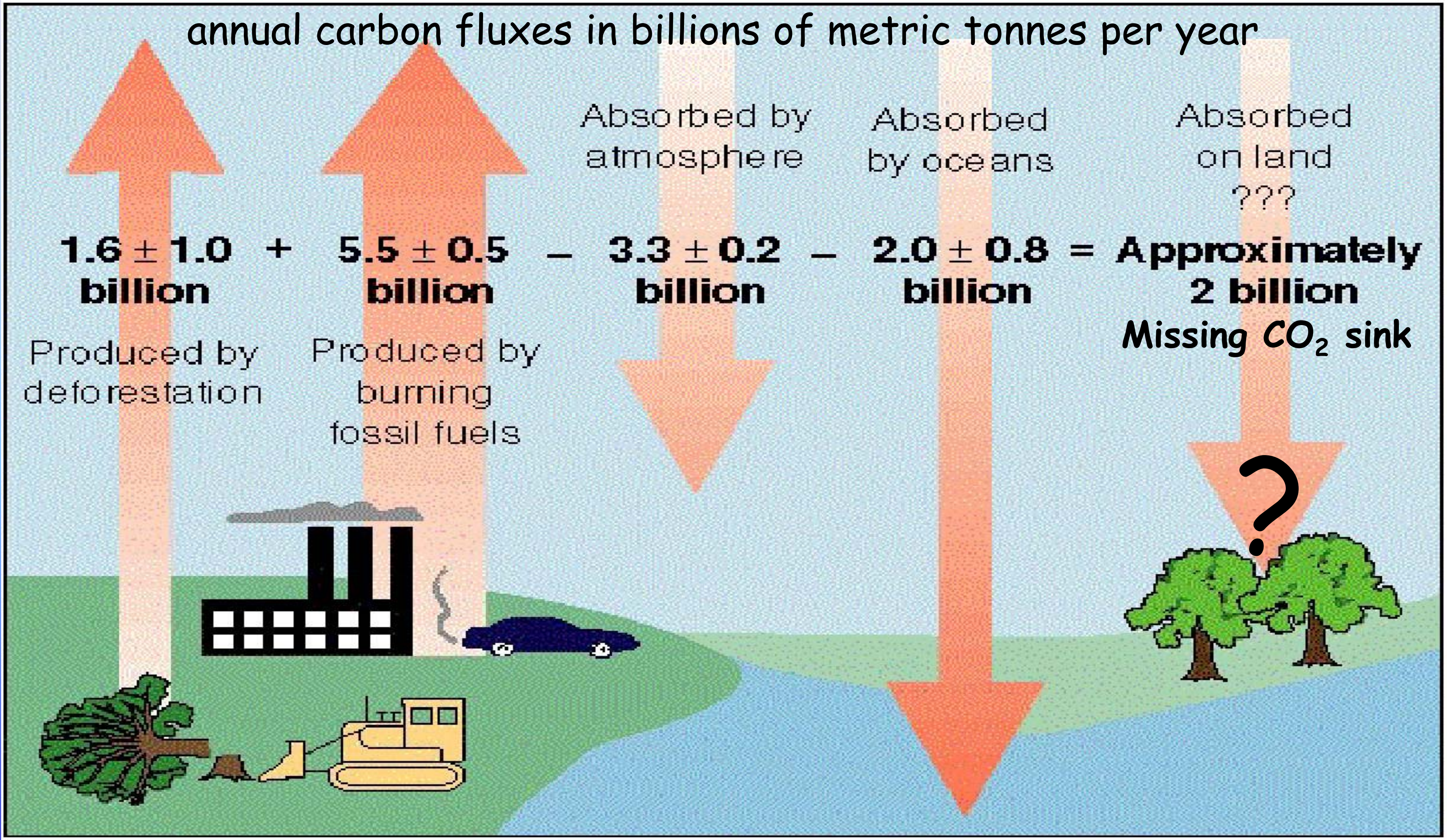


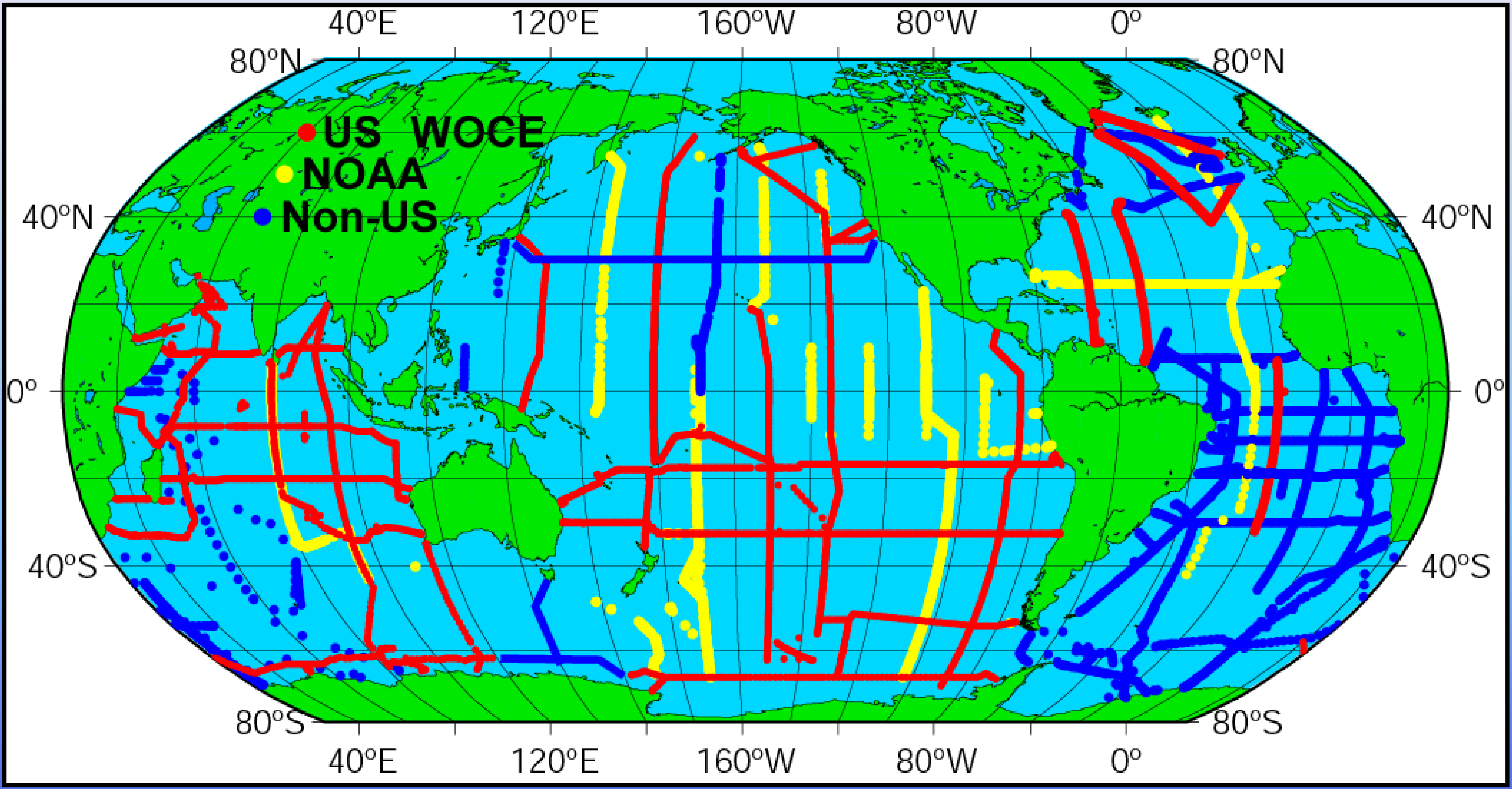

*adapted from Sabine et al., 2004*

# early 1990s view of the global carbon cycle could not account for all the $CO_2$ released to the atmosphere.




1 ppm in the atmosphere = 2.1 Pg C

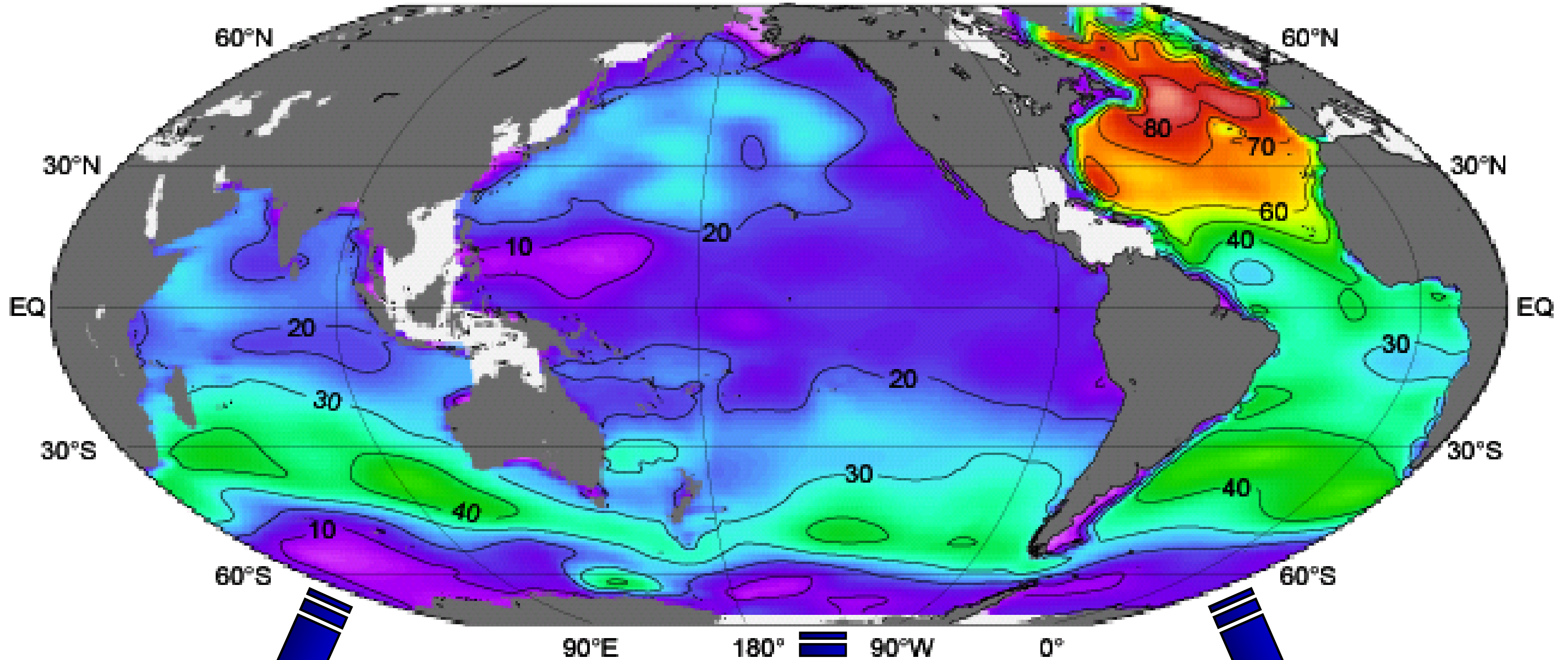
By the mid 1990s the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the NOAA/OACES program had completed a global survey of $CO_2$ in the oceans.




The GLODAP carbon database of >70,000 sample locations grew out of a 5 year NOAA synthesis effort.

http://cdiac.esd.ornl.gov/oceans/glodap/Glodap_home.htm

# Column inventory of anthropogenic $CO_2$ that has accumulated in the ocean between 1800 and 1994 (mol $m^{-2}$)




Indian Ocean
22 Pg C

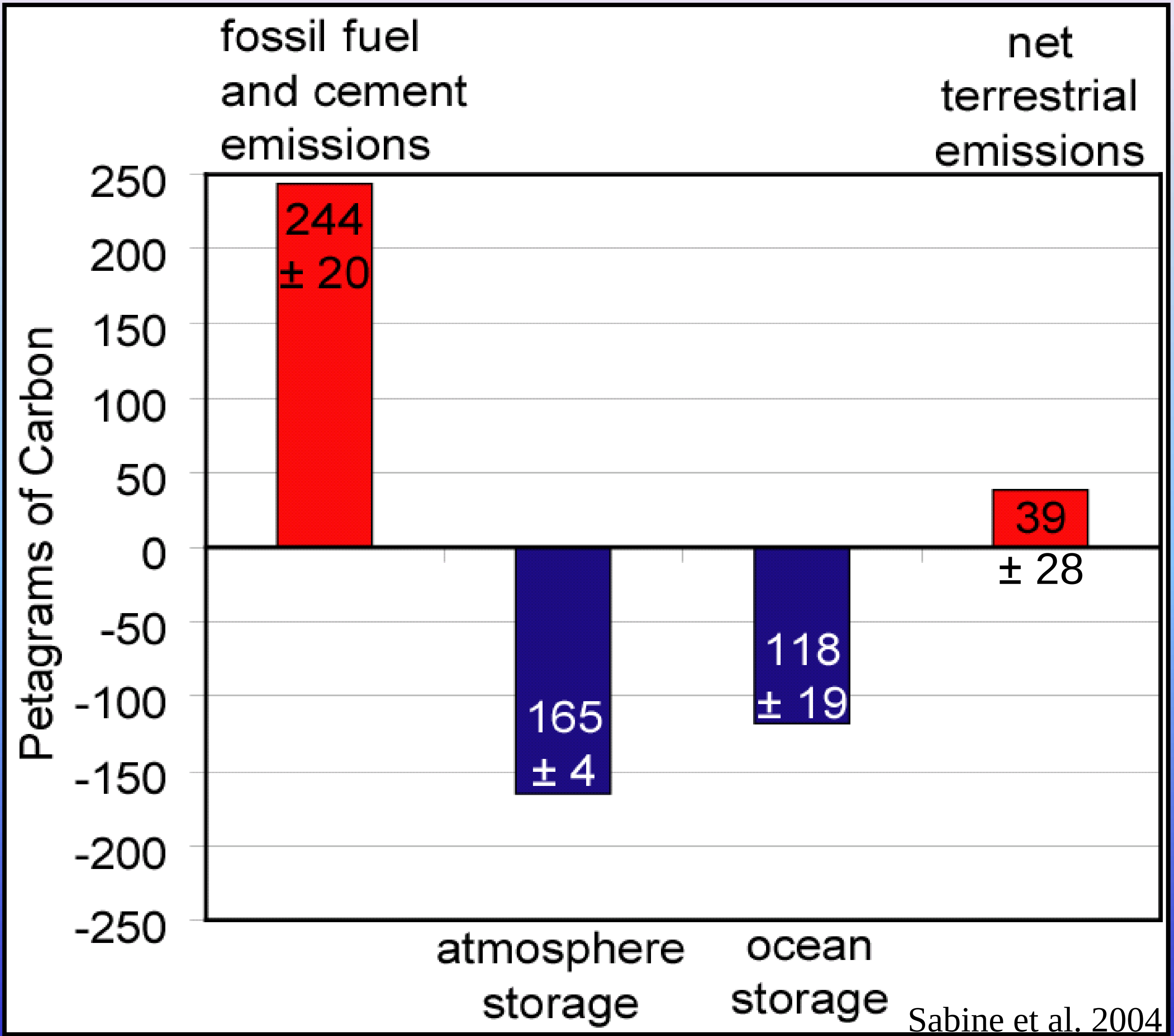
Pacific Ocean
44 Pg C

Atlantic Ocean
40 Pg C

From Sabine et al. 2004

**Mapped Inventory =106±17 Pg C; Global Inventory =118±19 Pg C**

# Quantifying the ocean inventory helped constrain the net terrestrial biosphere fluxes




Over the past 200 years, the ocean has been the only reservoir to consistently take up anthropogenic $CO_2$ from the atmosphere.

# CLIVAR/$CO_2$ Repeat Hydrography

R.A. Feely, C.L. Sabine, R. Wanninkhof, G.C. Johnson, J.L. Bullister, M. Barringer, C.W. Mordy, J.-Z. Zhang, D. Greeley, F.J. Millero, and A.G. Dickson

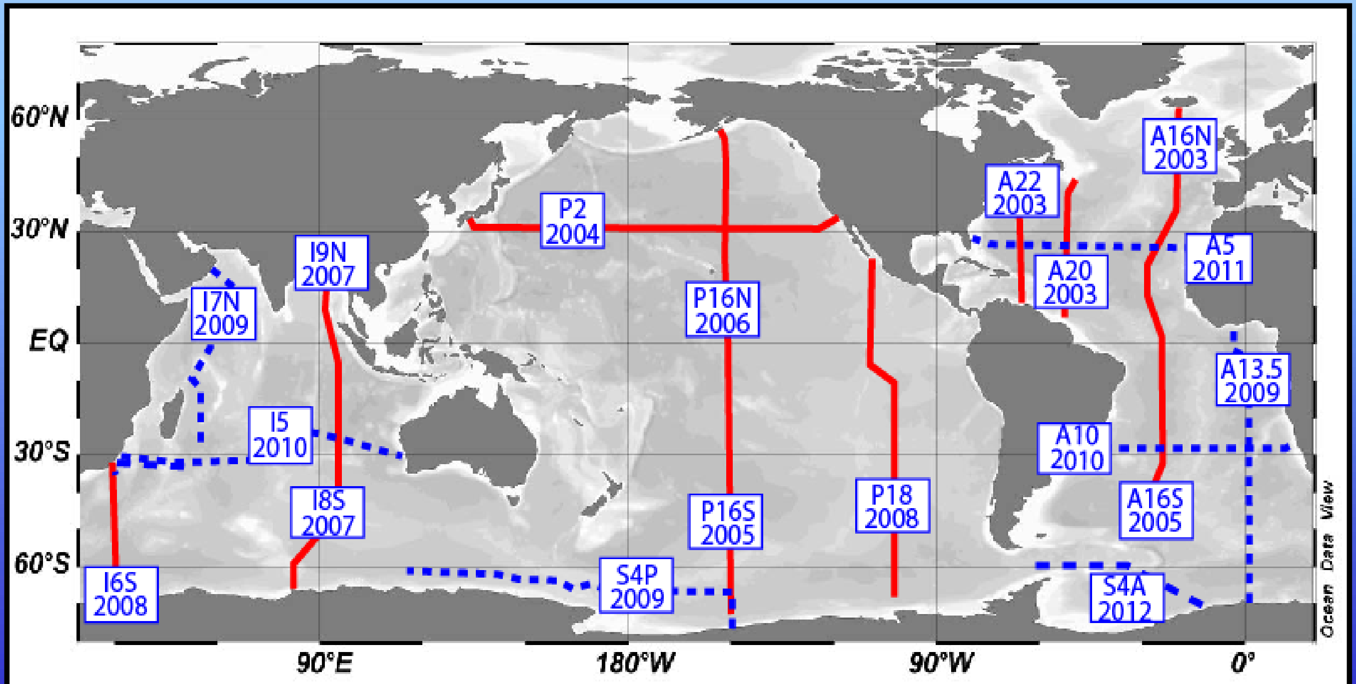
**Goal:** To quantify decadal changes in the inventory and transport of heat, fresh water, carbon dioxide ($CO_2$), chlorofluorocarbon tracers and related parameters in the oceans.

**Approach:** The sequence and timing of the CLIVAR/$CO_2$ Repeat Hydrography cruises have been selected so that there is roughly a decade between them and the WOCE/JGOFS global survey.

**Achievements:** The U.S. CLIVAR/$CO_2$ Repeat Hydrography Program has completed 11 of 18 lines and is on schedule to complete global survey by 2012.

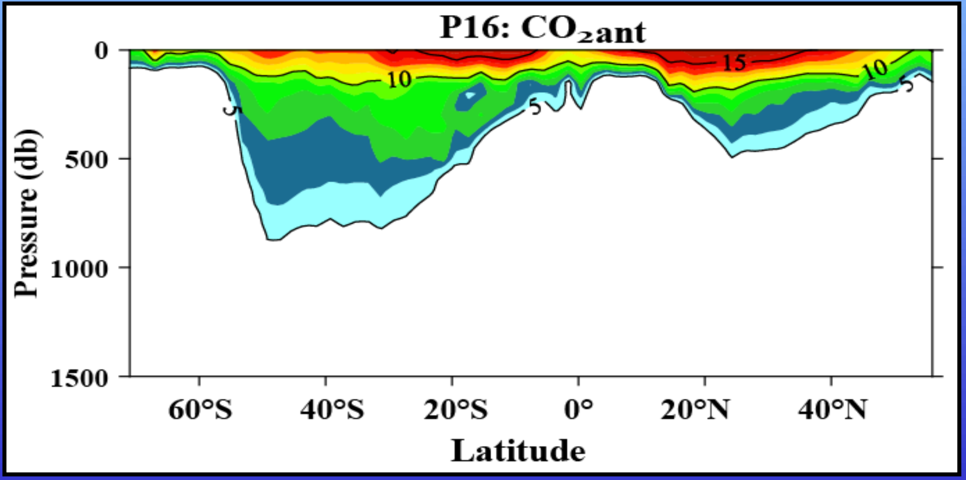
Global map of planned CLIVAR/$CO_2$ Repeat Hydrography Program hydrographic sections

http://ushydro.ucsd.edu/

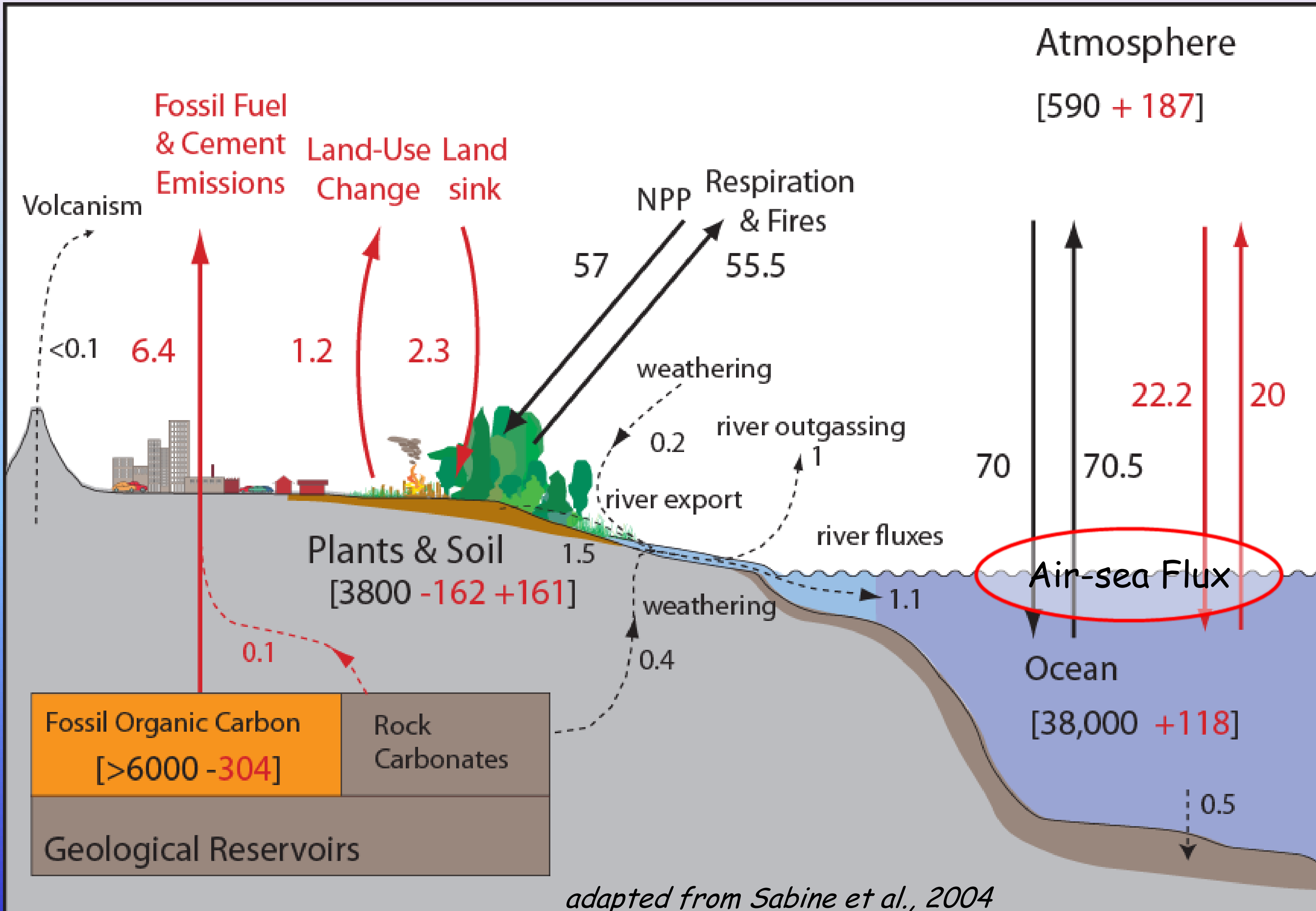


# CLIVAR/$CO_2$ Repeat Hydrography Interim Results

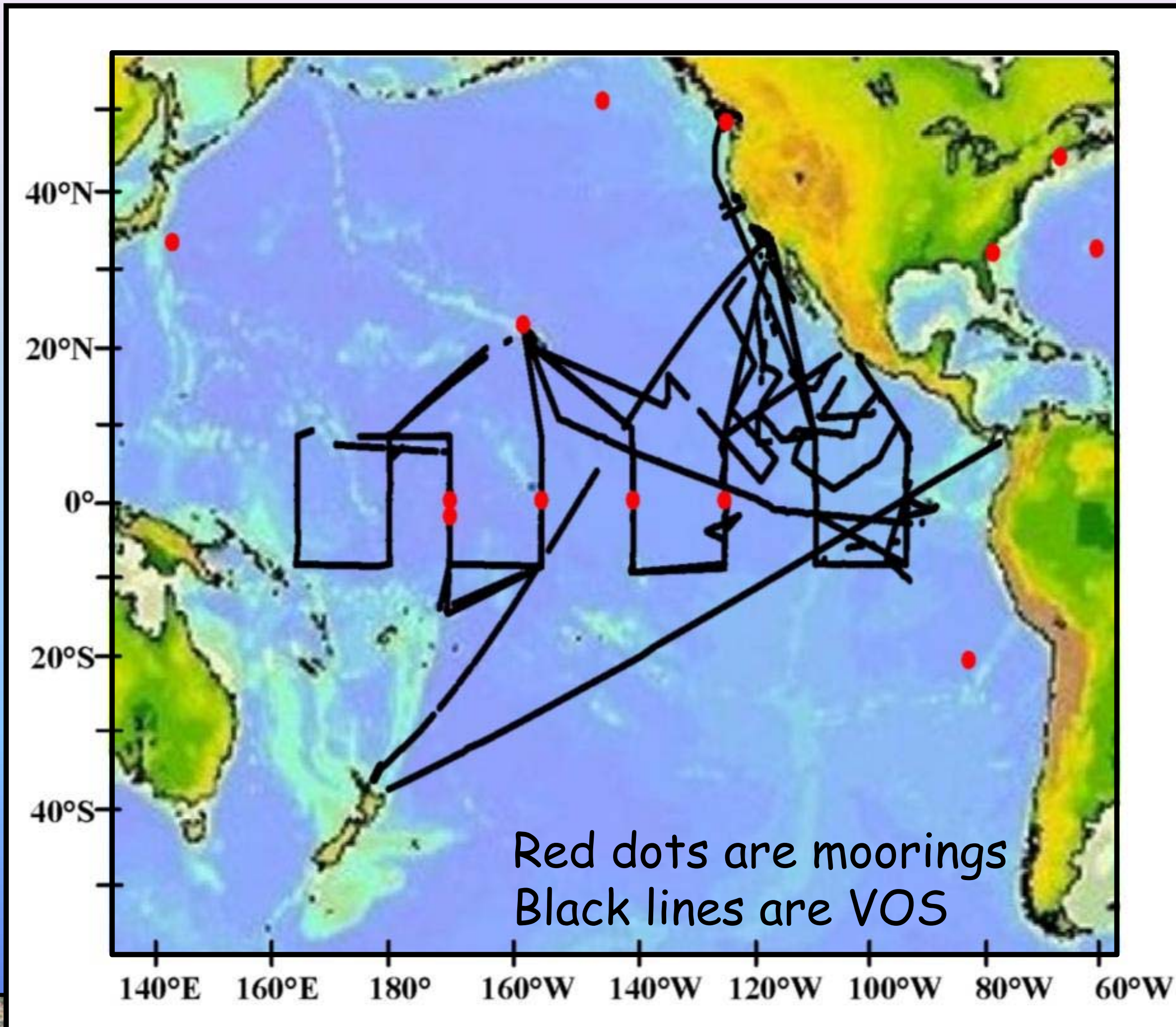
- Global Survey is 60% complete with all measurements meeting or exceeding anticipated quality requirements.
- Meridional sections in the Atlantic, Pacific and Indian oceans show that there are significant and measureable inorganic carbon changes in all three ocean basins over the last decade.
- We are working to improve our tools for isolating the anthropogenic component of the decadal carbon changes, including working with modelers to compare and interpret results.
- Diagnosis of the changes suggests that variations in ocean circulation can have an important, and sometimes dominant, impact on the observed regional carbon distributions.
- Preliminary analyses suggest that the regional anthropogenic carbon inventory changes over the last decade may have a different pattern from the long-term carbon storage distributions.



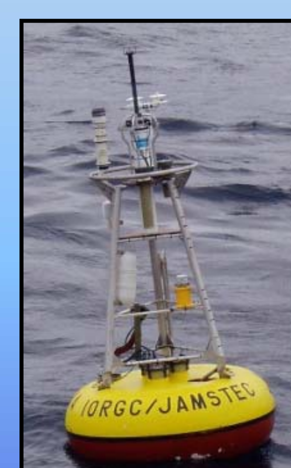
# Global Carbon Budget for 1990s published in the Nov. 2007 First State of the Carbon Cycle Report (SOCCR)



# PMEL surface $CO_2$ observation network








# In the early 1990s surface $CO_2$ measurements capture the influence of El Niño on equatorial $CO_2$ fluxes

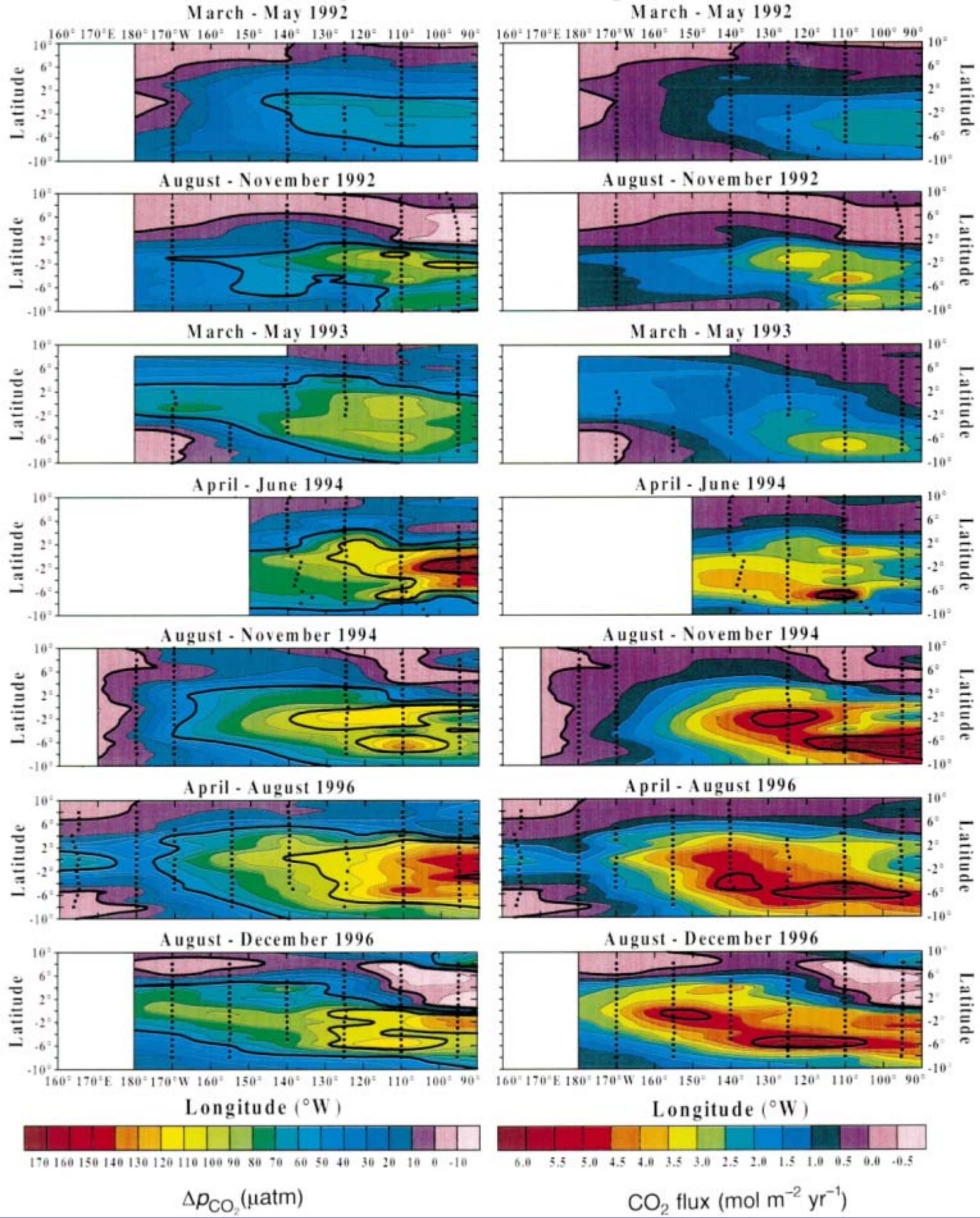
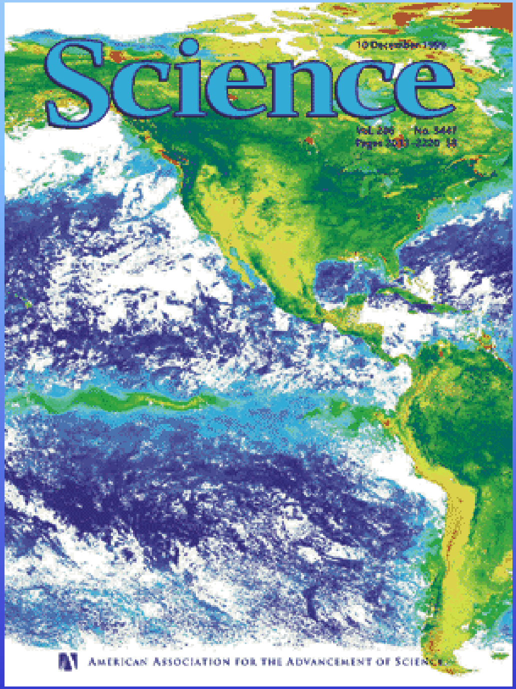


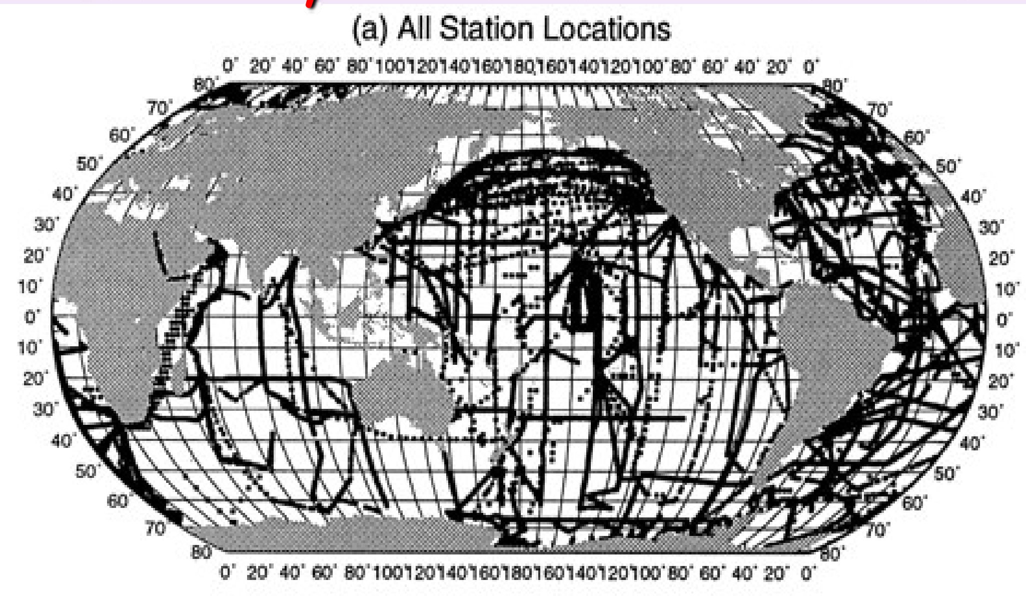

Figure from Feely et al., Nature, 1999

1992: Instrument placed on the ship that services the TAO array captured the low fluxes of the 1992 El Niño and was in place for the 1998 El Niño.

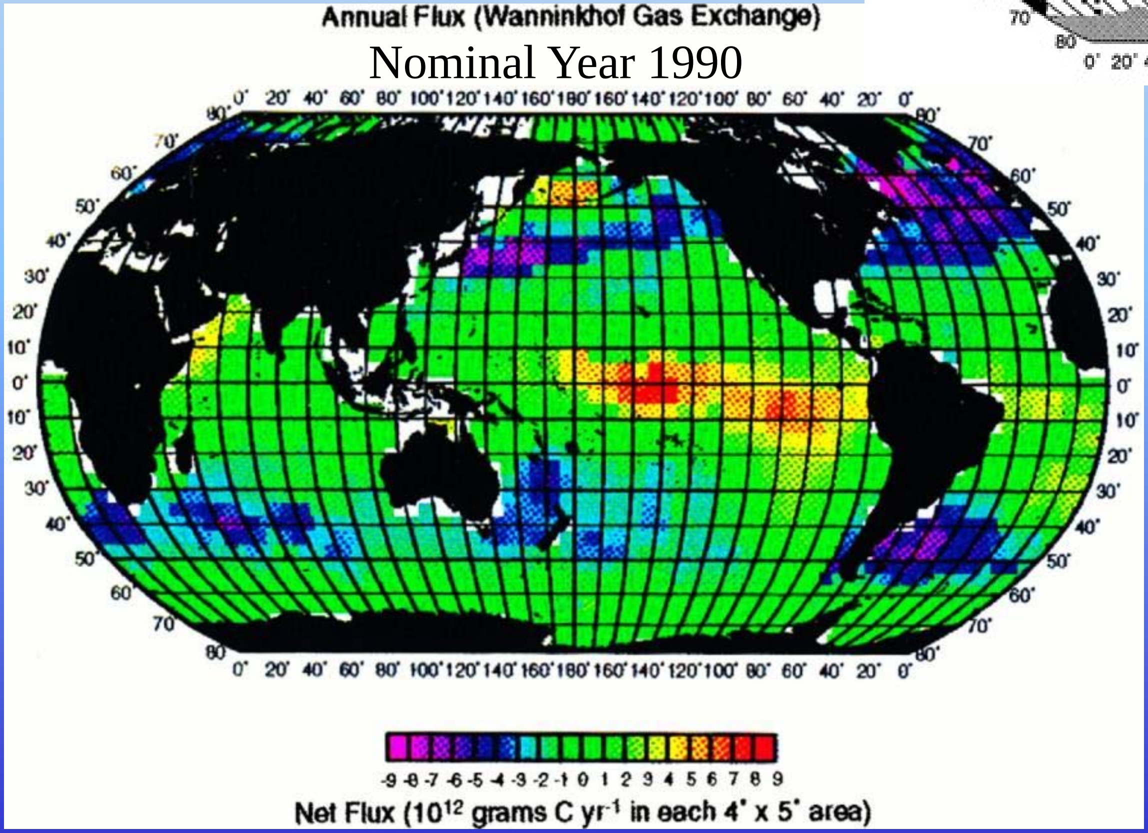
1998: Prototype moored $pCO_2$ systems developed by MBARI and placed on TAO moorings at 0, 155°W and 2°S, 170°W in collaboration with PMEL



# Mean annual net $CO_2$ flux estimated by Takahashi et al. 1997



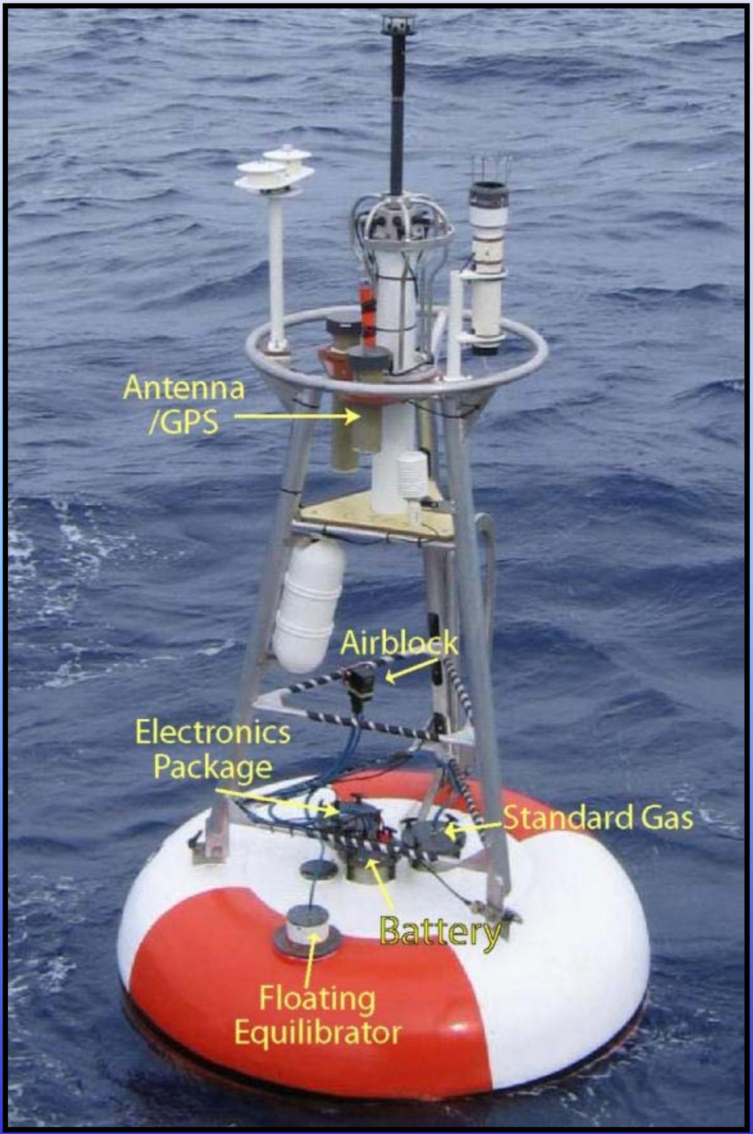

~ 250,000 measurements between 1960-1995




Net flux ranges from 0.6 to 1.34 Pg C $yr^{-1}$ with ~75% uncertainty

# 2003: MBARI transitions Moored Autonomous $pCO_2$ system to PMEL

After initial design modifications PMEL begins building moored $CO_2$ network




The Basics:

LiCor 820 NDIR detector to measure air and water $CO_2$

gas calibration traceable to WMO standards

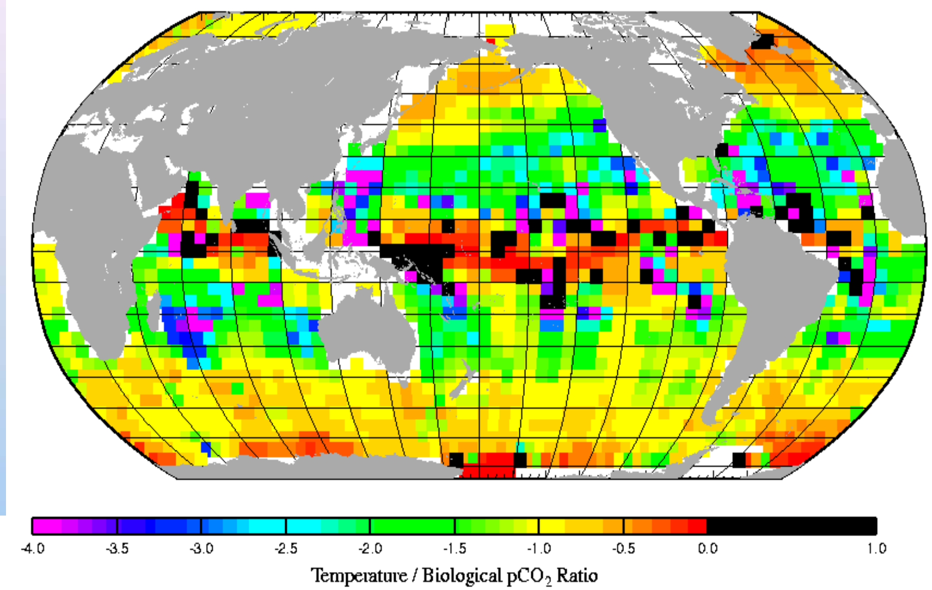
Self contained modular design to fit a range of buoys

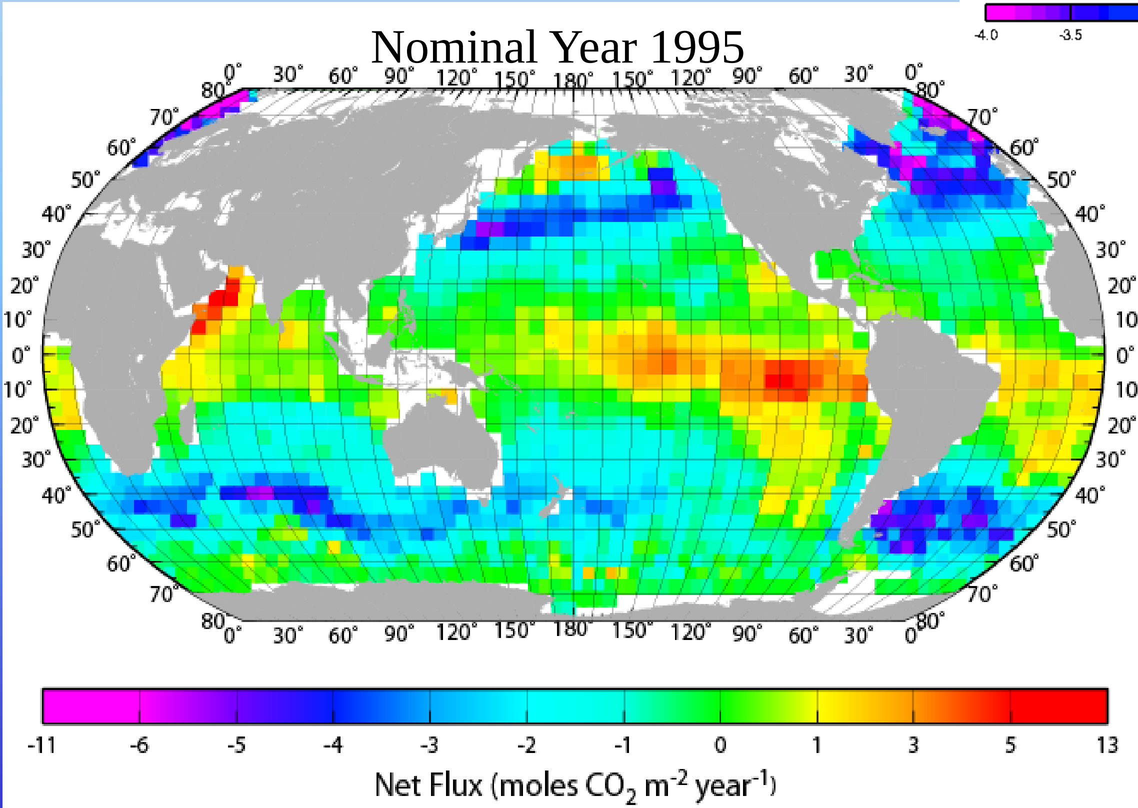
Daily satellite data transmission

# Annual net $CO_2$ flux estimated by Takahashi et al., DSR, 2002

~ 940,000 measurements between 1960-2000

Net flux ~2.2 (+22% or -19%) Pg C $yr^{-1}$ later this estimate was revised to 1.5 Pg C $yr^{-1}$ to correct an error in wind speed.




First global assessment of the relative biological and temperature controls on surface water $pCO_2$

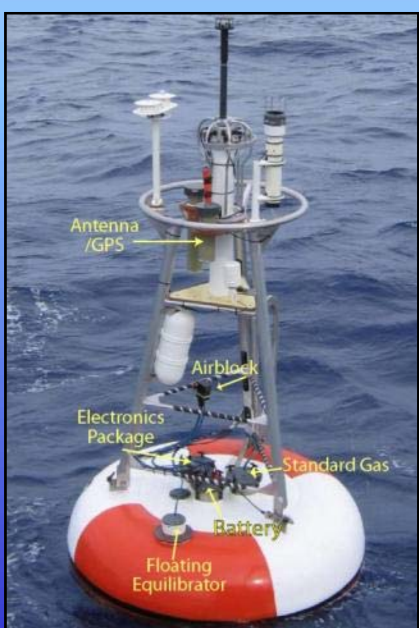
# Surface Ocean $pCO_2$ Measurement Project

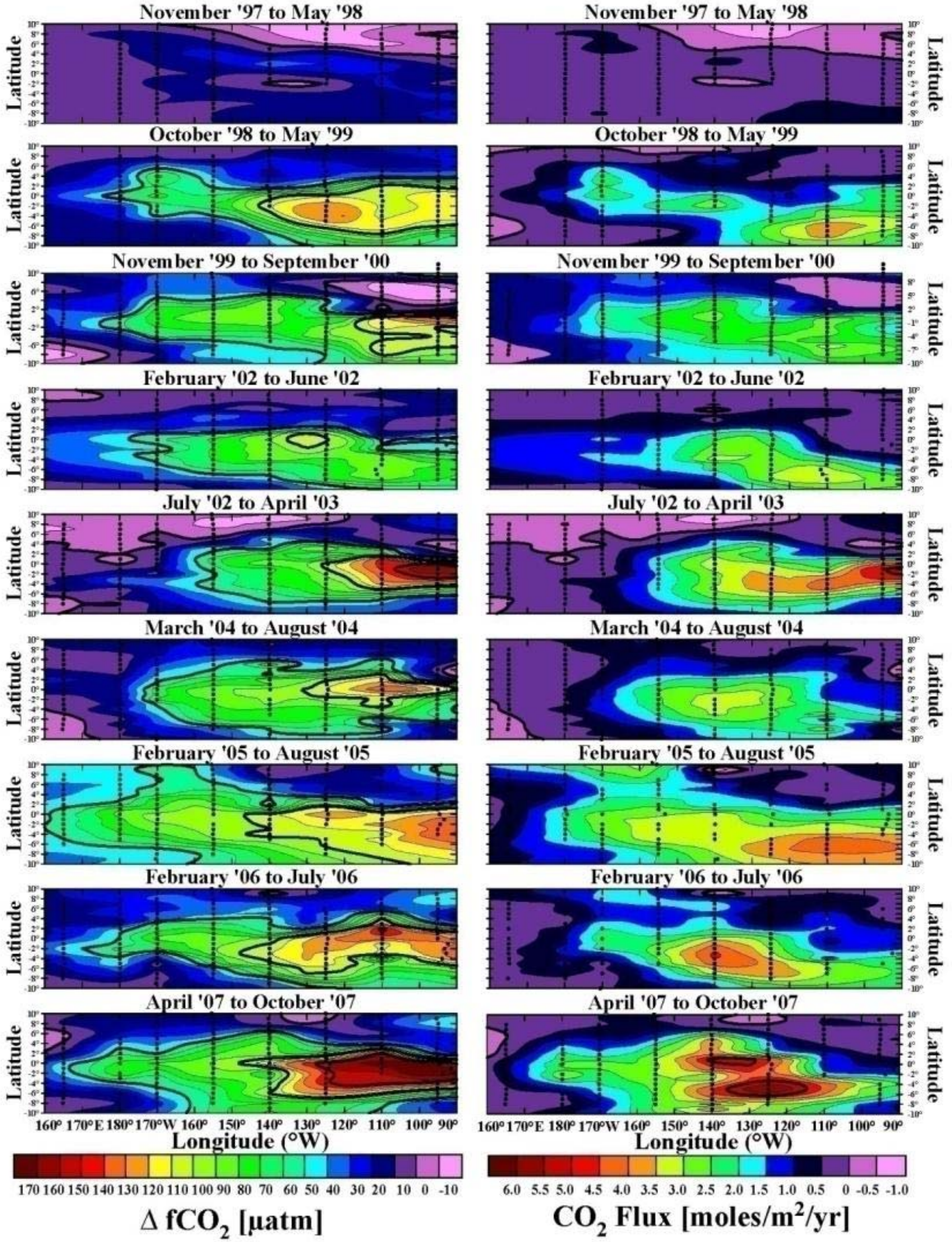
R. Wanninkhof, R. Feely, C. Sabine, T. Takahashi, S. Sutherland,
N. Bates, F. Chavez, S. Cooke, F. Millero and S. Maenner

**Goal:** To quantify the daily to interannual variability in air-sea $CO_2$ fluxes and understand the mechanisms controlling these fluxes.

**Approach:** Make autonomous surface $pCO_2$ measurements using research and volunteer observing ships (VOS) to get spatial coverage at seasonal time scales and using a network of surface moorings to get high frequency temporal resolution.

**Achievements:** The VOS program has outfitted 7 ships and has a full data exchange policy with 4 other ships. The moored $pCO_2$ program currently has 10 open ocean systems deployed.




# Large-Scale EqPac Results: 1997-2007

El Niño : 0.2-0.4 Pg C $yr^{-1}$

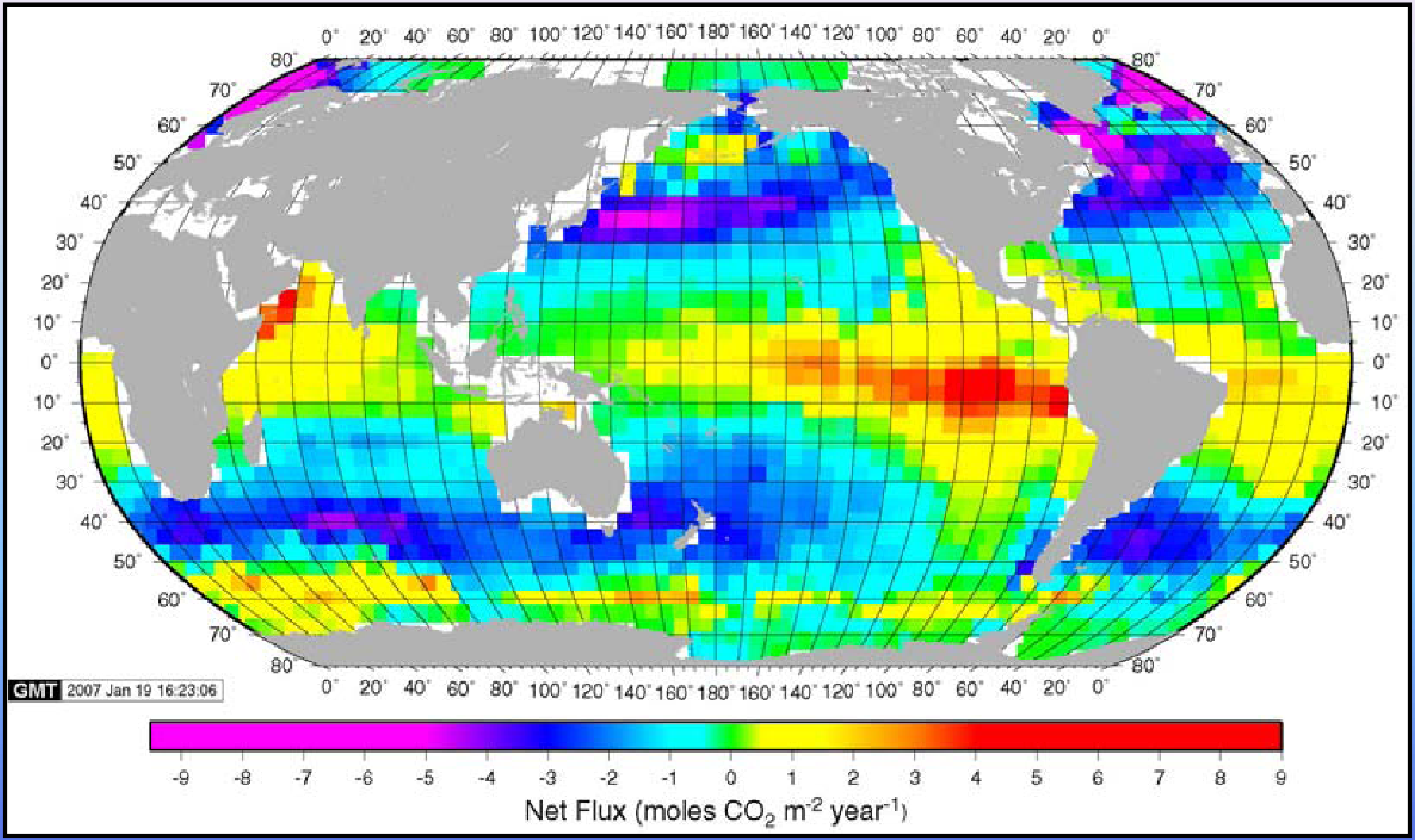
Non El Niño : 0.5-0.7 Pg C $yr^{-1}$

La Niña: 0.6-0.8 Pg C $yr^{-1}$

Average: 0.5 ± 0.2 Pg C $yr^{-1}$

Today we are working with a number of academic colleagues to instrument research and volunteer observing ships with underway $pCO_2$ systems

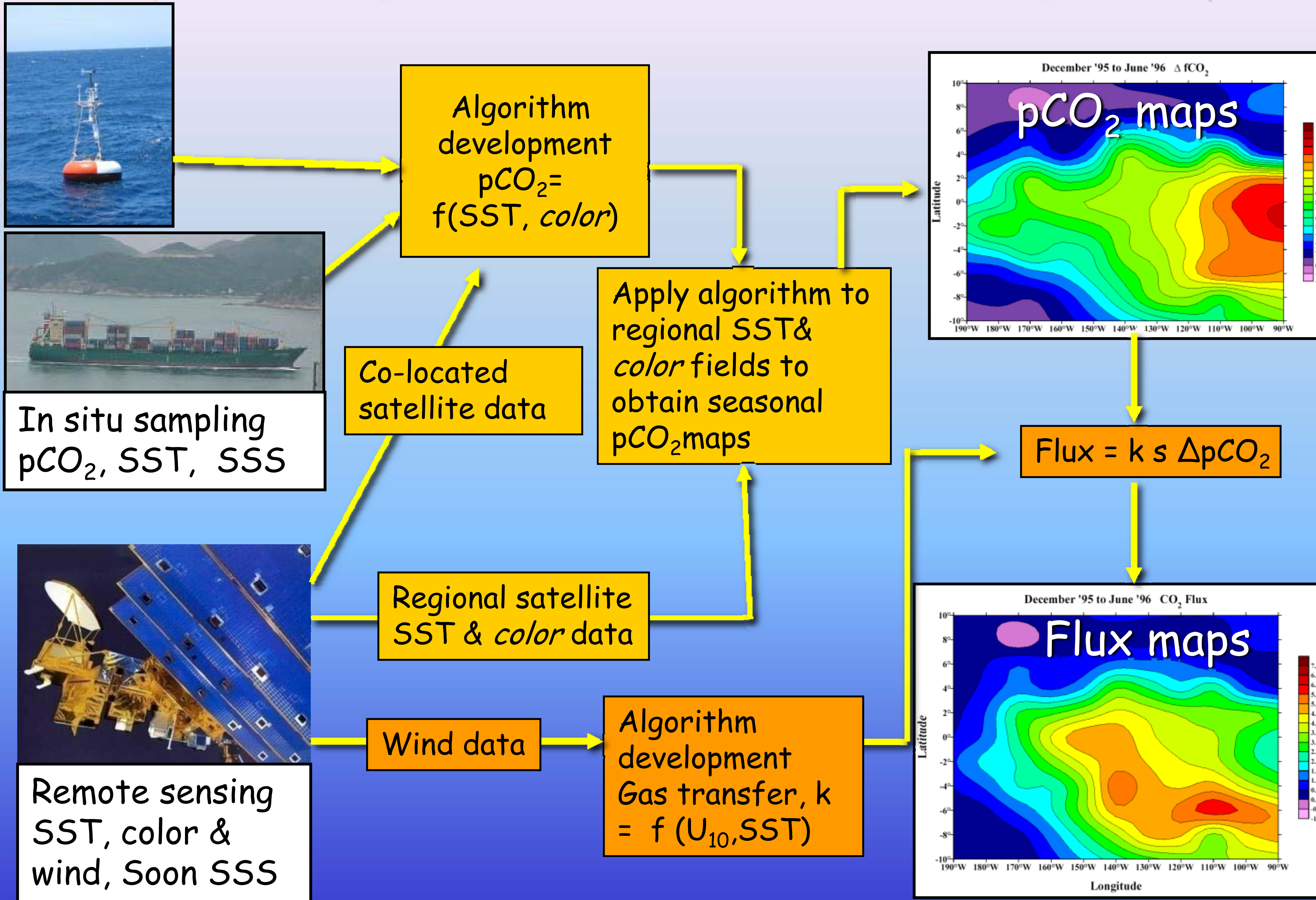
# Takahashi climatological annual mean air-sea $CO_2$ flux for reference year 2000



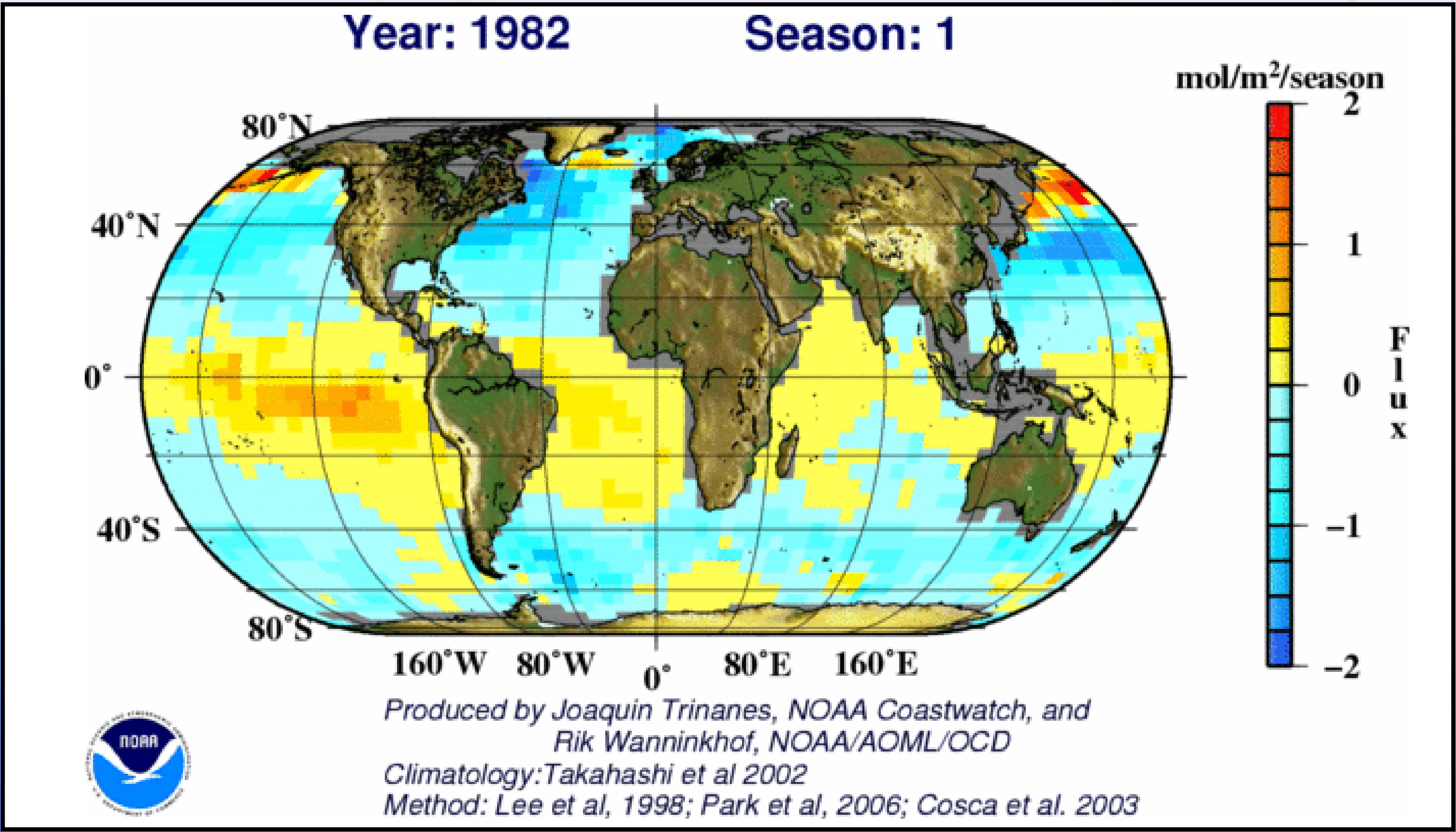

Based on 3 million measurements since 1970 and NCEP/DOE/AMIP II reanalysis winds.
Global flux is 1.4±0.7 Pg C/yr

*Takahashi et al., Deep Sea Res. II, in press*

# Concept: Use Multiple Platforms to Produce Seasonal $CO_2$ Flux Maps



# Global Flux Map suggests an interannual variability of 0.23 Pg C




Approach:
1. Improving regional relationships by incorporating additional parameters and observations as the network grows
2. Assessing uncertainty in flux maps using ship-based and moored $CO_2$ observations

# NOAA Ocean Carbon Cycle Program

NOAA Climate Strategic Plan Objective: Describe and Understand the State of the Climate System Through Observations, Analysis and Data Stewardship

Ocean Inventory:

10 yrs ago- making baseline measurements

5 yrs ago - first data-based global inventories

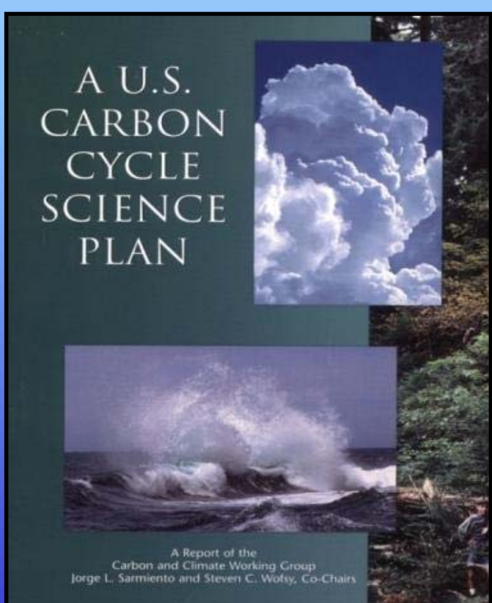
Today - looking at decadal inventory changes

Ocean Uptake:

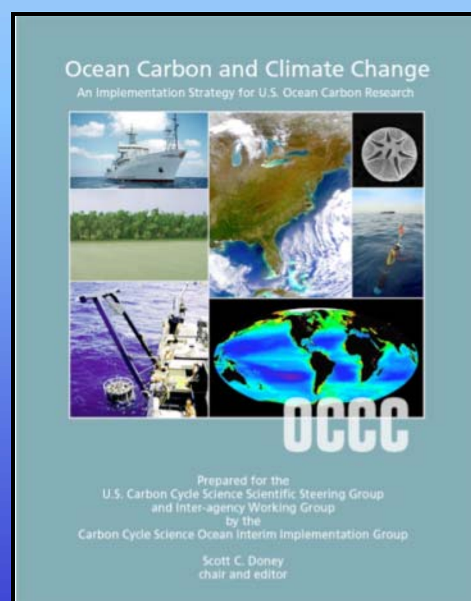
10 yrs ago - first ocean $CO_2$ flux climatology

5 yrs ago -T vs. Biological controls on global map

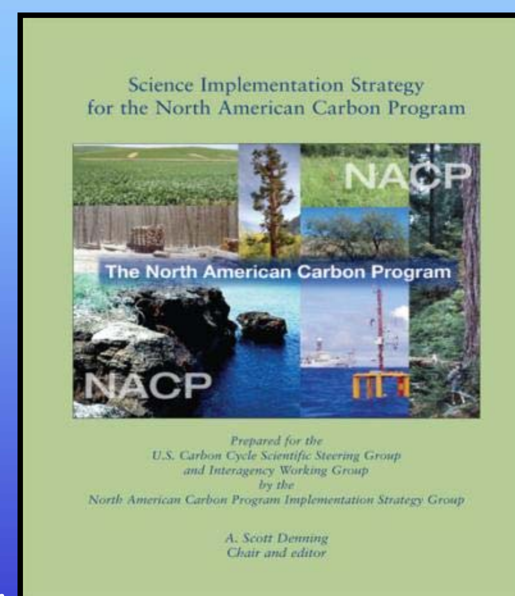
Today - looking at seasonal to interannual variability




1999




2004

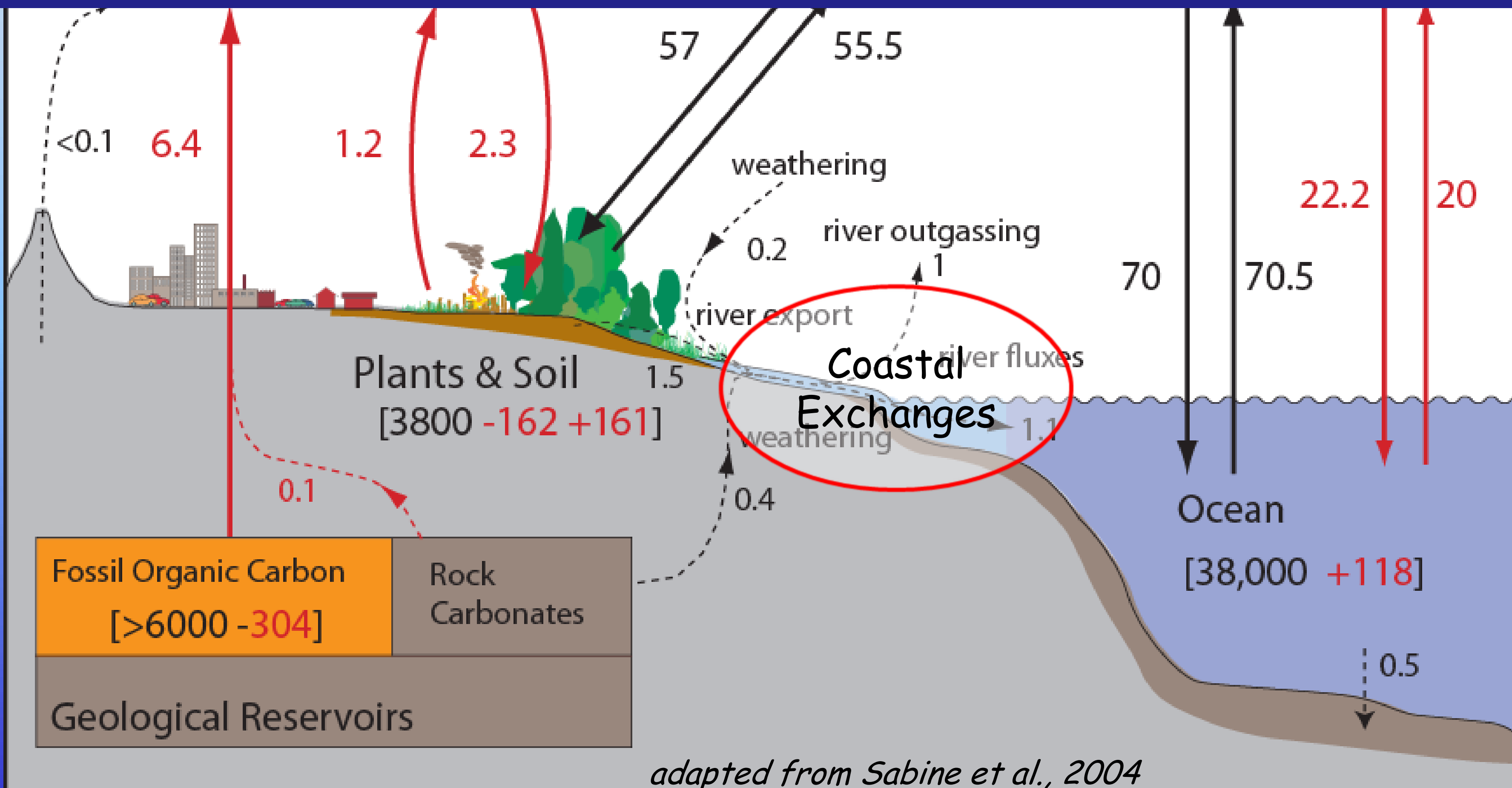



2005

# Global Carbon Budget for 1990s published in the Nov. 2007 First State of the Carbon Cycle Report (SOCCR)

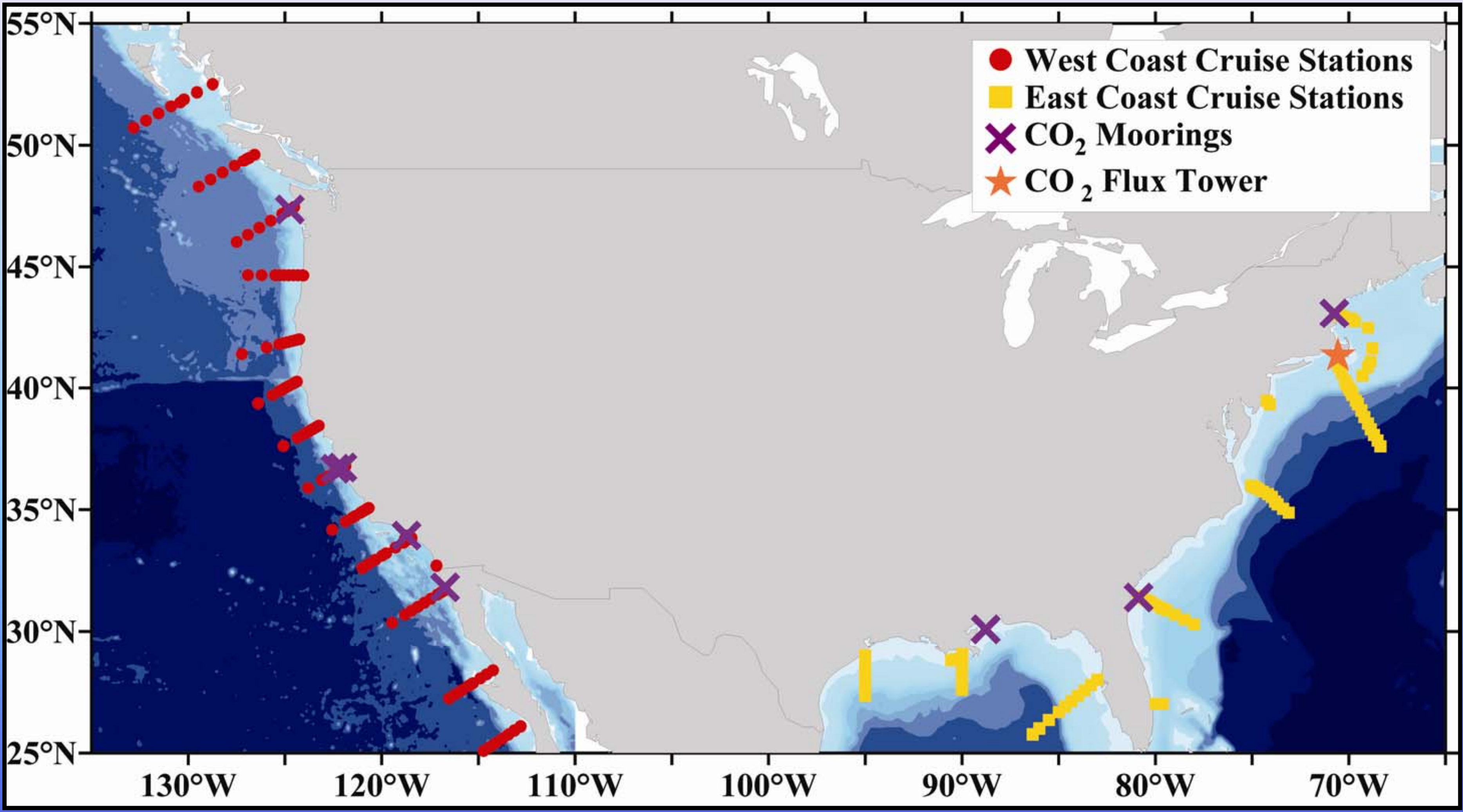
The carbon budget of ocean margins (coastal regions) are not well-characterized due to lack of observations coupled with complexity and highly localized geographic variability.

*2007 SOCCR, chapter 15 key findings*




*adapted from Sabine et al., 2004*

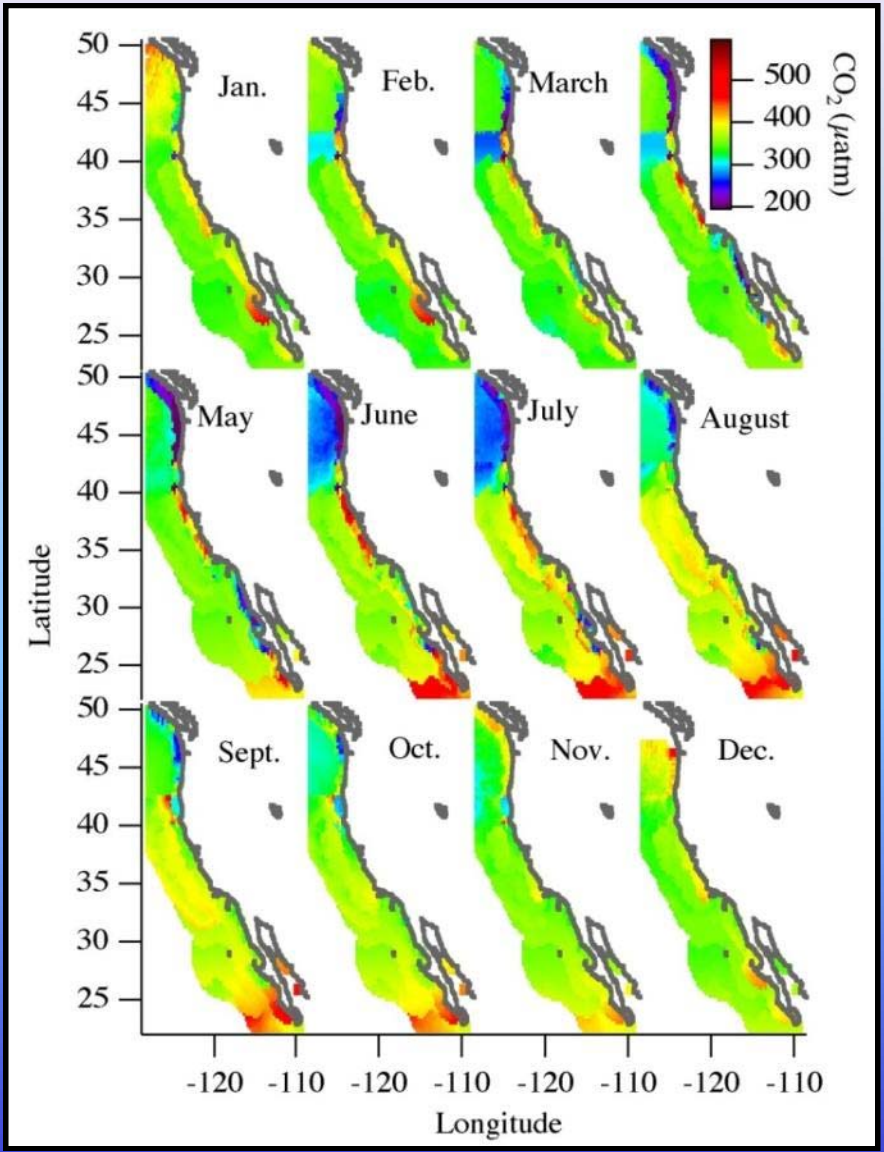
# New Directions: NOAA Coastal $CO_2$ Surveys, coastal $CO_2$ moorings, and underway $CO_2$ from coastal ships



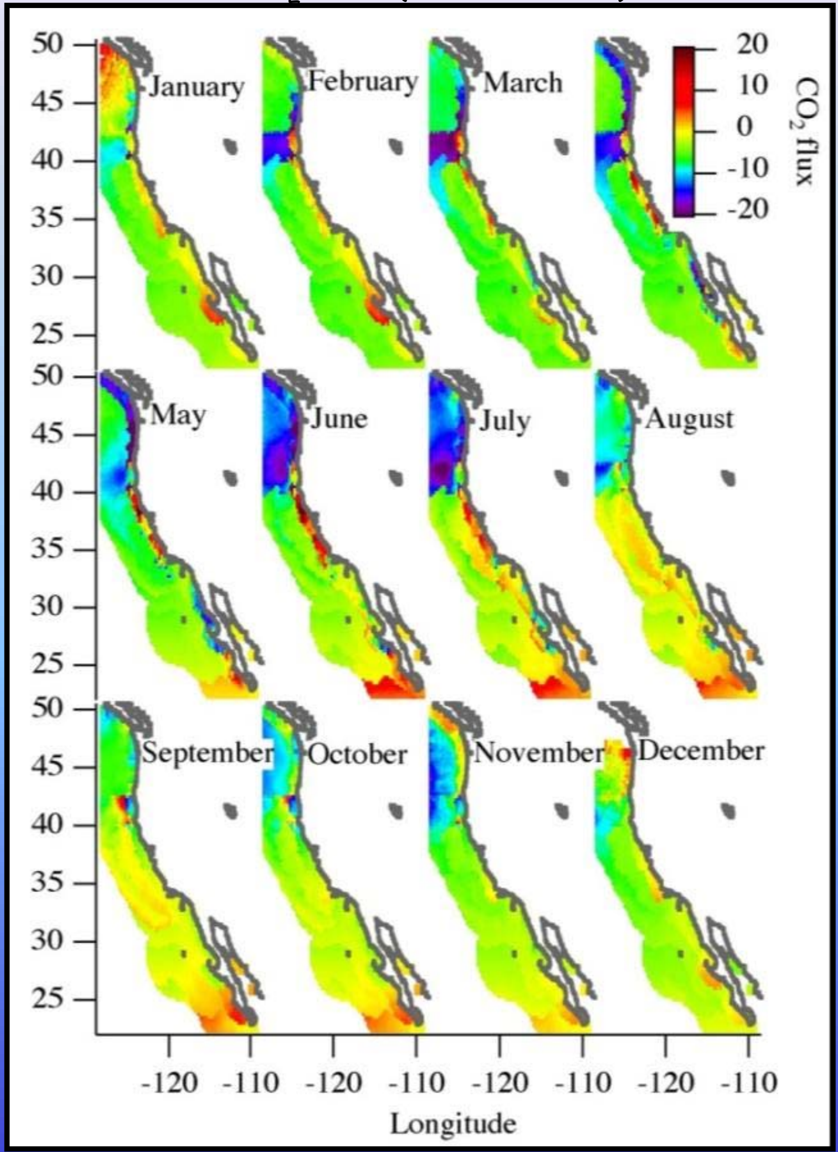

Goal: To gather large-scale coastal $CO_2$ data for the purpose of determining U.S. air-sea $CO_2$ fluxes

# Monthly climatological $pCO_2$ and flux maps for the West Coast

**$pCO_2$ (μatm)**

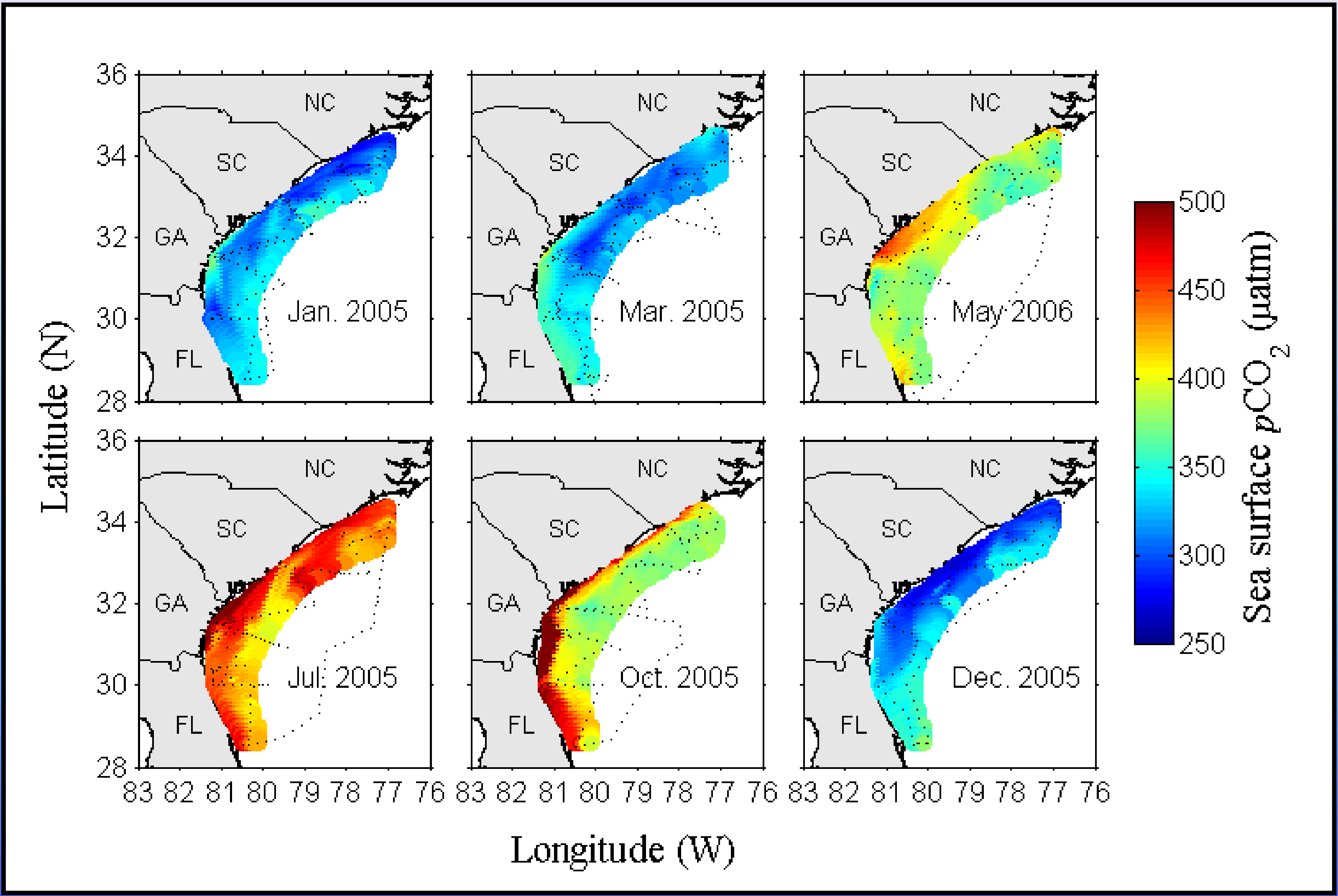



$CO_2$ flux (mmol $m^{-2}$ $d^{-1}$)




*Hales et al. (in prep.)*

# Bimonthly $pCO_2$ maps for the South Atlantic Bight




*Jiang et al. (2008)*

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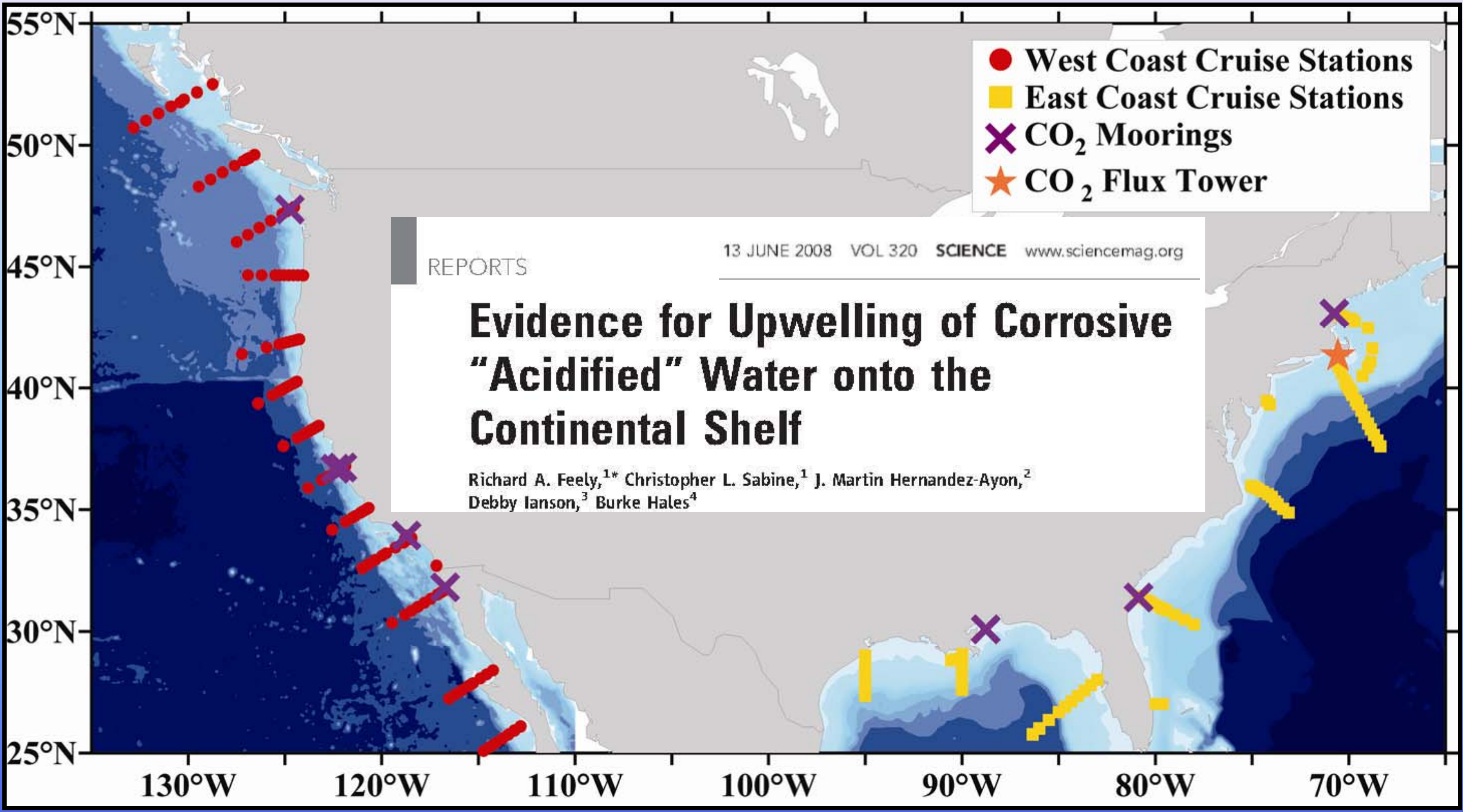



Goal: To gather large-scale coastal $CO_2$ data for the purpose of determining U.S. air-sea $CO_2$ fluxes

# Ocean Acidification

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.

- Decrease in pH 0.1 over the last two centuries
- 30% increase in acidity; decrease in carbonate ion of about 16%

Photo: Missouri Botanical Gardens

Corals

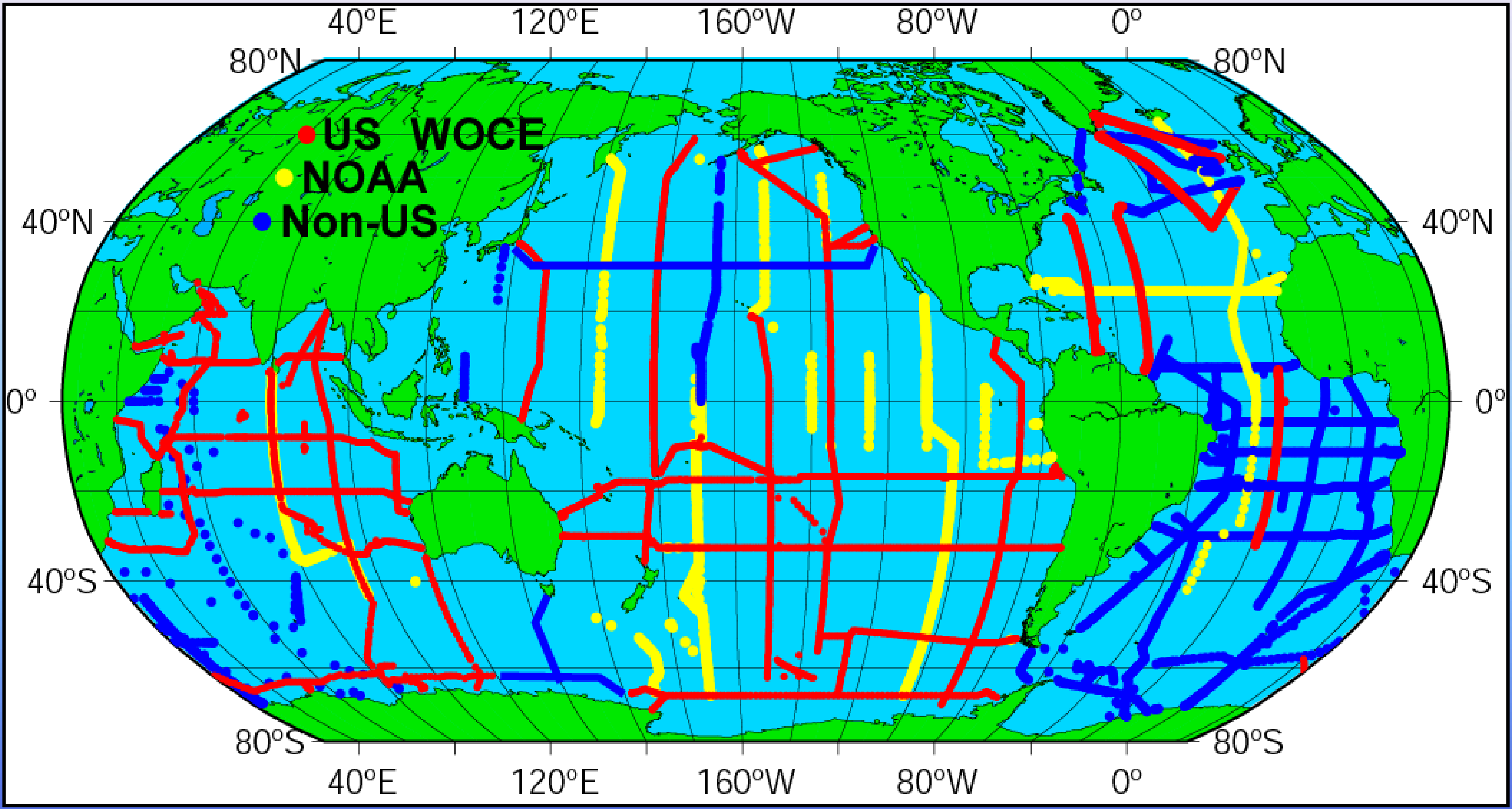

http://www.biol.tsukuba.ac.jp/~inouye

Calcareous Plankton

These changes in pH and carbonate chemistry may have serious impacts on open ocean and coastal marine ecosystems.

# 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

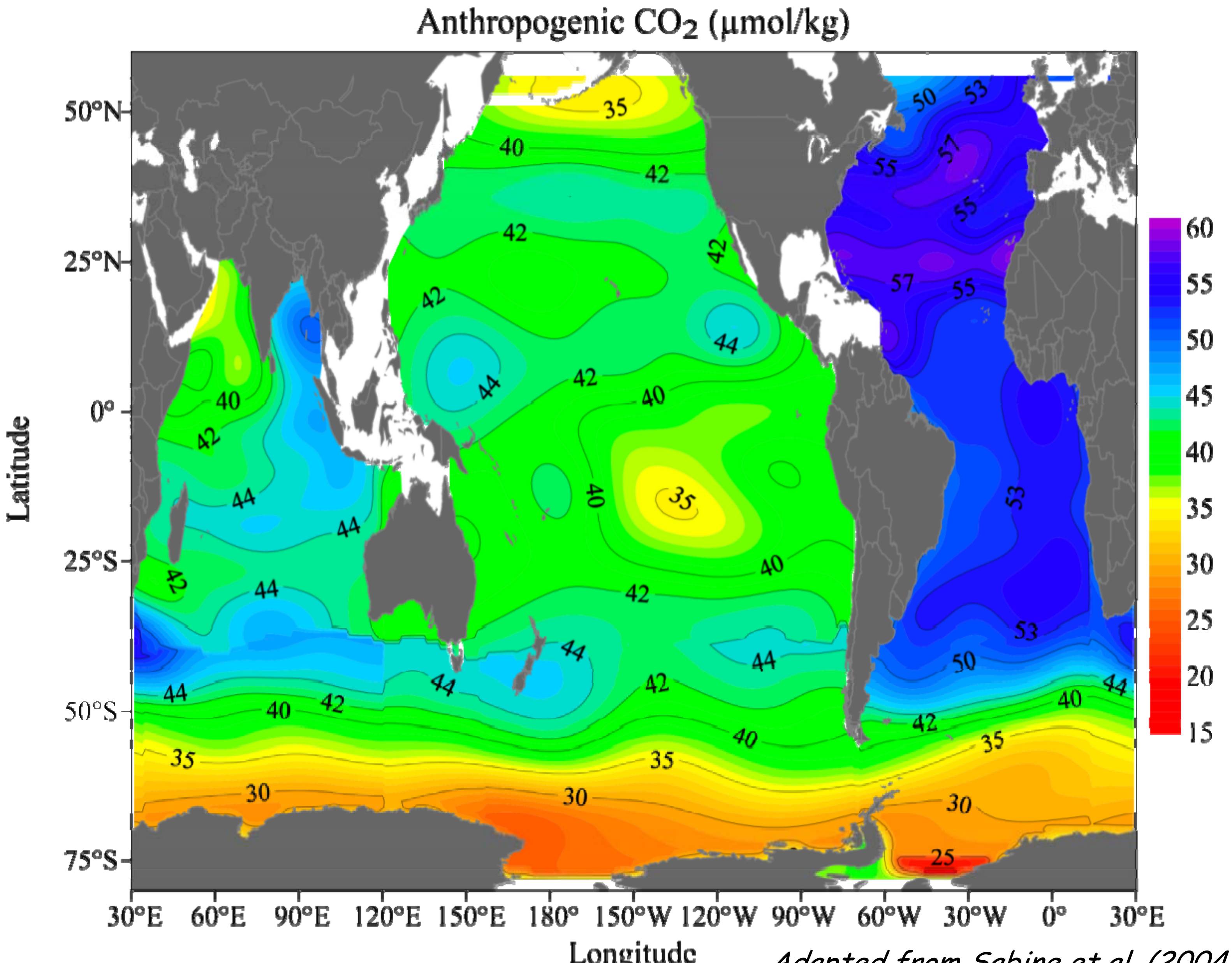
DIC ± 2 µmol $kg^{-1}$

TA ± 4 µmol $kg^{-1}$

*Sabine et al (2004)*

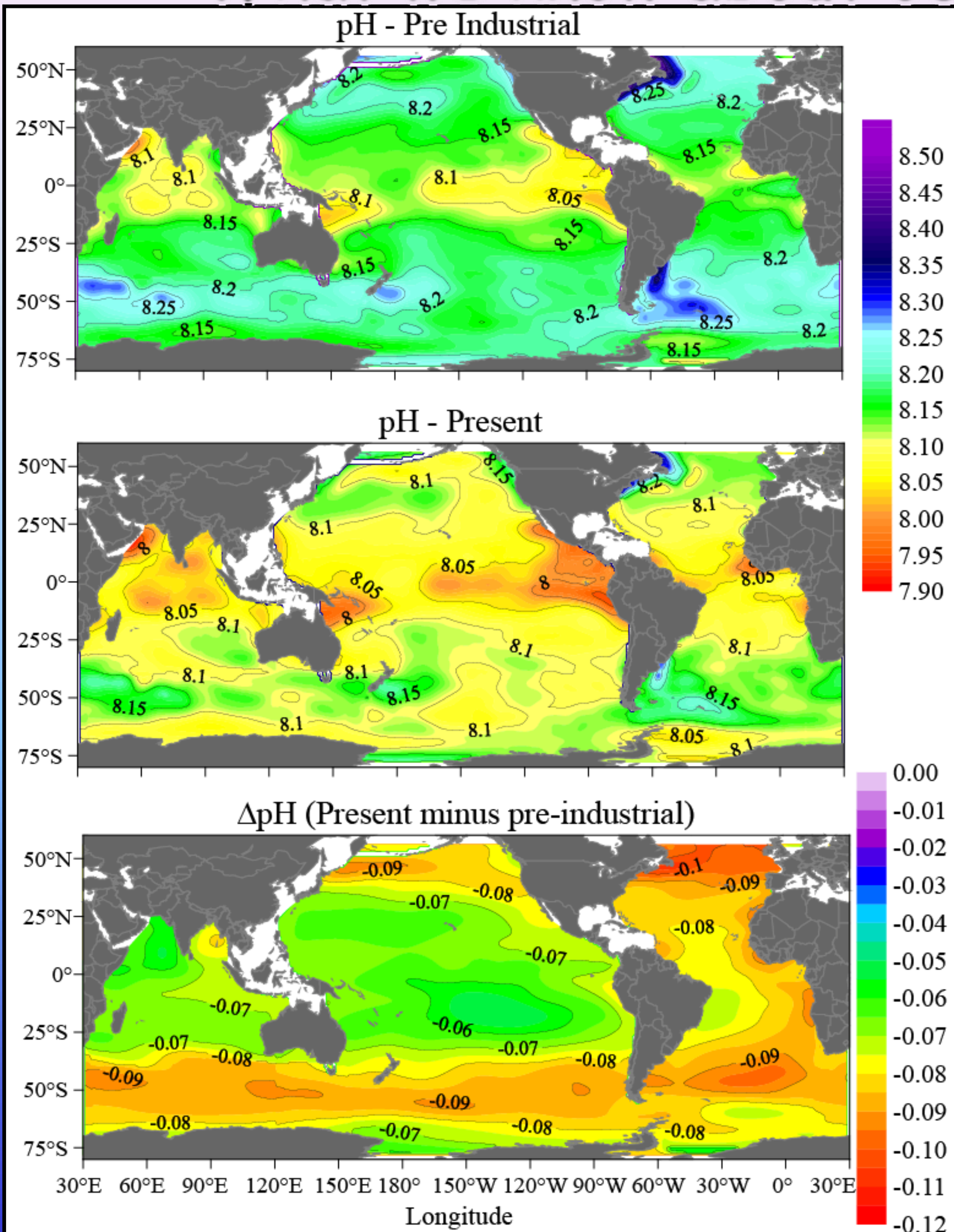
# What we know about ocean $CO_2$ chemistry

*…from present – preindustrial $CO_2$ concentrations in the surface oceans*




*Adapted from Sabine et al. (2004)*

# What we know about ocean $CO_2$ chemistry




*…from GLODAP data files*

Pre-industrial pH calculated from GLODAP residuals after Anthropogenic $CO_2$ values have been removed.

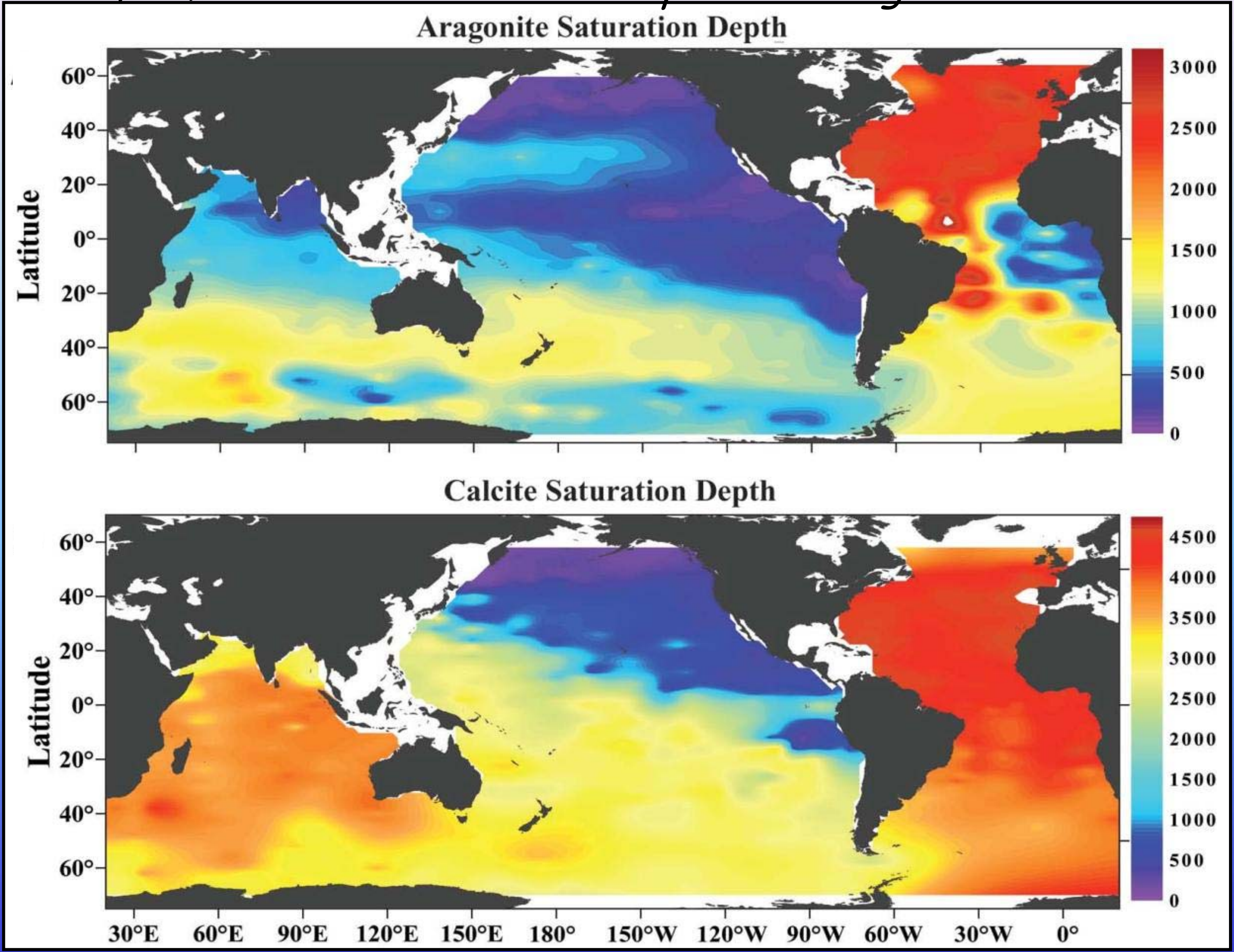
Present-day pH calculated from GLODAP DIC and TALK data.

pH difference (present – pre-industrial).

*Data from Key et al. (2004)*

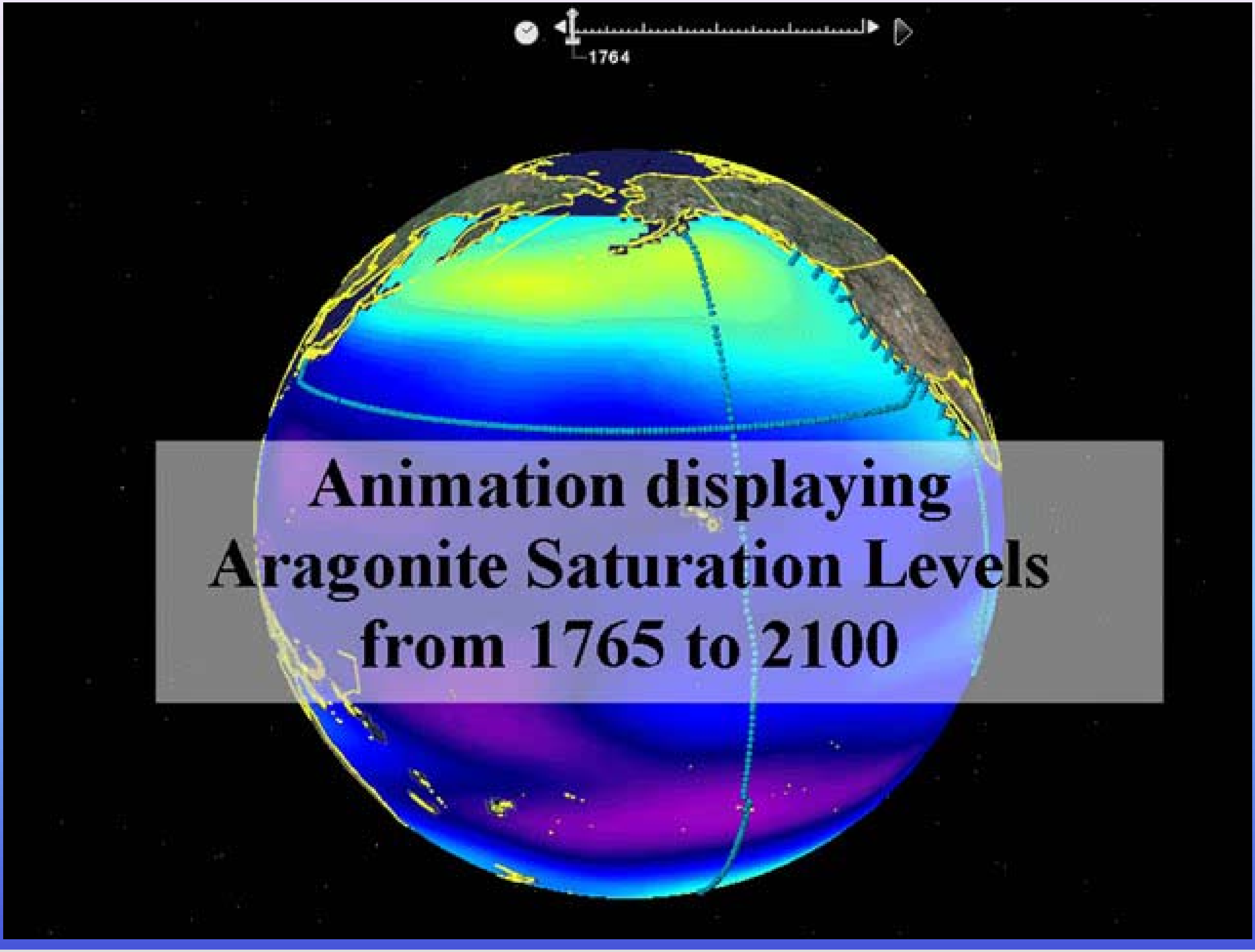
# What we know about ocean $CO_2$ chemistry

*…from observed saturation depths in the global oceans*




*Feely et al. (2004)*

# Predictions of Ocean Acidification in the Global Oceans

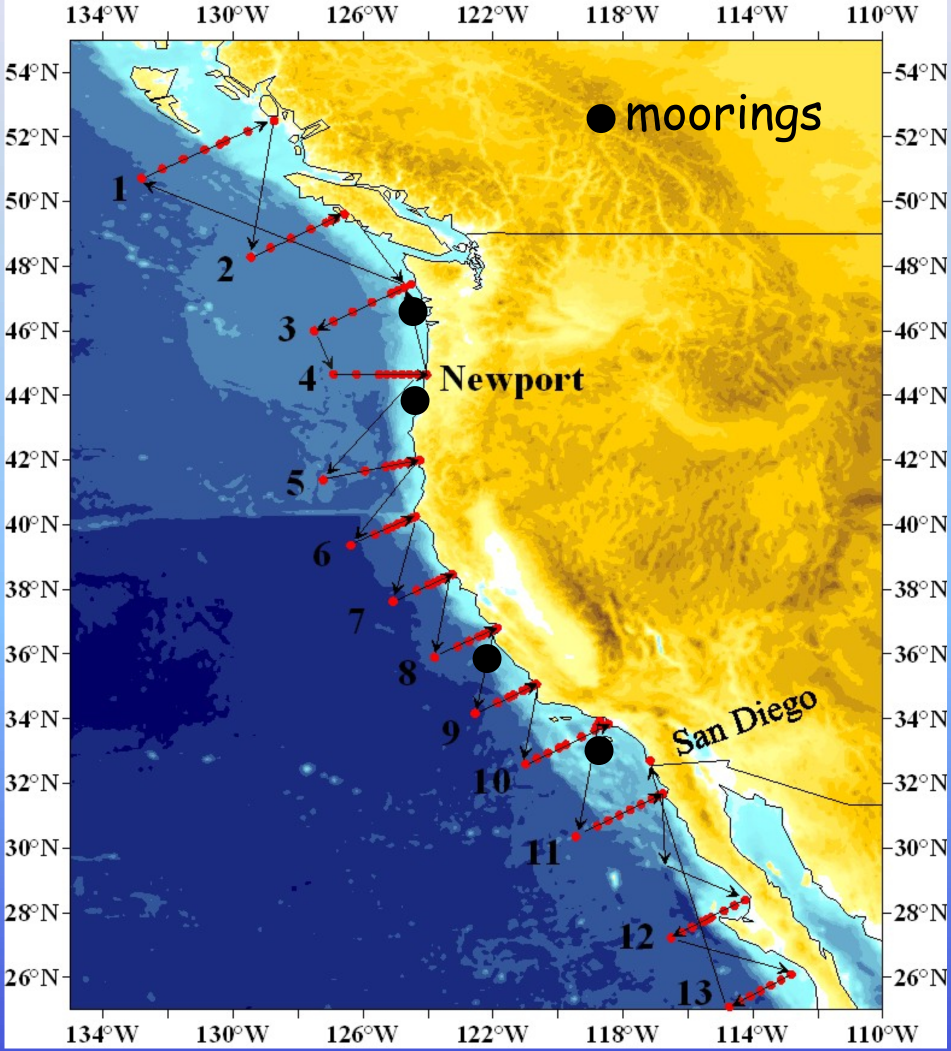



Calcification rates in the tropics may decrease by 30% over the next century

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

# North American Carbon Program

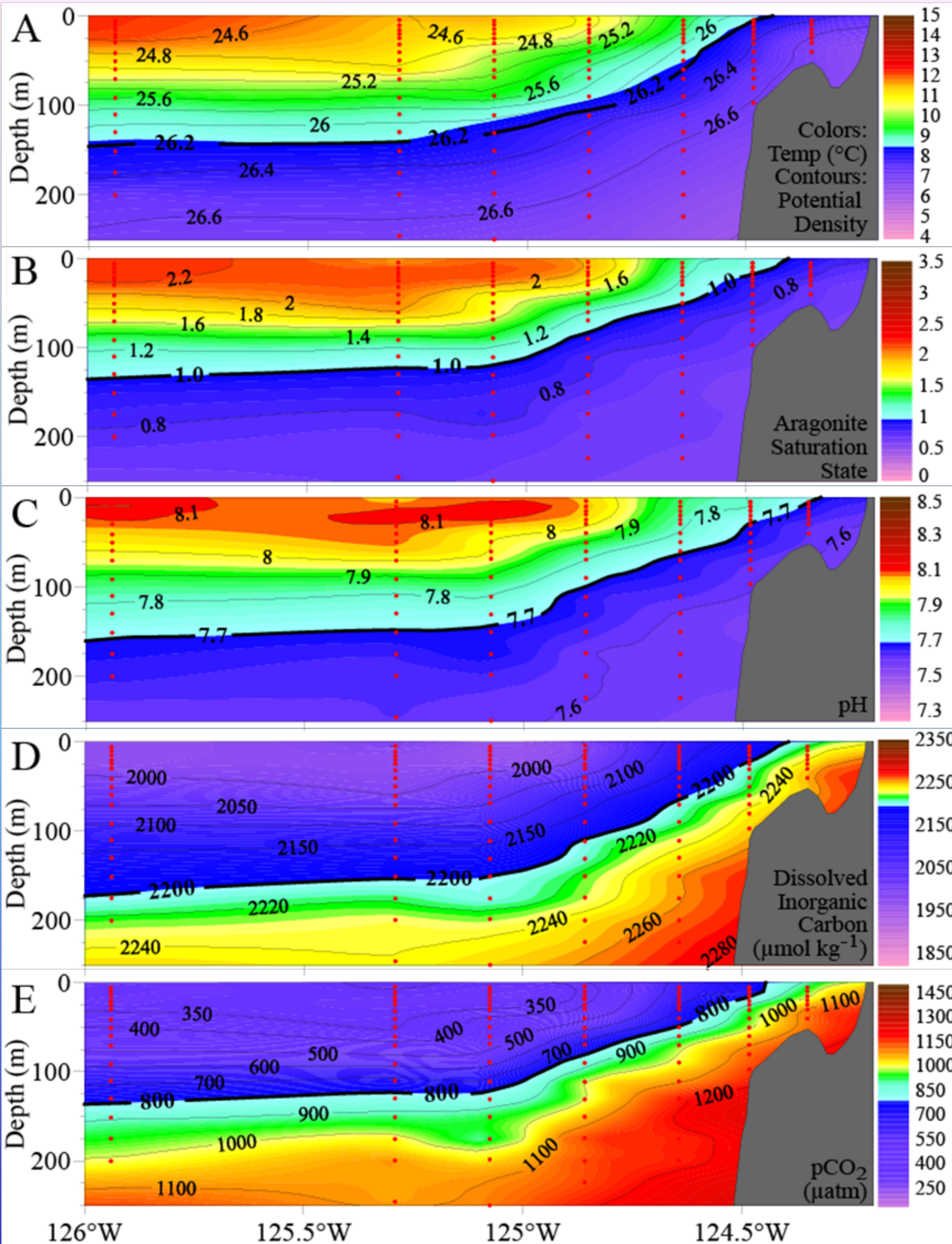
*Continental Carbon Budgets, Dynamics, Processes, and Management*


NACP West Coast Survey Cruise : 11 May - 14 June 2007
and mooring locations

*Feely et al. (2008)*

# Upwelling Induced Acidification of the Continental Shelf




Vertical sections from Line 5 (Pt. St. George, California)

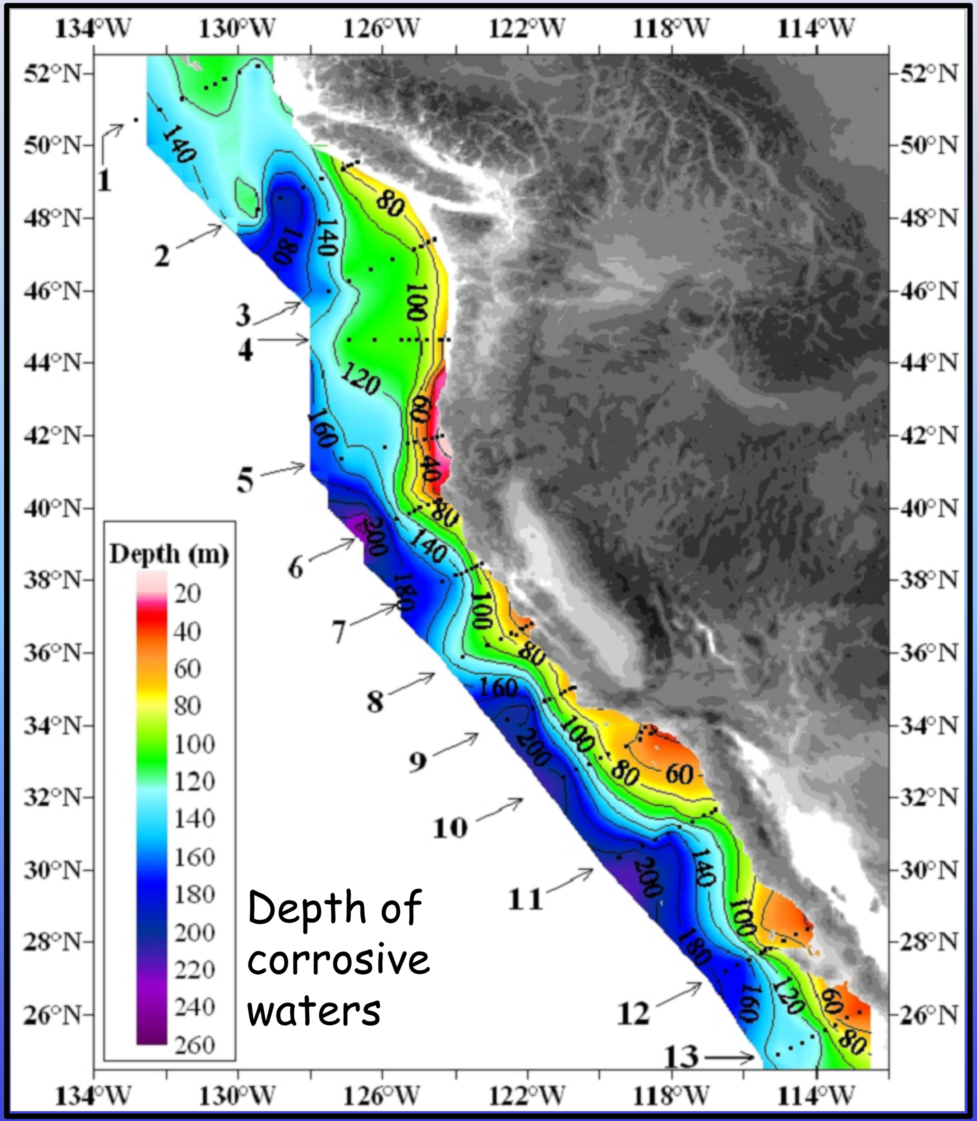
The 'ocean acidified' corrosive water was upwelled from depths of 150-200 m onto the shelf and outcropped at the surface near the coast.

*Red dots represent sample locations.*

*Feely et al. (2008)*

North American Carbon Program

Continental Carbon Budgets, Dynamics, Processes, and Management




*Feely et al. (2008)*

# Ocean Acidification of the North American Continental Shelf

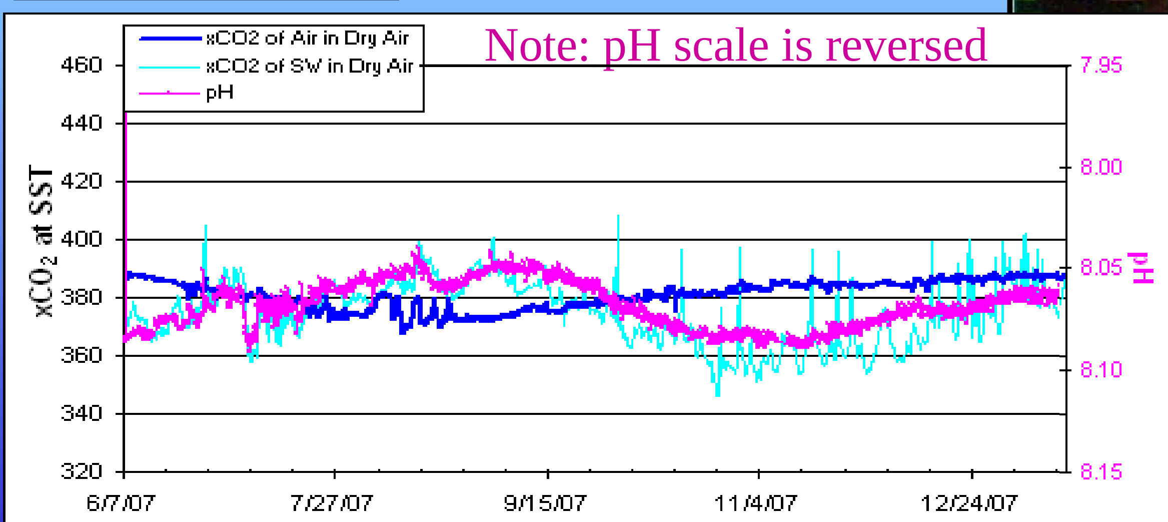
NACP Coastal Survey Cruise: 11 May - 14 June 2007

Distribution of the depths of the corrosive water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada to San Gregorio Baja California Sur, Mexico.

On transect lines 5 and 6 the corrosive water reaches all the way to the surface in the inshore waters near the coast.

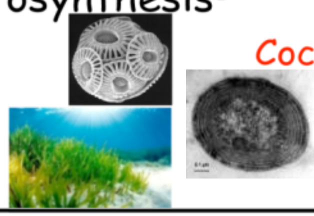
# First ocean acidification mooring in the Gulf of Alaska at Station Papa

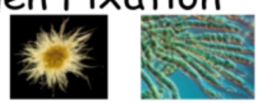
Preliminary results show a clear seasonal trend in pH and a strong correlation with $pCO_2$




# Scorecard of Biological Impacts of Ocean Acidification

| Physiological process | Major group | # species studied | Response to increasing $CO_2$ | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Calcification** | | | | | | |
| | Coccolithophores | 4 | 2 | 1 | 1 | 1 |
| | Planktonic Foraminifera | 2 | 2 | - | - | - |
| | Molluscs | 4 | 4 | - | - | - |
| | Echinoderms | 2 | 2 | - | - | - |
| | Tropical Corals | 11 | 11 | - | - | - |
| | Coralline Red Algae | 1 | 1 | - | - | - |
| **Photosynthesis**[1] | | | | | | |
| | Coccolithophores[2] | 2 | - | 2 | 2 | - |
| | Prokaryotes | 2 | - | 1 | 1 | - |
| | Seagrasses | 5 | - | 5 | - | - |
| **Nitrogen Fixation** | | | | | | |
| | Cyanobacteria | 1 | - | 1 | - | - |
| **Reproduction** | | | | | | |
| | Molluscs | 4 | 4 | - | - | - |
| | Echinoderms | 1 | 1 | - | - | - |





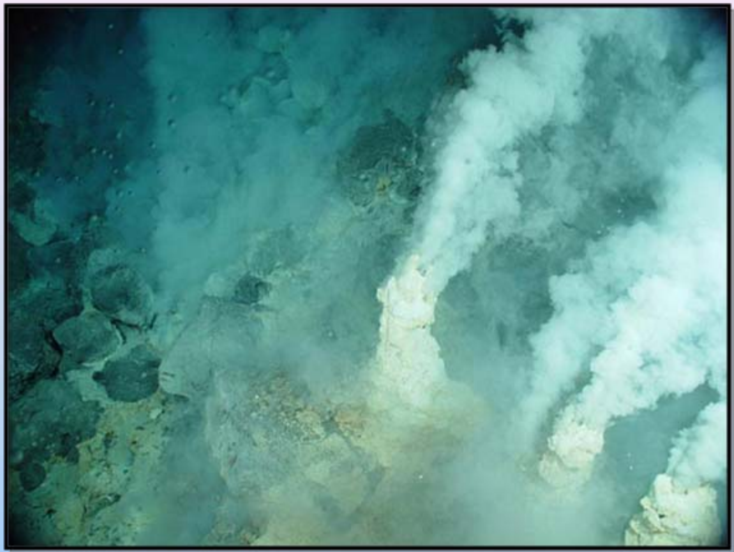
1) Strong interactive effects with nutrient and trace metals availability, light, and temperature
2) Under nutrient replete conditions

Figure from Doney et al. (2009)

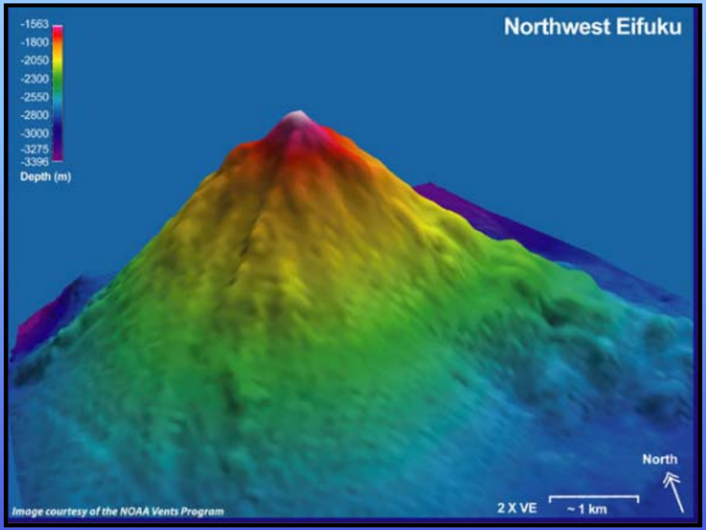
# NW Eifuku:
# A unique $CO_2$ laboratory

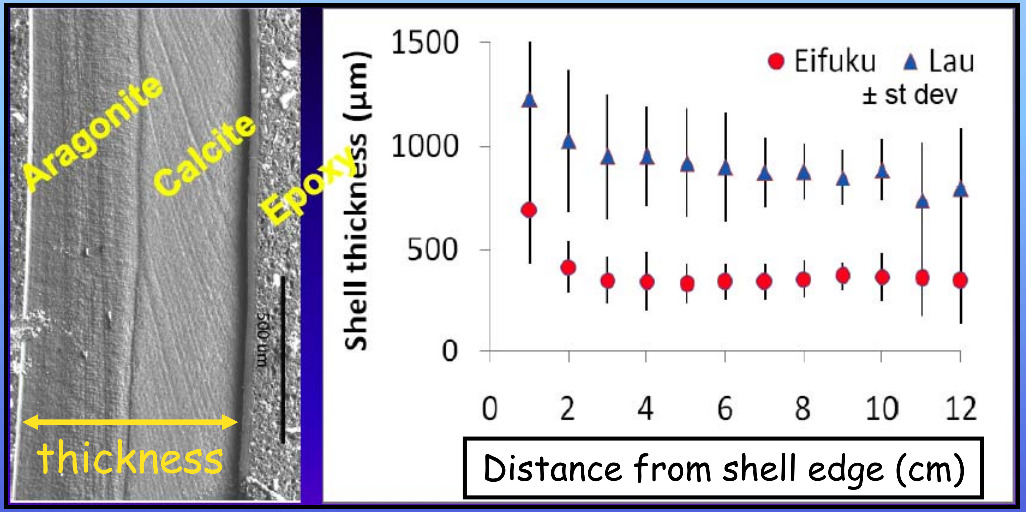
• One of only two sites in the ocean, and the only submarine volcano, known to be venting liquid $CO_2$ and forming natural $CO_2$ clathrates.

• A ideal natural laboratory for studying <u>the effects of ocean acidification</u> in the marine environment.



Supercritcial $CO_2$ and $CO_2$ droplets



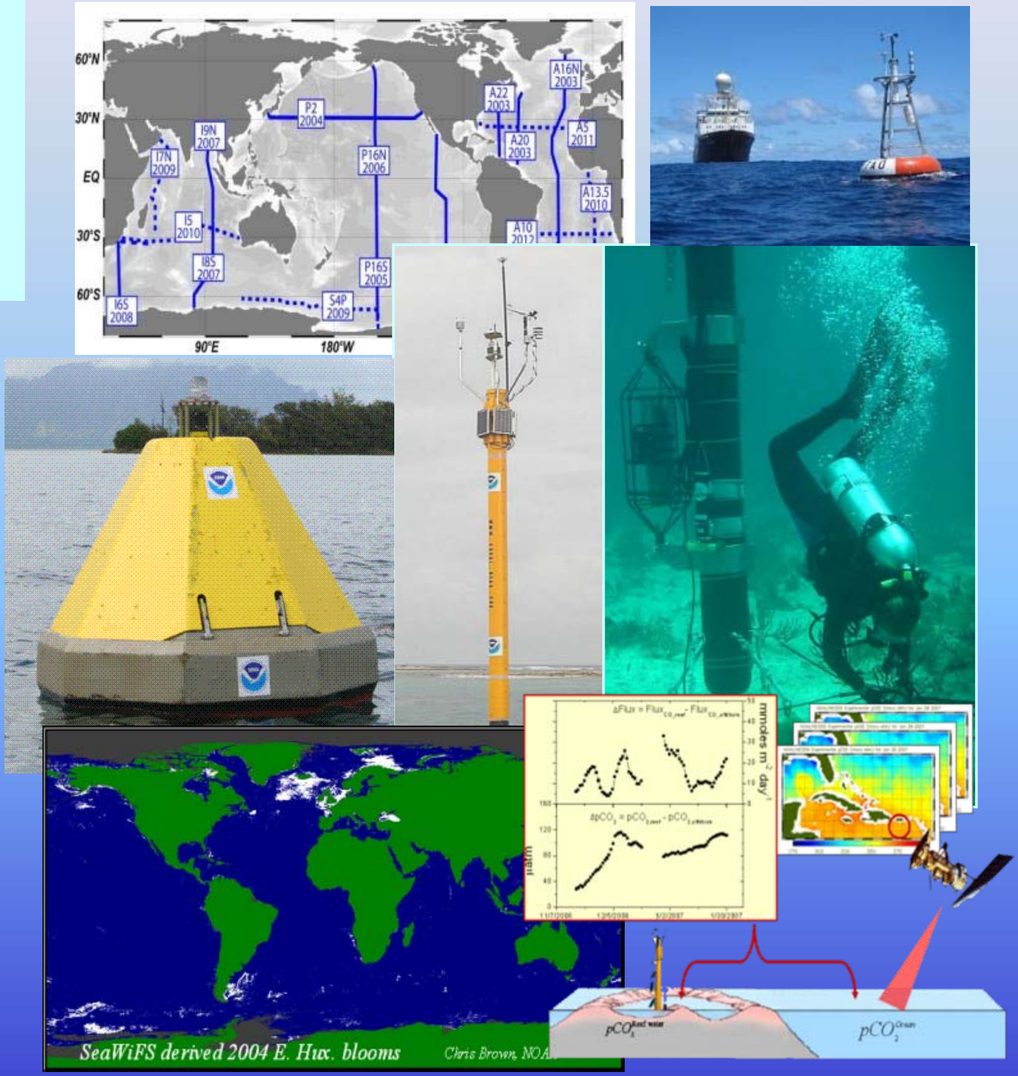

Shell thinning in an acidified ocean

Tunnicliffe et al. (2008)

# NOAA Ocean Acidification Research and Planning Activities

Existing and planned NOAA activities have important relevance to this rapidly emerging issue.

- VOS and Repeat Hydrography
- Technology Development
- Remote Sensing Applications
- $CO_2$ Mooring Network
- Environmental Modeling
- Physiological Research
- Joint Workshop's & Interagency Collaboration



# Future Challenges for the Ocean Carbon Program

1. Completion of the Observing System
2. Continuation of the Coastal Program
3. Integration of an Ocean Acidification Network with the Ocean Carbon Observing Network
4. Integration of the Ocean Carbon Observing System into Carbon Tracker


Thank you for your time!
The NOAA Ship Ronald H. Brown
Arriving in Easter Island for the
2nd Leg of P18 January 2008