PMEL CO$_2$ Program

Carbon Program Overview

1. Introduction and Motivation for Research

2. An Observational Program for Evolving Science Questions

3. New and Future Challenges

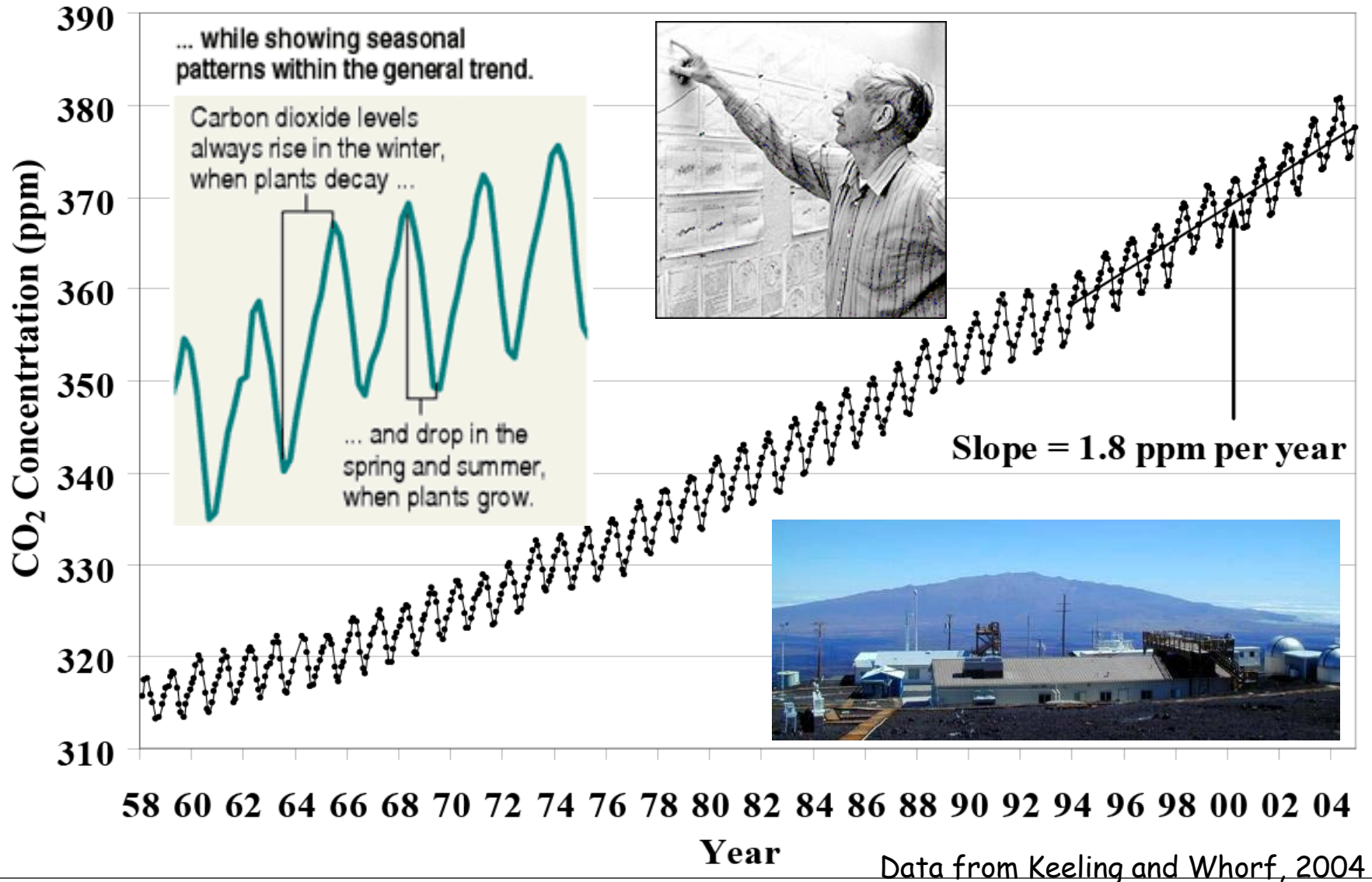**PIs:** Richard Feely, Christopher Sabine and Simone Alin

Full-Time Technical Staff: Cathy Cosca, Dana Greeley, Stacy Maenner, Paul Covert, Sylvia Musielewicz, Geoff Lebon, Cynthia Peacock

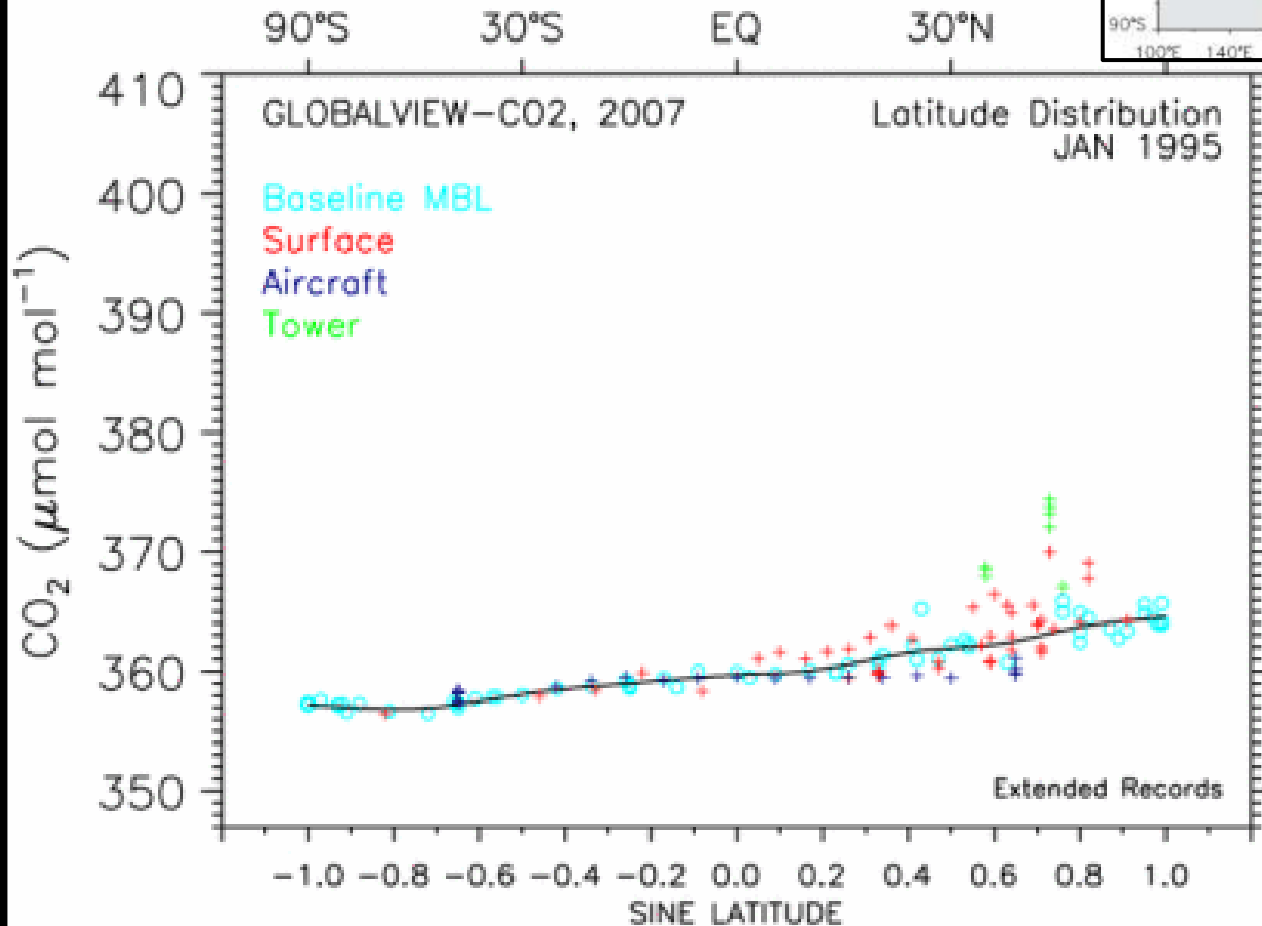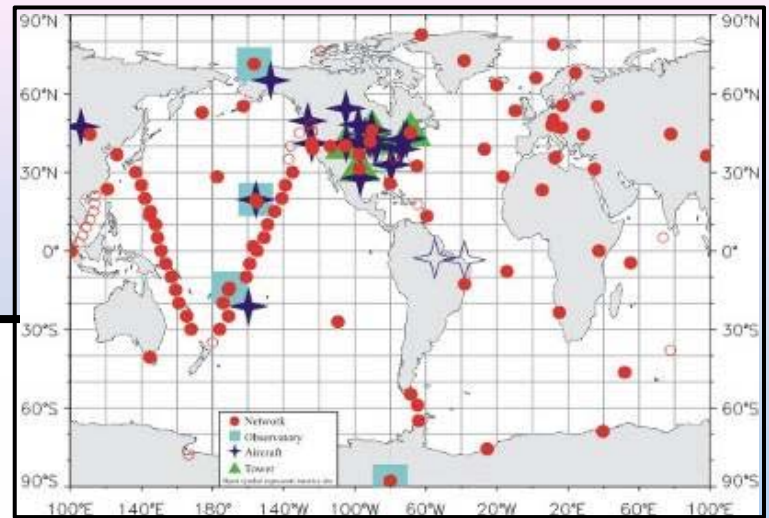**Part-Time Technical Staff:** Dave Wisegarver, Antonio Jenkins

Post-Doc: Laurie Juranek

Graduate Students (through UW): Katie Fagan, Andrea Fassbender

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

... while showing seasonal patterns within the general trend.

Carbon dioxide levels always rise in the winter, when plants decay ...

... and drop in the spring and summer, when plants grow.

Slope = 1.8 ppm per year

CO_2 Concentrtation (ppm)

Year

Data from Keeling and Whorf, 2004

Globalview Atmospheric CO_2 Network

GLOBALVIEW–CO2, 2007 — Latitude Distribution JAN 1995

Baseline MBL
Surface
Aircraft
Tower

Prepared by NOAA ESRL, 2007-08-14

Extended Records

Atmospheric CO_2 levels are rising everywhere in the world. This can easily be seen even with the natural variability.
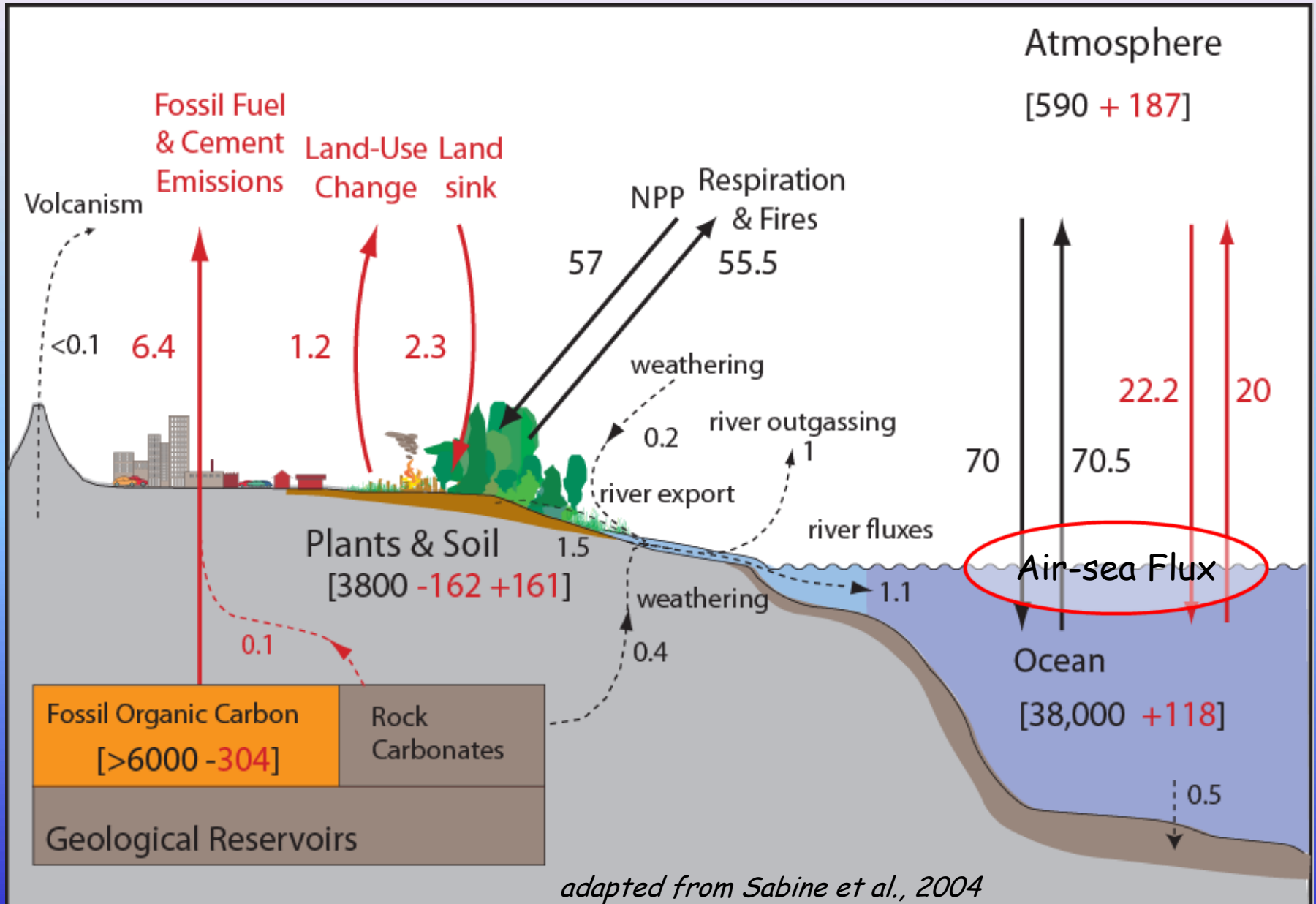
Motivation for the PMEL CO$_2$ Program

The NOAA's Climate Mission Goal -- To understand climate variability and change to enhance society's ability to plan and respond.
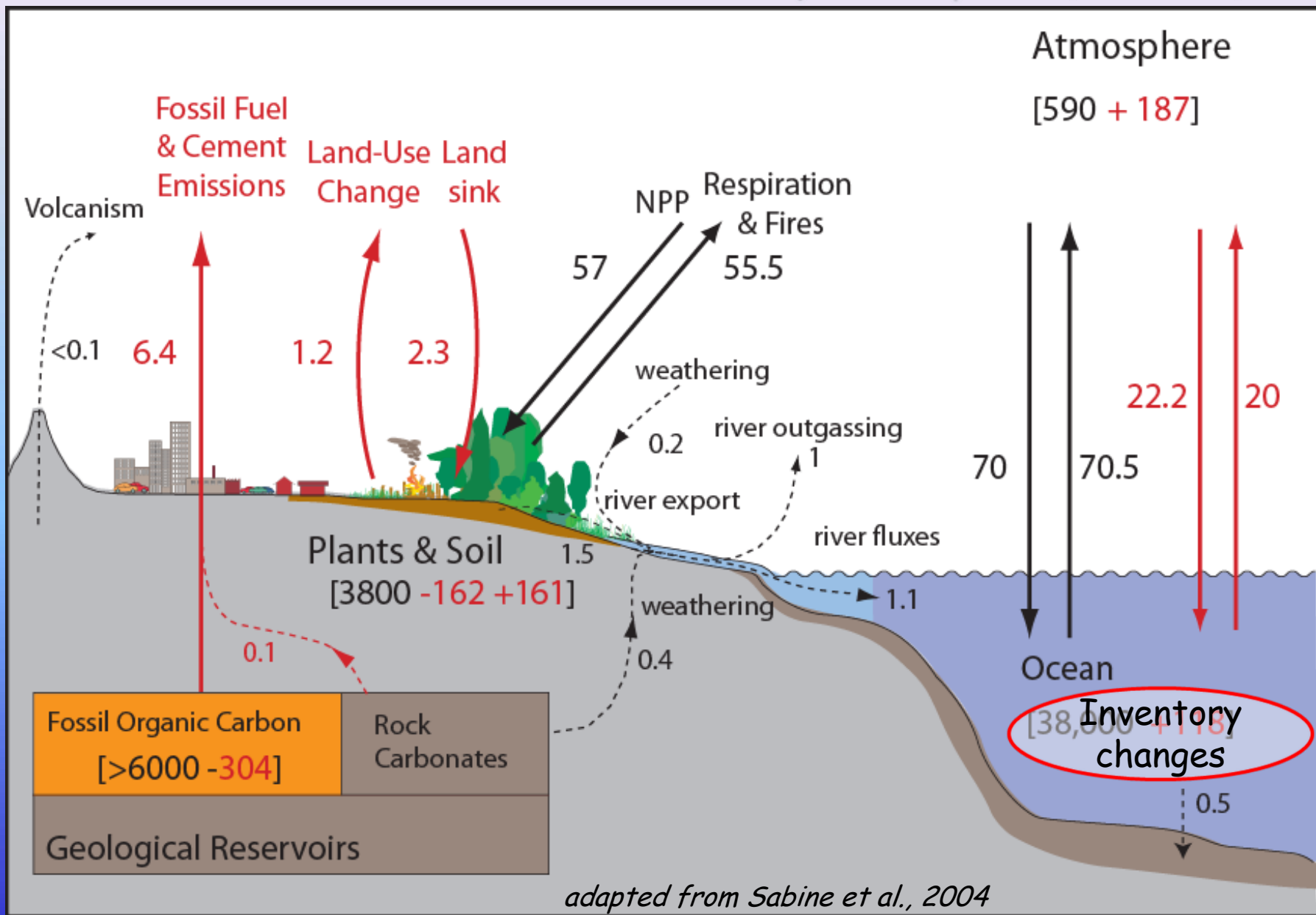
Research Area: Develop an Integrated Global Observation and Data Management System for routine delivery of information, including attribution of the state of the climate.

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)
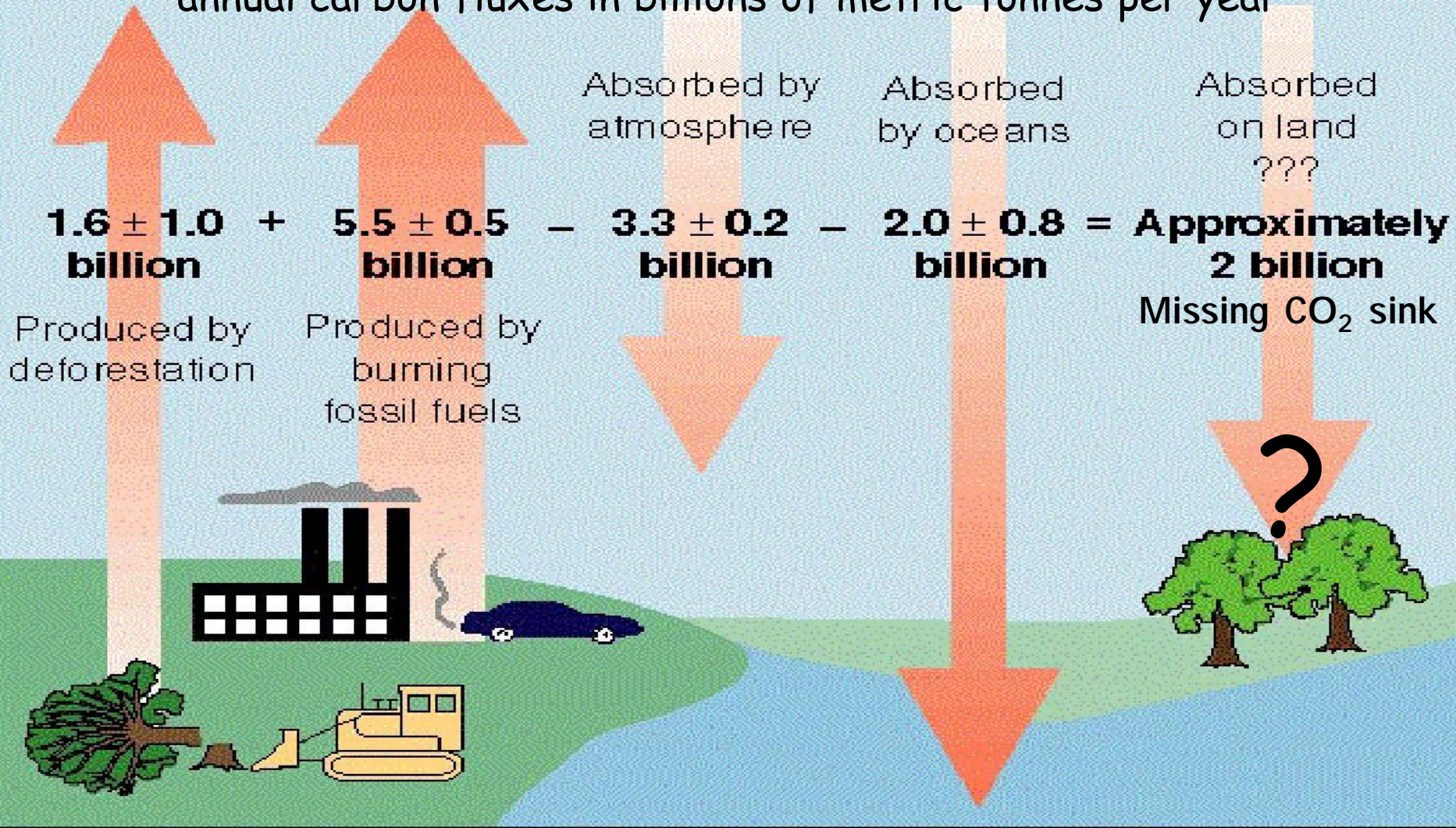

adapted from Sabine et al., 2004

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

Atmosphere

[590 + 187]

Volcanism

Fossil Fuel & Cement Emissions

Land-Use Change

Land sink

NPP

Respiration & Fires

<0.1   6.4   1.2   2.3

57   55.5

weathering

0.2

river outgassing

1

22.2   20

river export

70   70.5

Plants & Soil
[3800 -162 +161]   1.5

river fluxes

weathering   1.1

0.1

weathering

0.4

Ocean

Fossil Organic Carbon
[>6000 -304]

Rock Carbonates

Inventory changes

[38,000 +118]

0.5

Geological Reservoirs

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.

annual carbon fluxes in billions of metric tonnes per year

Absorbed by atmosphere

Absorbed by oceans

Absorbed on land ???

1.6 ± 1.0 billion + 5.5 ± 0.5 billion − 3.3 ± 0.2 billion − 2.0 ± 0.8 billion = Approximately 2 billion

Produced by deforestation

Produced by burning fossil fuels

Missing CO_2 sink

?

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.
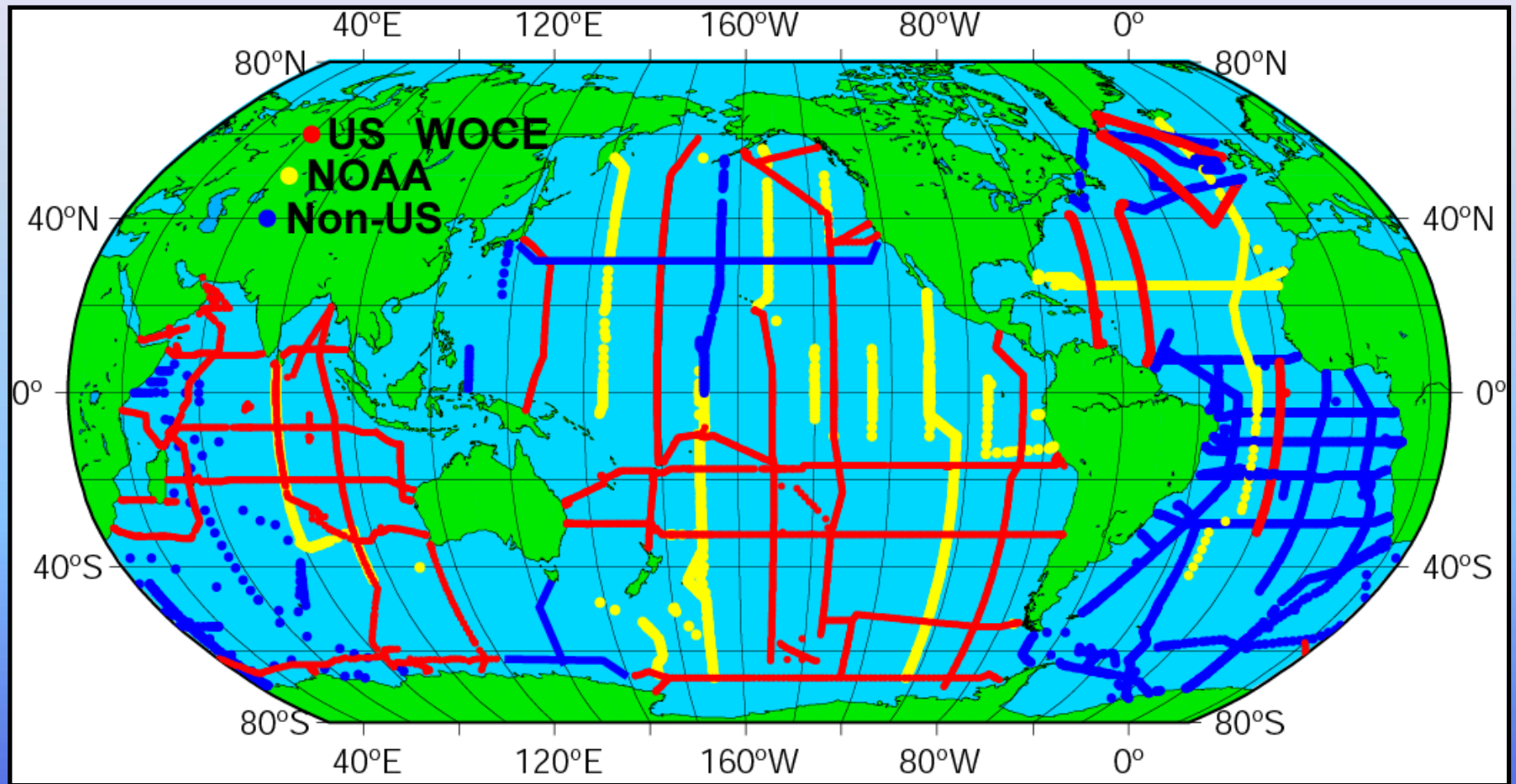
The GLODAP carbon database of >70,000 sample locations grew out of a 5 year NOAA synthesis effort.
http://cdiac.esd.ornl.gov/oceans/glodap/Glodap_home.htm

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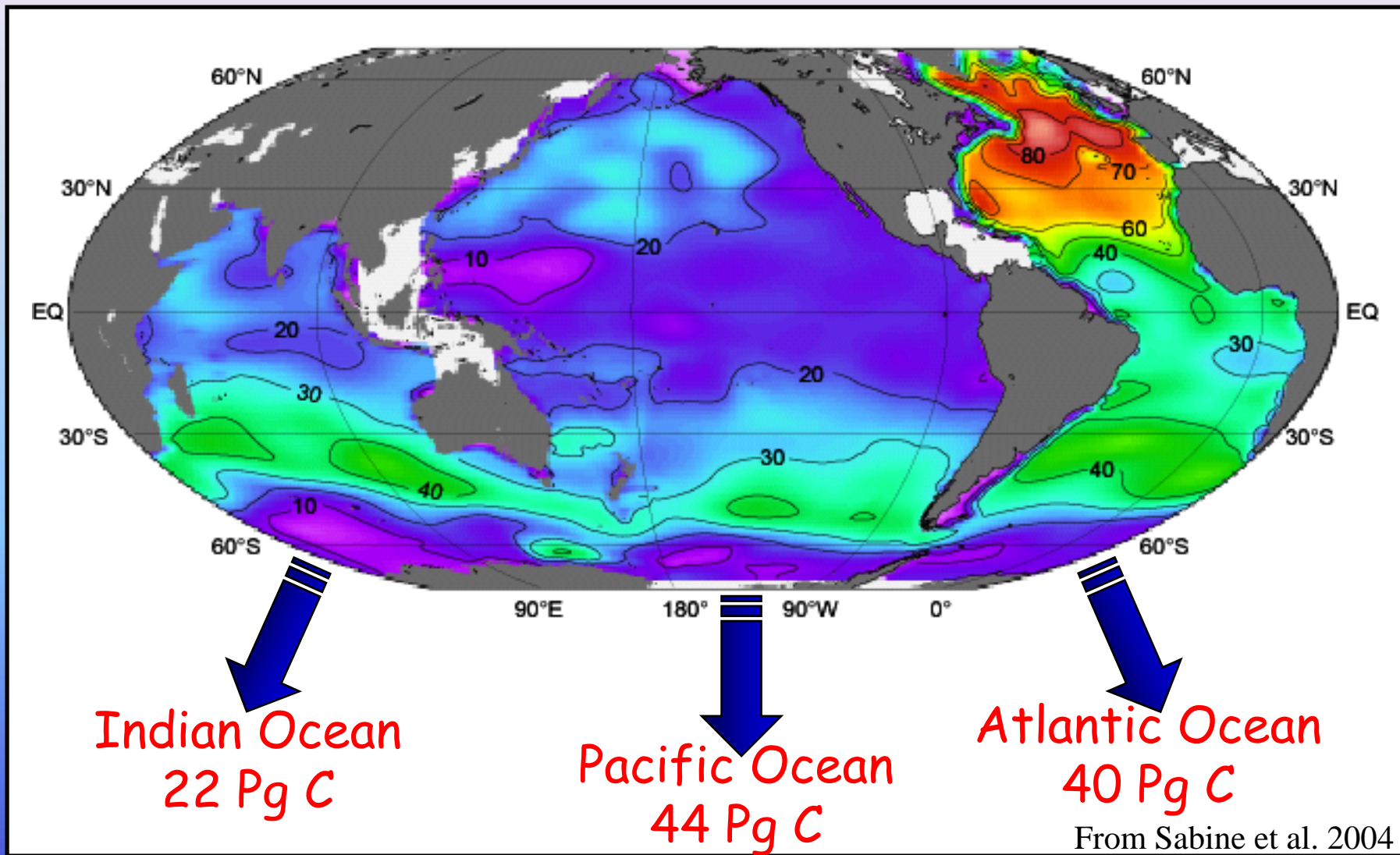
Mapped Inventory =106±17 Pg C; Global Inventory =118±19 Pg C

Quantifying the ocean inventory helped constrain the net terrestrial biosphere fluxes
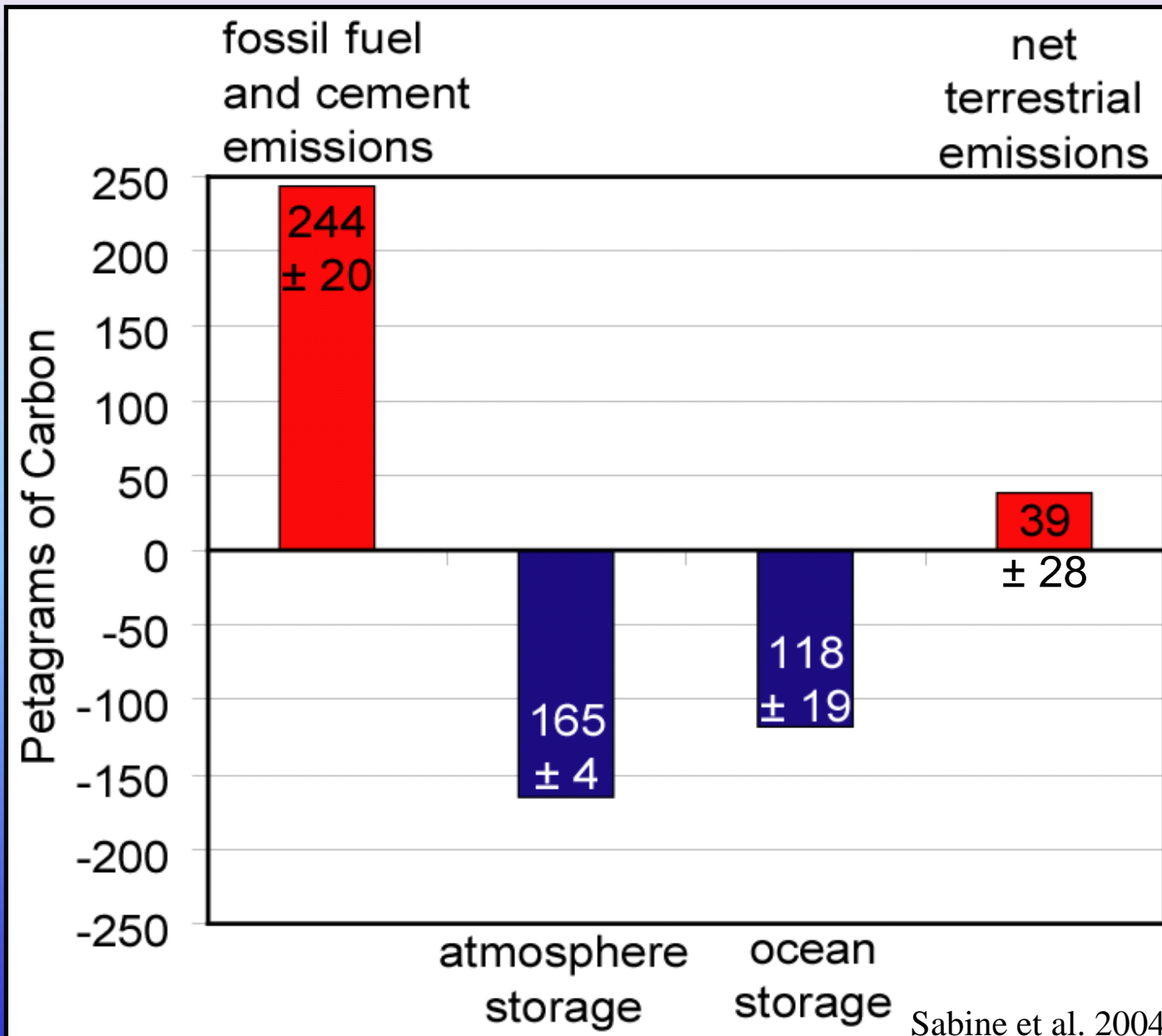
Over the past 200 years, the ocean has been the only reservoir to consistently take up anthropogenic CO_2 from the atmosphere.

Sabine et al. 2004

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
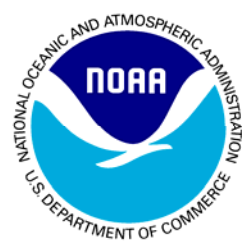
Goal: To quantify decadal changes in the inventory and transport of heat, fresh water, carbon dioxide (CO$_2$), chlorofluorocarbon tracers and related parameters in the oceans.

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/
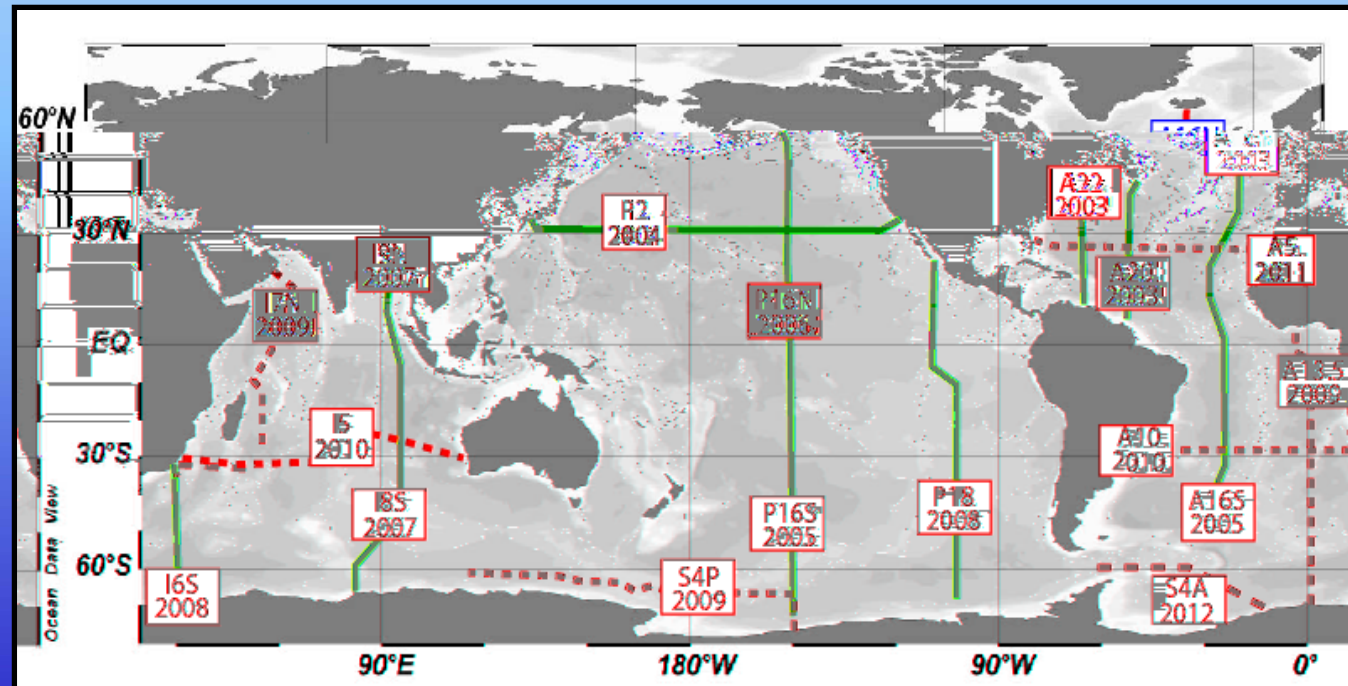
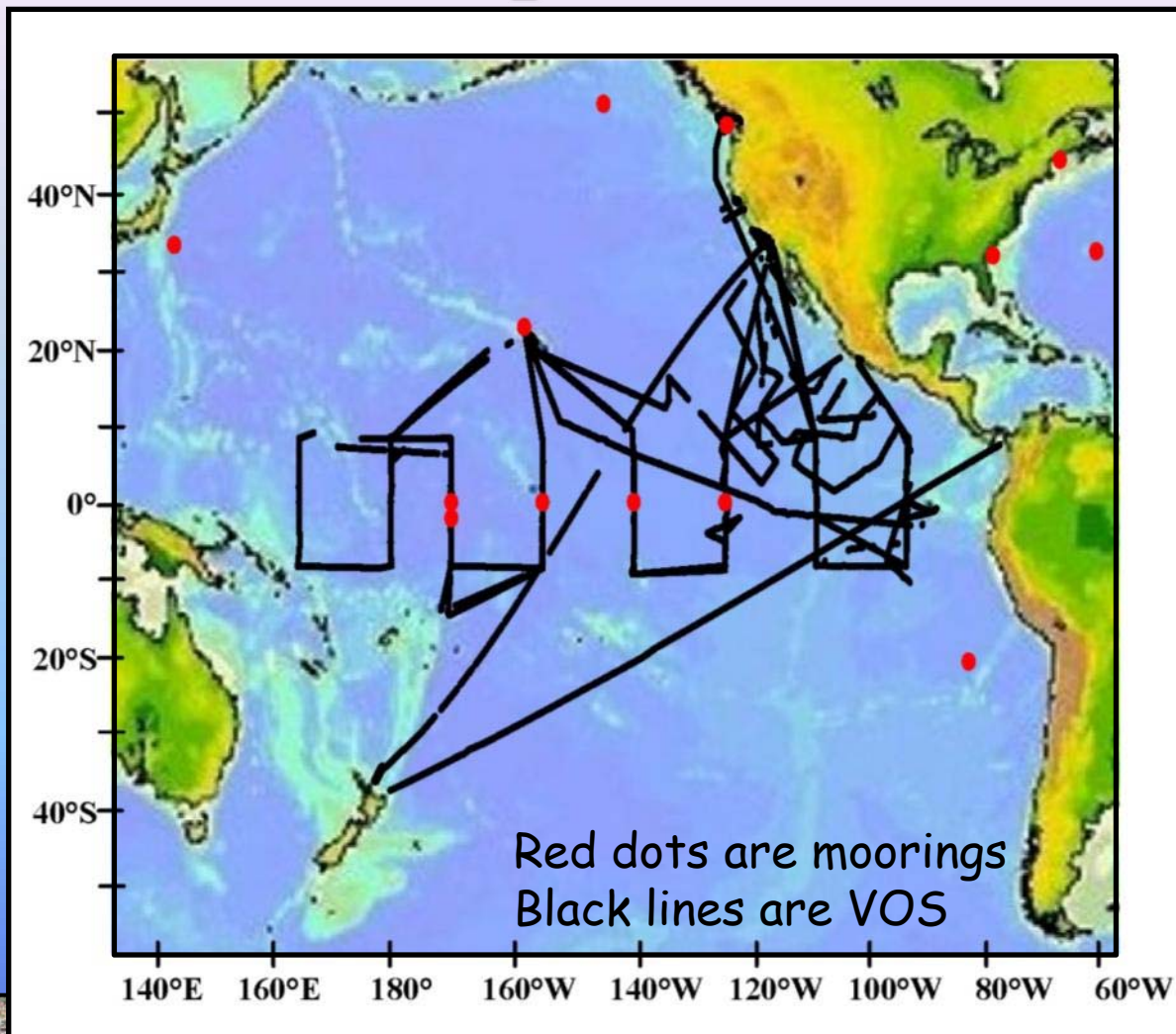# CLIVAR/CO$_2$ Repeat Hydrography Interim Results

- 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.
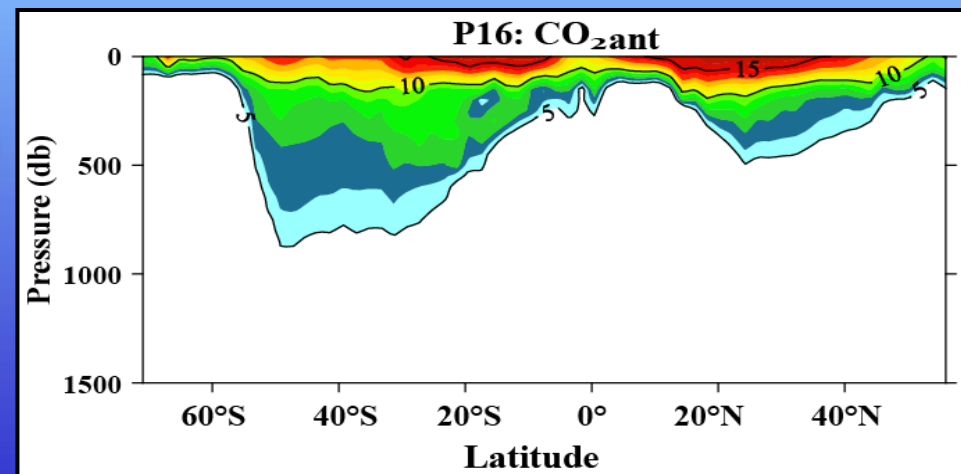
P16: CO$_2$ant

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

Atmosphere [590 + 187]

Fossil Fuel & Cement Emissions

Land-Use Change

Land sink

NPP

Respiration & Fires

Volcanism

<0.1   6.4   1.2   2.3

57   55.5

weathering
river outgassing
0.2   1

river export

river fluxes

Air-sea Flux

70   70.5   22.2   20

Plants & Soil [3800 -162 +161]   1.5

weathering
1.1

Ocean [38,000 +118]

0.1

0.4

Fossil Organic Carbon [>6000 -304]

Rock Carbonates

0.5

Geological Reservoirs

adapted from Sabine et al., 2004

PMEL surface CO₂ observation network

Red dots are moorings
Black lines are VOS
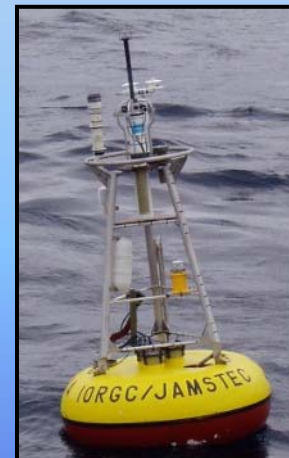
In the early 1990s surface CO_2 measurements capture the influence of El Niño on equatorial CO_2 fluxes

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
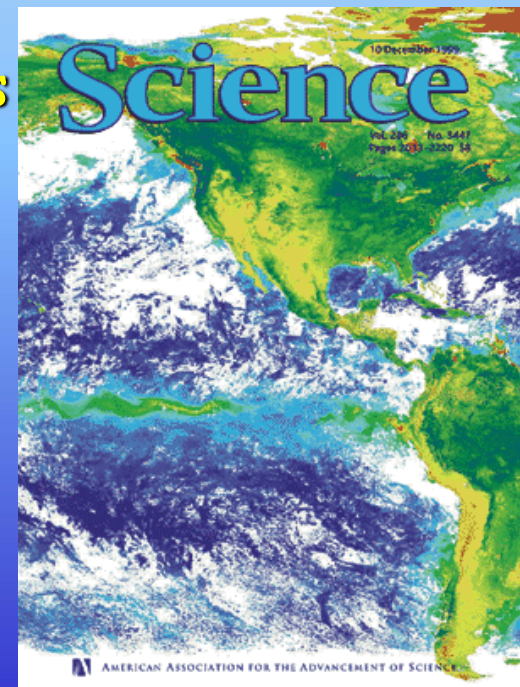
Figure from Feely et al., Nature, 1999

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

~ 250,000 measurements between 1960-1995

(a) All Station Locations
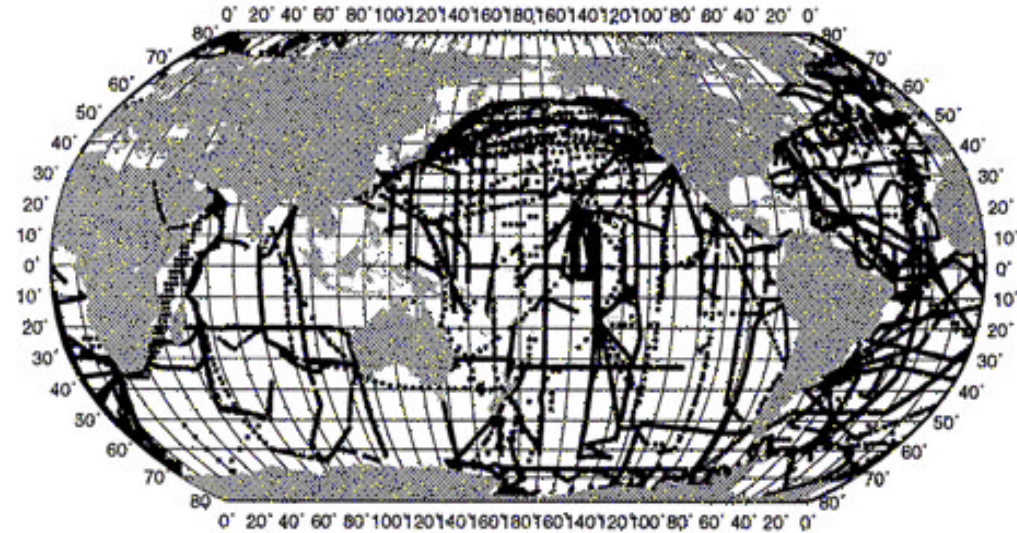
Annual Flux (Wanninkhof Gas Exchange)

Nominal Year 1990
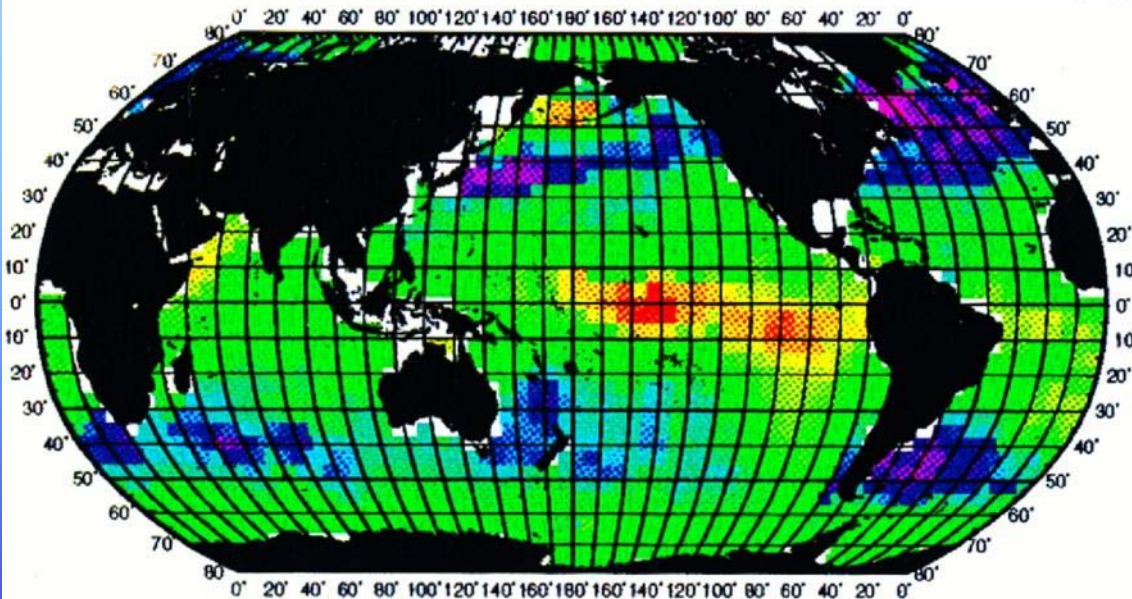
Net Flux (10^{12} grams C yr^{-1} in each 4° x 5° area)

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
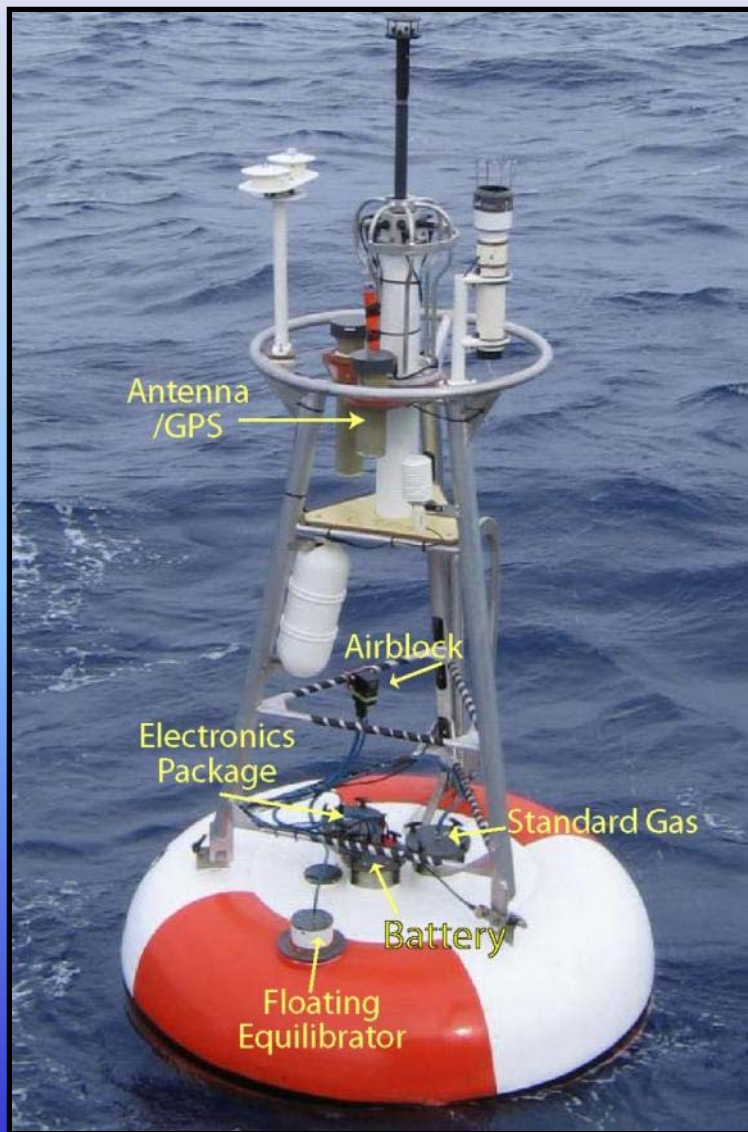
The Basics:

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
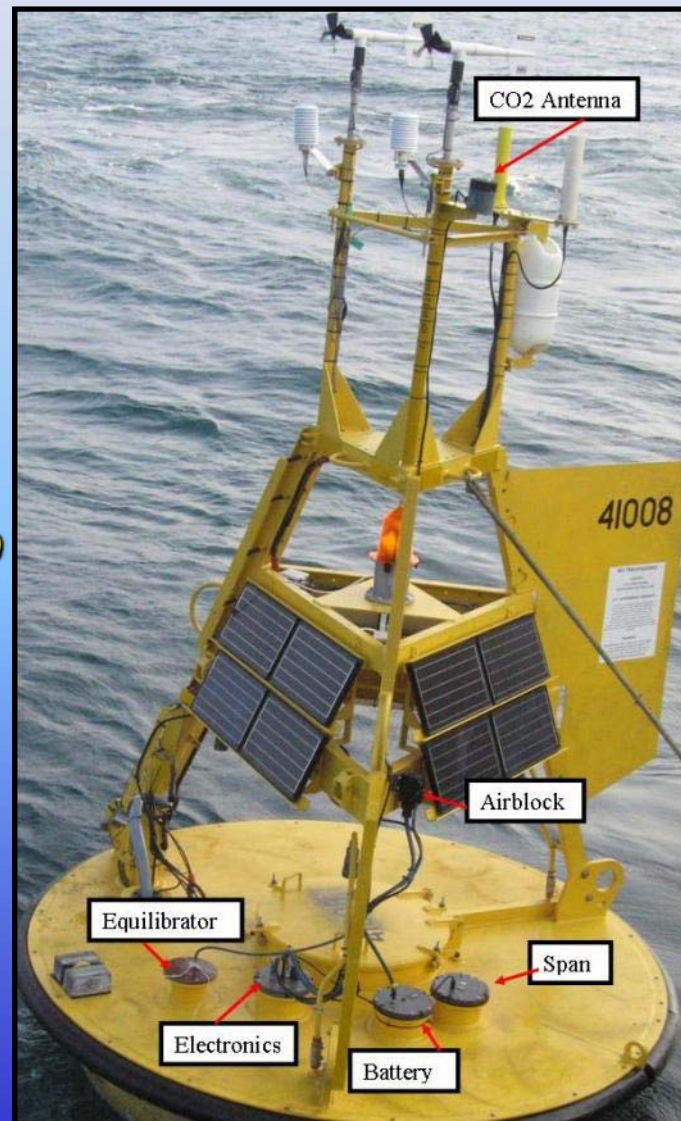
Annual net CO$_2$ flux estimated by Takahashi et al., DSR, 2002

~ 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.

Temperature / Biological pCO$_2$ Ratio

Nominal Year 1995

Net Flux (moles CO$_2$ m^{-2} year^{-1})
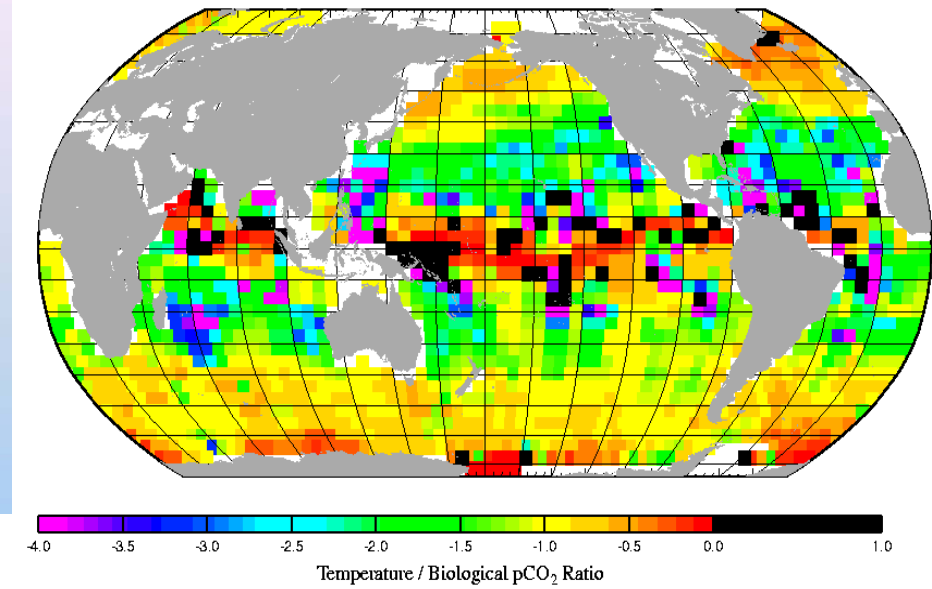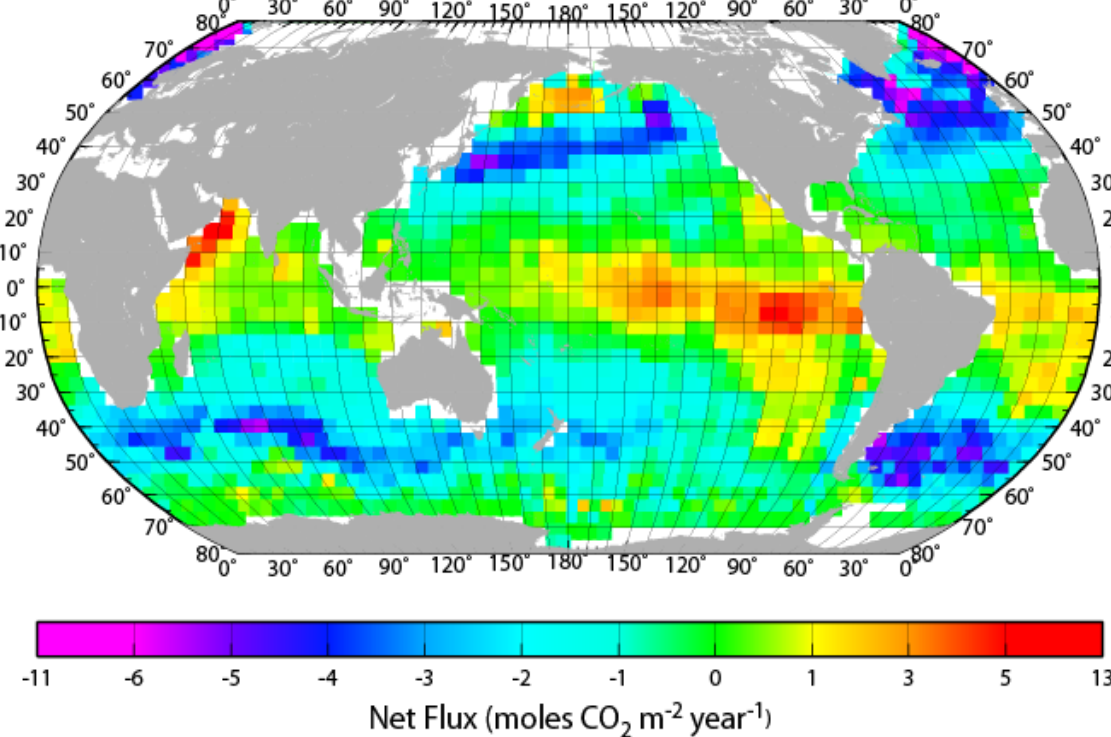
First global assessment of the relative biological and temperature controls on surface water pCO$_2$

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.
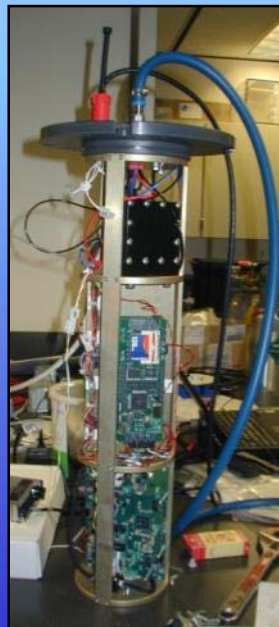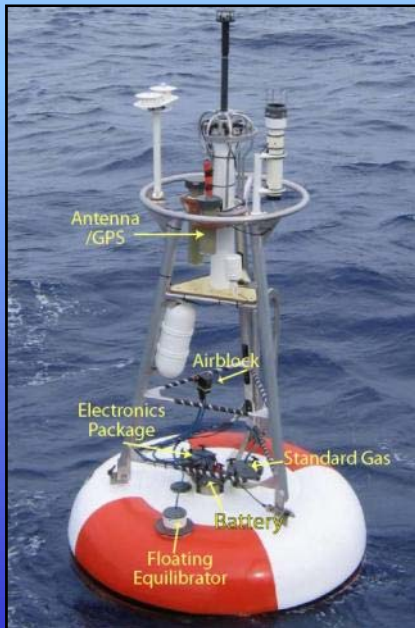
Large-Scale EqPac Results: 1997-2007

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
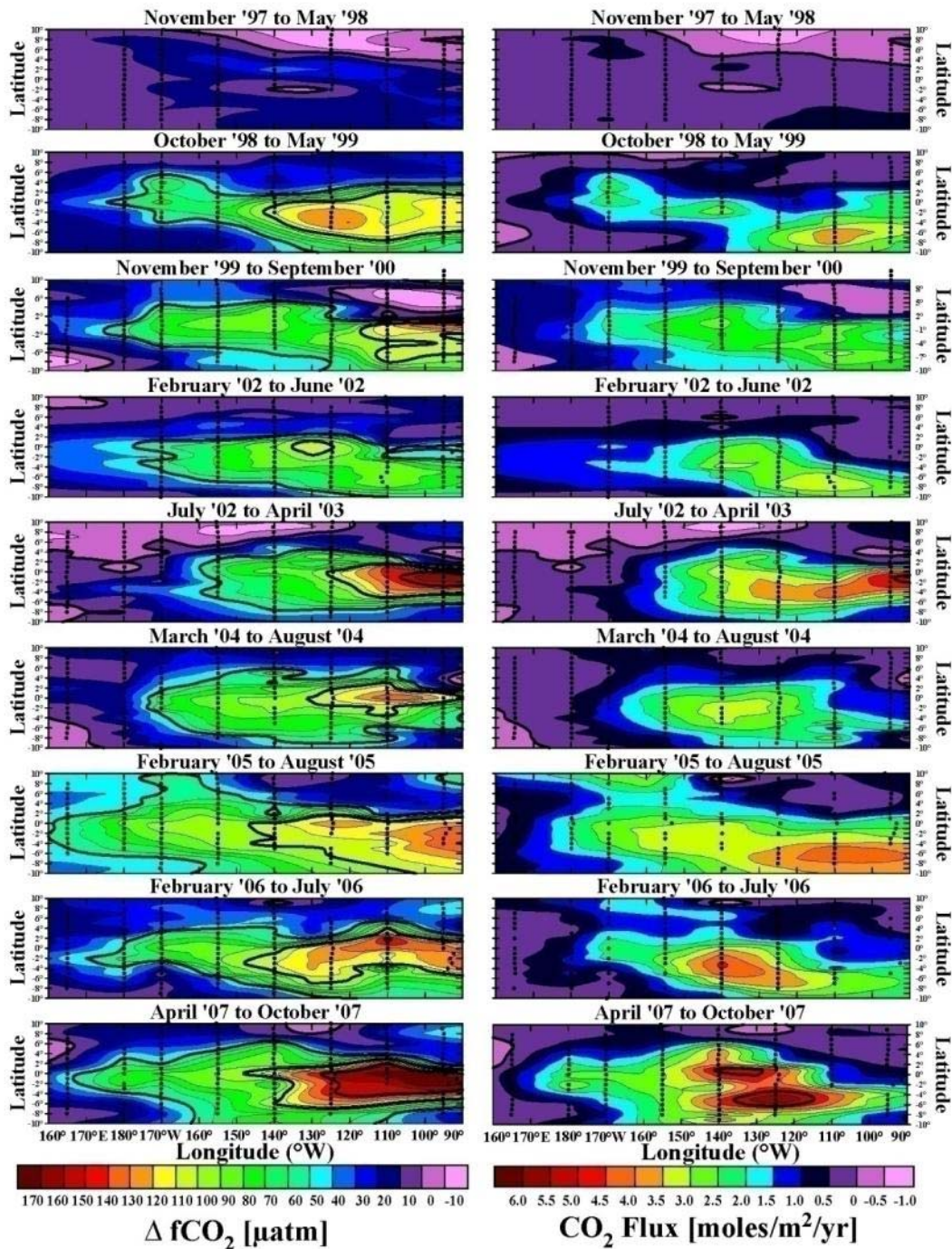
Takahashi climatological annual mean air-sea CO_2 flux for reference year 2000
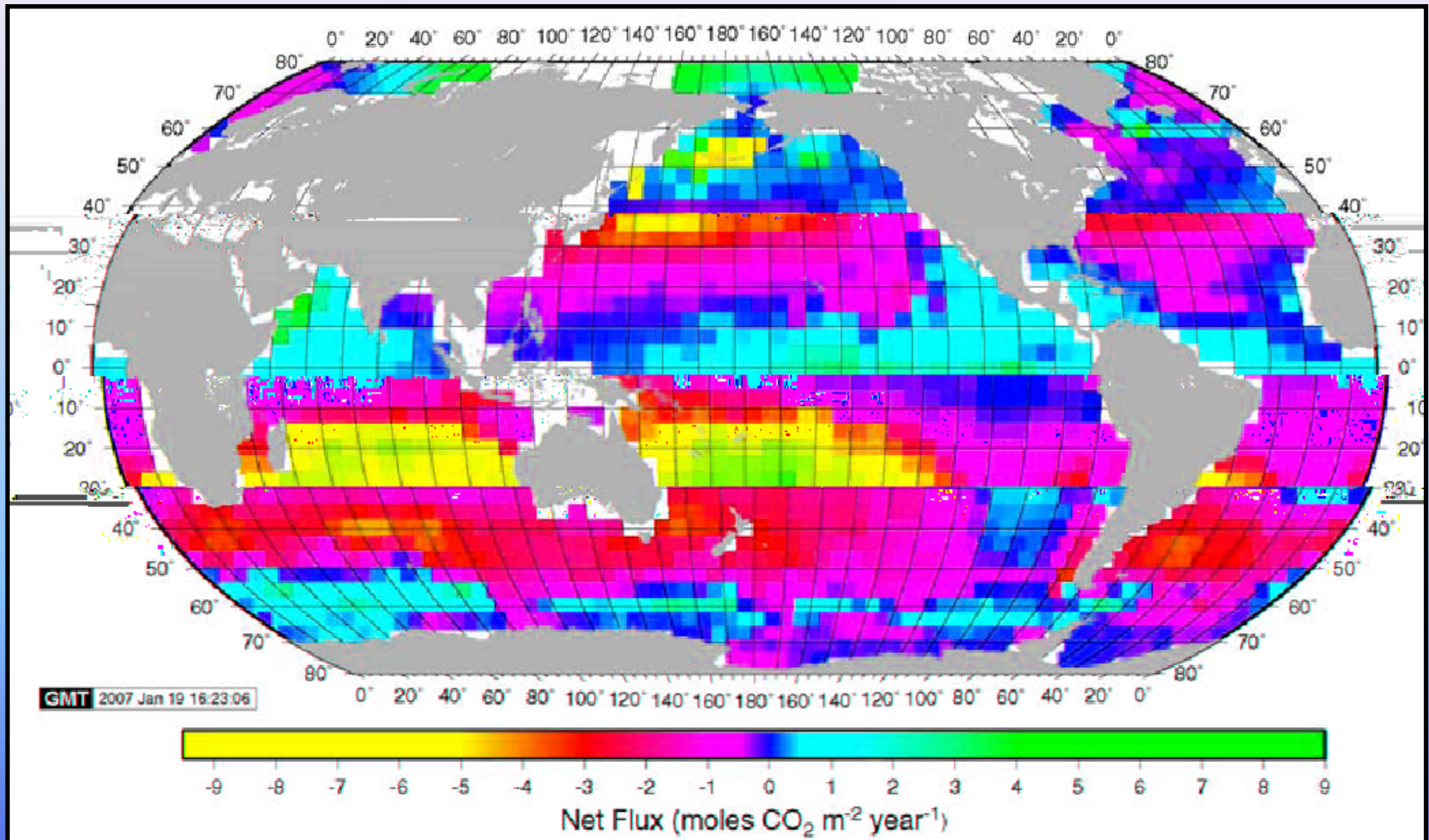
Based on 3 million measurements since 1970 and NCEP/DOE/AMIP II reanalysis winds.
Global flux is 1.4±0.7 Pg C/yr

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

Concept: Use Multiple Platforms to Produce Seasonal CO_2 Flux Maps
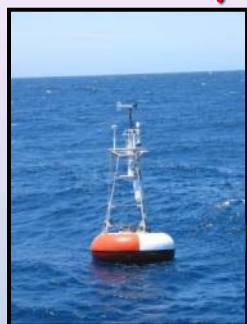
In situ sampling pCO_2, SST, SSS

Remote sensing SST, color & wind, Soon SSS

Algorithm development $pCO_2 = f(SST, color)$

Co-located satellite data

Regional satellite SST & color data

Wind data

Apply algorithm to regional SST& color fields to obtain seasonal pCO_2 maps

Algorithm development Gas transfer, k = f(U_{10},SST)

Flux = k s ΔpCO_2

pCO$_2$ maps

December '95 to June '96 ΔfCO_2

Flux maps

December '95 to June '96 CO_2 Flux

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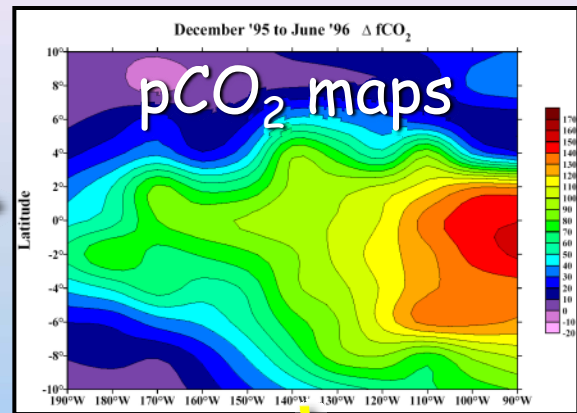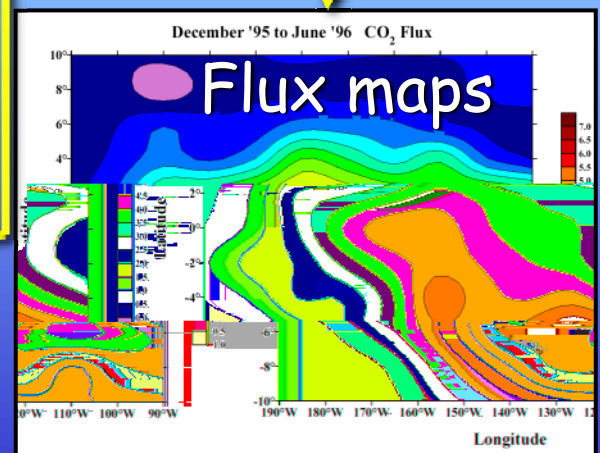
Global Flux Map suggests an interannual variability of 0.23 Pg C

Year: 1982   Season: 1

mol/m²/season
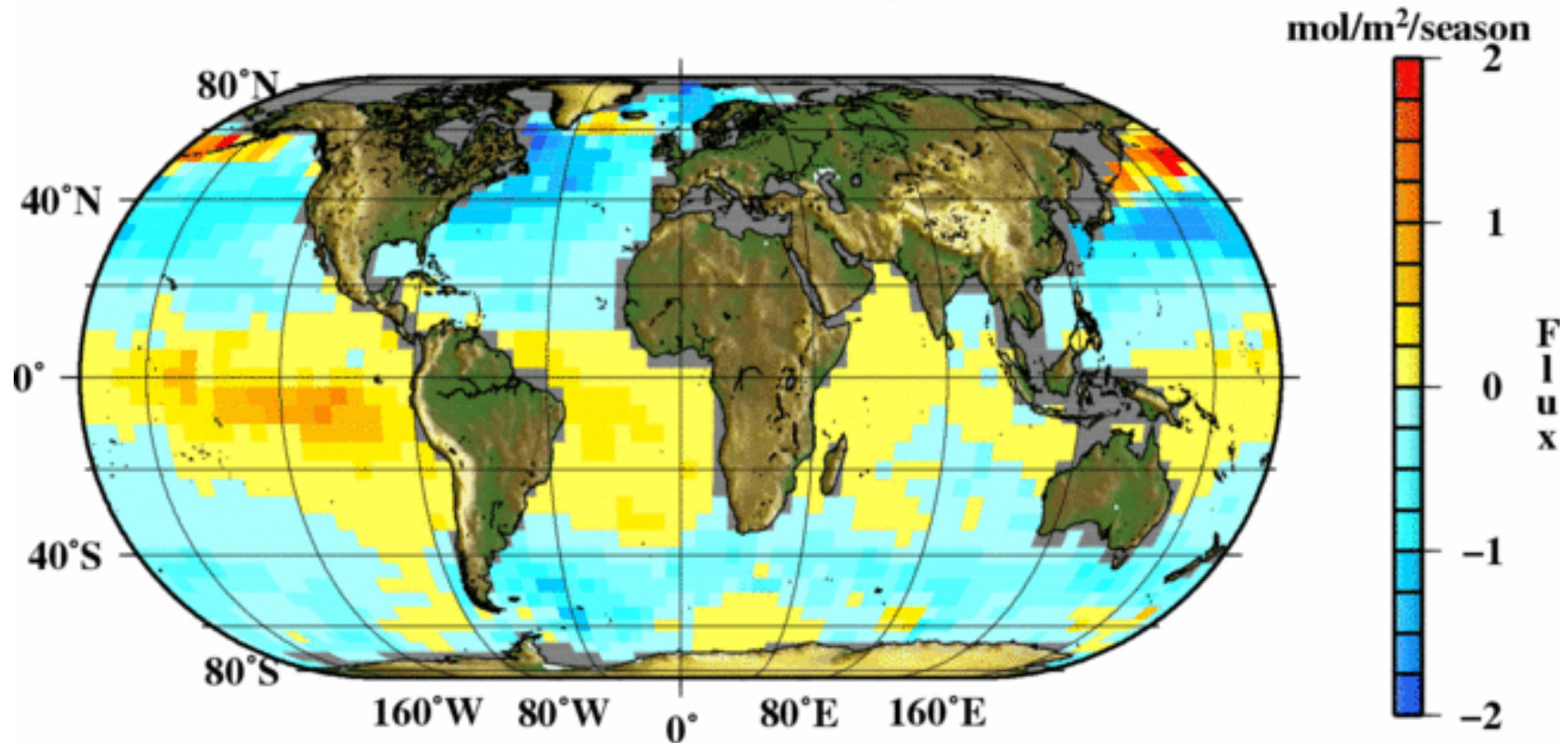
Produced by Joaquin Trinanes, NOAA Coastwatch, and
Rik Wanninkhof, NOAA/AOML/OCD
Climatology:Takahashi et al 2002
Method: Lee et al, 1998; Park et al, 2006; Cosca et al. 2003

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

A U.S. CARBON CYCLE SCIENCE PLAN

A Report of the Carbon and Climate Working Group
Jorge L. Sarmiento and Steven C. Wofsy, Co-Chairs

1999

Ocean Carbon and Climate Change
An Implementation Strategy for U.S. Ocean Carbon Research
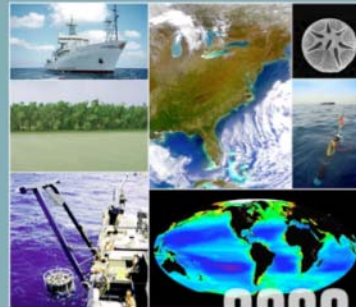
OCCC

Prepared for the
U.S. Carbon Cycle Science Scientific Steering Group
and Inter-agency Working Group
by the
Carbon Cycle Science Ocean Interim Implementation Group

Scott C. Doney
chair and editor

2004

Science Implementation Strategy
for the North American Carbon Program

NACP

The North American Carbon Program
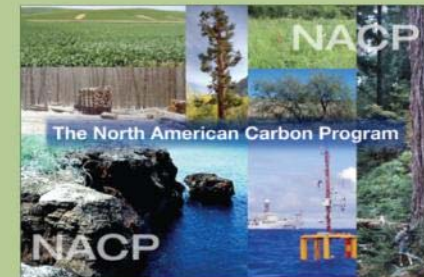
Prepared for the
U.S. Carbon Cycle Scientific Steering Group
and Interagency Working Group
by the
North American Carbon Program Implementation Strategy Group

A. Scott Denning
Chair and editor

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.
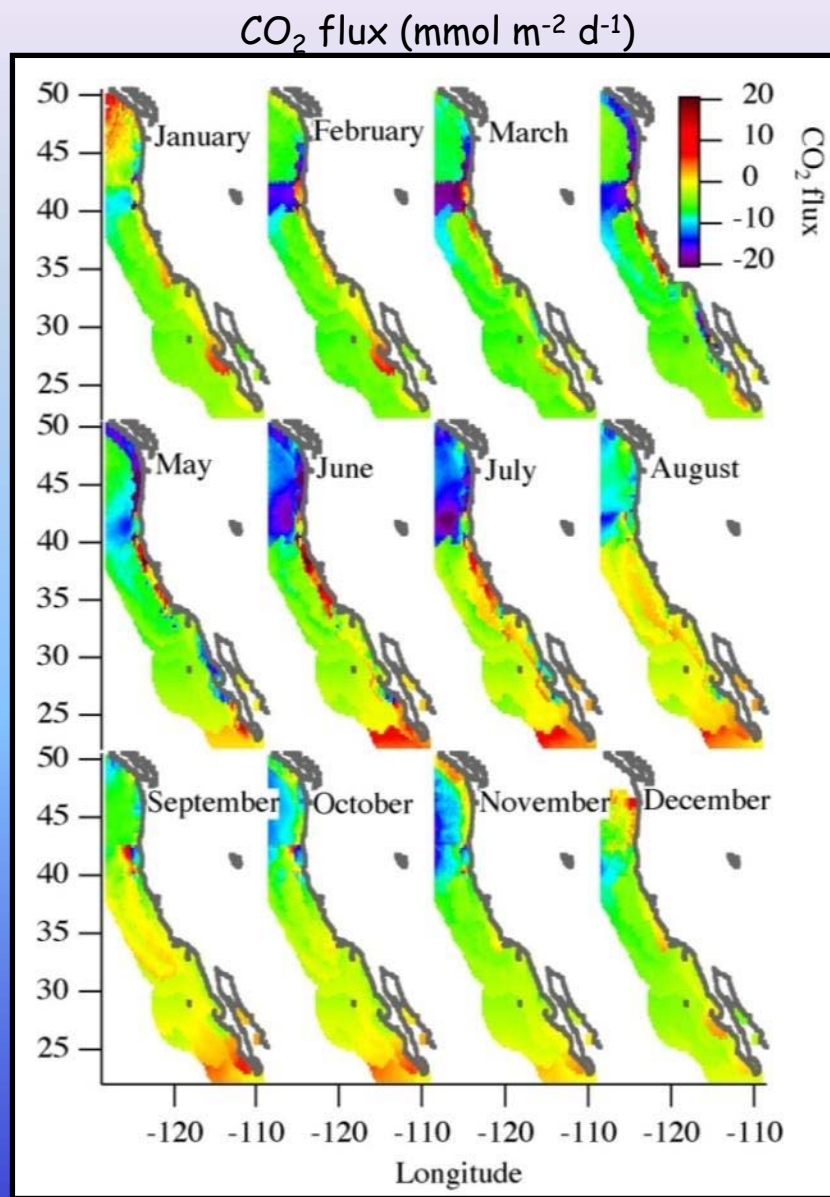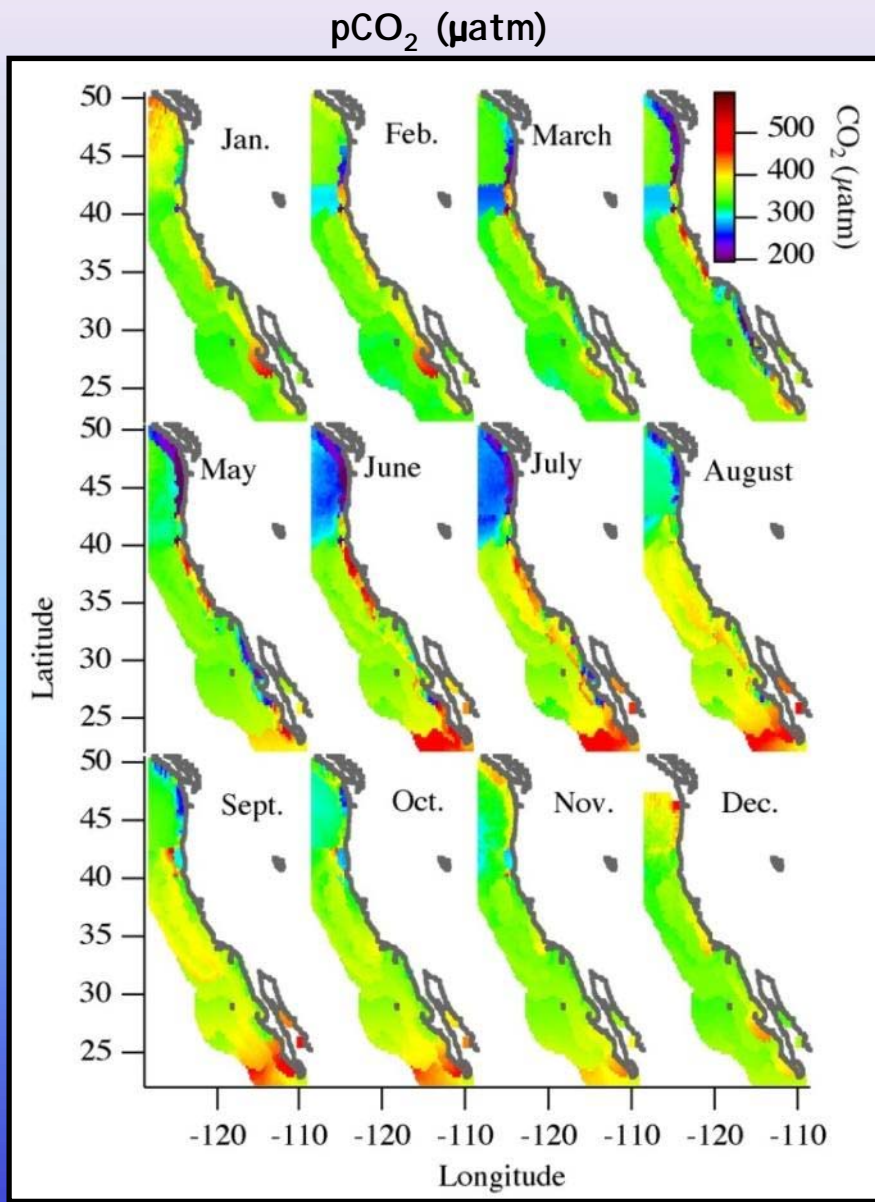
2007 SOCCR, chapter 15 key findings
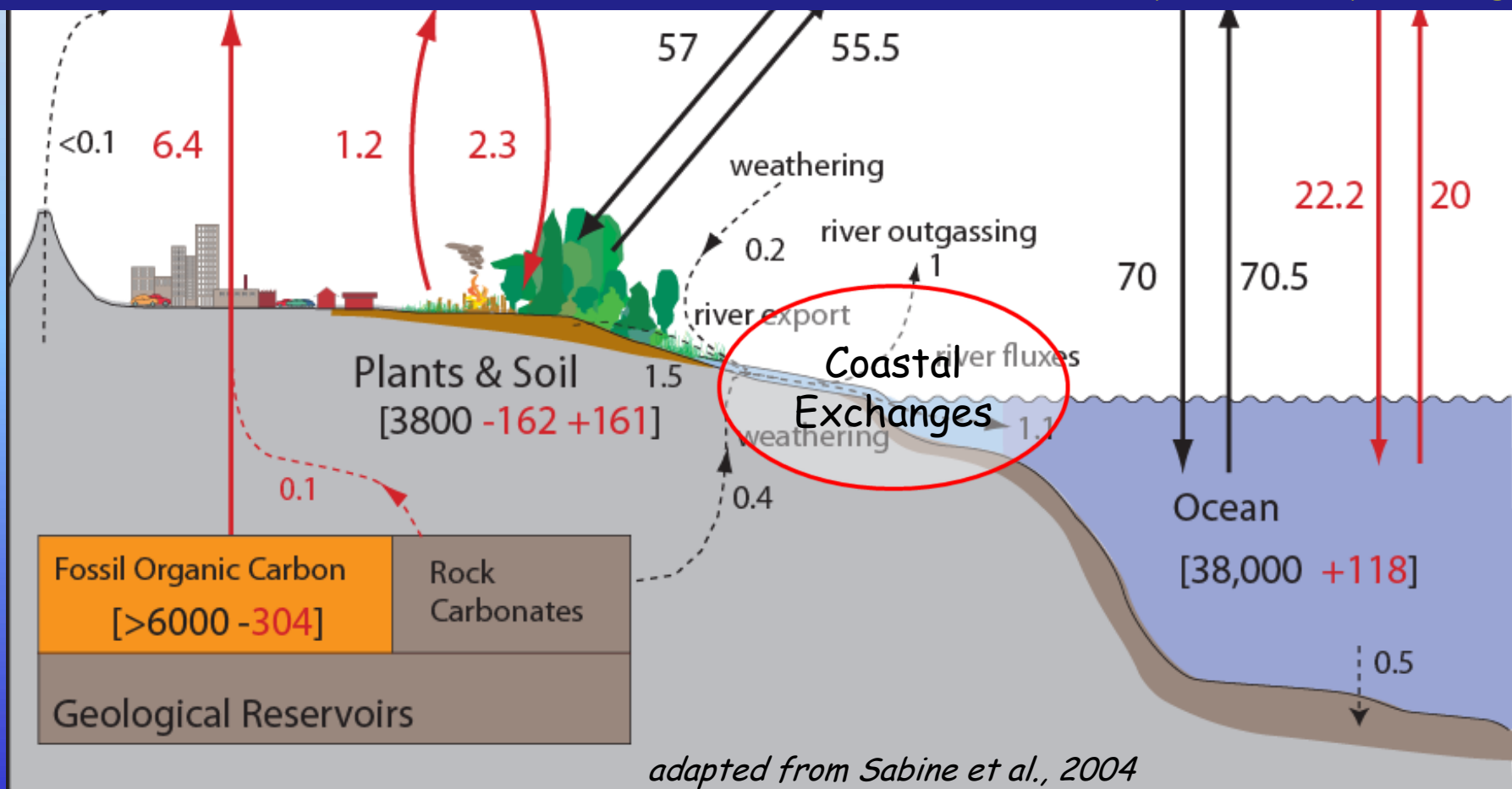
adapted from Sabine et al., 2004

New Directions: NOAA Coastal CO_2 Surveys, coastal CO_2 moorings, and underway CO_2 from coastal ships
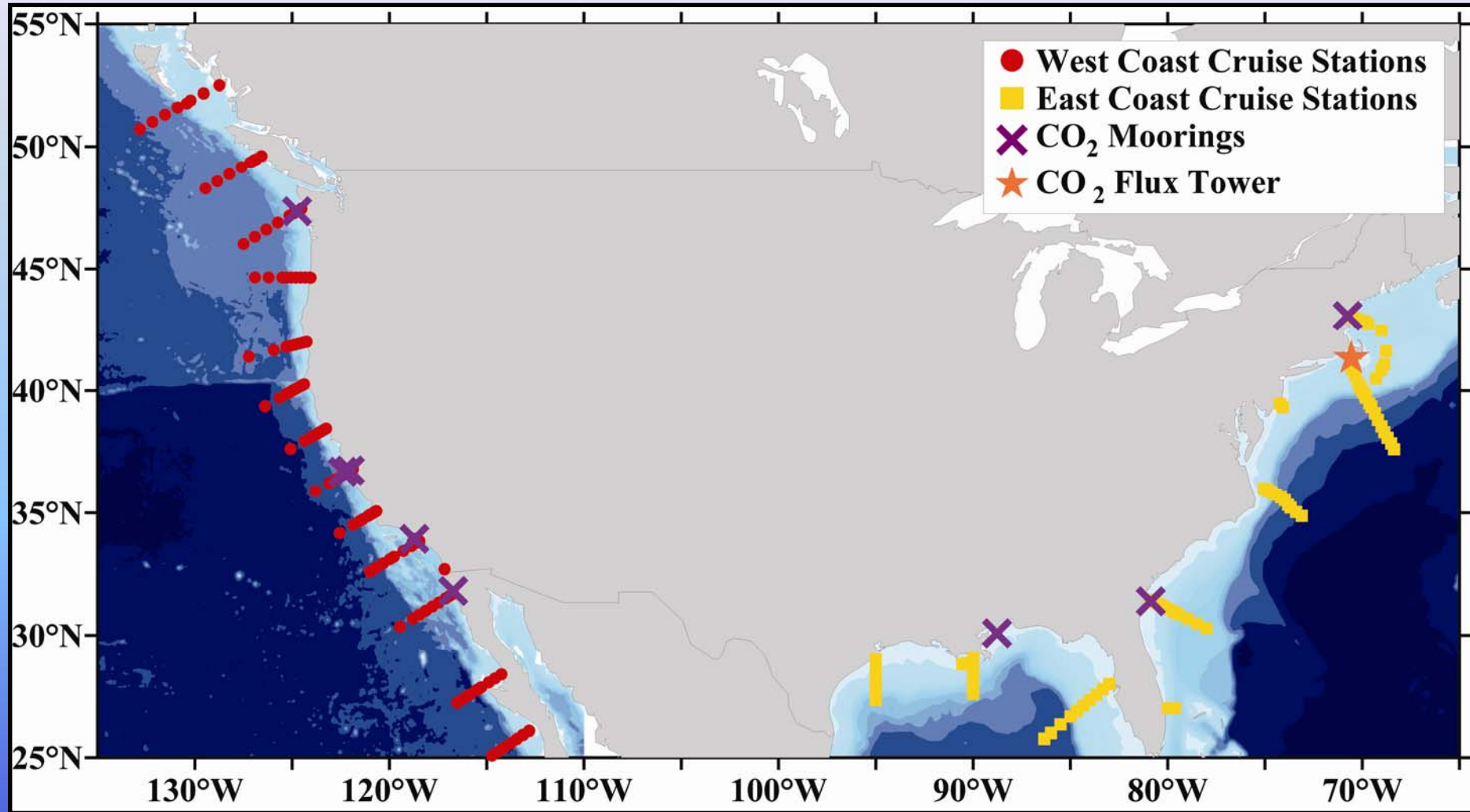
Goal: To gather large-scale coastal CO_2 data for the purpose of determining U.S. air-sea CO_2 fluxes

Monthly climatological pCO₂ and flux maps for the West Coast

pCO₂ (µatm)

CO₂ flux (mmol m⁻² d⁻¹)

Hales et al. (in prep.)

Bimonthly pCO₂ maps for the South Atlantic Bight
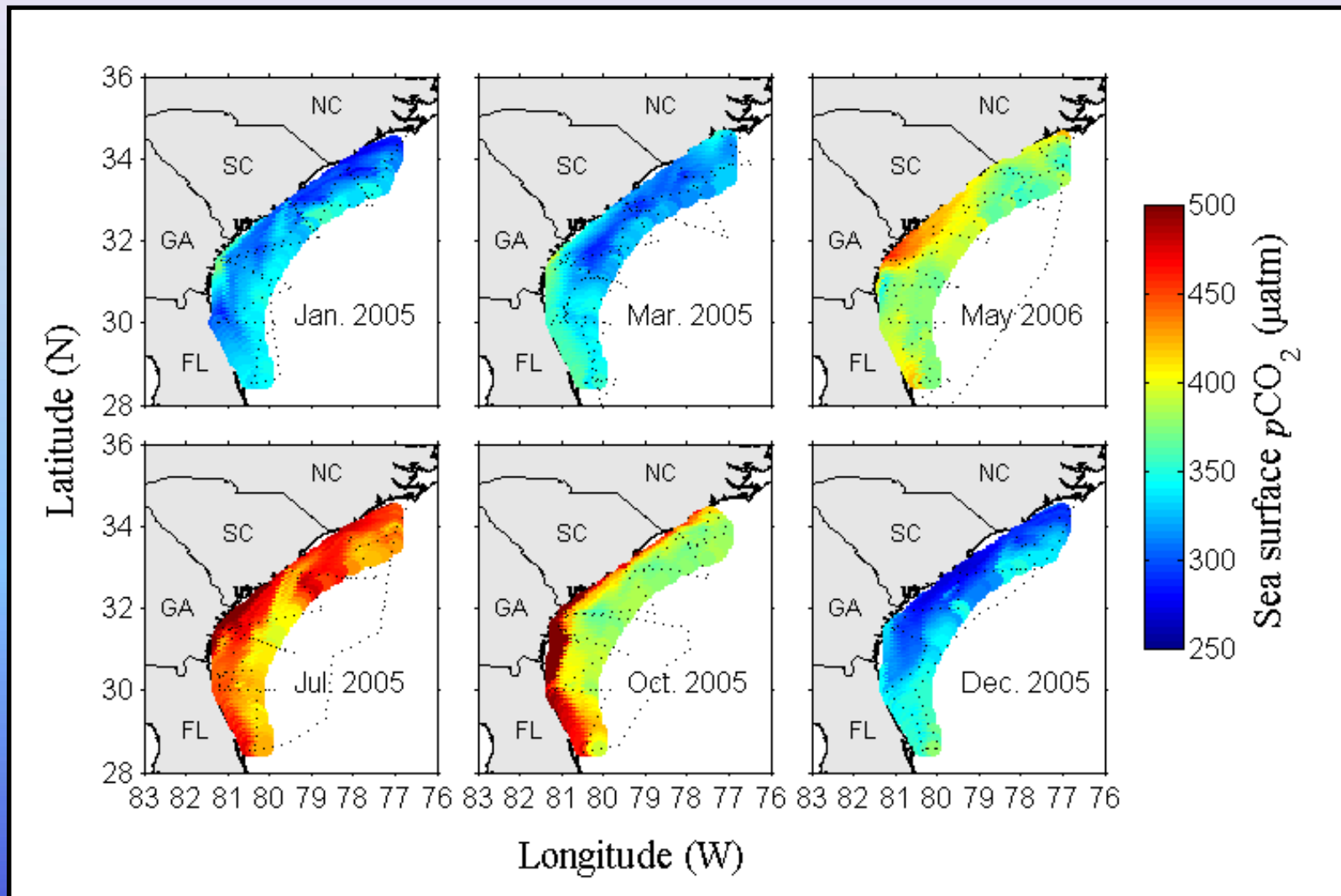
Jiang et al. (2008)

New Directions: NOAA Coastal CO₂ Surveys, coastal CO₂ moorings, and underway CO₂ from coastal ships
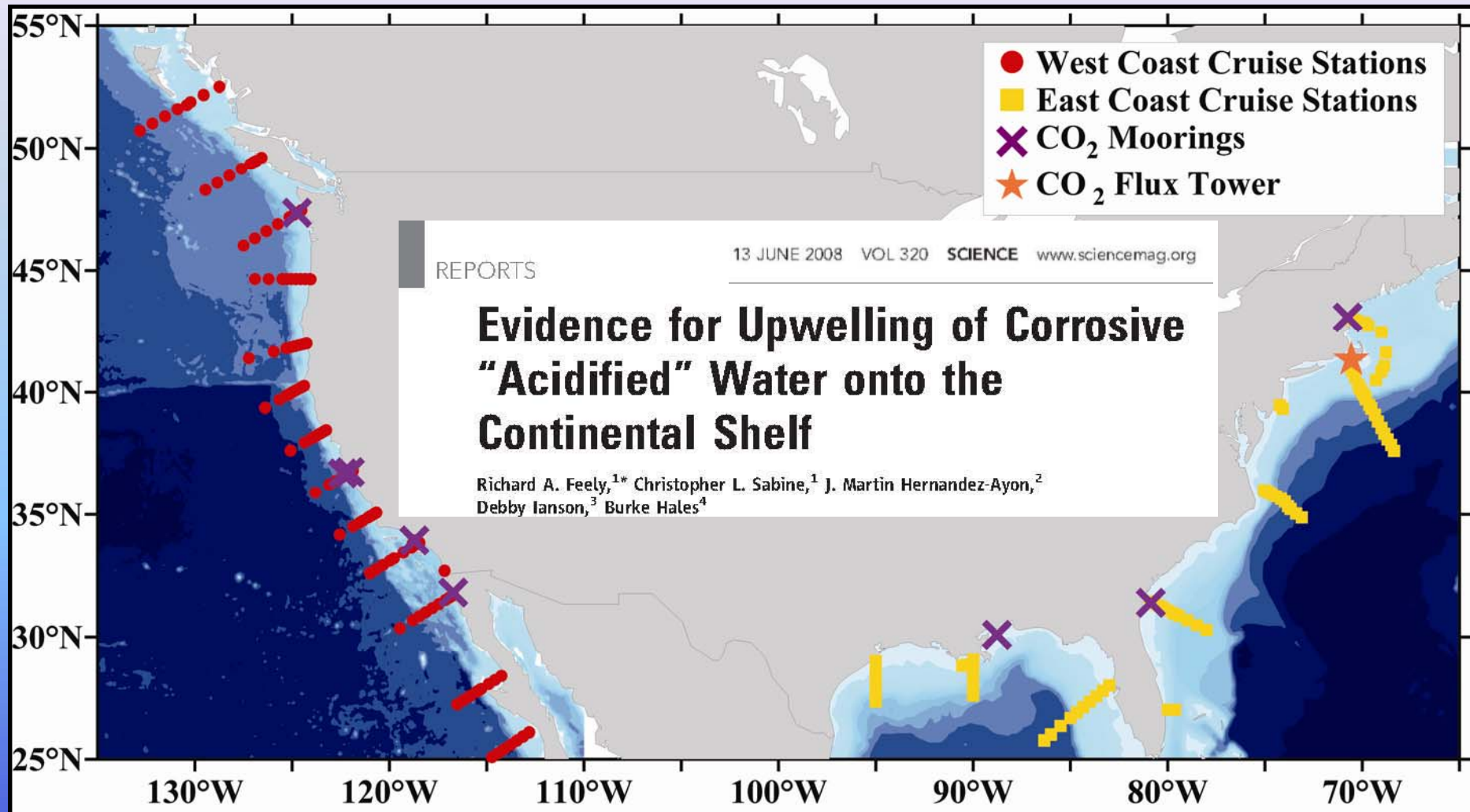
Goal: To gather large-scale coastal CO₂ data for the purpose of determining U.S. air-sea CO₂ fluxes

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

円石藻のいろいろ

Helicosphaera   Oolithus   Emiliania   Algirosphaera

Calcidiscus   Rhabdosphaera   Umbellosphaera

Braardosphaera   Cayptrolithina   Coronosphaera   Gephyrocapsa

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

Corals   **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
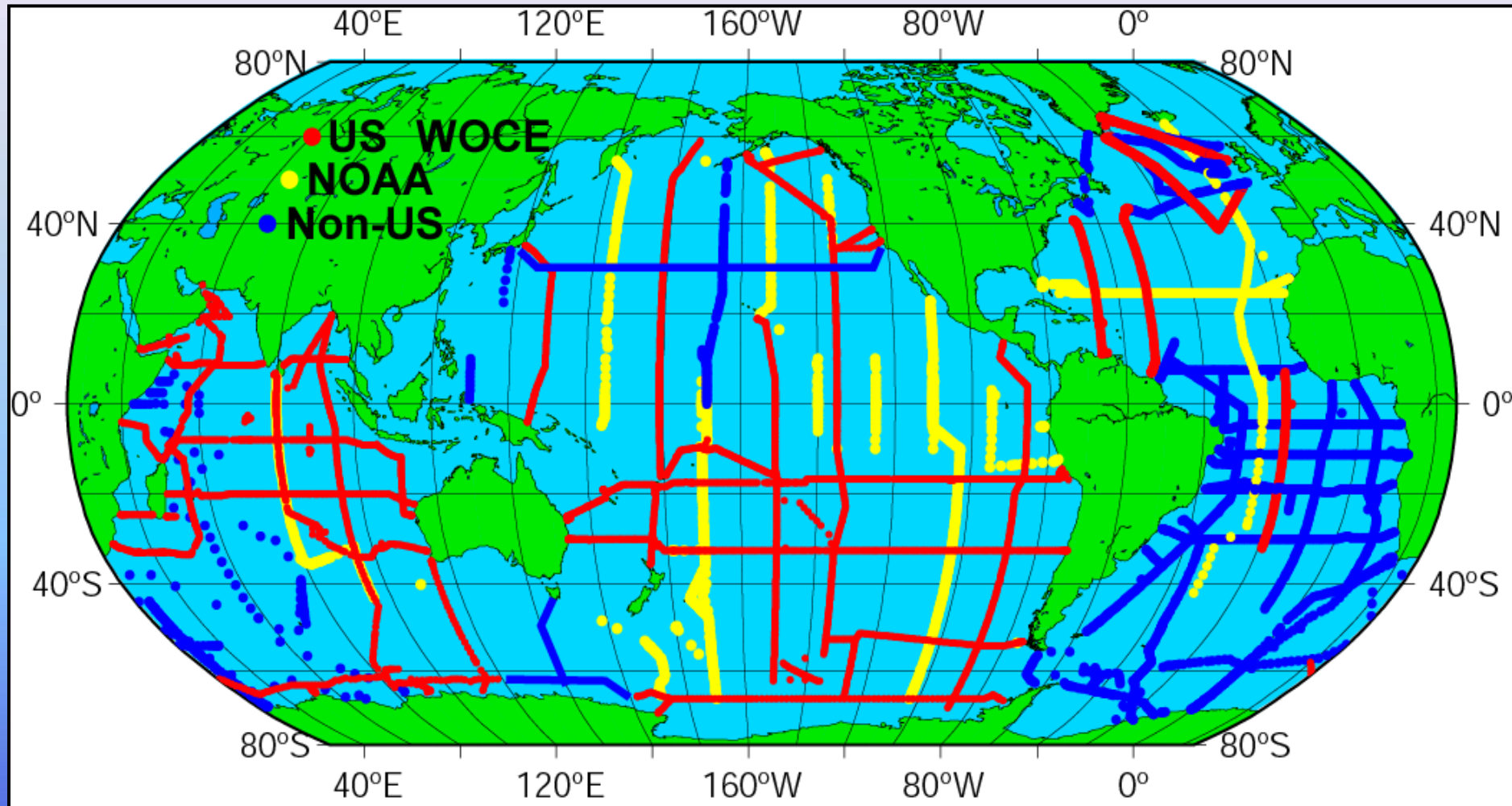
WOCE/JGOFS/OACES Global CO_2 Survey

~72,000 sample locations   DIC ± 2 μmol kg^{-1}
collected in the 1990s   TA ± 4 μmol kg^{-1}

Sabine et al (2004)

What we know about ocean CO₂ chemistry

…from present – preindustrial CO₂ concentrations in the surface oceans

Anthropogenic CO₂ (µmol/kg)

Adapted from Sabine et al. (2004)

What we know about ocean CO$_2$ chemistry

pH - Pre Industrial
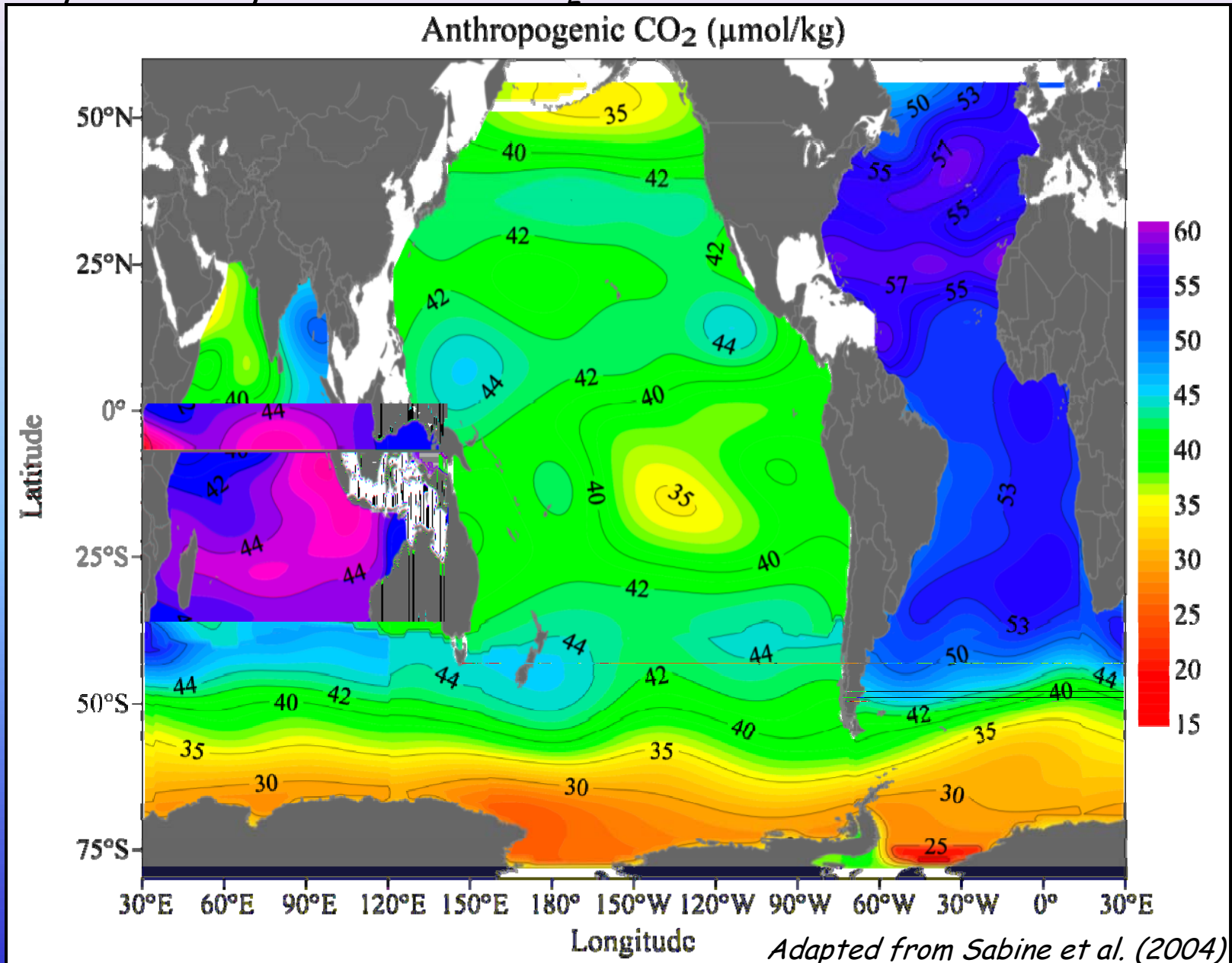
pH - Present
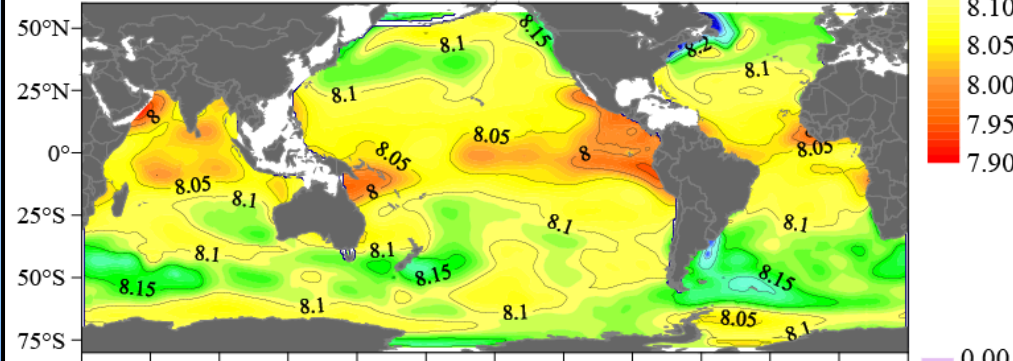
ΔpH (Present minus pre-industrial)

...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)
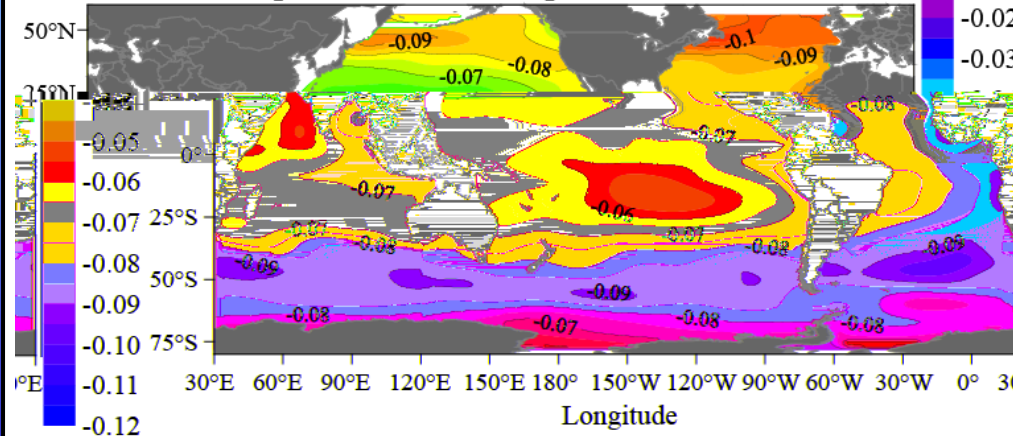
What we know about ocean CO$_2$ chemistry
...from observed saturation depths in the global oceans
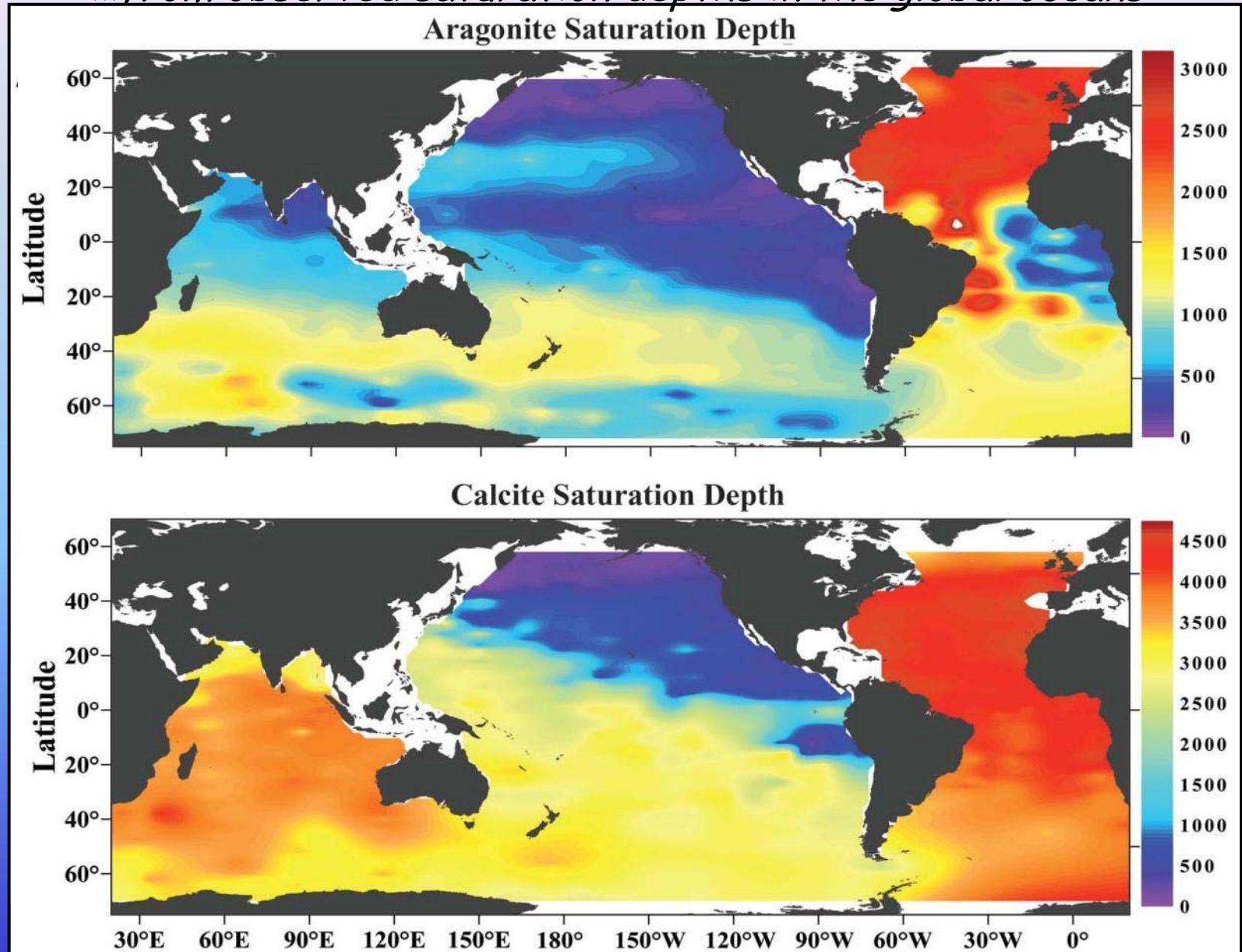
Feely et al. (2004)

Predictions of Ocean Acidification in the Global Oceans
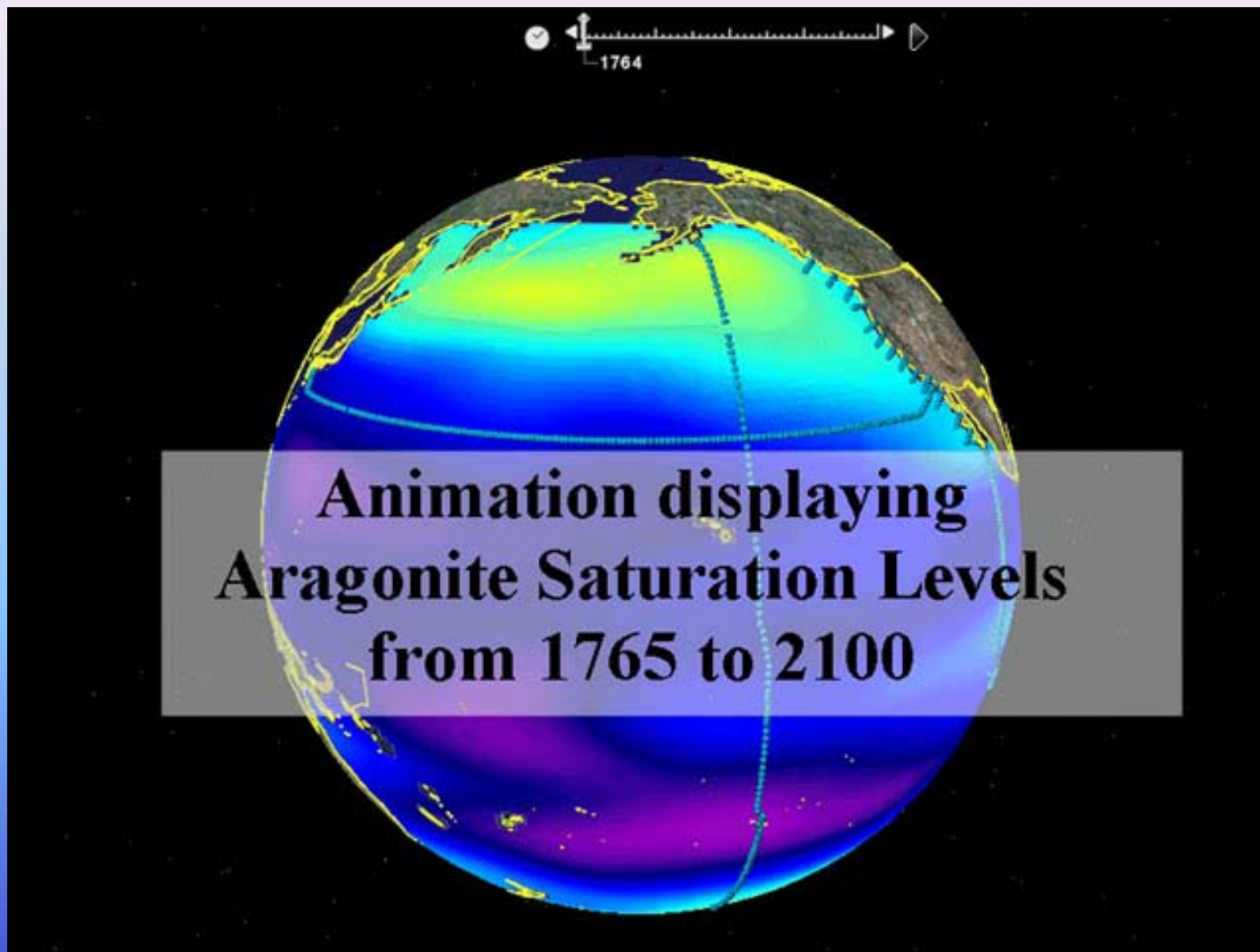
Calcification rates in the tropics may decrease by 30% over the next century

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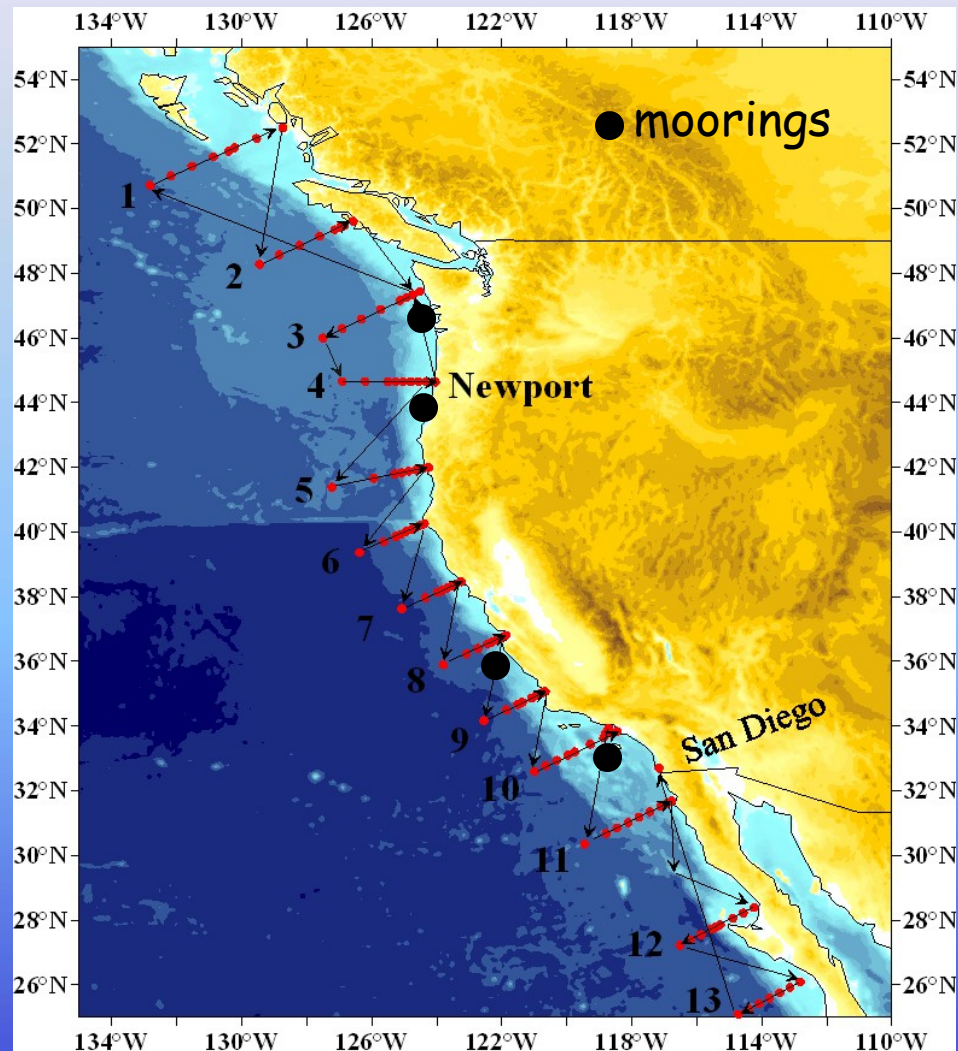
NACP West Coast Survey Cruise : 11 May - 14 June 2007
and mooring locations

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)

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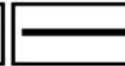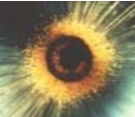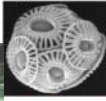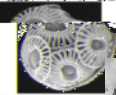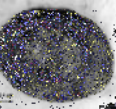
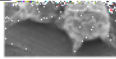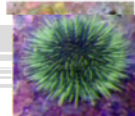# First ocean acidification mooring in the Gulf of Alaska at Station Papa

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

Note: pH scale is reversed
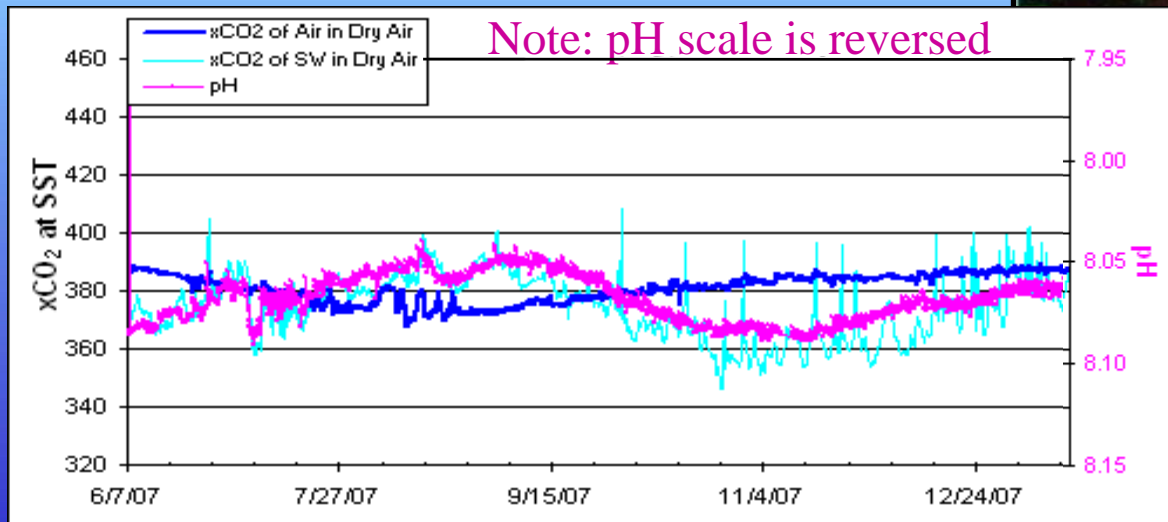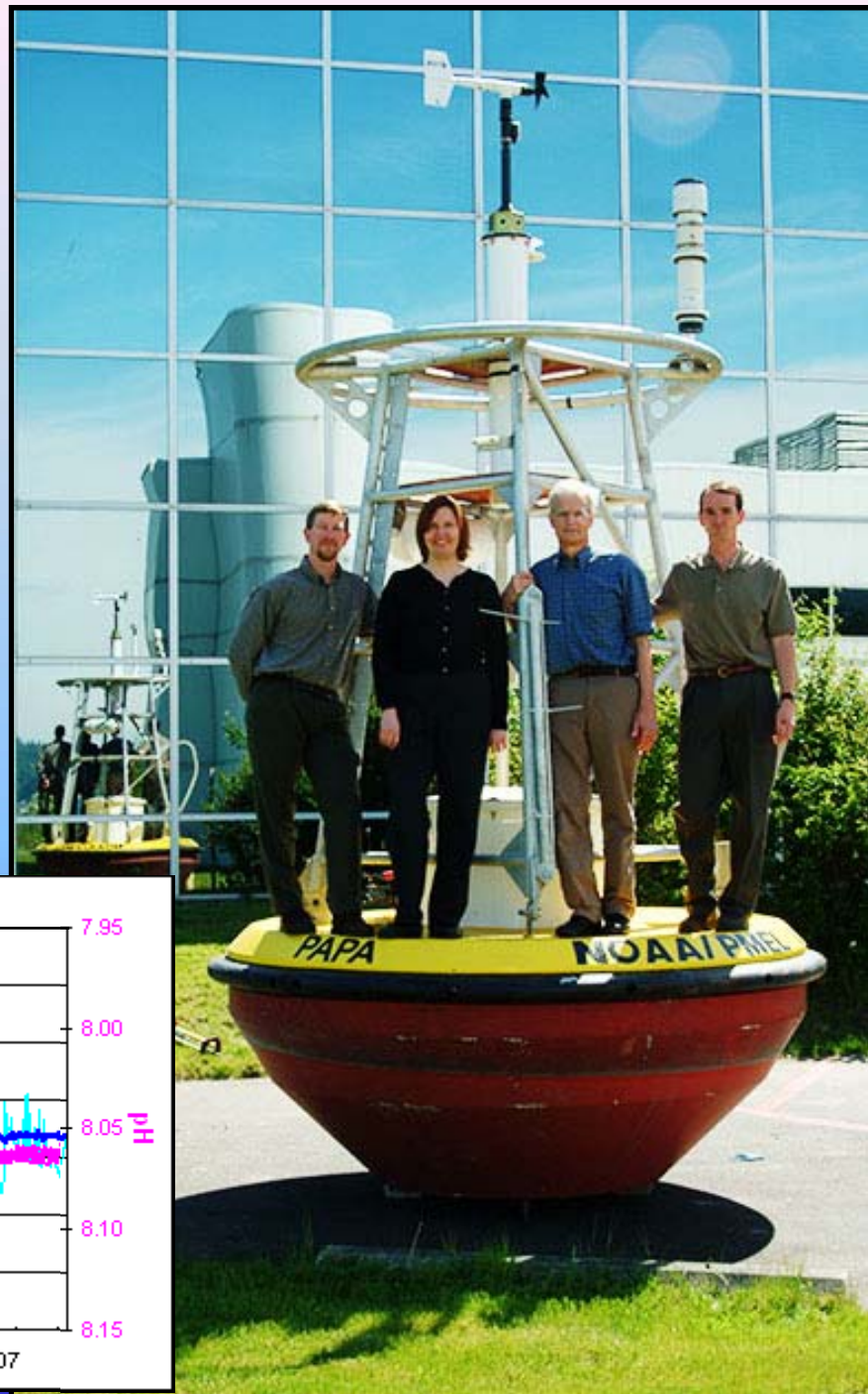
Scorecard of Biological Impacts of Ocean Acidification

Response to increasing CO_2

| Physiological process	Major group	# species studied	⟍	⌄	—	⌢
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

2009)

Figure from Doney et al. (2

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.
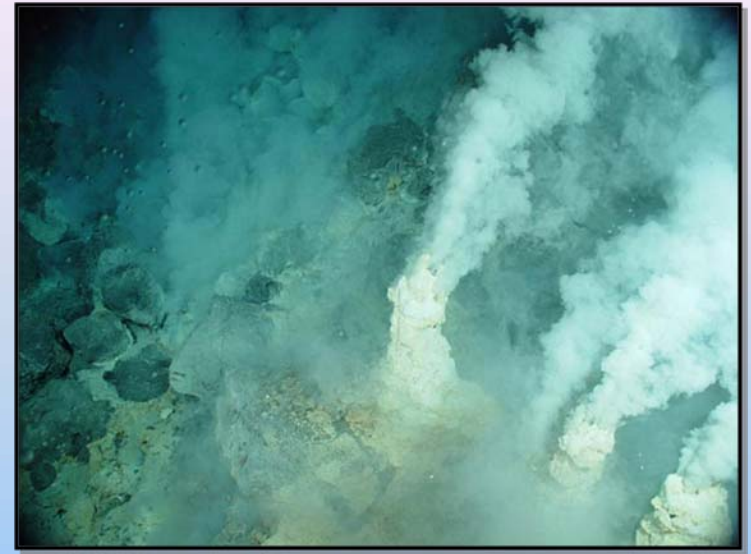
Supercritcial CO_2 and CO_2 droplets
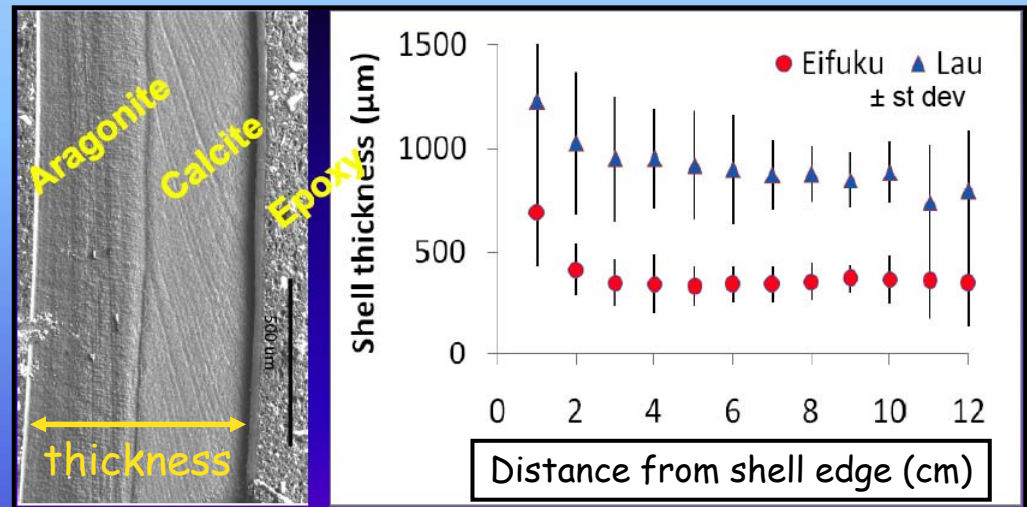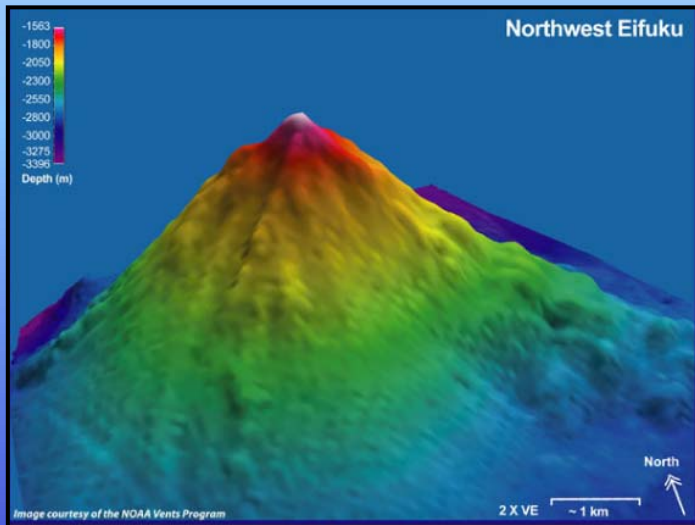
Shell thinning in an acidified ocean

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

SeaWiFS derived 2004 E. Hux. blooms   Chris Brown, NOAA
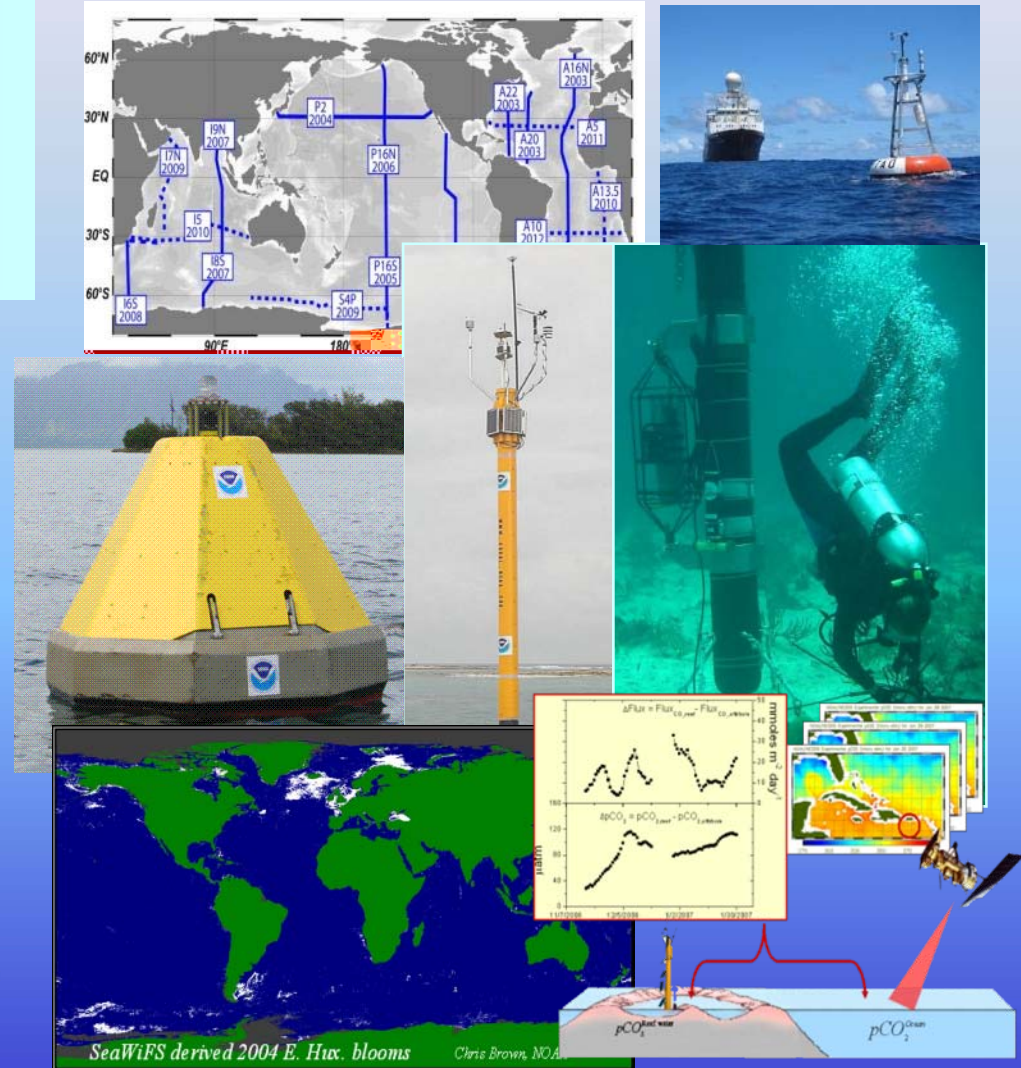
Future Challenges for the Ocean Carbon Program

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