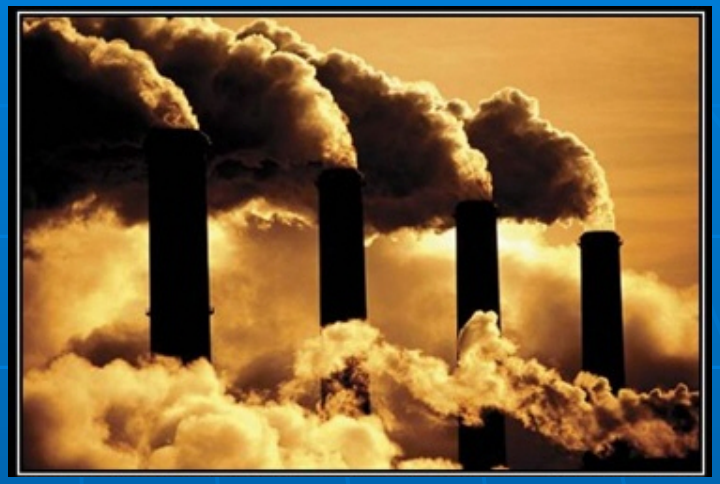
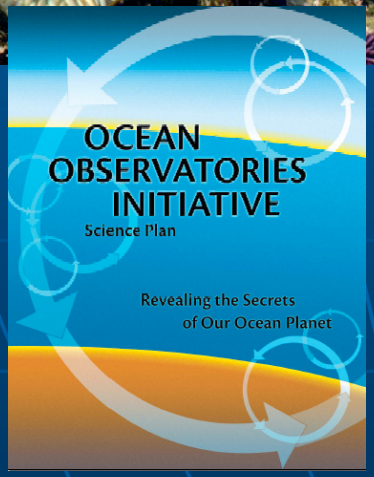
Ocean Acidification: What is in store for our oceans, our coasts, the species, the ecosystems and the human systems built upon these resources?



IOCCP

Scenes from P16S.

A CTD cast along the hydrographic section between Wellington and Tahiti.



Ocean Acidification research supported by the
National Science Foundation

Long history of foundation-building research for understanding ocean acidification – particularly in ocean chemistry, paleo-environmental studies, and calcification processes in marine animals.

Involvement of many NSF programs and program directors

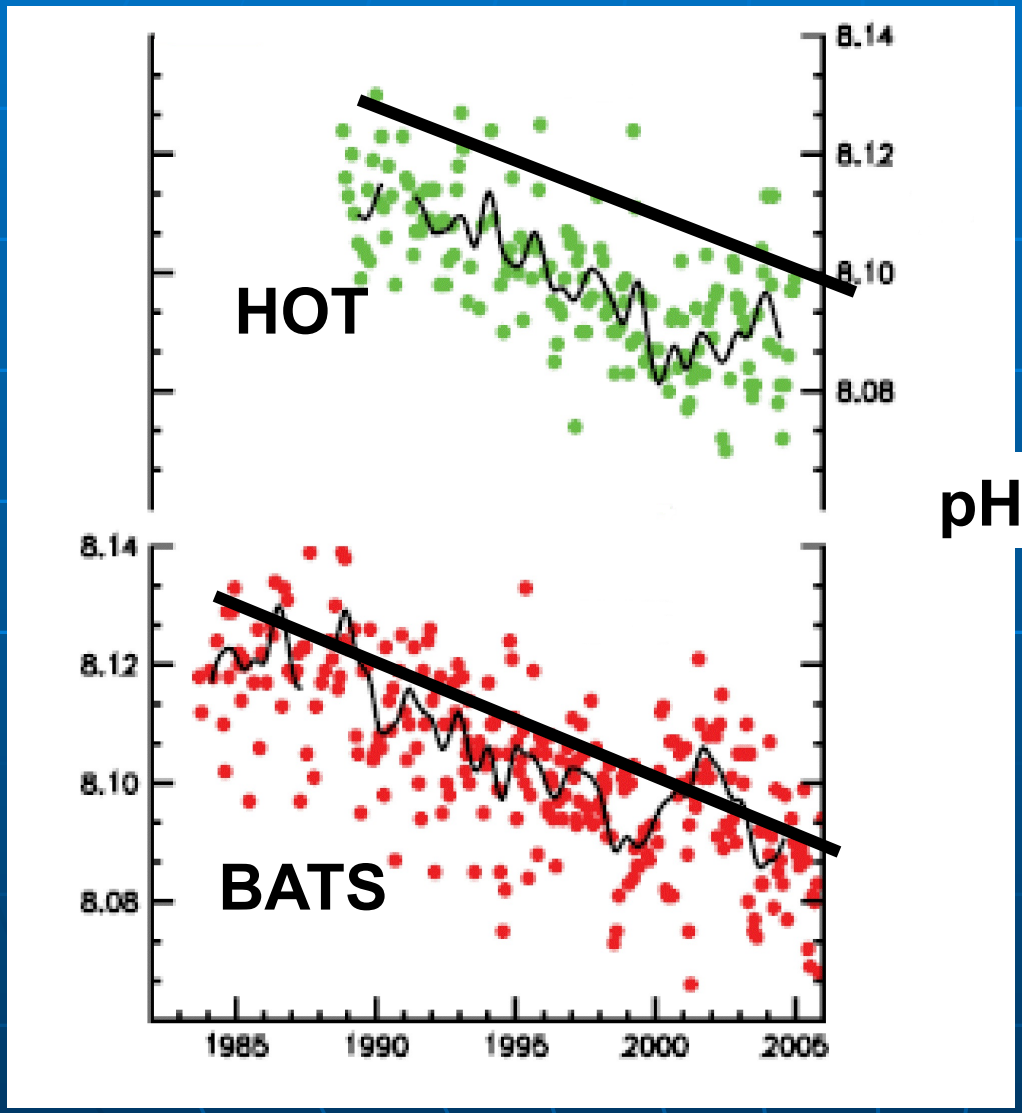
Ocean Sciences, Earth Sciences, Polar Programs, Biological Sciences:

"Core programs" and several special-focus programs

- IODP – Integrated Ocean Drilling Program;
- JGOFS - the Joint Global Ocean Flux Study;
- Biocomplexity;
- Environmental Genomics;
- Field Stations and Marine Labs
- Long-Term Ecological Research Program

1980's HOT and BATS, JGOFS and its legacy: decades of Ocean Time Series Research - Rapid Changes in the Surface Ocean pH.

Biological and Chemical Oceanography Programs



Hawaii Ocean Time-Series

Bermuda Atlantic Time-Series Study

2000 in JGOFS

David Battisti, University of Washington
Nicholas Gruber, UCLA
Robert Key, Princeton

Production and Dissolution of Calcium Carbonate in the Global Ocean: A Synthesis and Modeling Project

CO2 uptake by oceans is significantly weakening one of the major mechanisms for oceanic sequestration: *removal of CO2 via the sinking and burial of solid biogenic calcium carbonate.*

- diminished the capacity of seawater to neutralize CO2 and preserve precipitated carbonate particles,
- impacts the ability of carbonate-secreting organisms (coral reef communities as well as planktonic organisms) to thrive and to drive the "biological pump".

-These researchers calculated that the ocean has now reached about one-third of its potential to absorb and store anthropogenic carbon dioxide.

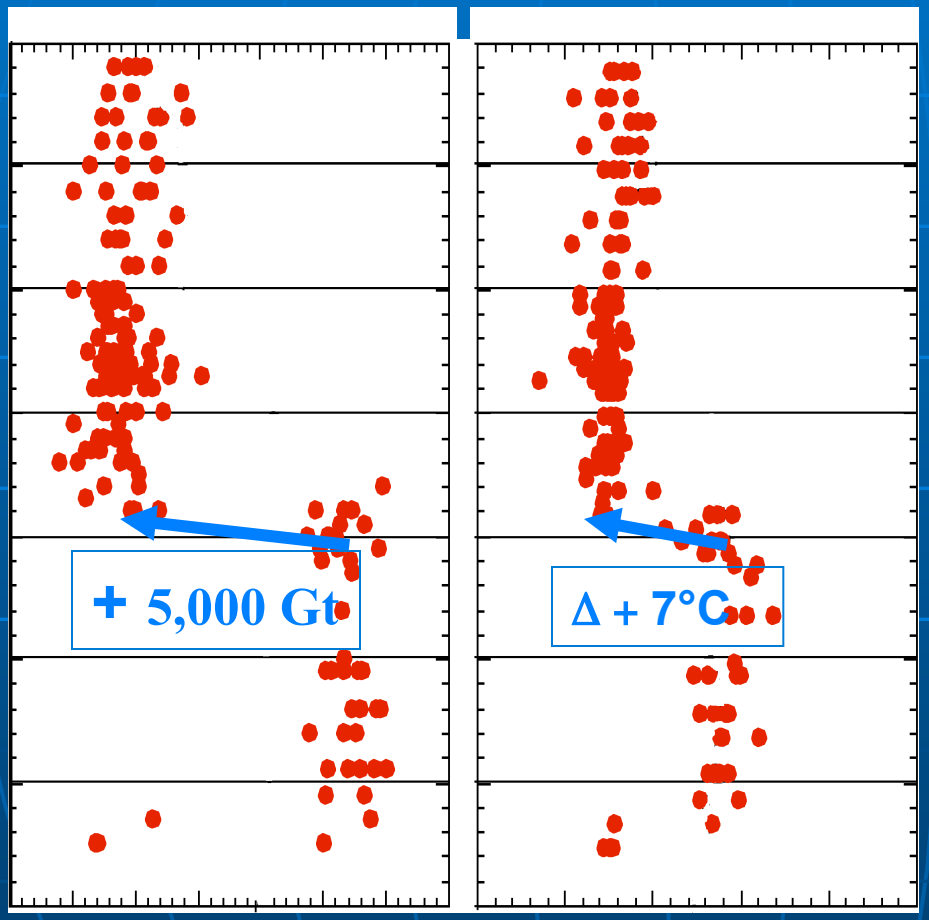
55 M years ago: 5,000 Gigaton input of Carbon to Oceans

54.95 Ma

$\delta^{13}C$

$\delta^{18}O$

100,000 years (0.8 m drilling depth below seafloor)



55.05 Ma

IODP INTEGRATED OCEAN DRILLING PROGRAM

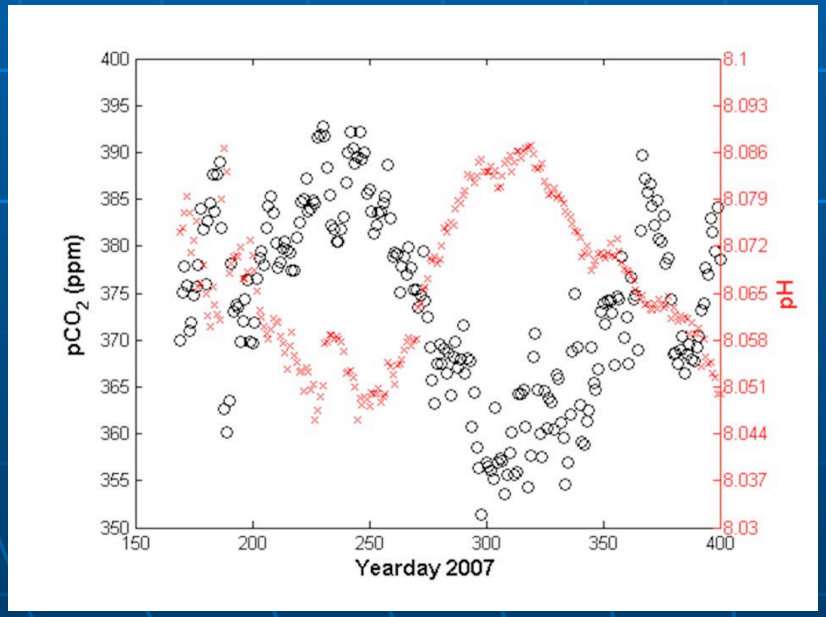
Zachos et al., 2005; *Science*

IODP and 2001 Biocomplexity Program

Consequences of Greenhouse Warming for Biocomplexity and Biogeochemical Cycles: A Multidisciplinary Case Study Across the Paleocene-Eocene Boundary

2006 – in Chemical Oceanography in collaboration with NOAA PMEL
Steve Emerson, University of Washington
Ricardo Letelier, Oregon State University
-- *Mechanisms Controlling Upper Ocean Carbon Fluxes in the North Pacific*

Figure shows the time course of pCO2 and pH on the mooring at Station Papa on which the O2 and N2 are also determined. With this kind of data it is possible to determine the organic carbon to inorganic carbon ratio in the particles produced in the euphotic zone.



2007 – in Chemical Oceanography
Robert Byrne, University of South Florida
--Purification and Calibration of Indicators for Measurement of Seawater pH

2007 – in Marine Geology/Geophysics and Chemical Oceanography
Anne Cohen, Justin Ries, and Daniel McCorkle,
--How Might Calcium Carbonate-Producing Marine Organisms Respond to Acidification of the Sea?

Working on corals and coralline algae to clams, crabs, and lobsters
Results: inhibition, enhancement and neutral responses in calcification

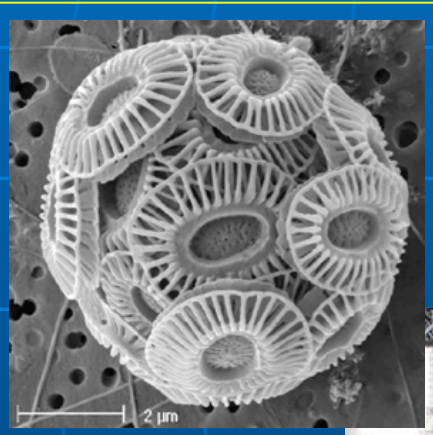
2007 – in Antarctic Organisms and Ecosystems
Victoria Fabry, California State University, San Marcos
--Impacts of Elevated pCO2 on a Dominant Aragonitic Pteropod (Thecosomata) and its Specialist Predator (Gymnosomata) in the Ross Sea.

2007 – **in Environmental Genomics**

Ed Carpenter and Jonathan Stillman, San Francisco State University

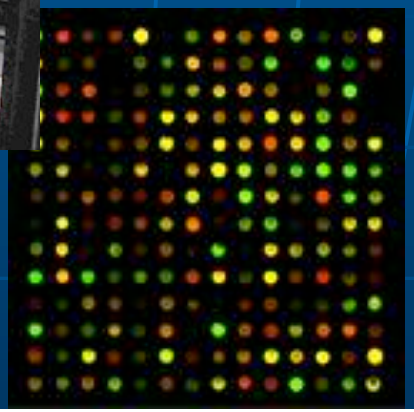
-- *A functional genomic analysis of how a major calcifying phytoplankter responds to ocean acidification predicted for the end of the century.*

How will populations and communities adapt or evolve in the face of lowering ocean pH?



Which species will be the winners and losers? How will that come about?

Experimental Systems and Genomic Microarrays Probing 100's of Generations



2008 – in **Field Stations and Marine Labs**

Kenneth Sebens, James Murray and Terry Klinger, University of Washington

-- Laboratory and Field Mesocosms for Ocean Acidification Research

Friday Harbor Laboratories facility includes

- in-water mesocosms for large-scale experimental manipulations,
- laboratory aquarium systems, and an
- analytical laboratory for essential carbon measurements to support experimentation.

2009 – **in Marine Geology and Geophysics**

James Zachos, U C Santa Cruz

Baerbel Hoensich, Columbia University

Ellen Thomas, Yale University

Richard Zeebe, University of Hawai'i

-- Reconstructing deep sea acidification during the Paleocene-Eocene Thermal Maximum

Activities in planning and coordination of the past few years, right out of the chutes of the Royal Society report.

- NSF, USGS, NOAA joint workshop on coral reefs – 2005
- OCB Program Office – facilitation of continuing community discussion and planning; support of the Ocean Acidification sub-committee (Oceans and Polar).
- Support for the IOCCP – International Ocean Carbon Coordination Project Office and activities at the IOC.
- Ocean Research Priorities Plan (ORPP) of the USG emerged in 2007. OA was a shadow priority, not one of the articulated near-term priorities but high attention.
- Ocean Carbon Biogeochemistry (OCB) Program La Jolla workshop 2008: *Present and future impacts of ocean acidification on marine ecosystems and biogeochemical cycles.*
- Support for Oceans in a High CO_2 World 2008: IGBP, SCOR, IOC, IAEA
- Reformulation of the Ocean Observing Investment (OOI) with Ocean Acidification as a primary rationale for need; OOI initiated (2009).
- NRC Report (2010), NOAA and NSF supported.
- Initiation of the Ocean Acidification element of the NSF Climate Research Investment; initial 5-year commitment.

First RFP for 2010-2011: $24 M funded. Next coming later in 2011.

Themes of the past few years (increasing to $6 M / year):

1. What are the impacts of changing pH upon ***marine chemical phenomena***:

2. What are the impacts of elevated seawater CO_2 and decreased pH upon marine organisms and their ***physiological adaptation***, on species ***genetic diversity***, on ***community structure***, and ***ecosystem processes*** of coastal, open ocean, and deep water systems?

3. In today's oceans, what are the ***major drivers impacting seawater acidity and alkalinity***?

4. ***What does the geologic record reveal*** about the relationship between seawater pH and carbonate ion, marine species and their evolution,

5. Can changes in the ***physical chemistry*** of the ocean affect other parameters in the water column, e.g., particle aggregation?

6. What are some existing and *potential* ***observational, experimental, and theoretical approaches*** for studying past, present, and future trends in ocean acidification?

FOARAM

The ***F***ederal ***O***cean ***A***cidification ***R***esearch ***a***nd ***M***onitoring Act

FOARAM passed in the House of Representatives and Senate respectively on 3rd and 19th March 2009.

The Act authorizes appropriations for NOAA and NSF for ocean acidification research for fiscal years 2009, 2010, 2011, and 2012, at $14 million, $20 million, and $27 million, and $35 million per year, respectively.

Establishes an interagency committee to develop an ocean acidification research and monitoring plan – The IWG-OA.

Establishes an ocean acidification program within NOAA

More information is needed to:

- ♦♦ understand the **chemical and physical processes** affecting acidification in coastal waters;
- ♦♦ understand the **physiological mechanisms of biological responses**;
- ♦♦ assess the potential for **acclimation and adaptation**;
- ♦♦ investigate the **response of individuals, populations, and communities of species**.
- ♦♦ understand the **ecosystem-level consequences**, including the implications for biogeochemical cycles
- ♦♦ investigate the interactive **effects of multiple stressors**;
- ♦♦ understand the **socio-economic impacts** and the **decisions that must be made for mitigation and human system adaptation**.

The needs are articulated strongly

A global network of chemical, biological and ecological observations to monitor changes in ocean conditions attributable to a lowering pH.

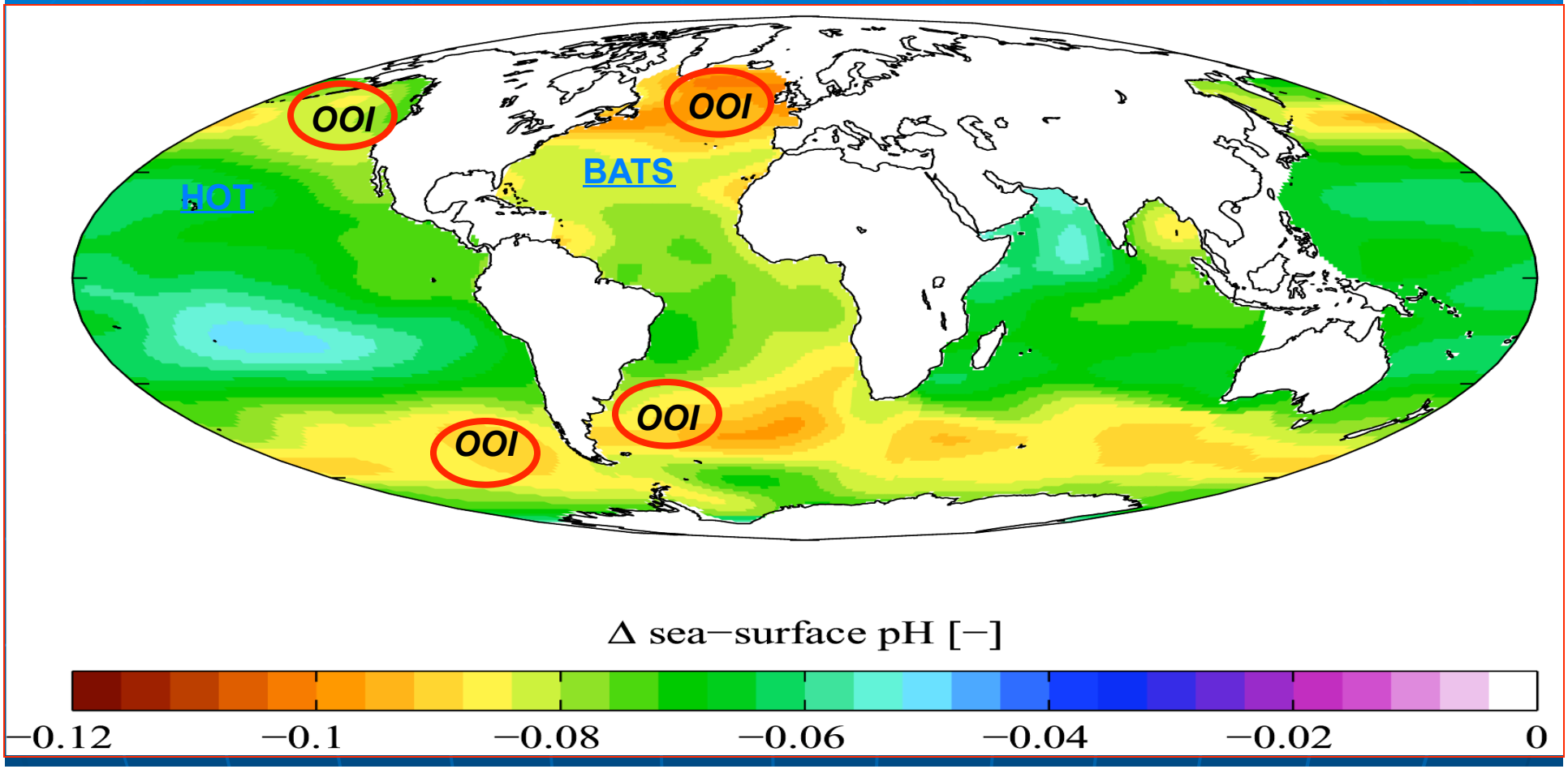
Support for infrastructure for this science: development of standards for measurements, systems for data collection and archiving to ensure that data is accessible and useful into the future.

International cooperation, coordination and collaboration.

Sustained support.

HOW ARE WE RESPONDING???

Looking at Global Ocean pH decreases in the past 200 years



30 % “increased acidity” for High Latitude Surface Waters

OOI - Ocean Observing Investment in higher latitude oceans

2010 Climate Research Investment - Interdisciplinary and Inter-unit at the NSF. Themes on hot topics related to global environmental change.

- Top levels of NSF provided the opportunity; required a group of interested NSF offices to agree on priority.
- Narrow focus on ocean problem overcome by the high interest in the research topic.
- Other topics – Water Sustainability; Earth System Modeling; Dimensions of Biodiversity.

- Coalition committed funds for O-A - the Geosciences Directorate (Ocean), the Office of Polar Programs (Antarctic and Arctic), the Biological Sciences Directorate (Molecular, Cellular, Organismal)

- 2010 RFP announced with $12-15 million anticipated, including facilities costs.

Research themes:

- To understand the ***chemistry and physical chemistry*** of ocean acidification and, in particular, its interplay with fundamental biochemical and physiological processes of organisms;
- To understand how ocean acidification interacts with ***processes at the organismal level***, and how such interactions ***impact the structure and function of ecosystems***, e.g. through life histories, food webs, biogeochemical cycling, and other interactions;
- To understand ***how the earth system history informs*** our understanding of the effects of ocean acidification on the present day and future ocean.

Called for full research proposals, exploratory proposals, and community development efforts

External review completed in the summer 2010 with awards completed in the late summer and fall (102 projects proposed).

22 awarded projects, about $24 million combining 2010 and 2011.

Ocean Chemistry

Tara Takahashi, Columbia University
Climatological Mean Distribution of pH in Surface Waters in the Unified pH Scale and Mean Rate of changes in Selected Areas

Uta Passow, University of California - Santa Barbara
Will high CO_2 conditions affect production, partitioning and fate of organic matter? (**POM and DOM**)

Observation and Modeling

Jeremy Mathis, University of Alaska
Rolf Sonnerup, University of Washington
Observation and Prediction of Ocean Acidification in the Western Arctic Ocean: Impacts of Physical and Biogeochemical Processes on Carbonate Mineral States

Jorge Sarmiento, Princeton University
Does the strength of the carbonate pump change with ocean stratification and acidification and how?

Methods / Technology

Robert Thunnel, University of South Carolina
Real time assessment of ocean acidification proxies and their incorporation in the marine sediment record.

Baerbel Hoenisch, Columbia University
Calibration and application of the boron isotope seawater-pH indicator in **deep-water corals.**

Lisa Levin, Scripps Institution of Oceanography
Ariel Anbar, Arizona State University
Development of geochemical proxies to evaluate **larval** pH-exposure history. (**mussels**)

Community Building

Ed Urban, SCOR
Third Symposium on The Ocean in a High-CO_2 World (2012, Monterey CA)

Fundamental Biology

Francois Morel, Princeton; Brian Hopkinson, University of Georgia
Effects of pCO_2 and pH on photosynthesis, respiration and growth in marine **phytoplankton**

Jeff Runge, University of Maine
Impact of ocean acidification on survival of early life stages of planktonic **copepods** in the genus *Calanus* in the northern

Paul Falkowski, Rutgers University
The molecular basis of ocean acidification effects on calcification in zooxanthellate **corals.**

Andrea Grottoli, Ohio State; Mark Warner, University of Delaware
Wei-Jun Cai, University of Georgia
Interactive Effects of Temperature, Nutrients, and Ocean Acidification on **Coral** Physiology and Calcification.

Anne Cohen, WHOI; Samantha de Putron, BIOS
An Investigation of the Role of Nutrition in the **Coral** Calcification Response to Ocean Acidification.

Fundamental Biology

George Waldbusser, Oregon State University
A mechanistic understanding of the impacts of ocean acidification on the early life stages of marine **bivalves.**

Emily Carrington, University of Washington.
Effects of ocean acidification on coastal organisms: an ecomaterials perspective. (**bivalves, snails, crustaceans, and seaweeds**)

Sean Place, University of South Carolina
Identifying adaptive responses of **polar fishes** in a vulnerable ecosystem

Jonathan Stillman, San Francisco State University
Lars Tomanek, California Polytechnic State University
Synergistic effects of temperature and pH variability on physiology, transcriptome and proteome of porcelain **crabs**

Adina Paytan, University of California - Santa Cruz
Calcification in low saturation seawater: What can we learn from organisms in the proximity of low pH, undersaturated submarine springs?

Ecology

Gareth Lawson, WHOI
Horizontal and Vertical Distribution of Thecosome **Pteropods** in Relation to Carbonate Chemistry in the Northwest Atlantic and Northeast Pacific

Robert Carpenter, California State University, Northridge
The effects of ocean acidification on the organismic biology and community ecology of **corals, calcified algae, and coral reefs** in Moorea. (w/ LTER)

James McClintock, University of Alabama – Birmingham
The effects of ocean acidification and rising sea surface temperatures on shallow-water **benthic organisms in Antarctica. (macroalgae and grazers)**

Bruce Menge, Oregon State; Eric Sanford, UC - Davis
Gretchen Hoffman, UC - Santa Barbara; Steve Palumbi, Stanford University
Peter Raimondi, UC - Santa Cruz; Margaret McManus, University of Hawaii
Acclimation and adaptation to ocean acidification of key ecosystem components in the California Current System.