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

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.*
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

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.
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 CO₂ 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.
  
Themes of the past few years (increasing to $6M/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?
The **Federal Ocean Acidification Research and Monitoring 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)
Effects of pCO$_2$ and pH on photosynthesis, respiration and growth in marine phytoplankton

Impact of ocean acidification on survival of early life stages of planktonic copepods in the genus *Calanus* in the northern

The molecular basis of ocean acidification effects on calcification in zooxanthellate corals.

Interactive Effects of Temperature, Nutrients, and Ocean Acidification on Coral Physiology and Calcification.

An Investigation of the Role of Nutrition in the Coral Calcification Response to Ocean Acidification.
<table>
<thead>
<tr>
<th>Author</th>
<th>Institution</th>
<th>Research Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>George</td>
<td>Oregon State University</td>
<td>A mechanistic understanding of the impacts of ocean acidification on the early life stages of marine <strong>bivalves</strong>.</td>
</tr>
<tr>
<td>Emily</td>
<td>University of Washington</td>
<td>Effects of ocean acidification on coastal organisms: an ecomaterials perspective. <em>(bivalves, snails, crustaceans, and seaweeds)</em></td>
</tr>
<tr>
<td>Sean</td>
<td>University of South Carolina</td>
<td>Identifying adaptive responses of <strong>polar fishes</strong> in a vulnerable ecosystem</td>
</tr>
<tr>
<td>Jonathan</td>
<td>San Francisco State University</td>
<td>Synergistic effects of temperature and pH variability on physiology, transcriptome and proteome of porcelain <strong>crabs</strong></td>
</tr>
<tr>
<td>Adina</td>
<td>University of California - Santa Cruz</td>
<td>Calcification in low saturation seawater: What can we learn from organisms in the proximity of low pH, undersaturated submarine springs?</td>
</tr>
</tbody>
</table>
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.