Oceanography: Future Science Questions and Research Opportunities

James W. Murray
School of Oceanography
University of Washington
Siesta Valley Syncline

**Stratiographic Column**

- Bald Peak (TB) - Dark Green (Plio.)
  - Basalt-Porphyrite
- Siesta (TS) - Yellow (Plio.)
  - Clays, mudstones, Sandstone
  - Lapilli Lens (TSV)
  - Freshwater Limestone
- Grizzly Peak (TGP) - Green (Plio.)
  - Andesite, Rhyolitic Tuff
- Orinda (TO) - Red (Mio.)
  - Sandstone, Conglomerate
- Claremont (Tc) - Purple (Mio.)
  - Chert, Shale

as it appeared in Spring 1966

Geol 5 w/ Dr. Curtis
Main US Programs in Oceanography

University of Delaware College of Marine Studies
University of Hawaii (SOEST)
Florida Tech
Florida State University (FSU)
Humboldt State University
Lamont-Doherty Earth Observatory
University of Miami (Rosenstiel School)
Old Dominion University
Oregon State University
Scripps Institute of Oceanography (UCSD)
University of Rhode Island
University of South Florida
Texas A&M University
University of Washington (UW)
University of Texas
University of Southern California
UC Santa Cruz
MIT/WHOI Joint Program
Programs subdivided into disciplines of physical, chemical, biological and geological oceanography

In most programs grad students are fully supported (stipends and tuition)

In addition apply for NSF and NDSEQ Graduate Fellowships

Students are evaluated and accepted based on their strength in core disciplines, GPA, GRE and Letters.

Research experience is invaluable, and many options are available. Here at Cal there must be many opportunities plus NSF supported REU programs all around the US.
Outline

1. The Fourth Assessment Report of the IPCC (AR4) Climate Change is occurring
2. Temperature ↑, Ocean Warming
3. CO2 ↑, Ocean Acidification

We need to study the impacts of both temperature and high CO₂ on the processes that affect ecosystem responses under natural conditions.
Framing the Questions for the Future

We Learn the Most When Systems are perturbed!

Examples:

Natural / Anthropogenic Forcing
- Glacial/Interglacial
- El Nino / La Nina
- Anthropogenic GHG Production
- Ocean Warming
- Ocean Acidification

Artificial Forcing
- Fe Fertilization Experiments
- Ocean Acidification Mesocosm Experiments
“It is very likely that [man-made] increases in greenhouse gases have caused most of the average temperature increase since the mid-20 century”
- IPCC 4th Assessment Report

- Man-Made Greenhouse gases (CO₂, CH₄, N₂O)
- Increased global temperatures
- Sea level rise
- Loss of sea ice
- Loss of biodiversity
- Ocean acidification

- Foreknowledge is Power
  For policy creation and mitigation
  Complex earth systems require predictive models

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

Antarctic Ice Core Record
Cause and effect...

Greenhouse Gases and Warming

Related?
$CO_2$ emissions (GtC/y)

Are we on track?
Recent emissions have been greater than before.
Verification

Geophysics is not an experimental science!

We have to use models.

Models predict recent increase in Global T well.

Simulated global annual mean warming from 1860 to 1990, allowing for increases in equivalent CO₂ only (light gray) and allowing for increases in equivalent CO₂ and the direct effects of sulphates (darker gray) (Mitchell et al., 1995, Nature, 376, 501-504). The observed changes are from Parker et al. (1994, J. Geophys. Res., 99, 14373-14399). The anomalies are calculated relative to the 1880 - 1920.
Prediction

Models for the future depend on CO2 production scenarios. A series of future worlds “Story Lines”

For Business as Usual
\[ \Delta T = +3 \text{ to } 5^\circ C \text{ by } 2100 \]

2°C is considered the tipping point for intolerable human impacts

Even if emissions were completely halted today
\[ \Delta T = +1.5^\circ C \]
Spatial Patterns

Warming will be largest over land and at high latitudes

Modelling Climate Change

Framing the Problem: Climate in a World of Multiple Stresses

- Increasing surface & sub-surface heat in the world ocean.
- Large scale changes in ocean chemistry (Feely et al., 2004; Sabine et al. 2004).
- Global overfishing—"Fishing down the food chain", (Pauly, 2003).
- Land-based pollution of the coastal ocean (GESAMP, 2001).
- Proliferation of invasive species
First Stress

Ocean Warming
Most Heat in the Ocean


Heat absorbed by the world ocean

- 0.9 Heat absorbed by the continents (Beltrami et al., 2002)
- 0.8 Heat required to melt continental glaciers at estimated maximum melting rate (Houghton et al., 2001)
- 0.7 Heat absorbed by the atmosphere during 1955-96 (Levitus et al., 2001)
- 0.3 Heat required to reduce Antarctic sea-ice extent (de la Mare, 1997)
- 0.1 Heat required to melt mountain glaciers at estimated maximum melting rate (Houghton et al., 2001)
- 0.005 Heat required to melt northern hemisphere sea-ice (Parkinson et al., 1999)
- 0.002 Heat required to melt Arctic perennial sea-ice volume (Rothrock et al., 1999)

$X \times 10^{22} \text{ J}$
Change in oceanic heat content (IPCC-2007)

$\Delta T = 0.10^\circ C$

0-700 m
1961-2003

larger rate
1993-2003
0.5 W m$^{-2}$

1961-2003: Rate of $3.3 \times 10^{21}$ J yr$^{-1} = 0.2$ W m$^{-2}$ (earth’s surface)
World Ocean Warming (°C) 1900 to 2000

Observed: matches model hindcasts very well

Between 1955 - 1998, world ocean heat content between 0 - 3000 m depth increased $14.5 \times 10^{22} \text{ J}$

$= \text{mean Temp increase of } 0.037^\circ \text{C at rate of } 0.20 \text{ Wm}^{-2}$.  

*Levitus et al., 2005*
Good News – so far

No evidence for trends in ocean circulation:

• no coherent evidence for a trend in the strength of the Meridional Overturning Circulation

• no evidence for a systematic trend in volume transport of the Antarctic Circumpolar Current

• growing evidence for changes in Antarctic Bottom Waters

• evidence for regional variability associated with NAO, PDO and SAM

Willebrand, Bindoff et al. in press IPCC-2007
Retreat of the South Cascades Glacier

Also: reduction of winter snowpack and reduces freshwater supply

Source: USGS ca. 2005
Surface Melt on Greenland

Melt descending into a moulin, a vertical shaft carrying water to ice sheet base.

Source: Roger Braithwaite, University of Manchester (UK)
Change in oceanic global sea level

Rates of sea level rise (mm yr\(^{-1}\))

1961-2003: 1.8 ± 0.5
1993-2003: 3.1 ± 0.7

Due to thermal expansion (25%) and melting of continental ice

Willebrand, Bindoff et al. in press IPCC-2007
A Serious Concern
Decline in Arctic Sea Ice
Sea ice extent in the Arctic—past, current, and future
Impacts on ocean ecosystems – global view

Ocean Warming will lead to contraction and expansion of different biomes.
By 2050 - in Northern Hemisphere
Marginal ice (-42%)
Subpolar Gyre (+16%)
Subtropical gyre (+4.0%)
vertical stratification increases
* decrease nutrient supply
* increase in growing season
Impacts on ocean ecosystems – local view

Temperature is arguably the key variable for the success of ‘northern’ fish stocks like cod
Second Stress

*Ocean Acidification*
Ocean Acidification: The Other CO$_2$ Problem

Scott C. Doney,¹ Victoria J. Fabry,² Richard A. Feely,³ and Joan A. Kleypas⁴

¹Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543; email: sdoney@whoi.edu

²Department of Biological Sciences, California State University, San Marcos, California 92096; email: fabry@csusm.edu

³Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, Washington 98115; email: Richard.A.Feely@noaa.gov

⁴Institute for the Study of Society and Environment, National Center for Atmospheric Research, Boulder, Colorado 80307; email: kleypas@ucar.edu
Global fossil fuel CO₂ emissions with division into portions that remain airborne or are soaked up by the ocean and land.
xsCO2 in the ocean today!

Total anthropogenic $CO_2$ Distributions.

Global Average Depth of $5 \, \mumol$ kg$^{-1}$ contour is $\sim 800$ m
Predictions of Ocean Acidification 
and the effects on coral reef calcification

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

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

Coastal Results

\[ \Omega = 1 = \frac{[Ca^{+2}][CO_3^{-2}]}{K'_{sp}} \]

Estimate that anthropogenic CO\textsubscript{2} has resulted in a shoaling of the aragonite saturation horizon by 50m on line 5.

Feely et al. (2008)
Oh Oh Chemistry!
Ocean Acidification

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}^+\text{CO}_3^- + \text{H}_2\text{O} \]

\[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}^+\text{CO}_3^- \rightarrow \text{HCO}_3^- \]

Provided by Dwight Gledhill
Ocean Acidification

\[ CO_2 + CO_3^{2-} + H_2O \rightleftharpoons 2HCO_3^- \]

Saturation State =

\[ \Omega_{phase} = \frac{[Ca^{2+}] [CO_3^{2-}]}{K_{sp, phase}} \]

Ca\(^{2+}\) + CO\(_3^{2-}\) → CaCO\(_3\)

calcium + carbonate → calcium carbonate

\( \Omega > 1 = \text{precipitation} \)
\( \Omega = 1 = \text{equilibrium} \)
\( \Omega < 1 = \text{dissolution} \)

Photos courtesy Katie Fagan
Calcifying marine organisms and calcium carbonate phases

Coccolithophores

Forams

Calcite

Calcite

T. Tyrrel

Calcareous algae

Corals

High-Mg calcite

Aragonite

Nancy Sefton

NOAA
Potential Effects on Open Ocean Food Webs

Coccolithophores

Copepods

Pacific Salmon

Pteropods

Barrie Kovish

Vicki Fabry

ARCOD@ims.uaf.edu
Mesocosm experiment, Bergen
Pelagic Ecosystem CO₂ Enrichment Study

Three pCO₂ treatments representing: Glacial, Present, and Year 2100

Large Scale Mesocosm Facility, University of Bergen, Norway

from U. Riebesell & B. Rost
Conclusions

We need to study the impacts of both temperature and high \( CO_2 \) on the processes that affect ecosystem responses under natural conditions.

- Ocean acidification and Ocean warming are growing problems
- Highly productive marine ecosystems such as coral reefs and the Bering Sea are especially sensitive to these changes
- Studies and monitoring (both satellite and in situ) are needed now to identify impacts

- Ocean acidification makes it critical that we combat stressors that we can address now
A Final Couple of Points
Models are incomplete... Feedbacks are not included

Example:

Effect of Warming on Ocean uptake of CO2

MAGNITUDE OF FEEDBACK

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1990-2065</td>
<td>1850-2100</td>
<td>1765-2100</td>
</tr>
</tbody>
</table>

| Warming (nat. CO2)   | -11%                    | -12%               | -13%               |
| Circulation (ant CO2)| -22%                    | -10%               | -3%                |
|                       | -33%                    | -22%               | -16%               |
Monsters Behind the Door

- Ocean Circulation
- Hurricanes
- Sahel Drought
- Ice Sheets
“When I think about the climate crisis today I can imagine a time in the future when our children and grandchildren ask us one of two questions. Either they will ask: What were you thinking, didn’t you care about our future? Or they will ask: How did you find the moral courage to cross party lines and solve this crisis? We must hear their questions now. We must answer them with our actions, not merely with our promises.

We must choose a future for which our children and grandchildren will thank us.”

-Testimony of the Honorable Al Gore
Before the U.S. House of Representatives
Energy & Commerce Committee
Subcommittee on Energy & Air Quality
and the
Science & Technology Committee
Subcommittee on Energy & Environment

March 21, 2007
The End