Despite these initially encouraging results, significant problems remain. The most important and one that was repeatedly raised was that of chronology. The offset (around 200 years) in the terrestrial dates for the Agassiz drainage and the ice core chronologies, while within error bars, is still quite significant. Other carbon-dated records in the ocean sediment or on land are affected by a carbon-dating plateau around this time, which suggests the need for more work on alternate dating techniques, such as tephrology, for cross-correlating the different records. Other questions are more subtle. The North Atlantic has a very complex and dynamic circulation on decadal to multi-decadal timescales, and modern observations do not support the notion that all of this variability can be associated with a single quantity (such as the overturning streamfunction). Fitting the disparate ocean records into a wider and more complex picture is not easy and work is clearly required to improve that. And finally, improved and higher resolution data from the tropics and sub-tropics—particularly in Asia—are going to be needed to resolve the amplitude of any far-field response. The latest results and initial modeling work strengthen the panel's initial view that this event is a key target for Holocene paleoclimatology and that it may prove helpful in providing tests of climate models and influencing their development. That potential has yet to be fully realized.

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IGBP-SCOR Workshop: Ocean acidification — modern observations and past experiences

GLOBAL CHANGE IGBP International Council for Science
Scientific Committee on Oceanic Research

Lamont-Doherty Earth Observatory of Columbia University, USA, 28-30 September 2006

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This workshop was the centerpiece of the Fast-Track Initiative (FTI) on Ocean Acidification of the International Geosphere-Biosphere Programme (IGBP) and the Scientific Committee on Oceanic Research (SCOR). The FTI is about exploring how we can learn from past changes in the Earth system to better understand the consequences of ongoing ocean acidification, and involves several projects with a marine focus (GLOBEC, IMBER, LOICZ, SOLAS, PAGES and IMAGES).

The workshop was attended by 65 international participants (Fig. 1). It was co-sponsored by IGBP, SCOR, and PAGES, and organized by the PAGES IPO and local hosts at Lamont. The goals of the workshop were to:

1) bring together researchers on modern ocean acidification with researchers investigating relevant events in Earth history and
(2) explore how paleo-studies can shed light on the consequences of fossil-fuel CO_2 release into our environment.

A series of overview talks, posters, and breakout-group discussions stimulated cross-disciplinary thinking between paleo and modern perspectives, and among chemical, geological, and biological researchers, as summarized below:

Modern observations ...

The rates and amounts of CO_2 currently being emitted exceed those inferred for at least the past 50 million years, and possibly much longer. Much of this CO_2 is being absorbed by the ocean, where it is causing changes in the carbonate chemistry of seawater. Today, the surface oceans are supersaturated with respect to aragonite and calcite. However, the degree of supersaturation is declining, and the saturation horizons are migrating toward the ocean surface. The fundamental chemistry of human-induced ocean acidification is well understood but we are unable to predict how marine organisms will be able to adapt to ocean chemistry changes. The most optimistic view is that for organisms with short generation times, micro-evolutionary adaptation could be rapid and that species adversely affected by high CO_2 could be replaced by more CO_2-tolerant strains or species, with minimal ecological impacts. The most pessimistic view is that CO_2-sensitive groups (e.g., marine calcifiers) will be unable to compete ecologically with profound ramifications up the food chain, including widespread extinctions.

The consequences of ocean acidification appear to be clearest for corals, with most studies suggesting a linear relationship between coral calcification rate and aragonite saturation state. Coccolithophores and foraminifera generally exhibit

Figure 1: Group photo of the participants at the IGBP-SCOR Workshop on "ocean acidification" in front of "Lamont Hall".

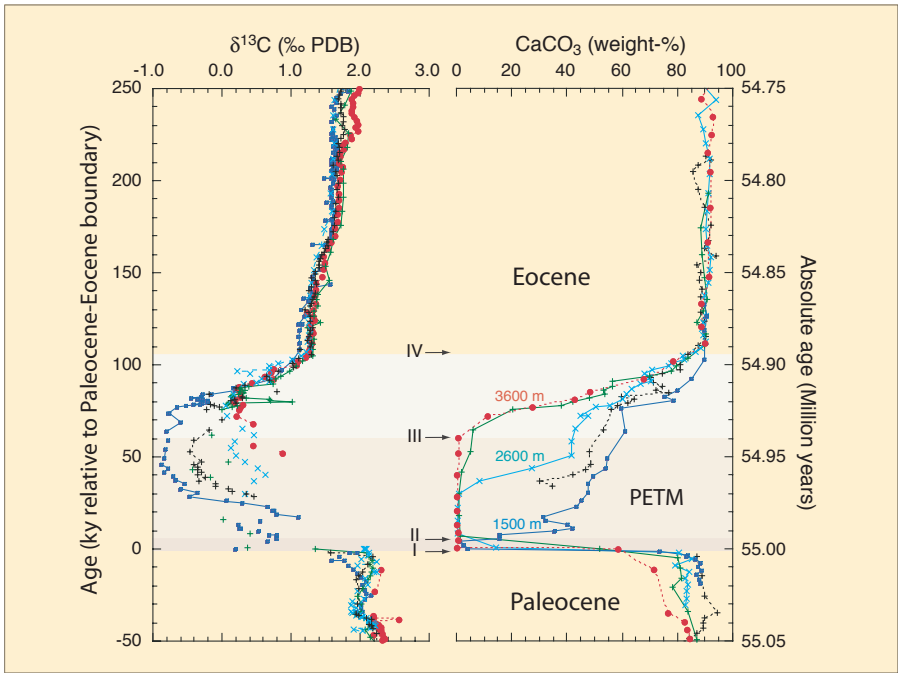

Figure 2: Geochemical records across the Paleocene Eocene Thermal Maximum (PETM) from a depth transect (paleodepths between 1500 and 3600 m) of five Ocean Drilling Program sites in the South Atlantic. The PETM is marked by a substantial negative carbonate isotope excursion. Note the rapid and massive drop in calcium carbonate content for all sites in the lowermost Eocene (marked I); the return of the CCD after roughly 5 ky at the shallow site (II); the return of the CCD to the deepest sites after only 60 ky; and the full recovery of the lysocline at 110 ky after the excursion (marked IV). After Zachos et al., Science 308, 1612-1615, 2005.

a weaker calcification response. However, laboratory and field experiments have involved only small numbers of individuals and populations over relatively short durations, and provide little basis for predicting marine ecosystem responses on decade-to-century timescales. All observed effects are subject to large species-specific differences.

Experiments on calcification mechanisms indicate that some organisms control calcification by elevating saturation state at the site of calcification by up to 7 times that of seawater. Under this model, it might be hypothesized that small changes in saturation state of the seawater would have little effect on calcification rates. Hence, it is unclear why many organisms are highly sensitive to ocean chemistry changes.

... and past experiences

Given these large uncertainties in predicting the biological response to future ocean acidification, many are looking for answers from relevant parts of the geologic record:

For the industrial era, there is the potential to obtain records of the response of the marine sedimentary carbonate system to changing atmospheric CO_2 content, using archives such as deep-sea corals, rapidly accumulating sediments and molluskan shells.

For the late Pleistocene, records of atmospheric CO_2, paleo-pH and carbonate preservation demonstrate that at the onset of the industrial revolution, interglacial ocean pH and carbonate mineral saturation states were near the minimum (interglacial) values reached over the Pleistocene; hence, the industrial revolution occurred at a time when these ocean chemical parameters were particularly susceptible to being pushed outside the range of natural variability.

From the (less well-constrained) Cenozoic record of ocean carbonate chemistry there is no indication of any undersaturation of the surface ocean, at least since the Cretaceous-Paleogene (K-Pg) boundary (65 Ma). While data so far suggest that there is no exact past analog of present-day CO_2 emissions, discussion centered on how near-future scenarios might compare with the Paleocene-Eocene Thermal Maximum (PETM; 55 Ma, Fig. 2) and mass extinction events such as at the K-Pg boundary.

The carbon isotope shift at the PETM (Fig. 2) indicates that the amount of carbon released into the environment was comparable to what we could release over the next decades and centuries, but it is unclear whether these releases occurred over a short time or over many thousands of years (with hence reduced ocean chemical response).

Ecological responses to past episodes of ocean acidification are reflected in the paleoceanographic record. For example, disruptions in marine fauna at the PETM were primarily confined to bottom dwellers, with no distinct changes in pelagic groups, whereas during the K-Pg extinction event, many planktonic calcifiers went extinct and most corals died. It took millions of years for the calcareous plankton and corals to recover their biodiversity. Ocean acidification could have been a factor in these events but co-occurring factors (warming, darkness, ocean circulation) also likely played a role. A future challenge is to uniquely relate the paleobiological effects to causes.

Ocean carbon models and the sedimentological record both indicate that chemical recovery from projected CO_2 emissions will take several thousand to hundred thousand years (Fig. 2). Past extinction events indicate that biological recovery is measured in millions of years. This timescale is associated with chemical recovery of the environment, the evolution of new organisms, and the development of new food webs. Thus, both the chemical and ecological effects of CO_2 releases are basically irreversible on societal timescales.

Themes that surfaced repeatedly at the workshop included:

(1) Ocean acidification at the rate and magnitude projected for the coming decades represents a major risk to at least some marine ecosystems.
(2) Effects of acidification will differ across different marine environments but cannot be determined with any certainty based on our present understanding.
(3) Research is needed to assess the consequences of ocean acidification, including a better understanding of present, past and future changes in ocean carbonate chemistry, and the biotic responses to these changes.
(4) It is important to improve our communication to policy makers of the risks associated with ocean acidification, as these risks may provide motivation for rapid reduction of CO_2 emissions.

Workshop materials including the program, abstracts, breakout-group summaries, and many of the poster and oral presentations can be found on the FTI-website (http://igbp-scor.pages.unibe.ch/). PAGES intends to further provide paleo-perspectives on marine biochemical changes in its new Focus 3, which is currently being established.

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