COLLABORATIVE RESEARCH; THE DYNAMICS OF CARBON RELEASE AND SEQUESTRATION: CASE STUDIES OF TWO EARLY EOCENE HYPERTHERMALs

Intellectual Merit: The ocean is the largest sink for anthropogenic CO$_2$ and has absorbed nearly 130 PgC of the 380 PgC emitted to the atmosphere since the onset of the Industrial Revolution. If emissions continue to rise unabated for the next three centuries, an additional 4000 PgC or more will be input to the atmosphere and ocean. Published model simulations of the ocean/atmosphere response to the eventual complete utilization of fossil fuels indicate that atmospheric CO$_2$ will rise to levels that Earth likely hasn’t experienced for at least 40 million years, and the surface ocean may undergo acidification to the extent that corals and other calcifying organisms will be unable to precipitate their skeletons.

Confidence in and refinement of these model simulations will benefit from application to, and comparison with, analogous events in Earth history. Approximately 55 million years ago (Mya), Earth experienced a similar episode of rapid and extreme transient warming, the Paleocene-Eocene Thermal Maximum (PETM), likely the product of massive carbon release. Intense study of the PETM over the last five years has led to a far clearer understanding of the consequences of this event on climate, biota, and biogeochemical cycles. One of the more prominent advances is the documentation of evidence for widespread ocean acidification and buffering, consistent with carbon cycle theory. A related advance was the discovery of second warming and ocean acidification event at ~53 Mya. This event, known as ELMO, was less extreme than the PETM in every sense, from the carbon cycle perturbation to the magnitude of warming. Advances have been accelerated by the recovery of spectacular new marine and terrestrial records of the two events, by new proxies for environmental reconstruction, and by techniques to resolve time to within a few thousand years.

The ancient global warming events, termed hyperthermals, provide a unique opportunity to gain insight into the long-term impacts of rapidly rising CO$_2$ levels on modern climate, ocean carbonate chemistry, and biotas. They also provide an opportunity to identify potential non-linear feedbacks, and test climate and biogeochemical model sensitivity. To this end, an interdisciplinary group of scientists with expertise in carbon cycle dynamics, sediment geochemistry, paleoceanography and paleobiology has been assembled, and will embark on a 4-year project to address critical questions regarding two hyperthermals, and their implications for understanding of the carbon cycle including: 1) what were the mass, rate, and origin of carbon released during the hyperthermals? 2) what were the rates of sequestration and recovery and what biogeochemical feedbacks came into play? and 3) how did associated extreme changes in ocean carbonate chemistry affect planktonic calcifiers? The strategy will involve integration of the observational database with numerical models. The observational database group will be responsible for providing the essential data for constraining and testing the carbon cycle models. This includes records of biogenic carbonate production, accumulation and preservation in 3-dimensions through the PETM and ELMO. This effort will require substantial refinement of age models. With a highly resolved and multifaceted data set for input, three modeling approaches will be used, each involving specific opportunities and compromises in terms of the time scales and scope of processes that can be modeled. Earth system models (GENIE and CCSM) will provide boundary conditions for the process-oriented models. Process model simulations will be designed to investigate problems identified during data/model validation of the Earth system models and to develop hypotheses to be tested with model simulations.

Broader Impacts: This highly interdisciplinary project will provide important insight into the short-term and long-term fate of anthropogenic CO$_2$ on the global carbon cycle, climate, and biota. Such information is essential to providing scientific leaders and policy makers with a better sense of the consequences of unabated anthropogenic CO$_2$ emissions for global climate, ocean chemistry and marine food chains. Moreover, the project places significant emphasis on a number of closely integrated research and educational activities that will lead to the development and circulation of educational materials related to abrupt climate change and training in how to integrate them in curricula. In addition, we will take advantage of highly successful existing programs to provide opportunities for undergraduates from under-represented groups to participate in cutting-edge, relevant, carbon-cycle research.
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RESULTS FROM PRIOR NSF SUPPORT

J.C. Zachos, T.J. Bralower, L.R. Kump - EAR-0120727: Consequences of greenhouse warming for biocomplexity and biogeochemical cycles: A multidisciplinary case study across the Paleocene-Eocene boundary: 10/01-9/06; $2.5 million (w/ 7 other investigators). Supported 12 graduate and 15 undergraduates, and 55 publications (http://es.ucsc.edu/~silab/biocomplex/researchnews_pubs.htm; Last 2: Kelly et al. 2005, Paleoceanography; Bowen et al., in press, EOS)

G. Bowen – No prior NSF support


M. Pagani – OCE-0095734: Collaborative Research: Reconstruction of Paleogene alkenone-based εp records. 8/02-8/05; $155,129 to Yale U., 1 publication (Pagani et al., 2005), others in progress.

H. Stoll OCE-0424474 (SGER). Improving the utility of paleoproxies from coccolith chemistry: calibration and analytical advances. 5/04-4/06; $50,000. Supported 6 undergraduates (3 summer, 3 academic year RA), 2 publications in review, others in prep.

A. Winguth – No prior NSF support


MOTIVATION

The capacity of the ocean to absorb anthropogenic CO2 is controlled largely by its ability to buffer the pH and carbonate ion concentration [CO3^2-] through several mechanisms or feedbacks, each of which operates on different time scales (Ridgwell and Zeebe, 2005). On time scales of thousands of years, the most important feedback involves the dissolution of carbonate sediments on the seafloor, which can restore pH and [CO3^2-], and thus allow the ocean to absorb additional carbon (Archer et al., 1997). The majority of carbonate sediment, however, resides on the deep sea floor. As a consequence, the process of buffering through carbonate dissolution is paced partly by the rate at which ocean overturn can deliver acidified water to the deep sea. Because the rate of overturn, roughly 10^3 y, is comparatively slow relative to the rate of emissions, CO2 is rapidly accumulating in the atmosphere. In theory, with several mixing cycles, the bulk of the anthropogenic carbon will slowly propagate into the deep sea, and trigger widespread dissolution of carbonate, thereby sequestering CO2 at a predictable rate. As the system drifts further from present conditions, however, the rate of sequestration could deviate from predictions. For one, the rate of oceanic overturn should slow as high-latitude surface waters become warmer and fresher, which would reduce absorption. Also, the chemical erosion of seafloor carbonate is limited by the rate of resupply of fresh carbonate sediment via bioturbation (Archer and Maier-Reimer, 1994). Should the organisms responsible for bioturbation disappear, say for a lack of oxygen or warmer temperatures, then the resupply of carbonate for weathering should cease as well. On even shorter time scales, the export production of carbon, which is controlled by factors such as production and flux of calcareous algae, could change with acidification and climate change. Each of these potential surprises increases the degree of uncertainty in forecasts of ocean carbon absorption and sequestration.

To evaluate our theoretical understanding of the complex processes that govern the carbon cycle, and to test the sensitivity of coupled climate/biogeochemical models to extreme forcing, researchers are increasingly turning to Earth’s past to study periods of rapid greenhouse warming. Of particular interest is a transient global warming event characterized by a carbon cycle perturbation at the Paleocene-Eocene boundary 55 Mya referred to as the Paleocene-Eocene Thermal Maximum (PETM). As evidenced by a prominent carbon isotope excursions (CIE) and global deep-sea dissolution horizon (Fig. 1), the PETM was accompanied by the release of ~4000 PgC over a period significantly shorter than the residence time of carbon in the ocean (<10 ky; Zachos et al., 2005). Interestingly, this carbon release, which left an indelible imprint in the sedimentary and fossil record, may not have been as large as the potential input of carbon from fossil-fuel burning.
The last five years have seen a surge in our understanding of the dynamics of the PETM event including far more precise constraints of the range of climatic, biotic and biogeochemical responses on both short and long time-scales. Significant discoveries have been made by an international team funded through NSF-Biocomplexity who have taken advantage of the recovery of spectacular new marine and terrestrial records of the event (e.g., Zachos et al., 2003; 2005; Bowen et al., 2004, in press; Wing et al., 2005; see http://es.ucsc.edu/~silab/biocomplex/index.htm for more information) as well as the development of powerful new geochemical proxies (Zachos et al., submitted). In addition, we now recognize that the PETM was not unique: a second event, referred to as ELMO (Lourens et al., 2005), occurred some two million years later and exhibits many of the same features of the PETM. While the pace of discovery has been rapid, the exact cause(s) of these events is still a matter of debate and we have been unable to fully quantify the processes responsible for evaluation of the long-term carbon cycle recovery rates and modes of sequestration, and to test models of how biogeochemical feedbacks work to buffer the ocean and sequester carbon. In particular, uncertainties in chronology prevent us from fully interpreting the rates of carbon addition during the onset of the events, and especially, removal during the recovery. Thus, our understanding of the dynamics of these events and potential implications for present and future carbon cycle perturbation is less than complete.

Here we propose a 4-year investigation focused on the dynamics of ocean carbon uptake and sequestration during two early Eocene hyperthermals, with a particular emphasis on the PETM. This investigation brings together an international team of experts in ocean and carbon cycle modeling, marine and sedimentary geochemistry, and paleocceanography, to jointly address, through data/model comparison, several key questions regarding the nature of the carbon cycle perturbations during these events; 1) What were the mass, rate, and origin of carbon released during the events? 2) What were the rates of sequestration and recovery and what biogeochemical feedbacks came into play? and 3) How did associated extreme changes in ocean carbonate chemistry affect planktonic calcifiers?

**EARLY EOCENE HYPERTHERMALS**

The PETM (55 Mya), first documented 15 years ago, (Kennett and Stott, 1991), still represents the most prominent rapid global warming event in Earth history linked to extreme greenhouse forcing. Evidence for a massive release of carbon includes a >3.0‰ negative carbon isotope excursion as recorded in marine and terrestrial fossils (e.g. Kelly et al., 1996; Koch et al., 1992) temporally coupled with a worldwide seafloor carbonate dissolution horizon (e.g., Bralower et al., 1997; Lu et al., 1998; Schmitz et al., 1996; Thomas et al., 1999; Thomas and Shackleton, 1996). The climatic impacts of this greenhouse forcing were significant. Sea-surface temperatures (SST) increased by 5 °C in the tropics (Tripati and Elderfield, 2004; Zachos et al., 2003), by 6 to 9°C in the Arctic and sub-Antarctic, respectively (Kennett and Stott, 1991; Pagani et al., in press; Thomas et al., 1999), and by 4-6°C throughout the deep sea. Global humidity or precipitation patterns changed as well (Pagani et al., in press; Robert and Kennett, 1994; Wing et al., 2005), as did deep-sea circulation patterns (Nunes and Norris, 2006; Thomas et al., 2003).

In recent years, significant progress has been made in detailing the impacts of the PETM on ocean climate and biogeochemistry, in large part, because of the success of a series of Ocean Drilling expeditions designed specifically to recover the boundary in depth transects. These depth transects, spanning as much as 2 km, provided insight into depth dependent changes in ocean chemistry (Bralower et al., 2002; Lyle et al., 2002; Erbacher et al., 2004; Zachos et al., 2004). The PETM sections exhibited dissolution patterns consistent with models of ocean acidification, for example, shoaling of the lysocline and calcite compensation depth (CCD), by as much as 2 km in some regions (Fig. 1; Zachos et al., 2005).

![Figure 1. The clay horizon and CaCO3 content in deep sea cores recovered from Walvis Ridge during ODP Leg 208 (Zachos et al., 2004)](image)
These expeditions also confirmed the existence of a second hyperthermal, ELMO (Zachos et al., 2004), roughly 2 m.y. post-PETM (Lourens et al., 2005; Westerhold et al., 2005). This event exhibits many of the same characteristics of the PETM including a transient warming and negative carbon isotope excursion, and dissolution horizons (Fig. 2). The magnitude of each, however, appears to be half that of the PETM. The CIE, which was first documented in multiple deep-sea cores by Cramer et al. (2003), also appears to be present in terrestrial records demonstrating that it was not a purely marine phenomenon (see online material; Lourens et al., 2005).

![Image](https://example.com/image.png)

**Figure 2.** ODP Site 1262 high-resolution magnetic susceptibility (MS (a^3)) and Fe concentration data from core logs and XRF scanner (Lourens et al., 2005; Westerhold et al., submitted), and bulk carbon isotope data (McCarren et al., in prep.). Filter shows prominent cycles which reflect the 100 and 400 kyr eccentricity cycles. Precession cycles are numbered. Similar records exist for each site in the Leg 208 depth transect.

Finally, the high-resolution, stratigraphically complete composite sections recovered during Leg 208 have proven to be highly suitable for astronomical tuning, and thus are being used to develop the first high-resolution age models for the entire upper Paleocene and lower Eocene (Fig. 2; Lourens et al., 2005; Westerhold et al., 2005). These tuned chronologies can be transferred to other sequences using high-resolution carbon isotope stratigraphy (e.g., Cramer et al., 2003), an achievement that will also allow us to frame these extreme perturbations within the context of the long- and short-term “background variability” in the time preceding and following the events.

**CARBON FLUXES AND OCEAN ACIDIFICATION**

In theory, the extent of ocean acidification should scale with the mass of carbon, thus providing an independent means of estimating the mass of carbon added to the ocean. Dickens and others (1995) posited the release of 1200 PgC from decomposition of methane hydrates. The thermal decomposition of sedimentary organics by a mantle plume penetrating the crust has been implicated as well (Svenson et al., 2004), as have the desiccation and oxidation of sedimentary organics in terrestrial soils (Kurtz et al., 2003) or shallow epicontinental seas (9000 PgC; Higgins & Schrag, 2004), and the introduction of extraterrestrial carbon from a comet.

The first attempt to quantitatively estimate the mass of carbon released at the PETM via a model/data comparison was accomplished using the Walker and Kasting (Walker and Kasting, 1992) carbon cycle box model (Dickens et al., 1997; Dickens et al., 1995). Assuming a methane hydrate source for carbon ($\delta^{13}$C = -60‰), CIE equivalent excursions ($\Delta\delta^{13}$C = -2.5 to -3.0‰) and lysocline shoalings (followed by overdeepenings) were simulated with a flux of 1200-2000 PgC over 10 ky, with a return to steady state $\delta^{13}$C in ~120 ky. More recent investigations using coupled ocean models of intermediate complexity, funded under the 2001 NSF-Biocomplexity project, are providing new insight as to how other factors such as ocean circulation, productivity, and dissolved oxygen influence carbonate deposition in 3-dimensions on a variety of spatial scales (Ridgwell et al., 2005; Panchuk et al., in prep.). For example, initial experiments suggest that locally dysoxic bottom waters can amplify shifts in the lysocline and carbonate preservation. Such effects, if not recognized, would lead to inaccurate estimates of the global carbonate dissolution fluxes as well as circulation patterns. These findings demonstrate the necessity of using dynamical models as a means of interpreting the sediment records of the hyperthermals.
RESEARCH OBJECTIVES

The early Eocene hyperthermals represent natural carbon cycle experiments involving rapid input of carbon to the atmosphere/ocean on scales comparable to the modern anthropogenic forcing. The success of recent ODP expeditions in recovering spectacular quality and complete sections of these events in depth transects coupled with recent advances in the development of coupled earth system models provide new opportunities to address the critical questions framed below. This effort, however, will require a highly focused, systematic reevaluation of how ocean carbon chemistry changed during such events, specifically regarding the magnitude of the CIEs and variations in carbonate accumulation rates on a global scale. It will also require a carefully coordinated series of modeling experiments and integration of observational data. Consequently the objectives of this project, framed as critical questions, are as follows:

1) What was the mass and rate of carbon released during the hyperthermals and was this release instantaneous or pulsed?

Detailed carbon isotope records exist for many marine and terrestrial PETM sections, and provide a key constraint for quantifying the mass and rate of carbon release to the ocean/atmosphere. However, two significant questions remain. First, the amplitude of the CIEs in pelagic, marine sections typically ranges from 2 to 4‰, while the CIE in terrestrial sections ranges from 5 to 6‰, so the true amplitude of carbon release remains uncertain. Second, coccolith and bulk carbonate isotope records show steps in the negative isotope excursion which are not observed in planktonic foraminiferal (single specimen) records, so it is unclear whether carbon was released in a single instantaneous event or in multiple pulses that would reflect periodic forcing or positive feedbacks. Resolution of both questions rests on identifying potential biological or vital effects on isotope fractionation which may bias components of marine or terrestrial records, and on assessing the degree to which variable dissolution of marine foraminifera and coccoliths may alter the preserved isotopic record. For example, changing CO₂ and humidity may amplify the CIE in terrestrial records (e.g., Bowen et al., 2004) while ocean acidification and lower [CO₂] of surface waters could diminish the marine CIE through a carbonate ion effect (e.g. Spero et al., 1997). An alternative hypothesis, that marine carbonate records were truncated by dissolution and sediment reworking, is consistent with depth transects where minimum CIE values recorded in bulk carbonate increases with depth (Kelly et al., 1996; Zachos et al., 2005). A combination of dissolution and reworking could also potentially introduce steps in the marine carbon isotopic record, as could variable vital effects in coccolith isotopic fractionation.

To empirically address these issues, we need to identify and constrain potential artifacts associated with microfossil shell production and deposition. To start, accumulation rates must be more tightly constrained. Dissolution horizons should be associated with sharp spikes in the accumulation of extraterrestrial He (²¹Heₑₓ), and be more pronounced in deeper sites. Also, the lack of transitional δ¹³C values in single planktonic shells might be an artifact of sampling biases, which could be resolved by analyzing rare taxa that might have displaced common taxa during the transitions (Kelly et al., 1998). A second solution is to measure the δ¹³C of organic compounds. Recent investigations show the presence of n-alkanes derived from terrestrial plant leaf waxes in marine PETM sections (Hasegawa et al., submitted; Pagani et al., in press). The δ¹³Cₙ-alk will allow for a direct measure of the δ¹³Cₚₑₓ relative to the marine carbonate record. Another strategy involves targeting near-shore marine sections that are relatively expanded (Giusberti et al., submitted; Zachos et al., submitted). And finally, interpretation of both marine and terrestrial archives of δ¹³Cₑₓ requires application of models that can evaluate the parameters that influence carbon isotope fractionation (e.g., Bowen et al., 2004). For this purpose, box models provide a fast and effective means of simulating the whole-ocean, time dependent C- isotope evolution over long time scales. However, circulation models that simulate the effects of deep-water aging and carbonate dissolution on sedimentation are clearly required to interpret the spatial variations recorded in bulk and benthic foraminiferal δ¹³C records.

2) How do the magnitude and rate of carbon release during hyperthermals affect the scale of the changes in the lysocline and CaCO₃ accumulation rates?
This question can be addressed by distinguishing between the acidification phase when carbon was being introduced and CCD/lysocline were rapidly shoaling, and the recovery phase, when carbon was being buffered and the same surfaces were deepening.

a) Acidification phase; carbonate undersaturation and chemical erosion. As discussed above, all PETM and ELMO sections are characterized by carbonate dissolution horizons. While dissolution is more pronounced at deeper sites, as expected (Fig. 1), spatially, there are significant differences in carbonate deposition patterns that are difficult to reconcile with simple models of ocean acidification. For example, in the Southern Ocean PETM intervals at Sites 689 and 680, the carbonate content drops, but only to 75 and 85% respectively, implying the local CCD did not shoal as much as elsewhere (Schellenberg et al., in prep). To the north, in the equatorial Atlantic, Caribbean, and North Atlantic, some sites show distinct clay layers with little to no carbonate (Bralower et al., 1997), while others show less carbonate dissolution. One hypothesis suggests that these spatial variations reflect the release and entry path of carbon into the deep sea. Alternatively, these trends may reflect the influence of circulation on local productivity, inorganic/organic carbon fluxes, and bottom water redox conditions (Ridgwell et al., 2005). These factors must be delineated to infer the full magnitude of carbonate dissolution.

b) Recovery phase: mass/rate of carbonate deposited (chalk layer). During recovery, deep-sea [CO$_3^{2-}$] transitions (in ~20-40 ky) from an extreme undersaturated state to what appears to be a supersaturated state as characterized by pure white, rapidly-deposited coccolith-rich chalks (Farley and Eltgroth, 2003; Kelly et al., 2005). The white chalk appears to be a common feature of most pelagic PETM sections. This response is not unexpected as carbon cycle models that utilize a sediment/rock weathering feedback exhibit this type of behavior. The oversaturation results directly from the loading of dissolved ions from accelerated dissolution of carbonates and silicates and, hence, reflects an important negative feedback. As CO$_2$ is extracted from the system during weathering and replaced with carbonate ion, [CO$_3^{2-}$] rises forcing the carbonate saturation horizon to great depths, thus allowing the ocean to purge the excess ions. As a consequence, carbonate sediment accumulation rates should rise. The issue we wish to resolve is where, and to what extent?

The magnitude of carbonate accumulation and carbon sequestration during the recovery interval remains highly uncertain because contrasting age models imply significantly different rates. Application of an orbital age model (Röhl et al., 2000) to the white chalk at Site 690, yields a duration of 100 ky, and creates an inflection in the C-isotope curves, which if real would imply a relative decrease in the burial of reduced carbon. In contrast, the $^3$He$_{ET}$ model (Farley and Eltgroth, 2003) implies a much faster carbonate accumulation rate and shorter duration (20 ky) for the recovery interval. In addition, the $^3$He$_{ET}$ age model implies that the removal of carbon from the ocean-atmosphere system during this phase was nearly as rapid as its addition to the ocean-atmosphere system, <20 ky. From a purely theoretical point of view, we might anticipate a rapid increase in carbonate accumulation rates during the period of supersaturation as the lysocline descends to the seafloor. Yet, increased carbonate/organic carbon burial ratios would have worked against the rapid rise in $\delta^{13}$C implied by the $^3$He$_{ET}$ age model, unless increased carbonate ballasting also elevated organic carbon burial fluxes (although the organic/inorganic burial ratio would also have to increase). These apparent paradoxes require further investigation.

Here, astronomical stratigraphy and $^3$He$_{ET}$ will be used to improve the estimates of carbonate accumulation on a global scale for the PETM and ELMO. Moreover, dissolution indexes, such as foraminiferal fragmentation and % coarse fraction will be used to constrain the position of the lysocline relative to the CCD. Because the differences in carbonate accumulation patterns almost certainly reflect on the influence of circulation on local productivity, inorganic/organic carbon fluxes, and bottom water redox conditions (Ridgwell et al., 2005), ocean models are required to assess these affects under a variety of scenarios. Multiple simulations (sensitivity tests) will be required to gauge the potential effects of each variable using models that can simulate in 3-D each of critical controls on carbon fluxes and burial.

3) How did lower/higher pH and other environmental changes affect production and/or calcification of coccolithophorids and foraminifera, and their relative contributions to fluxes?
In theory, the more rapid the rate of CO₂ input to the atmosphere, the more extreme the changes in surface ocean pH and carbonate saturation state. In the modern ocean, planktonic calcifiers and corals are potentially threatened by future increases in CO₂ (e.g., Ridgwell and Zeebe, 2005). With the PETM and ELMO, the major groups of planktonic calcifiers, coccolithophorids and foraminifera, did not experience major extinction implying that surface ocean pH did not reach extinction levels. This would be consistent with the relatively long period (>10 ky) over which the several thousand Pg of carbon were released. Still, significant changes in the relative abundances of coccoliths and planktonic foraminifera have been documented (Bralower, 2002; Kelly, 2002; Kelly et al., 1996). Some of the changes can be attributed to warming, increased stratification, and lower fertility. Did lower/higher pH have any noticeable impacts on the calcification rates of coccolithophorids and foraminifera?

To address this, a systematic quantitative assessment of coccolithophorids and foraminiferal assemblages, size, morphology, calcification rates, and growth rates is required. Such an assessment will help elucidate the degree to which changes in carbonate accumulation rates reflect shifts in the production by calcifying organisms vs. changes in the dissolution or preservation of carbonate. Trace metal indicators of growth rates and ocean chemistry, and isotope ratios will be measured on individual species at the level of shells and chambers. Models of biogenic calcification will be required to interpret these data. Ultimately, these data will lead to improvements in the way our numerical models calculate changes in rates of calcification in the surface ocean resulting from ocean acidification events.

4) Was the mass of carbon released during the PETM substantially greater than during ELMO? Did feedbacks play a role in amplifying the fluxes?

Given the findings from Objectives 2 and 3, can we quantify the mass and rate of carbon input to the ocean during the hyperthermals? Computations based solely on the CIE magnitude cannot provide a unique solution. An independent constraint is required. The degree of the model-simulated ocean acidification required to match reconstructed CCD shifts in the Atlantic and Pacific allows an independent estimate of total carbon input. The simulations will provide a temporal analysis of CCD variations, carbonate accumulation rates, ¹³C variations in surface and deep waters, and climate change, which, when constrained by observation, will permit assessment of magnitude, rate, and origin of the carbon released. Can the carbon flux from any one source (reservoir) account for the full mass of carbon added to the ocean/atmosphere? If not, what are the potential feedbacks that might supply additional carbon? Solution of the above questions is critical if we are to precisely compare the scale of the hyperthermals to the modern predicament.

5) How did feedback processes restore ocean carbonate chemistry and atmospheric CO₂?

Although the focus of past research has been on the onset and magnitude of the CIE, it is equally important to understand the time scale and mechanisms of recovery of the biosphere to massive carbon addition if we are to gauge the long-term implications of fossil fuel burning. Are there feedbacks that accelerate or damp this response?

Model sensitivity tests are required to simulate the time scale of C-cycle recovery from rapid injections of CO₂. One component of this recovery is weathering of carbonate (short-term) and silicate (long-term) rocks on land. Using a suite of numerical models, we will investigate the sensitivity of CO₂ consumption rates during weathering to temperature, freshwater fluxes, and soil development. Another important factor is the extent to which marine productivity and organic carbon burial are promoted or inhibited by changes in riverine nutrient delivery, climate, and ocean circulation associated with the hyperthermals. If the ³HePET age model is correct, an organic carbon burial event rivaling the carbon release itself must have occurred. What drove this response of the marine biota to the PETM and did a similar response occur during ELMO?

**RESEARCH STRATEGY**

**Research Team**

We have assembled an interdisciplinary research team with extensive experience in the core areas of this project. The project team is organized into two groups; a theoretical group (L. Kump (group leader),
co-PIs G. Bowen, A. Winguth, and R. Zeebe, and international collaborators, A. Ridgwell and D. Beerling), and an observational group (J. Zachos (group leader), T. Bralower, K. Farley C. Kelly, M. Pagani, and H. Stoll, and international collaborators U. Röhl, H. Brinkhuis, S. Gibbs, T. Tyrrell, I. Raffi, S. Galeotti, & P. Ziveri). We will continue to collaborate with investigators of the 2001 biocomplexity project (J. Dickens, P. Koch, E. Thomas, L. Sloan, P. Delaney, S. Schellenberg, C. Hollis, J. Kiehl), as well as several participants of ODP Legs 198, 207, and 208 (K. Kaiho, R. Norris, D. Kroon, L. Lourens, M. Petrizzo, M. Nicolo. S. Monetchi).

**Observational Database: Field and Lab Work**

*Sampling Network*

To constrain and test the model experiments, it will be necessary to improve the temporal resolution and spatial coverage of reconstructions of ocean carbon chemistry and flux changes during the hyperthermals. This includes reconstruction of $\delta^{13}$C$_{DIC}$, biogenic carbonate production, fluxes, dissolution and burial. To this end, we will construct high-resolution records for each site in then N. Pacific and S. Atlantic ODP depth transects (Legs 198, 207, and 208), plus a dozen or more pelagic and hemipelagic sites so that each major ocean sector, the North Atlantic (e.g. Sites 401, 549, 929), Tethys (e.g. Piave, Italy, Zumaya, Spain), central Pacific (Sites 1220, 1221), Southern Ocean (Sites 690,738, Dee & Mead Stream), and Indian Ocean (e.g., Sites 213, 762), is well represented for both events at multiple depths. Based on our preliminary survey, it appears ELMO is present at many of the same sites where the PETM has been documented (e.g.; Charisi & Schmitz, 1998; Speijer & Schmitz, 1998; Galeotti et al., 2000; Zachos et al., 2003; Crouch et al., 2001; Schmitz et al., 2001; Hancock et al., 2002; Egger et al., 2002; Cramer et al., 2003; Zachos, Kroon, Blum et al., 2003; Hancock et al., 2003; Crouch et al., 2003; McCarren et al., 2005; in prep., Hollis et al., 2005; Lourens et al., 2005; Nicolo et al., 2005; Nunes & Norris, 2006; Gusberti et al., submitted; Westerhold et al, 2005; in prep., Galeotti et al., in press; Kaiho et al., in press), so spatial coverage should be as good, if not better.

*Astronomical / Extraterrestrial $^3$He Age Control*

Highly precise time scales are fundamental to both the observational and modeling component of this project. New sections combined with recent improvements in techniques offer great potential to resolve chronology for PETM and ELMO sections. Thus, substantial effort will go into refining age models and computing the carbonate accumulation rates between and across the two hyperthermals. With the exception of the clay layers, orbital stratigraphy coupled with chemostratigraphy will be used to establish baseline accumulation rates prior to and after the events. Ba concentration data, obtained from XRF scanning, offer the potential to resolve cycles where other elemental data are non-cyclic. The Leg 208 orbitally tuned time-series, which is being developed using a combination of the high-resolution (~1-3 cm) core logging, XRF core scanner and isotope data from all 5 sites, spans the entire interval from C24N to C25N and includes both the PETM and ELMO (Fig. 2), and will thus serve as the primary section to which all others are correlated above and below the clay layers.

In the clay or condensed layers, we propose to expand on earlier work to establish the pace of the PETM and ELMO using extraterrestrial $^3$He as a constant flux proxy. $^3$He in most deep-sea sediments is overwhelmingly derived from ~10 nm diameter interplanetary dust particles (IDPs). Because terrestrial and extraterrestrial helium have very different $^3$He/$^4$He ratios, isotopic measurements can be used to establish the concentration of extraterrestrial $^3$He ($^3$He$_{ET}$) in a sample. For a given $^3$He$_{ET}$ flux (F, in atoms/area/time), $^3$He$_{ET}$ is related to the sediment mass accumulation rate ($\alpha$) by dilution: $^3$He=F/\alpha. This relationship can be

![Figure 3. Site 1209 on the Shatsky rise. The 3He data suggest nearly a 20-fold change in sedimentation rate through the PETM.](image-url)
inverted to calculate mass accumulation rates from $^3$He$_{ET}$ measurements, provided F can be determined, for example by measuring the amount of $^3$He$_{ET}$ accumulated over an orbitally-tuned time interval. Temporal variability of the apparent $^3$He flux to Earth over intervals comparable to the PETM is fairly small. Uncertainties in the apparent flux can be reduced by calibration using a sedimentary section located close in space and time to the section of interest. Similarly, comparisons among multiple sites provide an empirical test of the resulting age models, because sedimentary phenomena affecting the apparent flux are unlikely to be identical in timing and magnitude at geographically separated localities. The $^3$He method provides instantaneous sedimentation mass accumulation rate estimates for every analyzed sample, which can be converted into linear sedimentation rates, and by integration, used to establish an age model. This method successfully resolved fine scale changes in accumulation rate at ODP Sites 690 and 1051 (Farley and Eltgroth, 2003). The method will be applied to each site in the depth transects, plus a half-dozen sites in the North Atlantic and Indian Ocean. Preliminary data for Site 1209 from the Leg 198 transect shows a 20-fold increase in concentrations (similar to clay) suggesting a substantial loss of carbonate (Fig. 3).

**Global Carbon Isotope Excursions**

Detailed, carbonate based carbon isotope records exist for almost every PETM boundary section studied to date. This includes bulk, planktonic and benthic records. In the Leg 198/208 depth transects these records are currently being extended upward to include ELMO (Fig. 2). We will generate similar records for ELMO at a half-dozen additional sites where the PETM is present. The resolution will be on the order of 1-2 ky for the bulk carbonate isotope records, and at lower resolution for planktonic and benthic foraminifera (2-4 ky). Since there are discrepancies between coccolith-dominated bulk and planktonic foraminiferal stable isotope records from some sites during the PETM, we will also generate stable isotope records in restricted size fractions dominated by single coccolith genera, eliminating artifacts of changing species assemblages and in conjunction with cellular models elucidating the contribution of vital effects in stable isotope records (e.g., Stoll, 2005). Coccolith fraction stable isotope records will be produced in combination with trace element records from coccoliths which verify the primary rather than diagenetic nature of the coccolith calcite and reveal unique geochemical signatures in certain species during isotope plateaus which cannot be artifacts of mixing of pre-PETM and PETM material.

Understanding the full extent of the negative CIE during the PETM (and ELMO) is critical to modeling experiments (see above). Theoretically, a relatively larger terrestrial PETM CIE, measured from $\delta^{13}$C values of terrestrial leaf wax n-alkanes in the Arctic region, could be potentially explained by a floral shift from gymnosperms to angiosperms. However, similar floral shifts must have synchronously occurred at other localities to account for terrestrial $^{13}$C-excursions, derived from soil carbonates, of the same magnitude. Rather than explaining a similar observation by different processes, it is possible that the CIE expressed by higher plant n-alkanes reflects the full $\delta^{13}$C change of atmospheric CO$_2$ in equilibrium with the surface ocean during the PETM. This scenario implies that foraminiferal and coccolith $\delta^{13}$C values do not accurately represent the full CIE of ocean DIC due to effects related to dissolution and changes in pH. If this hypothesis is validated by the extensive compound-specific isotope analysis proposed in this study, evidence for a $\sim$ 5 to -6‰ CIE would require a substantial increase in the mass of carbon released. To test this, we intend to measure the carbon isotope ratios of n-alkanes extracted from the near-shore PETM boundary sections. High-resolution planktonic foraminifer carbon isotope

**Figure 4.** The %CaCO$_3$ and %CF (>63 $\mu$m/g) fraction of the Leg 208 Sites. IV represents the base of the white, coccolith chalk layer within which both measures are identical at all sites, regardless of depth (unpublished).
records already exist for two shallow marine sections from the New Jersey margin (Zachos et al., in press), and two from outer shelf, upper slope sections from the California margin (John et al., 2005). The California sections are currently being processed and preliminary results indicate abundant terrestrially derived n-alkanes are present. We will also sample hemipelagic sections along the Tethyan margin (e.g., Piave, Italy; Giusberti et al., submitted), and in New Zealand (Mead and Dee Stream; Nicolo et al., 2005), and several pelagic cores), to isolate n-alkanes. Moreover, similar coupled n-alkane δ13C and carbonate δ13C records for ELMO when carbon flux was smaller and marine carbonate dissolution less severe, should provide additional insight into the nature of the offset.

Biogenic Carbonate Accumulation

High-resolution %CaCO3 records already exist for most of the pelagic and hemipelagic PETM sections in our global sampling network. Moreover, all the depth transect cores have also been scanned by XRF, and thus have high-resolution Ca concentration records (U. Röhl, pers. comm.), which can be easily transformed through regression to %CaCO3. Thus, most of our analytical effort will focus on older DSDP and ODP cores and land-based outcrops. The archive halves of cores that have not been scanned will be shipped to Bremen University for scanning. For the few cores that are unsuitable for scanning, discrete samples will be collected for conventional coulometric analysis. For most land-based marine PETM and some ELMO sections, CaCO3 records already exist, so the number of sections to resample will be minimal.

The relative contribution of foraminifera vs. coccolithophorids to the carbonate flux shifts significantly through the PETM (Fig. 4). To ascertain the global extent of this important ecological shift, standard sieving and settling techniques will be used to partition and compute the accumulation of various biogenic components (forams vs. coccoliths). Samples from the depth transects have already been wet sieved at >38 μm and dry sieved in larger size fractions (>63, >150 μm). Settling techniques will be used to separate nanofossils (Stoll, 2005; Stoll and Ziveri, 2002).

Dissolution CCD/Lysocline:

In sites examined to date, the foraminiferal preservation in the white chalk/ooze layer is excellent, with little to no fragmentation (Kelly et al., 2005; in prep.). In the Leg 208 depth transect, %CF (& %CaCO3) in this layer is essentially identical at all depths (Fig. 4), an observation that suggests the entire water column was highly oversaturated. To determine the scale of this unusual phenomenon, we will construct proxy preservation records for both the PETM and ELMO in each ocean sector (as above). We will target sites that provide the broadest depth coverage possible. Proxies to be measured include the %CF, planktonic/benthic and fragmentation indexes, and microscale carbonate overgrowth. In the Leg 198 and 208 sites, we will investigate proxies sensitive to carbonate ion content such as depth-dependent variations in Zn/Ca in benthic foraminifera and Mg/Ca in planktonic foraminifera (Fehrenbacher and Martin, 2006).

Nanofossil preservation in PETM and ELMO samples will be evaluated by establishing the dissolution susceptibility of key nanofossil and foraminiferal species. This will be performed in three different ways: (1) To establish the solution susceptibility of ancient plankton taxa, samples will be reacted with seawater that is undersaturated with respect to CaCO3, as done by Hill (1975) with traps. We will conduct similar experiments, but in the laboratory using seawater solutions of controlled pH. (2) We are compiling a global dataset of PETM nanofossil and foraminiferal assemblage data and will use multivariate techniques (Ddetrended Correspondence Analysis (DCA)) to determine ecological groupings of taxa (Gibbs, Bralower, et al., in prep.). This same data set can be mined to determine the relative amount of dissolution of individual samples as well as the solution susceptibility of different taxa. And (3) We will quantify % etched or overgrown taxa for nanofossil and foraminiferal specimens and use quantitative metrics to determine the extent of alteration using a scanning electron microscope.

For planktonics, shell diameter/mass of specimens is also a useful gauge of their preservation (Bijma et al., 2002; Broecker, 2002). Average mass (and wall thickness) of globally distributed mixed-layer planktonic species Acarinina soldadoensis, and thermocline dweller Subbotina patagonica will be measured. In addition, we will measure the weight of Morozovella velascoensis and the “excursion taxa” of
**Morozovella (M. allisonensis)** and **Acarina (A. sibaiyensis)** that are restricted to tropical and temperate locations e.g., (Kelly et al., 1998). Preliminary work shows a substantial increase in the mean mass of foraminiferal shells in the white, chalk layer. The fragmentation of foraminiferal assemblages will also be determined (e.g., (Kelly, 2002); Colosimo et al., 2005).

Once the relative solution susceptibility of calcareous nanofossil taxa is known, we will calibrate assemblage data with grain size analysis of the <38µm fraction. Grain size analysis offers an advantage for determining assemblage and preservational changes because it is fast and relatively inexpensive and provide us with the means to observe changes at unusually high resolution (mm to cm) with a minimum of effort. We are currently using a Malvern Mastersizer and Coulter Counter particle analyzer for this purpose.

**Productivity of coccolithophore carbonate producers**

To ascertain the extent to which changes in productivity of coccolithophorid algae contributed to shifts in the carbon cycle and carbonate accumulation during the PETM and ELMO, we will use trace element ratios in coccoliths representative of primary trace-metal incorporation during calcification. The ratio of Sr/Ca in particular has been shown to vary with nutrient-stimulated growth rates in culture (Rickaby et al., 2002; Stoll et al., in review-a), sediment trap, and surface sediment transects (Stoll and Ziveri, 2004). Where dissolution is minor, coccolith Sr/Ca ratios covary with other indicators of coccolithophorid production including alkenone and carbonate accumulation rates (Rickaby et al., in review). This relationship likely arises due to variable polysaccharide extrusion in response to nutrient availability, which binds Sr preferentially to Ca and affects the near cell ratio of Sr/Ca available for uptake into the coccolith calcification vesicle (Langer et al., 2006).

Coccolith Sr/Ca and other elemental ratios can be measured using separated near-monogeneric size fractions (e.g., Stoll and Bains, 2003), as well as a new ion probe analysis of individually picked populations of monogeneric coccoliths (Stoll et al., in review-b). This latter technique is especially advantageous for studying lower Eocene sections where coccoliths are not abundant due to dissolution, when monogeneric coccolith fractions cannot be satisfactorily separated from sediments, and in shelf sections where high lithogenic input may hamper ICP analysis of coccolith size fractions. The ion probe technique also provides a clearer picture of how ecologically distinct coccolith genera responded to the events. The ion probe technique reproduced to within 1% the Sr/Ca ratios of monospecific cultured *Helicosphaera carteri* samples which had also been measured by inductively coupled plasma atomic emission spectroscopy. Analyses of replicate populations of *Toweius* coccoliths, from the same sample picked and analyzed several months apart, yield Sr/Ca ratios which differ by 1%.

**Figure 5.** Models and model co-ordination used to study the carbon cycle during the early Paleogene hyperthermal events. A) Three modeling approaches will be used, each involving specific opportunities and compromises in terms of the time scales and scope of processes that can be modeled. B) Modeling experiments (gray arrows) will be coordinated to assess each motivating question. Earth system models (GENIE and CCSM) will provide boundary conditions for the process-oriented models. Process model simulations will be designed to investigate problems identified during data/model validation of the Earth system models and to develop hypotheses to be tested with model simulations.

**Numerical Modeling**

Our modeling efforts to date have begun to constrain the magnitude and duration of carbon release required to generate the observed PETM isotopic and sedimentary response (see below), but a number of outstanding questions remain and new issues of CIE magnitude, duration, and truncation have arisen (described above) that we must address. Thus, we propose simulations with well-tested community models of various degrees of complexity to predict the oceanic and sedimentary response to a range of carbon addition scenarios (including the first quantitative analysis of the ELMO event). In addition we will assess which of the scenarios (e.g., clathrate or thermogenic methane vs. fossil carbon – CO₂ input, fast vs.

C-10
slow input) generate the proper isotopic, climatic, and CCD responses (both regional and global) for the onset, magnitude, and recovery from these events. Transient simulations will be carried out with the intermediate complexity Earth system model GENIE. This modeling will be supported by higher-resolution time-slice simulations using the comprehensive climate model CCSM-3. CCSM-3 will provide improved simulations of ocean biogeochemistry for the initiation and termination of the PETM and ELMO events, and necessary boundary conditions to GENIE. In this work we benefit greatly from the international team of experts whose primary task is model validation for modern-day and future prediction. In addition, box models of carbon cycle processes will be used to conduct long (multimillion-year) simulations, and process-specific models will be used to address particular components of the global response. These modeling efforts will be coordinated: GENIE and CCSM-3 will provide climate and ocean transport rates to the box models, and the process-oriented and box models will guide improvements to the parameterizations of the GCMs (Fig. 5).

All spatially resolved models will use late Paleocene - early Eocene paleogeography and physiography derived from GIS layers assembled by C. R. Scotese (www.scotese.com) and the techniques of Markwick and Valdes (2004). To assess the sensitivity to these boundary conditions, the paleogeography and paleobathymetry produced by the Paleogeographic Atlas Project of the University of Chicago (presently used in GENIE modeling as well as in the work of Bice and Marotzke, 2001, 2002) will also be employed.

Process-oriented models

Long-term simulations of the carbon cycle spanning the PETM and ELMO will be conducted with global atmosphere-ocean-sediment carbon cycle models, building upon the initial results for the PETM of Dickens (1997). The ocean component resolves the different ocean basins, high and low-latitudes, and surface/intermediate/deep waters (Walker and Kasting, 1992; Dickens, 1997; Sigman et al., 1998; Zeebe and Archer, 2005); water fluxes are derived from the Earth system models. Coupling to sediment models (Keir, 1982; Sundquist, 1986; Sigman et al., 1998) and inclusion of carbonate and silicate weathering feedbacks will allow quantitative analyses of carbon fluxes on time scales from thousands to millions of years. Model tracers include nutrients such as PO₄, stable carbon isotopes (δ¹³C), and total CO₂ and total alkalinity from which atmospheric CO₂ is calculated. These simulations will provide the baseline reservoir properties for initiating GENIE and CCSM-3 simulations.

A depth-explicit soil organic carbon and CO₂ model including stable isotopes (Bowen and Beerling, 2004) will be used to explore soil carbon processes and carbon isotope ratios to be compared to paleosol records, at vertical resolutions that cannot be achieved with the coupled Earth Systems models. Steady-state and dynamic vertical soil organic carbon decay and soil gas CO₂ profiles can be simulated from derived soil physical property and organic carbon input and decay parameters. Additional constraints for the model simulations will be given by n-alkane carbon isotope data made available by this project. Updates to the model will include development of schemes for interfacing the soils model with GENIE and CCSM-3 for grid-level simulation of PETM and ELMO soils.

Earth system model of intermediate complexity: The GENIE model

Intermediate complexity models present an unprecedented opportunity to perform time continuous simulations of geologic events like the PETM and ELMO (or both simultaneously); previous modeling has been largely restricted to snapshots using GCMs or 0-D box model simulations. GENIE (www.genie.ac.uk) consists of interconnected modules treating atmosphere, ocean, sediments, ice sheets, land surface and vegetation, soils, sea ice, and ocean biogeochemistry. The model uses a highly efficient frictional geostrophic 3-D representation of the ocean, a 2-D energy and moisture balance atmosphere (after Weaver et al., 2001; coarse-resolution 3-D treatments are possible), and a dynamic and thermodynamic sea-ice model (Annan et al., 2005; Edwards and Marsh, 2005). A sediment component of GENIE is currently under construction by A. Ridgwell (see letter of support) and based in part on the work of Archer et al. (2002). This component calculates sediment accumulation rates (carbonate, non-carbonate, and organic carbon), sediment compositions (e.g., %CaCO₃ and %Corg), and isotopic compositions. As such, it allows
for an assessment of the extent to which the magnitude of the marine CIE has been truncated by erosion, as hypothesized above based on the higher-plant alkane δ13C record. Kump and his graduate student, Karla Panchuk, together with Ridgwell, have been modifying GENIE for application to the PETM event. The first simulations of the PETM event are encouraging (Fig. 6). We are able to reproduce the Walvis Ridge carbonate record with a 6000 Pg C addition over 15ky, including the more rapid recovery of carbonate sedimentation at shallower depths. We propose here to evaluate the degree of the model-simulated ocean acidification required to match reconstructed CCD shifts in both Atlantic and Pacific sectors. Constrained by new estimates of carbonate accumulation rates and δ13C chronologies, the modeling will permit assessment of magnitude, rate, and origin of the carbon release. Also, with δ13C tracers, we can simulate bottom water gradients as captured in benthic foraminifera (Nunes & Norris, 2006), while including the effects of dissolution on sedimentary profiles.

Presently GENIE does not allow weathering responses to climate change, a critical part of the response to large carbon additions. Increased fluxes of kaolinite from the continents during the PETM (Gibson et al., 2000; Robert and Kennett, 1994), together with an Os isotope excursion (Ravizza et al., 2001) have been argued to reflect intensified silicate weathering, and thus may signal increased consumption of CO2 through chemical weathering (cf. Thiry, 2000). Thus we need to develop a weathering module for GENIE. The model will use a set of predictive functions to estimate clay mineral abundances in soils based on climate, vegetation type, bedrock mineralogy, and physiography, derived through multiple regression analysis of digital spatial data sets for modern soils (FAO, 2003) in the context of global climatological datasets (New et al., 2000), biome distributions (http://edc.s17.cr.usgs.gov/glcc/ globe_int.html), and physiography (USGS, 1996) in unglaciated, non-agricultural regions. Early Paleogene soil mineralogy will be predicted using these same variables, which are explicitly specified or calculated in GENIE. A paleogeologic map for the Eocene (following Bluth and Kump, 1991) will be constructed as a senior-thesis project in the first year of funding. Weathering rates will be determined using empirical rate laws derived from the data on river loads from modern-day, monolithologic watersheds (e.g., Bluth and Kump, 1994; Gibbs et al., 1999). The effect of relief and soil cover will be parameterized by analogy with modern drainages (e.g., Milliman and Syvitski, 1992; Summerfield and Hulton, 1994; Hooke, 2000). Validation will include comparison of chemical erosion rates calculated for the major rivers of the world compared to observation for the modern; fair agreement has been achieved in the past (Gibbs and Kump, 1994; Ludwig et al., 1999).

Moreover, the organic carbon weathering and deposition components of GENIE have not been implemented. As described above, the organic carbon cycle seems to be an important part of the recovery from the PETM, one that has been neglected to date. We will work with Ridgwell to activate this part of the model.

As described above, one explanation for the smaller amplitude CIE in the marine vs. terrestrial records is the dependence of the δ13C of marine carbonate on carbonate ion concentration. To evaluate this hypothesis, the carbonate ion effect will be incorporated into the carbon cycle models and the results compared with those generated without the effect.
Presently, GENIE does not resolve continental shelves and thus cannot fully represent the response to the PETM/ELMO perturbations. We will evaluate the sensitivity of CCD response to this partitioning by attaching low-, mid-, and high-latitude shelf “boxes” to the box model and to GENIE, with specified partitioning based on paleogeographic reconstructions of latitudinally dependent flooded shelf areas for the early Paleogene and estimated rates of carbonate deposition based on adjacent open-ocean water chemistries (after Opdyke and Wilkinson, 1993) from GENIE.

**Time-slice experiments for onset and recovery of the PETM and ELMO with the Community Climate System Model (CCSM)**

The CCSM-3 (see letter of collaboration) is a coupled climate model for simulating Earth’s climate system [http://www.ccsm.ucar.edu/models/ccsm3.0/](http://www.ccsm.ucar.edu/models/ccsm3.0/). Time-slice simulations with the CCSM3 for the onset and recovery of the CIE near the PETM and ELMO will be guided by previous simulations with older versions of the CCSM (e.g. (Huber et al., 2002; Huber and Caballero, 2003; Huber and Sloan, 2001; Shellito et al., 2003)) and coordinated with CCSM Paleoclimate Working Group. We are planning to carry our simulations of various greenhouse gas levels (i.e. 1xCO₂, 2xCO₂, and 8xCO₂) to explore interactions of the climate and the carbon cycle, in particular how the carbon cycle responds to changes in the climate state. The output of these simulations will be used for model-data validation and input for the offline three-dimensional carbon cycle modeling studies as well as for the process-oriented models and GENIE (surface wind velocities and shear stresses). Moreover, the role of geography will be investigated by comparison with a modern reference simulation.

Output from CCSM-3 will be used as input for offline carbon cycle models in order to investigate effects of different ocean circulation patterns on water column processes, fluxes at the sediment/water interface, and sedimentary composition. The offline carbon cycle model has been developed at the University of Chicago and includes the prediction of water mass tracers based on the HAMOCC model (Maier-Reimer, 1993; Archer and Maier-Reimer, 1994; Archer et al., 2000) with prognostic macro- and micronutrients (P, Si, Fe), oxygen, carbon tracers (δ¹³C), and a model (“Muds”) for oxic and anoxic diagenesis of shallow and deep-sea sediments based on an efficient solver for steady-state pore water and solid phase diffusion/reaction/advection equations (Archer et al., 2002). The sediment model used in the proposed project is similar to the one in GENIE and will be updated in collaboration with D. Archer. The dependence of carbon export rates on micronutrients (Fe) and mineral ballast (Armstrong et al., 2002) have been tested with the HAMOCC model and compared with carbon tracers and sediment traps (Howard et al., in press). We will improve a simplified sulfur cycle currently developed at the MPI Hamburg (E. Maier-Reimer) by adopting the code developed for GENIE. The off-line coupling of the carbon cycle model with POP_TM is under development and tested with ideal age tracers in collaboration with the NCAR Oceanography Section (OS) (S. Yeager, W. Large) and Climate Change Research Section (CCR) (J. Kiehl).

We will carry out experiments with both GENIE and CCSM-3 to study the sensitivity of the late Paleocene/early Eocene thermohaline circulation and carbon cycle to changes in the hydrological cycle, following the work of Bice and Marotzke (2001) that demonstrated a high degree of sensitivity of the ocean circulation to the amounts and location of freshwater discharge to the ocean. Possible switches in the thermohaline circulation related to changes in atmospheric moisture transport could lead to sufficient warming to destabilize seafloor gas hydrates over most of the world ocean to a water depth of at least 1900 m. We will determine changes in clathrate stability following the lead of Bice and Marotzke (2002) and calculate methane fluxes accordingly, but explicitly determining the delay in response resulting from the requirement for the warming to penetrate through the sedimentary pore waters to the clathrates. Furthermore, we will perform simulations similar to those of Heinze (2004) to address how significant ecological changes at the PETM (see Kelly, 2002, and Kelly et al., 2005, and references therein) likely altered POC fluxes into the abyssal layers and thus influenced the CCD. Sensitivity of the CCD to mineral ballasting of POC (Armstrong et al., 2002; Klaas and Archer, 2002; Howard et al., in press) will be also explored. Finally, we will continue our research on the effect that bioturbation on the capacity of seafloor dissolution to dmp the lysocline response to CO₂ (Ridgwell et al., 2005).
SIGNIFICANCE

The ocean is the largest sink for anthropogenic CO₂ and has absorbed nearly 130 PgC of the 380 PgC emitted to the atmosphere since the onset of the industrial revolution (Sabine et al., 2004; Feeley et al., 2004). If emissions continue to rise unabated for the next three centuries, an additional 4000 PgC or more will be added to the atmosphere and ocean. Because the emission rate is relatively short compared to the mixing time of the ocean, most of anthropogenic carbon will accumulate in surface waters, thereby lowering the seawater pH and [CO₃] to levels that might impact the ability of corals and coccolithophorids to calcify (Riebesell et al., 2000; Caldeira & Wickett, 2003; Orr et al., 2005), while also slowing the rate of uptake by the ocean. Only vertical mixing and dissolution of seafloor carbonate will buffer these changes. Because pCO₂ will rapidly rise to levels not seen on Earth in over 40 million years (Pagani et al., 2005), there is some uncertainty as to how fast the ocean will sequester this carbon. For example, as the climate rapidly warms, and the ocean pH decreases, it is not entirely clear that rates of sequestration will follow modeled scenarios. Worse yet, there is still insufficient understanding of how potential positive feedbacks may work to amplify the rise in CO₂.

Approximately 55 million years ago, the Earth experienced a similar episode of rapid and extreme transient warming, the Paleocene-Eocene Thermal Maximum that was also the product of massive carbon release. Intense study of this event over the last five years has lead to several major findings regarding the consequences of this event on climate, biota, and biogeochemical cycles. One of the more prominent advances is the documentation of evidence for widespread ocean acidification and buffering, consistent with carbon cycle theory. A related advance was the discovery of second ocean acidification event at ~53 million years ago. This warming event, referred to as ELMO, was less extreme in every sense, from the perturbation in the carbon cycle to the magnitude of warming. These hyperthermals provide a unique opportunity to gain insight into the long-term impacts of rapidly rising CO₂ levels on climate, ocean carbonate chemistry, and biota. They also provide an opportunity to identify potential non-linear feedbacks, and test model sensitivity.

MANAGEMENT PLAN

Our management structure follows a model used in a previous NSF-Biocomplexity project (http://es.uccs.edu/~silab/biocomplex/index.htm). To start we will hold two workshops. The first workshop will be convened within 6 months of the project start date to review the long and short-term goals and objectives, develop experimental design, coordinate integration of data with models, and then organize first and second year work plans. The second workshop ~ 20-24 months later will be designed to assess progress, identify additional observational needs and model experiments, and to organize publications.

The leaders of the two groups, theoretical and data (L. Kump & J. Zachos), will be responsible for organizing the activities of each team and disseminating information within and between groups. As for specific contributions, Kump will head the theoretical group coordinating the myriad of model experiments, and responsible for directing the GENIE collaboration between his graduate student, Andrew Ridgwell at UBC, and the UK GENIE group. Winguth and a graduate student will be responsible for the sensitivity experiments with CCSM-3 and the off-line carbon cycle model. Zeebe and his graduate student will develop/run simplified atmosphere-ocean-sediment carbon cycle models, provide comparison to future scenarios, and collaborate on laboratory dissolution experiments with PSU. Bowen and his group will develop and apply process-oriented models to study carbon cycle feedbacks involving the coupling of terrestrial and marine systems through soil and weathering processes. The observational group will be headed by Zachos who along with a graduate student will coordinate field sampling and be responsible for the stable isotope studies, and the integration of cycle stratigraphy with chemostatigraphy. Kelly and a graduate student will be responsible for quantifying foraminiferal assemblages and preservation indexes, and collecting specimens for isotope analyses. Farley and a graduate student will be responsible for developing ³He age models and will collaborate with Bralower, Zachos, and Röhl in mass accumulation rate estimates. Pagani and graduate student will undertake the isotope analyses of n-alkanes. Bralower and Stoll and their students will coordinate research activities focused on coccolithophore preservation and productivity using a variety of microscopic and geochemical methods.
BROADER IMPACTS

The proposed research has significant potential to educate the next generation of earth scientists, general education college and K-12 students about the fate of anthropogenic CO$_2$, a topic of significant societal concern. In addition, the research will contribute to the training and education of 6 undergraduate and 9 graduate students at all of the PI institutions combined. We propose to take advantage of the relevance of the proposed research to generate several additional educational activities:

- PIs Bralower, Kump, Stoll and Zachos will lead a workshop for educators on curriculum design involving abrupt ancient global warming. The workshop will include modules and exercises that will be developed jointly by these PIs and their undergraduates and graduate students engaged in the proposed research and include data-rich, inquiry-based laboratory/discussion sections aimed at general education and upper division elective courses. The three-day course at PSU will follow the model of *On the Cutting Edge* workshops and we will work with leaders of that highly successful program to design an effective program (see attached letter from Heather Macdonald). The Science Education Resource Center (SERC) will help advertise the workshop. Media and modules developed will be made available to faculty at other institutions by inclusion on the SERC web site.

- Summer undergraduate interns and all graduate students will be expected to develop and give a presentation on the climate system to a high school science class.

- Penn State University has recently formed a partnership with Fort Valley State University (FVSU) in Georgia and developed a 3+2 dual degree program (see attached letter). The first FVSU students will be arriving at PSU in Fall 2006. The proposed program will include two FVSU student interns as part of the well-established PSU Summer Research Opportunity Program for minority science majors. Bralower and Kump have been active in a range of summer programs including the Summer Experience in Earth and Mineral Sciences for high school minority students interested in science. Stoll will continue to be involved in the Williams College Summer Science Program that promotes the participation of under-represented groups in research. She has hosted four students from this program in her lab since 2001.

- The University of Wisconsin and Penn State, together with other Worldwide Universities Network partners, are developing an international summer workshop for graduate students and early career scientists (Summer Institute for Earth Systems / Transatlantic or SIES/TA). The first SIES/TA is scheduled for Summer, 2007 and will be focused on Arctic climate change (modern and ancient). We propose that the Summer, 2009 workshop be focused on Deep-Time Carbon Cycling: Modeling and Data Analysis, to be taught by the PIs, postdocs, and students supported by this proposal.

- UCSC has several proven programs in place that will benefit from, and contribute to, the broader impacts for education that are articulated in this proposal. First, UCSC is a participant in the NSF AGEP Program UCSC is building cohorts of graduate students in the fields of science, technology, engineering and math (STEM) with the goals of mentoring these students towards successful professorial positions. UCSC-AGEP would welcome the participation of UCSC graduate students in this proposal to the AGEP cohort. Second, UCSC is proud to be a participant in the UCLEADS program, which encourages and mentors under-represented minority junior and senior undergraduate students in the STEM fields to go to graduate school in the UC system. Zachos will mentor several UCLEADS students on this project (see attached letter).

- Our website will be a vehicle to share knowledge and progress in our investigation of carbon cycle dynamics. This website will include updates about research activities, publications, presentations, and opportunities for new student involvement, as well as links to appropriate resources, education modules, and FAQs. In addition, Zachos and Winguth will propose a topical session for the 2007 AAAS meeting in San Francisco on the “The Early Eocene Hyperthermals: Lessons for the Future”. Through group collaboration and activities including workshops, participating undergraduate and graduate students will experience involvement in a multidisciplinary, international research project. For example, the bi-annual workshop described will bring all project participants together and provide students with excellent opportunities to interact with an international group of scientists who can be mentors and role models.
Citation List


Bijma, J., Honisch, B., and Zeebe, R.E., 2002, Impact of the ocean carbonate chemistry on living foraminiferal shell weight: Comment on "Carbonate ion concentration in glacial-age deep waters of the Caribbean Sea" by W. S. Broecker and E. Clark - art. no. 1064: Geochemistry Geophysics Geosystems, v. 3, p. 1064.


Gibbs, M.T., Kump, L.R., 1994. Global chemical erosion during the last glacial maximum and the present; sensitivity to changes in lithology and hydrology. Paleoceanography 9, 529-543.


McCarren, H., Thomas, E., and Zachos, J.C., 2005a, Depth dependant variations in benthic foraminiferal assemblages and stable isotopes across the P-E boundary, Walvis Ridge (ODP Leg 208), AGU Fall Meeting: San Francisco.


Zachos, J.C., Schouten, S., Bohaty, S., Sluijs, A., Brinkhuis, H., Gibbs, S., Bralower, T., and Quattlebaum, T., submitted, Extreme warming of mid-latitude coastal ocean during the Paleocene-Eocene Thermal Maximum: Inferences from TEX86 and Isotope Data: Geology.


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EDUCATION:

Ph.D. 1988
Graduate School of Oceanography, University of Rhode Island

M.S. 1984
University of South Carolina

B.S. 1981
State University of New York, Oneonta

EMPLOYMENT

July 2000 - Present
Professor, Univ. of California, Santa Cruz

July 1999 – June 2003
Director, Center DELSI

July 1996 - 2000
Associate Professor, Univ. of California, Santa Cruz

July 1992 - June 1996
Assistant Professor, Univ. of California, Santa Cruz

November 1990 - June 1992
Assistant Research Scientist, Univ. of Michigan

September 1988 - November 1990
Post Doctoral Scholar, Univ. of Michigan

September 1983 - August 1987
Graduate Research Assistant, Univ. of Rhode Island

January 1982 -August 1983
Graduate Teaching Assistant, Univ. of South Carolina

OTHER PROFESSIONAL ACTIVITIES:

July-Dec 2004
Bremen University Visiting Fellow

March 2003
Chief Scientist, ODP Leg 208

August 2001
Sedimentologist, ODP Leg 198

Fall 2000
Cambridge University, Visiting Fellow

1996 - Present
Fellow, Canadian Inst. Advanced Research

January 1994
Sedimentologist, ODP Leg 154

February 1988
Organic Geochemist, ODP Leg 120

August 1985
Inorganic Geochemist, ODP Leg 105

1996-2001
Editorial Board, Geological Society America Bulletin

1995-2003
Editorial Board Palaeogeography, Palaeoclimatology, Palaeoecology

1995-1997
Editorial Board Geology

NATIONAL and INTERNATIONAL COMMITTEE & PANEL SERVICE

U.S. Carbon Cycle Scientific Steering Group (3/05-presenter); MESH, NSF Ocean Sciences Steering Committee (1/00 – present); NSF Panel (6/00); JOIDES Scientific Committee (6/99-6/01); Smithsonian Inst. Scholarly Studies Prog. Review Committee (6/99); JOIDES Arctic Program Planning Group (1/99-1/01); JOIDES Extreme Climates Program Planning Group (1/98-1/00); JOIDES Ocean History Panel (3/92-6/95)
SELECTED PUBLICATIONS (2001-2005)


**PhD. Advisor**
Michael Arthur, PSU

**Collaborators**
Tim Bralower, PSU
Clay Kelly, Wisconsin
Steve D’Hondt, URI
Lee Kump, PSU
Scott Wing, Smithsonian
Gabe Bowen, Purdue
Henk Brinkhuis, Utrecht
Ursula Rohl, Bremen
Lucas Lourens, Utrecht

Heiko Palike, SOC
Ellen Thomas, Yale
Stefan Schouten, NIOS
Jerry Dickens, Rice U
Lisa Sloan, UCSC
Paul Koch, UCSC
Peggy Delaney UCSC
Chris Hollis, NZ
Samantha Gibbs, SOC

**Former Post Docs**
Benjamin Flower, USF
Stephen Schellenberg,

Mark Pagani, Yale U.
Cedric John, TAMU

**Former Graduate Students**
K, Billups, U of Delaware
H. Paul, ETHZ
K. Salamy, MBARI
A, Tripati, Cambridge
Julia Frazier
Thomas Quattlebau
Biographical Sketch for Daniel Clay Kelly

(i) Professional Preparation

Ph.D., Geology, University of North Carolina at Chapel Hill, 1999
M.S., Geology, Florida State University, 1993
B.S., Geology, Florida State University, 1985

(ii) Appointments

2001 – present, Assistant Professor, Dept. of Geology and Geophysics, University of Wisconsin – Madison
2003, Ocean Drilling Program, Shipboard Scientist (Biostratigrapher) ODP Leg 208
2000, Ocean Drilling Program, Shipboard Scientist (Biostratigrapher) ODP Leg 189

(iii) Five publications related to proposal:


(iiib) Selection of five other publications:


**(iv) Synergistic Activities**

2003-06, Public Outreach: Collaborating with Geology Museum at the University of Wisconsin to design an exhibit that showcases how deep-sea cores are used to study ocean/climate change and biotic evolution.

2001-05, Curriculum development: Designed, taught, and implemented both Geobiology and Introductory Micropaleontology for department undergraduate/graduate curriculum. I also teach Survey of Oceanography to large undergraduate classes each year, and will be offering an upper division class on Marine Geology/Paleoceanography.

2001/02, Refurbished micropaleontology lab that is used daily by both undergraduate and graduate students.

**(va) Collaborators on papers in last 48 months:** Rebecca Tedford (Louisiana State Univ.), Timothy J. Bralower (Pennsylvania State University), Linda Elkins-Tanton (Brown University), Guy Harrington (Birmingham Univ., U.K.), Richard D. Norris (Scripps), James C. Zachos (U.C. – Santa Cruz), James P. Kennett (U.C. – Santa Barbara), Neville Exon (Australian Geological Survey Organization), Debbie Thomas (Texas A&M Univ.), Ellen Thomas (Wesleyan College, CT), Elizabeth Clechenko (Univ. of Wisconsin – Madison), Adam Eisenach (Univ. of Wisconsin – Madison), Stephen Schellenberg (San Diego State Univ.)

**(vb) Graduate and Postdoctoral Advisors:** M.S.: Anthony J. Arnold (Florida State University); Ph.D.: Timothy J. Bralower (University of North Carolina – Chapel Hill); Postdoctoral: Richard D. Norris (WHOI/Scripps)

**(vc) Undergraduate and Graduate Advisor for Univ. of Wisconsin Students:** Rebecca Tedford (M.S., 2003), Elizabeth Clechenko (Ph.D., 2007), Tina Nielsen (Ph.D., 2007), Jennifer Nielsen (M.S., 2006), Adam Eisenach (M.S., 2006), Eric Shullenberger (M.S., 2007), Laura Mitchell (M.S., 2007), Kathleen Bolger (M.S., 2007), Peter Gill (Senior Thesis, 2004)
TIMOTHY JAMES BRALOWE

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Education:
Ph.D. Earth Sciences, Scripps Institution of Oceanography, University of California, San Diego, 1986.

M.S. Oceanography, Scripps Institution of Oceanography, University of California, San Diego, 1982.

B.A. with Honours in Geology, Oxford University, England, 1980.

Professional Experience:
Assistant Professor, Florida International University, State University of Florida at Miami, 1987-1990.

Assistant Professor, Geological and Marine Sciences, University of North Carolina, Chapel Hill, 1990-1993.

Associate Professor, Geological and Marine Sciences, University of North Carolina, Chapel Hill, 1993-1996.

Joseph Sloane Associate Professor of Geological and Marine Sciences, University of North Carolina, Chapel Hill, 1997-1998.


Chair, Department of Geological Sciences, University of North Carolina, Chapel Hill, 1998-2002.

Professor and Head, Department of Geosciences, Pennsylvania State University, 2003-.

Awards:
Hettelman Junior Faculty Research Prize, UNC-CH, 1995.

Other Positions:
Biostratigrapher, Ocean Drilling Program Legs 122, 143, 165.
Advisory Board of CHRONOS; Steering Committee of GeoSystems
BIBLIOGRAPHY (five most relevant publications)


Five additional publications


Graduate Students—Current and Former

MS Sarah Mock (Middle School Teacher, Portland, OR), John Williams (Environmental company, Portland, OR), Celeste Burns (Owner of Forestry Company, Durham, NC), Deborah Thomas (Assistant Professor, Texas A&M), Linda de Romero (Independent consultant), Jason Eleson (Exxon-Mobil), Andrew Bowman (Nebraska Ph.D. program), Amanda Colosimo (Instructor, Monroe CC), Lauren Fuqua (Instructor, College of Charleston), Anna Hilting (Instructor, Carteret CC; with L. Kump), Andrea Kalb (current)

Ph.D. D. Clay Kelly (Assistant Professor, Wisconsin-Madison), Deborah Thomas (Assistant Professor, Texas A&M), Jocelyn Sessa (current, joint with M. Patzkowsky)

Collaborators

Lee R. Kump
Professor of Geosciences, Affiliate, Earth System Science Center, Associate, NASA Astrobiology Institute
The Pennsylvania State University, University Park, Pennsylvania 16802

Education
A.B. Honors, University of Chicago, 1981, Geophysical Sciences
Ph.D., University of South Florida, 1986, Marine Sciences

Professional Experience
1997- Professor of Geosciences, Penn State
2005 - Reviewing Editor, Science
2002- Editor, Virtual Journal of Geobiology
2002-2005 Associate Editor, Geochimica et Cosmochimica Acta
1996-2000 Co-Editor, Geology
1994-2000 Associate Head, Department of Geosciences, Penn State
1991-1997 Associate Professor of Geosciences, Penn State
1986-1991 Assistant Professor of Geosciences, Penn State
1981-1983 Geologist, United States Geological Survey Fisher Island Station (summers)

Honors and Awards
2005 Faculty Mentoring Award, Penn State, College of Earth and Mineral Sciences
2000 Distinguished Service Award, Geological Society of America
1999 Pardee (Keynote) Symposium Lecturer, Geological Society of America
1997 Fellow, Geological Society of America
1994 Deike Research Award, Penn State
1991-1995 Marine Biological Association of the U.K., Geophysiology Modeling Fellowship
1992 Provost's Award for Collaborative Instruction and Curricular Innovation
1990 Bursary Fellowship, Marine Biological Association of the UK
1986-1987 Faculty Research Award

Membership in Professional Organizations
Canadian Institute for Advanced Research, Earth System Evolution Program (Assistant Director), Geological Society of London, Geochemical Society, American Geophysical Union, Geological Society of America (Fellow)

Five Relevant Articles in Referred Journals and Books

Five Other Articles in Referred Journals and Books


**Synergistic Activities**
- Reviewing editor, Science 2005-present
- Served as Editor of Geology from 1996-1999
- Editor of Virtual Journal of Geobiology 2002-present.
- Associate Editor, Geochimica et Cosmochimica Acta, 2002-present
- Associate Head of Department of Geosciences, 1994-1999
- Served on NSF committee to develop Environmental Geochemistry and Biogeochemistry program
- Promoting Earth system science: Lead author on the new textbook *The Earth System, 2/e*, chairing sessions at national meetings on Earth system science in education
- Director of the Earth Systems Exemplar Area of the Worldwide Universities Network
- Participant in NSF-sponsored recruitment activities for underrepresented groups, including a summer coastal marine science program for Pittsburgh inner-city high-school students

**Collaborators and Other Affiliations**

**Collaborators outside Penn State within last 48 months**
- R. Capo (Pittsburgh), B. Stewart (Pittsburgh), M. Schoonen (SUNY-Stony Brook), K. Bice (WHOI), E. Shinn (USGS), W. Burnett (FSU), J. Chanton (FSU), P. Sheehan (U. Wisc.), P. Fawcett (Arizona), W. Seyfried (U. Minn.), M. Barley (U. W. Australia), J. Zachos (UCSC), M. Huber (Purdue), E. Grossman (Texas A&M), G. Dickens (Rice), L. Sloan (UCSC), E. Thomas (Yale), M. Saltzmann (Ohio State), T. Lyons (U. Missouri)

**Graduate Advisor:** R. Garrels (deceased)

**Thesis/Postdoctoral Advisor To:**
- Katherine Elliott (Langan Engineering), Lea Monaghan (consultant), Mark Gibbs (self-employed), Gregg Bluth (faculty, Michigan Tech), Don Machusak (RE Wright Environmental), Paul Richards (Research Scientist, Univ. Michigan), Andrew Gratz (deceased), Andrew Kurtz (faculty, Boston Univ.), Virginia Seymour (self-employed), Erin Griggs (ERM Corp, environmental consultant), Ellen Herman (Pursuing Ph.D.), Michael Moreland (Apex Environmental, consultant), Roberta Hotinski (Princeton)

Total Graduate Students and Postdoctoral Associates Advised: 13 + 6 currently active
Biographical Sketch(es)

Richard E. Zeebe
University of Hawaii at Manoa
SOEST
Department of Oceanography
1000 Pope Road
Marine Science Building 504
Honolulu, HI 96822

(i) Professional Preparation

Graduate Institution: Alfred Wegener Institute Bremerhaven, PhD, 1998.
Dissertation title: A diffusion-reaction model for carbon isotope fractionation in foraminifera.

Postdoctoral Institutions:
Alfred Wegener Institute, Bremerhaven, 1998-1999,
Lamont Doherty Earth Observatory, New York, 1999-2000,
Alfred Wegener Institute, Bremerhaven, 2000-2003.

(ii) Appointments
Assistant Professor, University of Hawaii at Manoa, SOEST, 12/2003-today.

(iii) Publications

Five publications most relevant to proposed research


Five other significant publications


**IV) Synergistic Activities**

1. Published a text book on CO$_2$ in seawater (Publication 4).
3. Advising of students at graduate and undergraduate level: L. Menviel, A. Andersson, K. Schulz, H. Jansen, A. Wischmeyer, I. Tebas, B. Hoenisch, B. Rost, I. Zondervan.
4. Lecturing in advanced courses for PhD students of German-Dutch collaboration. Teaching at University of Bremen: Master Course in Environmental Physics for mainly underrepresented groups in Germany (students from Asia).
5. Developed numerical routines for the calculation of the carbonate chemistry and made them freely available on the Internet.
   http://www.soest.hawaii.edu/oceanography/faculty_html/Zeebe2/C02_System_in_Sea water/csys.html

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ESF EuroCLIMATE: Co-PI of "Foraminiferal Chemistry in Unraveling Seasonality" (PIs: Peeters, F., Ganssen, G.), pending.