Eocene Hyperthermal Event Offers Insight Into Greenhouse Warming

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What happens to the Earth's climate, environment, and biota when thousands of gigatons of greenhouse gases are rapidly added to the atmosphere? Modern anthropogenic forcing of atmospheric chemistry promises to provide an experiment in such change that has not been matched since the early Paleogene, more than 50 million years ago (Ma), when catastrophic release of carbon to the atmosphere drove abrupt, transient, hyperthermal events.

Research on the Paleocene-Eocene Thermal Maximum (PETM)—the best documented of these events, which occurred about 55 Ma—has advanced significantly since its discovery 15 years ago. During the PETM, carbon addition to the oceans and atmosphere was of a magnitude similar to that which is anticipated through the 21st century. This event initiated global warming, biotic extinction and migration, and fundamental changes in the carbon and hydrological cycles that transformed the early Paleogene world.

The PETM demonstrates that extreme and rapid changes in Earth systems can be triggered by carbon cycle perturbation even in times of globally warm climate and in an ice-free world. As described here, an array of changes in the atmosphere, geosphere, hydrosphere, and biosphere have been documented during the PETM, and these studies have provided insight into the temporal patterns and coupling of changes in the Earth systems that accompany massive carbon release in a warm world.

Atmosphere

Atmospheric temperatures inferred from ocean surface [see Zachos et al., 2005, and references therein] and terrestrial [e.g., Wing et al., 2005] proxies warmed by 5°–9°C globally during the PETM. Warming was closely associated with the release of between approximately 1500 and 4500 gigatons of carbon to the ocean and atmosphere, resulting in large but poorly quantified increases in atmospheric carbon dioxide (CO_2) levels [Zachos et al., 2005]. Atmospheric moisture transport was also affected by the PETM, as evidenced by indicators of terrestrial discharge along the continental margins [e.g., Crouch et al., 2003] and isotopic records suggesting humid growing conditions across the northern midlatitudes [Bowen et al., 2004]. Floral evidence from Wyoming suggests that

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precipitation amounts varied there throughout the event [Wing et al., 2005].

Geosphere

Carbon input to the ocean-atmosphere system during the PETM most likely came from geospheric reservoirs in shallowly buried sediments or the crust. The carbon source and trigger have been debated since Dickens et al. [1995] proposed a methane clathrate source that was destabilized as ocean temperatures warmed from the late Paleocene to an early Eocene maximum.

Proposed alternative sources include thermogenic methane produced during the emplacement of igneous plutons in the North Atlantic seafloor [Svensen et al., 2004] or widespread peat and coal burning [Kurtz et al., 2003]. The geosphere played an important role in carbon sequestration during the later stages of the PETM when weathering feedbacks drove increased marine carbonate burial, buffering and ultimately leading to the recovery of the carbon cycle from the PETM [Zachos et al., 2005].

Hydrosphere

One potential consequence of future global warming is a perturbation to the ocean's thermohaline circulation, which may further change global climate. Indications that ocean circulation changes occurred during the PETM are thus of great significance.

Surface ocean warming was amplified at high latitudes (as much as 9°C) relative to low latitudes (5°C), while deep-water temperatures rose by 4°–5°C globally [see Zachos et al., 2005, and references therein]. During the PETM, reduced pole-to-equator sea surface temperature gradients or changes in continental freshwater runoff may have shifted the site of deep-water formation from a Southern Ocean locus to subtropical latitudes or to high latitudes in the Northern Hemisphere [e.g., Kennett and Stott, 1991; Bice and Marotzke, 2002; Nunes and Norris, 2006], introducing warm water to the deep sea and driving methane clathrate destabilization and further greenhouse warming [Bice and Marotzke, 2002].

Geographic patterns of benthic foraminifera carbon isotope fraction ($\delta^{13}C$) values have been used to reconstruct deep-water flow and support a circulation reversal during the PETM [Nunes and Norris, 2006]. Unfortunately, these data are geographically sparse, reflect water-mass characteristics of intermediate and deep waters (from ~1000
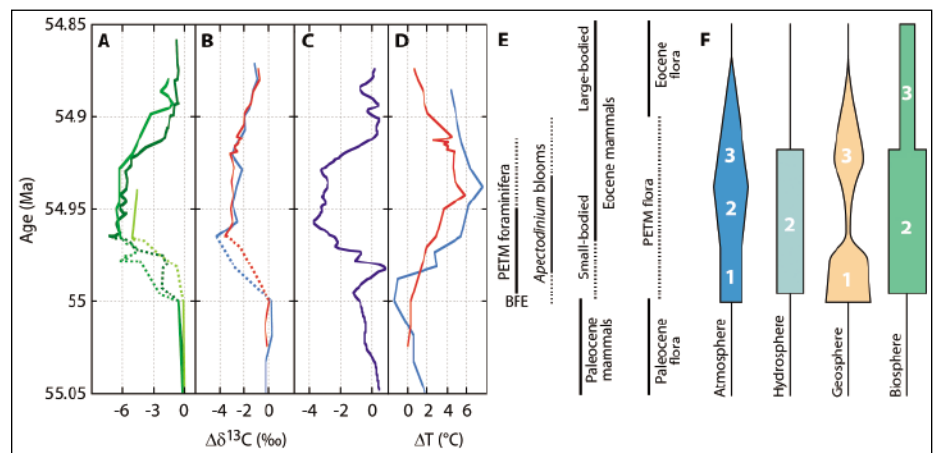

Fig. 1. Environmental records and a three-phase model of Earth systems evolution through the PETM (age model and data from Bowen et al. [2004]). (a and b) Carbon isotope records of the PETM given as anomalies relative to the interval 55.05–55.00 Ma. Terrestrial paleosol carbonate records (a) from northern Wyoming (dark green), northern Spain (light green), and southern China (olive green). Marine planktonic foraminifera records (b) from the subtropical Pacific (red) and southern Atlantic (blue). Carbon isotope changes during the onset of the PETM (dashed lines) occurred as a series of abrupt (~1 thousand years) steps that are not clearly resolved in these records. (c) Difference of the averaged $\delta^{13}C$ curves for the three terrestrial and two surface ocean records. (d) Surface temperature anomaly records for the two oceanic sites, with colors as in (b). (e) Patterns of biotic change through the PETM, compiled from a number of sources (including Kennett and Stott [1991], Thomas [1998], Crouch et al. [2003], and Wing et al. [2005]). BFE indicates benthic foraminiferal extinction. (f) A synthesis of global change associated with the PETM. The width of each shaded region corresponds to the severity of change relative to late Paleocene conditions. Numeral 1 indicates initiation of the PETM: intrinsic or extrinsic trigger; carbon release from geospheric reservoirs to the ocean/atmosphere; buildup of carbon in the atmosphere; ocean acidification and dissolution of seafloor carbonate sediments, benthic foraminiferal extinction, and intercontinental mammal migration. Numeral 2 indicates the body of the PETM: low marine carbonate burial rates; altered hydrologic cycle; distinctive PETM biotic communities; gradual climatic warming. Numeral 3 indicates the recovery interval: rapid burial of carbon in marine carbonate sediments; climate cooling; restructured biotic communities persist into the early Eocene.

to >3000 meter paleodepth), and may have been influenced by local organic-matter regeneration. The investigated sections display varying degrees of dissolution at the onset of the PETM, resulting in time gaps that make precise site-to-site correlation difficult or impossible. Other tools for the reconstruction of deep-water circulation—including patterns of deep-sea carbonate dissolution, oxygen content, and neodymium isotope concentrations—are not consistent with deep-ocean circulation change at the start of the PETM as inferred from $\delta^{13}C$ records [e.g., *Thomas et al., 2003*].

Biosphere

Global environmental perturbation at the PETM is no less apparent in biotic records than in those records documenting the climate or carbon cycle. Lasting changes in mammalian taxonomic composition and diversity, as well as transient body size reductions, were associated with the dispersal of terrestrial mammals among the Northern Hemisphere continents at the beginning of the PETM [e.g., *Clyde and Gingerich, 1998*]. PETM floras in midlatitudes document northward range extensions of hundreds to thousands of kilometers and intercontinental dispersal [*Wing et al., 2005*].

Marine communities also exhibited a complex array of responses, ranging from the loss of about 35 to 50 percent of deep-sea benthic foraminiferal species, which was the most severe extinction in the last 90 million years [e.g., *Thomas, 1998*], to significant but transient assemblage changes in other groups, including global dominance of the warm-water dinoflagellate *Apectodinium* [e.g., *Crouch et al., 2003*], rapid diversification of planktonic foraminifera [*Kelly et al., 1998*], and shifts in trophic strategies of nannoplankton in shelf and open-ocean locations. Overall rates and geographic patterns of terrestrial and marine ecosystem productivity appear to have varied substantially through the PETM [*Bowen et al., 2004; Thomas, 1998*].

A Synthesis of PETM Earth Systems Evolution

Changes in individual Earth systems and the interaction of systems through time reflect a three-stage scenario of perturbation and response associated with PETM greenhouse gas release (Figure 1).

Phase I: Initiation. Carbon isotope records documenting global $\delta^{13}C$ decreases during the first ~15,000–30,000 years of the PETM indicate one or more rapid (i.e., occurring within 1000–2000 years) releases of ^{13}C-depleted carbon to the atmosphere-ocean system. What triggered the PETM carbon release or releases remains a critical question. In considering the PETM as a potential analogue to modern global change, it is important to understand whether the PETM was initiated as a feedback (i.e., as climate crossed a warming

threshold) or as an externally forced event. If the PETM carbon release was a feedback, it implies that human-induced warming may also trigger a cascade of amplifying carbon cycle feedbacks. If the PETM carbon release was forced externally, it might be better considered analogous to anthropogenic carbon release itself. Although no clear consensus exists in this matter, the suggestion that multiple PETM-like events may have occurred in phase with orbital cycles potentially falsifies hypotheses linking the PETM to singular forcing factors such as bolide impacts or volcanic events [*Lourens et al., 2005*].

Whatever the trigger, the onset of the PETM was characterized by abrupt changes spanning the Earth systems, including the acidification of the oceans, rapid changes in terrestrial and marine biota, and the extinction of benthic foraminifera. The linkages between carbon cycle perturbation and synchronous biotic change are not completely understood—individual ecosystems may have responded directly to such aspects of environmental change as carbon addition (e.g., ocean acidification, elevated partial pressures of CO_2) and/or indirectly to consequences of carbon release (e.g., rising temperatures, increased precipitation, changes in nutrient supply and/or distribution).

Phase II: Alternate semistable state. A distinct, approximately 60,000 year interval beginning when $\delta^{13}C$ values reached their minimum has been called the 'body' of the PETM. This was characterized by continued increases in global temperature, low and relatively stable oceanic and terrestrial $\delta^{13}C$ values, increased $\delta^{13}C$ offsets between terrestrial and marine systems, slow dilution of oceanic acidity, and biotic assemblages (dinoflagellate cysts, benthic and planktonic foraminifera, and calcareous nannoplankton in the oceans; plants and mammals on the continents) that include transient, often unique taxa.

The body of the PETM demonstrates that the Earth systems response to initial PETM forcing was not simply a shift away from, and recovery to, equilibrium, but a shift to a fundamentally different, semistable state [*Bowen et al., 2004*]. This state may in some ways represent the global environmental future, and it is therefore critical that it be characterized. *Bowen et al.* [2004] proposed a model suggesting substantial terrestrial ecosystem change during the body of the PETM, but additional focused study of this interval is needed. Low $\delta^{13}C$ values are one unexplained and characteristic feature of the PETM body. The stable isotopic values may reflect temporary stagnation of components of the carbon cycle during a time of poor seafloor carbonate preservation [*Zachos et al., 2005*] and reduced open-ocean carbonate export production [*Thomas, 1998*]. If so, the continued rise of global temperatures and ecosystem change during the body of the PETM may represent changes associated with a long-term lag in carbon cycle recovery from massive carbon release, and may be indicative of patterns of future global change.

Phase III: Recovery. Over the final approximately 70,000 years of the PETM, the Earth's systems recovered to a state in the earliest Eocene that was in many ways similar to that of the late Paleocene. The details of the recovery process are relevant to understanding how the Earth's systems recover from carbon cycle perturbation and the degree to which such events lead to lasting changes in the Earth's climate, biota, and geochemical systems. Recovery included dramatic increases in seafloor carbonate burial rates, falling global temperatures, and a transition from distinctive PETM biotic assemblages to those typical of the early Eocene. Elevated marine carbonate burial represents a potential mechanism for restoring balance to the carbon cycle following massive carbon release; however, given the intervening 60,000 years of low carbonate burial during the PETM body, it is important to understand how this process proceeded.

The biotic record provides the strongest evidence for lasting change induced by the PETM. The earliest Eocene communities of terrestrial mammals and benthic foraminifera differ widely from their latest Paleocene counterparts in species composition and ecological features. These differences may reflect permanent environmental change, interactions among organisms brought together by range changes, or the irreversibility of evolution and extinction.

Fifteen years of study have revealed the PETM as a case study of the broad impacts of massive carbon cycle perturbation during a time of globally warm climate. Continued study promises not only to guide an understanding of global change mechanisms during the PETM, but also to illustrate modes of connectivity among the Earth's systems and patterns of change that may characterize the Earth's future.

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NEWS

Satellite Constellation Monitors Global and Space Weather

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Six identical microsatellites were successfully launched into a circular low-Earth orbit from Vandenberg Air Force Base, Calif., at 0140 UTC on 15 April 2006.

Termed the Formosa Satellite 3 and Constellation Observing System for Meteorology, Ionosphere, and Climate (FORMOSAT-3/COSMIC) mission, the new constellation's primary science goal is to obtain vertical profiles in near-real time of temperature, pressure, and water vapor in the neutral atmosphere and electron density in the ionosphere. The observations will be used to support operational global weather prediction, climate monitoring and research, space weather forecasting, and ionospheric research.

The mission is a collaborative project of the National Space Organization (NSPO) in Taiwan and the University Corporation for Atmospheric Research (UCAR) in the United States. Expected to last for five years, FORMOSAT-3/COSMIC provides the first satellite constellation for observing global weather using the Global Positioning System (GPS) radio occultation technique.

Science Payloads

Each satellite houses a GPS Occultation Experiment (GOX) payload. Developed at the Jet Propulsion Laboratory (JPL, Pasadena, Calif.), the GOX receiver measures the propagation time of radio signals from a GPS satellite to a FORMOSAT-3/COSMIC satellite as it rises or sets behind the Earth relative to the GPS satellite. As the radio waves pass through the atmosphere, they are refracted and slowed, with the degree of bending related to the vertical variation of refractivity, which is a function of temperature, pressure, and water vapor in the neutral atmosphere and electron density in the ionosphere.

From the raw phase and amplitude measurements of these refracted radio waves, profiles of bending angle and refractivity can be deduced. These profiles can be assimilated into numerical weather prediction models, yielding information on temperature, pressure, and water vapor. Vertical profiles of temperature and moisture can be deduced from the refractivity profiles with the use of additional information. A special issue of the journal *Terrestrial, Atmosphere and Oceanic Sciences* (TAO) for Applications of the Constellation Observing System for Meteorology, Ionosphere and Climate (*Tao, 11*(1), 2000) presents further information on the RO technique, the science payloads, and the FORMOSAT-3/COSMIC mission.

The GOX will be making use of the advanced open-loop (OL) signal tracking, which allows the RO soundings to penetrate deep into the lower troposphere at all latitudes, observing planetary boundary layer heights and structure and providing valuable information on low-level moisture.

The GOX will provide over 2500 atmospheric soundings every 24 hours around the globe (Figure 1). This is about twice the number of daily weather balloon observations (~1500 soundings from ~850 stations), which are concentrated mostly over land.

The RO soundings' high vertical resolution will complement the high horizontal resolution of conventional infrared and microwave satellite soundings.

In addition, the GOX will provide vertical profiles of electron density. The approximately 2500 electron density profiles between 90 and 800 kilometers will define the ionospheric structure, and the scintillation and electron density irregularities that contribute to satellite malfunctions.

Another instrument aboard each satellite is the tiny ionospheric photometer (TIP), which will monitor the density of emissions that result from recombination of oxygen ions with electrons at ionospheric altitudes, and will be helpful for improving the ionospheric occultation inversions. Moreover, TIP measurements will contribute to the determination of the nighttime auroral boundary.

The satellites are also equipped with a triband beacon (TBB), which will provide ionospheric observations to ground-based receivers. Data from the TBB can be used to retrieve the satellite-to-ground total electron content, allow for high-resolution tomography of the electron density distribution, and monitor phase and amplitude scintillations induced in radio waves propagating through the ionosphere.

Special Observation Campaigns and Data Management

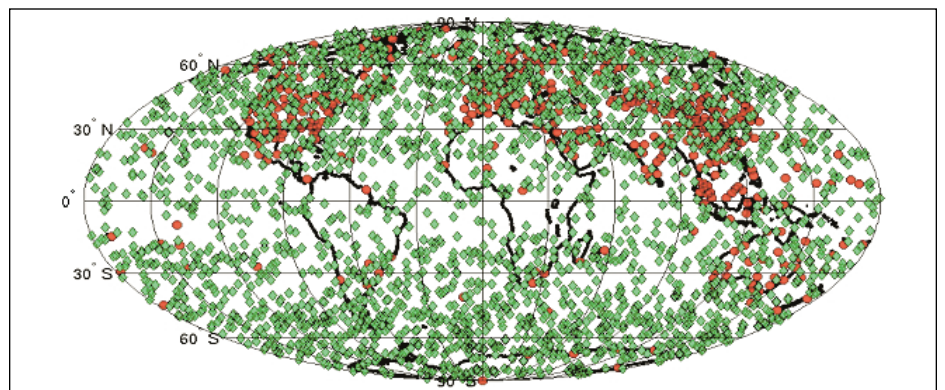During the first 13 months following launch, the six satellites will gradually separate as they

Fig. 1. More than 2500 radio occultation (RO) soundings (green dots) obtained by the GPS Occultation Experiment (GOX) each day. In comparison, radiosondes (red dots) provide only approximately 1500 soundings per day.