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El Niño in the Eocene Greenhouse Recorded by Fossil Bivalves and Wood from Antarctica

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El Niño in the Eocene greenhouse recorded by fossil bivalves and wood from Antarctica

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[1] Quasi-periodic variation in sea-surface temperature, precipitation, and sea-level pressure in the equatorial Pacific known as the El Niño – Southern Oscillation (ENSO) is an important mode of interannual variability in global climate. A collapse of the tropical Pacific onto a state resembling a so-called 'permanent El Niño', with a preferentially warmed eastern equatorial Pacific, flatter thermocline, and reduced interannual variability, in a warmer world is predicted by prevailing ENSO theory. If correct, future warming will be accompanied by a shift toward persistent conditions resembling El Niño years today, with major implications for global hydrological cycles and consequent impacts on socioeconomic and ecological systems. However, much uncertainty remains about how interannual variability will be affected. Here, we present multi-annual records of climate derived from growth increment widths in fossil bivalves and co-occurring driftwood from the Antarctic peninsula that demonstrate significant variability in the quasi-biennial and 3–6 year bands consistent with ENSO, despite early Eocene (~50 Mya) greenhouse conditions with global average temperature ~10 degrees higher than today. A coupled climate model suggests an ENSO signal and teleconnections to this region during the Eocene, much like today. The presence of ENSO variation during this markedly warmer interval argues for the persistence of robust interannual variability in our future greenhouse world. **Citation:** Ivany, L. C., T. Brey, M. Huber, D. P. Buick, and B. R. Schöne (2011), El Niño in the Eocene greenhouse recorded by fossil bivalves and wood from Antarctica, *Geophys. Res. Lett.*, *38*, L16709, doi:10.1029/2011GL048635.

1. Introduction

[2] Will climate oscillations in the 2–7 year ENSO band persist as our planet warms, or will the Earth move toward a permanent El Niño or La Niña-like state? Short of waiting for the future to happen, answering this question relies on predictions drawn from dynamical theories and coupled climate models or on insights drawn from warm intervals in the Earth's past. Most models and theory favor progression toward one or the other end-member state, but some argue for no change, and observational data are equivocal [*Fedorov and Philander*, 2001; *Fedorov et al.*, 2006; *Vecchi et al.*, 2008; *Collins et al.*, 2010]. Therefore, there is significant disagreement about which of these is more likely [*Vecchi et al.*, 2008; *Karnauskas et al.*, 2009]. Given this uncertainty, paleoclimate data can provide key insights. Datasets from the early Pliocene warm period (~3–5 mya), for example, indicate a flatter thermocline and comparatively warm temperatures in the eastern equatorial Pacific [*Molnar and Cane*, 2002; *Wara et al.*, 2005; *Fedorov et al.*, 2006], indicating a shift toward more El Niño-like mean conditions. However climate models have not produced a reduction in this variation, and a recent dataset suggests instead the persistence of ENSO-scale variability [*Watanabe et al.*, 2011]. It therefore remains an open question whether a warmer world is characterized by a less variable tropical Pacific.

[3] Demonstrating interannual variability in warmer worlds of the past offers an approach to evaluating predictions for the future, but this is not a simple task. Long, continuous, annually-resolved records from times when the planet was significantly warmer than today and from a region where the ENSO signal is expected to be strong are required. Such proxy datasets from the rock record are rare, however, as sediment and ice cores generally do not retain annual resolution far enough back in time to reach markedly warmer climate conditions. Previous attempts to investigate this issue in the distant past rely on varved sediment records, which might be challenged as not reflecting true interannual variability [*Ripepe et al.*, 1991; *Huber and Caballero*, 2003; *Galeotti et al.*, 2010; *Lenz et al.*, 2010; *Davies et al.*, 2011].

2. Interannual Variation Derived From Growth Increments

[4] Life histories of long-lived organisms that grow by accretion and preserve well in the fossil record have the potential to offer an archive with which to evaluate predictions of ENSO-like behavior in the distant past. Changes in environmental conditions that occur seasonally generally lead to changes in skeletal growth rate that manifest as visible growth bands, such as those seen in the wood of trees. If the widths of annual growth increments correlate with environmental variables, then long records of consecutive increment widths can be used to test for interannual variation in the ENSO band. Many authors have explicitly tied variation in increment widths and shell chemistry of modern long-lived bivalves to observed variations in temperature and primary production (food supply) [*Kennish and Olsson*, 1975; *Jones et al.*, 1989; *Schöne et al.*, 2003; *Strom et al.*, 2004; *Schöne et al.*, 2005; *Ambrose et al.*, 2006; *Black et al.*, 2009; *Butler*

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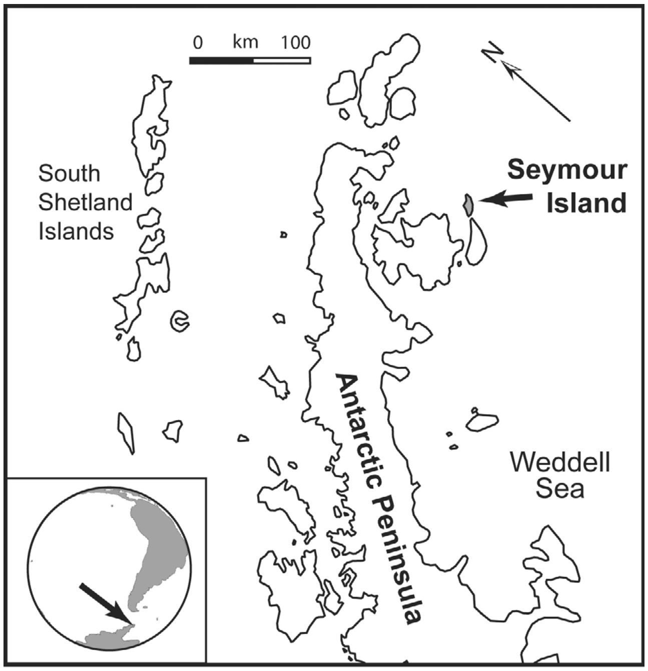

Figure 1. Location of Seymour Island off the Antarctic Peninsula.

et al., 2010], including those associated with ENSO [*Lazareth et al.*, 2006]. Others have similarly used the accretionary skeletons of corals [see refs in *Cane*, 2005] and tree rings [*D'Arrigo et al.*, 2005; *Rigozo et al.*, 2007] to extend the record of ENSO variation back beyond the instrument record [e.g.,*Gergis and Fowler*, 2006], but examples from the deep geologic past are thus far lacking.

[5] Shells of long-lived bivalves and wood from the early Eocene of Antarctica present an opportunity to examine climate variability in the Earth's distant past. The bivalves *Cucullaea raea* (Superfamily Arcoidea) and *Eurhomalea antarctica* (Superfamily Veneroidea) preserved in shallow marine sediments of the La Meseta Formation on Seymour Island, off the NE tip of the Antarctic Peninsula (Figure 1 and auxiliary material), have lifespans that can exceed 100 years as demonstrated by counts of growth bands (Figure 2); high-resolution stable isotope analysis verifies that growth bands are annual [*Buick and Ivany*, 2004; *Ivany et al.*, 2008].[1] A cross-section through a coeval piece of driftwood from a coniferous tree that had grown on the Peninsula and been washed into the nearshore marine environment reveals 157 consecutive annual bands (auxiliary material). Biostratigraphy and strontium isotope stratigraphy place the samples at about 50 million years in age [*Ivany et al.*, 2008], during the early Eocene, a global greenhouse interval representing the warmest time in the past 65 million years. Temperatures on the Antarctic shelf approached or exceeded 15°C [*Ivany et al.*, 2008], significantly warmer than today. Spectral frequencies derived from detrended increment width sequences of 5 bivalves exhibiting a minimum of 55 consecutive years of growth and co-occurring driftwood demonstrate significant and similar peaks within the ENSO band, at 2.8–3.0, 3.5–4.5, 4.3–5.2, and 5.7 years, as defined by the modern Nino 3.4 Index (Figures 3a–3c; see auxiliary material for details on methodology). Prominent quasi-biennial peaks are also noted in both the shell and wood spectra, similar to those observed today and regarded as an important component of ENSO [*Jiang et al.*, 1995; *Ribera and Mann*, 2002, 2003; *Kuroda and Yamazaki*, 2010]. These data suggest that climate variation on the same scale as today's ENSO influenced the growth of accretionary organisms in the sea and on land around the Antarctic Peninsula 50 million years ago.

3. ENSO in the Antarctic

[6] How likely is it that interannual variation recorded in these fossils is actually due to ENSO variability and not to some other factor varying with similar frequencies? Antarctica, though far removed from the equatorial Pacific where ENSO prominently figures, nonetheless experiences the effects of that oscillation today [*Turner*, 2004]. ENSO is tied to the Antarctic Dipole via atmospheric and oceanic connections [*Holland et al.*, 2005] such that warm events (El Niño) in the tropical Pacific produce warm anomalies in the SE Pacific sector of the Southern Ocean, cool anomalies in the Atlantic sector, and La Niña the reverse. Liu and

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048635.

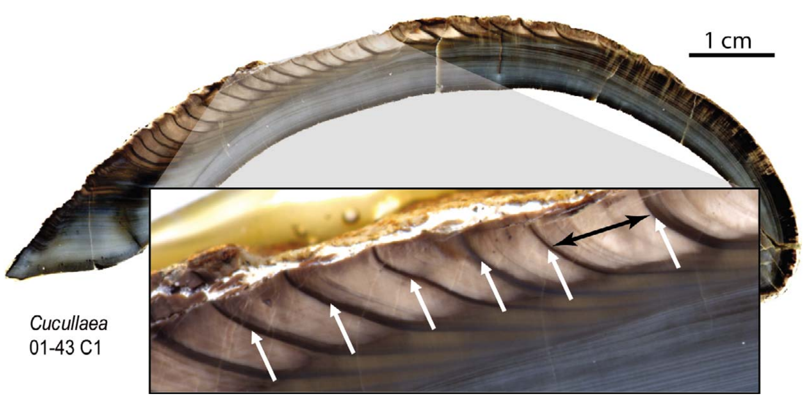

Figure 2. Cross section through the shell of *Cucullaea raea* showing annual growth increments. Detail shows close up of annual growth patterns (one year spanned by the black arrow), while white arrows indicate dark bands that represent the periods of slowest growth, in this case, summer [*Buick and Ivany*, 2004].

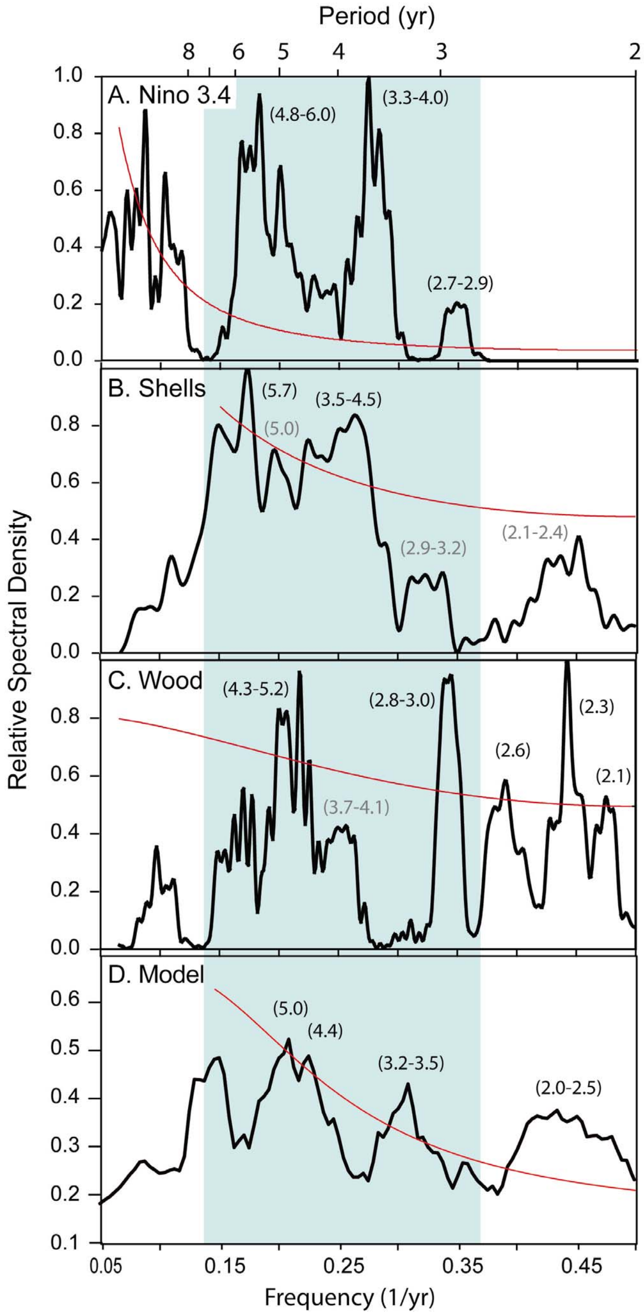

Figure 3. Spectral densities for (a) modern ENSO given by SST data from the Nino 3.4 region in the central equatorial Pacific, (b) SGIs of growth increments in fossil bivalve shells, (c) SGI of growth banding in fossil driftwood, and (d) model prediction for Eocene ENSO from coupled climate model [*Huber and Caballero*, 2003]. Periodicities in years are given at top. Vertical shading roughly encompasses range of modern spectral power for ENSO. Significant spectral peaks in each panel are indicated in parentheses; non-significant peaks in fossil spectra are given in gray. Longer period (lower frequency) peaks outside the ENSO range in Nino 3.4 cannot be evaluated in shell data due to lengths of time series. Solid lines are the 95% significance level relative to the estimated red noise background.

colleagues [*Liu et al.*, 2002] find that these temperature differences are the largest manifestations of ENSO outside the tropical Pacific, although other long-period variations like the Southern Annual Mode, or Antarctic Oscillation, are also important regionally [*Holland et al.*, 2005; *Meredith et al.*, 2008; *Divine et al.*, 2009]. Teleconnections between the Antarctic Peninsula and the equatorial Pacific today are particularly well documented [*Harangozo*, 2000; *Yuan*, 2004; *Ding et al.*, 2011], and are supported by shared spectral power in the ENSO range between the Nino 3.4 time series and sea-surface-temperatures offshore of Seymour Island (Figure 4a). Conditions on either side of the Peninsula illustrate the Antarctic Dipole well, as they are exactly out of phase. ENSO/Dipole variation here today is manifest as changes in sea surface temperature and wind speed [*Martinson et al.*, 2008; *Meredith et al.*, 2008], sea ice extent [*Yuan*, 2004; *Stammerjohn et al.*, 2008], and phytoplankton size structure [*Montes-Hugo et al.*, 2008]. Physical oceanographic effects on primary production are translated to higher trophic levels, as seen in correlated changes in growth rate and reproduction of marine mammals [*Turner*, 2004; *Proffitt et al.*, 2007, and references therein]. While the Drake Passage between Antarctica and South America had not yet opened in the early Eocene, Seymour Island was in essentially the same position relative to the Pacific Ocean as it is today. It stands to reason then, that if ENSO operated during the Eocene, its effects would be felt along the Antarctic Peninsula and would be evident in the growth rates of long-lived, suspension-feeding bivalves.

[7] The environmental conditions directly related to growth rate in the fossil bivalves can be assessed at least in part by high-resolution stable isotope data collected across 17 annual growth increments of one of the shells used to quantify periodicities here [*Buick and Ivany*, 2004]. Detrended increment widths, a measure of growth, demonstrate a positive relationship ($r^2 = .44$, $p = .006$) with austral summertime $\delta^{13}C$ values (Figure S8 and discussion in Text S1), a reflection of primary production on the shelf likely driven by increased wind speed. In addition, while thinner growth increments exhibit a range of oxygen isotope values, all thick increments correspond to lower $\delta^{18}O$ values and hence warmer temperatures (Figure S8 and discussion in Text S1). *Cucullaea* apparently precipitated more shell material during years with warmer and more productive summers, factors that characterize La Niña years around the Peninsula today. These factors are the same as those that enhance growth rate in the modern, long-lived bivalve *Arctica islandica* [*Schöne et al.*, 2005].

4. Support From a Coupled Eocene Climate Model

[8] Is there theoretical support for the existence of ENSO during the warm conditions of the Eocene? We have shown in previous work [*Huber and Caballero*, 2003] that ENSO variation is predicted by a fully coupled Eocene climate model, despite much warmer overall temperatures (Figure 3d). Spectral analyses reveal power in the Eocene time series for both model output and shell increment data at 2.5 yrs, 3.2–3.5 yrs, 4.4 yrs, and 5 yrs. Note that these peaks are quite similar to those indicated by the fossil spectra, and to middle Eocene peaks found by *Lenz et al.* [2010] in varved sedimentary records. The specific teleconnection between the equatorial Pacific and the peninsular region today is also

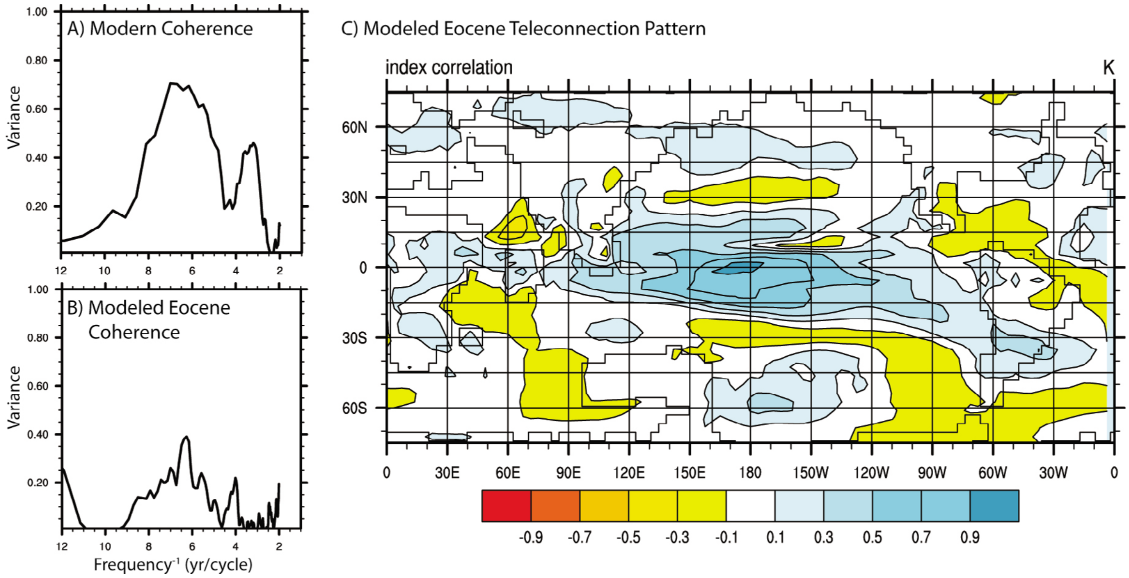

Figure 4. Coherence between spectra for the ENSO signal in the Nino 3.4 region and Seymour Island for both the (a) Modern and (b) Eocene derived from a coupled climate model. Spectral analyses use the annual SST time series for the Modern, and July SSTs for the Eocene. Note common peaks in the ENSO band for both sets of records. (c) Map showing the correlation between the Eocene Nino3.4 region SST time series and global July temperature variations. Note the 20–30% antiphase relationship between the Nino region and Seymour Island. The majority of the remaining variability can be characterized as red noise, and hence incoherent. See auxiliary material for more details.

produced by the Eocene model (Figure 4). Demonstrated coherence between Seymour Island SSTs and the NINO3.4 ENSO index today (Figure 4a) is mirrored by that between model output of Seymour Island SSTs and the predicted ENSO index during the Eocene (Figure 4b). The environmental variables in which the ENSO signal is most clearly manifest include surface temperature, precipitation, and wind speed, factors that influence growth in both (marine) bivalves and (terrestrial) trees today. In addition, the model teleconnection pattern (Figure 4c) is robust to a wide range of pCO_2 values and climate states corresponding to early and middle Eocene climates (auxiliary material).

5. Implications of ENSO Variation in the Eocene

[9] The peaks documented here from fossil growth increment sequences are in good agreement and correspond well to those recognized in varved lake sequences from the middle Eocene [*Huber and Caballero*, 2003; *Lenz et al.*, 2010], the only other accounts of interannual variability during the epoch. Importantly, the documented frequencies are effectively the same as those experienced today (Figure 3). This suggests that the fundamental processes driving the Bjerknes feedback responsible for ENSO variation on the modern Earth operated in a similar way in the Eocene, despite much warmer than modern temperatures and differences in the configuration of the Pacific Ocean margins. If so, either the equatorial thermocline tilt and associated modes of variability emergent in the Eocene climate model are robust, or the data support alternative models for ENSO in which modes of variability are not closely linked to the mean thermocline tilt [*Karnauskas et al.*, 2009]. Our data, from demonstrably annual records, bolster studies finding ENSO-scale oscillation in warm worlds based on sedimentary sequences [*Ripepe et al.*, 1991; *Huber and Caballero*, 2003; *Galeotti et al.*, 2010; *Lenz et al.*, 2010]. Data from the warm Pliocene implying a flatter thermocline [*Wara et al.*, 2005; *Fedorov et al.*, 2006], perhaps maintained by strong vertical mixing by cyclones [*Fedorov et al.*, 2010], present a challenge to explain. Recently published data from equatorial Pacific Pliocene corals suggest that ENSO-scale variability persists despite warm conditions [*Watanabe et al.*, 2011], in agreement with our findings. Either enough of a gradient in equatorial SSTs remained to produce ENSO variation despite the observed shift in mean state, or variability and mean state are not closely tied.

[10] In summary, growth increment series in Eocene fossils from the Antarctic Peninsula exhibit spectral peaks consistent with modern ENSO, the region is strongly teleconnected to the equatorial Pacific today, and ENSO variation and similar teleconnection during the Eocene are predicted by a coupled climate model. It is therefore likely that the interannual environmental variation affecting growth during the Eocene was ultimately controlled by ENSO. Our results run counter to predictions of a permanent El Niño and suggest that ENSO is a robust feature of the climate system that will persist into the warmer world of our collective future.

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[12] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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