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Orbital control of low-latitude seasonality during the Eemian

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[1] We used Sr/Ca and stable isotope data from well dated and preserved corals from the northeastern Caribbean to determine the seasonal environmental conditions for four continuous years during the Eemian, the last time the Earth was in a prolonged warm phase. We determined that the seasonal range in SST during the Eemian was 25°–30° C. This is ~1–2° larger than at present and caused primarily by winter cooling and, only to a small degree, by summer warming. As climate modeling studies indicate, the bias towards colder winters can be explained by changes in low latitude insolation induced by altered orbital parameters, modulated by atmospheric CO_2 levels that were lower than today. Milankovitch forcing at higher latitudes was probably less important. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4215 Oceanography: General: Climate and interannual variability (3309); 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 1040 Geochemistry: Isotopic composition/chemistry; 1065 Geochemistry: Trace elements (3670). **Citation:** Winter, A., A. Paul, J. Nyberg, T. Oba, J. Lundberg, D. Schrag, and B. Taggart, Orbital control of low-latitude seasonality during the Eemian, *Geophys. Res. Lett.*, *30*(4), 1163, doi:10.1029/2002GL016275, 2003.

1. Introduction

[2] The astronomical theory of paleoclimates [*Berger*, 1988], best known in its Milankovitch version, states that changes in the seasonal distribution of insolation brought about by changes in the Earth's orbital parameters exert a dominant influence on climate. One approach to corroborate this theory would be to study seasonal data, preferably from a period in the past in which the Earth's orbital parameters were markedly different from the present values. The last interglacial, which is believed to have occurred sometime between 140,000–130,000 to 117,000 a BP [*Adams et al.*, 1999], depending on location, is one such period [*Muhs et al.*, 2002]. It is commonly known as the Eemian on land, approximately equivalent to Marine Isotope Stage 5e. It is generally believed that the Eemian was the last time the Earth experienced warm conditions reminiscent of today. Sea level was higher than today [*Bard et al.*, 1990]. The mean atmospheric CO_2 concentration was at pre-industrial levels (~270 ppm from ice core measurements [*Petit et al.*, 1999]). There are indications that it was interrupted for a short period by a cold interval [*Stirling et al.*, 1998]. Coral reef building, which requires relatively stable climate conditions, took place for a period of at least 5,000 a, and concluded most likely before the beginning of the cold interval at ca. 122,000 a BP [*Adams et al.*, 1999].

[3] During the peak of the last interglacial, eccentricity was much greater than today (0.0394 as compared to 0.0167) and, in fact, greater than at any other time during the past 150,000 a, and perihelion (longitude of perihelion with respect to vernal equinox: 95.41° as compared to 282.04°) took place in northern summer (June) instead of northern winter (January). Obliquity, the tilt of the Earth's axis (24.04° as compared to 23.45°) was also slightly greater than today (all orbital element data are for 127,000 a BP and AD 1950, respectively [*Berger*, 1978]). The near-minimum precession during the Eemian (perihelion was quite close to the summer solstice, 90°) enhanced the seasonality in the northern hemisphere and weakened it in the other (Figure 1; *Tuenter et al.*, [2002]). The difference in obliquity added another small contribution to these seasonal insolation changes, by strengthening the contrast between the hemispheres during summer and winter, anti-symmetrical to the equator. A stronger seasonal contrast might therefore be expected for Eemian climate records from the northern hemisphere.

[4] Here we present two different SST proxy records derived from a Caribbean coral living at the height of the Eemian to test the theory that the seasonal distribution of insolation during Eemian times should result in a greater seasonality in low northern latitudes. We compare these seasonal proxy data with insolation and results from climate modeling.

2. Methods

[5] Reef building corals have thrived during only short time intervals in Earth's history. For example, in Western Australia Eemian reef building was confined to just a few thousand years between 127,000 to 122,000 a BP [*Stirling et al.*, 1998]. This is also true for most other areas of the tropics because sea level was constant only at the height of the Eemian allowing enough time for extensive coral building to take place. Abundant coral growth during the Eemian is evident on 4 to 6 m high reef terraces throughout the Caribbean.

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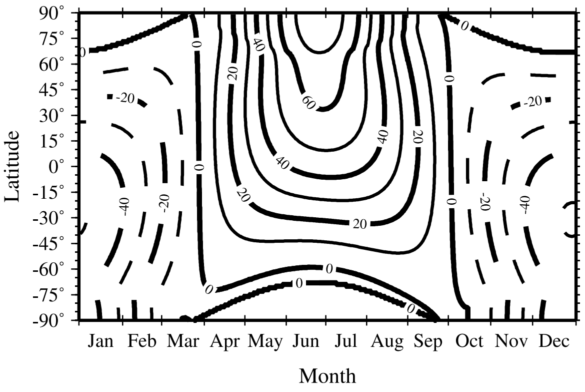

Figure 1. Anomaly of daily insolation (W m^{-2}), 127,000 a BP - present. Contour interval is 10 W m^{-2}. Dashed lines mark negative contour levels. Orbital element data taken from *Berger* [1978] . The time axis refers to the "angular months" as defined by *Jaussaume and Braconnot* [1997].

[6] Our Eemian record was obtained by drilling through a colony of *Montastraea faveolata* occurring on a raised reef terrace [*Taggart*, 1993] 4.1 m above sea level on Isla de Mona (18°N, 67°W) between Hispaniola and Puerto Rico in the northeastern Caribbean. The core was radiometrically dated by U-series alpha spectrophotometry and U/Th thermal ionization mass spectrometry (TIMS) [*Cheng et al.*, 1998]. Two TIMS U-Th dates gave ages of 127.5 ± 1.4 ka and 126.3 ± 1.9 ka, confirming that the corals grew during Substage 5e. Scanning electron microscope and X-ray diffraction studies of the aragonite show that the aragonite has undergone little or no diagenesis. The ^{238}U concentration of 2.5 ppm of the fossil coral is typical for the modern species and the similarity between the initial $^{234}U/^{238}U$ ratios of the Isla de Mona 5e corals, at 1.152 ± 0.003, to that of modern corals at 1.144 ± 0.004 [*Cheng et al.*, 1998] is further evidence that the samples are pristine.

[7] *M. faveolata* is well suited to the task of reconstructing past SSTs in the tropical Atlantic Ocean [*Leder et al.*, 1996]. Oxygen isotopic ratios and trace elements in the aragonitic framework of scleractinian coral species are the primary agents for SST reconstruction [*Gagan et al.*, 2000]. For stable isotope and trace elements analyses 24 samples were taken between annually produced high-density bands using the method *of Watanabe and Oba* [1999]. The $\delta^{18}O$ standard deviations (2σ; 95% confidence) for fifteen duplicate measurements of powdered carbonate samples measured by a Finnigan MAT 251 mass spectrometer were 0.04‰. To convert oxygen isotopes to SSTs we used the equation of *Leder et al.* [1996]. Using this equation to convert modern stable isotopes derived from *M. faveolata* to SST in the northeast Caribbean has consistently provided reliable results [*Watanabe et al.*, 2002].

[8] Stable oxygen isotopes record SST and the stable isotopic composition of the water in which the coral lived. Isla de Mona, situated between Hispaniola and Puerto Rico in the Mona Passage, a throughway for water exchange between the Atlantic Ocean and Caribbean Sea, lacks river discharge, and ocean salinity remains constant throughout the year suggesting that changes in coral $\delta^{18}O$ in Isla de Mona reflect only local SST variability. To convert Sr/Ca to SST we simply used the modern local temperature range for calibration. This yielded a slope of 0.55 similar to the 0.6 from the Bahamas for *M. faveolata* [*Guilderson*, 1997]. Trace element ratios are primarily a function of SST. For Sr/Ca, the primary assumption is that oceanic Sr was relatively constant [*de Villiers*, 1999]; that the increased growth rate of the coral did not cause appreciable kinetic effects [*de Villiers et al.*, 1995]; and that the analyzed aragonitic material was pristine so that possible distortion of the SST signal due to diagenesis was negligible [*Enmar et al.*, 2000]. Precision for Sr/Ca is better than 0.15% ($1\ \sigma$).

[9] To relate the change in SST to the solar forcing at the time, we compute the anomaly of daily insolation as a function of season and latitude as well as for a fixed latitude of 18°N for 127,000 a BP (Figures 1 and 2; the value of the solar constant is set at 1367 W m^{-2}). We define Eemian northern summer and winter as those periods that correspond to the same interval in true longitude as June–August (JJA) and December–February (DJF) today [*Joussaume and Braconnot*, 1997; *Montoya et al.*, 2000]. For present day, we employ the usual definitions for the meteorological seasons.

3. Results

[10] Compared to the present, the change in global annual-mean insolation during the Eemian was negligible (0.21 W m^{-2}). At the latitude of Isla de Mona (18°N), annual-mean insolation was 393.37 as compared to 393.87 W m^{-2}, a change of just 0.50 W m^{-2} or 0.13%. However, seasonality in the Eemian at low northern latitudes was greater than today because of altered orbital parameters of the Earth [*Berger*, 1978]. During northern summer, local insolation was greater than today (489.53 as compared to 442.87 W m^{-2}, an increase of 46.66 W m^{-2} or 10.54%), and during northern winter it was smaller than today (296.77 as compared to 328.60 W m^{-2}, a decrease of 31.84 W m^{-2} or 9.69%; Figure 2). Overall, the seasonal range in insolation was amplified in the Northern Hemisphere, but attenuated in the Southern Hemisphere [*Montoya et al.*, 2000].

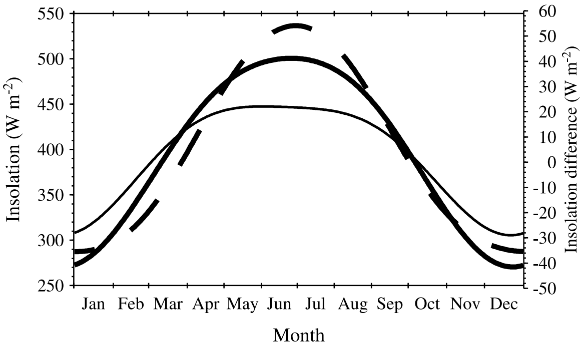

Figure 2. Daily insolation (W m^{-2}) at 18° N, i.e., at the latitude of Isla de Mona where the Eemian corals grew. Heavy line: 127,000 a BP. Light line: present day. Heavy dashed line: anomaly, 127,000 a BP - present, similar to what we would expect for the seasonal SST signal if there were no change in atmospheric CO_2.

Table 1. Annual Means, Minima, Maxima, Ranges, and Extremes of Sea Surface Temperatures (SST), Eemian vs. Present

	Present			Eemian	
SST °C	Obs.	$\delta^{18}O$	Sr/Ca	$\delta^{18}O$	Sr/Ca
Annual mean	28.0	28.3	28.0	26.9	27.7
Max.	30.6	30.6	30.2	32.3	30.7
Min.	24.5	26.2	25.0	22.8	23.4
Max. range	6.1	4.4	5.2	9.4	7.3
Ave. of Max.	29.7	29.7	30.0	29.6	30.0
Ave. of Min.	26.0	26.8	26.0	24.6	25.0
Ave. range	3.7	2.9	4.0	5.0	5.0

Values in first column are the observations (1966–1998) taken at La Parguera (LP), Puerto Rico. Second and third column show calculated SST values for the Present derived from LP coral Sr/Ca and $\delta^{18}O$. Fourth and fifth columns show SST values for Eemian corals taken at Isla de Mona (50 km from LP).

[11] Results of $\delta^{18}O$ and Sr/Ca analyses from a modern coral from Puerto Rico and the Eemian coral from Isla de Mona are presented in Figure 3. When converted to Eemian SSTs both proxies yield similar results. The fact that two different proxies yield similar temperature ranges gives us confidence in our results and therefore we believe that the Eemian range given here is reliable. Two major differences between the modern coral and the Eemian coral are apparent. The first is that the seasonal SST range of ~5°C in the Eemian sample (approximately 25°–30°C) is one to two degrees larger than the present range of ~3–4 °C (1965–1999; Figure 3 and Table 1). The second is that, in contrast to local insolation, the greater seasonality in Eemian SST was caused primarily by winter cooling and only to a small degree by summer warming. Thus, at our site, while the seasonal range of SST was larger during the Eemian than at present, its annual mean value was possibly slightly lower.

4. Discussion

[12] We realize that the Eemian samples are basically random snap shots of peak Eemian SST conditions. However, we believe that they are indicative of Eemian SST conditions for at least three thousand years (roughly from 127,000–124,000 a BP) for three reasons: First, sea level was nearly constant between 127,000 and 122,000 a BP. Second, although this interval was possibly punctuated by a cold event, the occurrence of coral reef building by itself provides evidence for otherwise relatively stable climatic conditions. Third, the orbital elements vary only very slowly through time, the fastest being the longitude of the perihelion with a period of about 20,000 a. Between 128,000–124,000 a BP, perihelion fell into northern summer (JJA), and insolation conditions were similar to 127,000 a BP (Figures 1 and 2).

[13] Furthermore, detailed information on Eemian climate is rare; few records actually resolve the seasonal cycle and few exist from outside the mid-to-high northern latitudes. Pacific records can be complicated by large salinity/precipitation changes associated with ENSO/monsoon variability. Atlantic corals should provide a more robust global SST signal. Indeed, work by Diaz (pers. com.) has shown that SST changes in the northeastern Caribbean are coherent with changes in global SST during the last 100 years. Finally, any data from low latitudes are particularly well suited because the local response of the climate system is less distorted by high-latitude albedo effects and ocean circulation changes and, thus, allows an assessment of the sensitivity of the climate system to radiative perturbations only.

[14] Using Eemian insolation and CO_2 forcings in their CLIMBER-2 model, *Kubatzki et al.* [2000] showed that the Caribbean experienced summer and winter near-surface air temperature anomalies of <1°C and ~−2°C respectively in comparison to present-day (or modern) climate with present CO_2 levels and of <2°C and ~−1°C in comparison to present-day climate with pre-industrial CO_2 levels (the CO_2 effect deduced from the CLIMBER-2 equilibrium simulations maybe higher than in reality because the present-day climate has not yet equilibrated with the high industrial CO_2

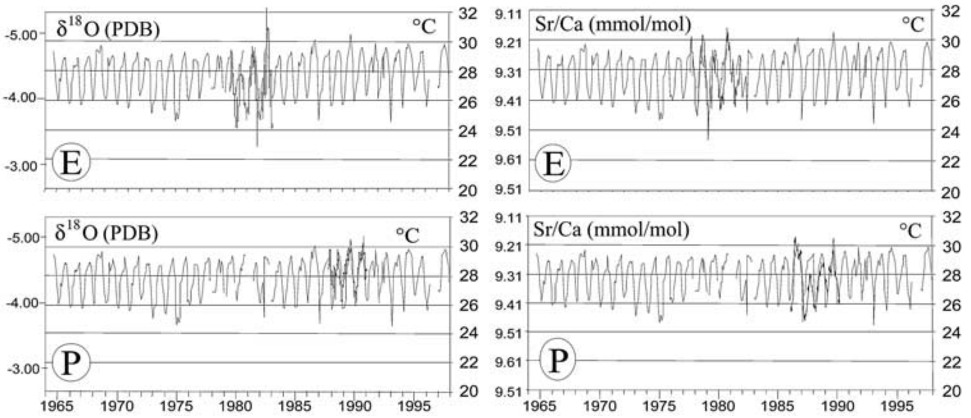

Figure 3. All boxes = monthly SSTs from 1966–1998 at La Parguera, Puerto Rico (light gray) compared to: P = present day (lower boxes) converted temperatures from oxygen isotopes and Sr/Ca ratios of *Montastraea faveolata* corals at La Parguera. E = Eemian (upper boxes), oxygen isotopes and Sr/Ca ratios from corals at nearby Isla de Mona, Puerto Rico using the same temperature conversion formulas. Notice greater seasonality during the Eemian primarily as a result of winter cooling. Shifts towards colder conditions could be explained by the CO_2 changes (see text for further discussion). Isla de Mona and La Parguera are only 50 miles apart and have practically the same modern SST records.

levels). Also, *Tuenter et al.* [2002] found in the ECBilt model that the difference in surface air temperature in the Caribbean for minimum and maximum precession insolation amounts to >1°C during summer and <−1°C during winter, not taking into account any CO$_2$ change. The Eemian SST average and annual range we derived from the coral proxies is therefore consistent with what one would expect from altered insolation at the coral site of 18°N (Figure 2) and lower CO$_2$ levels. Ocean and atmospheric circulation changes probably also played a role, but it is uncertain whether the Atlantic Ocean meridional overturning circulation strengthened or weakened relative to pre-industrial times [*Kubatzki et al.*, 2000].

5. Conclusion

[15] Geochemical paleo proxies from a *M. faveolata* coral colony on Isla de Mona (18°N 67°W) in the northeastern Caribbean, growing at the height of the Eemian, indicate a greater seasonal range in SSTs relative to today, caused primarily by winter cooling and, to a smaller degree, by warmer summers. A greater seasonal range is what would be expected from the seasonal distribution of insolation at that time. The apparent bias towards the winter season is due to greater seasonality combined with the lower CO$_2$ concentration in the atmosphere (about 270 ppm as compared to more than 360 ppm today). Thus, our findings demonstrate the orbital control of seasonality at low latitudes. At the same time they show the importance of changes in atmospheric CO$_2$ levels, because it appears that, in the annual mean, the present-day climate is already warmer than the last interglacial. This may be contrary to common belief, but is in accordance with climate model results [*Montoya et al.*, 1998; *Montoya et al.*, 2000].

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