A study of the TEX_{86} paleothermometer in the water column and sediments of the Santa Barbara Basin, California

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[1] Particulate organic matter collected during a 2-year period, as part of an ongoing sediment trap study, and a high-resolution sediment record from 1850 to 1987 A.D. from the Santa Barbara Basin were analyzed for TEX_{86}, a temperature proxy based on marine crenarchaeotal membrane lipids. Highest fluxes of crenarchaeotal lipids in the water column were found in May–June 1996 and from October 1996 to January 1997 and, in general, showed a good correlation with mass fluxes. TEX_{86} reconstructed temperatures from the sediment trap series ranged from 8 to 11°C and were usually substantially lower than sea surface temperatures (SST), indicating that unlike in previous studies, the TEX_{86} corresponds to subsurface temperatures, likely between 100 and 150 m. TEX_{86} temperature variations observed in trap samples were not coupled to changes in SST or deep-water temperatures and only to some degree with crenarchaeotal lipid fluxes. This suggests that a complex combination of different depth origins and seasonal growth periods of Crenarchaeota contributed to the variations in TEX_{86} signal during the annual cycle. TEX_{86} temperatures in the two sediment cores studied (8–13°C) were also substantially lower than those of instrumental SST records (14–17.5°C) confirming that TEX_{86} records a subsurface temperature signal in the Santa Barbara Basin. This result highlights the importance of performing calibration studies using sediment traps and core tops before applying the TEX_{86} temperature proxy in a given study area.

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1. Introduction

[2] A variety of sea surface temperature (SST) proxies exist for paleoceanographic applications, of which Mg/Ca ratios of planktonic foraminifera and the $U_{37}^{K'}$ index of long chain alkenones are presently the most frequently used. Five years ago, *Schouten et al.* [2002] introduced a new SST proxy, the TEX_{86} based on the relative distribution of glycerol dibiphytanyl glycerol tetraethers (GDGTs), which are membrane lipids produced by nonthermophilic Crenarchaeota. These organisms are ubiquitous and abundant in seawater [*Hoefs et al.*, 1997; *Massana et al.*, 2000; *Karner et al.*, 2001] and large lakes [*Powers et al.*, 2005]. Marine Crenarchaeota biosynthesize GDGTs with a varying number of cyclopentyl moieties, and the relative abundance of these moieties changes according to the water temperature [*Wuchter et al.*, 2004]. Therefore, by measuring the relative amounts of GDGTs present in sediments, the temperature at which Crenarchaeota were living can be reconstructed. Culture experiments showed that changes in salinity and nutrients do not substantially affect the temperature signal recorded by TEX_{86} [*Wuchter et al.*, 2004], the proxy also seems to be unaffected by water redox conditions [*Schouten et al.*, 2004].

[3] Recent evidence has shown that part of the marine Crenarchaeota are nitrifiers [*Wuchter et al.*, 2006a; *Könneke et al.*, 2005] and thus are not depending on light for growth. Indeed, they are distributed throughout the water column though highest abundances are usually noted in the upper few hundred meters both in the Pacific [*Karner et al.*, 2001] and in the Atlantic Ocean [*Herndl et al.*, 2005]. In contrast, a study of particulate organic matter (POM) at 10 different locations with various oceanographic conditions (i.e., upwelling, stratification) revealed that TEX_{86} correlates well with surface water temperatures (depths <100 m) and that the signal in deeper-water layers and surface sediments is primarily derived from these upper 100 m [*Wuchter et al.*, 2005]. This apparent contrast of a surface signal obtained from organisms living within a wide depth range was explained by the GDGTs transport mechanism to the sediment floor, i.e., through consumption and repackaging which mostly takes place in the active food web in the upper part of the water column [*Wuchter et al.*, 2005; *Huguet et al.*, 2006a].

[4] Laminated sediments from the central Santa Barbara Basin (SBB) represent an important and frequently used archive

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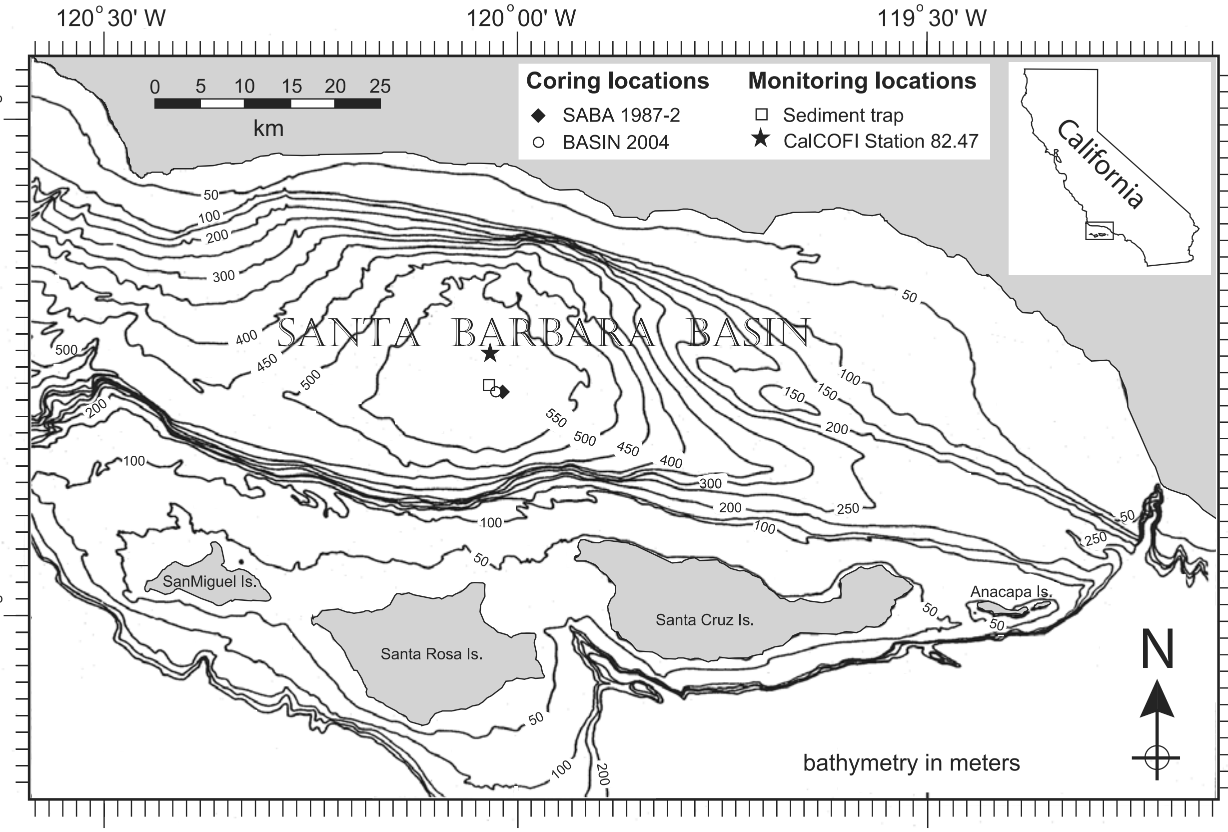

Figure 1. Map of the study area, with indication of sediment sampling locations for SABA 87-2 (34°13.5′N, 120°01.0′W) BASIN 2004 (34°13.41′N, 120°01.53′W) and the location of the sediment trap (34°14′N, 120°02′W). CalCOFI station 82.47 is located at 34°16′N, 120°2′W (http://www.calcofi.org).

of climate variability of the California coast [*Schimmelmann and Lange*, 1996; *Biondi et al.*, 1997; *Berger et al.*, 2004]. Subsill waters in the ~590 m deep SBB (Figure 1) have a low oxygen content that enhances preservation of organic matter and prevents bioturbation by macrobenthos. A high export production coupled with high sedimentation rates of several millimeters per year (before sediment compaction) result in the preservation of light and dark annual varve couplets [*Reimers et al.*, 1990; *Thunell et al.*, 1995] (Figure 2). Thus sediment cores of the SBB are excellent for high-resolution paleostudies of the climate and oceanographic conditions in the SBB area which is influenced, at different timescales, by the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the California Current system, and the upwelling regime related to the North Pacific High as well as local factors [*Weinheimer et al.*, 1999; *Berger et al.*, 2004].

[5] A variety of proxies have been used in this area. For example, SST reconstructions using long-chain alkenones revealed occasional warming during 20th century El Niño events [*Kennedy and Brassell*, 1992], although the same proxy was less successful detecting ENSO in older SBB sediments [*Zhao et al.*, 2000] or even during the last century [*Herbert et al.*, 1998]. Similarly, Mg/Ca ratios of planktonic foraminifera did not record the strong increase in surface temperatures during the 1997–1998 El Niño event [*Pak et al.*, 2004]. In contrast, other studies revealed that El Niño events can be recorded by changes in foraminifera assemblages [*Black et al.*, 2001; *Field et al.*, 2006] and that $\delta^{18}O$ of planktonic foraminifera records temperature changes associated with El Niño [*Thunell et al.*, 1999]. Thus the different proxies used in the SBB seem to yield partially contrasting information. This highlights the importance of a multiproxy approach and the need to understand the response and limitations of a proxy in the SBB area before paleoclimate studies can be performed.

[6] Here we investigated the potential of the TEX_{86} to reconstruct past temperatures in the SBB area by analyzing sediment trap material obtained over two annual cycles (1995–1997). In addition, we analyzed the TEX_{86} in a high-resolution sediment record with annual to triannual resolution representing the period from ~1849 to 1987 A.D. and compared this with the available COADS instrumental temperature record for the SBB.

2. Material and Methods

2.1. Sample Material

2.1.1. Sediment Trap

[7] An automated sediment trap has been deployed since 1993 in the center of the basin (34°14′N, 120°02′W) (Figure 1) at ~490 m water depth, ~50 m from the bottom

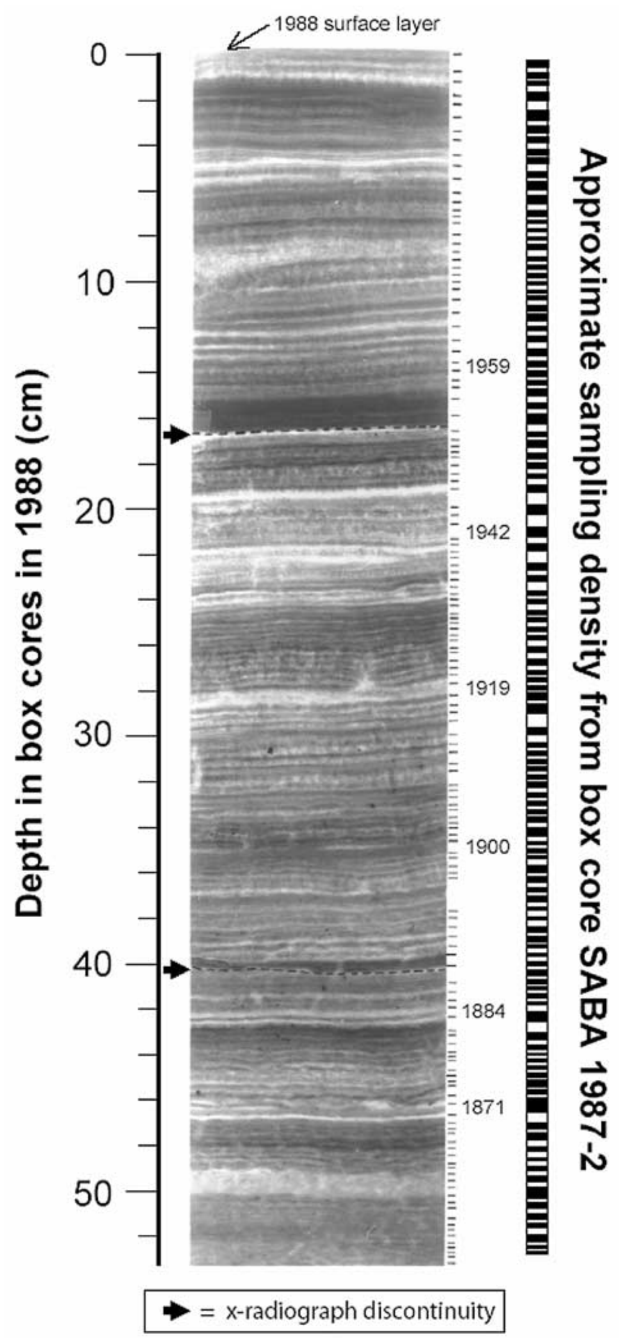

Figure 2. Composite of X radiograph contact prints showing varves form 1840 to 1988 in the depocenter of the Santa Barbara Basin. The black/white pattern indicates the approximate sediment sampling intervals for this study.

[*Thunell et al.*, 1995; *Thunell*, 1998]. Biweekly to monthly measurements of temperature and salinity to 100 m depth have been made at the mooring location of the trap sample. For this study we selected 22 samples from the period between December 1995 and December 1997 which were analyzed for GDGT concentration. These samples represent collection periods ranging from 6 to 18 days. Freeze dried and homogenized subsamples of 50–180 mg were used for this study.

2.1.2. Sediment Core

[8] Box cores from the depocenter of the SBB were recovered in 1987 during the cruise SABA 87-2 (34°13.5′N, 120°01.0′W), and in 2004 during cruise BASIN 2004 (34°13.41′N, 120°01.53′W, box core 1-MC3) (Figure 1). Cylindrical subcores from box cores were sectioned in layers with approximately annual to triannual resolution although the resolution is higher than annual in the upper third section of each core as sediment is less compacted (Figure 2). The sediment obtained from each section was freeze-dried and stored [*Schimmelmann et al.*, 1990]. BASIN 2004 samples dating from 1917 to 1959 A.D. were analyzed to cover a sampling hiatus in box core SABA 87-2. A total of 211 samples were analyzed from both cores, covering about 140 years of sedimentation from ca. 1850 to 1987 A.D.

[9] Dating of samples was performed by varve counting on sediment X radiographs that were correlated against high-resolution porosity profiles [*Schimmelmann et al.*, 1990]. Validation of varve counting for dating in SBB sediment had been independently achieved by ^{210}Pb geochronology, identification of specific diatom assemblages of El Niño events of 1941, 1958 and 1983 A.D., and the statistical relationship of varve thickness versus precipitation on land (reviewed by *Schimmelmann and Lange* [1996]) (Figure 2). The dating uncertainty for individual sediment samples is ~2 years below 1980 A.D. and ~1 year for younger sediments [*Schimmelmann et al.*, 1990].

2.2. TEX_{86} Analysis

[10] Freeze-dried samples between 50 and 180 mg were extracted using an Accelerated Solvent Extractor 200 (ASE 200, DIONEX) with a mixture of dichloromethane (DCM) and methanol (MeOH) (9:1, vol:vol) at 100°C and 7.6×10^6 Pa. A known amount of a C_{46} GDGT was added to the extract of the sediment trap samples as internal standard [*Huguet et al.*, 2006b]. The total extract was then divided into an apolar and a polar fraction, using a glass pipette column filled with activated alumina, and sequential elution with hexane/DCM (9:1 vol:vol) and DCM/MeOH (1:1, vol:vol), respectively. Polar fractions were analyzed for GDGTs according to the procedure described by *Hopmans et al.* [2000]. Analyses were performed in triplicate with an HP 1100 Series Liquid Chromatography–Mass Spectrometer (LC-MS) equipped with an autoinjector and ChemStation chromatography manager software. Separation was achieved on a Prevail Cyano column (2.1 × 150 mm, 3 μm; Alltech, Deerfield, Illinois), maintained at 30°C. GDGTs were eluted isocratically first with hexane/isopropanol (99:1, vol:vol) for 5 min, then using a linear gradient up to 1.8% vol of isopropanol over 45 min. Flow rate was 0.2 mL/min. After each analysis the column was cleaned by back flushing hexane/propanol (90:10, vol:vol) at 0.2 mL/min for 10 min. Detection was achieved using atmospheric pressure chemical ionization–mass spectrometry (APCI-MS) of the eluent using the following conditions; nebulizer pressure 4.1×10^5 Pa, vaporizer temperature 400°C, N_2 drying gas flow 6 L/min at 200°C, capillary voltage −3 kV,

corona 5 μA ($\sim$3.2 kV). Single ion monitoring (SIM) was used instead of full mass scanning because SIM increases the signal-to-noise ratio and thus improves reproducibility. SIM was set to scan the five $[M^+] + H$ ions of the GDGTs with a dwell time of 237 ms for each ion. Concentrations of GDGTs in the sediment trap samples were calculated based on the added internal standard and the relative response factor of the standard versus crenarchaeol [*Huguet et al.*, 2006b]. Relative abundances of GDGTs were used to calculate TEX_{86} values that relate to temperature in °C according to the following empirical relationship [*Schouten et al.*, 2002]:

$$TEX_{86} = 0.015 \cdot T + 0.28 \quad (1)$$

Equation (1) results from the correlation of TEX_{86} values from core top sediments with SST (see *Schouten et al.* [2002] for details).

[11] An aliquot of an Arabian Sea sediment extract was measured every 10 samples to assess the analytical error. The resulting mean TEX_{86} value for 72 repeat analyses was 0.68 with a standard deviation of ±0.034, corresponding to 26.6 ± 0.5°C according to equation (1).

2.3. Time Series Analysis

[12] Time series analyses were performed on (1) our 1849–1987 A.D. TEX_{86} record, (2) the ENSO index Niño 3.4 of *Kaplan et al.* [1998] and *Smith and Reynolds* [2003, 2004], and (3) the Pacific Decadal Oscillation (PDO) index of *Mantua et al.* [1997] (see http://jisao.washington.edu/pdo/PDO.latest). We also performed a first-order autoregressive (AR1) process to evaluate the influence of climatic red noise on the variability of all the data series. For this purpose we derived spectra directly from the unevenly spaced time series using the REDFIT program [*Schulz and Mudelsee*, 2002]. All time series were analyzed with a Welch spectral window and four segments with 50% overlap (n_{50} = 4) [*Schulz and Mudelsee*, 2002].

3. Results

3.1. Sediment Trap

[13] The sediment trap material analyzed covers two annual cycles for the period December 1995 to December 1997. The onset of the 1997–1998 strong El Niño was in March 1997 but the effects only reached the SBB in June 1997 [*Lynn et al.*, 1998], and thus our trap series covers both non-El Niño and initial El Niño conditions in the SBB area. The flux of GDGT lipids ranged from 29 $\mu g\ m^{-2}\ d^{-1}$ in November 1997 to 196 $\mu g\ m^{-2}\ d^{-1}$ in November 1996 (Figure 3a). These GDGT fluxes are similar to those reported for an upwelling station near the Californian coast but higher than those reported for the Arabian Sea (up to 40 $\mu g\ m^{-2}\ d^{-1}$) [*Wuchter et al.*, 2006b]. During the non-El Niño period, two clear peaks in GDGT fluxes were observed, one in May/June 1996 and the largest between October 1996 and January 1997. During the El Niño period there were no distinct maxima, and GDGT fluxes remained fairly constant oscillating between 25 and 100 $\mu g\ m^{-2}\ d^{-1}$ (Figure 3a).

[14] TEX_{86}-derived temperatures range from 7.5°C in November 1996 to 11.4°C in March 1997 (Figure 3a). The average flux-weighted TEX_{86} temperature over the time series is 9.6°C, with average values of 9.3°C in 1996 and 9.9°C in 1997, respectively. The average flux-weighted TEX_{86} temperatures were 9.6°C for the non-El Niño time period (December 1995 to June 1997) and 9.7°C for the El Niño period (June 1997 to December 1997) (Figure 3). Both years follow a similar pattern showing a decrease in temperature in late spring, an increase toward summer, and a second decrease in autumn followed by an increase in winter. Peak TEX_{86} temperatures are found during spring 1996 and 1997, while minima in TEX_{86} temperatures occur during October/November and June/July of both years (Figure 3a).

3.2. Sediment Core Record

[15] Samples from two partially overlapping sediment cores were analyzed to determine the historical record of TEX_{86}-derived temperatures. The main core analyzed, SABA 87-2 (in black; Figure 4a), covered the period from 1849 to 1987 A.D., but no material was available for the interval 1923–1942 A.D. We covered this gap with samples from core 1-MC3 from the BASIN 2004 cruise, by analyzing samples dating from 1917 to 1959 A.D. (in green, Figure 4a). Overall, TEX_{86} temperatures of the combined cores range between 8.4°C and 13.7°C (Figure 4a). Although the TEX_{86} values in 1-MC 3 are consistently lower than in SABA 87-2, the general trend and interannual variability are similar for the two cores (Figure 4a). Although with slightly lower temperatures for the BASIN 1-MC3 core, the overlap intervals show good correspondence in terms of temperature ranges and trends (Figure 4a), especially when the analytical error and the $\sim$2 year dating error are taken into account. Average temperatures for the 1942–1959 overlap interval are 10.9°C for SABA 87-2 and 10.4°C for BASIN 1-MC3, a difference which falls within the 0.5°C analytical error for TEX_{86}. For the 1917–1923 A.D. overlap we also find a 0.5°C difference with average SABA 87-2 and BASIN 1-MC3 values of 10.5°C and 10.0°C, respectively. The interannual variability shows similar trends with most of the differences having overlapping error limits.

4. Discussion

4.1. Glycerol Dibiphytanyl Glycerol Tetraether Fluxes in the SBB

[16] There are two distinct maxima in the GDGT fluxes during the non-El Niño period (Figure 3a). The first peak at the end of spring coincides with a general increase in sedimentation flux (Figure 3a) and is associated with upwelling and high phytoplankton productivity in the SBB area in spring [*Thunell et al.*, 1999]. Similar results were reported for a sediment trap study of GDGT fluxes in the Arabian Sea which showed that the highest fluxes in GDGTs are associated with the general increase in fluxes during upwelling [*Wuchter et al.*, 2006b]. This was attributed to increased primary production and subsequent increased food web turnover leading to enhanced transport of GDGTs to the sediment by settling particles rather than

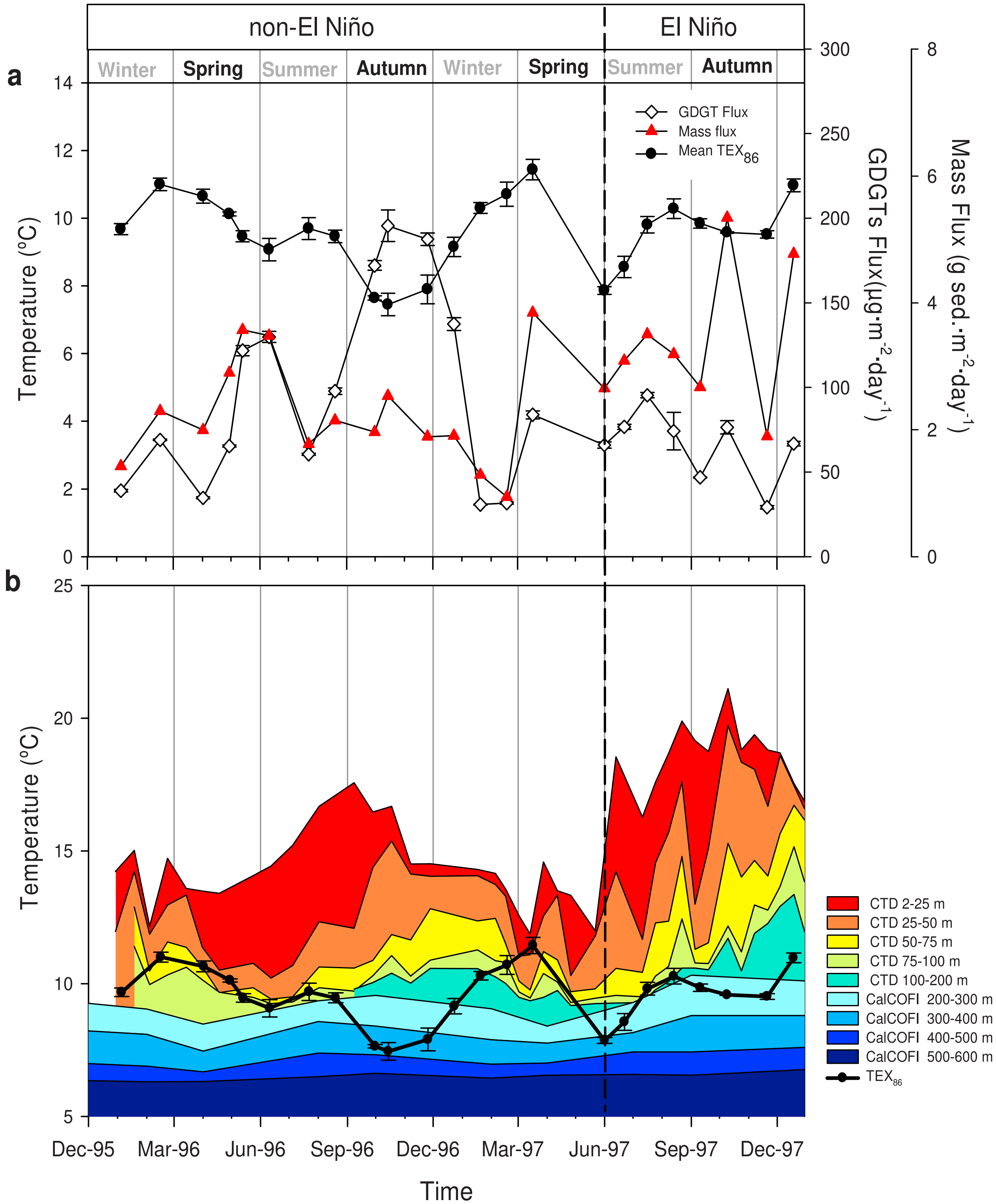

Figure 3. Flux and temperature data for the Santa Barbara Basin between December 1995 and December 1997. (a) Trap sample results for TEX_{86}-derived temperatures (solid circles), GDGT fluxes (diamonds), and mass fluxes (triangles). (b) Comparison of TEX_{86}-derived temperatures (solid circles) with in situ temperatures from 0 to 100 m (CTD data [*Thunell*, 1998]) and from 200 to 500 m (from the California Cooperative Oceanic Fisheries Investigations (CalCOFI, at http://www.calcofi.org). Error bars indicate analytical error of triplicate measurements.

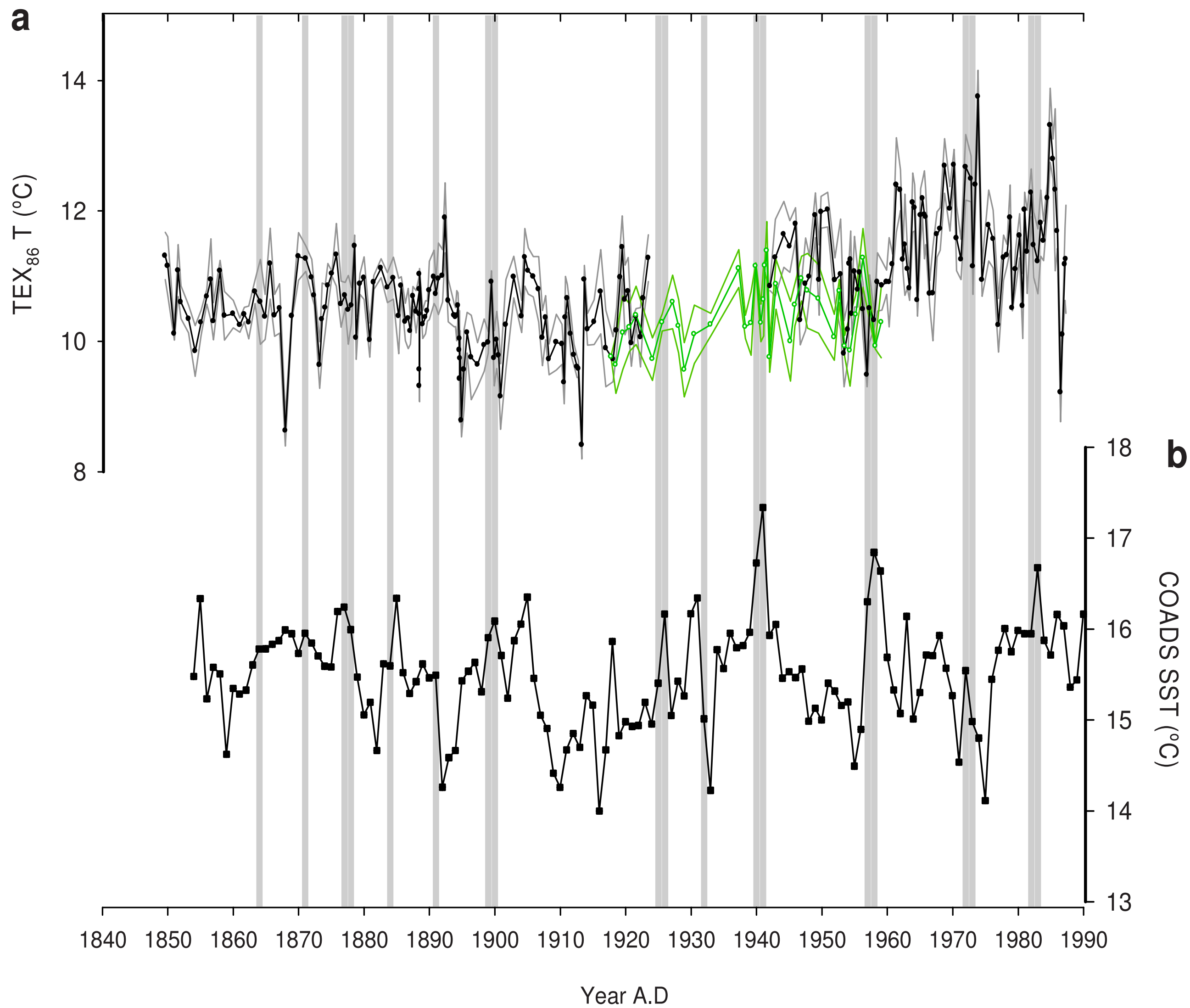

Figure 4. Temperature time series from the Santa Barbara Basin. (a) TEX_{86}-based temperature reconstruction from SABA 87-2 box core sediment (in black with solid circles) and from BASIN 2004 box core sediment (in green with open circles); temperatures were calculated using the standard TEX_{86} equation according to *Schouten et al.* [2002], with standard deviation indicated by grey and light green lines. (b) Mean annual SST (31–33° N, 119–121°W) from the Comprehensive Ocean-Climate Data Set project (COADS; http://www.ncdc.noaa.gov/oa/climate/coads/). Vertical grey bars indicate the timing of historic El Niño events with strengths 4, 5, and 6 according to the compilation by *Quinn* [1999].

increased production of GDGTs [*Wuchter et al.*, 2005; *Huguet et al.*, 2006a]. A similar explanation can thus be invoked for the first maximum in GDGT fluxes in the SBB. However, this is not the case for the second maximum in GDGT flux observed during winter 1996/1997 as sediment fluxes remained generally low. Reported molecular ecological data revealed that Crenarchaeota in the SBB area occur in higher abundance during winter [*Murray et al.*, 1999], suggesting that the higher flux of GDGTs during the winter months could be a reflection of higher Crenarchaeota production. Alternatively, the second maximum could be caused by a previously reported inshore meander of the California current at this time [*Schwing et al.*, 1997]. This inshore meander caused an unusual increase in chlorophyll concentrations [*Schwing et al.*, 1997] and foraminiferal flux [*Black et al.*, 2001] and may also have substantially increased Crenarchaeota production. Analysis of GDGT fluxes over longer time series should make clear which of these factors played a decisive role.

[17] For the El Niño period, there are no distinct maxima in GDGT fluxes during either spring/summer or early winter of 1997, even though there are increases in sediment fluxes at these times (Figure 3a). This suggests that the El Niño of 1997–1998 strongly reduced Crenarcheaota production during this period. El Niño does not only affect physical parameters such as temperature but also has an impact on nutrient availability and productivity [*Mantua et al.*, 1997; *Chavez et al.*, 2002]. During 1997, temperatures

were higher than normal (Figure 3b) and the upwelling was greatly reduced [*Thunell et al.*, 1999], leading to a reduction in primary production [*Black et al.*, 2001] which usually results in reduced secondary production [*Simpson*, 1992]. Recent evidence suggests that part of the Crenarchaeota are nitrifiers [*Könneke et al.*, 2005; *Wuchter et al.*, 2006a] and use ammonia, produced by decay of phytoplankton and zooplankton, as an energy source. As phytoplankton productivity was greatly reduced during El Niño this could have led to a severe decrease in ammonia availability and thus lower Crenarchaeota productivity.

4.2. Origin of the TEX_{86} Temperature Signal

[18] Comparison of the TEX_{86} temperature signal with instrumental records, obtained by monthly CTD casts (0–100 m) and quarterly shipboard measurements (200–500 m) (Figure 3b), revealed that the TEX_{86} temperatures, which range from 7.5 to 11.4°C, are always lower than SST values which range between 12°C and 21°C. TEX_{86}-derived temperatures seem, in general, to correspond better to temperatures below 75 m, suggesting that in the SBB area TEX_{86} represents a subsurface temperature signal, rather than SST (Figure 3b). This is in contrast to previous sediment trap results from the Arabian Sea where TEX_{86} temperatures were slightly higher than in situ surface temperatures [*Wuchter et al.*, 2006b]. Molecular ecological studies in the Santa Barbara Channel have shown that Crenarchaeota are most abundant below 75 m depth [*Murray et al.*, 1999] and a depth profile of GDGT concentrations in the water column of the Santa Monica Basin (SMB) [*Wuchter et al.*, 2005] also shows the highest abundance of Crenarchaeota lipids between 100 and 150 m depth. Furthermore, $\Delta^{14}C$ analysis of crenarchaeotal GDGTs in surface sediments of SBB and SMB showed a large ^{14}C depletion and a lack of bomb-derived ^{14}C, and thus a deep-water origin for the GDGTs was suggested [*Pearson et al.*, 2001]. Hence several lines of evidence suggest that crenarchaeotal GDGTs in the SBB are mostly derived from waters well below 75 m. TEX_{86}-derived temperatures for the sediment trap samples do not consistently reflect temperature at any particular depth through the annual cycle (Figure 3b), suggesting that other factors besides deep-water temperature changes must contribute to the changes in TEX_{86} signal. Closer examination of the seasonal variation in TEX_{86} temperatures reveals that in general, they correspond to temperatures between 100 and 300 m but that relatively much higher values are found in spring when TEX_{86}-calculated temperatures are only 1–3°C lower than SST (Figure 3b). These relatively warm temperatures correspond to times of upwelling and thus lower SSTs. The relatively high TEX_{86} values could be caused by an increase in surface phytoplankton production during upwelling which in turn would have increased the amount of marine snow and fecal pellet production in the surface during this period. GDGTs present in surface waters would then have been preferentially packaged and associated with sinking particles [*Wuchter et al.*, 2005; *Huguet et al.*, 2006a]. This would increase the relative contribution of the surface (0–100 m) versus deeper-water (below 100 m) signal. However, this should also be reflected in an increased flux in GDGTs which is not the case (Figure 3a). Alternatively, the deep-water Crenarchaeota could be carried upward with the upwelled and nutrient-rich waters thereby experiencing much higher temperatures before dying and sinking to the sediment, although this is not consistent with previously observed Crenarchaeota seasonality, as they are usually more abundant at times of low phytoplankton productivity [*Wuchter et al.*, 2005]. However, this is supported by molecular studies in the Santa Barbara Channel which showed that Crenarchaeota were only detected in surface waters during times of upwelling [*Murray et al.*, 1999]. This may also explain why the strong warming of surface waters during El Niño is not reflected in our TEX_{86} record, i.e., the reduced upwelling will have left the Crenarchaeota to thrive in deeper waters and prevented their upward transport to surface waters.

[19] Our results thus suggest that the seasonal variation in TEX_{86} is likely determined by the varying contributions of shallow versus deep-water signals. The behavior of the TEX_{86} proxy is quite different from that of other temperature proxies determined in SBB sediment trap studies. For example, the $U^{K'}_{37}$ [*Hardee and Thunell*, 2006] and planktonic foraminiferal $\delta^{18}O$ [*Thunell et al.*, 1999] signals from SBB sediment trap samples show a good correspondence with SST. Mg/Ca ratios of planktonic foraminifera from sediment traps in the SBB area also show a generally good correspondence with upper water column temperatures although some variation in depth habitat of the foraminifera was noted and the Mg/Ca ratio did not reflect the warming of surface waters during El Niño [e.g., *Pak et al.*, 2004].

4.3. Past Variation in TEX_{86} Temperatures

[20] Our results from the SBB sediment cores show that the TEX_{86} paleothermometer most likely records temperatures below 100 m, as the TEX_{86} temperatures are all well below the COADS instrumental mean annual SST at 31–33°N, 119–121°W (COADS http://www.ncdc.noaa.gov/oa/climate/coads/) (Figure 4b), in good agreement with results from our sediment trap study. However, TEX_{86} temperatures do not consistently reflect subsurface temperatures at a particular depth, as temperatures below the thermocline in the SBB have varied in general by less then 0.5°C over the last 50 years [*Field and Baumgartner*, 2000], while our TEX_{86} temperatures vary by more than 4°C. Thus it is unlikely that changes in subsurface temperature alone caused the TEX_{86} variation observed in the sediment cores (Figure 4). Instead, changes in depth of origin of the GDGT signal and/or changes in seasonality of GDGT production may be responsible for much of the observed variation.

[21] The large increase in SST in the SBB during some El Niño events is reflected in a number of temperature proxies preserved in SBB sedimentary records [*Kennedy and Brassell*, 1992; *Field et al.*, 2006]. However, comparison of the TEX_{86} temperature record with SST anomalies caused by El Niño (strengths 4, 5, and 6 according to the compilation by *Quinn* [1999]; indicated by vertical grey bars in Figure 4) reveals no obvious correlation and generally no elevated TEX_{86} temperatures coinciding with strong El Niño events (Figure 4a), although El Niño-related SST spikes are apparent in the instrumental SST

record (Figure 4b). This is in agreement with sediment trap data where a strong El Niño warming of surface waters after June 1997 was not recorded by TEX_{86}; that is, the flux-weighted average TEX_{86} temperature of 9.6°C for the non-El Niño period was similar to the 9.7°C for the El Niño period.

[22] We performed frequency analysis to investigate other possible controlling factors in past variations of TEX_{86}-derived temperatures. The results were compared to those from frequency analyses of both ENSO and PDO as the latter have been reported to influence temperatures, the structure of the water column, upwelling dynamics in the SBB, and thus also nutrient availability and primary production [*Mantua et al.*, 1997; *Chavez et al.*, 2002]. Frequency analyses of the Niño 3.4 (1856–2006 A.D.) and PDO (1900–2005 A.D.) indices revealed both highly significant (>99%-χ^2 false-alarm level) periods at 5.6–5.8 years. A ~5.7 year cycle has been reported in various other records and seems to be rooted in ENSO forcing [*Felis et al.*, 2000]. It is evidently widespread in polar to tropical areas [*Felis et al.*, 2000; *Jevrejeva et al.*, 2004; *Felis et al.*, 2004; *Cronin et al.*, 2002] and may influence atmospheric indices such as the North Atlantic Oscillation (NAO) [*Felis et al.*, 2000]. A 5.7 year cycle is also present in our 1849–1987 A.D. sedimentary TEX_{86} record, although its amplitude does not exceed the 80%-χ^2 false-alarm level. The lack of any highly significant cycles in the sedimentary TEX_{86} record of the SBB is most likely due to the strong decoupling between TEX_{86} and the temperature at any fixed depth interval.

[23] The TEX_{86} signal in the SBB sedimentary record might also be complicated by fluctuating strengths of the California and Davidson currents, changing wind patterns, intermittent upwelling, and the tidal regime. The sedimentary input received by the SBB depocenter may include allochthonous material that is transported from nearby areas by currents, as well as tidally resuspended sediment [*Berger et al.*, 2004]. However, the reported multiannual tidal variability is dominated by the lunar nodal cycle of 18.3 years, a cycle which we do not find in our TEX_{86} record. In addition, our frequency analysis shows no cycles that can be associated with those found for varve thickness or TOC records [*Zhao et al.*, 2000; *Berger et al.*, 2004], although all records use spatially compatible data from the same or similar sediment cores. This suggests that the variations observed in our TEX_{86} record are likely not caused by tidally induced resuspension but by a complex array of varying depths of GDGT production and environmental factors such as upwelling.

5. Conclusions

[24] TEX_{86} analyses of sediment trap samples reveal that temperatures inferred from this proxy do not reflect SST but predominantly subsurface temperatures (below 100 m) in the SBB. They also indicate that either the Crenarchaeota change depth habitat or that the relative contributions of surface and deep-water signals change during times of upwelling when TEX_{86} reflects shallower water temperatures. Analyses of TEX_{86} from a time series of varved sediment intervals from the depocenter of the SBB also show lower than expected TEX_{86} values, suggesting a subsurface signal over the last 150 years from varying water depths with time. Like in the sediment traps, these changes are likely caused by changes in Crenarchaeota depth habitat or varying depth origin of the TEX_{86} signal as influenced by environmental factors. Thus, in contrast to TEX_{86} signals from other marine areas, TEX_{86} in the SBB cannot be used to trace changes in surface temperature. Therefore care must be exercised when applying TEX_{86} in regions where environmental conditions lead to a crenarchaeotal GDGT signal that is derived from various depths rather than predominantly from the upper part (<100) of the water column.

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