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S. C. Sanchez and N. Westphal contributed equally to this work.

Key Points:

- New young fossil and living coral $\delta^{18}\text{O}$ records from Fanning and Palmyra provide central equatorial Pacific observations over 1863–2016
- This new composite record reveals a strong trend toward warmer and wetter conditions in the central equatorial Pacific since 1960
- Many of the largest El Niño events were preceded by a warm event in the central equatorial Pacific 18–12 months prior to the event

Supporting Information:

- Supporting Information S1

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A Continuous Record of Central Tropical Pacific Climate Since the Midnineteenth Century Reconstructed From Fanning and Palmyra Island Corals: A Case Study in Coral Data Reanalysis

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Abstract Accurate estimation of central tropical Pacific (CTP) climate variability on interannual to centennial time scales is required for robust projections of future global climate trends. Here we outline an approach that blends instrumental and coral proxy observations to yield a continuous, monthly resolved record of climate evolution in the CTP spanning the past 160 years. We concatenate coral oxygen isotope ($\delta^{18}\text{O}$) records from multiple living and fossil corals collected from Fanning Island (4°N, 160°W) and Palmyra Island (5°N; 162°W) located in the heart of the El Niño–Southern Oscillation. We use the regularized expectation maximization (RegEM) method to impute missing data across short gaps of 5 to 23 years within and beyond individual coral records. The resulting monthly resolved Fanning/Palmyra Island climate record spans continuously from 1863 to 2016 and provides an example of how extended time series can be built from shorter coral segments. The extended record highlights the strong trend toward warmer and wetter mean conditions in late twentieth century, in agreement with the majority of climate model hindcast simulations. The continuous reconstruction also enables a direct comparison of four exceptionally strong El Niño events (1877–1878, 1940–1941, 1997–1998, and 2015–2016). Three of these very strong El Niño events in the CTP featured a precursor warm event in the prior year and that may have favored the development of a strong El Niño event.

1. Introduction

Many of the uncertainties in the projection of future global climate—the sensitivity to greenhouse forcing, the variability on interannual-decadal time scales, and magnitude and frequency of the extreme events—relate directly to uncertainties in the behavior of the central tropical Pacific (CTP). There is currently a wide spectrum of responses of different global climate models (GCMs) forced by increasing greenhouse gases: Some modeling studies predict a weakened zonal sea surface temperature (SST) gradient in the tropical Pacific and a trend akin to El Niño-like conditions (Stevenson et al., 2012; Timmermann et al., 1999; Vecchi et al., 2006), while others predict an enhanced SST gradient and thus a shift toward more La Niña-like background conditions (Kohyama et al., 2017; Seager et al., 2019). Furthermore, in some models, the frequency of extreme El Niño and La Niña events increases under greenhouse warming (e.g., Cai et al., 2014, 2015). A potential strengthening of tropical Pacific SST variability carries globally significant consequences for temperature and rainfall extremes, and thus, it is essential to assess the accuracy of projected trends.

In principle, it should be possible to use the observed evolution of the CTP since preindustrial times as a gauge for future behavior and model validation. However, there are significant limitations to this approach. As an example, twentieth century trends in equatorial Pacific temperature are uncertain; existing instrumental SST reconstructions could be taken to support either a progressively more El Niño-like or La Niña-like state over the latter half of the twentieth century and are dependent on data set and filtering methodology (Coats & Karnauskas, 2017; Deser et al., 2010; Solomon & Newman, 2012). The discrepancies in

instrumental data sets are mostly the result of the scarcity in spatial and temporal coverage, especially prior to 1950 CE. This scarcity in turn limits confident and comprehensive assessment of the variability of the El Niño–Southern Oscillation (ENSO) over the twentieth century from instrumental observations alone (Pörtner et al., 2019; Stevenson et al., 2012; Wittenberg, 2009), though advances have come from reanalysis products (e.g., Giese & Ray, 2011).

Climate proxy observations could supplement the scarce instrumental observations, given that the analysis of coral skeletal chemistry can deliver time series of sufficient statistical fidelity and appropriate resolution (e.g., Cobb et al., 2001; Cobb, Charles, Cheng, & Edwards, 2003; Cole et al., 1993; Evans et al., 1999; Linsley et al., 2000; McGregor et al., 2011; Urban et al., 2000). Existing paleoclimate archives do suggest an increase in the variability of ENSO over the latter half of the twentieth century (Li et al., 2013; McGregor et al., 2011), particularly in the Central Pacific (Freund et al., 2019; Grothe et al., 2020; Liu et al., 2017). But these inferences from paleoclimate proxies are also limited in geographic and temporal extent. For example, multicentury coral reconstructions are extremely rare in the CTP, for two reasons: Long-lived colonies are not nearly as abundant in central Pacific reefs as they are elsewhere, and diagenesis tends to overprint the skeleton at the base of the longest-lived colonies. Thus, the objective of generating long continuous records from the ENSO “center of action” in the CTP—that is, archives that are capable of resolving not only the various interannual extremes but also the low frequency trends in temperature and hydrological variability—requires a different approach that leverages the strengths of both instrumental and climate proxy archives.

Here we present a collection of six individual monthly resolved coral $\delta^{18}\text{O}$ records from Fanning and Palmyra Islands that can be combined to form a continuous extended time series of central equatorial Pacific climate. Three of the records have been published previously; the others are presented here for the first time. Of these new records, two derive from U/Th-dated Fanning fossil corals that cover the time periods from 1863 to 1888 CE and from 1907 to 1944 CE, respectively, thus capturing major El Niño events that are poorly constrained by instrumental data sets (Figure 1a). The other previously unpublished record derives from a short core from a living Palmyra coral colony that was collected following the 2015–2016 El Niño event and that extends through the 1997–1998 El Niño event. When combined with existing records from these two sites, we generate a monthly resolved, quasi-continuous record spanning from 1863 to 2017 CE. The continuous $\delta^{18}\text{O}$ time series illustrates both the promises and challenges of constructing long, multi-century climate records by combining modern and fossil corals with instrumental observations.

2. Material and Methods

Palmyra and Fanning islands are located in the core region of ENSO activity (Figure 1b) and are sensitive to a full spectrum of tropical Pacific climate variability. These islands lie, respectively, at the northern and southern edges of the eastward flowing North Equatorial Counter Current (NECC) that originates in the Western Pacific Warm Pool (WPWP). SST in the region varies by $\sim 1.3^\circ\text{C}$ on seasonal time scales, around an annual average of $\sim 28^\circ\text{C}$ (NOAA ERSSTv5, Huang et al., 2017), and by $\sim 3^\circ\text{C}$ on interannual time scales related to ENSO extremes (Figures 1c and 1d). Maximum (minimum) SSTs typically occur in July (February) (NOAA ERSSTv5, Huang et al., 2017). Precipitation variations are mainly driven by seasonal migration of the Intertropical Convergence Zone (ITCZ). The ITCZ resides just north of Fanning island for most of the year, delivering rainfall rates to the region that are maximal in April (~ 8.3 mm/day) and minimal in September (~ 2.6 mm/day) (CPC-CMAP, Xie & Arkin, 1997). Seasonal rainfall variations in turn induce sea surface salinity (SSS) variations of ~ 0.35 psu and up to ~ 0.92 psu between ENSO extremes (over an average of ~ 34.8 psu; Roemmich & Gilson, 2009). ENSO is the dominant source of precipitation variability in the region (Evans et al., 1999; Cobb, Charles, Cheng, & Edwards, 2003), but the precise nature of the relationship between SST and precipitation variability in this region remains an open question and an important issue for future climate projections and, in part motivates the coral-based reconstructions presented here.

The morphology of the islands is important in several respects. Fanning Island is relatively small and is surrounded by a relatively narrow fringing coral reef (Figure 1e). Thus, the ambient reef water presumably approximates open ocean surface water. However, the island also features a shallow interior lagoon consisting of numerous hypersaline ponds (Maragos, 1974). Mixing of the interior waters with ocean waters is mainly restricted to a few existing outlets (Gallagher et al., 1971; Stroup & Meyers, 1974), dominated by tidal exchange across a large channel on the leeward side. As a result, lagoon waters exhibit significantly different

Figure 1. (a) Monthly number of instrumental observations for the Niño 3.4 SST box (5°N to 5°S; 120–170°W) derived from the Met Office Hadley Centre observations data set (MOHSST5) (Kaplan et al., 1998). (b) Tropical Pacific SST and precipitation. Climatological December–January–February (DJF) SST in colors (°C) and precipitation in contour lines (mm/day) averaged over the 1979–2020 time period. Niño 3.4 region and location of Fanning and Palmyra are highlighted. (c) DJF El Niño composite SST in colors (°C) and precipitation in contour lines (mm/day) (Years 1982–1983, 1997–1998, 2009–2010, and 2015–2016). (d) DJF La Niña composite (1988–1989, 1998–1999, 1999–2000, 2007–2008, and 2010–2011). (e) Google Maps image of Fanning displaying the sample locations of the *Porites* coral cores analyzed in this study (F4 and F5) and the modern coral (Fspl) previously published in Cobb et al. (2013). (f) Satellite image of Palmyra Atoll showing the location of the new coral record presented in this study (RT10) and that of the previously published Palmyra modern coral from Cobb et al. (2001).

chemical and physical properties relative to the open ocean (Guinther, 1971). Palmyra Island features an extended submerged platform that is generally less than 10 m deep. It is expected that the seawater across this extensive platform should be well mixed on time scales of coral skeletal extension (about 2 weeks). A characteristic feature of the northern Line Islands is that the beaches are strewn with fossil corals ranging in age from the twentieth century to 7 ka (Cobb, Charles, Cheng, & Edwards, 2003; Cobb et al., 2013), likely tsunami and/or storm deposits. These fossil corals provide archives of climatic variability over the time interval of their skeletal growth (typically 20–50 years).

For this study, we make use of two relatively young fossil coral cores of the genus *Porites* that were recovered during field expeditions to Fanning Island in May 2005. The F4 and F5 cores were drilled from large coral heads on beaches facing the main channel that connects Fanning's lagoon with the ocean (Figure 1c). We also extend the published chronology from Palmyra toward the present by analyzing a core (RT10) drilled in October 2016 from a living *Porites* colony growing on the same reef terrace as that previously published (Figure 1f). Prior to stable isotopic analysis, the fossil corals were U/Th-dated at the Minnesota Isotope Laboratory, University of Minnesota, following the procedures outlined in Edwards et al. (1987) (Table 2).

Table 1
Coral and Instrumental Network used in the RegEM Algorithm

Location	Latitude	Longitude	Time interval (CE)	Record type	Proxy	Reference
Palmyra	6°N	162°W	1886–1998	coral	$\delta^{18}\text{O}$	Cobb et al. (2001)
			1995–2016	coral	$\delta^{18}\text{O}$	this study, PRT10
			1886–1998	coral	$\delta^{18}\text{O}_{\text{SW}}$	Nurhati et al. (2011)
			1886–1998	coral	Sr/Ca	Nurhati et al. (2011)
Fanning	4°N	160°W	1949–2005	coral	$\delta^{18}\text{O}$	Cobb et al. (2013)
			1907–1944	coral	$\delta^{18}\text{O}$	this study, F4
			1863–1888	coral	$\delta^{18}\text{O}$	this study, F5
			1972–2005	coral	$\delta^{18}\text{O}$	Nurhati et al. (2009)
			1972–2005	coral	$\delta^{18}\text{O}_{\text{SW}}$	Nurhati et al. (2009)
Christmas	2°N	157°W	1972–1998	coral	$\delta^{18}\text{O}$	Nurhati et al. (2009)
			1972–1998	coral	$\delta^{18}\text{O}_{\text{SW}}$	Nurhati et al. (2009)
			1972–1998	coral	Sr/Ca	Nurhati et al. (2009)
			1938–1993	coral	$\delta^{18}\text{O}$	Evans et al. (1999)
			2007–1978	coral	$\delta^{18}\text{O}$	McGregor et al. (2011)
			1949–2005	coral	$\delta^{18}\text{O}$	Grothe et al. (2020)
			1894–1990	coral	$\delta^{18}\text{O}$	Cole et al. (1993)
Tarawa	1°N	173°E	1859–1995	coral	$\delta^{18}\text{O}$	Urban et al. (2000)
Maiana	1°N	172°E	1959–2010	coral	$\delta^{18}\text{O}$	Carilli et al. (2014)
Butaritari	3°N	173°E	1959–2010	coral	$\delta^{18}\text{O}_{\text{SW}}$	Carilli et al. (2014)
			1959–2010	coral	Sr/Ca	Carilli et al. (2014)
Equatorial Pacific	7.5°N to 7.5°S	170°E to 120°W	1863–2016	In situ, 64 individual grid boxes	SSTA	Kennedy et al. (2011a, 2011b)

Coral preparation and stable isotopic analysis were conducted at the Scripps Institution of Oceanography (for more information, see Westphal, 2015). The mean coral growth rate of ~1.5–1.8 cm/year enables sampling at an approximately monthly resolution (in 1-mm increments).

Previous studies from the CTP have shown that coral $\delta^{18}\text{O}$ -based reconstructions over the twentieth century are strongly correlated with the regional-scale Niño 3.4 index (Niño 3.4 index defined as 5°N to 5°S, 170–120°W, Cobb et al., 2001; Evans et al., 1999; Nurhati et al., 2009). This correlation results from the fact that both the warm SST and lower salinity (increased P-E) accompanying ENSO warm events drive $\delta^{18}\text{O}$ to lower values, with relatively well known but potentially variable regional sensitivities on interannual time scales (e.g., Gagan et al., 1998; Russon et al., 2013; Stevenson et al., 2015).

The explicit combination of modern and fossil coral $\delta^{18}\text{O}$ records requires that the age of the (otherwise floating) fossil series must be well enough constrained to splice into the absolutely dated modern coral chronology. In our case, the U/Th ages of the Fanning fossil coral samples are 1876 CE $\pm$ 1 year (F5) and 1927 CE $\pm$ 1 year (2 σ) (F4; Table 1), respectively. Previous studies of some Palmyra fossil corals have reported relatively large dating uncertainties associated with high concentrations of initial ^{230}Th as estimated from the concurrent measurements of nonradiogenic ^{232}Th (Cobb, Charles, Cheng, Kastner, & Edwards, 2003); however, both F4 and F5 contain negligible ^{232}Th (Table 1). Additionally, we are able to precisely fix the absolute chronology for both fossil corals by the presence of the large El Niño excursions in the $\delta^{18}\text{O}$ record. Annual growth bands provide an initial chronology for the fossil corals (away from the U/Th dated samples).

Table 2
U/Th Systematics for Fanning Island Fossil Corals Shown in Figure 2

Sample	^{238}U ^a (ppm)	$(^{230}\text{Th}/^{238}\text{U})^{\text{b}}$ activity $\times 10^3$	$\delta^{234}\text{U}$ (i) ^c (‰)	^{232}Th (pg/g)	^{230}Th age (uncorrected) (CE)	^{230}Th age ^d (corrected) (CE)
F4	3.386 $\pm$ 3.2	0.86 $\pm$ 0.01	146.6 $\pm$ 1.4	5 $\pm$ 0.4	1,927 $\pm$ 1	1,927 $\pm$ 1
F5	2.842 $\pm$ 2.9	1.39 $\pm$ 0.01	144.5 $\pm$ 1.5	23 $\pm$ 0.5	1,876 $\pm$ 1	1,876 $\pm$ 1

^aAll errors reported in this table are quoted as 2 σ ; for ^{238}U , error is for last significant figure. ^bThe measured, uncorrected $(^{230}\text{Th}/^{238}\text{U})$ activity ratio; 2 σ error is for last significant figure. ^c $\delta^{234}\text{U} = \{[(^{234}\text{U}/^{238}\text{U})/(^{234}\text{U}/^{238}\text{U})_{\text{eq}} - 1] \times 10^3\}$, where $(^{234}\text{U}/^{238}\text{U})_{\text{eq}}$ represents the atomic ratio at secular equilibrium; $\delta^{234}\text{U}$ (i) represents the initial value calculated using U/Th dating equations. Decay constants from Cheng et al. (2000). ^dDate corrected with $(^{230}\text{Th}/^{232}\text{Th})$ atomic of $4.4 \pm 2.2 \times 10^{-6}$, which is the value for materials at secular equilibrium, assuming a bulk Earth crustal $^{232}\text{Th}/^{238}\text{U}$ ratio of 3.8.

Figure 2. Individual Fanning Island and Palmyra Atoll raw coral $\delta^{18}\text{O}$ records over the past ~150 years. (a) Fanning records in red (Fm, Fanning modern splice) (Cobb et al., 2013; Nurhati et al., 2009), blue (F5), and orange (F4) (both this study). Black triangles indicate obtained U/Th dates (CE) and associated errors (2σ). (b) Palmyra records in green (PC01, Cobb et al., 2001) and purple (PRT10, this study).

However, the more refined conversion from a depth series into a time series was obtained by assigning the maximum (most positive) peak in $\delta^{18}\text{O}$ to January of each year, which coincides with the average minimum SST in the CTP (Cobb, Charles, Cheng, & Edwards, 2003). Subsequently, each time series was linearly interpolated between each of the tie points to achieve monthly resolution (12 samples/year).

The existing collection of Fanning Island coral segments (Figure 2a) thus consists of discontinuous time series that span 1863–1888, 1907–1944, and 1949–2005. The Palmyra segments (Figure 2b) include the modern sample from 1995–2017 and the core from 1886–1998 (Cobb et al., 2001). Our objective of combining these segments might be accomplished in a number of ways, but, regardless of methodology, this combination requires that the mean and variance of the segments be consistent in their representation of large-scale climate variability. In general, the $\delta^{18}\text{O}$ of scleractinian corals is far from equilibrium, and the absolute value of any coral $\delta^{18}\text{O}$ time series is known to be taxon-specific and dependent on skeletal calcification rate, among other possible factors (Felis et al., 2003; Guilderson & Schrag, 1999; Linsley et al., 1999; McGregor & Gagan, 2003). However, in the case of the young fossil corals presented here, the mean extension rate is indistinguishable from that of the modern counterparts. At Palmyra, given samples from the same species and with comparable extension rate, Cobb, Charles, Cheng, and Edwards (2003) found that the mean values of individual, overlapping coral $\delta^{18}\text{O}$ time series differed by $\pm 0.11\text{‰}$ (2σ) from one another. However, here we observe no mean offset between the new Palmyra modern RT10 core (mean -5.30‰ over common 1995–1998 period) and the Cobb et al. (2001) core (mean -5.31‰ over the same interval). The same is true for all the overlapping segments of the Fanning and Palmyra corals presented here, so we make no adjustment to the mean value of any of the individual fossil coral $\delta^{18}\text{O}$ time series.

On the other hand, the Fanning fossil coral $\delta^{18}\text{O}$ sequence F4 shows distinctly enhanced variance (Figure 3a), relative to both the modern coral record, the contemporaneous interval of the Palmyra and Christmas Island corals, and instrumental SST products (supporting information Figure S2). This systematically high variability observed across the entire F4 core cannot be ascribed to diagenetic alteration, which can shift mean coral $\delta^{18}\text{O}$ values and introduce artifacts including excursions toward heavier coral $\delta^{18}\text{O}$ (Sayani et al., 2011). Scanning electron microscope (SEM) images of both fossil corals reveals that the

Figure 3. (a) Fanning record (colored, Fanning F5, Fanning F4, and Fanning modern [Fm]) and RegEM infilled (black) $\delta^{18}\text{O}$ records. The original F4 record is in orange, and the variance adjustment is in gray (F4a). (b) Palmyra record (colored, Palmyra from Cobb et al. 2001 and Palmyra RT10) and RegEM infilled (black) $\delta^{18}\text{O}$ records. (c) Temperature anomalies reconstructed from the averaged Fanning Island and Palmyra Atoll $\delta^{18}\text{O}$ records (F+Precon) using the RegEM algorithm with (black) and without HadSST3 (gray) observations with the ERSSTv5 Niño3.4 anomalies (red). Anomalies are calculated relative to the 1961–1990 mean. The ERSSTv5 record is scaled into expected coral $\delta^{18}\text{O}$ space by multiplying anomalies by $-0.22\text{‰}/^{\circ}\text{C}$, as in Epstein et al. (1953) and Thompson et al. (2011) (and references therein). Trend lines are plotted over the time series in the respective colors, highlighting the greater centennial trend found in the coral archives. More information on trends can be found in supporting information Table S2.

coral skeletons are essentially pristine throughout the length of the cores, with only minor traces of secondary alteration (Westphal, 2015; supporting information Figure S1). Furthermore, there is no evidence that diagenetic alteration could systematically increase the amplitude of $\delta^{18}\text{O}$ variance in corals as documented here. Rather, the enhanced variance in the fossil coral $\delta^{18}\text{O}$ records likely reflects the influence of localized (lagoon) mixing on the coral isotopic variability. For example, if the lagoon becomes warmer and fresher than the open ocean during El Niño events and warm seasons, then the coral $\delta^{18}\text{O}$ anomaly during these events would be likewise amplified relative to open ocean corals. The F4 record displays an amplification of variability across all time scales, but this amplification is slightly exaggerated across ENSO extremes relative to seasonal cycles. In any case, we account for this amplification by scaling the F4 $\delta^{18}\text{O}$ (variations relative to its mean) values by a factor of 0.56 such that the running 3-year standard deviation matches that of corresponding interval of the available Palmyra coral and closely resembles the interannual variability in the instrumental record (supporting information Figure S2). Interestingly enough, a similar enhancement of variance is not apparent in the nineteenth century Fanning fossil series (F5), despite the fact that both F4 and F5 fossil corals were found in close proximity to one another albeit separated by 19 years in time, during which circulation conditions could have changed markedly. In the 5 years of overlap (1882 to 1887) between F5 and the Palmyra coral (supporting information Figure S4), the means and the variance of the two different corals are identical. Thus, we leave the nineteenth century Fanning fossil coral record untouched and only scale the variance of the twentieth century Fanning fossil coral (F4, Figure 3a) to make it compatible with the other segments.

We impute the missing sections of the Fanning and Palmyra coral records using the regularized expectation maximization (RegEM) algorithm as described by Schneider (2001) to create continuous reconstructions of both the Palmyra and Fanning records over the last 153 years. The RegEM methodology is based on the conventional expectation maximization algorithm, which, through iterative regressions, estimates the mean and the covariance matrix of an incomplete data set and imputes missing values within the record (Schneider, 2001). We use a truncated total least squares (TTLS, using a k -fold ($k = 5$) cross validation to estimate the truncation parameter) approach to estimate the regularized regressions as previous studies have documented that this method preserves variance well (Mann et al., 2007a, 2007b). However, in our case here, the choice of methodology does not have a significant influence on results because of the small fraction of missing months and the relatively long length of record compared with the number of variables (supporting information Figure S5). The RegEM algorithm assumes that the covariance relationships between all variables are well represented by the available data. As such, the algorithm is best suited to estimate missing values when stationary covariance relationships are a fair assumption.

To impute missing values, we compiled a matrix of monthly resolved coral and instrumental SST data (1,838 months $\times$ 81 timeseries; timeseries comprising 17 geochemical records and 64 instrumental grid boxes) from the CTP covering 1863–2016 (Table 1). In performing the RegEM calculation, we calculate the anomalies relative to a 1961–1990 mean for consistency with the HadSST3 archive (Kennedy et al., 2011a, 2011b). We chose to include the Hadley Centre SST data set (HadSST3) (Kennedy et al., 2011a, 2011b) because it is composed solely of in situ SST measurements (from the International Comprehensive Ocean-Atmosphere Data Set [ICOADS]; Woodruff et al., 2011). In addition to the Fanning and Palmyra records, we rely on eight additional coral $\delta^{18}\text{O}$ records from the CTP: Tarawa (Cole et al., 1993), Maiana (Urban et al., 2000), Christmas (Cobb et al., 2013), and Butaritari (Carilli et al., 2014), Christmas (Evans et al., 1999; Grothe et al., 2020; McGregor et al., 2011). Additionally, we use four available coral-derived Sr/Ca and $\delta^{18}\text{O}$ of seawater ($\delta^{18}\text{O}_{\text{sw}}$) records from Fanning and Christmas (Nurhati et al., 2009), Palmyra (Nurhati et al., 2011), and Butaritari (Carilli et al., 2014). Strictly similar coral $\delta^{18}\text{O}$ variability between the Fanning and Palmyra reconstructions would not be expected from SST alone. Across the CTP, the variance of SST anomalies decreases from the equator to higher latitudes. However, the magnitude of $\delta^{18}\text{O}_{\text{sw}}$ variability and thus the relative contribution of $\delta^{18}\text{O}_{\text{sw}}$ on coral $\delta^{18}\text{O}$ tend to increase with latitude. We assess the expected variance and relative contributions of $\delta^{18}\text{O}_{\text{sw}}$ and SST on coral $\delta^{18}\text{O}$ at Palmyra and Fanning locations with both instrument-derived pseudocoral experiments and analysis of the paired Sr/Ca and $\delta^{18}\text{O}$ measurements from Nurhati et al., 2009 (supporting information Figure S6). Our analyses indicated that at these locations, variability in $\delta^{18}\text{O}_{\text{sw}}$ and SST generally strongly covary and that coral $\delta^{18}\text{O}$ records from both sites are both dominated by SST variability. However, analyses of ARGO SST and SSS data from the region confirm that $\delta^{18}\text{O}_{\text{sw}}$ variations result in a larger fraction of coral $\delta^{18}\text{O}$ variability at Palmyra, relative to Fanning, as expected (supporting information Figure S6). It is important to note that the RegEM methodology accounts for these differences in SST and $\delta^{18}\text{O}_{\text{sw}}$ covariability and allows us to create a self-consistent record of Northern Line Islands variability from each site. Unless otherwise noted, our principal reconstruction refers to the TTLS methodology using all unique available central equatorial Pacific records (defined as individual records within 7.5°N to 7.5°S, 170°E to 120°W with 40 years of observations).

In total, the new composite sequences span the interval of May 1863 through June 2016 and are constructed from two Fanning fossil records, one Fanning modern record, and two Palmyra modern records. Neither the Fanning nor Palmyra composite coral records span the 153-year-long interval in its entirety; the Fanning segments span 76% of the total months over this interval, while the Palmyra segments span 85% of the months of interest. The continuous Fanning and Palmyra reconstructions could stand alone, but for the remainder of our analysis here, we average these reconstructions to create a joint record (hereafter referred to as F+Precon) to assess climate variability across the Northern Line Islands over this period.

3. Results and Discussion

After imputing missing data using RegEM, the monthly resolved, continuous F+Precon displays several features of interest. Perhaps the most obvious feature is the strong trend toward more negative $\delta^{18}\text{O}$ (Figure 3c and supporting information Figure S8) in the latter part of the twentieth century, implying a trend toward warmer/wetter conditions in the CTP since 1960 (supporting information Table S2). Over the full 1863–

Table 3
Pearson's Correlation Coefficient between F+Precon and the Niño 3.4 Index

Correlation coefficient, R	F+Precon raw	F+Precon linear detrend	F+Precon BP filter 2–7 years	F+Precon (no HadSST3) raw	F+Precon (no HadSST3) linear detrend	F+Precon (no HadSST3) BP filter 2–7 years
ERSSTv5 N3.4	−0.67 Neff = 128 $p = 5.37\text{E}−18$	−0.65 Neff = 150 $p = 9.09\text{E}−20$	−0.91 Neff = 22 $p = 1.06\text{E}−09$	−0.60 Neff = 131 $p = 2.08\text{E}−14$	−0.58 Neff = 160 $p = 5.42\text{E}−16$	−0.87 Neff = 22 $p = 6.05\text{E}−08$
SODA 2.2.4 N3.4	−0.52 Neff = 127 $p = 2.78\text{E}−10$	−0.59 Neff = 142 $p = 4.11\text{E}−15$	−0.92 Neff = 22 $p = 2.66\text{E}−10$	−0.44 Neff = 133 $p = 4.91\text{E}−08$	−0.52 Neff = 155 $p = 1.19\text{E}−12$	−0.89 Neff = 22 $p = 7.79\text{E}−09$
HADISST N3.4	−0.55 Neff = 155 $p = 1.62\text{E}−13$	−0.57 Neff = 166 $p = 3.86\text{E}−16$	−0.91 Neff = 22 $p = 1.94\text{E}−09$	−0.49 Neff = 155 $p = 6.37\text{E}−11$	−0.51 Neff = 178 $p = 1.26\text{E}−13$	−0.87 Neff = 22 $p = 7.11\text{E}−08$
COBE SST2 N3.4	−0.59 Neff = 146 $p = 1.23\text{E}−15$	−0.60 Neff = 166 $p = 3.17\text{E}−18$	−0.89 Neff = 21 $p = 8.78\text{E}−09$	−0.53 Neff = 149 $p = 1.81\text{E}−12$	−0.54 Neff = 177 $p = 5.97\text{E}−15$	−0.85 Neff = 21 $p = 3.23\text{E}−07$
Kaplan N3.4	−0.68 Neff = 94 $p = 1.82\text{E}−14$	−0.73 Neff = 112 $p = 2.97\text{E}−20$	−0.91 Neff = 21 $p = 1.07\text{E}−9$	−0.61 Neff = 149 $p = 1.62\text{E}−11$	−0.66 Neff = 122 $p = 3.63\text{E}−17$	−0.87 Neff = 21 $p = 5.96\text{E}−08$

Note. We define the Niño 3.4 (N34, 5°N to 5°S, 170–120°W) Indices From a Variety of SST Reanalysis and Interpolated Products at Monthly Resolution Over the 1863–2016 Interval (or Through the Duration of Data Availability, SODA2.2.4 Only Covers 1871–2010, and HADISST Covers 1870–2016). We consider two versions of the F+Precon index: The first version uses the available data from the HadSST3 data set to infill missing values into the reconstructed index. The second version only uses coral data to infill missing values into the reconstructed index. We consider correlations with three types of filtering: (1) raw values, (2) both the Niño3.4 and F+Precon index have been linearly detrended, and (3) both the Niño3.4 and F+Precon index have been band-pass filtered to highlight frequencies between 2 and 7 years. While the available time series is 1,838 months long, we alter the number of effective degrees of freedom to account for autocorrelation as in Bretherton et al. (1999). We find all calculated correlation coefficients significant at the 99% confidence level.

2016 interval, the F+Precon shows a decline of -0.37% . This trend is wholly consistent with previously published coral $\delta^{18}\text{O}$ records from the tropical Pacific (Charles et al., 2003; Cobb et al., 2001; Cole et al., 1993; Linsley et al., 2000; Quinn et al., 2006; Tudhope et al., 2001; Urban et al., 2000). Our extension of the Line Islands reconstruction with three new coral segments underscores the significance of the trend with respect to natural decadal-scale variability at these sites. Available evidence from the application of temperature-only proxies (Sr/Ca) in the Palmyra coral cores indicates that roughly half of the observed trend in coral $\delta^{18}\text{O}$ can be ascribed to a regional warming of $\sim 1^\circ\text{C}$, with the other half originating from a shift toward lower seawater $\delta^{18}\text{O}$ in the region (Nurhati et al., 2009, 2011). The seawater $\delta^{18}\text{O}$ component of this trend is also immediately apparent in the comparison with instrumental observations from the region (Figure 3c and supporting information Figure S7)—the twentieth century trend in $\delta^{18}\text{O}$ is significantly larger than that of the observations. Isotope enabled model results suggest that this seawater $\delta^{18}\text{O}$ trend may reflect an eastward advection of the western Pacific conditions of low $\delta^{18}\text{O}_{\text{sw}}$, perhaps as a result of more El Niño-like conditions under continued greenhouse forcing (Stevenson et al., 2019).

We observe significant correlations between the reconstructed F+Precon coral $\delta^{18}\text{O}$ record with Niño 3.4 SST variability, regardless of (i) filtering methodology (raw, detrended, or 2- to 7 year band-passed filtered), or (ii) the inclusion of the HadSST3 data in the RegEM reconstruction, or (iii) which SST products—NOAA ERSSTv5 (Huang et al., 2017), COBE SST2 (Hirahara et al., 2014), HADISST (Rayner et al., 2003), SODA 2.2.4 (Giese & Ray, 2011), and Kaplan (Kaplan et al., 1998)—are used for comparison (Table 3 and supporting information Figure S7). The correlations are especially good after ~ 1960 , and it is probably not coincidental that this interval is associated with the highest density of instrumental observations (Figure 1a). Previous attempts to reconstruct tropical Pacific variability using a similar hybrid RegEM-TTLS methodology noted the discrepancies in instrumental observations of the Niño 3.4 region prior to 1950 and found that these data set discrepancies generated some of the largest uncertainties in reconstructing preindustrial tropical Pacific behavior (Emile-Geay et al., 2013a, 2013b). These comparisons with various SST products reinforce the suggestion that the F+Precon offers valuable information on CTP climate variability that is potentially more consistent than instrumental-only reconstructions, despite the fact that coral $\delta^{18}\text{O}$ represents a compound variable

Figure 4. Comparison of the reconstructed (F+Precon) $\delta^{18}\text{O}$ record with instrumental records over the 1877–1878 El Niño event. All anomalies are relative to the 1961–1990 mean. The SST anomalies are converted into coral $\delta^{18}\text{O}$ space by multiplying anomalies by $-0.22\text{‰}/^{\circ}\text{C}$, as in Epstein et al. (1953) and Thompson et al. (2011) (and references therein).

(SST and $\delta^{18}\text{O}_{\text{sw}}$). Along those lines, while our focus is to generate self-consistent regional climate record from the Northern Line Islands, it is possible to generate an alternative Niño 3.4 index with the RegEM methodology and the coral and Hadley SST3 data set (supporting information Figure S8).

The comparison between the F+Precon record and the Niño 3.4 index over extended (100+ year) intervals is essential for addressing the question of whether the characteristics of ENSO have been altered by the rise in global mean temperature (Freund et al., 2019; Stevenson et al., 2019). In fact, the new Fanning and Palmyra coral records allow for a direct comparison of the magnitude and temporal evolution of the four most extreme El Niño events of the past 150 years—in 2015/2016, 1997–1998, 1940–1941, and 1877–1878. We evaluate event magnitude relative to the 50-year running mean to highlight interannual variability. Considering the magnitude alone, our results suggest that the 1877–1878 El Niño event was the strongest of the Fanning-Palmyra reconstruction at 4.4 standard deviation units (-0.89‰ relative to the running mean), followed by the 1997–1998 (2.8 standard deviation, -0.57‰), then the equivalent magnitude 1940–1941 (2.2 standard deviations, -0.44‰), and 2015–2016 (2.2 standard deviations -0.44‰) El Niño events. These results differ from the relative magnitudes deduced from a variety of Niño 3.4 SST products (e.g., Kaplan et al., 1998), which typically depict the 1997–1998 event as the strongest El Niño event of the instrumental record (Figure 3c, supporting information Figure S7). The underestimation of the magnitude of the 1877–1878 event likely results from the severe undersampling of core ENSO region over this interval (Kaplan et al., 1998; Figure 1a).

We can make a more direct comparison between the F+Precon $\delta^{18}\text{O}$ reconstructed 1877–1878 event and the instrumental SST products by converting the SST reconstructions into estimated $\delta^{18}\text{O}_{\text{coral}}$ using the relationship of $-0.22\text{‰}/^{\circ}\text{C}$ (Epstein et al., 1953; Thompson et al., 2011). This comparison (Figure 4) must necessarily neglect the potential influence of $\delta^{18}\text{O}_{\text{sw}}$ over the course of a single ENSO event, given the uncertainties associated with potential nonlinear precipitation (and therefore $\delta^{18}\text{O}_{\text{sw}}$) responses to individual ENSO events. However, forward models for $\delta^{18}\text{O}_{\text{coral}}$ over the most recent ENSO events suggest that SST is by far the strongest driver of $\delta^{18}\text{O}_{\text{coral}}$ in this region (supporting information Figure S6). Through this conversion, we find that only the SODA 2.2.4 reanalysis (Giese & Ray, 2011) estimates the 1877–1878 El Niño event as a higher magnitude than the coral reconstruction. The SODA product estimates anomalies of 3.5°C in the Niño 3.4 region (Giese & Ray, 2011), falling within recent estimates of anomalies of $2.8\text{--}3.5^{\circ}\text{C}$ and

uncertainty (0.5°C) in the Niño 3 region (Huang et al., 2020), especially when considering the 1877–1878 event peak SST anomalies were amplified westward (Singh et al., 2018). In the F+Precon coral reconstruction, the 1877–1878 event is explicitly resolved by a Fanning coral $\delta^{18}\text{O}$ record, while the Palmyra contribution to this event is derived from the RegEM extension. The RegEM algorithm can dampen the variability of imputed-missing values during periods when a small number of observations are required to estimate a large number of missing values. As such, the Palmyra RegEM component dampens the total variability in the F+Precon average over the 1877–1878 event. In an analogous situation, during the 2015–2016 El Niño event, the Fanning contribution is derived from the RegEM extension driven by observed Palmyra coral $\delta^{18}\text{O}$ variability. In this case, the RegEM extension of Fanning Island record over the 2015–2016 El Niño reconstructs the maximum $\delta^{18}\text{O}$ anomaly to be within 0.02‰ of pseudocoral $\delta^{18}\text{O}$ generated solely from ARGO SST records, and 0.14‰ when compared with pseudocoral $\delta^{18}\text{O}$ generated from combined ARGO SST and SSS observations (supporting information Figure S9), lending confidence to the validity of the Palmyra RegEM extension for 1877–1878.

The coral-based reconstruction, together with the SODA 2.2.4 SST product, provides evidence that the 1877–1878 may have been the largest of the last 150 years. There is abundant evidence that climate in ENSO-teleconnected regions was strongly perturbed during this event: For example, 1877–1878 was characterized by the absence of the monsoon that resulted in devastating famine across Indo-China (D'Arrigo et al., 2008, Singh et al., 2018). The 1877–1878 event is also associated with highly anomalous values in coral $\delta^{18}\text{O}$ records from the Seychelles and Mentawai Islands, indicative of an exceptionally strong perturbation Indian Ocean temperatures (Abram et al., 2003, 2007; Charles et al., 1997). In the eastern equatorial Pacific, anomalous rainfall accompanied by fatal floodings was reported across large portions of northwestern coastal South America (Aceituno et al., 2008).

Perhaps equally interesting as the magnitude, the temporal evolution of the large El Niño events of 1877–1878, 1941–1942, 1997–1998, and 2015–2016 included a tropical ocean warming that preceded the actual El Niño event (Figure 5a). Our analysis suggests that in the Northern Line Islands, this warming averaged roughly 1 standard deviation and appeared about 18–12 months before the peak of the large El Niño event. The pre-El Niño warming manifested as warm SST anomalies in the CTP, but it is unclear if these events would have been classified as unique central Pacific El Niño events or if they would have resembled the “failed” 2014–2015 El Niño (Levine & McPhaden, 2016). Recent work by Wu et al. (2019) has identified that multiyear El Niño events can be prompted by a delayed later summer development, developing initial SST anomalies around June prior to the first El Niño event and the associated thermocline preconditioning. Highly persistent El Niño events are also thought to be encouraged by favorable interbasin SST gradients (Wu et al., 2019), off equatorial westerly wind bursts (McGregor et al., 2016), interactions between decadal variability and stochastic forcing by the atmosphere (Di Lorenzo & Mantua, 2016; Okumura, 2017). Future work would benefit from pairing this F+Precon index with other long archives to test for consistency with these hypotheses.

The 2015–2016 El Niño event featured sustained SST anomalies in the CTP and along a corridor trending NE toward Baja California, remaining high from late 2014 through the beginning of the 2015 El Niño in boreal fall. We plot the average SST anomaly associated with the “pre-El Niño warming” over June–December 2014 and indicate with a blue box the region critical for the Pacific Meridional Mode (PMM)—a mechanism by which extratropical atmospheric variability can influence the equatorial Pacific (Chiang & Vimont, 2004) (Figure 5b). The similarities between the evolution of this event and three of the other major El Niño events observed in the Fanning-Palmyra composite coral $\delta^{18}\text{O}$ record may describe a characteristic maturation of very strong El Niño events. Given the footprint of the 2015–2016 precursory warming, which extended into the subtropics, our observations here likely add to a growing body of evidence illustrating extratropical influence on ENSO. Though it is only possible to approximate PMM activity prior to 1948 due to the method of calculation, area-averaged SST ($15\text{--}28^{\circ}\text{N}$, $140\text{--}120^{\circ}\text{W}$, as in Middlemas et al., 2019) represents this variability reasonably well (Figure 5c). With this approximation, it is apparent that at least three of the four largest El Niño events in the F+Precon record were preceded by a positive PMM (Figure 5d). The remaining event, 1877–1878, is associated with a weak negative PMM event, but perhaps this association is a result of the sparsity of high quality of observations. The basin-wide SST comparisons therefore suggest that the PMM might be considered not only as a precursor to ENSO generally (Chiang & Vimont, 2004) but also as a precondition for the large ENSO events.

Figure 5. (a) Comparison of individual El Niño events of 2015–2016 (purple) 1997–1998 (green), 1940–1941 (orange), and 1877–1878 (blue) in coral and instrumental SST reconstruction over a 7-year period. Warm events clearly precede the El Niño events in the Line Island coral records. For illustration purposes, and to highlight interannual variability, records were centered at the December of the respective El Niño event, and the local 50-year running mean was subtracted. Arrows over 18–12 months prior to the El Niño event indicate the precursor warming. (b) Same as (a) but SSTa from the Niño 3.4 index in ERSST v5 (Huang et al., 2017) over the 2015–2016 (purple) 1997–1998 (green) events. (c) SST anomalies averaged over the –18- to –12-month period before the 2016 El Niño (i.e., June–December 2015). The region of PMM activity is highlighted in blue. (d) Observed March–April–May averaged PMM index (black) and simplified PMM index (blue). The largest El Niño events in the F+Precon are starred. The dashed line indicates a 0.75 standard deviation PMM event.

4. Conclusions

In this study, we present two young fossil coral $\delta^{18}\text{O}$ records from Fanning Island, located in the CTP, dating to the midnineteenth and midtwentieth centuries. These young fossil coral records can be combined effectively with new and existing coral records derived from living colonies. Among other applications, the combination of various coral segments allows for investigation of sparsely sampled, but significant El Niño events

in a continuous record of climate from the CTP. The newly generated coral $\delta^{18}\text{O}$ record complements existing coral and instrumental records from the tropical Pacific and illustrates how a coral-based network of observations, extending to the midnineteenth century, may be constructed by combining living and fossil coral archives. The primary source of uncertainty for the resulting reconstruction derives from the different variance of fossil versus modern coral $\delta^{18}\text{O}$ at Fanning Island; this uncertainty likely results from the fact that the sampling site for one particular fossil coral segment was located just outside the lagoon. Without overlapping segments from other sites, it would be difficult to concatenate fossil coral records without introducing appreciable bias. In our case, the Fanning F4 core has overlapping intervals of coral $\delta^{18}\text{O}$ from adjacent sites (in this case, Palmyra and Christmas Islands), as well as instrumental SST observations, that can be combined to allow us to minimize this uncertainty. Once the continuous coral record was constructed, a monotonic trend toward warmer/wetter conditions over the twentieth century emerges, consistent with published coral reconstructions from the surrounding region. Collectively, such evidence provides support for dynamical models documenting significant shifts in central Pacific convection and freshwater advection associated with large-scale hydrological shifts under greenhouse forcing. Comparison of four major El Niño events over the past ~150 years implies that the 1877–1878 El Niño event was the strongest, followed by the El Niño events of 1997–1998, 2015–2016, and 1940–1941, respectively. The coral records further demonstrate that the major El Niño events were preceded by smaller-scale El Niño-like events that may have preconditioned the system for the development of much larger event in the subsequent year. Given the ubiquity of young fossil corals on many beaches of the low lying atolls of the tropical Pacific, the type of observations presented here could be easily expanded throughout the tropical/subtropical Pacific to effectively extend the instrumental record of temperature through the late nineteenth century and possibly even into the late eighteenth century. This pursuit is rendered feasible by the recent developments in rapid radiocarbon-based age screening of fossil corals. The statistics of coral proxy records presented here suggests that such a pursuit would be fruitful.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Data will be available on NOAA paleoclimate (<https://www.ncdc.noaa.gov/paleo/study/30493>) upon publication. Code and information behind the RegEM algorithm can be found at GitHub (<https://github.com/tapios/RegEM>).

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