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El Niño–Southern Oscillation (ENSO) and Tropical Pacific Climate Across the 4.2 Ka BP Climate Excursion

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El Niño–Southern Oscillation (ENSO) and Tropical Pacific Climate Across the 4.2 Ka BP Climate Excursion

A thesis in partial satisfaction of the requirements
for the degree of Master of Science

in

Earth Sciences

by

Karen Vianney Gutierrez

Committee in charge:
Professor Christopher Charles, Chair
Professor Jade d'Alpoim Guedes
Professor Jane Teranes

2021

The thesis of Karen Vianney Gutierrez is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2021

DEDICATION

Dedicado a mi familia for su apoyo infinito.

And to my fellow geology nerd, Zack.

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ABSTRACT OF THE THESIS

El Niño–Southern Oscillation (ENSO) and Tropical Pacific Climate Across the 4.2 ka BP Climate Excursion

by

Karen Vianney Gutierrez

Master of Science in Earth Sciences

University of California San Diego, 2021

Professor Christopher Charles, Chair

The origin and influence of the "4.2 kyr event"– a climate excursion characterized by century-long drought hypothesized to have affected civilizations throughout the northern subtropics– is uncertain, despite its registration in multiple paleoclimatic archives. As the dominant source of global interannual climate variability, the El Niño-Southern Oscillation

(ENSO) might be expected to have shaped the expression of global precipitation and temperature across the 4.2 kyr event. However, the role of ENSO has not been explored, owing to a general lack of temporally extended observations in the tropical Pacific. Here I analyze a number of tropical Pacific *Porites* coral fossils spanning this interval, between ~4600 and 4100 years B.P., building on the previously published record of ENSO activity as well as the prevailing mean state of tropical Pacific climate. Monthly resolved oxygen isotopic records of three corals from Fanning Island and one from Christmas Island overlap with and extend existing records to produce a nearly-continuous sequence that spans several hundred years. Oxygen isotopic values of the overlapping segments of the fossil corals strengthen the reliability of the paleoclimate record and the radiometric dating. The new coral data generated in this study confirm the previous inference of low ENSO activity over an extended time interval encompassing the 4.2 kyr event. Additionally, the new coral data show that the interannual variability, though reduced in amplitude relative to the modern climate, was expressed as repeated episodes of prolonged and intense La Niña conditions. This characterization stands in contrast with a single multi-decadal excursion, as initially hypothesized for the 4.2 kyr event. Finally, the mean values of overlapping coral segments from Fanning and Christmas Islands are similar, suggesting that the modern temperature and salinity gradient was not present during the interval of the 4.2 kyr event. The simplest explanation for this lack of temperature/salinity gradient is that the southern boundary of the North Equatorial Counter Current was shifted north of Fanning Island.

Introduction and Background

1.1 Introduction

Past ENSO activity can be inferred from paleoclimate proxies using analysis of different geochemical tracers and archives, which store information of conditions the climate at the time of the proxies' growth or accumulation. Specifically, a continuous record of ENSO can be created from oxygen isotope analysis of corals collected across the Line Islands, a chain of atolls located in the central Pacific. The El Niño phase of ENSO brings warmer-than-average sea surface temperatures (SSTs) across the tropical Pacific Ocean. Conversely, La Niña is the colder phase of ENSO, bringing colder SST to the tropical Pacific. Mean SSTs can then be inferred from the oxygen isotopic composition of coral skeletons, which store information of local conditions in upper ocean and atmosphere. Coral samples collected from these equatorial-laying islands are ideal for observations of ENSO activity, and as mean climate proxies, as they lie in the center of action for ENSO and at boundaries of both the warm North Equatorial Counter Current (NECC) and the colder South Equatorial Current (SEC) (Sanchez et al., 2020).

1.2 Study site

The corals used in this project were collected from Fanning (Tabuaeran) Island (4°N, 160°W) and Christmas (Kiritimati) Island (2°N, 157°W) during field expeditions in May 2005 and August 2005, respectively (Cobb et al., 2013). The sampled corals were found along the beaches of these islands, likely the deposits after a storm (Cobb et al., 2013).

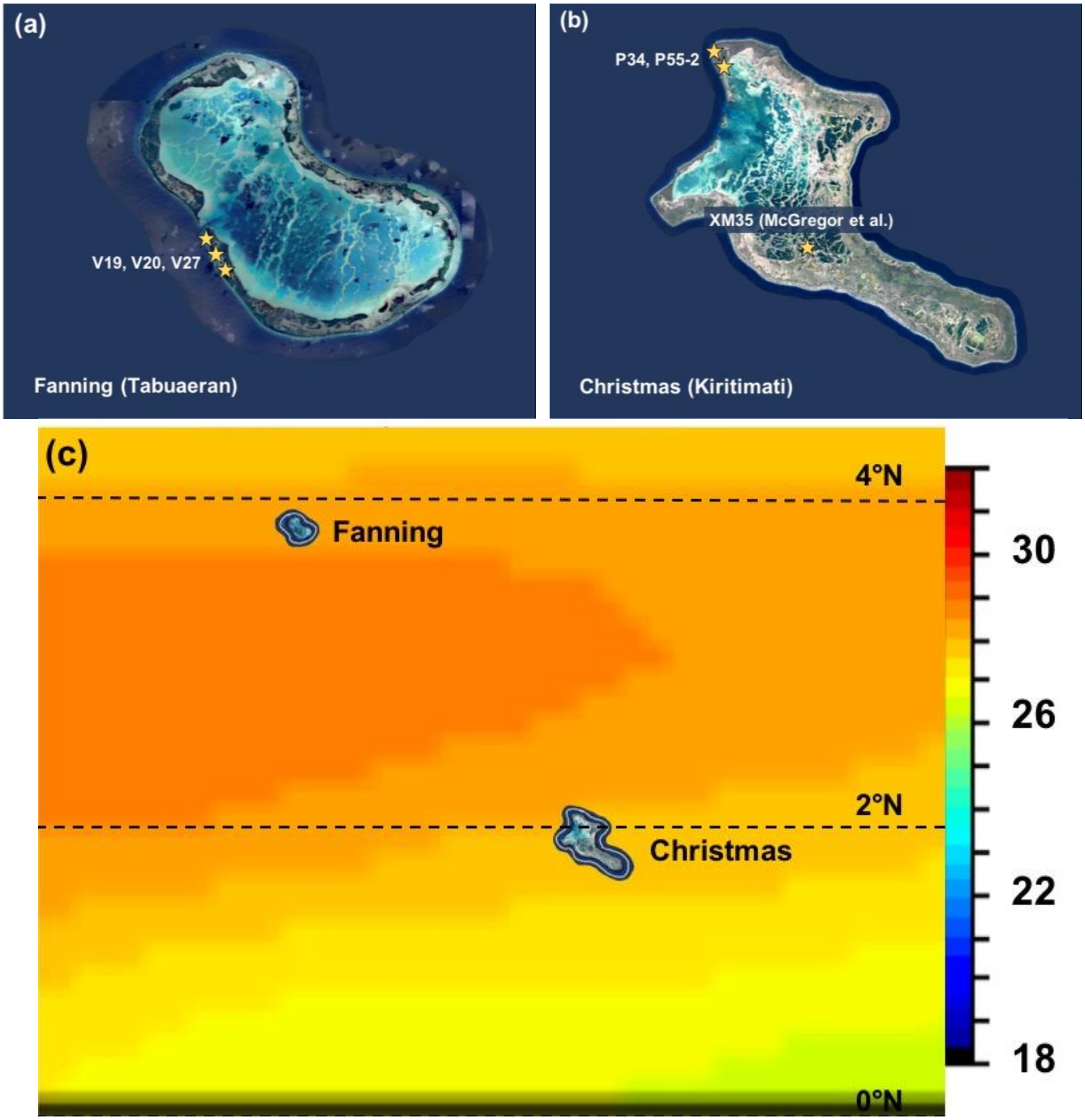

Figure 1.1 Google Earth images of: (a) Fanning and (b) Christmas Island with coral fossil collection sites marked; (c) Fanning and Christmas Island's approximate latitudinal locations and SST overlay during normal conditions in December 1993. Modified from PMEL/NOAA. (Source: *What is La Niña? | El Nino Theme Page - A comprehensive Resource*, 2016).

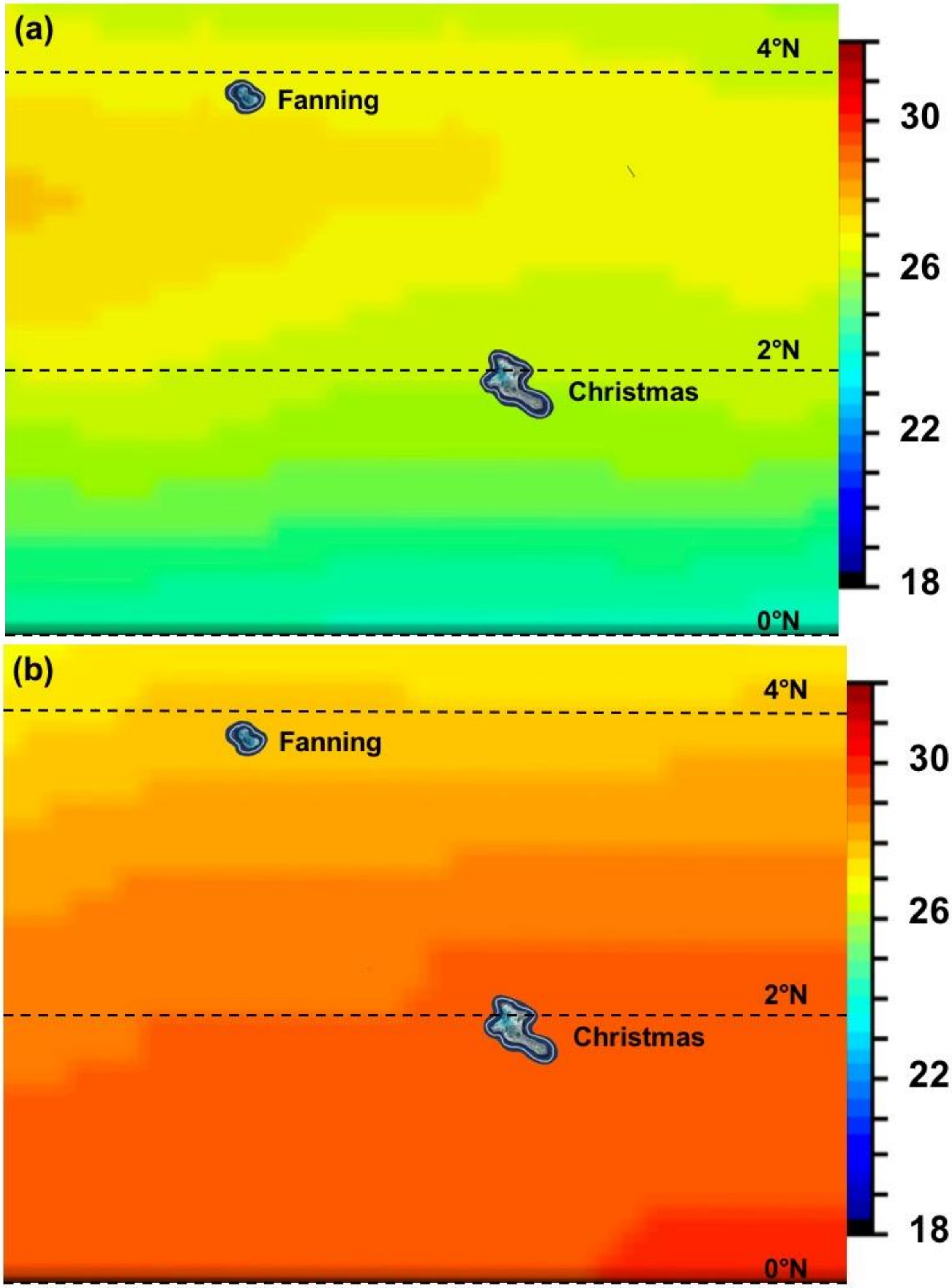

Figure 1.2 SST overlay over Fanning and Christmas Island during: (a) La Niña conditions and (b) El Niño conditions for December of respective event years (1998 and 1997). Modified from PMEL/NOAA. (Source: *What is La Niña? | El Nino Theme Page - A comprehensive Resource*, 2016).

1.3 The 4.2 kyr Event

H.M. Cullen and colleagues were first to publish a proxy record showcasing evidence of climate anomalies surrounding the 4.2 kyr event. Analysis of a marine sediment core sourced off the Gulf of Oman, a prime location for climate-driven aeolian deposits, was done to build a number of age-depth chronologies. An increase in accumulation of aeolian dolomite and calcite deposits was observed between 4194 and 3626 calendar years B.P. (Cullen et al., 2000). This type of sediment accumulation in the Arabian Sea has also previously been seen during other well-known periods of extensive aridity and lower temperatures, such as the Last Glacial Maximum and Younger Dryas, thus supporting the case of abrupt climatic disruption leading to drier conditions in the region circa the 4.2 kyr event. Additionally, evidence of desertification –a land degradation process through which fertile land deteriorates into desert– and desertion dating to around 4200 years B.P. has been found at Tel Leilan, a major city-state in the Habur Plains of northern Mesopotamia (Weiss et al., 1993), thus posing a possible connection between the 4.2 kyr climatic event and the theorized collapse of the Akkadian Empire occupying this region.

1.4 Published Record So Far

A number of papers have since been published further detailing the changes in ENSO variability through the mid-Holocene. Notably, H. V. McGregor et al. also used a *Porites* coral from the tropical Pacific dated to around 4300 years B.P. for oxygen isotope analysis to reconstruct an ENSO record during the coral's growth period. Their coral fossil (denoted as XM35) was also source from one of the Line Islands, Christmas Island. Altogether, McGregor et al. obtained 175 years of data at a monthly-resolution. The results from their reconstruction demonstrated a dampening in ENSO variability during the full 175 years of the mid-Holocene when compared to modern coral records, indicating a decrease in frequency of ENSO events for the time period (McGregor et al., 2013). A compilation of ENSO variability from coral reconstructions over the last 7000 years agrees with McGregor et al.'s results and also emphasizes that the period in the mid-Holocene between 3000 and 5000 years B.P. was a minimum for ENSO variability (Grothe et al. 2019).

1.5 Project Motivation

While McGregor et al.'s study is the most succinct summary of principle findings for the topical Pacific during this interval so far, large uncertainty still remains regarding the full record of ENSO activity during the mid-Holocene. Additionally, even though this is perhaps the single most diagnostic region for global climate variability, other records from the tropical Pacific are largely absent from existing compilations of the 4.2 kyr event. Lastly, considering that archeological evidence suggests this was a period of societal unrest and other cultural shifts, understanding the climate influence over those events would be a valuable addition. Thus, by geochemically analyzing the *Porites* fossils sourced from Fanning and Christmas Island, we hope to achieve replicability of SST conditions (and thus infer ENSO activity) and increase confidence of radiometric dating.

Methods

2.1 Corals as Climate Archives

Conditions of El Niño-Southern Oscillation are recorded in the aragonitic skeleton of *Porites* corals as low $\delta^{18}O$ values, due to the inverse relationship between warmer SSTs and more depleted $\delta^{18}O$ values. This isotopic record can then be used to characterize the behavior of El Niño in comparison to the mean climate conditions from the same time. The corals for this project have been radiometrically U/Th-dated to a time hovering around 4200 years B.P. Specifically, each coral slab was dated at about the mid-point to approximately: 46244± 9 for V20, 300 ± 9 yr. BP for V27, 4158 ± 9 yr. BP for V19, and 4107 ± 9 yr. BP for P55-2. This is a significant time period because it coincides with the paleo climatological 4.2 kyr climate excursion, hypothesized to be a severe and long-lasting global drought that brought about not only climatic consequences but also anthropological ones. By collecting data from tropical Pacific corals that coincide with this event, we can observe if the large shift in climate and temperature during this time correlates with the expressed ENSO activity.

Furthermore, mean $\delta^{18}O$ values can also be compared across islands. Normal, modern SST measurements exhibit an existing gradient between the Line Islands with warmer, fresher seawater further away from the equator. As a result of this gradient, modern corals taken from the Line Islands show a difference in mean $\delta^{18}O$ values, with corals from Fanning and Palmyra being more depleted in $\delta^{18}O$ compared to corals from Christmas Island by 0.4‰ on average (Carilli et al., 2017).

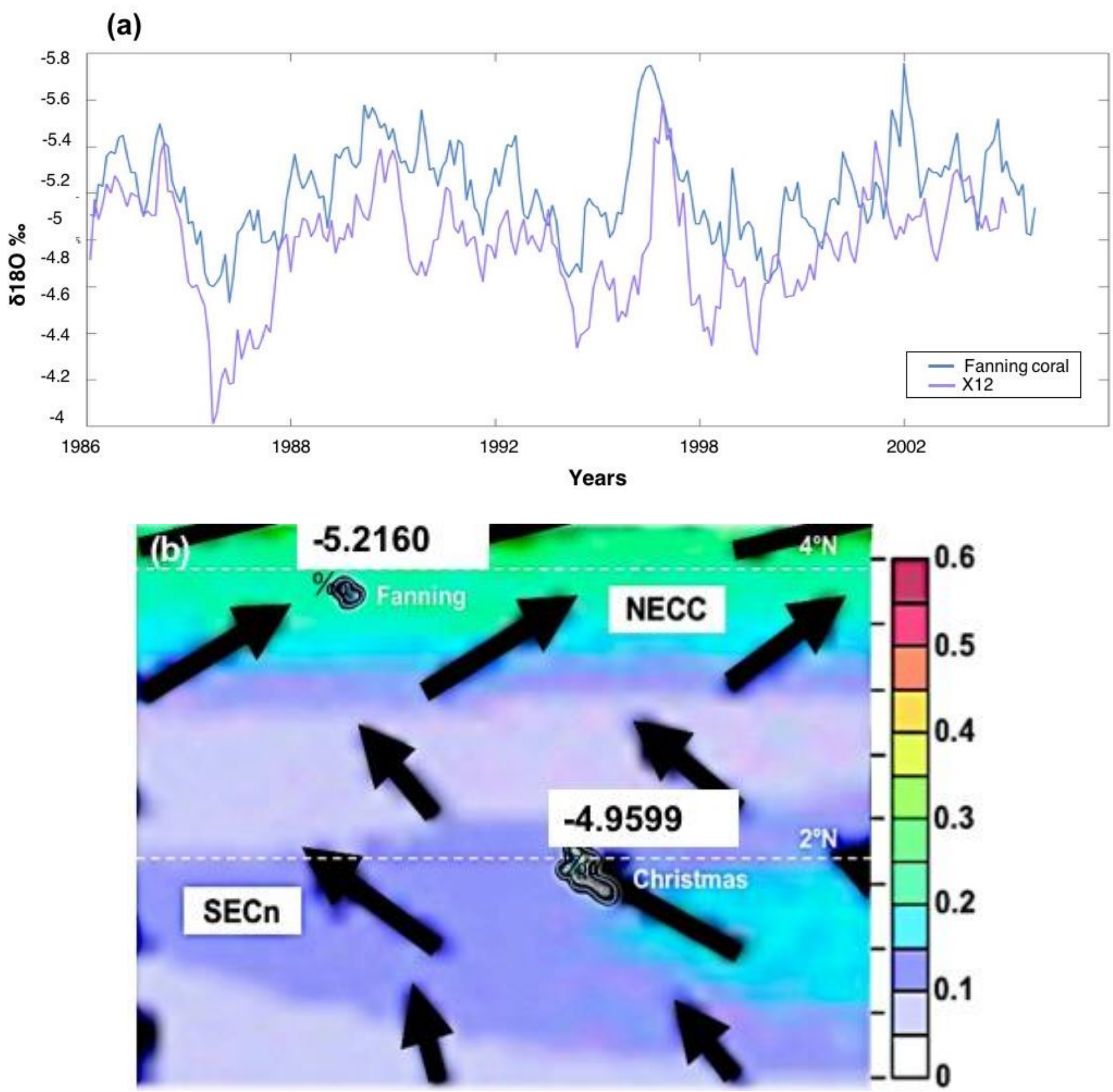

Figure 2.1 (a) Time series of two modern corals: one from Fanning (Nurhati et al., 2010) and X12 from Christmas (Grothe et al., 2019) over a 19-year period. Mean circulation (m/s) of the Eastern Pacific during normal conditions to show boundaries of the North Equatorial Counter Current (NECC) and northern branch of the South Equatorial Current (SECn) overlaid with mean $\delta^{18}O$ values from the corals in (a) during 19-year record. Modified from (Wang and Wu, 2013).

2.2 Sample Collection

A number of coral cores were drilled during expeditions to the Line Islands in 2005. Corals collected from Fanning Island are denoted by names starting with the letter “V” (V19, V20, and V27) while corals from Christmas Island have names starting with the letter “P” (P55-2 and P34) as they were sourced near the island pier. Each core was cross-sectioned into three vertical parts, making up two outer core pieces and a flat, 1cm middle slab used for sample preparation.

2.3 Sampling and Isotopic Analysis

The coral slabs were sampled with a hand drill at 1mm intervals along the growth axis to obtain the highest resolution possible. Each powdered sample was weighted to measure no more than 150 micrograms in preparation for mass spectrometry analyze using a Thermo-Scientific MAT 253 gas mass spectrometer. Either a PDA or NBS-19 standard was also analyzed alongside each 20-40 sample run for comparison. The mass spectrometer produces raw $\delta^{18}O$ values for each depth sampled per the isotope ratio formula:

$$\delta^{18}O \text{ ‰} = [[(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}]-1]\times 1000$$

2.4 Building a Time Series

Corals V19 and P55-2 were also x-rayed to help identify and label approximate annual banding, registered as density differences in the skeleton, due to seasonal changes in SST. The density banding helps to determine a total approximate length of the coral record in years. It is also used to convert sampling depths into a time series with age. After labeling the approximate years of coral growth, corresponding depths could then be selected to use as annual markers. A monthly resolution is ideal for statistical isotopic analysis. In order to achieve even, monthly samples between years, samples were interpolated to result in twelve $\delta^{18}O$ values per year.

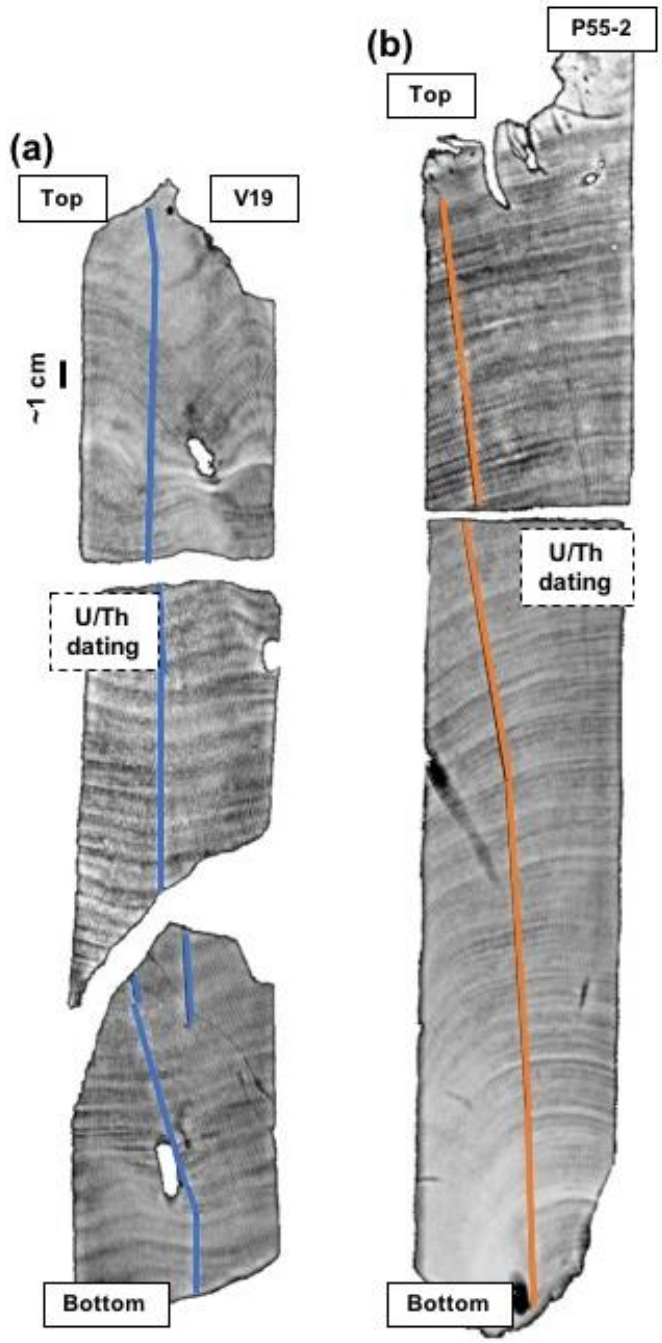

Figure 2.2 X-ray images of (a) three pieces that make up V19 and (b) two pieces that make up P55-2 with transects labeled.

Results

3.1 Constructing a $\delta^{18}O$ Time Series

Coral XM35 (from McGregor et al.) is a microbial atoll coral, which does exhibit differences to open-ocean corals, as those sampled in this project. As a result, the values for XM35 had to be adjusted using the offset number (0.4‰) found between different modern island corals to get comparable means with our open-ocean corals.

While the sampled corals (V20, V27, V19, and P55-2) cannot be completely spliced together for a continuous record, their addition to the published McGregor fossil coral (XM35) does fill in gaps and extends those parts of the record. Additionally, the sampled corals also help reinforce the uranium-thorium dating of the published record through observable overlaps between V27 with XM35 and P55-2 with P34 at their approximate, expected ages.

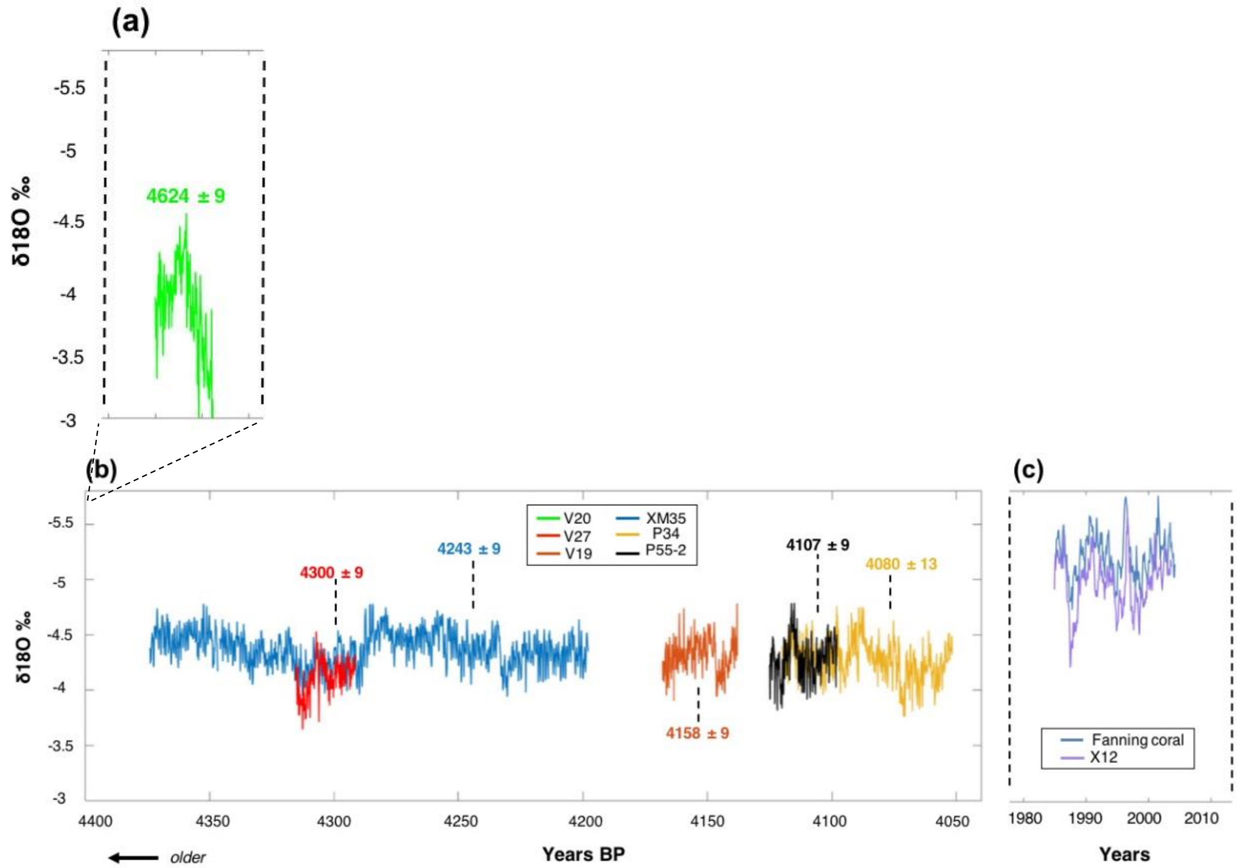

Figure 3.1 Preliminary splicing of fossil corals: (a) V20 with (b) V27, XM35 (McGregor et al., 2013), V19, P34 (Cobb et al., 2013), and P55-2. Values for XM35 have been adjusted by 0.4‰ to get more comparable means with corals sampled for this project due to offset between lagoonal and open-ocean corals. (c) Modern Fanning and Christmas Island coral values plotted on the same y-axis as (a) and (b). This side-by-side comparison demonstrates the less negative and less variable, $\delta^{18}O$ values from the fossil corals compared to modern corals.

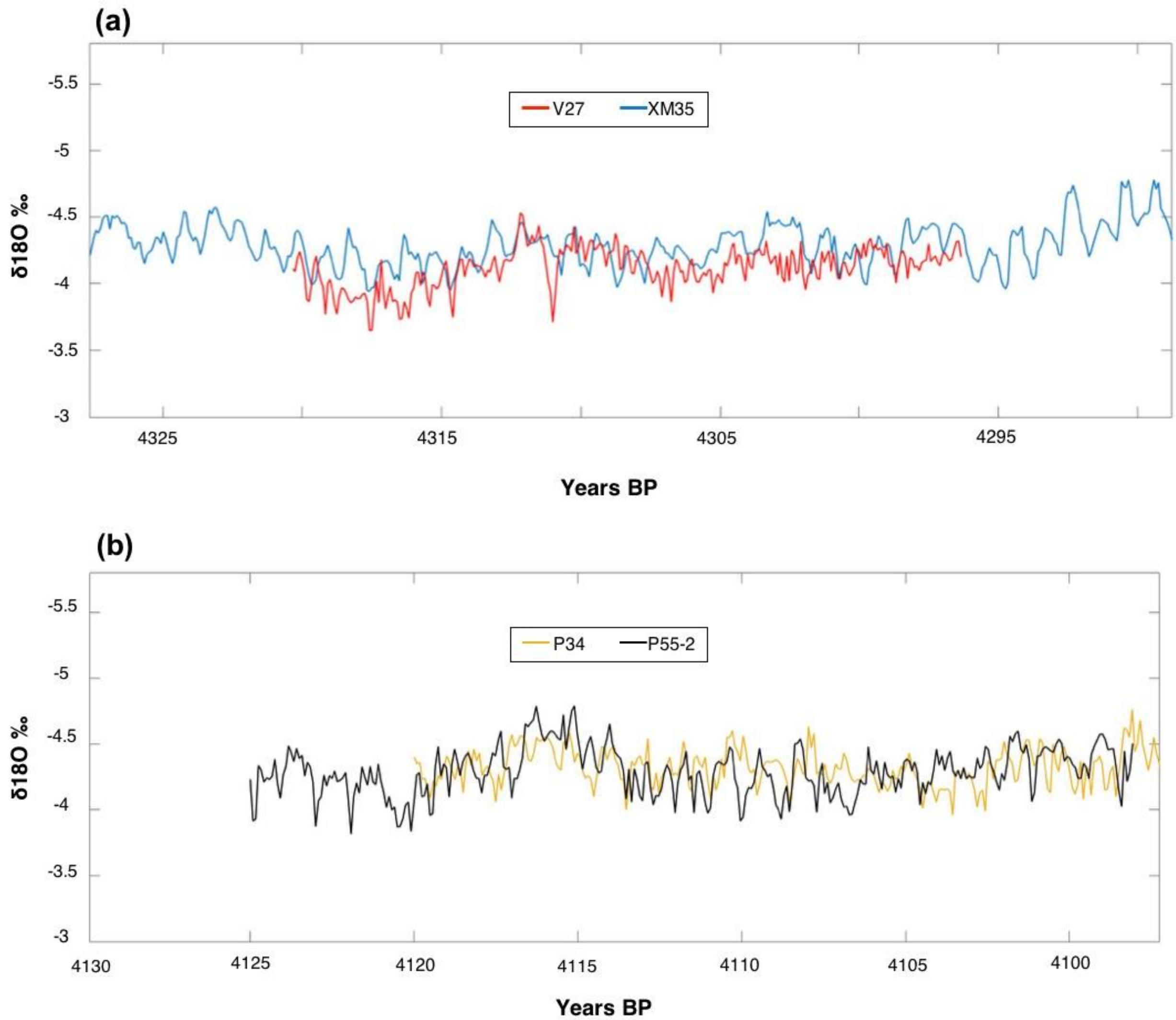

Figure 3.2 Zoom in to splicing of fossil corals: (a) V27 and XM35 (McGregor et al., 2013) and (b) P55-2 and P34 (Cobb et al., 2013) at time of approximate overlaps.

3.2 δ^{18}O and the SST Gradient

Mean δ^{18}O values in modern Line Island corals express an SST gradient that exists across latitudes. Seawater in this region is warmer away from the equator. Therefore, corals collected at 4°N, the latitude of Fanning Island are more depleted in δ^{18}O compared to those from Christmas Island at 2°N (Carilli et al., 2017). For example, the mean δ^{18}O of modern corals over a 10-year period from Fanning Island (Sanchez et al., 2020) was calculated to be -5.2106‰ compared to a mean value of -4.9599‰ for modern Christmas Island corals over the same decade (Grothe et al., 2019).

However, little difference is observed in the mean values between the Fanning Island and Christmas Island fossil corals compared to today.

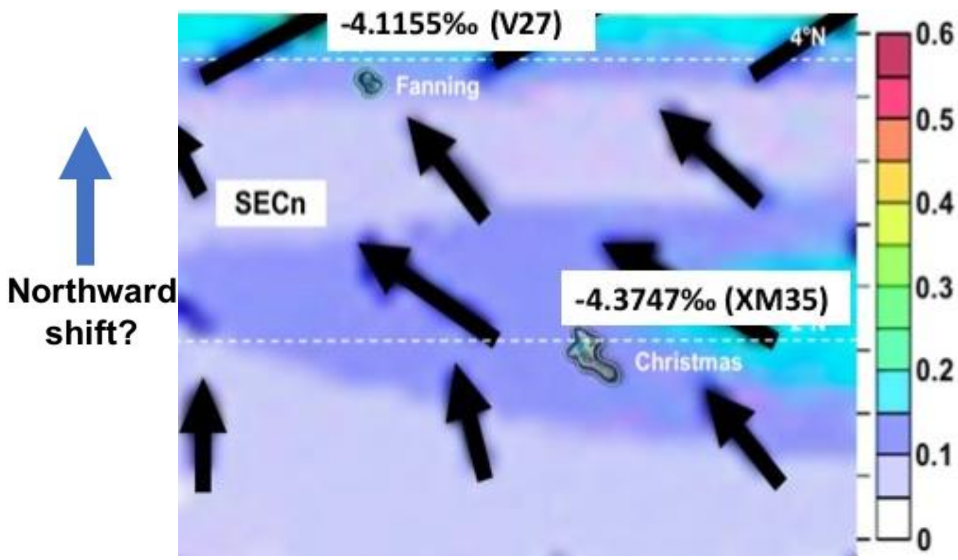

Figure: 3.3 Calculated mean δ^{18}O values for fossil corals: (a) V27 and (b) XM35 (offset by 0.4‰) (McGregor et al., 2013). Their values are much similar in the fossil samples. Overlay of hypothesized northward shift in current boundaries as possible source of more comparable mean values is modified from (Wang and Wu, 2013).

Discussion

4.1 Interpretation of Results

The inclusion of values for coral fossils V27, V19, and P55-2 to the published record of other tropical Pacific corals from this time interval (XM35 and P34) accomplishes a number of things. While the low ENSO activity over this time period has been previously established, and is reaffirmed in this project's coral fossils, evidence of an interannual variability dominated by La Niña conditions can be seen a number of intervals shifts toward less negative $\delta^{18}O$ values. Additionally, the oldest fossil coral sampled (V20), dated to approximately 4624 yrs. B.P., shows similar mean $\delta^{18}O$ values as the younger fossil corals, which are centralized over the 4.2 kyr event. This suggests an extended cold period of low ENSO activity, even beyond the 4.2 kyr event, rather than being just a one-off multi-decal excursion.

4.2 Updated Archeological Connection

While a collapse of the Akkadian empire was originally hypothesized to be a consequence of the 4.2 kyr event due to prolonged drought, a more modern archeological interpretation around the 4.2 kyr event suggests more nuanced responses to it. For example, separate crops seemed to respond differently to the change in temperature and humidity in the Tibetan Plateau as a response to the 4.2 kyr event. A 2016 modeling study by Jade D'Alpoim Guedes et al. looked at the change in agricultural thermal niches of this region. This study found that millets, which likely require more growing degree days for their growth cycle experienced a reduction in their available niche due to the onset of cooler conditions and were less likely to be in the thermal growing niche between 4000 and 3500 years B.P., while wheat and barley remained largely in the niche (Jade D'Alpoim Guedes et al., 2016). They argue that this change in climatic conditions is one of the reasons that Tibetans adopted barley agriculture. This interpretation offers a more nuance perspective of coevolution of climate and the agricultural landscape, compared to the original hypothesis. Humans will be impacted by changes in climate primarily through the way that changes in climate can impact returns on their food resources. These returns can be highly variable depending on the requirements of the type of crops that people grew. Crops require both sufficient temperature and water to complete their lifecycles. In high altitude and in high latitude parts of the globe, changes in temperature and in particular planetary cooling events are likely to result in a decline in crop niches. In tropical or sub-tropical environments, temperature is less likely to have been a limiting factor. Water can also play a critical role particularly when dealing with rainfed crops like wheat, barley or millets. Other crops, like rice are frequently irrigated and may be more resilient to changes in rainfall, however at their northern boundaries of expansion might be impacted by temperature.

4.3 Future Work

The result figures in this thesis are still only preliminary plots, which require further fine-tuning in order to achieve maximized correlation. Possible future work could also continue sampling additional fossil corals, as gaps ranging up to ~30 years still remain between coral records.

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