Caribbean Sea Surface Temperatures and El Niño

A New Outlook

by

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Abstract

Mass coral bleaching in recent years has become a recurring event and was suspected to have a relationship with El Niño events. Changes in the understanding of what constitutes an El Niño event prompted further research into the relationship with Caribbean sea surface temperatures due to their impact on corals.

Multiple statistical tests were employed to profile the relationship between the individual event types and the Caribbean. Ultimately, a bootstrapping technique determined that Central Pacific El Niño events bear a relationship, while Eastern Pacific event types do not.

An attempt to hindcast El Niño events in order to comment on the history of impacts upon the Caribbean was unsuccessful due to a lack of sufficient input data, but a model determining potential locations of data is presented.
Preface

This thesis is original, unpublished, independent work by the author, Justin A. Lau, based upon data from publicly available satellite and in-situ geochemical proxy data hosted by NOAA – meticulously analyzed for your intellectual consumption, and in partial fulfillment of the degree of Master of Science in the Department of Geography at the University of British Columbia.
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Glossary

ASO  August-September-October

AVHRR  Advanced Very High Resolution Radiometer

CCA  Cross-Correlation Analysis

CMIP5  Coupled Model Intercomparison Project Phase 5

CP  Central Pacific

DHM  Degree Heating Month

DJF  December-January-February

ENSO  El Niño-Southern Oscillation (used interchangeably with El Niño)

EOF  Empirical Orthogonal Function

ERSST  Extended Reconstruction Sea Surface Temperature

EP  Eastern Pacific

ITCZ  Intertropical Convergence Zone

MMM  Maximum Monthly Mean

NINO3  A sea-surface temperature index used to identify El Niños. Defined by the region bounded by 5°N–5°S, 150°W– 90°W

NINO4  A sea-surface temperature index used to identify El Niños. Defined by the region bounded by 5°N–5°S, 160°E– 150°W
NOAA  National Oceanographic and Atmospheric Administration of the United States of America

OI-SST  Optimum Interpolation Sea-Surface Temperature. A dataset from the National Oceanographic and Atmospheric Administration of the United States of America

PC1  Primary Principal Component

RCP4.5  Intergovernmental Panel on Climate Change Representative Concentration Pathway, 4.5 W/m² scenario

SPCZ  Southern Pacific Convergence Zone

SST  Sea-Surface Temperature

SSTA  Sea-Surface Temperature Anomaly
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Chapter 1

Introduction

Climate varies everywhere on Earth at different temporal and spatial scales. These variations can have wide-ranging effects that make them both difficult and interesting to study. The El Niño-Southern Oscillation (ENSO) is one such example of a coupled ocean-atmosphere system that affects much of the globe in many different ways. Recently, new insights into the identification and characteristics of ENSO have arisen, which are altering the perception of potential impacts of ENSO events (Ashok et al., 2007; Yeh et al., 2009; Yu et al., 2012).

Many of the effects of ENSO events exist within the tropics – a region dense with coral reefs, which are sensitive to changes in their environment. Occurrences of mass coral bleaching in recent times have appeared to follow certain types of ENSO events, leading to questions regarding the links between them.

First described by Rasmusson and Carpenter (1982), ENSO is the primary source of short-term climatic variability in the Pacific Ocean (McPhaden, 2004)– explaining 45% of Sea-Surface Temperature Anomaly (SSTA) from 1979–2004 (Ashok et al., 2007). The coupled system is composed of an atmospheric portion called the Southern Oscillation and the oceanic portion called El Niño, but there is very high correlation between the components, thus, an analysis of either component is indicative of the whole system.

Both El Niños and La Niñas (negative, or cold phase of ENSO) are phase locked with the seasonal cycle, with peaks occurring in the boreal winter (Wang and Fiedler, 2006). Warm phases generally occur every 3-7 years and are very fre-
Figure 1.1: Composite of seasonal SSTAs from the summer (top) before the event until the spring (bottom) after the event for the EP ENSO (left) and CP ENSO (right). SSTA are in °C (from Banholzer, 2012).

Subsequently followed by La Niñas (Mock, 2007). The predominant interval between El Niños is 4 years (Cane, 2005), but it should also be noted that events have occurred in back-to-back years as well as not arisen for more than a decade at a time.

Since the early 2000’s, scientists have begun to take notice of ENSO-like events that do not fit in with the traditional model identified by Rasmusson and Carpenter (1982). These discoveries were often associated with the inability of the NINO3.4 index to capture what appeared to be an El Niño signal in SSTAs. This new ENSO has had various names associated with it: El Niño Modoki (Ashok et al., 2007), Dateline El Niño (Trenberth and Stepaniak, 2001), and Central Pacific (CP) El Niño (Kao and Yu, 2009; Lee and McPhaden, 2010; Yeh et al., 2009). The classical El Niño is now referred to as canonical or Eastern Pacific (EP) El Niño (Figure 1.1).

CP El Niños exhibit a tripole pattern where a warm pool resides in the centre of the Pacific, close to the International Date Line, flanked by cold SSTAs on either side along the equator (Ashok et al., 2007; Kao and Yu, 2009; Yeh et al., 2009). The analysis by Ashok et al. (2007) established that since the last climate regime shift in 1978, CP El Niño’s have been responsible for 12% of Sea-Surface
Temperature (SST) variability in the Pacific Ocean. Ashok et al. (2007), as well as Trenberth and Stepaniak (2001), used their analysis to establish a new index for determining the CP El Niños; however, most other studies used the NINO4 index. Ashok et al. (2007) warn against this practice as the NINO4 index is correlated with both El Niño and El Niño Modoki. This difference may account for why Yeh et al. (2009) and Ashok et al. (2007) have slight differences in the years that they label CP/Modoki events (Table 1.1).

Table 1.1: CP/Modoki events identified by 2 different studies (1985-2005)

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<tbody>
<tr>
<td>Ashok et al., 2007</td>
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<td>x</td>
<td>x</td>
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<td>Yeh et al., 2009 raw</td>
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<td>Yeh et al., 2009 detrended</td>
<td>x</td>
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</table>

Yeh et al. (2009) discovered that the frequency of ENSO event types experienced a shift between 1854-2007. Comparing pre- and post-1990, EP El Niños have occurred 0.19 times per year versus 0.29 times per year respectively, whereas CP El Niños have occurred 0.01 times per year compared to 0.29 times per year. Another analysis in the time domain found that CP ENSO events tend to have a lifespan of only 8 months compared to EP ENSOS, which are 15 months on average (Kao and Yu, 2009).

Due to the differences in the CP and EP El Niños, the associated teleconnections are different (Ashok et al., 2007; Yeh et al., 2009), and need to be explored.

To extend ENSO records beyond the instrumental record, there are two different methods: dendrochronology and sclerochronology (Mock, 2007). Sclerochronology analyzes ratios of geochemical tracers within the corals’ aragonite skeletons as a proxy for SST. δ¹⁸O ratios have been used to establish several hundred years of data (Cobb et al., 2003; Mock, 2007). Positive SST are associated with negative δ¹⁸O values; however, a confounding issue with δ¹⁸O is that it is also dependent on salinity, which can lead to complications if the salinity of the location at the same point in time is unknown (Pfeiffer, 2009). A proxy that only relies on temperature is the Sr/Ca ratio in the coral aragonite, which varies predictably with temperature.
due to the long residence time of Sr and Ca in the ocean (Pfeiffer, 2009). The only reason that more Sr/Ca data do not exist has been the associated cost, so it is foreseeable that the scientific community will continue to rely upon $\delta^{18}O$ primarily.

ENSO cycles are known to have significant climate teleconnections. They generate a response by global circulation pattern alterations that result in altered temperature and precipitation around many parts of the world (Cane, 2005; Mock, 2007). These changes generally follow the same patterns, but occasionally the teleconnections may propagate slightly differently as ENSO events are all unique in some way (Mock, 2007).

Climate often dictates the local biota, and when that climate is disturbed, the biota are forced to acclimatize or evolve; thus, many organisms in ENSO regions have adapted to the highly variable ENSO regime (Wang and Fiedler, 2006). Wang and Fiedler (2006) reviewed many of the biotic responses to El Niño. Their results suggest that the primary biotic response begins at the lowest trophic levels of marine life due to the change of the oceanic nutricline. All the other impacts are connected via the trophic chain leading from this up to marine mammals and seabirds (Wang and Fiedler, 2006).

This study aims to draw links between climatological and oceanographic variability of the tropical Pacific with that of Caribbean SST. The findings will help further our knowledge about teleconnections of the recently discovered CP El Niños. Additionally, coral biologists and marine management specialists will be better informed about what the different types of El Niño will mean for the Caribbean and integrate it into their work.

### 1.1 Questions

1. What is the correlation between different El Niño types and their strength in the Caribbean?

2. What is the lag time between the peaks of the different types of El Niño and their associated peak in the Caribbean?

3. Can hindcasts be developed that differentiate between ENSO type?
Chapter 2

Caribbean Sea-Surface Temperature Response to Central Pacific and Eastern Pacific El Niño Influence During the Satellite Era

2.1 Introduction

Corals reefs (Figure 2.1) are very important systems that consist of carbonaceous structures that provide a diverse range of services. Approximately 400-2000 imperial tons/ha/yr of CaCO$_3$ is laid down and added to reefs by living coral each year (Chave et al., 1972). Even though reefs only occupy a small portion of the ocean floor, they provide habitat for ~33% of marine fish, and account for ~10% of fish consumption by humans (Lough and van Oppen, 2009). Individual corals have a symbiotic relationship between host cells and algal organisms called zooxanthellae. Approximately 17% of the world’s coastlines are made from tropical coral reefs (Birkeland, 1997). These corals live in this region because the optimal temperature range is 26-28°C, but the average maximum temperature is 29.5°C, thus
they are very sensitive to change (Hubbard, 1997; Sheppard et al., 2009b). If this stress is sustained at greater than 3°C above seasonal maximum for more than two days, or greater than 1°C for several weeks, the coral will begin to ‘bleach’ (Brown, 1997). The term bleach comes from the fact that the coral appears very white. The change in colour occurs when the colourful zooxanthellae leave the host cells, meaning the carbonaceous skeleton beneath the translucent cells becomes visible (Lough and van Oppen, 2009; Muller-Parker and D’Elia, 1997; Sheppard et al., 2009b). In extreme cases, the magnitude of temperature change as well as persistence can lead to the death of the coral as it has insufficient nutrients to survive (Muller-Parker and D’Elia, 1997).

Widespread bleaching was first observed during the 1982-1983 ENSO event, and has since occurred multiple times, being labeled “profound”, “unprecedented”, and a “critical threat” linked to global warming (Lough and van Oppen, 2009; McCarthy et al., 2007; Oliver et al., 2009; Sheppard et al., 2009a; Wood, 2007). The bleaching events of 2005 and 2010 were so widespread that they were considered “global bleaching events” by experts (Eakin et al., 2010).

Very high levels of bleaching, disease, and mortality responses were recorded across the Caribbean in 2005 (Eakin et al., 2010). During 2010, Tobago and
Venezuela were two examples of areas in the Caribbean Sea that experienced bleaching and mortality worse than in 2005 amidst widespread bleaching throughout the region (Alemu and Clement, 2014; Bastidas et al., 2012) – a region where Donner et al. (2007) placed the probability of the 2005 event at 1-in-500.

Heat stress and coral bleaching events in some parts of the tropics are correlated with ENSO events, and have occurred at the same time as all known mass bleaching events: 1982/1983, 1986/1987, 1997/1998, 2004/2005, 2009/2010 (Brown, 1997; Oliver et al., 2009; Veron, 1995; Wood, 2007). The ENSO events do not directly cause the bleaching; however, they increase the likelihood of positive SST anomalies that induce the bleaching response (Eakin, 2009).

In the Caribbean, these bleaching events happen after the peak of the ENSO event. Known as the tropical atmospheric bridge, anomalous cloud cover and evaporation patterns that alter the heat flux into the surface of the ocean due to El Niño is currently the mechanism used to explain the teleconnections between Pacific ENSO events, and its effects around the global tropics, including the Caribbean (Klein et al., 1999). The current literature on these bleaching events predates the differentiation between EP and CP ENSO events, thus the associated lags and impacts need to be reassessed. However, both the 2005 and 2010 bleaching events in the Caribbean followed a large CP ENSO event, suggesting that there may be a link between bleaching and CP events.

2.1.1 Objectives

To establish the links between different ENSO types and their Caribbean SST teleconnection(s).

1. Are there relationships between particular El Niño types and different regions (East versus West) of the Caribbean Sea?
   (a) What are their associated SST impacts?
   (b) What is the lag time between the peaks of the different types of El Niño and their associated peak in the Caribbean?
   (c) Is heat stress related in the Caribbean associated with these SST impacts?
2.2 Methods

2.2.1 Data

Data from the National Oceanographic and Atmospheric Administration (NOAA) Optimum Interpolation Sea-Surface Temperature (OI-SST) v.2 dataset was utilized (Reynolds et al., 2007) for a 29 year period (January 1982 – December 2010), and uses a climatological baseline of 1986–2005. 1982 was the first full year of high-resolution satellite SST data available, and for this reason was chosen as the start date. The dataset consists of $\frac{1^\circ}{4} \times \frac{1^\circ}{4}$ latitude-longitude resolution gridded, daily data prepared by the National Centers for Environmental Prediction and the National Climatic Data Center, and has been averaged into monthly units for this study. The dataset is based on observations from the Advanced Very High Resolution Radiometer (AVHRR) instruments aboard the Pathfinder satellites and in situ data (Reynolds et al., 2007). Analysis of SST in the Caribbean focused on August-September-October (ASO), which are the summer months with the highest SST.

2.2.2 Indices of El Niño

El Niño indices are used to determine the state of the climate, and whether a particular event type exists at a given point in time (Table 2.1). It has been argued that due to its geographical limitations, the NINO4 index alone is insufficient for identifying CP events (Li et al., 2010). These limitations lead to the mis-categorization of events, and a lack of mathematical orthogonality to the EP indices (Table 2.2). Li et al. (2010) introduces the IEMI index, which is nearly completely orthogonal, but has a tendency to stop identifying CP events partway through boreal winter due to warming in the Eastern region, before being classified as an event again later in the year. This flaw occasionally forces events to not meet the minimum threshold of 5 consecutive months at $>1$ standard deviation above baseline (Banholzer, 2012). As a compromise, all time-series analysis is conducted using the NINO4 index. However, when identifying individual CP years for analysis, only the years with agreement between multiple studies with different methods were selected (Yu et al., 2012).

The NINO3 and NINO4 indices were computed using SSTA data with a climato-
Table 2.1: El Niño indices (adapted from Ashok et al. (2007))

<table>
<thead>
<tr>
<th>Index Name</th>
<th>Definition</th>
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<tbody>
<tr>
<td>NINO3</td>
<td>the region is bounded by (5°N–5°S, 150°W–90°W); the area-averaged SSTA over this region is known as NINO3 index, which is a well-known ENSO index</td>
</tr>
<tr>
<td>NINO3.4</td>
<td>the region is bounded by (5°N–5°S, 170°W–120°W); the area-averaged SSTA over this region is known as NINO3.4 index</td>
</tr>
<tr>
<td>NINO1+2</td>
<td>the region is bounded by (equator to 10°S, 90°W–80°W); the area-averaged SSTA over this region is known as NINO1+2 index</td>
</tr>
<tr>
<td>NINO4</td>
<td>the region is bounded by (5°N–5°S, 160°E–150°W); the area-averaged SSTA over this region is known as NINO4 index</td>
</tr>
<tr>
<td>EMI</td>
<td>([\text{SSTA}_A] - 0.5*\text{SSTA}_B - 0.5*\text{SSTA}_C) where the brackets are geographically averaged SSTAs: A(165°E-140°W, 10°S-10°N), B(110°W-70°W, 15°S-5°N), C(125°E-145°E, 10°S-20°N)</td>
</tr>
<tr>
<td>IEMI</td>
<td>(3*\text{SSTA}_A - 2*\text{SSTA}_B - \text{SSTA}_C) where the brackets are geographically averaged SSTAs over the same regions as the EMI</td>
</tr>
</tbody>
</table>

Table 2.2: Correlation values between the indices and the first two PC’s during 1979-2008. Maximum and minimum correlations in each column are bold. (from Li et al. (2010))

<table>
<thead>
<tr>
<th>Index</th>
<th>PC1</th>
<th>PC2</th>
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<tbody>
<tr>
<td>NINO3</td>
<td>0.97</td>
<td>-0.12</td>
</tr>
<tr>
<td>NINO3.4</td>
<td>0.95</td>
<td>0.17</td>
</tr>
<tr>
<td>NINO1+2</td>
<td>0.84</td>
<td>-0.47</td>
</tr>
<tr>
<td>NINO4</td>
<td>0.79</td>
<td>0.50</td>
</tr>
<tr>
<td>IEMI</td>
<td>-0.02</td>
<td>0.94</td>
</tr>
<tr>
<td>EMI</td>
<td>0.24</td>
<td>0.91</td>
</tr>
<tr>
<td>TNI</td>
<td>0.04</td>
<td>0.90</td>
</tr>
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logical baseline of 1986–2005. The NINO indices are defined as the area averaged SSTA values within their respective regions as outlined in Table 2.1.

Classification criteria for different ENSO events vary. Event years were identified by comparing results from papers studying CP & EP ENSO via different methods (Ashok et al., 2007; Banholzer, 2012; Lee and McPhaden, 2010; Li et al., 2010; Wang and Fiedler, 2006; Yeh et al., 2011), and the four most prominent events of each kind that were agreed up between studies, were selected. As many of the studies were completed prior to the end of the study period, the methods were replicated by this study to extend the results for a more representative comparison in the latter years. The years in this study agree with analysis conducted by Yu et al. (2012), who put together a “consensus” list of CP and EP events.

2.2.3 Empirical Orthogonal Functions

In order to determine the primary modes of SST variability, and the effect of spatial scale on the variability signal, Empirical Orthogonal Function (EOF) analysis was conducted on the SSTA data within two different regions in the Caribbean: ‘west’ and ‘east’ Figure 2.2. As a data compression technique, this analysis mathematically defines a new set of theoretical eigenvectors designed to maximally capture variability in a single dimension, orthogonal to subsequent eigenvectors (Preisendorfer and Mobley, 1988). In this case, the technique identifies the mathematical function of SST along a theoretical dimension within both space and time.

2.2.4 Cross-Correlation Analysis

Cross-Correlation Analysis (CCA) was employed in order to determine the length of time between the peak of the ENSO signal, and the peak SST response in the Caribbean Ocean. The Primary Principal Component (PC1) for each region and each index time series were ran through the CCA with a maximum lag of 12 months between event the event peak as determined by the NINO indices, and the peak of the regional PC1 in question. Normalized correlations were computed for each time step in the range, leading to 25 results per test with the assumption that if an identifiable effect is to be felt from an ENSO event, it would occur within the next 12 months.
2.2.5 Bootstrap Model

In traditional statistical tests, low population members and/or degrees of freedom are less likely to lead to statistical significance being established, thus potentially leading to a Type II statistical error. In this case, \( n = 4 \) for both the EP & CP events. In order to counteract this, a bootstrap technique (Efron and Tibshirani, 1991) was adapted from Kim et al. (2009). For both EP and CP events, four ASO composites are chosen at random from the 29 year (1982–2010) time series of ASO SST data to generate a time-series for which a t-test is conducted between it and the four EP or CP events. The result was a lat-long matrix of statistical significance (0 or 1) at the \( \alpha = 0.10 \) level. This process was repeated 10000 times per event type, then the average of the result matrices was taken, resulting in a single lat-long matrix outlining the probability of statistical significance per event type.
2.2.6 Degree Heating Months

Degree Heating Month (DHM) measurements are a method of determining heat stress accumulation in the surface ocean. The method of computing DHM employed in this study was developed by Donner et al. (2005), and is based on the NOAA Coral Reef Watch degree-heating week real-time prediction method for coral bleaching and stress. A DHM value of \( >2^\circ \text{C} \cdot \text{months} \) suggests thermal stress sufficient enough to cause severe mass coral bleaching, and possibly coral mortality (Donner, 2009). The DHM values only accumulate when the SST exceeds the Maximum Monthly Mean (MMM), which is calculated by identifying the warmest monthly SST within the 1985–2000 monthly climatology. The DHM value for any month is then given by Equation 2.1 (Donner et al., 2005).

\[
DHM_{month} = \sum_{m=0}^{-3} (SST_m - MMM) > 0
\] (2.1)

In the Caribbean, DHM values accumulate during summer, so the maximum annual DHM is calculated by selecting the greatest single monthly DHM value in a given year, resulting in a 29 value time-series.

The bootstrap analysis was re-conducted using this DHM maximum time-series data instead of SST data for a comparison with the SST bootstrap results.

2.3 Results

This section summarizes the results of the various analyses conducted using the Reynolds et al. (2007) SST data. As the analysis was conducted in an exploratory fashion, it is organized in a manner that lays out a path of results that were necessary for the next piece of analysis to take place. Thus, a discussion of general trends in the Caribbean and Pacific Oceans precedes EOF results for the Caribbean, then lag derivation between the EOF results and Pacific indices allowing for time-series correlations that necessitate bootstrap analysis and DHM work to come to definitive conclusions.

To consider the background trends, the entire SSTA time-series was considered. In the Pacific Ocean, the East and Central regions have changed temperatures in opposition (Figure 2.3). The EP region, as defined by the NINO3, has cooled by
0.55°C during the study period. However, the Central Pacific, within the NINO4 region, has experienced a cooling of only 0.18°C.

In the Caribbean, the SST regime follows a Northern Hemisphere seasonal cycle with temperatures fluctuating by > 2°C annually. In both of the defined Caribbean sub-regions (Figure 2.2) temperatures have been increasing. In the East, SST has increased by 0.87°C, but in the West, the increase has only been 0.40°C during the study period (Figure 2.4).

In the ‘West’ region, PC1 accounts for 46.1% of the variability in SST. The variability has an even distribution throughout most of the Caribbean Sea, but is slightly less active in the northwest part of the region, which reaches into the Gulf of Mexico (Figure 2.5).

In the ‘East’ region, the primary centre of variability exists slightly to the East of the Lesser Antilles, but also small intense regions of variability along the North coast of South America, close to the mouths of the Magdalena and Orinoco Rivers. In this area, PC1 accounts for 76.3% of the variability (Figure 2.6).

Cross-correlation could not render a statistically significant result, but showed that the difference between the peak of an EP ENSO event and its response in the ‘East’ region of the Caribbean Sea is seven months. The same analysis conducted for the CP signal reveals a peak of 8 months (Figure 2.7). In the ‘West’ region, there does not appear to be a detectable response to either the EP or CP ENSO signals, evident by a lack of a peak in correlation within the 12 month window.

Using a Durbin-Watson test, it was found that the PC1 time-series exhibits high first-order autocorrelation (DW=0.19). To account for this, all correlation tests were tested for significance using an adjusted sample size as outlined by Santer et al. (2000). In the East, the adjusted sample size was 16 ($n_e = 16.54$).

Linearly detrended SST data for EOF analysis produced results similar to the non-detrended results being presented, and are therefore not presented.

The correlations between the NINO3 region and the lagged Eastern Caribbean PC1 was not significant at the $\alpha = 0.1$ level ($r = 0.412$, $p=0.113$) (Figure 2.9), suggesting there may not be a strong link between EP events and the Eastern Caribbean. The correlation between the NINO4 region and the lagged Eastern Caribbean PC1 was significant at the $\alpha = 0.1$ level ($r = 0.457$, $p=0.0751$) (Figure 2.9), suggesting linkage between CP events and this region of the Caribbean.
Figure 2.3: Time series of Eastern (NINO3) and Central (NINO4) Pacific temperatures. Linear temperature trends are indicated. The Eastern region has cooled by 0.55°C, and the Central region has cooled by 0.18°C over the study period.
Figure 2.4: Time series of East and West Caribbean temperatures. Linear temperature trends are indicated. The Eastern region has warmed by 0.87°C, and the Western region has warmed by 0.40°C over the study period.
Figure 2.5: First empirical orthogonal function of the West and East Caribbean regions (1982–2010). Analysis was conducted on the individual regions (East and West), but is being presented simultaneously. The Eastern Caribbean region has more intense levels of variability, and less of a uniform distribution than the West.

For both the NINO3 & NINO4, the Western Caribbean did not have significant correlations.

The bootstrap analysis indicates that in the Caribbean, the probability that SSTA variability is statistically attributable to EP ENSO events are extremely low (Figure 2.10). The highest probability within either of the defined East or West Caribbean regions does not exceed 25%. In the entire analyzed region, the maximum probability is under 60%, and is centred at 28°N, 68°W.

In contrast, CP ENSO events have very high likelihoods of affecting SST in the Caribbean (Figure 2.11). The maximum probability lies eastward of the regions of concern with a probability of >85%. However, the probabilities within the regions remains high, with a majority in excess of 50%.

When the bootstrap model was run with scalar area averages of the two regions, resultant likelihoods were extremely low or nil for both the EP and CP events, ne-
Figure 2.6: Pareto plot of the Eastern region identifying the amount of variability explained by each EOF mode (bars), and the sum of total explained variability for modes 1:x (line).

Figure 2.7: The lead/lag correlation plot of the East Caribbean’s leading principal component against the NINO3 and NINO4 indices. The NINO3 index peaks at 7 months (July), but the NINO4 peaks at 8 months (August).
Figure 2.8: Time series of NINO3 & the lagged first principal components of the Caribbean regions. Both regions of the Caribbean lack significant correlation based upon the adjusted sample size.
Figure 2.9: Time series of NINO4 & the lagged first principal components of the Caribbean regions. The Eastern Caribbean was correlated at $r=0.45$, but once again the Western Caribbean was insignificant.
cessitating the use of high-resolution analysis. If detrended SST data is utilized within the bootstrap model, results are similar.

A time-series of annual maximum DHM values show regions within the Caribbean that have accumulated heat stress. For instance, 1998 accumulated >3.5°C-months than 1983 in certain areas, as shown in the image of the four strong EP years’ heat stress, Figure 2.12. Between the four EP years, there does not seem to be a consistent pattern of intensity or distribution. Similarities only exist between the intensity levels experienced in 1998 and 2007 events; however, this is not the case with the four CP years. In all four of the CP years, large regions of high stress accumulation >3.5°C-months, as well as spatial pattern similarities (Figure 2.13). These results corroborate the results produced by Eakin et al. (2010).

The re-application of the bootstrap model to the maximum DHM data identifies that the DHM results are very likely to be both significant and insignificant with comparable magnitudes and distributions to that of the original SST bootstrap results. The results are not identical down to grid-cell resolution, but exhibit similarities that are visually indistinguishable, and whose residuals appear to be stochastic. As in the case of the original bootstrap analysis, the EP years have extremely low probabilities of being significant within the Caribbean, and the CP probabilities are generally high, and widespread Figure 2.14.

2.4 Discussion

Multiple statistical methods were employed to determine the characteristics of Caribbean SST teleconnections from Pacific ENSO events. EOF analysis identified sub-regions of variability, cross-correlation analysis identified the lag period from event peaks in the Pacific to the regional modes of variability in the Caribbean, correlation with an adjusted sample size for the overall time series identified what was regionally significant while accounting for autocorrelation, and bootstrap analysis identified whether the events are significant on a much finer resolution and targeted time frame.

Regionally, the East Caribbean is not significantly related to EP ENSO events; however, CP ENSO is ($\alpha = 0.1$). This differentiation is based on comparing the entire time-series, and not only important subsets of the data. If the mechanism of
Figure 2.10: Average probability of statistically significant differences during EP ENSO events via bootstrapping using the t-test method ($\alpha = 0.10$). The entire Caribbean is not significantly different from background conditions during ASO following the peak of an EP ENSO event.
Figure 2.11: Average probability of statistically significant differences during CP ENSO events via bootstrapping using the t-test method($\alpha = 0.10$). Much of the Caribbean has a high probability (>50%) of being significantly distinguishable from background ASO conditions during CP ENSO events.
Figure 2.12: EP year DHM results. The spatial distribution and intensity during EP years lack a discernible pattern from background variability. Only 1983 does not exhibit a region of heat stress > 2°C-months, but a coherent pattern of intensity in the stress distribution is lacking.
Figure 2.13: CP year DHM results. During CP events, the Caribbean experiences consistent instances of amplified heat stress. 2005 & 2010 have both the largest values of accumulation and distribution, but all four years identify regions of high stress (> 2°C-months)
Figure 2.14: CP DHM bootstrap results showing a similarity between DHM and SSTA bootstrap probabilities and distribution. Residuals between the two analyses does not reveal a bias, but rather, a direct relationship.
teleconnection is only related to certain periods within the year (i.e. December-January-February (DJF)), the signal may be lost by comparing the entire time-series, hence the necessity of bootstrapping. Bootstrapping refines the spatial scale, as well as targets subsets of data as best representations of the events, and compares it to all other states of the system within the time series of ASO data.

The motivation behind the bootstrap analysis is that it avoids the problems associated with small sample sizes. The probability of a statistically significant t-test result in a grid-cell is represented in the results of both bootstrap tests. The results of this analysis identify that not all ENSO event types are the same. CP events significantly affect the SSTA intensity and distribution in the Caribbean, but EP events do not.

Due to the distribution and intensity of DHM also being linked to only CP ENSO events, it is important to be able to identify the category of El Niño event in order to predict the impacts. As identified, by Kim et al. (2009), hurricane development is impacted during the development phase of ENSO, but Caribbean SST are also affected on an eight month lag.

The years 1997/1998 and 2006/2007 were both EP years that experienced thermal stress in the Caribbean that may have caused bleaching, but as an event type, there is no significantly detectable difference from background conditions. The 2005 bleaching event in the Caribbean was one of the largest mass bleaching events on record Eakin et al. (2010). The extent and intensity of heat stress in 2010 was larger in some areas than that of the 2005 event (Alema and Clement, 2014; Bastidas et al., 2012); however, reports of bleaching were not as widespread, possibly because of a different response by reefs, or a lack of reporting. Both 1994/1995 and 2002/2003 were the other CP years considered and also had high DHM$_{max}$ values, indicating areas likely to have been bleached. Sustained bleaching conditions are not tolerated by corals, thus the most extremely impacted regions are likely to have experienced reef mortality.

Since the 1990s, there has been a shift towards more CP events (Lee and McPhaden, 2010) related to a shift in mean state of the Pacific Ocean (Banholzer and Donner, 2014). Concurrent with this shift has been an increase in the frequency, its associated impacts, which in this case are anomalously warm regions of the Caribbean. Results from Coupled Model Intercomparison Project Phase
CMIP5 suggest a shift towards more CP events under the Intergovernmental Panel on Climate Change Representative Concentration Pathway, 4.5 W/m² scenario (RCP4.5) will continue (Kim and Yu, 2012), thus corals and their associated ecosystems will suffer stress or mortality if they cannot acclimatize or adapt.

Results from the bootstrap analysis indicate variability further east of the Caribbean than the regions of interest, but may be of interest due to its existing within the “Main Development Region” for hurricanes (10°–20°N; 20°–85°W). This may have implications for hurricanes in the year following an event, not just in the development phase of ENSO events as Kim et al. (2009) identified. Investigation appears warranted.

The tropical aspect of the atmospheric bridge concept for ENSO teleconnections was introduced by Klein et al. (1999) in which they identified correlations between ENSO events and weakening of the Hadley cell. Around the Caribbean Sea, anomalous southwesterlies weaken the trade winds, but the primary change in SST appears to be related to changes in evaporation rather than cloud cover. In addition, Latif and Grötzner (2000) found a contribution from the positive phase of the annual cycle to lag time associated with ENSO. Both studies identify an approximate six month lag.

These and related studies address EP ENSO teleconnections until the spring of the year after the ENSO peak. As noted by Alexander et al. (2004) in their study highlighting Indian and Western Pacific Ocean teleconnections, most teleconnection studies relating to ENSO examine the summer preceding the peak, through to the following spring only. This practise neglects to properly address ocean and ocean-coupled teleconnections that are only fully effective beyond periods greater than their adjustment period (Liu and Alexander, 2007). The results indicate that there is warming before the peak correlation found by this study, thus the teleconnection is apparent in other studies, but not necessarily fully expressed in the SSTAS. The warming teleconnection found by other studies may continue to propagate as SST in the Caribbean is autocorrelative in nature, and it is also likely that the mechanism of teleconnection for CP events is a coupled ocean-atmosphere process, rather than purely atmospheric pushing the observed peak impact later in the year, which would account for the difference of 6 months from these studies to the results of this one.
Since the peak SST influence from EP events do not occur at the same time as the seasonal cycle causes background SST maxima, this could explain the lack of a pronounced thermal stress impact. However, a delayed teleconnection to the Caribbean during CP events may explain the heat accumulation, and the associated effects on coral reefs.

With time, this study can be reconducted with additional data for EP and CP years. Additional events may increase the power of the CCA to the point of statistical significance, which is a challenge with the sample size adjusted for autocorrelation. Until many more events occur, it is likely that bootstrap analysis will still be required, but the accuracy of the tests will only be improved by having more data.

Currently, reporting of coral bleaching is voluntary and not sensible in real time, thus DHM analysis is the best proxy for bleaching available, but high quality bleaching data would improve the value of the analysis for marine biologists.
Chapter 3

Paleo-Oceanographic Records of El Niño Influenced Sea-Surface Temperatures

3.1 Introduction

Currently, ENSO reconstructions that differentiate between EP and CP events only extend to the late 1800s, but are weakly supported due to the lack of availability and data quality pre-1950. These reconstructions are based on satellite data, ship logs, and statistical interpolation of the data (Smith et al., 2008). ENSO reconstructions that do not differentiate between event types are currently available for much longer time periods using fossilized coral δ¹⁸O records, tree ring measurements, and lake varves (McGregor et al., 2013).

In order to extend the records that differentiate event types, this chapter attempts to create a hindcast model for both event types by combining multiple in-situ geochemical proxy temperature records from the NOAA paleoclimate data archive for coral cores in the tropical Pacific and Atlantic Oceans. A second model predicts the locations of suitable coral reefs that could be geochemically analyzed with the intention of strengthening the results of the hindcast model. The results of this work intends to answer two questions: whether a combination of geochemical
temperature proxy data from the tropical Pacific and Atlantic Oceans be used to model the occurrence of past EP and CP ENSO events, and if a model can be developed that predicts where to attain additional data that may strengthen the power of the hindcast model.

A lack of input data from appropriate locations and timeframes prevented the hindcast model producing practical results. Because of this, the results of the second model became more important, and will be of use to those conducting paleoclimate work in the future hoping to answer similar questions about ENSO.

3.2 Methods

3.2.1 Data

Reef presence data was obtained from the United Nations Environment Program for coral reef coverage between 1954–2009, which is currently the most comprehensive dataset for tropical reefs. The reef data was analyzed at \( \frac{1}{4} \) resolution to match the satellite data (IMaRS-USF, 2005; IMaRS-USF and IRD, 2005; Spalding et al., 2001; UNEP-WCMC et al., 2010).

Extended Reconstruction Sea Surface Temperature (ERSST) v3b (Smith et al., 2008) provided SST data for the models. The data is spatially resolved at 2°x2°, and temporally at monthly intervals from 1854–2011. This dataset was developed from in situ measurements, and statistical reconstructions in regions of sparse data.

Geochemical Data

Geochemical proxy data were used to create historical SST reconstructions. Sr/Ca ratios are a function of temperature, while \( \delta^{18}O \) is a function of both temperature and salinity. Due to the difference in cost between Sr/Ca analysis versus that of \( \delta^{18}O \), Sr/Ca ratios are less available in high resolution. The NOAA paleoclimatology database was searched for the following criteria: monthly resolution, Sr/Ca or \( \delta^{18}O \), located within the tropical Pacific or Atlantic Oceans. When both values were available, individual raw chemistry data took precedence over composite geochemical values and modelled SST/SSTA values. The data utilized is listed in Table 3.1.
Table 3.1: Geochemical Proxy Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Proxy Type</th>
<th>Contributor(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Islands (Palmyra, Fanning, and Christmas)</td>
<td>x  x</td>
<td>Nurhati et al. (2010)</td>
</tr>
<tr>
<td>Amedee Island, New Caledonia</td>
<td>x  x</td>
<td>Quinn and Sampson (2003) &amp; Stephans et al. (2005)</td>
</tr>
<tr>
<td>New Ireland, Papua New Guinea</td>
<td>x</td>
<td>Alibert and Kinsley (2009)</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>x</td>
<td>Linsley et al. (2000b)</td>
</tr>
<tr>
<td>Palmyra</td>
<td>x</td>
<td>Cobb and Charles (2001)</td>
</tr>
<tr>
<td>Clipperton</td>
<td>x</td>
<td>Linsley et al. (2000a)</td>
</tr>
<tr>
<td>Guam</td>
<td>x</td>
<td>Asami et al. (2005)</td>
</tr>
</tbody>
</table>

3.2.2 NINO Hindcast Model

All input timeseries of geochemical temperature proxies were independently correlated with both the NINO3 and NINO4 time periods that overlap with the ERSST data.

Calibration required the development of event identification criteria from correlating ERSST data with temperature proxy data. Each criterion response was intended to be binary in nature based upon individual cores, leading to a decision tree that would identify an event based upon a set of conditions being met, rather than a direct quantitative correlation.

To determine which datasets were useful in differentiating between event types, and thus useful for hindcasting, comparisons of DJF data distribution from known ENSO event years were compared with each other and neutral conditions from the same dataset using boxplots. By finding locations where an event type would be isolated in its distribution would suggest that it may be suitable for significance testing.

Each dataset of geochemical proxy measurements was correlated with both
the NINO3 and NINO4 regions independently (Pearson’s Correlation Coefficient, \( \alpha = 0.05 \)), then plotted side by side. As with the boxplots, correlations were only analyzed for subsets of the data containing DJF of that region’s event type (NINO3 (NINO4) = EP (CP)). Each dataset’s value was determined by whether the correlation values with the NINO3 were significantly different from that of the NINO4.

### 3.2.3 Drill Prediction Model

In order to determine ideal drilling locations for geochemical data that can discern between CP and EP events, correlations between the NOAA OI-SST DJF SST anomalies time-series of each grid cell between 20° N and 20° S latitude was correlated with the DJF time-series of the scalar NINO3 and NINO4 regions with zero lag (\( \alpha = 0.01 \), \( n = 81 \)). Grid cells were then filtered for reef presence, and whether significant correlations existed between the individual cell and only one of the NINO regions (i.e. correlated with the NINO3, but not the NINO4 region). Those that met the conditions were then presented as final output.

### 3.3 Results

#### 3.3.1 Existing Data

Boxplots of Sr/Ca data reveal that current data cannot clearly discern all three states (Neutral/EP/CP) of ENSO from one another (Figure 3.1). It is seen that in all cases, the interquartile ranges of at least two of the three states of each location display overlap. Inclusion of \( \delta^{18}O \) to try and find sufficiently discriminatory data yields the same results (not pictured). For all sites with available geochemical records, the condition of having a single ENSO type (represented by a NINO region) differing from both the other ENSO type and neutral conditions was not met.

In spite of the lack of differentiation in the data distribution, Pearson’s Correlation Coefficients were derived for each of the Sr/Ca datasets. During EP years, none of the analyzed Sr/Ca data are significantly correlated (\( \alpha = 0.05 \)) with the NINO3 region. However, during CP years, the Palmyra and Amedee (2004) cores are both significantly correlated (\( \alpha = 0.05 \)) with the NINO4 region (Figure 3.2). Interestingly, the Christmas Island core is significantly correlated with the NINO3 region during
Figure 3.1: Boxplots of Sr/Ca ratios reveal that none of the sites have either EP or CP events discernible from both other types.
these times too, but not during EP years. At the $\alpha=0.01$ level, none of the cores are significantly correlated for either region during either event type.

### 3.3.2 Potential Data

Grid cells containing potential data sources are only listed for areas significantly correlated (Pearson’s Correlation Coefficient, $p<0.01$) with the NINO3 but not NINO4 (EP events), and NINO4 but not NINO3 (CP events) and test positive for reef presence. In the analysis, there are a total of 230400 cells, with 176616 being oceanic, and 6518 containing coral reefs. There are 492 cells (7.55% of possible) with potential data available for identifying EP ENSO, and 890 (13.65% of possible) for CP ENSO.

#### Data for Identifying Eastern Pacific Events

Possible data that could lead to the hindcasting of EP ENSO events may exist in:

- Fiji, Northern Marshall Islands, French Polynesia, Lamon Bay in the Philippines, Spratly Islands, the islands surrounding Batam in Indonesia, Paracel islands, and South East Celebes Sea off the coast of East Kalimantan (Figure 3.3).

#### Data for Identifying Central Pacific Events

Possible data that could lead to the hindcasting of CP ENSO events may exist in:

- Tuvalu and southeast to American Samoa, Southern Marshall Islands, Micronesia, Solomon Islands, Louisiade Archipelago of Papua New Guinea, Bismarck Archipelago, the islands at the north of Cendrawasih Bay in Papua New Guinea, the islands at the north of Helmahera Sea in Papua New Guinea, Palau, entire Southern Philippines excluding Palawan, west coast of the north half of Sumatra in Indonesia including the islands nearby, and Nicobar Islands of India (Figure 3.4).

### 3.4 Discussion

The paleoclimate records of EP and CP ENSO currently do not pre-date observational records (1950). Without differentiating between EP and CP events, records of ENSO exist back to 930 CE (with gaps between at several points) (Kim et al.,
Figure 3.2: Correlations between Sr/Ca core raw ratios or temperature reconstructions (blue) and ERSST temperature data (green).
Figure 3.3: Map of tropical Pacific plus Eastern Indian Ocean and Caribbean Sea with green grid cells indicating regions where reefs exist and are correlated with the NINO3, but not the NINO4 region.
Figure 3.4: Map of tropical Pacific plus Eastern Indian Ocean and Caribbean Sea with green grid cells indicating regions where reefs exist and are correlated with the NiNO4, but not the NiNO3 region.
2009), however, this unsuccessfully provides indications of historical impacts on
the Caribbean (Chapter 2). The difficulty in separating correlations between proxy
data and only one of the NINO3 or NINO4 regions is the limiting factor in creating
hindcast output. Even with this complication, there is useful information offered
by this research that could lead to a valuable hindcast.

Ashok et al. (2007) identifies a tripole in the second EOF of the Pacific Ocean,
which they identify as characterizing CP ENSO. The Western Pacific pole is not
as intense as the Central and Eastern poles, but it is still notable around Eastern
Indonesia, and Papua New Guinea with an inverse signature. The Eastern Pacific
has a strong inverse signal, which is strongest at the Eastern boundary of the Ocean
where it meets land. It is apparent that CP ENSO events have relationships with the
entire equatorial Pacific.

From the results, it is interesting to note that in the Pacific Ocean, data appears
to be available outside 5N–15S for EP, but within that region for CP. This may
have a relationship with the Intertropical Convergence Zone (ITCZ) and the Southern
Pacific Convergence Zone (SPCZ), as previous studies have drawn links between
ENSO and these climatological features, but without differentiation between
CP and EP events (Folland et al., 2002; Juillet-Leclerc et al., 2006). Referring back
to the EOF analysis of the Pacific Ocean by Ashok et al. (2007), the intensity of EP
ENSO signature is higher in the equatorial region, but the relationship is latitudi-
nally narrower than that of the CP events. Along with the difference in latitudinal
signal thickness, wind stress anomalies indicate that the Western arm of the SPCZ
experiences northerlies during development until it peaks, and then the eastern arm
experiences southerlies. A differentiation may reveal a closer relationship between
a particular ENSO event type and the SPCZ as found in Chapter 2, or just a change
in the characteristics of the SPCZ based on the differences in wind stress anomalies
and relationships SSTA.

Existing research indicates that monsoon conditions are coupled to at least one
ENSO type (Krishnamurthy and Kirtman, 2003; Kug and Kang, 2006; Qu et al.,
2005). Unfortunately, the research does not have an indication of which type of
ENSO as their definition is based off of undifferentiated events. The South China
Sea and Indian Oceans are both involved in the ENSO–Monsoon system coupling,
therefore their appearance in the list of potential data sites. However, it is unfortunate
that there is not more of an abundance of reefs in the region from which to collect data. Qu et al. (2005) found changes in wind stress due to ENSO weakened the inter-ocean heat flux through the South China Sea and into the Indian Ocean via the Indonesian Throughflow. It is conceivable that a reanalysis differentiating between ENSO types would find that different heat transport pathways would correspond with channels containing the reefs outlined in both Figure 3.3 and Figure 3.4.
Chapter 4

Conclusions

Recent changes in the understanding of ENSO dynamics created the necessity for new investigations into its teleconnections. In this study, implications for the Caribbean were investigated prompted by the appearance of severe coral bleaching events following CP ENSO events. By understanding the links between different types of ENSO and their affect on SST in the Caribbean, as well as when they have happened historically, a better understanding of the effects on coral reefs as well as other topics of regional importance (e.g. hurricane development) can be investigated.

Though the timing of the lagged response in the Caribbean could not be determined with statistical significance, it appears that there is a 7 month delay between an ENSO event, and a response in the Eastern region of the Caribbean. The bootstrap model determined that CP ENSO activity has a strong probability of affecting SST in the Caribbean (> 50% in a majority of the region), and are also related to the DHM responses.

When investigating the possibility of a hindcast model, which would be useful in understanding historical impacts upon the Caribbean, a lack of sufficient high resolution proxy data became apparent. In lieu of available data, a model suggesting locations to obtain data that can be used in the hindcast model discovered that there are many potential sites distributed throughout the tropics. The sites of most importance appear to be related to the SPCZ, ITCZ, and asian monsoons, warranting further investigation into the difference between ENSO types and their relationships.
with those features.

The limited availability of known EP and CP ENSO events necessitated the use of the bootstrapping technique in the model. With time, additional ENSO events will be identified expanding the input data that can be run through the model, but the need for bootstrapping will still exist. Nevertheless, the confidence of the model will be stronger with a larger sample size.

When it comes to obtaining new high resolution core analyses, the results of this work ought to be considered. This may be sufficient from a pure scientific view, but geopolitical concerns are a reality of any research, thus an important consideration about where to drill for data. Luckily, the potential sites for drilling appear to be plentiful, providing sufficient options even if certain sites are not considered feasible.

Globally, there are many teleconnections of ENSO events that can be investigated. While previous schools of thought believed that there were connections between ENSO events and SST in the Caribbean, they did not have an understanding of the different types of ENSO. This thesis provides evidence for a relationship with CP ENSO, and in doing so, shows that there is insufficient evidence to establish a relationship with EP ENSO. Additionally, it highlights the necessity for further data collection in order to understand the history of different event types, and makes suggestions on where to drill in order do so.
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