2015

El Niño Southern Oscillation During The 15th Century: A Reconstruction From The Equatorial Central Pacific

Follow this and additional works at: https://ro.uow.edu.au/thsci

UNIVERSITY OF WOLLONGONG
COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author.

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Faddy-Vrouwe, Robert, El Niño Southern Oscillation During The 15th Century: A Reconstruction From The Equatorial Central Pacific, BEnviSci Hons, School of Earth & Environmental Science, University of Wollongong, 2015.

https://ro.uow.edu.au/thsci/141

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
El Niño Southern Oscillation During The 15th Century: A Reconstruction From The Equatorial Central Pacific

Abstract
The coupled oceanic-atmospheric convective system in the tropical Pacific Ocean, known as the El Niño Southern Oscillation (ENSO), is one of the most significant climatological phenomena on the globe. Due to the relatively short length of time covered by instrumental records over the equatorial Pacific Ocean, the variation of this phenomenon through time has been difficult to evaluate. By characterising past climate variability we gain insight into how ENSO behaved under different climatic regimes, and this provides predictive power to forecasting future climate. The implementation of proxy climate records can provide valuable windows into past climate variability and extends our current understanding of such phenomena. This study presents a 46-year long fossil coral Sr/Ca reconstruction of past sea surface temperature (SST) from Kiritimati Island (2ºN 157ºW) in the central equatorial Pacific Ocean during the 15th century. The fossil coral record shows slightly cooler SST’s during this time period and an 18% reduction in ENSO variability compared to modern climate. This is consistent with other paleoclimate records from around the Pacific Ocean that also show a reduction in ENSO variability during this time period. The results of this study, along with other studies from around the Pacific, indicate that the increase in ENSO variability in recent times may be an indication of increasing El Niño strength under a warming climate.

Degree Type
Thesis

Degree Name
BEnviSci Hons

Department
School of Earth & Environmental Science

Advisor(s)
Helen McGregor

Keywords
El Niño, Sr/Ca stable isotope, central pacific, coral, paleoclimate

This thesis is available at Research Online: https://ro.uow.edu.au/thsci/141
El Niño Southern Oscillation During The 15th Century: A Reconstruction From The Equatorial Central Pacific

By

Robert Faddy-Vrouwe

November 2015

Faculty of Science, Medicine and Health, University of Wollongong
Bachelor of Environmental Science, Environmental Chemistry

A thesis submitted in part fulfilment of the requirements of the Bachelor of Environmental Science or Bachelor of Environmental Science Advanced in the School of Earth and Environmental Sciences.
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Robert Faddy-Vrouwe

16th November 2015
ACKNOWLEDGMENTS

First and foremost I would like to thanks my supervisor Helen McGregor whose support, wisdom and guidance throughout this project has been invaluable, and without whom this project would not have been possible. Also I would like to extend my thanks to Henri Wong for the geochemical analysis that was performed at ANSTO, and also for all his help and support throughout the entire project. Thank you to Colin Woodroffe for your support throughout the year. A big thank you to Laurent Devriendt for all his encouragement and guidance throughout the year, he has made this experience much more enjoyable with his unexpected visits to break the solitude in the lab! Thanks to José Abrantes for his assistance with preparation of thin sections. Thanks to Jian-Xin and the team at the Radiogenic Isotope Laboritory at the UOQ for U/Th analysis. Also I would like to extend a thanks to all my friends who have provided endless support throughout the year.

Finally I would like to thank all my family, with a special thanks to my sister Christina Faddy-Vrouwe and brother in law Chris Hastings for their love and support throughout the course of my studies, and for keeping me (mostly) sane throughout the year! (oh and also for picking up the slack with the house work on the rare occasions when I was too busy with uni work 😊).
ABSTRACT

The coupled oceanic-atmospheric convective system in the tropical Pacific Ocean, known as the El Niño Southern Oscillation (ENSO), is one of the most significant climatological phenomena on the globe. Due to the relatively short length of time covered by instrumental records over the equatorial Pacific Ocean, the variation of this phenomenon through time has been difficult to evaluate. By characterising past climate variability we gain insight into how ENSO behaved under different climatic regimes, and this provides predictive power to forecasting future climate. The implementation of proxy climate records can provide valuable windows into past climate variability and extends our current understanding of such phenomena. This study presents a 46-year long fossil coral Sr/Ca reconstruction of past sea surface temperature (SST) from Kiritimati Island (2ºN 157ºW) in the central equatorial Pacific Ocean during the 15th century. The fossil coral record shows slightly cooler SST’s during this time period and an 18% reduction in ENSO variability compared to modern climate. This is consistent with other paleoclimate records from around the Pacific Ocean that also show a reduction in ENSO variability during this time period. The results of this study, along with other studies from around the Pacific, indicate that the increase in ENSO variability in recent times may be an indication of increasing El Niño strength under a warming climate.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................ iv

ABSTRACT ............................................................................................................................ v

TABLE OF CONTENTS .......................................................................................................... vi

LIST OF FIGURES ................................................................................................................ viii

LIST OF TABLES .................................................................................................................. x

1. INTRODUCTION ............................................................................................................. 1

2. LITRAURE REVIEW ........................................................................................................ 3

2.1 The El Niño Southern Oscillation ................................................................................. 3

2.2 Global climate of the past 1000 years .......................................................................... 4

2.3 ENSO in the central Pacific during the 15th Century .................................................... 6

2.3.1 Proxy records ............................................................................................................. 7

2.3.2 Models ....................................................................................................................... 9

2.4 Corals as Climate Proxies ............................................................................................ 11

2.4.1 Sr/Ca SST tracer ...................................................................................................... 12

2.4.2 Factors that affect coral Sr/Ca geochemistry ............................................................ 13

2.5 Regional setting (Kiritimati Island) ............................................................................. 14

2.5.1 Location .................................................................................................................. 14

2.5.2 Morphology and climate ......................................................................................... 15

2.5.3 Kiritimati climate compared to NINO3.4 region ..................................................... 16

3. METHODS ..................................................................................................................... 18

3.1 Collection and sample preparation ............................................................................. 18

3.2 X-Radiography ............................................................................................................ 19

3.3 Physical and Geochemical quality of the fossil coral .................................................. 20

3.4 Dating ......................................................................................................................... 22

3.5 Sr/Ca Analysis .............................................................................................................. 23

3.6 Age model and calibration to SST .............................................................................. 25
3.7 Sr/Ca – SST calibration .................................................................26

4. RESULTS ......................................................................................28

5. DISCUSSION ..............................................................................30

5.1 Comparison of fossil coral Sr/Ca SST to modern records ......................30

5.1.1 Modern baseline for comparison ..................................................30

5.1.2 Wavelet Analysis .......................................................................31

5.1.3 Spectral Analysis .......................................................................32

5.1.4 ENSO Signal Variability ...............................................................33

5.2 Kiritimati fossil record compared to other 15th century record ..............38

5.3 Discrepancies between δ18O and Sr/Ca reconstructions .........................40

5.4 Uncertainties and limitations of Sr/Ca as a SST tracer ..........................43

Conclusions ......................................................................................44

Recommendations for future work .........................................................45

References: ......................................................................................46

Appendix 1 ......................................................................................53
LIST OF FIGURES

Figure 1: Diagrammatic comparison between La Niña events and El Niño events depicting the relative positioning of the walker circulation and SST anomalies across the equatorial Pacific Ocean..............................................4

Figure 2: Geographic representation of the spread, location and relative availability of proxy records through time from two independent studies modelling climate over the past 1000 years.................................................................6

Figure 3: Comparison of the different climate records covering the equatorial central Pacific for the 15th century.................9

Figure 4: Location of Kiritimati Island inside the NINO3.4 region in the Pacific Ocean.................................15

Figure 5: Average monthly temperature and rainfall profile typical for the region of the republic of Kiribati and Kiritimati showing very little annual SST variability.................................................................16

Figure 6: Correlation between ERSST from the NINO3.4 region and Kiritimati Island between 1950 and 2015........17

Figure 7: Site map of Kiritimati Island located in the central Pacific Ocean.........................................................18

Figure 8: X-ray positives of coral CH32 .................................................................................................................21

Figure 9: ARAND interpolation results for fossil coral CH32 Sr/Ca ratios before and after Interp processing.................26

Figure 10: CH32 Sr/Ca ratio geochemistry as a function of distance along the length of the coral........................28

Figure 11: SST variability based on Sr/Ca-SST reconstruction for fossil coral CH32 and detrended 2-7 year bandpass filter representing the ENSO cycle .........................................................................................29

Figure 12: Comparison between modern coral XM22 SST reconstructed from Sr/Ca–ratios, instrumental SST and 2-8 year bandpass filtered ENSO signals for both modern coral and instrumental record from Kiritimati Island................31

Figure 13: Part 1: The wavelet power spectrum for CH32. Part 2: The wavelet power spectrum for modern ERSST instrumental record from Kiritimati Island from 1880 to 2015.................................................................34

Figure 14: Comparison between ENSO cycles from the most recent 46 years of the instrumental record and 15th century fossil coral record from Kiritimati Island in the central Pacific..............................................37

Figure 15: Comparison of fossil coral and instrumental record ENSO variability through time from Kiritimati Island........38

Figure 16: Geographic location of the Kiritimati Island fossil coral proxy record (red star) in relation to other existing proxy records across the tropics and around the Pacific Ocean.........................................................39

Figure 17: Comparison between fossil coral climate reconstructions from a) Kiritimati, b) Palmyra, c) PAG, and d) the modelled NINO 3.4 region.................................................................40
Figure 18: Comparison between Sr/Ca ratio SST reconstruction, $\delta^{18}O$ isotope reconstruction and the instrumental record for the modern climate record from Kiritimati, covering the large 1997/8 El Nino event.
LIST OF TABLES

Table 1: ICP-AES calibration concentration ranges for each of the elements analysed for within samples. .................................................................24

Table 2: Instrumental parameters used for the ICP-AES analysis of Sr/Ca ratio sample elemental analysis. .................................................................25
1. INTRODUCTION

ENSO has been recognised as one of the largest climatic system on the globe (Philander 1990). It involves the oceanic-atmospheric coupling over the central Pacific Ocean that results in variations of SST gradients, atmospheric convections, and precipitation patterns (Wang et al. 2012). ENSO effects the climate in many regions around the world through teleconnection pathways, and as such has global importance to many countries (Bjerknes 1969, Cai et al. 2011). Characterisation of the full extent of ENSO variability has been limited due the relatively short length of instrumental records, and as a result the prediction of how ENSO will change in the future has many limitations and uncertainties associated with it (Brown et al. 2007). Some of the main limitations associated with predicting future ENSO state is our limited understanding of the driving forces behind ENSO variability (Brown et al. 2007, Lewis and LeGrande 2015). As such the response of ENSO to external forcing, such as under a warming climate, are still not well described or predictable. This has led great interest in characterising the climate of the past, particularly in relation to ENSO variability through time in the hope of better understanding ENSO’s natural variability and its response to external forcing (Nurhati et al. 2011, Cobb et al. 2013).

One time period that is of particular interest is the most recent 1000 years as the climate forcings have been well described during this time (Sigl et al. 2015). Although there are a number of different means by which past climate can be reconstructed, including: tree rings, ice cores, speleothems and the like, the most useful climate proxy for ENSO reconstruction is corals (Dunbar et al. 1999). Corals are ideal for ENSO reconstruction for the fact that they are common, widely distributed, can be accurately dated and they allow for high resolution (annually resolved) multi-elemental climate reconstruction (Dunbar et al. 1999). As a result a number of studies have been produced looking at ENSO variability from coral records originating from a number diverse regions (Cobb et al. 2013, Hereid et al. 2013). One region that has surprisingly few reconstruction is the equatorial central Pacific (ECP), where ENSO is seen to have the greatest influence on local climate. ENSO reconstruction within the ECP provides the greatest scope for improvement of climate records not only due to the current sparsity of records over the region but also due to its reconstructive potential (McGregor et al. 2013a). By characterising ENSO variability from within the ECP, much of the uncertainty
associated with other climate proxy reconstructions from teleconnected regions can be avoided (Lewis and LeGrande 2015).

As such the aims of this thesis are to: 1) characterise the climate during the 15\textsuperscript{th} century with specific reference to ENSO strength and variability; 2) relate climate from the 15\textsuperscript{th} century to modern climate and; 3) provide a proxy record to fill gaps in the currently sparse central Pacific climate record and help to bring together a more complete understanding of past climate within the central Pacific. This thesis presents new estimates of sea surface temperature for the 15th Century, during the transition interval from the Medieval Climate anomaly to the Little Ice Age. Previously published coral studies for this interval are based on the coral δ\textsuperscript{18}O proxy, a mixture of SST and δ\textsuperscript{18}O seawater variability, which makes it harder to detect which ENSO processes may be changing. The SST estimates in this thesis are based on a 45 year coral Sr/Ca record from Kiritimati Island, where a reliable relationship between coral Sr/Ca and SST has been established for the instrumental period (McGregor \textit{et al.} 2013a).
2. LITERATURE REVIEW

2.1 *The El Niño Southern Oscillation*

ENSO has been recognised as one of the world’s most significant climatological systems with teleconnections influencing climate globally (Philander 1990). ENSO refers to the asymmetric oscillations between La Niña cold state and El Niño warm state of the tropical Pacific Ocean, and occurs at interannual timescales, approximately every 2 to 7 years (Philander 1990). There are a number of distinctive features of the tropical Pacific Ocean that play an important role in the development and understanding of ENSO. First is the Walker Circulation, which is the dominant trans-equatorial atmospheric cycle, driven by differential atmospheric pressures on either side of the Pacific (Bjerknes 1969). The Walker Circulation consists of a generally lower sea level pressure (SLP) over the western tropical Pacific creating a body of rising air and a higher SLP over the eastern tropical Pacific creating sinking air (Bjerknes 1969, Philander 1990). These differences in SLP are linked by east to west flowing trade winds close to the ocean surface and west to east flowing winds in the upper troposphere thus completing the cycle (Bjerknes 1969). The second key feature of the Pacific which is important in the development of ENSO is the cool water upwelling from the deep ocean off the coast of Peru, South America. The Peruvian upwelling is extended into the central equatorial Pacific by the east-to-west trade winds formed by the Walker Circulation to create a “cold tongue” of anomalously cool water. The presence of the Pacific cold tongue in the eastern-central Pacific along with the warmer tropical waters in the western Pacific together create a SST gradient between the eastern and western Pacific which acts as a feedback to strengthen the east-to-west trade winds (Philander 1990). This coupling of the atmospheric and oceanic forces work together to create positive and negative feedbacks which induce El Niño – La Niña events that are at present phase locked to the seasonal cycle (Rasmusson and Carpenter 1982, Philander 1990, Wang *et al.* 2012).

The onset of El Niño events are characterised by a weakening in the east-to-west trade winds and reduction in the penetration of the cold tongue into the eastern Pacific Ocean resulting in positive SST anomalies throughout the central Pacific. Warmer SST’s create more intense atmospheric convection over the central Pacific leading to higher precipitation in the region.
along with anomalous weather patterns in teleconnected parts of the globe (Figure 1) (Philander 1990). La Niña events, on the other hand, are characterised by higher eastern SLP and lower western SLP resulting in the intensification of trade winds along with the extension of the Pacific cold tongue. This leads to negative SST anomalies in the central and eastern Pacific resulting in lower regional precipitation over the central Pacific (Figure 1) (Philander 1990). La Niña events have a similar SLP and SST configuration to what is considered normal conditions in the equatorial pacific.

Figure 1: Diagrammatic comparison between La Niña events (left) and El Niño events (Right) depicting the relative positioning of the walker circulation and SST anomalies across the equatorial Pacific Ocean (Australian Bureau of Meteorology 2008). Darker blue oceanic colours represent the general location of relatively cooler water bodies (negative SST anomalies) and red oceanic colours represent the general location of warmer water bodies (positive SST anomalies) during El Niño-La Niña events. Arrows depict the direction and strength of atmospheric trade winds as well as the prominent locations of convective precipitation. La Niña events are characterised by cool SST in the ECP whereas El Niño events show warm SST in the ECP.

2.2 Global climate of the past 1000 years

One way of trying to gain a better understanding of the factors that influence ENSO variability and increase the predictive power of modelling ENSO is by characterising the state of past climate and determining how ENSO has changed over time (Brown et al. 2007). Climate of the past 1000 years is of particular interest for ENSO reconstruction because the climate forcings over this time interval have been well characterised (Schmidt et al. 2012). Two instances of change in climate over the past 1000 years have been reported: the Medieval Climate Anomaly (MCA) from around 900-1300 in the Common Era (CE), and the ensuing Little Ice Age (LIA) from around 1500-1800 CE (Lamb 1965, Xoplaki et al. 2011). The end of the LIA was followed by the phase of industrially induced anthropogenic global warming, which faces society today (PAGES 2k Consortium 2013).

The presence of the MCA and LIA was first noted back in 1965 by one Hubert Lamb who recognised an anomalously warm period around 1000CE followed by a decline in temperatures (Lamb 1965). Since Lamb’s early pioneering work there has been considerable effort in trying
to characterise these time periods with a number of studies alluding to a well-defined globally synchronous MCA and transition into the LIA (Mann *et al.* 2009, Xoplaki *et al.* 2011, Ljungqvist *et al.* 2012). Previously there has been a debate as to whether or not such well-defined climatic time periods were actually represented globally, and contrary to earlier beliefs it is now suggested that there is little evidence supporting a globally synchronised MCA and following LIA (PAGES 2k Consortium 2013). Instead the timing of the warmer MCA and cooler LIA have been found to vary regionally superimposed over a global cooling trend, with most regions around the globe entered into a cold period by 1580CE (PAGES 2k Consortium 2013, McGregor *et al.* 2015). The onset and subsequent continuance of this global cooling trend, corresponding to the LIA, is thought to have been caused by a downturn in solar activity along with a clustered series of large volcanic eruptions (Mann 2002, McGregor *et al.* 2015). The collective effect of these two forcing’s caused a decrease in the global energy budget, which in turn resulted in the global cooling trend which is seen in the records from this time (PAGES 2k Consortium 2013, Sigl *et al.* 2015). How these forcing’s affected climate in the Pacific during this time period, however, is not well understood due to the limited proxy data from the region (Lewis and LeGrande 2015).

When considering the locations from which the majority of the climate reconstructions, spanning the past 1000 years come from, there is a notable bias towards climate reconstruction in the northern hemisphere (particularly in the higher latitudes) (Mann *et al.* 2009, Xoplaki *et al.* 2011, Ljungqvist *et al.* 2012, Emile-Geay *et al.* 2013b, PAGES 2k Consortium 2013). The majority of these climate records are also from continental settings with a distinct paucity of information from locations in the Pacific Ocean, particularly with relation to the central tropics (Figure 2) (Emile-Geay *et al.* 2013b, PAGES 2k Consortium 2013, McGregor *et al.* 2015, Tierney *et al.* 2015). As such a thorough deconstruction of the relationships between climate forces and ECP climate over the past 1000 years has not been possible, thereby leaving the effects of climate forcing’s on the ECP climate poorly understood. This spatiotemporal paucity of climate information across the tropical Pacific Ocean, coupled with the deficiencies in knowledge of the mechanisms behind ECP climate, has made ENSO characterisation spanning the past 1000 years particularly problematic (Lewis and LeGrande 2015).
2.3 **ENSO in the central Pacific during the 15th Century**

There is surprisingly little information for the LIA from the ECP, where ENSO can best be characterised (Emile-Geay *et al.* 2013a, Emile-Geay *et al.* 2013b). This is particularly true in relation to the early part of the LIA interval (15th century) due to the decreasing number of proxy records back in time from the Pacific (Figure 2). As such little is known about conditions in the ECP during the 15th century particularly in terms of specific characteristics of ENSO. Information from, or pertaining to, the ECP during the 15th century is broadly available in two forms: modelled ENSO reconstructions, and direct proxy reconstruction. Whilst each have their own associated inherent uncertainties and limitations both forms provide valuable insight into the climate of the time.
2.3.1 Proxy records

There are only a small number of proxy records from around the Pacific that cover the 15th century. Figure 2.a) broadly shows a rough representation of the number, location and types of proxy records used to infer the climate (ENSO) from the ECP (NINO3.4 region) (Emile-Geay et al. 2013b). This shows that there are less than a total of ten proxy records covering the length of the 15th century from around the Pacific (Emile-Geay et al. 2013b). Of these proxy records the least amount of coverage is seen in the NINO3.4 region of the central Pacific, with a SST record from Palmyra, and a rainfall record from the Line Islands (Cobb et al. 2003, Sachs et al. 2009) (Figure 2). Other records covering the 15th century are all located in less ideal locations, away from ECP or the ENSO ‘centre of action’. Some of these are directly affected by ENSO (i.e. SST or rainfall patterns) (Hendy et al. 2002, Conroy et al. 2010, Yan et al. 2011, Hereid et al. 2013), while others are connected through teleconnection pathways (Li et al. 2011, Fowler et al. 2012). This broad range of spatially diverse proxy records, unsurprisingly, give a somewhat mixed view of climate and ENSO in the ECP during the 15th century.

The majority of records suggest that SST’s in the ECP during the 15th century were either similar to modern SST or slightly cooler. The records also show a mixed indication as to how SST changed over the century with the entire range of possible options represented from: no change (Cobb et al. 2003, Hereid et al. 2013), to an increasing SST (Li et al. 2011, Yan et al. 2011), to a decreasing SST (Hendy et al. 2002, Oppo et al. 2009). This lack of coherency between records, however, may be influenced by more localised factors effecting the records. The ENSO signal from the Palmyra record suggests an overall reduction in strength (amplitude) of ENSO but greater variability within the record, in terms of changes in strength with both the amplitude and frequency of events changing in the matter of a decade (Figure 3) (Cobb et al. 2003, Cobb et al. 2013). This is supported by other records which also show a weaker but more variable ENSO signal (Li et al. 2011). This weaker, more variably unstable ENSO signal during the 15th century is different to the modern ENSO signal which shows a much more stable ENSO strength through time (Cobb et al. 2003, Cobb et al. 2013). Many of records indicate a tendency for more La Niña like conditions consistent with overall reduction in El Niño strength (Sachs et al. 2009, Conroy et al. 2010, Li et al. 2011, Yan et al. 2011), however, Hereid et al. (2013) found that whilst there was a reduction in ENOS activity, there were significant El Niño events during the time of similar magnitude as modern events. This was attributed to more El Niño like conditions during the 15th century which is also supported by other studies (Cobb et al. 2003, Oppo et al. 2009). It was also found that the ENSO signal during the 15th century appears
to possess a spectrally different periodicity to modern which is suggested could indicate a reorganisation in ENSO during this time, however, it is noted that this could also indicate a change in teleconnection pathways during that time (Li et al. 2011, Fowler et al. 2012). The combination of the Palmyra record with other teleconnected proxy records, sensitive to ENSO, suggest a weaker than modern trans-equatorial Pacific SST gradient during the LIA (Cobb et al. 2003). This is contrary to the finding in Conroy et al. (2010) which indicate a slightly strengthened trans-equatorial SST from east to west during the 15th century.

A number of the records suggest rainfall characteristics indicative of La Niña like conditions in the ECP during the 15th century, however; due to the reported southward migration of the Inter Tropical Convergence Zone (ITCZ), and associated shift in the tropical monsoonal rains, this could in fact be a reflection of changed hydrological conditions rather than an indication of La Niña (Hendy et al. 2002, Sachs et al. 2009, Yan et al. 2011). This is supported by evidence pointing towards a reduction in monsoonal precipitation around the globe, due to shifting of the ITCZ and enhanced longitudinal transport of moisture to the extra tropics (Hendy et al. 2002, Fallah and Cubasch 2015, Yan et al. 2015). This shift in the ITCZ and related monsoonal rainfall could be confounded with a tendency for La Niña like conditions in records that rely on rainfall reconstructions such as tree rings or sediment cores.

Another caveat to considered is that the majority of the records come from either a continental setting or from coastal regions away from the ECP where topographic and land-ocean interactions play a significant role in local climatology. Therefore interpretation of records from continental settings and near coastal regions must consider more localised climatological influences as well as possible non-stationarity of teleconnection pathways through time when reconstructing conditions in the ECP (Lewis and LeGrande 2015, Russon et al. 2015). This is evident by the fact that the main deficiency of teleconnected regions is their differential ability to capture ECP SST and ENSO amplitude, which is the main indication of ENSO strength (Yan et al. 2011, Russon et al. 2015). This highlights the need for more proximal records throughout the ECP to de-convolute teleconnection issues and contradictions between different records particularly in relation to those from continental settings.
Figure 3: Comparison of the different climate records covering the equatorial central Pacific for the 15th century. a) The Palmyra δ¹⁸O climate reconstruction from Cobb et al. (2003) showing the coral δ¹⁸O signal (black), with 10 year running mean (Yellow) and the northern hemisphere temperature reconstruction (green). b) The Papua New Guinea δ¹⁸O climate reconstruction from Hereid et al. (2013) covering the period of 1400 – 1650 CE. The upper plot in b) represents the monthly resolved data and the lower plot is the filtered ENSO record. c) The NINO3.4 region SST reconstruction presented in Emile-Geay et al. (2013b).

2.3.2 Models

Modelling of the ECP region during the 15th century is generally consistent in showing slightly cooler than modern SST as well as a general warming trend over the century (Mann et al. 2009, Emile-Geay et al. 2013b, McGregor et al. 2015). The majority of models found a reduction in ENSO strength compared to modern and they also depicted a shift in ENSO strength, from weaker to stronger, in the late 15th century (Mann et al. 2009, McGregor et al. 2013b, Fang et al. 2014). Different studies produced conflicting results on the general tendency of ENSO towards El Niño or La Niña during the 15th century. One study by Mann et al. (2009) indicated a tendency for La Niña like conditions, however, this was not replicated in the results of two separate global model simulations presented in Mann et al. (2009) used as a comparison. These latter global model simulations are supported by a separate study that also suggests El Niño like conditions during this time (Fang et al. 2014). The discrepancy between these models was attributed to the implementation of differing theories about the driving mechanisms thought to be behind ENSO variability (Mann et al. 2009). This highlights some of the deficiencies in our
knowledge and understanding of the mechanisms and physical forces driving ENSO variability (Gonzalez-Rouco et al. 2011, Lewis and LeGrande 2015). Yet another study, based on modelled reconstructions from hydrological records, showed an increase between the east and west zonal precipitation across the equatorial Pacific, enhancing the Walker Circulation, which indicated La Niña like conditions (Yan et al. 2015). Yan et al. (2015) notes, however, a distinction between SST record derivation producing El Niño-like conditions, whereas those based on hydrological reconstructions tend to indicate La Niña-like conditions during the 15th century. A more robust method for studying ENSO variance was found through the application of changes in variance within proxy records to General circulation Models, rather than to simply force the models using the records raw variability. This method was found to circumvent the issue of systematic offsets between various records, thus improving the accuracy of the model (McGregor et al. 2013b). These inconsistencies between modelled ECP climate during the 15th century indicate the uncertainties and errors associated with current models.

A major limitation to current forced climate models is the spatiotemporally sparse and sometimes low resolution (down to decadally resolved) proxy records from around the Pacific, specifically in the ECP, which are used to calibrate model simulations (Emile-Geay et al. 2013b). This therefore represents a significant source of uncertainty within the models which is subsequently translated into the conflicting results presented above (McGregor et al. 2013b). Due to the calibration of models on reconstructing ENSO based on records located in regions outside of the ECP, they are all inherently prone to influences from changes in teleconnection pathways affecting the proxies used to force the climate models (Lewis and LeGrande 2015). These identified non-stationary characteristics of some teleconnections can be seen as a major source of error, due to stationarity of teleconnection pathways being one of the main assumptions underpinning a lot of the models (Phipps et al. 2013). As such it has been noted that modelling around the 15th century in the central tropical Pacific can appear to be only moderately reasonable with about 50% reconstructive power of Nino 3.4 variance (Gonzalez-Rouco et al. 2011, Emile-Geay et al. 2013a). This has resulted in the suggestion that: reconstructions estimating ENSO variance from a single well correlated area should be viewed with caution (McGregor et al. 2013b). This is, however, mediated by the finding that the implementation of a diversity of records from multiple well correlated locations significantly improves ENSO reconstruction in models (McGregor et al. 2013b). However modelling of ENSO variability would benefit greatly from a more continuous and complete proxy record
from the ECP that does not rely on teleconnection pathways for ENSO reconstruction. Thus there is a need for longer well-placed proxy reconstructions within the ECP dating further back in time so as to reduce uncertainties in modelled climate reconstructions of (Mann et al. 2009, Emile-Geay et al. 2013b).

2.4 Corals as Climate Proxies

As corals grow they incorporate a variety of different trace elements into their aragonite skeleton which reflect the composition of their surrounding environment (Corrège 2006). This incorporation of trace elements into their aragonite skeletons varies through time depending on the climatic factors which influence them. Such environmental-elemental relationships include; SST (Sr/Ca), sea surface salinity (SSS) ($\delta^{18}$O in conjunction with Sr/Ca), upwelling (Ba/Ca), Ocean Circulation ($^{14}$C), and pH (Boron isotopes) (McConnaughey 1989, Cobb et al. 2008). In conjunction with their multi-elemental proxy characteristics there are many other benefits of using corals to reconstruct paleoclimate including: their long lifetime (hundreds of years of continual growth), their abundance and widespread distribution around the tropics, and their fast growth rates of up to 3cm/yr thereby allowing for high resolution (weekly to monthly) continuous records (Lough 2010). Corals also have the ability to be dated accurately using $^{14}$C radioisotopes (up to 40,000 years old) and U/Th (for up to 400,000 years old) (Corrège 2006, Lough 2010). Once a fossil coral is accurately dated an internal chronology can be constructed for the record based on annual banding within the coral structure (Barnes and Lough 1993). Ultra violet (UV) light can be used to see luminescent banding within corals which are thought to reflect river discharge events and can loosely be related to seasonal cycles in region with seasonally different rainfall patterns (Dunbar et al. 1999, Barnes and Taylor 2001). This information is useful in conjunction with X-radiographs (X-rays) which distinguish differences in density within the objects being imaged (Chalker et al. 1985, Barnes and Lough 1993). In relation to corals differences in density within the coralline structure come about due to variability in seasonal growth rates as well as the inherent structure of the individual polyps (hollow polyp cavities with dense aragonite skeletons). By examining X-rays of coral slices one can often clearly see intricate growth features, such as the linear growth axis of the polyps.
and seasonal banding not clearly visible to the naked eye (or under UV-Light) (Chalker et al. 1985, Barnes and Lough 1993).

2.4.1 Sr/Ca SST tracer

By examining the geochemical changes throughout the coralline matrix of fossil corals past climatic information can be reconstructed and compared to other climate records (Dunbar et al. 1999, Lough 2004, McGregor et al. 2013a). As the use of corals to reconstruct paleoclimate has become well established through time it has allowed for the extension of climatic records and a better understanding of past climate features, particularly in relation to ENSO variability (Gagan et al. 2000, Lough 2010). The main climatic feature used to infer information about the characteristics of past ENSO has been through SST reconstruction (Grottoli and Eakin 2007, McGregor et al. 2013a). Earlier studies focused mainly on the use of stable oxygen isotope ($\delta^{18}O$) ratio to reconstruct SST however it has been noted that there is a significant hydrological influence on the $\delta^{18}O$ signal due to fluctuations in evaporation and precipitation over time (Gagan et al. 2000, McGregor et al. 2011). Sr/Ca ratios have been found to be a much ‘cleaner’ geochemical tracer of SST due the concentrations of Sr and Ca being more stable in sea water, and fluctuation in sea surface salinity (SSS) having no effect on $\text{Sr}^{2+}$ fractionation (Corrège 2006, Grottoli and Eakin 2007, Moreau et al. 2015). Sr/Ca ratios have been shown to closely match instrumental SST in modern corals replicating annual cycles well in high resolution sampling (McGregor et al. 2013a). Sr/Ca – ratios are calibrated to SST by regressing modern coral Sr/Ca – ratios to local instrumental SST records over the same time period. Unfortunately there is no one universal Sr/Ca – SST calibration equation which can be applied across all coral Sr/Ca reconstructions, therefore, Sr/Ca-SST calibration equations must be established on a case by case basis for each coral location (Corrège 2006). The physical location from which a coral is removed, in terms of both its geographic location on the globe and its local proximity to the open ocean, can greatly affect its usefulness to accurately replicate the wider climate of the region (Cobb et al. 2008). This is an important aspect which must be considered as enclosed shallow bays respond to daily temperature fluctuations more readily than open ones, thereby producing much more erratic water temperature fluctuations than the surrounding ocean. This leads to a corals climate signal representing the more localised heating and cooling effects
rather than the broader scale climate (Cobb et al. 2008). It is important, therefore, that corals are sourced from well flushed bays with good connectivity to the open ocean as thorough water exchange means that water temperatures in the bay are representative of SST’s of the region.

2.4.2 Factors that affect coral Sr/Ca geochemistry

Although Sr/Ca ratios are a good source of paleoclimate information, and are perceived to be a more accurate reflection of SST, there are a number of caveats which must be taken into account when using corals to reconstruct past climate. It has been noted that factors other than SST, such as light levels and growth rate, may have an effect on Sr\(^{2+}\) uptake into coralline aragonite and thus confound the temperature effect on Sr/Ca ratios to a certain degree (Lough 2004, Reynaud et al. 2004, Grove et al. 2013). To minimise this confusion it is recommended that sampling occur along the maximum growth axis of the corals fan where growth rates are seen to be the fastest and most constant and other factors such as light levels are considered stable (Cobb et al. 2008). However, further study of these effects on coral SST reconstruction is needed to better understand these process and possibly correct for such influences (Grove et al. 2013).

Other factors that can effect coral Sr/Ca geochemistry include post-depositional processed, both physical and chemical (McGregor and Gagan 2003). As paleoclimate reconstruction is generally done on corals which have been dead for many centuries, or longer, there are a number of post depositional processes that can affect the quality of the coralline material over this time frame. These process include, but are not limited to; bioturbation and physical destruction of the coral, as well as chemical diagenesis (dissolution and/or precipitation of calcium carbonates) (McGregor and Gagan 2003). Once coral growth has been established the corals are exposed to the dangers of bioturbation in terms of boring animals which can burrow deep into the structure of the corals and precipitate their own habitable structures independent of coral growth. The greatest potential source of error associated with the use of fossil corals for paleoclimate reconstruction, however, is diagenetic degradation of the coralline material (McGregor and Gagan 2003, McGregor and Abram 2008). Degradation of coral material in this way has been seen to produce highly erroneous analytical results with secondary
precipitation of calcite producing artificially warm reconstructed SST and aragonite leading to artificially cool reconstructed SST (McGregor and Abram 2008). Establishing the quality of coral material and screening for such things is therefore prudent to ensure good quality, reliable climate reconstructions.

2.5 Regional setting (Kiritimati Island)

2.5.1 Location

The climatological region of interest relating to this study is that of the equatorial central Pacific, with the climatic record presented herein coming from a coral that was located on the island of Kiritimati. Kiritimati is located 2ºN, 157ºW within the equatorial central Pacific which places it within the NINO 3.4 region; one of the four regions the equatorial Pacific has been divided up into for the purpose of the study and characterisation of ENSO (Figure 4) (Bunge and Clarke 2009). NINO indices from this region are used as a means of characterising ENSO events, and a strong correlation has been found between the NINO 3.4 region and average annual SST anomalies around the island of Kiritimati (as described in section 2.4.3 below) (Evans et al. 1999, Bunge and Clarke 2009). As described in section 2.1 of this thesis, there is a strong relationship between central Pacific SST anomalies and larger scale climatic features both directly in the development of ENSO and indirectly via teleconnection pathways (Philander 1990). By characterising SST’s surrounding Kiritimati in the NINO3.4 it is possible to not only obtain valuable climatic information for the central Pacific by also to infer climatic information from teleconnected regions such as Australia, America, Africa, India and southeast Asia (Evans et al. 1998).
2.5.2 Morphology and climate

Kiritimati is a low lying Pacific atoll whose inland area is dominated by vast semi-connected networks of hyper-saline lakes and its external shoreline is skirted by narrow (~80m) live reef flats (Scott et al. 1993). The core of island is composed of highly weathered and fractured karstified limestone originating from shallow marine biota (including a variety of coral species) dating back to the Pleistocene from whence it is thought to have maintained geomorphic stability (Woodroffe and McLean 1998). The older core limestone structure of the island is covered by a veneer of more modern corals including *Tridacna*, branching *Acropra*, and *Porites* microatolls which pose high potential for paleo-climatic reconstructions (Woodroffe and McLean 1998, Woodroffe 2003).

The current climate of Kiritimati is hot and humid, typical of the tropical Pacific; however the island is located in an equatorial dry zone leading to lower than expected rainfall. Average annual rainfall at Kiritimati is around 850mm but varies from lows of 170mm to highs of 2,600mm depending on the ENSO phase (Scott et al. 1993). Kiritimati typically experiences a wet season from January to June which is driven by shifts in the intertropical convergence zone (KMS, 2011). Air temperatures of the region are strongly correlated to ocean temperatures which average about 27.4°C and have seasonal variability of around the range of 1.2°C (Figure 5) (Philander 1990, Evans et al. 1998). Ocean temperatures around the Island are strongly

![Figure 4: Location of Kiritimati Island (white dot) inside the NINO3.4 region (box) in the Pacific Ocean. Coloured contours represent characteristic SST anomalies during an El Nino event in the ECP, with darker colours representing more positive SST anomalies. This shows that Kiritimati Island is ideally located to be affected by changes in SST associated with ENSO. (Figure adopted from McGregor et al. (2013a))](image-url)
influenced by the ENSO which causes anomalous SST variability of ± 3°C which is more than twice that of fluctuations caused by the seasonal cycle. Due to this low seasonal variability of SST compared with the fluctuations caused by the ENSO around this region Kirimiti represents an ideal location from which to study thermal-oceanographic fluctuations relating to ENSO (Evans et al. 1998). This also means that there is much less likelihood of confounding annual cycles with ENSO events making Kirimiti an ideal location from which to investigate the ENSO.

![Temperature and Rainfall Profiles](image)

**Figure 5**: Average monthly temperature and rainfall profile typical for the region of the republic of Kiribati and Kirimiti showing very little annual SST variability. (Figure adopted from Kiribati Meteorology Service (2011))

2.5.3 Kirimiti climate compared to NINO3.4 region

As this study is reproducing ENSO variability from a fossil coral located on Kirimiti Island it is important that we evaluate how much Kirimiti SST’s are influenced by ENSO, and how well they capture ENSO variability. The NINO3.4 region is widely used as an index of ENSO strength and variability (Bunge and Clarke 2009), and as such by determining how well Kirimiti and the NINIO3.4 region correlate, we get an indication of how well climate reconstruction from this location relates to ENSO on the larger scale. To examine this relationship the instrumental records for the NINO3.4 region and Kirimiti Island, obtained using ERSSTv4 data, were compared to one another between 1950 and 2015 (Huang et al. 2015).
The comparison between Kiritimati and NINO3.4 SST’s shows a high correlation of 0.81 (r²) which indicates that SST reconstruction from Kiritimati is a strong reflection of ENSO as described by the NINO3.4 region (Figure 6). Two things to note from this comparison, however, are that the amplitude of warm events at Kiritimati are slightly greater than that over the NINO3.4 region, and also there is a lag in cooling of SST’s at Kiritimati after warm events compared to the NINO3.4 region. This is due to the fact that the NINO3.4 region is an average of SST’s over the area of 5ºN -5ºS, 120ºW-170ºW whereas Kiritimati is a single point within this zone (Figure 4). This means that Kiritimati experiences the more intense SST’s near the centre of the NINO3.4 region during warm events, such as El Niño’s. This indicates that Kiritimati Island is right in the centre of action for ENSO, however, when comparing to other records further away, it may show a slightly stronger response to El Niño events. This shows that Kiritimati Island is not only ideally placed to capture ENSO signals but reconstructions of past climate from the island will be highly relatable to the wider climate and broader regions (Evans et al. 1999, McGregor et al. 2013a).

Figure 6: Correlation between ERSST from the NINO3.4 region (orange) and Kiritimati Island (blue) between 1950 and 2015. Records show a high r² correlation value of 0.81 between each other. Note the slightly higher amplitude of Kiritimati during warm events and also the slight lag in cooling thereafter, suggesting the location of Kiritimati in the middle of the centre of action for ENSO.
3. METHODS

3.1 Collection and sample preparation

The fossil coral (CH32) presented in this study comes from Kiritimati Island, (157.5°W, 1.8°N), Kiribati located within the NINO3.4 region of the central Pacific (Figure 4). CH32 was collected in 2011 from a shallow reef flat at Cecile peninsula, on the south-western end of the Island (Figure 7). Cecile peninsula is an open intertidal bay, connected to the open ocean creating a well flushed environment representative of the regional oceanic conditions. A thick slab of fossil coral CH32, around 100-150mm wide and 950mm in length, was sawn using a portable circular saw with a diamond blade, and included material from the centre of the coral, where growth initiated, through to the outer growth surface, where growth terminated. The coral slab was broken into a series of connecting blocks. Both the growth direction and the top surface of the coral were marked on each block of coral along with a unique ID.

Figure 7: Site map of Kiritimati Island located in the central Pacific Ocean (~2°N, 157°W). The location that the fossil coral, CH32, came from is marked by the green star.
Coral blocks were assembled in growth order and sliced into 7mm (± 0.2mm) thick slices using a water lubricated table mounted diamond saw. Each block was cut into 3-5 slices, depending on their thickness and the condition of each block. Multiple slices were cut so as to ensure good connectivity between slices. Slices were cut into individual pieces and trimmed using a bandsaw with the material directly opposite the sampling transect being retained for use as thin sections. Thin section material was collected in order to check for any evidence of diagenesis as close to the sampling transect as possible due to the reportedly large impact of diagenesis on results (McGregor and Gagan 2003). A 10mm wide by 2.3mm thick ledge was made along the coral maximum growth axis in each of the 9 pieces of coral. Coral pieces and associated thin section material were thoroughly cleaned (with particular focus on the ledge section of the pieces) in milli-Q water using an ultrasonic probe to remove any contaminants. Once cleaned the pieces and thin section material were air dried on lint free paper wipes for a minimum of 24hrs.

3.2 X-Radiography

Based on visual inspection under UV-light, two of the slices with the best connectivity between pieces and least evidence of diagenesis from each slab were chosen for X-raying. This was done so as to identify the one with the clearest banding and straightest growth axis to be used for sampling. X-rays were used to distinguish differences in density within the coral slices relating to both the seasonal growth banding of the coral and the growth direction (Barnes and Lough 1993). X-rays of CH32 were taken at the Illawarra Radiology Group in Corrimal using an X-ray imaging machine. The settings used to obtain the best image quality were 42KV at 3mA. X-ray images were manipulated using InteleViewer 4.1 software (from Intelerad Medical Systems). Image colour was inverted from X-ray negatives to X-ray positives so that lighter coloured bands correspond to less dense material and darker coloured bands correspond to more dense material (Chalker et al. 1985, Barnes and Lough 1993). X-ray image brightness and contrast was also optimise so as to make the coral growth directionality and banding as clear as possible.
Geochemically the most reliable section of the coral to reproduce climatic tracers is from the maximum growth axis (MGA) (McConnaughey 1989); therefore, these sections were targeted for sampling along each slice. The MGA relates to the section of the coral where growth rate is the highest, growth direction is the most linear and can be identified by the characteristic fan like pattern it produces (with the MGA being the central line of the fan) (Barnes and Lough 1993, Cobb et al. 2008). Sampling transects were drawn along the MGA on X-ray transparencies and a 30mm boarder was marked along one side of the MGA to create individual pieces from each coral slice. Each piece was overlapped slightly with its neighbouring piece by following the growth banding (seasonal bands) from one MGA to another in order to insure good continuity of the record between pieces. Nine individual pieces from the four slices were produced in order to most closely follow the MGA throughout the coral (Figure 8). Borer holes, area’s identified to have possible diagenesis and the surface “rind” of the coral were specifically avoided due to risk of secondary precipitation of calcite and the potential of obtaining misleading results (McGregor and Gagan 2003, Cobb et al. 2008). From the X-ray images it was possible to calculate a rough average growth rate for the coral by measuring the distance between annual bands visible within the coral. The average growth rate based on these density bands is 16-18mm/year.

3.3 Physical and Geochemical quality of the fossil coral

When reconstructing climatic records from fossil corals there are a number of factors that can influence how reliably these reconstructions capture the climatic signals of the past, as outlined in section 2.3.2 of this thesis. To verify the reliability of a corals climatic record a number of quality control check can be undertaken. These quality control considerations include characterisation of the preservation of the coral material (McGregor and Gagan 2003, Cobb et al. 2008, McGregor and Abram 2008), the Sr/Ca-SST calibration equation used to derive SST’s and the physical location from which the coral was taken (McGregor and Gagan 2003, Cobb et al. 2008). The following section outlines the steps taken to characterise the quality of preservation of the fossil coral, CH32’s, coralline material used in this thesis.
Figure 8: X-ray positives of coral CH32 with sampling transects marked in red along the MGA distinguished by fanning patterns splaying out away from a central line of growth. Seasonal banding is visible roughly perpendicular to the sampling transect identifiable by characteristic lighter and darker bands representative of differential growth rates. Connectivity of pieces is such that piece D joins with C; C with B; and B with A to form a continuous slice of coral roughly 950mm in length. The origin of growth, indicated in blue, represents the oldest section of the coral from which growth initiated extending laterally to the outer surface which is the youngest. X-ray shows good preservation, with the little amount of bioturbation confined to the outer surface, and good connectivity between sections along with clear growth forms within the coral structure.

Large scale physical alterations of coral material are readily detectable both visually and using X-ray images of the coral slices, through the identification of borer holes, plant root invasion or fracturing within the coral (McGregor and Gagan 2003). UV-luminescence can also be used to identify possible diagenesis within the coral as secondary precipitation cross-cuts the coral banding, thereby highlighting area’s to avoid sampling (Barnes and Taylor 2001). Each of the slices were visually assessed using UV-light to determine their quality in terms of banding clarity, visual evidence of diagenesis, and continuity of slices. CH32 showed no evidence of
physical alteration apart from some minor bioturbation from boring animals which was
confined to the outer surface of the coral, well away from sampling transects (Figure 8). Whilst
physical degradation of coral material is easily detected (visually and on X-ray’s), chemical
diagenesis on the micro scale requires a more in-depth investigation through X-Ray Diffraction
(XRD) and thin section (TS) analysis (McGregor and Abram 2008, Smodej et al. 2015).

XRD analysis was performed in order to determine the amount of aragonite compared to calcite
present in the coral. Samples were prepared as per the methods outlined in McGregor et al.
(2013a). In short a small section of the coral was cleaned using an ultrasonic probe, dried and
crushed to a fine powder. The powder was then analysed on a Phillips Goniometer to determine
its composition. XRD analysis for CH32 produced an aragonite weight of 99.4% ±0.25 and a
calcite weight of 0.3% ±0.18. The high aragonite and low calcite values indicate a high quality
of coral material with low possibility of diagenetic material. This high aragonite value and low
calcite value indicated a low possibility of diagenesis, which was verified by the TS analysis
that showed well preserved polyp structures with no notable dissolution or infilling of
secondary material (Appendix 1). Based on the high quality of the coralline material (lack of
physical destruction, high XRD aragonite and good quality TS) it was determined that there
were no suspect physical or chemical factors, due to deterioration of the coralline material over
time, which would adversely affecting the fossil corals climate reconstruct (McGregor and

3.4 Dating

The absolute age of the fossil coral CH32 was estimated by U/Th dating, with a total of two
dates taken from either end of the coral. Samples were milled parallel to clear annual growth
bands within the coral and covered a distance relating to 4 months of coral growth. Each of the
milled samples produced roughly 360mg of powder, which was enough to allow for multiple
U/Th analyses. The U/Th dates were measured at the Radiogenic Isotope Laboratory at the
University of Queensland (on the 15/11/2015) as per the method described in Zhou et al.
(2011). The U/Th dates produced ages of 1434.6 CE (±3.9 years) from one end of the coral and
1468.4 CE (±3.7 years) from the other end of the coral. Both the dates are being replicated
using a second split of the sample powder and in the interim the age of coral CH32 is taken as the average of the two dates: 1452 ±4 CE.

3.5 **Sr/Ca Analysis**

Sr/Ca ratios were measured using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) at the Australian Nuclear Science and Technology Organisation (ANSTO). Prior to analysis each of the coral samples needed to first be milled and digested. Based on the growth rate of the coral estimated from the X-rays a 1mm sampling resolution was determined to allow for just better than monthly sample resolution (or 16 samples per year). Sample milling produced a fine coral powder with weights of around 5.5-6.0mg per sample. The samples were then digested as the ICP-AES machine uptakes samples for analyses by aspirating them from a liquid phase. Samples were weighted out into 10ml acid washed centrifugal vials (soaked in 5%HNO₃ for 24hours) using an Orian Cahn C-35 microbalance at the University of Wollongong. Every second sample was analysed giving approximately bimonthly resolution (8 samples per year). Coral samples were weighed out with weights ranging from 450μg-550μg ±1μg. A 1% solution of Suprapur grade HNO₃ was pipetted into each sample vial containing the weighed out coral at a ratio of 1ml HNO₃:10ug coral powder to produce a Ca²⁺ concentration of around 35-40ppm. In order to produce universally comparable results a recognised, lab tested coral standard (JCP-1) was also weighed out and prepared in the same manner as unknown samples along with sample blanks (containing no coral) for later use to correct and calibrate data (Hathorne et al. 2013). After addition of acid sample vials were shaken to encourage mixing of solution and coral powder and then placed in a 40°C sonicator bath for 30 minutes to promote complete digestion of samples.

Sample were analysed on a Thermo Fisher Scientific iCAP 7600 series ICP-AES to an accuracy of ±0.1%, which was calibrated using calibration standards containing Ca, Ba, Mg, P and Sr at a range of concentrations (Table 1). Calibration ranges used to produce calibration curves were determined based on expected values for the 35-40ppm sample concentrations (McGregor, Wong pers comm). Sample runs were accompanied by an Internal Calibration Verification (ICV) standard which was used to correct for internal drift within each run. The ICV standard
was prepared containing a precisely known concentration of each of the analytes that were to be tested, and the associated error for Sr/Ca values after correction was 0.36% (RSD). The multi-analyte ICV standard was run after every 2 unknown samples to identify and correct for any internal drift within the machine during runs. Blanks followed by JCp-1 standards were run at the start and at the end of each run to correct for background noise and calibrate the data to a known value respectively. Each sample was analysed a total 6 times per aspiration to produce an averaged value and samples were run according to the instrumental parameters set out in table 2. Sr/Ca ratios were calculated from the intensity peaks showing the clearest and highest signal (421.6 nm for Sr and 422.7 nm for Ca). Samples were blank corrected against the average blank response for their respective frequencies and then the ICV standard was used to correct for internal drift by Henri Wong at ANSTO. Sr/Ca ratios were JCp-1 corrected using the internationally recognised calibration coral standard with a known ANSTO lab value of 8.811±0.089 mmol/mol (Okai et al. 2002, Hathorne et al. 2013). JCp-1 standards were the only samples which were repeated and therefore provide an indication of reproducibility. The Standard error associated with repeat JCp-1 Sr/Ca analysis was 0.027 mmol/mol (n=8) showing good reproducibility of results.

Table 1: ICP-AES calibration concentration ranges for each of the elements analysed for within samples. Concentration ranges differed between each of the elements depending on the expected elemental levels in the coral material.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration Range (mg/kg or ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>36.8 to 37.6</td>
</tr>
<tr>
<td>Ba</td>
<td>0.000301 to 0.000391</td>
</tr>
<tr>
<td>Mg</td>
<td>0.0720 to 0.0931</td>
</tr>
<tr>
<td>P</td>
<td>0.128 to 0.166</td>
</tr>
<tr>
<td>Sr</td>
<td>0.620 to 0.801</td>
</tr>
</tbody>
</table>
An age model for the coral was constructed using the time-series analysis program Analyseries (Paillard et al. 1996). First a Sr/Ca-distance relationship was created by matching samples with their cumulative distance along the coral. This was then correlated to a generic annual SST cycle of roughly 50 years in length (estimated from the length of the coral and a rough growth rate of 20mm/yr) with arbitrary years ranging from 1-50 to produce an internal coral age. The generic SST annual cycle was generated from a climate model Mk3L simulation, configured with the orbital parameters of the 15th Century. Correlation between the general cycle and Sr/Ca-distance series was achieved by attaching tie-points between minima (mid-February) in the generic annual cycle and maxima in the Sr/Ca-distance series (McGregor et al. 2013a). Sr/Ca maxima were tied to the generic annual cycle’s minima as there is an inverse relationship between SST and Sr/Ca ratio. Where maxima in the Sr/Ca-distance series were not clearly resolved no tie-points were created for that year so as to avoid over-fitting. In these instances the age model was interpolated between the previous and subsequent tie-points for that period (McGregor et al. 2013a). When creating tie-points in the time-depth relationship the number of samples between annual cycles (normally 8/year) and the x-ray seasonal banding were all taken into consideration. The constructed age model was processed using the ‘Interp’ function of the ARAND software (Howell et al. 2006), which interpolated the time series into 6 evenly-spaced (bimonthly) Sr/Ca values. Interpolation was such that the data points created at the

### Table 2: Instrumental parameters used for the ICP-AES analysis of Sr/Ca ratio sample elemental analysis.

<table>
<thead>
<tr>
<th>ICP-AES parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure time</td>
<td>5 sec</td>
</tr>
<tr>
<td>RF power</td>
<td>1150W</td>
</tr>
<tr>
<td>Nebuliser Gas Flow</td>
<td>0.45L/min</td>
</tr>
<tr>
<td>Coolant Gas</td>
<td>12L/min</td>
</tr>
<tr>
<td>Auxiliary Gas Flow</td>
<td>0.5L/min</td>
</tr>
<tr>
<td>Analysis Mode</td>
<td>Speed</td>
</tr>
<tr>
<td>Pump Speed</td>
<td>30rpm</td>
</tr>
<tr>
<td>Flush Pump Speed</td>
<td>100rpm</td>
</tr>
<tr>
<td>Pump Stabilisation Time</td>
<td>30 sec</td>
</tr>
<tr>
<td>Repeats</td>
<td>6 readings</td>
</tr>
</tbody>
</table>
equally spaced time intervals were always between two or more existing point and a linear interpolation between the original values created the new data point (Howell et al. 2006). Whilst there were some notable differences between the pre-interpolated and post-interpolated time-series, mainly the reduction in amplitude of peaks and troughs, the resulting interpolated data series retained the vast majority of its integrity and signal noise and was deemed not to have affected the data signal negatively (Figure 9).

**Figure 9:** ARAND interpolation results for fossil coral CH32 Sr/Ca ratios before (blue) and after (orange) Interp processing. Post interpolation Sr/Ca values appear to have lost a proportion of their intra-annual frequency (which could be attributed to random noise), however, both pre and post interpolation Sr/Ca values show the same annual and inter-annual variability comparatively.

3.7 **Sr/Ca – SST calibration**

This study presents a Sr/Ca record derived from a fossil coral that had no overlap with the instrumental record. Therefore the Sr/Ca-SST calibration equation presented in McGregor et al. (2013a) was adopted for the purpose of converting the Sr/Ca ratios to SST (Equation 1)

**Equation 1:**  
\[-12.056 \times \text{Sr/Ca} + 138.2681\]
Equation 1 was derived using a reduced major axis regression between a modern *Porites* Sr/Ca record and SST from ERSSTv3b over a length of record 13 years long (McGregor *et al.* 2013a). The reported correlation between the reconstructed modern coral Sr/Ca-SST and the instrumental record was $R^2 = 0.64$ (McGregor *et al.* 2013a). This equation was chosen because the modern coral from which it was derived (XM22) was located in the same bay as the fossil coral CH32, merely tens of meters apart, and both modern and fossil coral were of the same species (*Porites*) (McGregor *et al.* 2013a). It is assumed therefore that any poorly understood geographical dependence relating to the incorporation of Sr$^{2+}$ into the CaCO$_3$ structure of the corals is minimised, *ceteris paribus* (Reynaud *et al.* 2004). Furthermore, the calibration equation was created at a similar temporal resolution as that of the fossil coral, which is to say that there is expected to be no differentiating effect of averaging Sr/Ca-temperature relations between the two corals. Finally, equation 1 was implemented in the reconstruction of SST from other fossil coral records from Kiritimati Island and as such has been proven useful and, therefore, is appropriate for use here (McGregor *et al.* 2013a).
4. RESULTS

Sr/Ca ratios for the record ranged from 8.9 mmol/mol to 9.6 mmol/mol with a mean value of 9.2 mmol/mol and covered a total length of 874 mm of coral. The coral record shows clear seasonal cycles depicted by an oscillation between minima and maxima around every eight samples. There is also evidence for larger El Niño like events, depicted by prolonged 2 (or more) year lower than average Sr/Ca ratios, as well as longer term trends (Figure 10).

![Graph of Sr/Ca ratio vs. distance along the coral](image)

**Figure 10**: CH32 Sr/Ca ratio geochemistry as a function of distance along the length of the coral. As there is an inverse relationship between SST and Sr/Ca ratios the axis has been inverted so that peaks represent warmer SST and troughs represent cooler SST. Distance was measured from the youngest surface of the coral to oldest and thus time runs from 900 to 0.

Application of the Sr/Ca-distance relationship to the age model produced a record spanning 46 years in length. When the length of coral is considered this equates to a coral growth rate of around 18 mm/year which is consistent with what was expected for a *Porites* coral (Barnes and Taylor 2001). Conversion of Sr/Ca values to SST produced SST’s ranging from a minimum of 23.1 °C to a maximum of 30.6 °C with the average SST for the record being 26.6°C. There is an overall cooling trend of around 0.02°C/year in over the length of the record which equates to a rough decrease in temperature of about 1°C over the 46 year period. The record shows a strong cooling event which was initiated at year 20 of the internal chronology, correlating to the year 1445 ± 4 CE, which lasted for 5-6 years. This cooling event was not associated with diagenesis and as such represents a real feature of the data (Appendix 1). The fossil record shows clear ENSO like properties which were extracted using the bandpass filter (Figure 11). The variance of the resulting ENSO signal was 0.545°C and shows both a number of large El Niño and La Niña events. The strength and number of the El Niño events is greater than that
of the La Niña events with El Niño events reaching a maximum of +1.6°C compared to the -1.3°C of La Niña’s.

**Figure 11:** SST variability based on Sr/Ca-SST reconstruction for fossil coral CH32 (Top) and detrended 2-7 year bandpass filter representing the ENSO cycle (bottom). The blue line in the top graph represents reconstructed SST from Sr/Ca values and the black line is a yearly rolling average SST to highlight longer term trends. Red peaks in the lower figure represent positive deviation from mean SST (warm SST) and indicate El Niño events if over 0.5°C and Blue peaks represent negative deviations from mean SST (cooler SST) indicating La Niña events if over 0.5°C.
5. DISCUSSION

5.1 Comparison of fossil coral Sr/Ca SST to modern records

5.1.1 Modern baseline for comparison

The 15th Century coral Sr/Ca record presented herein was calibrated using equation 1, derived from the modern coral XM22 spanning 1994-2007 (McGregor et al. 2013a). The 13 year modern coral Sr/Ca record however, is too short an interval to characterise present day ENSO variability and for time series comparisons with the fossil record. Instead the modern instrumental record is used for comparison. Instrumental SST was extracted from the ERSSTv4 data product for the 2ºx2º grid square centred on 2ºN, 157ºW covering the Island of Kiritimati, and was downloaded from the climate data library IRI Ingrid, accessed from http://iridl.ldeo.columbia.edu/index.html?Set-Language=en (Huang et al. 2015).

However, before comparing the fossil coral Sr/Ca record to the modern instrumental SST data it is worth comparing instrumental SST to modern coral Sr/Ca SST to assess possible offsets between the two that may skew any fossil coral-instrumental SST comparisons. The modern coral SST and the ERSSTv4 data show similar variability for the 1994-2007 interval, which includes the 1997/8 El Nino event, with the modern coral Sr/Ca geochemistry showing the annual cycle as well as interannual variability. Comparison between the 2-7 year filtered ENSO signals from both show a very close correlation of $r^2 = 0.79$ (Figure 12). The filtered ENSO signals from the modern coral and instrumental record have similar variances of 0.74 ºC and 0.66 ºC respectively. This strong comparison suggests that the bay from which the fossil and modern corals were taken has good connectivity with the open ocean and indicates that reproduction of climate signals from corals extracted from this bay should represent regional climate variability well. Although the modern coral Sr/Ca record is short the similarity between the modern coral Sr/Ca-SST and the instrumental SST suggest that it is possible to compare the fossil Sr/Ca record to the modern instrumental SST to make inferences about possible changes in ENSO through time. Herein the 46 year long Sr/Ca-SST record from the fossil coral (CH32) is compared to Kiritimati Island modern instrumental SST (ERSSTv4) for the full period of 1880 to 2015, or for selected intervals therein.
Figure 12: Comparison between modern coral XM22 SST reconstructed from Sr/Ca ratios (light blue), instrumental SST (orange) and 2-8 year bandpass filtered ENSO signals for both modern coral (dark blue) and instrumental record (red) from Kiritimati Island. The modern coral Sr/Ca was calibrated to SST using equation 1. The filtered coral signal shows similar variations to the instrumental record.

5.1.2 Wavelet Analysis

Wavelet analysis of time-series provides a quantitative visual representation of the dominant modes or frequencies of variability which make up the time-series, as well as changes in period variability through time (Torrence and Compo 1998). This is particularly useful in distinguishing whether or not there is periodicity in a signal and helps determine whether the signal is stationary in time. Wavelet analysis also highlights whether or not there are a number of different frequency oscillations in the signal and identifies cycles of different frequencies within the time-series (Torrence and Compo 1998). The application of the wavelet analysis is in essence a continuous discrete Fourier transformation varying the winnowing size over all frequencies along the length of the time series. This allows for a two dimensional power plot of the filtered record for multiple frequencies along the length of the time series showing changes in the power spectrum with time (Torrence and Compo 1998). The key difference and advantage of a wavelet analysis compared to other time-series analysis methods, is that where other Fourier transformation filters normally assume stationarity within the time series the wavelet analysis does not, meaning that time-varying periodicities in a record can be identified. This is useful for characterising what periodicities are present in a record and whether or not they are stationary in time, particularly in relation to ENSO variability which is known to be non-stationary (Torrence and Compo 1998, Lewis and LeGrande 2015). In this study a Morlet wavelet analysis of both the modern and fossil data was undertaken using the free to access

The wavelet analysis of the fossil coral Sr/Ca record highlights temporal variability for a number of periodicities including annual (1 year peaks), inter-annual (ENSO; peaks at ~2 years, 4 years, and ~8 years), and decadal (16-32 years), though the decadal variability is not significant due to the short length of record (Figure 13). The highest power in the fossil record falls around 4 years and this is interpreted to be an ENSO signal. The interannual ENSO peaks in the fossil record are significant, however, due to the short length of time covered by the record it is not possible to comment on any shifts in ENSO variability through time. Similarly the wavelet analysis found the 2-8year variability range in the modern instrumental SST record to have the strongest power, however, due to the greater length of the modern record we see that ENSO variability shifts its highest power between 2-4 years and 4-8 years (Figure 13). This shows that the power spectra from the fossil coral is not unprecedented within the modern record however the power shown in the spectra suggest a weaker variability in the fossil coral.

Whilst the wavelet analysis is good for identifying broad scale changes in different frequency periodicities over time it is not a perfect analysis tool, and as such there are some limitations to this type of analysis. One such shortfall with this type of analysis is that the strength, shape and size of El Niño and La Niña events cannot be readily or easily determined from such a plot. Also wavelet analysis does not allow for comparison between El Niño warm states and La Niña cold states, as it simply shows overall variability; for this a targeted record filter is needed (Paillard et al. 1996, Torrence and Compo 1998, Howell et al. 2006).

5.1.3 Spectral Analysis

A spectral analysis was conducted on the time-series data of both the modern and fossil records, and this indicated major frequencies peaks correlating to a 1 year (annual) cycle and 2-7 year (ENSO) cycle for both records (Figure 13 part 1&2 c – note: due to technical difficulties with the program used to create the spectral analysis, a legible spectral figure could not be produced in time for inclusion in this thesis. However, the global wavelet is very similar). The spectral analysis showed a stronger power spectrum in the 2-7 year range for the modern record compared to the fossil record, however, it is suspected that this is more of a factor of the limited
length of the fossil record than a true difference in the signals. This is generally consistent with what is suggested by the wavelet analysis, as indicated by the global wavelet plots for both records, which shows a much stronger 2-7 year peak in the modern record than that of the fossil. The cross-hatching on both wavelet graphs show the boundaries at which edge effects start to come into play, which also gives weight to the idea that rather than a true difference in ENSO periodicity the difference is more a function of the length of the record. It is also true that when looking at the wavelets from both records there are clear periods in the modern record which show stronger power in the 2-4 year range than the 4-8, namely pre 1905 and also in the most recent 20 or

5.1.4 ENSO Signal Variability

Whilst it is useful to consider all the frequency ranges within a record's signal the focus of this study is on ENSO variability. Examining the changes in variance between the filtered 2-7 year records provides a much clearer picture of differences between modern and past ENSO variability (Cobb et al. 2013, McGregor et al. 2013a). The time-series analysis program Analyseries was used to filter out the 2-7 year ENSO signal from both the fossil coral and instrumental SST records by extracting the frequency of 0.321 yr\(^{-1}\) (relating to the midpoint of the 2-7 year) with a bandwidth of 0.178 yr\(^{-1}\) (Paillard et al. 1996). This method automatically de-trended the signal and removed the mean. Through this we find that the fossil coral record (σ = 0.55°C) shows a 14% reduction in ENSO signal relative to the entire length of the modern (1880-2015) ENSO record (σ = 0.63°C) (based on filtered ENSO signals standard deviation [σ] as a measure of strength/variability). Although this broadly shows a reduced ENSO signal in the fossil coral record compared to instrumental data it is not strictly correct to directly compare two records of such distinctly different length (46yrs compared to 135yrs).
Figure 13: Part 1: a) CH32 Fossil Coral SST reconstruction from Sr/Ca geochemistry. b) The wavelet power spectrum for CH32. Part 2: a) Modern ERSST instrumental record from Kiritimati Island from 1880 to 2015. b) The wavelet power spectrum for the modern ERSST instrumental record. For both parts 1&2 the coloured contour levels are chosen so that 75\%
50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence indicating regions where edge effects influence the power spectra, where zero padding has reduced the variance. Black contour is the 10% significance level (based on a chi-squared 90% confidence), using the global wavelet as the background spectrum. c) The global wavelet power spectrum indicating the dominance of periods within the wavelet power spectrum. (Note: Figure caption automatically generated by wavelet software by Torrence and Compo (1998)).

A more statistically valid approach is to compare the fossil coral record with a period of time of the same length (Agresti and Franklin 2013). For this reason characterisation of the change in ENSO from the fossil record was compared to the most recent 46 year time period from 1969 to 2015 so as to give an indication compared to the most current climatic conditions. The fossil coral record shows a 20% reduction in ENSO variability/strength when compared with only the most recent 46 year period from the modern record ($\sigma = 0.68^\circ$C).

Along with the difference in ENSO strength found between the two records, reduced numbers of El Niño events in the fossil record (6) were found compared to the modern (9). The same result was also found for the number of La Niña events, with the fossil record showing 6 La Niña events compared to the 8 in the modern record (Figure 14). Although multiple 46 year windows along the length of the modern record should be considered and statistical analysis on the significance of these differences should be undertaken before conclusively relating this finding to a cause, due to time constraints a more in depth analysis of this was not undertaken. With these limitations in mind the reduction in the number of events over the same time lengths is thought to be a factor of the reduction in ENSO strength during the 15th century causing the more frequent smaller events to be suppressed below the classification limit of $+0.5^\circ$C.

The maximum amplitude (and average strength represented by standard deviation) of any El Niño event in the fossil coral record was $1.6^\circ$C ($\sigma = 0.36^\circ$C) compared to $1.8^\circ$C ($\sigma = 0.44^\circ$C) in the most recent 46 years of the modern. This represents only a 10% difference in extreme El Niño strength compared to the 20% reduction in overall ENSO variability/strength. Also something which is evident from the plot in Figure 15 is that the strong El Nino events in the fossil record are not only comparable to the large events during the most recent 46 year period of the modern record, but in fact they rival the majority of those represented throughout the length of the instrumental record. This shows that even though ENSO was reduced in the fossil record, large El Nino events were stronger compared to their background signal than they are today (Figure 14), and may indicate that a reduction in ENSO mean state variability does not necessarily represent a reduction in extreme events.
The maximum La Niña amplitude recorded in the fossil coral was -1.3°C ($\sigma = 0.29°C$) compared with -1.5°C ($\sigma = 0.35°C$) in the modern which represents a 16% difference in extreme La Niña events. This is consistent with the idea of a tendency for more El Niño like conditions found in other studies from the time period (Oppo et al. 2009). When we consider the average strength (as represented by standard deviations) we notice that in general both El Niño events and La Niña events in the most recent 46 years have been greater in strength than that recorded by the fossil coral during the 15th century (Figure 14). Also both records show a stronger El Niño signal compared to La Niña with fossil and modern La Niña only being 82% and 79% the strength of El Niño respectively. This not only illuminates the asymmetrical nature of ENSO amplitude between warm and cool states but also shows that the current asymmetry of ENSO is very similar to the ENSO asymmetry during the 15th century. This indicates that whilst ENSO was reduced in the past, the strength of the physical drivers behind the ENSO proportionate to each other are similar now to what they were during the 15th century (Im et al. 2015). This is important because the asymmetry of ENSO is driven by a number of processes and by understanding these processes in the modern climate we can infer details about past climate based on this similarity in signal asymmetry (Im et al. 2015). It is, however, important to note that this figure of asymmetry is an average over the entire 46yr period and does not allow for representation of individual extreme events, and changes in signal pattern. Also more work still needs to go into better understanding the relationship between the identified processes and ENSO asymmetry before definitive conclusions can be made (Im et al. 2015).

A visual assessment of the fossil ENSO record shows that in general the majority of the ENSO signal appears to be even weaker than the 20% reduction found, with large events appearing to be more sporadically superimposed over the top of a lower variable background ENSO signal (Figure 14). This represents a seemingly different pattern to that of modern ENSO where the strength of El Niño - La Niña events are much more consistent through time. This is highlighted in Figure 15 which shows changes in ENSO variability through time indicated by shifts in the 15 year sliding window of ENSO Standard deviation. The ENSO Standard deviation sliding window is an indication of the variability within the ENSO cycle and shows shifts in ENSO activity through time (Cobb et al. 2003, McGregor et al. 2013a). The width of the sliding window was set to 15 years based on the finding that there seems to be a possible 15 year natural modulation of ENSO variance through time (Torrence and Compo 1998). By setting the bounds of the window at 15 years it was deemed appropriately broad to capture changes in
the 2-8yr ENSO variance but small enough to circumvent the influence of longer term modulation effects.

Figure 14: Comparison between ENSO cycles from the most recent 46 years of the instrumental record (top) and 15th century fossil coral record (bottom) from Kiritimati Island in the central Pacific. ENSO signal extracted using a 2-7 year bandpass filter on reconstructed Sr/Ca-SST from the fossil coral CH32 and instrumental ERSSTv4 records. Red peaks indicate positive SST anomalies (El Niño warm state) and blue peaks indicate negative SST anomalies (La Niña cool state). Peaks which deviate more than +0.5°C and -0.5°C for a duration of three months of longer represent El Niño and La Niña events respectively (Huang et al. 2015).

Based on the results of the sliding window analysis it was found that ENSO in the fossil coral record seem to show more abrupt shifts in the strength (σ) and thus appears to be more variable than the modern record (Figure 15). One thing which is important to note however is that whilst we see these more abrupt shifts compared to the majority of the modern record, the magnitude of these shifts in ENSO strength are not unprecedented within the record, particularly when focusing on the most recent 40 or so years. Also whilst we find a reduction in fossil ENSO variability, the strength of the variability which is exhibited in the fossil record is encapsulated within the range of variabilities seen in the length of the modern record (Figure 15). This shows
that even though 15\textsuperscript{th} century ENSO was weaker in general compared to ENSO in more recent times, its strength is not unprecedented when compared to instrumental records.

![Figure 15: Comparison of fossil coral (left panel) and instrumental record (right panel) ENSO variability through time from Kiritimati Island. The orange line represents the ENSO SST anomaly signal extracted from a 2-7 year bandpass filter of the bimonthly resolved fossil coral reconstructed Sr/Ca-SST and instrumental ERSSTv4. The blue lines represent a 15 year sliding windows of ENSO standard deviation, centred over the midpoint of the sliding window, indicating the change in ENSO variability/activity through time.](image)

5.2 Kiritimati fossil record compared to other 15th century record

The Kiritimati Island fossil coral record presented in this study represents one of only a handful of other records (Figure 16). The climate record from fossil coral, CH32, was compared to those published records that reconstruct ENSO and tropical climate during the 15\textsuperscript{th} century. In general the reconstructed climatic conditions from the Kiritimati Island fossil coral agree with the wider published records for the time period. The majority of other published records support the 0.8 ± 1.3°C (1\textsigma) cooler than modern SST’s found in the fossil coral record (Oppo \textit{et al.} 2009, Conroy \textit{et al.} 2010, Fowler \textit{et al.} 2012, Emile-Geay \textit{et al.} 2013b, Li \textit{et al.} 2013). It should be noted, however, that SST estimates of this kind have been found to be somewhat erroneous due to the identification of offsets between coral record Sr/Ca-SST reconstructions over long periods of time, and as such should be accepted cautiously (Grove \textit{et al.} 2013). The Kiritimati fossil record also indicates an overall cooling trend of around, of around 1°C over the length of
the 46yr record, which is consistent with other records findings for the time (Oppo et al. 2009, McGregor et al. 2015). However, when compared with the record presented in Cobb et al. (2003) it is noticed that similar cooling trends are seen within sections of their record, although no tendency for either cooling or warming over the time period is apparent. Furthermore, other studies suggest a warming trend during the 15th century (Emile-Geay et al. 2013b). The cooling in the Kiritimati record, may be an artefact of the limited length of the coral record coupled with the strong cooling event which is initiated around 1445 CE (Figure 11).

![Figure 16: Geographic location of the Kiritimati Island fossil coral proxy record (red star) in relation to other existing proxy records across the tropics and around the Pacific Ocean (Map modified from Emile-Geay et al. (2013b)). The black box representing the NINO3.4 region highlights the records idyllic location in the reported ENSO centre of action. Note the proximity of Kitirimati and Palmyra (yellow dot on the edge of the NINP3.4 box).](image)

The reduced ENSO strength found in the Kiritimati Island fossil record is consistent with similar findings in a number of other related studies (Cobb et al. 2013, Hereid et al. 2013, Li et al. 2013, McGregor et al. 2013b). ENSO syntheses of the ECP’s 15th century climate also generally agree with the observations found in the Kiritimati fossil record, with most consistently showing a reduction in ENSO strength during this time, albeit with relatively large uncertainties (McGregor et al. 2013b, Lewis and LeGrande 2015). Also the greater variability within individual ENSO signals depicted in the Kiritimati fossil climate record presented in this study are consistent with what others have found for the 15th century (Cobb et al. 2003, Li et al. 2013).
There are some discrepancies between the findings in this study and what others have found, specifically in relation to the magnitude of the reduction of ENSO variability, whilst the Kiritimati Island record presented herein shows a 14-20% reduction in ENSO strength compared to modern records, depending on which modern baseline is chosen, the Palmyra record show a much greater decrease in ENSO of around 44% (Figure 17) (Cobb et al. 2003). This difference in magnitudes is similarly mirrored in the Papua New Guinea (PNG) record covering the same time period (Hereid et al. 2013). And whilst it could be expected that the PNG record might see a weaker ENSO signal than the Kiritimati record, due to the difference in locations, it is expected that the Palmyra record should be quite similar to the Kiritimati fossil record due to its similar location in the NINO3.4 region (Figure 16) Cobb et al. (2003). This could be a function of the limitations and uncertainties relating to the δ18O paleoclimate reconstructions.

**Figure 17:** Comparison between fossil coral climate reconstructions from a) Kiritimati, b) Palmyra, c) PAG, and d) the modelled NINO 3.4 region. Left hand plots represent fossil record, while right hand plots represent modern records from the same locations. Fossil and modern coral records represent 2-7 year bandpass filtered records, while the modelled record is modelled ERSTT for the NINO3.4 regions. (Data downloaded from NOAA paleoclimate archives, First produced in Cobb et al. (2003), Emile-Geay et al. (2013b), Hereid et al. (2013)).

5.3 **Discrepancies between δ18O and Sr/Ca reconstructions**
The discrepancies found between the fossil coral, CH32, and other records, specifically the Palmyra and PNG δ¹⁸O reconstructions (Figure 17), could be attributed to a number of factors. However, the factor which is thought to be the main source of the differences between the reconstructed signals is attributed to changes in SSS due to differing rainfall patterns between modern times and the 15th century. Both the Palmyra and PNG records are based δ¹⁸O isotope reconstructions which use the fractionation of δ¹⁸O isotopes in the corals from sea water to infer past climate in a similar way Sr/Ca ratios are used (Cobb et al. 2003, Hereid et al. 2013). Coral δ¹⁸O isotopes represent both SSS, through hydrologic changes affecting sea water, as well as SST (McGregor et al. 2011, Nurhati et al. 2011). As such when inferring SST form δ¹⁸O signals the rainfall component, which is seen to enhance the SST signal through increased amplitude, can be accounted for based on the response of the modern reconstructed signal to the effect of rainfall (Figure 18) (McGregor et al. 2011). This means comparisons can be made between δ¹⁸O amplitudes and SST using modern calibration equations based on the well-recognised δ¹⁸O temperature dependant fractionation ratio of negative 0.2‰/ºC, as was applied in the comparison between the Palmyra and PNG records (Cobb et al. 2008). This temperature dependant fractionation ratio, however, incorporates the underlying assumption that δ¹⁸O oceanic ratios are stable through time and are only temporarily affected by rainfall events.

This assumption is believed to be the basis for the discrepancies in ENSO strength between the different fossil records. A number of studies have documented a freshening of the Pacific Ocean in recent years which has produced a shift in the δ¹⁸O oceanic ratios towards a higher ¹⁸O signal (Hendy et al. 2002, Stott et al. 2004, Nurhati et al. 2009, Nurhati et al. 2011). This higher concentration of δ¹⁸O in the modern Pacific means that δ¹⁸O– SST/SSS equations created based on modern corals are calibrated to oceanic conditions which are not representative of the condition prior to the initiation of the freshening (Hendy et al. 2002, Nurhati et al. 2009). This would subsequently lead to an overestimation of the rainfall fraction in the fossil corals oxygen isotope signal due to a naturally “heavier” (¹⁸O rich) ocean signal. In conjunction with this reported freshening of the modern Pacific, shifts in the position of the ITCZ, which significantly affects the distribution of monsoonal rains in the tropics, have been characterised throughout the past millennium (Sachs et al. 2009, Yan et al. 2015). These studies have found that the ITCZ was shifted considerably south of its current position (ranging from 10ºN in summer and 3ºN in winter) during the 15th century, with it reaching its most southerly extent over the equator (consistently south of 4ºN) around 1420 CE (Sachs et al. 2009, Yan et al. 2015). This is thought to be accompanied by a synchronous contraction of the ITCZ during
this time (Yan et al. 2015). This would have caused a significant reduction in the amount of rainfall both Palmyra and PNG would have received during the 15th century (Sachs et al. 2009, Yan et al. 2011, Yan et al. 2015).

The reduction in rainfall over these key locations during the 15th century due to the contraction and southward shift of the ITCZ, coupled with the freshening trend seen in the modern Pacific, would result in an underestimation of ENSO amplitude (and therefore strength) in reconstructions based on modern coral $\delta^{18}$O -SST calibrations. These changed conditions are considered not to have affected the Kiritimati Island Sr/Ca record as it has been found that changes in SSS do not influence Sr/Ca ratios as a SST tracer as they do $\delta^{18}$O (Figure 18) (McGregor et al. 2011, Nurhati et al. 2011, Moreau et al. 2015). Therefore, the Sr/Ca-SST reconstruction presented herein represents a relatively unimpeded representation of ENSO strength compared to previous records. However, as stated previously there are other contributing factors which could help to explain the difference between the records, such as differing geographic location being influenced by ENSO unevenly (section 2.5.3), although, these are considered to be less contributory to the discrepancies seen between the records than the changes in $\delta^{18}$O/salinity.

Figure 18: Comparison between Sr/Ca ratio SST reconstruction (Blue), $\delta^{18}$O isotope reconstruction and the instrumental record for the modern climate record from Kiritimati, covering the large 1997/8 El Nino event. The green plot shows the $\delta^{18}$O
residual which is the difference between the instrumental SST and the δ¹⁸O signal and represents the rainfall effect on δ¹⁸O during El Niño years. Note that while δ¹⁸O isotope shows an enhanced signal due to rainfall during El Niño events the Sr/Ca reconstruction continues to mimic the instrumental record. (Figure modified from McGregor et al. (2013a)).

5.4 Uncertainties and limitations of Sr/Ca as a SST tracer

Although Sr/Ca – ratios are seen to be a much clearer representation of SST than other similar tracers, they are not without limitations. A fairly comprehensive review of the different uncertainties relating to coral Sr/Ca reconstructions of climate is presented in Cobb et al. (2008). One of the apparent reason for some of these uncertainties seems to be due to a lack of knowledge about the mechanisms behind the temperature dependant incorporation of Sr²⁺ into the aragonite structure of corals (de Villiers et al. 1995, Cobb et al. 2008, Jones et al. 2009). Due to these uncharacterised processes affecting the corals, some non-temperature dependant effects cannot be accounted for and as such provide potential confounding of factors affecting Sr/Ca ratios (Cobb et al. 2008). One such factor is the effect of growth and calcification rate on Sr/Ca ratios. It has been seen that growth rate and calcification rate have an effect on Sr/Ca ratios which seems to be unrelated to SST and due, rather, to apparent biological factors (Grove et al. 2013). Another limitation within coral records more generally, is the possibility of hiatus’s in coral growth while the coral was alive (due to coral bleaching events and the like) producing discontinuity within the coral records (Nurhati et al. 2009). These hiatus can sometimes be quite difficult to identify and failure to do so would result in possibly quite incorrect internal chronologies. Generally, however, there is fairly good consistency between individual coral Sr/Ca reconstruction (Hendy et al. 2002). Due to these possible confounding factors it is suggested that a number of coral records be replicated over a single time period of interest to identify and control for any non-climate related inconsistencies within corals (Lough 2004). The main hindrance to performing multiple replicates over a single time period is the expense of sample analysis and highly demanding level of physical preparation required to produce a single replicate, making performing multiple replications over a single time period prohibitive (Lough 2010).
Conclusions

The Kiritimati Island fossil coral record presented in this study represents a unique window into the climate of the 15th century. The aim of this study was to reconstruct 15th century climate and ENSO variability from the ECP using a fossil corals Sr/Ca ratio geochemistry as a SST tracer. This was achieved and the geochemical climate signal from the coral were produced to reconstruct ENSO variability of the ECP from 1425 CE to 1471 CE ± 4 years. This climate record indicated cooler than modern SST and also showed a significantly reduced ENSO strength of 20% compared to modern ENSO. In conjunction with this the 15th century ENSO signal was seen to be less stable in time compared to modern, with more erratic shifts in ENSO variability seen in the fossil record. The findings presented in this study were reflected in other studies that covered 15th century climate in the ECP (Cobb et al. 2003, Hereid et al. 2013).
Recommendations for future work

This study provides a platform from which further investigation into the climate of the ECP during the 15th century can be made. Such further investigation should focus on:

- Compare the variability found in the fossil coral CH32 to a period of low ENSO activity in the modern record, ideally between 1915 and 1940 when ENSO strength is seen to be at its lowest, to better understand how the decreased ENSO signal during the 15th century differs from the entire range of the modern record.
- Compiling δ18O data for the fossil coral CH32 and comparing this to the Sr/Ca record presented herein.
- Attempting to decouple the SSS and SST relationship during the 15th century based on the CH32 fossil record to further investigate the proposed causes behind the discrepancies seen between the other existing proxy records.
- Continuing to extend the ECP coral proxy climate records back during the 15th century, focusing on both Sr/Ca in conjunction with δ18O as climate tracers from the island of Kiritimati
- Further characterising potential confounding factors in Sr/Ca ratios as a SST tracer particularly in relation to the effects of growth rates in order to better recreate climate signals in the future.
References:


46


**Appendix 1**

Thin-section analysis of fossil coral CH32
Figure 1: Coral Thin Sections (TS) from fossil coral CH32 viewed under plain-polarised light (left) and cross-polarised light (right) from the start (A1), middle (B3) and end (D3) of the coral. TS images were taken from locations along the slides that were assessed to be representative of the entire slice in terms of quality. The greyer areas in D3 are indicative of a TS that is slightly too thick, whereas the fluorescently bright colours in B3 are indicative of a TS that is slightly too thin. TS B3 correlates with the part of the coral that produced the strong cooling trend seen in the centre of the record, the absence of diagenetic features in the TS show it to be a feature of the climate rather than degradation of the coral material. All thin sections (including those not presented here) were determined to be of a similarly high standard with no evidence of either dissolution or re-precipitation of foreign CaCO₃ material.