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El Niño-Southern Oscillation during the past 50 years:

Jessica Jean Gaudry

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El Niño-Southern Oscillation during the past 50 years:

Abstract
Atmospheric and oceanographic fluctuations across the tropical Pacific Ocean are partly a function of the phenomena known as the El Niño Southern Oscillation (ENSO), which is recognised as the strongest signal of interannual climate variation in the world. Pioneering studies, which utilise recent living corals from Tarawa (1°N, 172°E) and Maiana (1°N, 173°E), in the western equatorial Pacific Ocean, indicate that coral oxygen isotope ($\delta^{18}$O) records from this region can be used to reflect variations in ENSO-related climate patterns (Cole et al. 1993; Urban et al. 2000). The $\delta^{18}$O signal, however, is a combination of both changes in sea surface temperature (SST) and in the $\delta^{18}$O of seawater ($\delta^{18}$O$_{sw}$), yet both these factors may change with ENSO variations. This study investigates the coral-derived climate signals of the past 50 years (~1960 to 2010) from Butaritari Atoll (~172°30′E, 3°30′N) located in the western central equatorial Pacific using paired Sr/Ca and $\delta^{18}$O proxies to separate the SST and $\delta^{18}$O$_{sw}$ signals. The Sr/Ca-derived SST results show a warming trend of $0.77 \pm 0.17$ °C and that decadal variability dominates over interannual. The Butaritari $\delta^{18}$O$_{sw}$ results provide additional climatic information about the balance of evaporation and precipitation, although no significant freshening trend is evident. Taken together, the Butaritari Sr/Ca-derived SST and $\delta^{18}$O$_{sw}$ results suggest the warming and/or freshening trends observed in coral $\delta^{18}$O reflect predominantly changes in SST for the past 50 years. The Butaritari SST trend is also consistent with Sr/Ca estimates from central equatorial Pacific islands and suggests warming at broader scale.

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El Niño-Southern Oscillation during the past 50 years: Reconstructions from a western Pacific coral

Jessica Jean Gaudry

A research report submitted in partial fulfilment of the requirements for the award of the degree of

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ABSTRACT

Atmospheric and oceanographic fluctuations across the tropical Pacific Ocean are partly a function of the phenomena known as the El Niño Southern Oscillation (ENSO), which is recognised as the strongest signal of interannual climate variation in the world. Pioneering studies, which utilise recent living corals from Tarawa (1°N, 172°E) and Maiana (1°N, 173°E), in the western equatorial Pacific Ocean, indicate that coral oxygen isotope (δ18O) records from this region can be used to reflect variations in ENSO-related climate patterns (Cole et al. 1993; Urban et al. 2000). The δ18O signal, however, is a combination of both changes in sea surface temperature (SST) and in the δ18O of seawater (δ18Osw), yet both these factors may change with ENSO variations. This study investigates the coral-derived climate signals of the past 50 years (~1960 to 2010) from Butaritari Atoll (~172°30′E, 3°30′N) located in the western central equatorial Pacific using paired Sr/Ca and δ18O proxies to separate the SST and δ18Osw signals. The Sr/Ca-derived SST results show a warming trend of 0.77 ± 0.17 °C and that decadal variability dominates over interannual. The Butaritari δ18Osw results provide additional climatic information about the balance of evaporation and precipitation, although no significant freshening trend is evident. Taken together, the Butaritari Sr/Ca-derived SST and δ18Osw results suggest the warming and/or freshening trends observed in coral δ18O reflect predominantly changes in SST for the past 50 years. The Butaritari SST trend is also consistent with Sr/Ca estimates from central equatorial Pacific islands and suggests warming at broader scale.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .................................................................................................................................................. i

ABSTRACT .................................................................................................................................................................. ii

TABLE OF CONTENTS .................................................................................................................................................. iii

LIST OF FIGURES ......................................................................................................................................................... v

LIST OF TABLES ........................................................................................................................................................... xiii

1. INTRODUCTION ....................................................................................................................................................... 14

2. LITERATURE REVIEW .................................................................................................................................................. 16
   2.1 Tropical Pacific climate .............................................................................................................................................. 16
      2.1.1 *El Niño Southern Oscillation* ........................................................................................................................... 16
      2.1.2 *Western equatorial Pacific* ............................................................................................................................. 17
   2.2 Climate reconstruction using corals ......................................................................................................................... 21
   2.3 Regional setting: Butaritari Atoll, Kiribati .............................................................................................................. 24
      2.3.1 Local climatology ................................................................................................................................................ 26

3. MATERIALS AND METHODS ....................................................................................................................................... 28
   3.1 Coral collection .......................................................................................................................................................... 28
   3.2 X-Radiography .......................................................................................................................................................... 29
   3.3 Coral dating and preservation ................................................................................................................................... 32
   3.4 Sample preparation .................................................................................................................................................... 32
   3.5 Sr/Ca analysis ........................................................................................................................................................... 33
   3.6 Isotope analysis ........................................................................................................................................................ 35
   3.7 Assigning chronology .............................................................................................................................................. 36

4. RESULTS ...................................................................................................................................................................... 38
   4.1 Butaritari geochemistry ........................................................................................................................................ 38

5. DISCUSSION ................................................................................................................................................................ 41
   5.1 Calibrating Sr/Ca to SST .......................................................................................................................................... 41
      5.1.1 Potential calibration uncertainties ....................................................................................................................... 44
      5.1.2 Sr/Ca-derived SST ............................................................................................................................................. 47
   5.2 Deciphering SSS from δ¹⁸O using coral-derived SST .................................................................................................. 48
   5.3 Coral geochemistry compared to local climatology ............................................................................................... 51
      5.3.1 Wavelet analysis .............................................................................................................................................. 55
LIST OF FIGURES

**Figure 1** – NINO regions of the Pacific Ocean (Australian Bureau of Meteorology 2012b). NINO 4 region covers the area 5°N-5°S, 160°E-150°W and contains Butaritari Atoll (yellow circle; ~172°30’E, 3°30’N), the area of interest in this study. ................................................................. 17

**Figure 2** – Colour enhanced image of 10-year mean (1982 to 1991) SST from satellite data. The warmest temperatures evident in the Western Pacific Warm Pool (dark orange and red colours correspond to SST higher than 28°C; from Yan et al. 1992). ......................................................................................... 18

**Figure 3** – a) The IPWP in February (blue) and September (red) as given by the 28°C isotherm based on the long-term (1900–2009) mean SST from the HadISST dataset. (b) Seasonal variation of the WPWP size (blue) and maximum SST (red) respectively. Units for the size and SST are 107 km2 and °C, respectively (from Bolan and Lixin 2012). ................................................................. 19

**Figure 4** – Migration of the eastern edge of the Western Pacific Warm Pool. Left panel is the longitude-time distribution of 4°N-4°S averaged SST, and the right panel is SSS for the same area. The thick white line is the Southern Oscillation Index (SOI). Sustained positive and negative SOI correspond to La Niña and El Niño phases, respectively. Contours are 1°C for SST and 0.25 psu for SSS. Dark shading in the left and right panels indicates higher SST and higher SSS, respectively. Orange lines indicate the longitudinal positions of Butaritari Atoll (~172°30’E, 3°30’N; this study), Tarawa (1°N, 172°E) and Maiana (1°N, 173°E). (Modified from Picaut et al. 2001). ......................................................................................... 20

**Figure 5** – Republic of Kiribati (Australian Bureau of Meteorology and CSIRO 2011). Butaritari Atoll is highlighted by the red rectangle and is located at ~172°30’E, 3°30’N, just north of the capital of Kiribati, Tarawa. ........................................ 25

**Figure 6** – A typical fore reef environment throughout the Gilbert Islands (Carilli pers. comm.). Dominant genera include *Porites*, *Pocillopora*, *Acropora*, *Heliopora* and crustose coralline algae (CCA). ......................................................................................... 25

**Figure 7** - Mean monthly SST for the time period between 1959 to 2010 derived from ERSSTv3b (Smith et al. 2008. Black contours = 0.5°C. The location of Butaritari
(this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a red square and green star respectively.

Figure 8 – Mean precipitation data for the time period between January 1979 to November 2011 derived from CMAP Precipitation data from NOAA NCEP CPC Merged Analysis monthly latest version 1 precipitation estimate (Xie and Arkin 1996; Xie and Arkin 1997). The location of Butaritari (this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a red square and purple star respectively.

Figure 9 – Map of Butaritari Atoll, Kiribati (~172°30’E, 3°30’N; N. Biribo pers. comm.). The yellow circle indicates the location of the modern coral used in this study.

Figure 10 – The underwater drilling of the *Porites sp.* modern coral (BUT3-2) from the fore reef on the southern side of Butaritari Atoll, Kiribati (~172°30’E, 3°30’N). The top surface of the coral was approximately 4 m underwater. A coral core approximately 83 cm in length and 4.5 cm in diameter was collected.

Figure 11 – X-ray positive images of the Butaritari modern coral (BUT3-2). The coral pieces are ordered sequentially such that the top surface of piece 1 is the youngest surface of the coral core, and the bottom of piece 7 is the oldest surface of the core. Red lines correspond to the maximum growth axis, and thus indicate the position of sampling transects used for both Sr/Ca and δ18O geochemical analysis.

Figure 12 – Preliminary bulk Sr/Ca samples test results for the Butaritari modern coral. Samples with weights of ~0.5 mg are represented by a triangle symbol and ~0.75 mg samples by a square symbol. Samples were measured from BUT3-2 piece 3 (blue symbols), BUT3-2 piece 5 (red symbols), and BUT3-2 piece 6 (green symbols).

Figure 13 - SST (ERSSTv3b; Smith *et al.* 2008) for the 2° x 2° grid square at 2°N, 172°E containing Butaritari for the period between 1959 and 2010. Monthly SST (red line) is compared to bi-monthly SST, derived from interpolation of monthly data (blue line). The bi-monthly SST trace overlies the monthly SST trace.
Figure 14 – Butaritari coral geochemistry (BUT3-2); Sr/Ca (red line), δ¹⁸O (green line) and δ¹³C (black line). Note: inverted y-axes. All values have been derived from along the same sampling transect. .............................................................. 38

Figure 15 – Time series of Butaritari coral geochemistry (BUT3-2); Sr/Ca (red line) and δ¹⁸O (green line), using ERSSTv3b SST data for the 2° x 2° grid square at 2°N, 172°E containing Butaritari (blue line; Smith et al. 2008). Note: inverted y-axes for Sr/Ca and δ¹⁸O. All data including SST have been interpolated to a bi-monthly resolution corresponding to 6 data points per year ........................................... 39

Figure 16 – Sr/Ca and δ¹⁸O residuals with the annual cycle removed for the period between 1959 and 2010. .............................................................. 40

Figure 17 – Bi-monthly Sr/Ca values of the Butaritari modern coral (BUT3-2) compared to bi-monthly SST. SST is from ERSSTv3b (Smith et al. 2008) for the 2° x 2° grid square at 2°N, 172°E, which includes Butaritari Island. Solid filled circles and coloured squares indicate the maxima and minima points used in the Sr/Ca-SST calibration (n = 90). These solid filled points are on average at an annual resolution corresponding to the summer maximum and winter minimum values for each year. The pair of green squares denotes the maxima point in the Sr/Ca record and the corresponding point in SST. The pair of orange squares denotes the minima point in the Sr/Ca record and the corresponding point in SST. The pair of pink squares denotes the minima SST point and the corresponding point in Sr/Ca. The pair of yellow squares denotes the maxima point in the SST record and the corresponding point in Sr/Ca. .............................................................. 42

Figure 18 – Butaritari modern coral (BUT3-2) Sr/Ca-SST calibration points and equation. Red crosses indicate the Sr/Ca values and corresponding SST from Figure 17. Blue line is a linear regression through the Sr/Ca-SST points. Green circle denotes the maxima Sr/Ca value and orange circle denotes the Sr/Ca minima value (Also shown in Figure 17). .............................................................. 43

Figure 19 – Modern Butaritari Sr/Ca-SST reconstructions. Blue line is SST for Butarirari (ERSSTv3b; Smith et al. 2008). Red line is the coral-derived estimates of SST, calculated from the Butaritari Sr/Ca-SST relationship: Sr/Ca = 10.904 – 0.0688 * SST (r² = 0.5818). A line of best fit has been fitted to both datasets. Black
dotted line is monthly IGOSS SST for the 1° x 1° grid square at 171.5°E, 2.5°N, containing Butaritari (Reynolds et al. 2002). ................................................................. 44

**Figure 20** – Monthly observation counts for data points used in the International Comprehensive Ocean Atmosphere Data Set (ICOADS), from which ERSSTv3b is derived (Research Data Archive 2012). ................................................................. 45

**Figure 21** – Modern Butaritari coral geochemistry compared to local climatology and ENSO indices. a) Butaritari δ¹⁸O (green). b) Butaritari Sr/Ca-derived SST (red). c) Butaritari Δδ¹⁸Osw (blue). d) SST (red) from ERSSTv3b (Smith et al. 2008) for the 2° x 2° grid square at 2°N, 172°E. The SST dataset has been interpolated to bi-monthly resolution to correspond with the resolution of the coral geochemistry data. e) Normalised mean daily Butaritari precipitation for each month from NOAA NCDC GCPS MONTHLY STATION mean precipitation (Baker et al. 1994) for 1959 to 1982 (light blue) from Butaritari, station ID 9160100, at 3.03N, 172.78E; and monthly CMAP Estimated Precipitation (Xie and Arkin 1996; Xie and Arkin 1997) for 1979 to 2010 (dark blue) for the 2.5° x 2.5° grid square at 1.25N, 171.25W. f) Monthly SSS (at 5.01 meters depth) from CARTON-GIESE SODA latest version (v2p1p6) for the 0.5° x 0.5° grid square at 172.25E 3.25N containing Butaritari Island (Carton and Giese 2008). g) Monthly NINO 4 data (yellow) for the NINO 4 region (5°N-5°S, 160°E-150°W) sourced from http://www.cpc.ncep.noaa.gov. h) Monthly SOI data (pink) sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soi2.shtml). El Niño threshold (SOI < -8; Australian Bureau of Meteorology 2012a) is marked by a dotted line on the SOI trace. La Niña threshold (SOI > 8) is marked by a dashed line on the SOI trace. El Niño events (SOI < -8 for sustained periods) are shaded dark grey. La Niña events (SOI > 8 for sustained periods) are shaded light grey. Note: inverted y-axes for a), c), f) and h). .................................................................................................................................................. 53

**Figure 22** – Modified version of **Figure 4**. Migration of the eastern edge of the Western Pacific Warm Pool. Left panel is the longitude-time distribution of 4°N-4°S averaged SST, and the right panel is SSS for the same area. The thick white line is the Southern Oscillation Index (SOI). Sustained positive and negative SOI correspond to La Niña and El Niño phases, respectively. Contours are 1°C for SST
and 0.25 psu for SSS. Dark shading in the left and right panels indicates higher SST and higher SSS, respectively. Orange lines indicate the longitudinal positions of Butaritari Atoll (~172°30'E, 3°30'N; this study), Tarawa (1°N, 172°E) and Maiana (1°N, 173°E). (Modified from Picaut et al. 2001). Blue shaded areas correspond to years of slight misalignment between Butaritari coral and ENSO indices evident in Figure 21).

Figure 23 – Part 1 and 2 is wavelet analysis for Butaritari coral δ18O and Sr/Ca-derived SST, respectively. (a) Coral record. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Figure 24 – (a) NINO4 anomaly. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Figure 25 – (a) SOI. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.
Figure 26 – (a) SST (ERSSTv3b; Smith et al. 2008). (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Figure 27 – Coral δ¹⁸O records from three western equatorial Pacific islands. A) 1840 to 2000. Green dotted line corresponds to bi-monthly Butaritari (3°30’N, 172°30’E) δ¹⁸O data from this study. Blue dotted line corresponds to monthly Tarawa (1°N, 172°E) δ¹⁸O data from Cole et al. (1993). Red dotted line corresponds to bi-monthly Maiana (1°N, 173°E) δ¹⁸O data from Urban et al. (2000). Solid lines correspond to moving averages (12 point for Butaritari and Maiana, and 24 point for Tarawa), which remove < 2 year variability from the data. Black bracket indicates the area of overlap with the Butaritari record. B) Same as for A) except for 1959 to 2000, the area of overlap with the Butaritari record. Monthly SOI data (pink) sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soi2.shtml). El Niño threshold (SOI < -8) is marked by a dotted line on the SOI trace. La Niña threshold (SOI > 8) is marked by a dashed line on the SOI trace. El Niño events (SOI < -8 for sustained periods) are shaded dark grey. La Niña events (SOI > 8 for sustained periods) are shaded light grey.

Figure 28 – (a) Tarawa δ¹⁸O for the period of overlap with the Butaritari record. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.
Figure 29 – (a) Maiana δ¹⁸O for the period of overlap with the Butaritari record. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Figure 30 – Zoomed in section of Figure 8. Mean precipitation data for the time period between January 1979 to November 2011 derived from CMAP Precipitation data from NOAA NCEP CPC Merged Analysis monthly latest version 1 precipitation estimate (Xie and Arkin 1996; Xie and Arkin 1997). The location of Butaritari (this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a red square and purple star respectively. Central Pacific islands: Palmyra (blue rectangle; 6°N, 162°W), Fanning (black rectangle; 4°N, 159°W) and Christmas (orange rectangle; 2°N, 157°W).

Figure 31 – Zoomed in section of Figure 7. Mean monthly SST for the time period between 1959 to 2010 derived from ERSSTv3b (Smith et al. 2008). Black contours = 0.5°C. The location of Butaritari (this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a black square and purple star respectively. Central Pacific islands: Palmyra (blue rectangle; 6°N, 162°W), Fanning (black rectangle; 4°N, 159°W) and Christmas (orange rectangle; 2°N, 157°W).

Figure 32 – δ¹⁸O records and trend lines for Butaritari (green), Tarawa (blue) and Maiana (red). The Tarawa and Maiana data are from longer datasets however they have been truncated to the period of overlap with the Butaritari record (see Figure 27). The black bracket indicates the common interval between all three datasets.

Figure 33 – Coral δ¹⁸O records from three western (a) and three central (b) equatorial Pacific islands. a) δ¹⁸O records from Butaritari (green line; bi-monthly resolution; 3°30’N, 172°30’E; this study), Tarawa (blue line; monthly resolution; 1°N, 172°E;

Figure 34 – Coral Sr/Ca-derived SST records from one western (a) and three central (b) equatorial Pacific islands. a) Sr/Ca-derived SST record from Butaritari (green line; bi-monthly resolution; 3°30’N, 172°30’E; this study) between 1959 and 1990. b) Sr/Ca-derived SST records from Palmyra (pink line; monthly resolution; 6°N, 162°W; Cobb et al. 2001), Fanning (black line; monthly resolution; 4°N, 159°W; Nurhati et al. 2009) and Christmas (orange line; monthly resolution; 2°N, 157°W; Nurhati et al. 2009) islands between 1972 and 1998. c) Monthly Southern Oscillation Index (SOI) as described in Figure 33. The black bracket indicates the common interval between datasets (1972-1998).

Figure 35 – Relative variations in δ¹⁸Osw records (SSS proxy) from one western (a) and three central (b) equatorial Pacific islands. a) δ¹⁸Osw record from Butaritari (green line; bi-monthly resolution; 3°30’N, 172°30’E; this study) between 1959 and 1990. b) δ¹⁸Osw records from Palmyra (pink line; monthly resolution; 6°N, 162°W; Cobb et al. 2001), Fanning (black line; monthly resolution; 4°N, 159°W; Nurhati et al. 2009) and Christmas (orange line; monthly resolution; 2°N, 157°W; Nurhati et al. 2009) islands between 1972 and 1998. c) Monthly Southern Oscillation Index (SOI) as described in Figure 33.
LIST OF TABLES

**Table 1** – ICP-OES instrument settings for Sr/Ca runs in this study..........................34

**Table 2** – Preliminary Butaritari bulk Sr/Ca samples test results. ..............................35

**Table 3** - δ¹⁸O trends in Butaritari (this study), Tarawa (Cole *et al.* 1993) and Maiana (Urban *et al.* 2000) for the common data interval (1959-1990) and overall (1959-2010 for Butaritari and 1959-1994 for Maiana). ........................................69

**Table 4** - Butaritari (this study), Tarawa (Cole *et al.* 1993) and Maiana (Urban *et al.* 2000), Palmyra, Fanning and Christmas (Nurhati *et al.* 2009) δ¹⁸O trends. ......70

**Table 5** - Butaritari (this study), Palmyra, Fanning and Christmas (Nurhati *et al.* 2009) Sr/Ca-SST trends. ..............................................................................................................72

**Table 6** - Butaritari (this study), Palmyra, Fanning and Christmas (Nurhati *et al.* 2009) δ¹⁸O_sw trends. ..............................................................................................................73
1. INTRODUCTION

El Niño Southern Oscillation (ENSO), has been recognised as the strongest signal of interannual climate variation in the world (Wang et al. 1999). While ENSO primarily occurs within the tropics, it has also been recognised to influence global climate through atmospheric teleconnections (Philander 1990). ENSO forcing of both the atmosphere and ocean is strongest in the west/central equatorial Pacific between approximately 150°E and 150°W (Clarke 2008). The western equatorial Pacific is recognised by warm and fresh water, primarily corresponding to the Indo-Pacific Warm Pool (IPWP) (Yan et al. 1992). This large body of warm water plays an integral role in convection patterns across the Pacific. Changes in the IPWP can be attributed to variability in solar radiance, ENSO events, atmospheric aerosols (from volcanic activity) and global warming (Yan et al. 1992).

Despite the Pacific region having a major influence on global climate, short and sparse instrumental datasets limit the investigation of climatic patterns across this region. The skeletal material of modern and fossil coral can be used as a high resolution geochemical record to reconstruct localised climatic information (Cohen and McConnaughey 2003). Previous work based on δ¹⁸O in corals from Tarawa (1°N, 172°E; Cole and Fairbanks 1990; Cole et al. 1993) and Maiana (1°N, 173°E; Urban et al. 2000) Islands, located close to Butaritari Island (~172°30’E, 3°30’N) and at the eastern edge of the Indo-Pacific Warm Pool (IPWP), show that this region is sensitive to ENSO. Cole et al. (1993) used spectral analysis of a 96 year long coral record to show shifts in the distribution of variance between annual and interannual periods within the twentieth century. These observed changes suggest variation in the strength of the ENSO signal over time. The Maiana coral record reflects a gradual transition of ENSO variability in the early twentieth century and abrupt shift in 1976, both towards warmer and wetter climatic conditions (Urban et al. 2000). Changes of ~2.9 to 4 year periodicity of ENSO have also been noted to occur during this time. These studies indicate that ENSO variability can change even with only small climatological changes. One limitation of these studies is that they only use δ¹⁸O to interpret these climatic variations. The δ¹⁸O signal reflects both changes in sea surface temperature
(SST) and in the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$), which corresponds to the balance of evaporation/precipitation (Swart and Quay 1980). Paired Sr/Ca and $\delta^{18}O$ data can help separate SST and $\delta^{18}O_{sw}$ influences from one another (Gagan et al. 2000). Paired geochemical records from the Line Islands in the central equatorial Pacific suggest significant warming and/or freshening trends in the late twentieth century (Nurhati et al. 2009). However, additional records are needed to test if these trends are specific to the central Pacific or occur more broadly across the equatorial Pacific and Pacific basin.

This study aims to investigate the climatic variability of the western equatorial Pacific, with particular reference to ENSO. A ~50 year $\delta^{18}O$ and Sr/Ca record was produced from a coral core from Butaritari Island. The Butaritari coral records, spanning 1959-2010 were compared to existing instrumental data (SST, precipitation and SSS) to comment on the localised variability surrounding Butaritari. The Butaritari coral records were also compared to published records from nearby Tarawa and Maiana Islands, and to records from the Line Islands, in the central equatorial Pacific. The records showed a similar $\delta^{18}O$ trend towards warmer and wetter conditions for the late twentieth century. Comparisons of Sr/Ca-derived SST trends for corals from Butaritari and the Line Island corals suggest that SST accounts for only part of the trend. Prior to this study there were no other published coral proxy records from Butaritari Atoll. This study is also therefore able to contribute to the limited coral-derived climatological information from the western equatorial Pacific.
2. LITERATURE REVIEW

2.1 Tropical Pacific climate

2.1.1 El Niño Southern Oscillation

In the equatorial Pacific, easterly trade winds across the equatorial Pacific are driven by a clear sea surface temperature (SST) gradient and coupled surface level pressure (SLP). These trade winds enable the upwelling of cold water in the eastern Pacific, which further forces an equatorial climatic feedback loop. During El Nino events, trade winds relax, upwelling diminishes, and warm waters from the western tropical Pacific migrate eastward.

Through the influential work of Bjerknes (1969), the El Niño oceanic signal was linked to the atmospheric fluctuation of the Indo-Pacific, known as the Southern Oscillation. The Southern Oscillation combines the eastern Pacific SST and pressure gradient together (Sarachik and Cane 2010). The resulting phenomena, El Niño Southern Oscillation (ENSO), has been recognised as the strongest signal of interannual climate variation in the world (Wang et al. 1999). While it typically occurs in the tropics, the impacts of ENSO are felt globally, as the climate outside of the tropics is altered through ENSO teleconnections (Philander 1990). ENSO involves both oceanic and atmospheric processes and the fundamental relations between them (Neelin et al. 1998).

ENSO can affect global climate through atmospheric teleconnections. Teleconnections can be described as ‘statistically significant correlations between weather events that occur at different places of the Earth’ (Stewart 2008). Through ENSO teleconnections, equatorial ENSO events and resulting regional climatic patterns have a much larger global effect. Understanding these effects is important for both current and future patterns of climate, especially in relation to anthropogenic-induced warming of the earth.
In order to describe changes in the ocean-atmosphere dynamics associated with ENSO the tropical Pacific Ocean has been divided into ‘NINO’ regions. NINO 1 and 2 are located in the far eastern Pacific just below the equator, while NINO 3, and NINO 4 cover much wider areas across the eastern, central and western equatorial Pacific (Figure 1). The NINO 3.4 region is the intersection of the NINO 3 and NINO 4 regions, and an index of sea surface temperature anomalies in the NINO 3.4 region is the most commonly used measure of ocean-related ENSO variability. The NINO 4 region is of most relevance in this study as the coral utilised for geochemical analysis is sourced from Butaritari Atoll (~172°30′E, 3°30′N), which is situated well within this region.

The strength of the Southern Oscillation is measured by the Southern Oscillation Index (SOI). SOI suggests the intensity of El Niño and La Niña episodes across the Pacific. SOI values less than 8 for sustained periods (generally 5-6 months) often indicate El Niño events and SOI values greater than 8 for sustained periods indicate La Niña events (Australian Bureau of Meteorology 2012a).

![Figure 1 – NINO regions of the Pacific Ocean (Australian Bureau of Meteorology 2012b). NINO 4 region covers the area 5°N-5°S, 160°E-150°W and contains Butaritari Atoll (yellow circle; ~172°30′E, 3°30′N), the area of interest in this study.](image)

2.1.2 Western equatorial Pacific

ENSO forcing of both the atmosphere and ocean is strongest in the west/central equatorial Pacific between approximately 150°E and 150°W (Clarke 2008). In addition to ENSO, the Indo-Pacific Warm Pool (IPWP) is another prominent climate-
related feature of the equatorial Pacific. The IPWP is typically situated laterally within the Indo-Pacific region, throughout the Indonesian archipelago and the eastern equatorial Indian Ocean (Figure 2), and can also be termed the Western Pacific Warm Pool. As its name suggests, the IPWP is characterised by a pool of warm sea water, and through definition has a mean sea surface temperature (SST) greater than 28°C (Figure 2; Yan et al. 1992). It has been recognised as the warmest open-ocean water body on Earth (Abram et al. 2009). Hénin et al. (1998) found that the IPWP also exhibits relatively low salinity (< 35psu), and hence it is sometimes termed the ‘fresh pool’. On average the area west of the International Date Line which includes the IPWP receives in excess of 3 m of rainfall per year and this contributes to low salinity (Webster and Lukas 1992).

**Figure 2** – Colour enhanced image of 10-year mean (1982 to 1991) SST from satellite data. The warmest temperatures evident in the Western Pacific Warm Pool (dark orange and red colours correspond to SST higher than 28°C; from Yan et al. 1992).

SSTs higher than 28°C are associated with intense atmospheric convection (Lau and Chan 1988). Fu et al. (1994) suggest the onset of deep convection requires both positive convective available energy and an unstable planetary boundary layer, and is generally enhanced with SSTs greater than 28°C. Intense atmospheric convection occurs over the IPWP and impacts heat and water vapour distribution (Abram et al. 2009). The dynamics of IPWP, notably involving high SSTs are highly interlinked with both the Walker and Hadley circulations across the Pacific (Bolan and Lixin
The high SSTs in the IPWP can thus project a strong influence on tropical climate and also global climate through teleconnections. The climate dynamics in the IPWP are thought to play a major role in initiating El Niño events (Abram et al. 2009).

The IPWP migrates seasonally, with the northward movement of the northern boundary peaking around September (Figure 3; Bolan and Lixin 2012). By February, the IPWP has migrated back south. In addition, the size of the IPWP varies at a seasonal scale, with largest extent occurring in September and smallest in January (Figure 3a). Yan et al. (1992) demonstrate that from 1983 to 1987 both the mean annual SST and size of the IPWP increased and between 1987 and 1991 warm pool size and SST fluctuated. These variations were attributed to variability in solar radiance, ENSO events, atmospheric aerosols (from volcanic activity) and global warming (Yan et al. 1992).

![Figure 3](image)

**Figure 3** – a) The IPWP in February (blue) and September (red) as given by the 28°C isotherm based on the long-term (1900–2009) mean SST from the HadISST dataset. (b) Seasonal variation of the WPWP size (blue) and maximum SST (red) respectively. Units for the size and SST are 107 km2 and °C, respectively (from Bolan and Lixin 2012).

The eastern edge of the IPWP experiences a number of unique conditions compared to the rest of the warm pool. The eastern edge corresponds to a separation front...
between the warm, low salinity waters of the IPWP, and the colder, high salinity water of the central eastern tropical Pacific (Picaut et al. 2001). The main characteristic of this eastern edge is the distinct salinity changes near the equator. There are also differences in SST along this front, however they are not well defined. The salinity front along the eastern periphery of the IPWP is mainly a product of zonal convergence between the western and central Pacific water bodies (Picaut et al. 1996; Eldin et al. 2004). This recognised Eastern Warm Pool Convergence Zone (EWPCZ) can migrate some thousands of kilometres eastward or westward along the equator, relative to El Niño (warm phase) and La Niña (cold phase) of ENSO (Picaut et al. 2001). For example, during the progression of the 1982/83 ENSO event, warm waters from the western equatorial Pacific migrated eastward (Yan et al. 1992; Figure 4). Zonal advection is the primary process driving the migrations of the eastern edge of the warm pool (McPhaden and Picaut 1990; Picaut and Delcroix 1995). Picaut et al. (2001) show that El Niño (negative SOI) is clearly delineated by eastward migration of the EWPCZ and La Niña (positive SOI) by westward migration (Figure 4).

![Figure 4 - Migration of the eastern edge of the Western Pacific Warm Pool. Left panel is the longitude-time distribution of 4°N-4°S averaged SST, and the right panel](image-url)
is SSS for the same area. The thick white line is the Southern Oscillation Index (SOI). Sustained positive and negative SOI correspond to La Niña and El Niño phases, respectively. Contours are 1°C for SST and 0.25 psu for SSS. Dark shading in the left and right panels indicates higher SST and higher SSS, respectively. Orange lines indicate the longitudinal positions of Butaritari Atoll (~172°30'E, 3°30'N; this study), Tarawa (1°N, 172°E) and Maiana (1°N, 173°E). (Modified from Picaut et al. 2001).

The dynamics of the IPWP and its distinct eastern edge are clearly very important to the climate of the western and central Pacific. Tracking the IPWP can reveal valuable information about annual fluctuations in SST and the varying extent of the IPWP. Furthermore the relationship between the dynamics of the IPWP and ENSO events can be used to help understand global climate changes (Yan et al. 1992).

As the dynamics of the IPWP strongly affect this region, and are tied to ENSO events, records of past SST and SSS from corals in this region could provide long-term reconstructions of past ENSO events, possibly extending records to pre-instrumental time periods.

### 2.2 Climate reconstruction using corals

Corals are clonal animals and consist of living anemone-like polyps and zooanthellae algae (Cohen and McConnaughey 2003). Colonies can live for significant periods of time, wherein their continuous skeletal calcification forms a geochemical record of the environment in which they live. Massive modern and fossil corals sourced from the tropical ocean are extremely useful for investigating modern and paleoclimate variability. In regard to paleoclimate, they are some of the only known archives that provide records of tropical marine conditions with both annual resolution and multi-century length, which are required for the quantification of seasonal-centennial fluctuations at the tropical ocean surface (Dunbar and Cole 1993). A large number of geochemical tracers can be identified within the aragonite skeleton of massive corals. In recent decades, major effort has been put into identifying and testing the robustness of tracers of SST and salinity (SSS) in corals (Corrège 2006). Coral strontium/calcium (Sr/Ca) ratios and oxygen isotope ratios (δ¹⁸O) have been recognised as the most
useful tracers of SST, although $\delta^{18}O$ is also significantly influenced by changes in seawater $\delta^{18}O$, which can alter the SST signal (Corrège 2006).

Coral samples are measured for $\delta^{18}O$ via mass spectrometry and the results are reported in the following form (Epstein et al. 1953, Weber and Woodhead 1972), where $\delta^{18}O$ is the difference in per mil of the O$^{16}$ to O$^{18}$ ratio between the sample and reference gas:

$$\delta^{18}O \, (‰) = \left( \frac{18O/^{18}O}_{sample} - \frac{18O/^{18}O}_{standard} \right) \times 1000$$

$\delta^{18}O$ is receptive to both SST and hydrology changes. Epstein et al. (1953) found that a change of approximately -0.22 ‰ per 1°C increase in temperature is reflected by the $\delta^{18}O$ in biogenic carbonates, such that more negative $\delta^{18}O$ values correspond to warmer temperatures and more positive values correspond to cooler temperatures.

Fairbanks and Dodge (1979) show that monthly variability in SST could be resolved using coral $\delta^{18}O$. However, coral $\delta^{18}O$ also reflects variations in the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) (Swart and Quay 1980). Changes in $\delta^{18}O$ due to seawater are a function of evaporation and precipitation cycles, wherein more positive $\delta^{18}O$ values reflect net evaporation and more negative $\delta^{18}O$ values reflect net precipitation (Dansgaard 1964).

As the $\delta^{18}O$ signal is inherently linked to both SST and $\delta^{18}O_{sw}$ and this relationship can change over time, determining a pure SST signal from coral $\delta^{18}O$ can be difficult. In areas such as the tropical Pacific, warm water bodies (more negative $\delta^{18}O$) are tied to convection patterns and hence precipitation (higher rainfall equates to more negative $\delta^{18}O$). In this region, it is thus generally accepted that more negative $\delta^{18}O$ values correspond to warmer and/or wetter environmental conditions, and more positive $\delta^{18}O$ values reflect colder and/or drier conditions (Gagan et al. 2000; Corrège 2006; Grottoli and Eakin 2007).

Sr/Ca ratios derived from corals have the potential to provide information on the temperature of seawater (Smith et al. 1979), which depending on the study site, can provide further information about atmospheric and oceanographic patterns such as ENSO. Sr substitutes for Ca in coral aragonite lattices and there is an inverse linear
relationship between coral Sr/Ca and ambient water temperature in with the aragonite skeletal precipitation occurred (Smith et al. 1979). In 1992, Beck et al. first used Sr/Ca ratios to accurately reconstruct SST. Using high precision Thermal Ionisation Mass Spectrometry (TIMS), SST was sufficiently resolved to show annual tropical SST variations. Since then, Sr/Ca has become a well-developed proxy for SST (Shen et al. 1996; Alibert and McCulloch 1997; Gagan et al. 1998). As the proportion of variability in seawater Sr/Ca is much lower than that of δ¹⁸O, Sr/Ca is considered a much ‘cleaner’ SST tracer compared to δ¹⁸O (Corrège 2006).

When taken together, high resolution measurements of coral Sr/Ca and δ¹⁸O can offer insight into the surface-ocean hydrologic balance and can be used to determine the evaporation and precipitation balance at the particular coral collection site (Gagan et al. 2000). Through a number of methods, the Sr/Ca-derived SST contribution can be removed from coral δ¹⁸O, to reconstruct coral δ¹⁸O_sw information (McCulloch et al. 1994; Gagan et al. 1998; Ren et al. 2002; Cahyarini et al. 2008). When analysed in this way, corals can provide both SST and δ¹⁸O_sw signals. Changes in SSS can be inferred from the relative variations in δ¹⁸O_sw using a linear δ¹⁸O_sw-SSS relationship such as the one proposed by Fairbanks et al. (1997).

Corals collected from across the equatorial Pacific can capture changes in SST and SSS/precipitation that develop from oscillations in ENSO (Cole and Fairbanks 1990; Cole et al. 1993; Evans et al. 1998; Urban et al. 2000; Tudhope et al. 2001; Cobb et al. 2003; Woodroffe et al. 2003; McGregor and Gagan 2004; Nurhati et al. 2009). In addition to supplementing existing instrumental records of ENSO variability, corals can extend beyond these records and provide insight into how ENSO has varied over larger time scales. A pioneering study by Cole et al. (1993) used spectral analysis of a 96 year long δ¹⁸O record from Tarawa Atoll (1°N, 172°E) in the western equatorial Pacific to show shifts in the distribution of variance between annual and interannual periods within the twentieth century. These observed changes suggest variation in the strength of the ENSO signal over time. The Tarawa δ¹⁸O record offers an high resolution and high quality ENSO history to rival instrumental climate records for the same time period (Cole et al. 1993). A 155 year long δ¹⁸O coral record from Maiana Atoll just east of Tarawa, shows a gradual transition of ENSO variability in the early
twentieth century and abrupt shift in 1976, both towards warmer and wetter climatic conditions (Urban et al. 2000). ENSO periods changed from ~2.9 years to 4 years over this time. These results suggest tropical Pacific variability is linked to mean background climate and changes have occurred during both episodes of natural and anthropogenic-driven climate variations.

2.3 Regional setting: Butaritari Atoll, Kiribati

This study will investigate the climatological information derived from coral cores collected from Butaritari Atoll. Butaritari Atoll is part of the Republic of Kiribati, located in the western and central equatorial Pacific Ocean. Butaritari is just west of the International Date Line, which runs directly through Kiribati. Kiribati encompasses three major island groups, the Gilbert Islands, Phoenix Islands and Line Islands, which are spread across 3 million km$^2$ of the central Pacific Ocean between latitudes 4°N and 3°S, and longitudes 172°E and 157°W, corresponding to both the western and central equatorial Pacific (Figure 5; Tebano et al. 2008). The 33 low-lying coral islands including 10 coral atolls that make up Kiribati cover a total land area of 811 km$^2$. The Gilbert group is comprised of 17 islands (including Banaba on the eastern border of Kiribati) and has a total land area of 286 km$^2$. The raised coral island of Banaba stands 81 m above sea level and is the highest point within the Republic of Kiribati (Tooru et al. 2010). Butaritari is located at ~172°30′E, 3°30′N and is in the northern part of the Gilbert group. It is situated along the eastern edge of the IPWP and covers an area of 13.6 km$^2$. Tarawa (1°N, 172°E), the capital of Kiribati, is situated approximately 200 km$^2$ due south of Butaritari.
**Figure 5** – Republic of Kiribati (Australian Bureau of Meteorology and CSIRO 2011). Butaritari Atoll is highlighted by the red rectangle and is located at ~172°30’E, 3°30’N, just north of the capital of Kiribati, Tarawa.

**Figure 6** – A typical fore reef environment throughout the Gilbert Islands (Carilli pers. comm.). Dominant genera include *Porites*, *Pocillopora*, *Acropora*, *Heliopora* and crustose coralline algae (CCA).

The hard substrates on forereef habitats throughout the Gilbert Islands are dominated by *Porites spp*, *Pocillopora spp*, and *Acropora spp*, scleractinian corals, *Heliopora coerulea* octocorals and crustose coralline algae (CCA) (**Figure 6**). The location of Butaritari is advantageous as a study site for the investigation of equatorial ENSO-
driven climatic patterns, particularly in regard to changes in the EWPCZ. As evident in Figure 4, Butaritari and its neighbouring islands of Tarawa and Maiana, are centrally located within the eastward-westward migration zone of the eastern edge of IPWP. Along the EWPCZ, El Niño events (negative SOI) are clearly delineated by eastward migration of the eastern edge and La Niña (positive SOI) by westward migration (Picaut et al. 2001). Overall Butaritari is considered to be located at the heart of equatorial zone in which the IPWP, central Pacific and ITCZ converge.

2.3.1 Local climatology

Butaritari Atoll is situated in the western equatorial Pacific, along the eastern edge of the IPWP. Figure 7 illustrates in location of the IPWP with SST equal to or greater than 28°C (Yan et al. 1992). Over the time period between 1959 and 2010, Butaritari has experienced mean SST of 28.9°C, with values between 26.9°C and 30.4°C (Smith et al. 2008). The variation in these temperatures may be a result of the east-west migration of the east edge of the IPWP, according to ENSO. Butaritari is commonly associated with high precipitation, with an average rainfall rate of approximately 4 to 8 mm/day (Figure 8; Baker et al. 1994; Xie and Arkin 1996; Xie and Arkin 1997). In cool ENSO phases, easterly surface winds and the Indonesian Low convective maximum moves over the western Pacific and westerly flows move drier air to the central and east Pacific (Cole et al. 1993). During ENSO warm phases, this region experiences enhanced convection accompanied by intense rainfall (Cole and Fairbanks 1990). During El Niño events Butaritari experiences warmer SSTs and above average precipitation. In contrast, La Niña events are periods of cooler SST and lower precipitation.
Figure 7 - Mean monthly SST for the time period between 1959 to 2010 derived from ERSSTv3b (Smith et al. 2008. Black contours = 0.5°C. The location of Butaritari (this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a red square and green star respectively.

Figure 8 – Mean precipitation data for the time period between January 1979 to November 2011 derived from CMAP Precipitation data from NOAA NCEP CPC Merged Analysis monthly latest version 1 precipitation estimate (Xie and Arkin 1996; Xie and Arkin 1997). The location of Butaritari (this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a red square and purple star respectively.
3. MATERIALS AND METHODS

3.1 Coral collection

A core from a modern *Porites sp.* coral (BUT3-2) was collected from Butaritari Atoll, Kiribati (~172°30’E, 3°30’N; Figure 9) in May 2010 by J. Carilli. The coral was situated on the fore-reef on the southern side of the Atoll, in a similar reefscape environment depicted in Figure 6 (See Section 2.3). This area is on the ocean side of the Butaritari Atoll, and hence is exposed to surrounding oceanic currents and influences. The core was collected underwater using a power drill (Figure 10). The top surface of the coral was approximately 4 m underwater. The core was drilled from the top surface in the middle of the coral head and was approximately 83 cm in length and 4.5 cm in diameter.

![Figure 9](#) – Map of Butaritari Atoll, Kiribati (~172°30’E, 3°30’N; N. Biribo pers. comm.). The yellow circle indicates the location of the modern coral used in this study.
Figure 10 – The underwater drilling of the *Porites sp.* modern coral (BUT3-2) from the fore reef on the southern side of Butartari Atoll, Kiribati (~172°30’E, 3°30’N). The top surface of the coral was approximately 4 m underwater. A coral core approximately 83 cm in length and 4.5 cm in diameter was collected.

The coral core was cut into a 6 to 7mm thick slice, through the length of the core, using a water-lubricated diamond saw. The slice was taken perpendicular to the coral’s main vertical growth axis to ensure annual density banding could be identified when the slice was x-rayed (Lough 2008). This slice was used for geochemical analysis in this study.

3.2 X-Radiography

The x-radiographs of the Butaritari modern coral slice were obtained at Illawarra Radiology Group Warrawong in 2011, prior to the commencement of this project (J. Carilli pers. comm.). The images were fitted to a 1:1 scale to enable a direct and accurate overlay on top of the coral slice, which is important in establishing the location of the maximum growth axis. The images were changed from x-ray negative to x-ray positive images, to ensure that the darker bands correspond to denser material and conversely, lighter bands correspond to less dense material. In addition, the
contrast and brightness of the x-ray images were modified to show the density banding as clearly as possible. The coral slice is made up of 7 pieces, all of which were x-rayed. However, only pieces 1 to 4 were utilised in this study (Figure 11).

X-radiography was used to examine the density differences within each coral sample. Differences in the density of coral material can provide useful visual information about defects within a coral such as borer holes and major diagenesis such as large areas of dense calcite (McGregor and Gagan 2003), and also reveal the coral annual growth rates and the maximum growth axis. Corals show annual variations in their skeletal density (shown in x-ray), and arise from small differences in the magnitude of linear extension rates relative to calcification rate (Dunbar and Cole 1996). The growth rate of a coral can be estimated through examining the dark and light density banding in the x-ray, wherein each major dark and light band pair can reflect one year’s growth (McGregor 2011). Furthermore, by noting the overall direction of coral growth and the ‘peaks’ and ‘troughs’ in the growth pattern, the maximum growth axis of the coral can be identified. Identifying this axis is important in determining the most suitable milling paths within the coral and most appropriately milling increments to capture a monthly/bi-monthly resolution of the coral record and its related climatological data. The most stable extension rates and environmental conditions of coral growth are found along the maximum growth axis (De Villiers et al. 1995).

The x-rays of the Butaritari modern coral reveal clear annual density banding (Figure 11). The minimum growth distance of any annual cycle along the coral pieces is ~10 mm and the maximum is ~17 mm. Overall the average distance of growth is 12.5 mm/year. Based on these, a high resolution milling increment of 0.5mm was chosen and corresponds to approximately 25 milled samples per year, equal to a fortnightly resolution.
Figure 11 – X-ray positive images of the Butaritari modern coral (BUT3-2). The coral pieces are ordered sequentially such that the top surface of piece 1 is the youngest surface of the coral core, and the bottom of piece 7 is the oldest surface of the core. Red lines correspond to the maximum growth axis, and thus indicate the position of sampling transects used for both Sr/Ca and δ18O geochemical analysis.
3.3 Coral dating and preservation

The top surface of the modern *Porites sp* head coral BUT3-2 was still living when it was collected from its underwater environment on the relatively sheltered fore reef on the lee side of Butaritari Atoll. This top surface acts as a marking point for the age of the coral. The coral core was drilled in May 2010, and thus it can be assumed that this is the age of the top surface. Moving down the core, the chronology of the coral can be visualised using x-radiography, through inspecting the growth rate and annual density bands within the core (See Section 3.2 X-Radiography). Counting the annual banding throughout the coral core indicates the number of years the coral has been alive and preserved within the coral. The Butaritari modern coral core extends over approximately 60 years, from 1950 to 2010, based on density band counts. However, this study only analysed the ~50 year period between ~1960 to 2010.

3.4 Sample preparation

Each 6 to 7 mm coral piece was trimmed so that the area corresponding to the sampling transect was positioned along the edge of the piece. The area encompassing the sampling transect was reduced in thickness using a 10 mm drill bit on a semi-automated computer-controlled CNC mill (Gagan *et al.* 1994). These 2 mm thick, 10 mm wide areas became the milling ledges. The ledge pieces were cleaned thoroughly using a Branson 450 ultrasonic probe and Milli Q water, and left to air-dry for 24 hours. This cleaning allows for the removal of any loose foreign material lodged within the skeletal coral surfaces, for example any coral powder or dust that may have accumulated during the ledge milling. The ledges were milled on the mill facilities at both Australian Nuclear Science and Technology Organisation (ANSTO) and the University of Wollongong (UOW). After cleaning, one sample was milled every 0.53 mm along the top 23.5 cm of the ledge, corresponding to piece 1 pf the core, and one sample was milled every 0.5 mm along the remainder of the coral ledge. Each sample was collected onto glassine paper and the powder was placed into a plastic Eppendorf vial. To prevent contamination between samples, a clearing cut was taken after every sample and compressed air was used to blow away any loose coral material from the milling area.
3.5 Sr/Ca analysis

An Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) was used to measure the Sr/Ca ratios of the coral samples. Prior to the Sr/Ca analysis, 10ml plastic centrifuge vials were systematically cleaned. The vials and accompanying lids were submerged in 5% HNO₃ for at least 24 hours. The vials and lids were rinsed three times with Milli Q water and left overnight to dry in a ~40°C oven. Milled coral samples were weighed out on an Orian Cahn C-35 microbalance at UOW and then placed in clean HNO₃ acid-washed vials. Each vial contained 0.5 ± 0.05 mg of milled coral material. These samples were dissolved with 1% HNO₃ (Merck Suprapur) using an adjustable Eppendorf pipette. The volume of acid added was relative to the weight of sample present in each vial. To obtain a ~35 ppm final [Ca] concentration, 0.1 mL of acid was added for every 0.01 mg of sample material. The amounts of acid were rounded down to one decimal place, because a slight increase in concentration was deemed more appropriate than a slight dilution. The vials were then transferred into a 40°C sonicator bath for ~1 hour to thoroughly dissolve the coral material.

The samples were analysed on a Vista-PRO Simultaneous ICP-OES, produced by Varian Inc at ANSTO. The instrument was optimised for Sr/Ca and was calibrated with a number of standard solutions containing Ca, Sr, Ba, P and Mg across a range of concentrations. These concentrations fell across an appropriate range relative to the expected values of the coral samples. A single blank vial with 1% HNO₃ solution was run before the samples to make sure the vials and acid were free from contamination. A reference solution, known as the Internal Calibration Verification (ICV) was run after every two coral samples to monitor and measure any internal drift in the machine’s measurements during each analysis. If there was any internal drift, the Sr/Ca ratios were corrected against this ICV solution. The average deviation of the ICV from its expected value was used to determine the precision of the experiment (RSD error) and impacts the final uncertainty.
A recognised international calibration standard (JCp-1; Okai et al. 2002) with a known ANSTO lab value was also run with the samples, so that the results could be corrected and compared to other analyses from different runs and laboratories. The samples in each run were corrected back to the ANSTO mean laboratory value of 8.811 ± 0.014 mmol/mol for the JCp-1 standard. The standard deviation (SD) of repeat JCp-1 analyses was 0.02 mmol/mol (n = 8) with an average JCp-1 value of 8.716 mmol/mol. To ensure consistency, the ICP-OES instrumental settings (Table 1) were maintained throughout the runs.

### Table 1 – ICP-OES instrument settings for Sr/Ca runs in this study.

<table>
<thead>
<tr>
<th>ICP-OES parameter</th>
<th>Setting</th>
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<tbody>
<tr>
<td>Power</td>
<td>1.2 kW</td>
</tr>
<tr>
<td>Plasma gas flow</td>
<td>15 L/min</td>
</tr>
<tr>
<td>Auxiliary gas flow</td>
<td>1.5 L/min</td>
</tr>
<tr>
<td>Nebuliser pressure</td>
<td>200 kPa</td>
</tr>
<tr>
<td>Replicate time</td>
<td>5 sec</td>
</tr>
<tr>
<td>Stabilisation time</td>
<td>30 sec</td>
</tr>
<tr>
<td>Sample uptake</td>
<td>40 sec</td>
</tr>
<tr>
<td>Rinse time</td>
<td>20 sec</td>
</tr>
<tr>
<td>Pump rate</td>
<td>10 rpm</td>
</tr>
<tr>
<td>Fast pump</td>
<td>On</td>
</tr>
<tr>
<td>Replicates</td>
<td>6</td>
</tr>
</tbody>
</table>

Prior to running the high resolution samples, several bulk Butaritari samples were run. These samples consisted of powder from between 5 and 10 years of coral growth from BUT3-2 piece 3, piece 5 and piece 6 (Figure 11). Replicate analyses were performed on samples of different weights (0.5 mg and 0.75 mg). This was to test the most appropriate weight for the Sr/Ca samples, and whether a smaller weight could be used in order to conserve coral sample material for potential repeats and δ¹⁸O analysis. This preliminary bulk samples test was also done as a first check of the Butaritari Sr/Ca values on the ICP-OES device. The samples were corrected for JCp-1. The results show that the Sr/Ca values obtained for all three pieces at both sample weights are very similar (Table 2) and demonstrate that different sample weights do not have a major influence on the Sr/Ca value (Figure 12). Based on these findings,
an individual sample weight of $0.5 \pm 0.05$ mg was utilised for high resolution Sr/Ca analysis.

**Table 2** – Preliminary Butaritari bulk Sr/Ca samples test results.

<table>
<thead>
<tr>
<th>Piece No.</th>
<th>Average Sr/Ca for 0.5 mg sample</th>
<th>Average Sr/Ca for 0.75 mg sample</th>
<th>Difference in Sr/Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUT3-2 piece 3</td>
<td>8.929</td>
<td>8.920</td>
<td>-0.009</td>
</tr>
<tr>
<td>BUT3-2 piece 5</td>
<td>8.995</td>
<td>8.997</td>
<td>0.002</td>
</tr>
<tr>
<td>BUT3-2 piece 6</td>
<td>9.131</td>
<td>9.172</td>
<td>0.041</td>
</tr>
</tbody>
</table>

**Figure 12** – Preliminary bulk Sr/Ca samples test results for the Butaritari modern coral. Samples with weights of ~0.5 mg are represented by a triangle symbol and ~0.75 mg samples by a square symbol. Samples were measured from BUT3-2 piece 3 (blue symbols), BUT3-2 piece 5 (red symbols), and BUT3-2 piece 6 (green symbols).

The high resolution Butaritari modern coral samples were analysed for Sr/Ca at every fourth sample (± bi-monthly resolution). For some samples, Sr/Ca ratios were measured in duplicate or triplicate on the same digested solution. The average standard error (SE) for these repeat sample solutions within multiple runs was 0.01 mmol/mol ($n = 109$)

**3.6 Isotope analysis**

The Butaritari modern coral samples were analysed for $\delta^{18}O$ and $\delta^{13}C$ in addition to Sr/Ca. These analyses were undertaken at the Australian National University (ANU)
on a Finnigan MAT 251 mass spectrometer, using a Kiel 1 device. For each sample, 200 ± 20 μg of powder was weighed out into a glass thimble. If there was not enough coral material in a sample for this due to the previous Sr/Ca analysis from the same sample, the powder was taken from a neighbouring sample (representing material from the previous or following fortnight). This powder was then dissolved in 105 % H₃PO₄ at 90°C in an automated Kiel carbonate device. The NBS-19 (δ¹⁸O = -2.20 ‰) standard was used to calibrate the isotope results relative to the Vienna Pee Dee Belemnite (V-PDB). The standard deviation for in-run measurements on NBS-19 (n = 105) was 0.04 ‰ for δ¹⁸O during the course of the analyses.

3.7 Assigning chronology

The Analyseries software program (Paillard et al. 1996) was used to construct an age model for the Butaritari modern coral. The SST used in this study was sourced from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature analysis Version 3b (ERSSTv3b; Smith et al. 2008). This data product has a spatial coverage of 2° latitude x 2° longitude across a global grid and is developed using in situ SST data and enhanced statistical methods that enable reconstruction from limited data. Other SST data products with higher resolutions are available, for example, Integrated Global Ocean Services System (IGOSS) SST has a resolution of 1° latitude x 1° longitude (Reynolds et al. 2002). However, IGOSS SST only extends back to November 1981. This study requires a continuous SST data record from between 1959 and 2010. ERSSTv3b was therefore chosen due to the length of instrumental SST data required.

Sr/Ca and δ¹⁸O analyses of the Butaritari coral were undertaken at a bi-monthly resolution, and therefore should be compared with instrumental data of the same or similar resolution. Monthly SST was compared with bi-monthly SST derived from interpolation of the original monthly SST data using ARAND time series analysis software (Howell et al. 2006). Figure 13 illustrates that while there are expectedly slight differences between monthly and bi-monthly SST, namely in the amplitude of some peaks and troughs, the bi-monthly SST replicates the overall temperature
pattern effectively. It is therefore sufficient to use the bi-monthly resolution SST data when comparing to the Sr/Ca and $\delta^{18}$O values.

Figure 13 - SST (ERSSTv3b; Smith et al. 2008) for the $2^\circ$ x $2^\circ$ grid square at $2^\circ$N, $172^\circ$E containing Butaritari for the period between 1959 and 2010. Monthly SST (red line) is compared to bi-monthly SST, derived from interpolation of monthly data (blue line). The bi-monthly SST trace overlies the monthly SST trace.

Coral Sr/Ca data was matched up to local monthly instrumental ERSSTv3b (for the $2^\circ$ x $2^\circ$ grid square at $2^\circ$N, $172^\circ$E containing Butaritari) primarily by visually tying Sr/Ca maxima (cold peaks, winters) to SST minima in Analyseries (Paillard et al. 1996). Major Sr/Ca minima (warm peaks, summers) were assigned to SST maxima. The yearly spacing of Sr/Ca data remained mostly similar throughout the record. Using ARAND time series analysis software (Howell et al. 2006), Sr/Ca and $\delta^{18}$O data was interpolated to six equally spaced samples per year, corresponding to bi-monthly resolution. The interpolation did not introduce any new data points outside the range of the input data.
4. RESULTS

4.1 Butaritari geochemistry

The average Sr/Ca value for the Butaritari coral was 8.93 ± 0.066 mmol/mol (1σ) (Figure 14). The standard deviation is a measure of the seasonal cycle and ENSO variability reflected in the coral. The range of Sr/Ca values was 8.77 to 9.24 mmol/mol. The mean δ¹⁸O value was -5.18 ± 0.25 ‰ (1σ). The range of δ¹⁸O values was -6.00 to -4.54 ‰. The mean δ¹³C value was -1.35 ± 0.53 ‰ (1σ). The range of δ¹³C values was -2.94 to 0.17 ‰.

![Figure 14](image_url) – Butaritari coral geochemistry (BUT3-2); Sr/Ca (red line), δ¹⁸O (green line) and δ¹³C (black line). Note: inverted y-axes. All values have been derived from along the same sampling transect.

δ¹³C is not of primary interest in this study, however the raw data has been included as it was measured at the same time as δ¹⁸O (Figure 14). The δ¹³C values appear to reflect a slightly different pattern to the Sr/Ca and δ¹⁸O traces. There are a range of complex factors that affect δ¹³C values, such as changes in amounts of photosynthesis, irradiance and SST (Hartmann et al. 2010), bleaching events (Suzuki et al. 2003), and
coral spawning (Gagan et al. 1994). Without further information and investigation, the factors influencing the Butaritari coral δ¹³C cannot be clearly understood.

The Butaritari modern coral (BUT3-2) geochemical records extend from May 2010 back to 1959 and the Sr/Ca and δ¹⁸O data reflect a very similar pattern throughout the full length of the coral core (Figure 15). For Sr/Ca and δ¹⁸O the largest, most distinct changes in amplitude occur around 1967, 1976 and 1996 to 2000/2001 (Figure 15). The Sr/Ca record shows an extremely high value in 1967, which through the inverse Sr/Ca-SST relationship, corresponds to cool SST. While this specific pattern is also reflected in the δ¹⁸O, the amplitude of change is much greater in the Sr/Ca.

**Figure 15** – Time series of Butaritari coral geochemistry (BUT3-2); Sr/Ca (red line) and δ¹⁸O (green line), using ERSSTv3b SST data for the 2° x 2° grid square at 2°N, 172°E containing Butaritari (blue line; Smith et al. 2008). Note: inverted y-axes for Sr/Ca and δ¹⁸O. All data including SST have been interpolated to a bi-monthly resolution corresponding to 6 data points per year.

A linear regression of the entire Sr/Ca and δ¹⁸O datasets further indicates that these two coral parameters are significantly well correlated (Pearson correlation coefficient, \( r = 0.65 \)). Sr/Ca and ERSSTv3b SST for the 2° x 2° grid square at 2°N, 172°E containing Butaritari (Smith et al. 2008) also correlate significantly well with \( r = -0.62 \).
To further investigate the correlation between the Sr/Ca and δ¹⁸O, the average annual cycle was removed from each to ensure that correlation was not solely a function of sinusoidal annual cycle variations. This was done by averaging the Sr/Ca and δ¹⁸O for each bi-monthly time period over the length of the record, and then subtracting these averages from the corresponding bi-monthly data values. This provides Sr/Ca and δ¹⁸O residuals without the annual cycle (Figure 16). Through regression of these residuals, a Pearson correlation coefficient of $r = 0.64$ was found ($p < 0.001$). This indicates that the relative variability within Sr/Ca and δ¹⁸O records correlates well within time periods greater than the annual cycle.

![Figure 16](image)

**Figure 16** – Sr/Ca and δ¹⁸O residuals with the annual cycle removed for the period between 1959 and 2010.

The Butaritari coral Sr/Ca and δ¹⁸O values follow similar interannual and decadal pattern (Figure 16), in addition to annual cycles (Figure 15). The four major troughs in the Sr/Ca data mentioned previously 1967, 1976, 1985-1990 and 1996 to 2000 are present in the SST data although the magnitude of change varies and some major shifts are not as pronounced. The climate signal in the Butaritari coral will be discussed further in the following Discussion chapter.
5. DISCUSSION

5.1 Calibrating Sr/Ca to SST

An inverse relationship exists between coral Sr/Ca and SST, such that lower Sr/Ca values correspond to higher SST and higher Sr/Ca values correspond to lower SST. Commonly, coral Sr/Ca reflects the key peaks and troughs in the instrumental SST record. Calibrating coral Sr/Ca to SST is used to estimate absolute SST changes within the coral’s living environment, and in conjunction with coral δ¹⁸O to infer changes in sea surface salinity (SSS) (see Section 5.2).

There is no standard Sr/Ca-SST calibration for *Porites* sp. and as a result, Sr/Ca-SST calibrations must be devised for each specific locality (Corrège 2006). Apart from this study, there are no other published Sr/Ca-SST calibrations for *Porites* sp. or any other corals from Butaritari. There are however, numerous Sr/Ca-SST calibrations for corals from other equatorial Pacific islands, such as Kirimiti in the central Pacific (e.g. Nurhati *et al.* 2009; Glasbergen 2010) and PNG in the western Pacific (e.g. McGregor 2003) as well as some from further afield such as Rarotonga (e.g. Ren *et al.* 2002), New Caledonia (Corrège 2006), Great Barrier Reef (GBR) in Australia (e.g. Gagan *et al.* 1998; Fallon *et al.* 2003), Hawaii (e.g. Allison and Finch 2004) and Japan (e.g. Fallon *et al.* 1999). The range of Sr/Ca-SST calibration equations is likely due to differences in local environments, varying internal workings of different individual corals, and difference in the way in which the calibration was calculated for example, interlaboratory Sr/Ca measurement differences and which SST data product was used for comparison (Corrège 2006).

In an attempt to produce a universal Sr/Ca calibration Corrège (2006) averaged published Sr/Ca-SST relationships for *Porites* sp. corals, and derived the following mean calibration equation, in the format: Sr/Ca (mmol/mol) = a + b * SST (°C).

\[
\text{Sr/Ca} = 10.553 - 0.0607 \times \text{SST (°C)}
\]
This equation brings together coral Sr/Ca-SST calibrations from many globally dispersed locations, and also coral Sr/Ca data derived from a number of different analytical methods.

The Butaritari calibration was constructed by pairing up maxima and minima Sr/Ca values with time-equivalent SST (ERSSTv3b; Smith et al. 2008). Figure 17 indicates the individual Sr/Ca-SST data pairs used for the calibration. Maxima and minima Sr/Ca points were chosen based on visual correlation with their corresponding points in the SST record. It was noted that the overall Sr/Ca maxima and minima points, denoted by the green and orange squares in Figure 17, did not necessarily match the SST maxima and minima points, denoted by pink and yellow squares in the same Figure, possibly due to slight misalignment of Sr/Ca points when interpolating to 6 values per year (see Section 3.7). On average a calibration point was selected for every summer and winter, where discernible, of each year across the ~50 year record, except between May 2010 and Jan 2009 (the top ~12 mm of the core). The Sr/Ca values for this top surface correspond to the coral tissue layer where the Sr/Ca values may be biased by partial density band formation (Gagan et al. 2012) or organics.. In total, 90 Sr/Ca points were used for the Sr/Ca-SST calibration.

![Figure 17](image)

**Figure 17** – Bi-monthly Sr/Ca values of the Butaritari modern coral (BUT3-2) compared to bi-monthly SST. SST is from ERSSTv3b (Smith et al. 2008) for the 2° x 2° grid square at 2°N, 172°E, which includes Butaritari Island. Solid filled circles and coloured squares indicate the maxima and minima points used in the Sr/Ca-SST calibration (n = 90). These solid filled points are on average at an annual resolution corresponding to the summer maximum and winter minimum values for each year. The pair of green squares denotes the maxima point in the Sr/Ca record and the corresponding point in SST. The pair of orange squares denotes the minima point in
the Sr/Ca record and the corresponding point in SST. The pair of pink squares denotes the minima SST point and the corresponding point in Sr/Ca. The pair of yellow squares denotes the maxima point in the SST record and the corresponding point in Sr/Ca.

Figure 18 – Butaritari modern coral (BUT3-2) Sr/Ca-SST calibration points and equation. Red crosses indicate the Sr/Ca values and corresponding SST from Figure 17. Blue line is a linear regression through the Sr/Ca-SST points. Green circle denotes the maxima Sr/Ca value and orange circle denotes the Sr/Ca minima value (Also shown in Figure 17).

An ordinary least squares linear regression was performed between the chosen Sr/Ca and SST calibration values (Figure 18) The SST was the independent variable and the Sr/Ca was the dependent variable. The following equation is the calibration equation derived for the Butaritari modern coral, in the same format as the mean Corrège equation, with r² representing the correlation coefficient:

\[ \text{Sr/Ca} = 10.904 - 0.0688 \times \text{SST}; \ r^2 = 0.5818 \]

The overall Butaritari calibration equation corresponds quite well to the mean Corrège (2006) equation, and falls well within the range of published Sr/Ca-SST calibration slopes (-0.04 to -0.08) for Porites sp. corals (Corrège 2006). The y-intercept (10.904)
is slightly higher than the Corrège intercept (10.553), however, both gradients are very similar, 0.0688 and 0.0607 respectively.

Figure 19 – Modern Butaritari Sr/Ca-SST reconstructions. Blue line is SST for Butarirari (ERSSTv3b; Smith et al. 2008). Red line is the coral-derived estimates of SST, calculated from the Butaritari Sr/Ca-SST relationship: Sr/Ca = 10.904 – 0.0688 * SST ($r^2 = 0.5818$). A line of best fit has been fitted to both datasets. Black dotted line is monthly IGOSS SST for the 1° x 1° grid square at 171.5°E, 2.5°N, containing Butaritari (Reynolds et al. 2002).

5.1.1 Potential calibration uncertainties

There is some discrepancy between the Butaritari modern coral Sr/Ca SST data and the instrumental SST data (Figure 19). This could be due to the different scales of the data (Corrège 2006). The ERSSTv3b instrumental SST data is derived from a 2° x 2° grid square focused on 2°N, 172°E. While this includes Butaritari Island, it also encompasses a significant portion of the surrounding ocean. The SST data product is therefore a reflection of estimated averaged water temperature over this entire area, providing a somewhat more regional representation of the Butaritari locality. The SST derived from the Butaritari coral is much more localised, reflecting the specific temperature changes at the reef collection site.

Notable differences can exist between SST datasets (Corrège 2006). It is thus important to recognise the properties of the chosen SST dataset. Local in situ SST measurements are particularly useful in Sr/Ca calibrations, as they typically reflect very similar SST variations to those expected from coral Sr/Ca, however they are
rarely available. Different climatic patterns, in particular ENSO and its related warm pool and cold tongue regions, may be reflected differently in different SST datasets (Solomon and Newman 2012). Solomon and Newman (2012) show that SST anomalies over the last century from four datasets, ERSSTv3b (used in this study), HadISST version 1.1 (Rayer et al. 2003), Kaplan Extended SST version 2 (Kaplan et al. 1998) and COBE SST (Ishii et al. 2006), exhibit the same general trends, however there are slight variations in the magnitude of change especially prior to ~1960s. These slight variations may influence the Sr/Ca-derived SST, depending on which one is used for the calibration. Figure 19 illustrates the slight SST differences between ERSSTv3b and IGOSS for the Butaritari locality. The satellite-based 1° x 1° IGOSS SST dataset only extends back to November 1981, and was therefore not used in this Sr/Ca-SST calibration, although a slightly different Sr/Ca-derived SST record may have been produced if it was used.

Furthermore, the ERSSTv3b SST data product is based on the International Comprehensive Ocean Atmosphere Data Set (ICOADS). For the Gilbert Islands (3°S to 4°N, 172°E to 177°E), the number of observations per month used to create ICOADS increase dramatically from ~30 in the 1950s to ~12000 to 2010 (Research Data Archive 2012). Relatively sparse data points earlier on in this time period, may introduce sources of error in the SST reconstructions.

Figure 20 – Monthly observation counts for data points used in the International Comprehensive Ocean Atmosphere Data Set (ICOADS), from which ERSSTv3b is derived (Research Data Archive 2012).
The bi-monthly resolution of the Sr/Ca record for the Butaritari coral may also be a limiting factor in the strength of the correlation between Sr/Ca and SST calibration points. The data at bi-monthly resolution does generally follow the pattern of the instrumental SST, although there are some differences, especially in the amplitude of SST change. Increasing the coral dataset to monthly resolution could provide additional Sr/Ca information, which could further support the current calibration trend and increase the correlation coefficient, although previous studies have shown that four to five samples per year, approximately bi-monthly resolution, of skeletal coral growth can be sufficient for seasonal environmental variability detection (e.g. Aharon 1991; Delaney et al. 1993; Carriquiry et al. 1994). This is also likely true for coral records from Butaritari. Figure 13 (Section 3.7) shows that SST data from ERSSTv3b does not change greatly between monthly and bi-monthly resolution. Thus, increasing the resolution of the coral data to monthly may not provide much new information, though additional analysis around the maximum and minimum values of each coral year may help to better constrain these maxima and minima, and improve the Sr/Ca-SST calibration.

There is a relatively extreme cold temperature point in the late 1960s compared to the rest of the Sr/Ca values and the corresponding instrumental SST. Figure 19 illustrates the deviation of this data point from the calibration regression line. The next closest data point is 0.11 mmol/mol lower than the overall maxima. This equates to a 1.38°C difference between the overall maxima and the next closest point, based on the Sr/Ca-SST calibration equation derived for the Butaritari modern coral. This extremely cold point may well be an outlier, however there are currently no reasons, analytically or otherwise, to exclude or discount it. According to physical inspection of the relevant coral ledge and the x-ray (Figure 11, Section 3.2 X-Radiography) there were no visual abnormalities in the coral material. The laboratory preparation of this sample was exactly the same as all the other samples. It was run under the same conditions and on the same ICP-OES machine. The digested Sr/Ca sample solution was analysed twice, in two separate ICP-OES runs. The resulting Sr/Ca values of 9.25 and 9.23 mol/mol, from which the maxima point was derived, are very similar, suggesting that this is a real data point.
As a result, the extremely cold point has been included in the Sr/Ca-SST and may very well be a true Sr/Ca value for this coral. The Sr/Ca values presented in this study are a reflection of the SST in this specific coral, which while they indicate the key peaks and troughs in the SST record, they can also reflect very localised changes. The extreme Sr/Ca cold point may just be a reflection of the environmental SST changes experienced by this coral. Also, despite including a potential ‘outlier,’ the resulting Sr/Ca-SST calibration equation correlates well with the average published calibration equation for Porites sp. corals (Corrège 2006). A future recommendation would be to reprepare and rerun the maxima Sr/Ca sample as well as the samples directly either side of it from scratch, to further confirm its validity within this Sr/Ca dataset and Sr/Ca-SST calibration.

5.1.2 Sr/Ca-derived SST

Despite differences, the general amplitudes of change in the Sr/Ca-derived SST and the SST data product are similar (Figure 19) The mean value and SD for Sr/Ca-derived SST is 28.83 ± 0.89 °C, and the SST data product is 28.90 ± 0.66 °C. There is a statistically significant correlation of r = 0.62 (Pearson correlation coefficient) between these two datasets. (Note same/similar correlation coefficient as for constructing the coral age model). This suggests that both datasets are successfully recording the key changes in SST for the area. Consistent with the findings of Mantua and Hare (2002), an abrupt climatic shift in SST can be identified in the mid-1970s. The slope of the trends have been calculated using the following standard regression equation used in Nurhati et al. (2009):

\[ \text{SST} = a + m \times \text{year} \]

The error of the slope is calculated using the following equations, also used in Nurhati et al. (2009). The errors reported are solely for the trends.

\[ \text{trend} = (m \pm \sigma_m) \times \text{total period of trend (in years)} \]

\[ \sigma_{\text{trend}} = \sigma_m \times \text{total period of trend (in years)} \]
Taking Butaritari Sr/Ca-derived SST as an example,

\[
\text{Sr-Ca/derived SST} = -1.176 + 0.0151 \times \text{Year}
\]

\[
\text{trend} = (0.0151 \pm 0.003) \times 51 \text{ years}
\]

\[
\text{trend} = 0.77^\circ \text{C}
\]

\[
\sigma_{\text{trend}} = 0.003 \times 51 \text{ years}
\]

\[
\sigma_{\text{trend}} = 0.17^\circ \text{C}
\]

There are statistically significant warming trends (p < 0.001) in both the Sr/Ca-SST and SST data product. The Butaritari coral Sr/Ca-SST record suggests there has been a 0.77 ± 0.17 °C increase in SST at Butaritari over the 1959 to 2010 period. The SST data product record suggests that there has been a 0.67 ± 0.12 °C increase in SST over the 1959 to 2010 period. These suggested warming trends at Butaritari are consistent with tropical and sub-tropical SST increases of 0.4°C to 1°C estimated from a variety of data sources over the past 100 years (Deser et al. 2010), and more specifically with an estimated 0.2°C to 1°C warming of the WP region over the past 50 years (Cravatte et al. 2009). A further investigation of this warming SST trend is detailed in Section 5.5 through comparison with coral records from the western and central equatorial Pacific.

5.2 Deciphering SSS from δ¹⁸O using coral-derived SST

Paired Sr/Ca and δ¹⁸O coral data is particularly useful in determining the balance of SSS (and thus the evaporation/precipitation balance) versus SST within a δ¹⁸O record. An understanding the SSS balance is important in understanding the climatic processes that exist at the coral site, such as increases in precipitation in El Niño years. There are a number of recognised methods to separate the δ¹⁸O_{sw} signal from coral δ¹⁸O. An early method (McCulloch et al. 1994; Gagan et al. 1998) utilises linear regression equations for coral Sr/Ca-SST and coral δ¹⁸O-SST in the univariate form of
y = mx + c, where y = Sr/Ca or δ¹⁸O, x = SST, m = regression coefficient and c is constant. From these equations, coral Sr/Ca and δ¹⁸O are converted to temperature units. Through multiplying the slope of the δ¹⁸O-SST relationship by the difference in δ¹⁸O-derived SST and Sr/Ca-derived SST, the residual δ¹⁸O can be calculated, which reflects the effects of seawater δ¹⁸O composition (δ¹⁸Osw). In an attempt to minimise error associated with the independent variable (instrumental SST) in the above method, Ren et al. (2002) proposed a different method, wherein the intercept values were excluded from the calculation. They determine δ¹⁸Osw using instantaneous changes in paired δ¹⁸O and Sr/Ca, with the following equation:

\[ \Delta \delta^{18}O_{(coral)} = \Delta \delta^{18}O_{(SST\, contr)} + \Delta \delta^{18}O_{(sw\, contr)} \]

\[ = (\partial \delta^{18}O_{(coral)}/\partial SST) \ast \Delta SST + (\partial \delta^{18}O_{(coral)}/\partial \delta^{18}O_{sw}) \ast \Delta \delta^{18}O_{sw} \]

where, \( \Delta SST = \Delta Sr/Ca_{(coral)}/(\partial Sr/Ca_{(coral)}/\partial SST) \). \( \Delta \delta^{18}O_{SST} \) is the SST contribution to coral δ¹⁸O, and \( \Delta \delta^{18}O_{sw} \) is the δ¹⁸Osw contribution to coral δ¹⁸O. \( \partial \delta^{18}O_{(coral)}/\partial SST \) and \( \partial \delta^{18}O_{(coral)}/\partial \delta^{18}O_{sw} \) are the partial derivatives of coral δ¹⁸O in regard to SST and δ¹⁸Osw. \( \partial \delta^{18}O_{(coral)}/\partial SST \) and \( \partial Sr/Ca_{(coral)}/\partial SST \) correspond to the slopes of proxy-SST regression equations.

Absolute δ¹⁸Osw values are calculated through summing the instantaneous changes to a reference salinity value. The reference salinity value is usually derived from climatological SSS data and/or a δ¹⁸Osw-SST relationship, such as Fairbanks et al. (1997), and varies depending on where the coral was collected from (Ren et al. 2002; Nurhati et al. 2009).

Through comparison of early and Ren et al. (2002) methods, Huppert and Solow 2004 found that the results obtained from each are identical. Furthermore, Cahyarini et al. (2008) show that their proposed centering method provides the same results as Ren et al. (2002). Cahyarini et al. (2008) exclude the intercept from their calculation, by removing the mean from the input variables, termed centering the linear regression equation (Draper and Smith 1981). The advantage of using the centering method is that it involves much simpler mathematical calculations than Ren et al. (2002). In
this study, $\delta^{18}O_{sw}$ was derived for the Butaritari coral using the centering method described in Cahyarini et al. (2008):

$$\Delta \delta^{18}O_{sw-center} = (\delta^{18}O_{coral_i} - \text{mean } \delta^{18}O_{coral}) - \gamma / \beta \cdot (\text{Sr/Ca}_i - \text{mean Sr/Ca})$$

where, $\Delta \delta^{18}O_{sw-center}$ is the centered $\delta^{18}O_{sw}$ contribution to $\delta^{18}O$, $\delta^{18}O_{coral}$ is measured coral $\delta^{18}O$, Sr/Ca is measured coral Sr/Ca, mean $\delta^{18}O_{coral}$ and Sr/Ca are the mean values of the measured respective terms, $\gamma$ is the regression slope of coral $\delta^{18}O$ vs SST, and $\beta$ is the regression slope of coral Sr/Ca vs SST.

For corals the $\delta^{18}O$-SST slope value generally falls within a range of -0.15 to -0.22 ‰/°C (Weber and Woodhead 1972; Wellington et al. 1996; Boiseau et al. 1998; Gagan et al. 1998; Juillet-Leclerc and Schmidt 2001). The $\gamma$ value of -0.18 ‰/°C (Gagan et al. 1998) is considered a reasonable average (Corrège 2006) of published $\delta^{18}O$-SST slopes and was utilised in this study. The $\beta$ value of -0.0688 mmol/mol/°C was derived from the regression between Butaritari coral Sr/Ca and ERSSTv3b SST (see Section 5.2). The mean $\delta^{18}O$ coral value was -5.20 ‰ and the mean Sr/Ca coral value was 8.92 mmol/mol. The resulting $\Delta \delta^{18}O_{sw}$ (Figure 21c) is discussed in the following section (Section 5.3)

The $\Delta \delta^{18}O_{sw}$ trend and associated error was calculated using the standard regression equations from Nurhati et al. (2009) (see Section 5.1.2). The error reported is solely for the trend, and the calculation is as follows:

$$\Delta \delta^{18}O_{sw} = 0.477 - 0.000240 \cdot \text{Year}$$

trend = (0.000240 ± 0.0007) * 51 years

trend = -0.01

$$\sigma_{\text{trend}} = 0.0007 \cdot 51 \text{ years}$$

$$\sigma_{\text{trend}} = 0.03 \text{ ‰}$$
The $\Delta \delta^{18}O_{sw}$ values at Butaritari do not reflect a statistically significant trend over the 51 year period ($-0.01 \pm 0.03 \%e; p > 0.001$; Figure 21c). A further investigation of this is detailed in Section 5.5 through comparison with coral records from central equatorial Pacific.

5.3 Coral geochemistry compared to local climatology

The Butaritari coral geochemistry (Sr/Ca-derived SST and $\delta^{18}$O) records show similar variations to the local climatology of the region (SST and precipitation) and the NINO 4 and SOI ENSO indices (Figure 21). As described in Section 4.1, the Sr/Ca and $\delta^{18}$O reflect very similar patterns, and Sr/Ca and ERSSTv3b SST correlate well with each other.

Major ENSO events between 1959 and 2010 are predominantly reflected in both the Sr/Ca-derived SST and $\delta^{18}$O Butaritari records, although the relative amplitude of change does vary from climatological datasets (Figure 21). At Butaritari El Niño events (SOI < -8 for sustained periods) are visible as minima in Sr/Ca-derived SST and $\delta^{18}$O, warmer SSTs and above average precipitation. In contrast, La Niña events (SOI > 8 for sustained periods) at Butaritari show Sr/Ca-derived SST and $\delta^{18}$O maxima, and are periods of cooler SST and lower precipitation (Figure 21).

Relative differences between the Sr/Ca-derived SST and $\delta^{18}$O exist for the 1987/1988 and ~1991-1995 El Niño years, such that $\delta^{18}$O exhibits a relatively larger amplitude signal in those years compared to Sr/Ca-derived SST (Figure 21). $\delta^{18}$O is a function of both SST and the $\delta^{18}$O of seawater ($\delta^{18}$O$_{sw}$), and the larger amplitude $\delta^{18}$O signal may reflect an increase in El Niño-driven precipitation changing the $\delta^{18}$O$_{sw}$ in 1987/1988 and 1991-1995.

The relative changes in $\delta^{18}$O$_{sw}$ (Figure 21c) visually correlate well to the regions of greatest difference between $\delta^{18}$O and Sr/Ca-derived SST (Figure 21a, b), predominantly 1965-1982 and 1989-1997. These two periods reflect the freshest
periods in the Butaritari record, suggesting that the precipitation influence on $\delta^{18}O$ is prominent during these periods. While the generally pattern of $\delta^{18}O_{sw}$ and instrumental SSS and precipitation (Figure 21e, f) is somewhat similar, the amplitude of change does vary. Similar to the variations seen between the Sr/Ca values and ERSSTv3b SST (see Section 5.1), these differences could be a result of the resolution of the different records. The coral $\delta^{18}O_{sw}$ is reflecting very localised changes, whereas the SSS and precipitation are an average across a larger area.

Butaritari is commonly associated with high precipitation, with an average rainfall rate of approximately 4 to 8 mm/day (Baker et al. 1994; Xie and Arkin 1996; Xie and Arkin 1997). These monthly average values depend on the specific precipitation dataset used. The NOAA NCDC GCPS MONTHLY STATION mean precipitation (Baker et al. 1994) for 1959 to 1982 is derived from on-site Butaritari measurements and reflects higher precipitation compared to the 1979 to 2010 monthly CMAP Estimated Precipitation derived from a 2.5° x 2.5° grid square over Butaritari (Note precipitation datasets are normalised to unit variance in Figure 21). Due to the larger area covered, the CMAP precipitation data may under or over estimate the specific rainfall at Butaritari. Nonetheless, rainfall still correlates with the ENSO indices (Figure 21).
Figure 21 – Modern Butaritari coral geochemistry compared to local climatology and ENSO indices. a) Butaritari δ¹⁸O (green). b) Butaritari Sr/Ca-derived SST (red). c) Butaritari Δδ¹⁸Osw (blue). d) SST (red) from ERSSTv3b (Smith et al. 2008) for the 2⁰ x 2⁰ grid square at 2⁰N, 172⁰E. The SST dataset has been interpolated to bi-monthly resolution to correspond with the resolution of the coral geochemistry data. e) Normalised mean daily Butaritari precipitation for each month from NOAA NCDC GCPS MONTHLY STATION mean precipitation (Baker et al. 1994) for 1959 to 1982 (light blue) from Butaritari, station ID 9160100, at 3.03N, 172.78E; and monthly CMAP Estimated Precipitation (Xie and Arkin 1996; Xie and Arkin 1997) for 1979 to 2010 (dark blue) for the 2.5⁰ x 2.5⁰ grid square at 1.25N, 171.25W. f) Monthly SSS (at 5.01 meters depth) from CARTON-GIESE SODA latest version (v2p1p6) for the 0.5⁰
x 0.5° grid square at 172.25E 3.25N containing Butaritari Island (Carton and Giese 2008). g) Monthly NINO 4 data (yellow) for the NINO 4 region (5°N-5°S, 160°E-150°W) sourced from http://www.cpc.ncep.noaa.gov. h) Monthly SOI data (pink) sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soi2.shtml). El Niño threshold (SOI < -8; Australian Bureau of Meteorology 2012a) is marked by a dotted line on the SOI trace. La Niña threshold (SOI > 8) is marked by a dashed line on the SOI trace. El Niño events (SOI < -8 for sustained periods) are shaded dark grey. La Niña events (SOI > 8 for sustained periods) are shaded light grey. Note: inverted y-axes for a), c), f) and h).

Although overall the coral geochemistry and related local climatology corresponds well with the ENSO indices, the coral signals do appear to be slightly out of synch with SOI and NINO 4. Some coral peaks (warm and wet periods) seem to appear just before the SOI and NINO 4 peak events (El Niño periods), suggesting that Butaritari may experience changes slightly earlier than the ENSO indices indicate. These differences are noted to occur around 1972-73, 1977, 1986-87, 1991 and 1997 just before the correspond El Niño periods are evident in the SOI and NINO 4 indices. Butaritari is located at the equatorial eastern edge of the IPWP, which migrates east-west as one of the first stages of the development of El Niño events (Picaut et al. 2001). Figure 22 is a modified version of Figure 4 in Section 2.1, and through highlighting the above years of slight misalignment, illustrates SST and SSS differences between the EWPCZ migration and SOI. The east-west (El Niño-La Niña) migration of EWPCZ indicates a slightly greater movement relative to SOI. Taking 1991 as an example, the Butaritari coral Sr/Ca-derived SST and δ18O (Figure 21a, b) show peaks just before the SOI-recognised El Niño period starting in 1992. This early peak is reflected in the 2° x 2° resolution SST data product (Figure 21c) although not clearly reflected in the 2.5° x 2.5° resolution precipitation record (Figure 21d). In 1991 (Figure 22) SST shifts in the eastern edge of the IPWP are shown to migrate further eastward relative to the strength of the SOI. For the same year, SSS is in relative synch with the SOI. In this way, shifts to warmer SST can be seen to occur slightly earlier than the in SOI in some years and these appear to be reflected in the Butaritari coral record. The Butaritari coral is reflecting localised variations in SST and SSS that may not be recognised to the same extent in the large-scale ENSO indices, and is thus providing more subtle insights into local ENSO dynamics.
Figure 22 – Modified version of Figure 4. Migration of the eastern edge of the Western Pacific Warm Pool. Left panel is the longitude-time distribution of 4°N-4°S averaged SST, and the right panel is SSS for the same area. The thick white line is the Southern Oscillation Index (SOI). Sustained positive and negative SOI correspond to La Niña and El Niño phases, respectively. Contours are 1°C for SST and 0.25 psu for SSS. Dark shading in the left and right panels indicates higher SST and higher SSS, respectively. Orange lines indicate the longitudinal positions of Butaritari Atoll (~172°30′E, 3°30′N; this study), Tarawa (1°N, 172°E) and Maiana (1°N, 173°E). (Modified from Picaut et al. 2001). Blue shaded areas correspond to years of slight misalignment between Butaritari coral and ENSO indices evident in Figure 21).

5.3.1 Wavelet analysis

Wavelet analysis is used to provide a quantification of the visually recognisable patterns in the data discussed above in Section 5.1. It examines localised variations of power within a time series (Torrence and Compo 1998). This type of analysis is effective for analysing time series with multiple timescales and/or changes in variance (Asami et al. 2005). Wavelet analysis, using the Morlet wavelet was carried out
through the online Interactive Wavelet Plot (Torrence and Compo 1998), available at http://paos.colorado.edu/research/wavelets/. Wavelet analysis of Butaritari Sr/Ca-derived SST and $\delta^{18}$O, ERSSTv3b, NINO 4 and SOI further quantifies the dominant variability in these records and shows that they are influenced by annual, interannual and decadal variability, albeit in different proportions in each record. All wavelet analyses in this study have been fitted with a cone of influence (indicated by cross hatching). This hatched area denotes the region of the wavelet spectrum wherein edge effects due to finite-length input time series, have had an impact (Torrence and Compo 1998). These regions have been padded with zeros to reduce edge effects, however this reduces the amplitude of the variance near the edges, and decreases the power across the periods near the edges.

- **Sr/Ca-derived SST and $\delta^{18}$O**

The wavelet results for the Butaritari coral Sr/Ca-derived SST and $\delta^{18}$O show the strongest power in the decadal to multi-decadal periods, though these periods are at the limit of statistical significance since the Butaritari coral is ~50 years long and there are only a few realisations of these periods in the record. **Figure 23 Part 1** shows a persistent power at the 12-24 year period (multi-decadal variability; coloured red). Between 1965 and 1984 the cycles of significant power predominantly fall around periods of 16 to 24 years, and then between 1985 and 2004 the cycles of significant power predominantly fall around periods of 12 to 16 years. There are some fluctuations in power at annual periods, though the global wavelet power spectrum (Figure 23, Part 1c), defined as the time average over the series of wavelet powers (Ge 2007), suggests this variance is low. There is greater variance in power for the 2-8 years (interannual) period.

Similar to the $\delta^{18}$O, the wavelet results for the Butaritari coral Sr/Ca-derived SST (Figure 23, Part 2) indicate multi-decadal variability. The time period between 1961 and 1990 sees areas of highest power (although relatively low compared to the other wavelet results in Figure 24, Figure 25 and Figure 26) in the 24 to 32 year periods. At 1990 there is a step to variability at decadal periods, which continues through to 2005. A low power annual cycle exists, along with an interannual cycle.
Figure 23 – Part 1 and 2 is wavelet analysis for Butaritari coral δ¹⁸O and Sr/Ca-derived SST, respectively. (a) Coral record. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding
has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

**ENSO indices and SST**

As expected, the wavelet analysis of the ENSO indices, NINO 4 and SOI, show dominant interannual cycles throughout the 1959 to 2010 time period. These interannual cycles correspond directly to interannual ENSO events, which the NINO 4 and SOI indices are designed to represent. The NINO 4 anomaly (Figure 24) indicates high power interannual cycles (2-8 years) across the record, especially around 1970 and 1985-1990. The SOI results (Figure 25) reflects a similar pattern to NINO 4. Both records also include high power near-decadal variance pattern between 1970 and 2005, along with a low power annual cycle.

The SST product wavelet analysis (Figure 26) indicates a prominent near-decadal variance, similar to the coral proxies. A medium power interannual cycle can be identified as well as a lower power annual cycle.
Figure 24 – (a) NINO4 anomaly. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Figure 25 – (a) SOI. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.
Figure 26 – (a) SST (ERSSTv3b; Smith et al. 2008). (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Overall the wavelet analysis results reveal a persistent decadal and/or multi-decadal pattern within the Butaritari coral Sr/Ca-derived SST and δ¹⁸O, and in the instrumental SST. Interannual variability is present in these three records, but in the SOI and NINO 4 records interannual variability dominates. The decadal variations evident in the ~50 year Butaritari coral record are in line with the observational findings of Wang and Mehta (2008). In their explorative study of decadal variability of the IPWP, significantly strong peaks (9.7 year) were revealed in a power spectrum analysis of a 50 year (1952-2001) record of instrumental SST, and atmospheric and oceanic reanalyses. Decadal variation in the IPWP may be influenced by the Pacific Decadal Oscillation (PDO). A positive PDO can enlarge the IPWP at both seasonal and decadal time scales (Bolan and Lixin 2012), and this warm pool enlargement during these periods may be influencing the Butaritari signal. In spite of this however, Newman et al. (2003) conclude that PDO is dependent upon ENSO on all timescales,
and hence ENSO maintains a prominent influence over the climatic variability in this region.

It is however, somewhat challenging to infer decadal or larger patterns within a 50 year record, as is the case for the Butaritari coral and SST records, since even one 10 year oscillation covers one fifth of the available data. A data record of 100 years or more would provide greater information about the frequency and amplitude of these ~10 year cycles. The decadal and multi-decadal variance evident in the wavelet analysis of the 50 year-long Butaritari record, suggest that a longer coral time series record is needed to define this variance.

Although differences in the variance patterns do occur between the instrumental and coral records, the 50-year Butaritari coral reflects the climatic variance changes of the region (comparison with SST), and of the broader tropical Pacific processes (SOI, NINO 4) at the decadal/multi-decadal and interannual periods. Thus the Butaritari coral record can be used to investigate the climate dynamics of the eastern edge of the warm pool.

5.4 Butaritari compared to Tarawa and Maiana

Similar to Nurhati et al. (2009) wherein Sr/Ca and δ¹⁸O coral records from several closely situated central tropical Pacific islands were examined for spatial variability, the geochemical results from this Butaritari study are compared with those from other nearby sites to gain a broader understanding of the climatological forces at work in the western equatorial Pacific region.

δ¹⁸O data from Tarawa located directly due south of Butaritari (1°N, 172°E) (Cole et al. 1993) and Maiana located south-south-east of Butaritari (1°N, 173°E) (Urban et al. 2000) were compared to the δ¹⁸O Butaritari data (3°30’N, 172°30’E). Including Butaritari, these three neighbouring islands are located in the Gilbert Island group of Kiribati, and are situated along a known precipitation gradient and along the salinity
front at the eastern edge of the IPWP. ENSO variability is recorded at all three sites (Cole et al. 1993; Urban et al. 2000; this study see Section 5.3).

The complete dataset for Tarawa (1894-1990; monthly resolution) was smoothed using a 24 point moving average. Maiana (1840-1994; bi-monthly resolution) and Butaritari (1959-2010; bi-monthly resolution) data was smoothed using a 12 point moving average. This smoothing removed all < 2 year signals, so that a comparison between interannual signals, primarily ENSO, and decadal signals could be made (Figure 27a). The Maiana δ¹⁸O is the longest record of the three examined and extends furthest back in time to 1840. The Butaritari δ¹⁸O record from this study covers the period between 1959 and 2010, and hence the other two datasets were truncated to this ~50 year period of overlap with the Butaritari record (Figure 27b).

**Figure 27** – Coral δ¹⁸O records from three western equatorial Pacific islands. A) 1840 to 2000. Green dotted line corresponds to bi-monthly Butaritari (3°30’N, 172°30’E) δ¹⁸O data from this study. Blue dotted line corresponds to monthly Tarawa (1°N, 172°E) δ¹⁸O data from Cole et al. (1993). Red dotted line corresponds to bi-monthly Maiana (1°N, 173°E) δ¹⁸O data from Urban et al. (2000). Solid lines correspond to moving averages (12 point for Butaritari and Maiana, and 24 point for Tarawa), which remove < 2 year variability from the data. Black bracket indicates the area of overlap with the Butaritari record. B) Same as for A) except for 1959 to 2000, the area of
overlap with the Butaritari record. Monthly SOI data (pink) sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soi2.shtml). El Niño threshold (SOI < -8) is marked by a dotted line on the SOI trace. La Niña threshold (SOI > 8) is marked by a dashed line on the SOI trace. El Niño events (SOI < -8 for sustained periods) are shaded dark grey. La Niña events (SOI > 8 for sustained periods) are shaded light grey.

Visual comparison of the moving average data in Figure 27b, suggests that with the ~annual signals removed, Butaritari, Tarawa and Maiana reflect somewhat similar patterns of peaks and troughs across the overlapping time interval, although the consistently more negative δ¹⁸O values show that Butaritari is warmer and wetter than both Tarawa and Maiana.

The Tarawa moving average data were interpolated using ARAND software (Howell et al. 2006) from monthly to bi-monthly resolution to enable a linear regression between datasets to be undertaken. Through regression the Pearson correlation coefficient between Butaritari and Tarawa was found to be $r = 0.008$, indicating very weak or no correlation. The correlation relationship between Butaritari and Tarawa is not statistically significant ($p > 0.001$). The Pearson correlation coefficient between Butaritari and Maiana is $r = 0.56$, indicating a moderate correlation. This relationship is statistically significant ($p < 0.001$). The Tarawa record sits between Butaritari (warmer, wetter) and Maiana (colder, drier) and appears to follow a more similar pattern to Maiana than Butaritari. The correlation is good between Tarawa and Maiana, $r = 0.72$ ($p < 0.001$). The fact that Tarawa and Maiana are more correlated with each other than they are with Butaritari is interesting as it they are situated at the same latitude, only 1° of longitude apart. Butaritari and Tarawa are at the same longitude, only 1° of latitude apart. This suggests that there is more of a latitudinal variation (north-south) than longitudinal variation (east-west) in δ¹⁸O for these three neighbouring islands.

As discussed earlier in Section 5.1, a decadal and/or multi-decadal pattern appears to exist within the 50 year Butaritari coral record. Wavelet analysis of Tarawa and Maiana δ¹⁸O data for the period of overlap with the Butaritari record, suggest that decadal to multi-decadal patterns also exist at these neighbouring locations. Tarawa
δ¹⁸O exhibits a decadal and/or multi-decadal period throughout the whole record, though the record is dominated by variance around 2 to 8 years, corresponding to interannual ENSO-related variation, particularly between 1965 and 1975 (Figure 28). This is consistent with the interannual frequency periods identified for Tarawa through spectral analysis by Cole et al. (1993). Maiana exhibits some lower power interannual (2 to 8 year) variability compared to Tarawa (though the interannual variance still dominates the record), and some lower power decadal patterns and a signal at a ~32 year period (Figure 29). When the wavelet results for all three islands are taken together, Butaritari shows the strongest near-decadal oscillations (Figure 23). It must be noted however, the Tarawa record used for wavelet analysis was only 31 years in length between 1959 and 1990. The Maiana record was 35 years in length between 1959 and 1994. Therefore, the decadal and/or multi-decadal patterns must be taken with caution, as the time period for analysis is quite short, and the results may vary significantly if longer records are used for wavelet analysis.

Figure 28 – (a) Tarawa δ¹⁸O for the period of overlap with the Butaritari record. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to
interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

**Figure 29** – (a) Maiana $\delta^{18}$O for the period of overlap with the Butaritari record. (b) The wavelet power spectrum (Torrence and Compo 1998), red indicates areas of highest power. The 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, where zero padding has reduced the variance. (c) The global wavelet power spectrum, which is the average variance of each period for the whole time series. Grey shading corresponds to annual variance; purple shading corresponds to interannual (2-8 years) variance; and orange shading corresponds to ~decadal variance.

Between 1959 and 2010 the mean $\delta^{18}$O value for Butaritari is -5.20 ‰. Between 1959 and 1990 the mean $\delta^{18}$O value for Tarawa is -4.90 ‰. Between 1959 and 1994 the mean $\delta^{18}$O value for Maiana is -4.67 ‰. The differences in the mean $\delta^{18}$O in the three records (averaged over the overlapping intervals with Butartari, 1959 to 1990 for Tarawa and 1959 to 1994 for Maiana) appear to correlate with the geographical positions of each island (**Figure 27**). Butaritari is the most northern of the three islands, located at 3°30’N, 172°30’E, and indicates the warmest/wettest $\delta^{18}$O signal. The precipitation instrumental record (**Figure 30**) supports a north-south rainfall gradient between Butaritari (3°30’N) and Tarawa and Maiana (1°N). According to **Figure 30**, Tarawa and Maiana experience the same levels of rainfall, which suggests
the differences between the Tarawa and Maiana δ¹⁸O signals are not primarily due to changes in precipitation. The IGOSS SST data product indicates a similar pattern to precipitation however there appears to be a slight difference in SST between Tarawa and Maiana even though they are on the same latitude (Figure 31). Tarawa is closer to the 29°C contour line than Maiana. Correspondingly, the δ¹⁸O signal is more positive at Maiana, indicating cooler SST. The differences between Tarawa and Maiana appear to be driven mostly by temperature. This small east-west SST difference may be attributed to the fluctuations in the convergence of the western and central equatorial water bodies along the eastern edge of the IPWP.

Figure 30 – Zoomed in section of Figure 8. Mean precipitation data for the time period between January 1979 to November 2011 derived from CMAP Precipitation data from NOAA NCEP CPC Merged Analysis monthly latest version 1 precipitation estimate (Xie and Arkin 1996; Xie and Arkin 1997). The location of Butaritari (this study; 3°30’N, 172°30’E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a red square and purple star respectively. Central Pacific islands: Palmyra (blue rectangle; 6°N, 162°W), Fanning (black rectangle; 4°N, 159°W) and Christmas (orange rectangle; 2°N, 157°W).
Figure 31 – Zoomed in section of (Figure 7). Mean monthly SST for the time period between 1959 to 2010 derived from ERSSTv3b (Smith et al. 2008). Black contours = 0.5°C. The location of Butaritari (this study; 3°30′N, 172°30′E) is indicated by a yellow circle. The locations of Tarawa (1°N, 172°E) and Maiana (1°N, 173°E) are indicated by a black square and purple star respectively. Central Pacific islands: Palmyra (blue rectangle; 6°N, 162°W), Fanning (black rectangle; 4°N, 159°W) and Christmas (orange rectangle; 2°N, 157°W).

Figure 32 – δ¹⁸O records and trend lines for Butaritari (green), Tarawa (blue) and Maiana (red). The Tarawa and Maiana data are from longer datasets however they have been truncated to the period of overlap with the Butaritari record (see Figure 27). The black bracket indicates the common interval between all three datasets.
Using the same methods as in Section 5.2.2, the slope of the trend for Butaritari $\delta^{18}O$ (1959-2010) is,

$$\delta^{18}O = 1.104 - 0.00318 \times \text{Year}$$

$$\text{trend} = (-0.00318 \pm 0.0009) \times 51 \text{ years}$$

$$\text{trend} = -0.16 \text{‰}$$

$$\sigma_{\text{trend}} = 0.0009 \times 51 \text{ years}$$

$$\sigma_{\text{trend}} = 0.04 \text{‰}$$

All three islands $\delta^{18}O$ records reflect statistically significant trends over the common data interval (1959-1990) towards depleted $\delta^{18}O$ values, which reflect trends in combined warming and/or freshening ($p < 0.001$) (Figure 32; Table 3). The greatest trend is evident at Maiana and the smallest trend is evident at Tarawa, although the Tarawa and Butaritari trends are very similar. The $\delta^{18}O$ Butaritari record suggests a combined warming and freshening trend of $-0.28 \pm 0.06 \text{‰}$ over 31 years between 1959 and 1990. The $\delta^{18}O$ Tarawa record indicates a trend of $-0.23 \pm 0.03 \text{‰}$ over the same time period, and the $\delta^{18}O$ Maiana record suggests a trend of $-0.49 \pm 0.05 \text{‰}$ over the same time period. The differences in these trends between the neighbouring islands imply that despite the relatively close distances between them, each island experiences localised variations in $\delta^{18}O$. $\delta^{18}O$ is a function of both localised SST and/or SSS, which is primarily influenced by precipitation/evaporation. Move negative $\delta^{18}O$ values correspond to warmer and wetter conditions. Apart from the Butaritari coral, which has paired Sr/Ca and $\delta^{18}O$, the $\delta^{18}O$ for Tarawa and Maiana cannot be separated into its components parts, SST and SSS. Taken together however, these three corals suggest significant warming and/or freshening trends over the common data interval (1959-1990) that increase both towards the equator and in an easterly direction.

The overall trend in the full Butaritari record (1959-2010) reflects a slightly lower yet still significant warming and/or freshening pattern, compared to the 1959-1990 period for the same coral (Table 3). The Maiana record (1959-1994 for the period of overlap
with the Butaritari coral) reflects a slightly higher yet still statistically significant warming and/or freshening trend, compared to the 1959-1990 period.

Table 3 - $\delta^{18}O$ trends in Butaritari (this study), Tarawa (Cole et al. 1993) and Maiana (Urban et al. 2000) for the common data interval (1959-1990) and overall (1959-2010 for Butaritari and 1959-1994 for Maiana).

<table>
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<th>Island</th>
<th>Location</th>
<th>Trend in common interval (1959-1990)</th>
<th>Length of trend period (years)</th>
<th>Significance</th>
<th>Trend overall</th>
<th>Length of trend period (years)</th>
<th>Significance</th>
</tr>
</thead>
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<td>Butaritari</td>
<td>3°30'N, 172°30'E</td>
<td>-0.28 ± 0.06 ‰</td>
<td>31</td>
<td>p &lt; 0.001</td>
<td>-0.16 ± 0.04 ‰ *for 1959-2010</td>
<td>51</td>
<td>p &lt; 0.001</td>
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<tr>
<td>Tarawa</td>
<td>1°N, 172°E</td>
<td>-0.23 ± 0.03 ‰</td>
<td>31</td>
<td>p &lt; 0.001</td>
<td>Same as common interval trend</td>
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<tr>
<td>Maiana</td>
<td>1°N, 173°E</td>
<td>-0.49 ± 0.05 ‰</td>
<td>31</td>
<td>p &lt; 0.001</td>
<td>-0.55 ± 0.05 ‰ *for 1959-1994</td>
<td>35</td>
<td>p &lt; 0.001</td>
</tr>
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</table>

5.5 Butaritari compared to other Pacific records

A significant late 20th century warming and freshening trend has also been observed in paired coral $\delta^{18}O$ and Sr/Ca records from Palmyra, Fanning and Christmas Islands (2°N-6°N, 157°W-162°W) in the central equatorial Pacific (Figure 33b; Nurhati et al 2009). These islands are part of the Line Island group of Kiribati and are located at similar latitudes to Butaritari, Tarawa and Maiana in the western equatorial Pacific (Figure 30, 31). $\delta^{18}O$ records from all six islands suggest similar freshening and warming trends (Figure 33) and show interannual variability related to ENSO. El Niño and La Niña signals reflected in the SOI are evident in all coral records, albeit in varying degrees. Additional coral data from Christmas Island (Evans et al. 1998; McGregor et al. 2011) has been plotted on the following figures to provide a visual representation of a longer dataset for Christmas. It must be noted however, that only the Nurhati et al. (2009) trends are compared with western Pacific corals. It also must be noted that the trends reported by Nurhati et al. (2009) include estimates of the total error. The Butaritari trends include estimates of the trend slope error, one component
of the total error. Despite differences in the error estimates, the relative trends indicated at each locality can be compared to each other.

The western Pacific corals from Butaritari, Tarawa and Maiana indicate a combined freshening and/or warming overall trend of between -0.16 and -0.55 ‰ (Figure 33a; see Section 5.4). However, for the period of overlap with the central Pacific corals (1972-1998), Butaritari exhibits no statistically significant warmer or freshening trend (0.06 ± 0.05 ‰, p > 0.001). The Tarawa and Maiana records indicate warming and/or freshening trends (p < 0.001), however due to the limits of the coral records, they do not span the full overlapping period (1972-1998) with Nurhati et al. (2009), and therefore the trends cannot be compared on equal terms. In comparison to the Butaritari insignificant trend, the central Pacific corals from Pamlyra, Fanning and Christmas suggest a combined freshening and/or warming of between -0.32 and -0.52 ‰ (Figure 33b; Nurhati et al. 2009).

**Table 4** - Butaritari (this study), Tarawa (Cole et al. 1993) and Maiana (Urban et al. 2000), Palmyra, Fanning and Christmas (Nurhati et al. 2009) δ¹⁸O trends.

<table>
<thead>
<tr>
<th>Island</th>
<th>Location</th>
<th>Trend overlapping period (1972-1998)</th>
<th>Length of trend period (years)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butaritari</td>
<td>3°30’N, 172°30’E</td>
<td>0.06 ± 0.05 ‰</td>
<td>26</td>
<td>p &gt; 0.001</td>
</tr>
<tr>
<td>Tarawa</td>
<td>1°N, 172°E</td>
<td>-0.28 ± 0.04 ‰ *for 1972-1990</td>
<td>18</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Maiana</td>
<td>1°N, 173°E</td>
<td>-0.26 ± 0.06 ‰ *for 1972-1994</td>
<td>22</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Palmyra</td>
<td>6°N, 162°W</td>
<td>-0.52 ± 0.09 ‰</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Fanning</td>
<td>4°N, 159°W</td>
<td>-0.40 ± 0.09 ‰</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Christmas</td>
<td>2°N, 157°W</td>
<td>-0.32 ± 0.10 ‰</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
</tbody>
</table>

There appears to be a slightly smaller relative gradient between trends in the central Pacific coral records compared to the western Pacific corals (Figure 33). There is a greater gradient difference between corals that are closer together (i.e. Butaritari, Tarawa and Maiana) than in corals that are a few more degrees of latitude and longitude apart (Palmyra, Fanning and Christmas). This may indicate that there may be more climate variability in the western equatorial Pacific, although the forces driving the variability are slightly different, for example the eastern edge of the IPWP in the west fluctuates significantly during ENSO events, which may have a more
pronounced impact on those islands in the west, through increased advection and rainfall from warmer SST.

There appears to be the same geographical gradient in both central and western Pacific, wherein more negative δ¹⁸O values are given by the islands located furthest north (Butaritari in the west and Palmyra and Fanning in the central). This may be a result of the impact of the ITCZ, which brings substantial rainfall (and thus a decrease in SSS) to the northern islands (Nurhati et al. 2009).

Figure 33 – Coral δ¹⁸O records from three western (a) and three central (b) equatorial Pacific islands. a) δ¹⁸O records from Butaritari (green line; bi-monthly resolution; 3°30′N, 172°30′E; this study), Tarawa (blue line; monthly resolution; 1°N, 172°E; Cole et al. 1993) and Maiana (red line; bi-monthly resolution; 1°N, 173°E; Urban et al. 2000) islands between 1959 and 1990. b) δ¹⁸O records from Palmyra (pink line; monthly resolution; 6°N, 162°W; Cobb et al. 2001), Fanning (black line; monthly resolution; 4°N, 159°W; Nurhati et al. 2009) and Christmas (orange line; monthly resolution; 2°N, 157°W; Nurhati et al. 2009) islands between 1972 and 1998; Christmas between 1959 and 1993 (Evans et al. 1998), and between 1978 and 2007 (McGregor et al. 2011). c) Monthly Southern Oscillation Index (SOI) available from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soi2.shtml). El Niño threshold (SOI < -8) is marked by a dotted line on the SOI trace. La Niña threshold (SOI > 8) is marked by a dashed line on the SOI trace. The black bracket indicates the common interval between datasets (1972-1998).
The Butaritari Sr/Ca-derived SST record reveals a significant warming trend of $0.77 \pm 0.17 \, ^\circ C$ between 1959 and 2010 (Figure 34a; see Section 5.1). For the period corresponding with the Nurhati et al. (2009) data, Butaritari exhibits an identical significant warming trend of $0.77 \pm 0.15 \, ^\circ C$. Palmyra, Fanning and Christmas also reveal significant warming trends, $0.94 \pm 5.81 \, ^\circ C$, $1.37 \pm 0.67 \, ^\circ C$ and $1.65 \pm 5.73 \, ^\circ C$, respectively, between 1972 and 1998 (Table 5, Figure 34b; Nurhati et al. 2009). The trends between the western and central Pacific are similar, although more warming appears to occur in the central Pacific corals.

**Table 5** - Butaritari (this study), Palmyra, Fanning and Christmas (Nurhati et al. 2009) Sr/Ca-SST trends.

<table>
<thead>
<tr>
<th>Island</th>
<th>Location</th>
<th>Trend overlapping period (1972-1998)</th>
<th>Length of trend period (years)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butaritari</td>
<td>3°30’N, 172°30’E</td>
<td>$0.77 \pm 0.15 , ^\circ C$</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Palmyra</td>
<td>6°N, 162°W</td>
<td>$0.94 \pm 5.81 , ^\circ C$</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Fanning</td>
<td>4°N, 159°W</td>
<td>$1.37 \pm 6.57 , ^\circ C$</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Christmas</td>
<td>2°N, 157°W</td>
<td>$1.65 \pm 5.73 , ^\circ C$</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
</tbody>
</table>
Figure 34 – Coral Sr/Ca-derived SST records from one western (a) and three central (b) equatorial Pacific islands. a) Sr/Ca-derived SST record from Butaritari (green line; bi-monthly resolution; 3°30’N, 172°30’E; this study) between 1959 and 1990. b) Sr/Ca-derived SST records from Palmyra (pink line; monthly resolution; 6°N, 162°W; Cobb et al. 2001), Fanning (black line; monthly resolution; 4°N, 159°W; Nurhati et al. 2009) and Christmas (orange line; monthly resolution; 2°N, 157°W; Nurhati et al. 2009) islands between 1972 and 1998. c) Monthly Southern Oscillation Index (SOI) as described in Figure 33. The black bracket indicates the common interval between datasets (1972-1998).

The δ¹⁸O<sub>sw</sub> values for Palmyra, Fanning and Christmas Islands (Nurhati et al. 2009) were calculated using the Ren et al. (2002) method. As discussed earlier in Section 5.3, Cahyarini et al. (2008) found that the their proposed centering method for determining δ¹⁸O<sub>sw</sub> produces the same results as the Ren et al. (2002), except Ren et al. (2002) go one step further and calculate the cumulative contributions of δ¹⁸O<sub>sw</sub> to an arbitrary reference. To make the results from both methods directly comparable, the mean reconstructed δ¹⁸O<sub>sw</sub> value calculated using the Ren et al. (2002) method in Nurhati et al. (2009) is subtracted from reconstructed δ¹⁸O<sub>sw</sub>. This provides the relative variations in δ¹⁸O<sub>sw</sub> (Cahyarini et al. 2008). Removing the mean reconstructed δ¹⁸O<sub>sw</sub> from each reconstructed δ¹⁸O<sub>sw</sub> value does not alter the trend, and thus any trends evident from Butaritari and the three central Pacific corals can be compared on common terms.

Table 6 - Butaritari (this study), Palmyra, Fanning and Christmas (Nurhati et al. 2009) δ¹⁸O<sub>sw</sub> trends.

<table>
<thead>
<tr>
<th>Island</th>
<th>Location</th>
<th>Trend overlapping period (1972-1998)</th>
<th>Length of trend period (years)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butaritari</td>
<td>3°30’N, 172°30’E</td>
<td>0.15 ± 0.05 ‰</td>
<td>26</td>
<td>p &gt; 0.001</td>
</tr>
<tr>
<td>Palmyra</td>
<td>6°N, 162°W</td>
<td>-0.32 ± 0.08 ‰</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Fanning</td>
<td>4°N, 159°W</td>
<td>-0.12 ± 0.08 ‰</td>
<td>26</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Christmas</td>
<td>2°N, 157°W</td>
<td>0.03 ± 0.11 ‰</td>
<td>26</td>
<td>p &gt; 0.001</td>
</tr>
</tbody>
</table>

The δ¹⁸O<sub>sw</sub> record from Butaritari exhibits no statistically significant trends over the 51 year period between 1959 and 2010 (-0.01 ± 0.03 ‰; p > 0.001, Section 5.2), nor over the period of comparison with Nurhati et al. (2009), 0.15 ± 0.05 ‰ (p > 0.001).
δ¹⁸Ows records from Palmyra and Fanning show significant freshening trends of -0.32 ± 0.08 ‰ and -0.12 ± 0.08 ‰, respectively over the period between 1972 and 1998 (Nurhati et al. 2009). Christmas shows no statistically significant trend in δ¹⁸Osw (0.03 ± 0.11 ‰). As Palmyra is situated closest to the ITCZ and exhibits the largest freshening trend, Nurhati et al. (2009) suggest that increases in equatorial SST may have forced a strengthening and/or an equatorward migration of the ITCZ. This may explain the central Pacific, but the ITCZ may not be able to maintain its strength across to the west. In this way, Butaritari in the west could experience less of the ITCZ forcing and therefore experience less of a trend in δ¹⁸Osw. Although, no significant SSS trends exist in the Butaritari coral record, the record does fluctuate over the ~50 year period. The δ¹⁸Osw at Butaritari may be influenced by the east-west migration of the IPWP, wherein warm waters are dominant during El Niño events. These EWPCZ dynamics are localised to the IPWP and do not extend fully to the central Pacific where Palmyra, Fanning and Christmas are situated.

Figure 35 – Relative variations in δ¹⁸Osw records (SSS proxy) from one western (a) and three central (b) equatorial Pacific islands. a) δ¹⁸Osw record from Butaritari (green line; bi-monthly resolution; 3°30’N, 172°30’E; this study) between 1959 and 1990. b) δ¹⁸Osw records from Palmyra (pink line; monthly resolution; 6°N, 162°W; Cobb et al. 2001), Fanning (black line; monthly resolution; 4°N, 159°W; Nurhati et al. 2009) and Christmas [Nurhati et al. 2009].
Christmas (orange line; monthly resolution; 2°N, 157°W; Nurhati et al. 2009) islands between 1972 and 1998. c) Monthly Southern Oscillation Index (SOI) as described in Figure 33.

CONCLUSIONS AND RECOMMENDATIONS

This project aimed to investigate the climatic variability of the western equatorial Pacific, with particular reference to ENSO. Paired Sr/Ca and δ¹⁸O were measured from a Butaritari coral core, and coral-specific SST and δ¹⁸O_sw were calculated, respectively. The Butaritari coral records correlate well with local climatology (SST, precipitation and SSS), and the applicable ENSO indices, NINO 4 and SOI. Wavelet analysis indicates similar interannual, decadal and/or multi-decadal between data across the ~50 year time period. The Butaritari coral-derived SST exhibits a warming trend over the ~50 year period that is consistent with instrumental data products in both the IPWP and Pacific-wide basin, and coral records from the central Pacific. The δ¹⁸O trend indicates a combined warming and/or freshening, while no significant trends have been identified within the δ¹⁸O_sw component over the past 50 years. These results have been compared to corals from nearby Tarawa and Maiana and central equatorial Pacific islands.

Recommendations for future work related to this study:

- Measure the geochemistry in a second, potentially longer modern coral from the Butaritari locality to verify the results found in this study, in particular the Sr-Ca-SST calibration.
- Analyse the entire Butaritari modern coral core. This study investigated the time period ~1960 and 2010, however the coral core extends back to at approximately 1948/1950. An additional decade worth of geochemistry data could be useful in further exploring the patterns and trends evident in the current analysis.
Further comparisons of the trends evident at Butaritari with other equatorial Pacific coral records such as those from Nauru (0°30’S, 166°E) (Guilderson and Schrag 1999), and Madang, Papua New Guinea (5°13’ S, 145°49’E) (Tudhope et al. 1995), over longer long periods.

Investigate the geochemical signals of fossil coral cores collected from Butaritari Atoll. Well preserved fossil corals from the tropical Pacific can act as very useful archives of past climates as they extend beyond the limited modern instrumental data. Reliable instrumental SST data for this tropical region rarely extends beyond 1950 (Gagan et al. 2000). Fossil coral corks and cores were collected from Butaritari in May 2010 and August 2011, respectively. Some of these samples have been preliminarily dated to have ages circa 1500 to 1600 AD. These ages correspond to a period known as the ‘Little Ice Age’, wherein ENSO is thought to be influenced by small fluctuations in the extent of incoming solar radiation (Cobb et al. 2003). Preliminary preservation checks (x-ray diffraction and thin section analysis) of one fossil core have indicated potential suitability for high resolution geochemical analysis, especially δ¹⁸O. A comparison could be made between the Butaritari modern coral-derived climate records and the fossil corals, and the evolution of ENSO could be further explored.

The results of this study are significant as they establish Butaritari Atoll as a useful site for coral climate reconstructions, particularly at the dynamic equatorial eastern edge of the IPWP.
REFERENCES


Research Data Archive (2012). *ICOADS Observation counts dataset for the Gilbert Islands.* RDA is maintained by the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation No. ds540.0. Available at, [http://dss.ucar.edu](http://dss.ucar.edu).


APPENDIX: (Data CD)
The samples utilised in this study have been archived in the School of Earth and Environmental Sciences at the University of Wollongong (catalogue number: R22001).