Climatic influences on modern coral isotopic records from the Cocos (Keeling) Islands

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In order to look for correlations, Oxygen isotope data and various climatic datasets, including sea surface temperature and precipitation, were analysed statistically, using singular spectral analysis, cross-spectral analysis, multi-taper method analysis, and wavelet analysis in addition to visual analysis, to determine the significance of cycles occurring between 1924 and 1992. As a consequence of initial Oxygen isotope results, Strontium-Calcium analysis was also undertaken for the years 1935 to 1992 and the results were statistically analysed with relation to climate records. SST was shown to be influenced by the El Niño Southern Oscillation and potentially by the Indian Ocean Dipole whereas precipitation did not correlate with either. Neither the SST data nor the precipitation data correlated significantly with the geochemical records at meaningful frequencies. The Oxygen isotopes and Strontium-Calcium ratio of Porites coral at the Cocos (Keeling) Islands did not, therefore, appear to be suitable for use as Palaeoclimate proxies. Further research would be necessary to determine the full range of factors that influence the geochemistry of coral at this isolated site and whether alternative proxies from the coral better correlate with climate conditions at the Cocos (Keeling) Islands.

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Climatic influences on modern coral isotopic records from the Cocos (Keeling) Islands

A thesis submitted in (partial) fulfilment of the requirements for the award of the degree of

INTERNATIONAL BACHELOR OF SCIENCE

From

The University of Wollongong

By

JACQUELINE FENWICK

School of Earth and Environmental Sciences

October, 2011
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Jacqueline Fenwick 12-10-2011
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In order to look for correlations, Oxygen isotope data and various climatic datasets, including sea surface temperature and precipitation, were analysed statistically, using singular spectral analysis, cross-spectral analysis, multi-taper method analysis, and wavelet analysis in addition to visual analysis, to determine the significance of cycles occurring between 1924 and 1992. As a consequence of initial Oxygen isotope results, Strontium-Calcium analysis was also undertaken for the years 1935 to 1992 and the results were statistically analysed with relation to climate records. SST was shown to be influenced by the El Niño Southern Oscillation and potentially by the Indian Ocean Dipole whereas precipitation did not correlate with either. Neither the SST data nor the precipitation data correlated significantly with the geochemical records at meaningful frequencies. The Oxygen isotopes and Strontium-Calcium ratio of *Porites* coral at the Cocos (Keeling) Islands did not, therefore, appear to be suitable for use as Palaeoclimate proxies. Further research would be necessary to determine the full range of factors that influence the geochemistry of coral at this isolated site and whether alternative proxies from the coral better correlate with climate conditions at the Cocos (Keeling) Islands.
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Even in the most ideal conditions, with the greatest willpower, a single coral polyp would be unable to produce a significant coral structure on its own.

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This coral polyp couldn’t have done a thing without your help!
CHAPTER ONE: Introduction

Climate bears an unavoidable influence on humanity. From the agricultural plights of past civilisations to the political settings of the modern world, climate has had, and will continue to have, a profound impact on human society. In recent decades, the dynamic nature of Earth’s climate has become apparent and it is now a priority to better understand its complexities. The ability to interpret climatic behaviour of the past is key to understanding Earth’s present and future climate variability. Palaeoclimatology, the study of past climate, is a rapidly developing field of study which has led to a growing demand for quantitative, high resolution, reconstructions of past conditions and has subsequently encouraged further research into proxies, methodologies and analysis techniques. Proxies are entities, often biological or geological, which have indirectly recorded information on past climate and are used to develop or extend records into times and places lacking adequate instrumental data (Mann et al. 2008). The use of geochemical records in coral has proven a particularly insightful palaeoclimate proxy in tropical marine environments. The isotopic and elemental ratios, particularly Oxygen-18/16 ($\delta^{18}$O) and Strontium/Calcium (Sr/Ca) ratios, often exhibit close covariance with climatic parameters such as sea surface temperature, precipitation and ocean upwelling. Where modern corals can be shown to align with recent climatic records the longer term climate can then be interpreted from older coral records and applied to understanding climate variability over time.

In the tropical Pacific Ocean, the use of coral geochemical records in palaeoclimate studies has proven highly successful in reconstructing the El Niño Southern Oscillation (ENSO) for years pre-dating reliable instrumental measurements (Linsley et al. 2000, McGregor & Gagan 2004, Corrège) and has contributed to understanding present and future variability. Recently, research has focused on the influences on climatic variability of the Indian Ocean. The principal influence on the tropical Indian Ocean is, like the Pacific Ocean, the El Niño Southern Oscillation however research since the late 1990’s has revealed the possibility for other climatic influences such as the Indian Ocean Dipole (Saji et al. 1999,
Allan et al. 2001, Kayanne et al. 2006). Instrumental measurements of climate and ocean parameters for this region are generally scarce and limited to the past few decades and suitable proxy records from the area are, likewise, limited. The relative effects of these processes on Indian Ocean climate and ocean variability may have significant impact on the climates of Australia and other countries surrounding the Indian Ocean.

This research investigates geochemical records from a modern coral in the tropical eastern Indian Ocean, and compares these to instrumental climate records, in order to examine the suitability of coral from this site as a proxy for past climate in the region. Research into this field is significant because; the climatic factors influencing the region are still contentious, the oceanic and climatic conditions over the Indian Ocean have significance for surrounding terrestrial climates, and because further insight into climate and ocean patterns of the past may help to explain present and future trends.

The Cocos (Keeling) Islands are an isolated atoll in the eastern Indian Ocean. Microatolls, flat-topped corals of the genus Porites, occur extensively on reef flats and in shallow lagoon environments surrounding the atoll. Their upper surface has been shown to be constrained by sea-level and has been useful in the investigation of sea level change (Smithers & Woodroffe 2001). A Porites microatoll from the eastern reef flat in the Cocos (Keeling) Islands was sampled, alive, in 1992 and a slice extracted from it has been studied using x-ray density banding, luminescence banding and interpolation methods. Carbon-14 research was conducted using the coral to establish surface water origin (Hua et al. 2004) and monthly samples were extracted and analysed for $\delta^{18}O$ isotope records using Mass Spectrometry at UOW and ANU.

This study looks at the results of that $\delta^{18}O$ isotope analysis and uses samples from that coral to produce Sr/Ca records which were measured using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) at the Australian Nuclear Science and Technology Organisation (ANSTO). The collection of frequency domain information from the $\delta^{18}O$ and Sr/Ca time series and its analysis against existing climatic data is intended to explain whether correlations exist between geochemical variability and the influence of atmospheric and oceanic behaviour in the past. Several spectral analysis methodologies
have been used to investigate data of this nature, particularly Multi-Taper Method analysis, Singular-Spectral Analysis, Cross-Spectral analysis and Wavelet Analysis.

The primary objective of this study is to examine whether the geochemical analysis of coral skeletons of the Cocos (Keeling) Islands, in the eastern Indian Ocean, offers a proxy record of climate or ocean variables between 1924 and 1992. To achieve this, the project will;

a) determine the dominant cycles and variability present in the $\delta^{18}$O isotopic records of coral in the Cocos (Keeling) Islands,
b) compare this with dominant cycles and variability in the Sr/Ca within coral in the Cocos (Keeling) Islands,
c) statistically investigate the correlations between past $\delta^{18}$O and Sr/Ca variability and the influence of known climatic and oceanic phenomena and trends, and
d) establish whether the Indian Ocean Dipole and El Niño Southern Oscillation are manifested at this locality and whether coral might offer a proxy record for its variability.

In meeting these aims, we will better understand the nature of the climatic signals influencing coral geochemistry at the Cocos (Keeling) Islands, and the eastern Indian Ocean region, throughout the 20th Century. In doing so the suitability of coral geochemical records from the Cocos (Keeling) Islands as proxies for past climate can be determined. Furthermore, the study will provide insight into Indian Ocean atmospheric and oceanic variability which could be of benefit to prediction and management on landmasses surrounding the Indian Ocean.
CHAPTER TWO: Climate of the tropical Indian Ocean

2.1 Mean Climate and Ocean Characteristics

The climate surrounding the tropical Indian Ocean, and the ocean circulation within the region, are influenced by a complexity of different factors and interactions. The dynamics of both the climate and the mean ocean conditions in this region are unique from those across other Oceanic regions due, in part, to the northern hemisphere landmass which prevents direct interaction with the Arctic.

2.1.1 Climate

The mean climate of the tropical Indian Ocean aligns with many core characteristics of tropical climates worldwide in response to latitude and subsequent energy fluxes. With regards to air temperature, the consistent warm temperatures of the underlying Ocean itself maintain warm air temperatures with low variability throughout the year. The annual mean wind patterns across the tropical Indian Ocean are characterised by weak equatorial westerly winds, due to atmospheric convection surrounding Indonesia to the east of the Indian Ocean. This contrasts with the Atlantic and Pacific Ocean regions where the mean annual wind direction is easterly (Webster 1999, Xie et al. 2002, Feng & Meyers 2003). South of 10°S the south-easterly trade winds are persistent year-round and are strongest from June to September.

North of 10°S, the tropical Indian Ocean climate is also influenced by the annual Asian monsoon which involves a semi-annual reversal of winds which blow south-west from May to October and north-east from November to April (Xie et al. 2002). The monsoonal climate results from surface air pressure changes and causes seasonal rainfall trends in the tropics which are not observed in the other oceans (Pfeifeer & Dullo 2006).

2.1.2 Ocean

Mean Sea Surface Temperature (SST) conditions in the tropical Indian Ocean can be considered a westward extension of the Pacific Ocean’s warm pool and surrounding climate with temperatures reaching well above 28°C and the presence of a gradual east to west decrease (Webster et al. 1999, Feng & Meyers 2003, Pfeifeer & Dullo 2006). Long-term
trends in SST, evident in data collected since the early 1900’s, show increasing temperatures as well as increasing salinity in the upper 150m of the Indian Ocean at most latitudes with the salinity increase most evident north of 10°S (Boyer et al 2005, Urban et al. 2000). In the subsurface ocean layer between 100m and 300m depth, however, the tropics between 7° and 15°S have exhibited a cooling trend since the mid 1900’s (Schwarzkopf & Boning 2011). It is likely that this subsurface trend results somewhat from upwelling of the Indian Ocean thermocline and is influenced by Rossby Waves, or large-scale thermocline waves, from the Pacific Ocean. Between 0° and 40°S a freshening trend is also evident in the subsurface layer at 250m to 1000m depth (Boyer et al 2005) and a low salinity tongue is pronounced in the eastern equatorial region due to lower salinity flow from the western Pacific (Rao & Sivakumar 2003).

An important oceanic parameter, within the study of the climate surrounding the tropical Indian Ocean, is thermocline depth and variability. Thermoclinal variance is often matched with covariance in climatic parameters including changes in wind strength and direction, atmospheric convection, and precipitation patterns. While the Atlantic and Pacific Oceans have a sloping thermocline and equatorial cold tongue in mean conditions, the Indian Ocean exhibits this state only occasionally. In the Indian Ocean, the thermocline at the equator is, typically, relatively deep and flat, sloping only slightly to the east (Xie et al 2002, Saji et al 2006). Upwelling in the eastern equatorial Indian Ocean along the Javanese coast, Indonesia, occurs seasonally with alongshore winds. When conditions are suited a more extensive cold tongue develops to the east of the equatorial Indian Ocean as the thermocline shoals more prominently against Indonesia (Xie et al 2002). Due to wind-shear between the equatorial westerlies and the south-eastern trade winds the southern, tropical, Indian Ocean also features a band of upwelling between 5° and 15°S with the thermocline rising more to the west of the Indian Ocean (Xie et al 2002).

2.2 El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO), the most prominent interannual climate cycle in the world, was recognised by Bjerknes in the 1960’s (Bjerknes 1969, Enfield 1989) and is now considered to be of global significance. The phenomenon is dependent on oceanic and atmospheric processes and the inherent interactions between the two (Neelin
et al. 1998). ENSO involves the shifting of surface air pressure between the east and west tropical Pacific Ocean and is defined by a Southern Oscillation Index (SOI) which is calculated by air pressure difference between Tahiti and Darwin such that a ‘normal’ year has a near-zero SOI value (BOM 2011a). The three phases of the SOI, normal, negative and positive, are depicted in Figure 1. A strongly negative SOI, indicating abnormally low pressures over Tahiti and abnormally high pressures over Darwin, is termed an El Niño event (Enfield 1989). These events involve warmer SSTs with decreased upwelling in the east of the Pacific Ocean and simultaneous colder SSTs to the west. Trade winds are decreased and Australia experiences drier and cooler terrestrial conditions while warmer, wetter, conditions impact on South America (BOM 2011a, Hidore et al. 2010). These abnormal conditions, resulting from ENSO events, are considered anomalies as they occur outside the mean range of variability. A La Niña event, the opposite of El Niño, occurs when the SOI is strongly positive and results in reversed anomalies relative to El Niño.

The effects of ENSO on SST anomalies in the Pacific Ocean are clearly depicted in images a and b of Figure 2 which contrasts 1997 and 1988 conditions which were strong El Niño and La Niña events respectively. Images c and d, of Figure 2, show the tropical Indian Ocean in the same two years illustrating that the impact of ENSO is also apparent in the Indian Ocean. El Niño events occur at periodicities of three to seven years, averaging one every four years, and last for 14-22 months (Cole et al. 1993, Hidore et al. 2010, NOAA 2011). ENSO is largely self-sustaining which is explained through Bjerknes’ hypothesis (Bjerknes 1969, Hidore et al. 2010) which describes an inherent positive feedback between ocean and atmosphere in the equatorial regions. Bjerknes explained that the weakening of trade winds caused a weakening of equatorial upwelling, which subsequently decreased the gradient in SSTs and resulted in further weakening of trade winds. The feedback is impaired when the supply of warm water shifts away from the equator and weakens the ENSO effects (Hidore et al. 2010).
Figure 1: Atmospheric and oceanographic conditions during the three phases of ENSO: Normal, El Niño and La Niña.
Figure 2: Sea surface temperature anomaly plots, based on Kaplan reconstructions, for the tropical Pacific Ocean (a & b) and the tropical Indian Ocean (c & d). The data is averaged over 12 months, from January, for; a) and c) - a strong El Niño year, 1997, and for b) and d) - a strong La Niña year, 1988. These two ENSO phases are shown to be distinctly different, with opposing positive and negative anomalies. (Figures compiled with climexp.knmi.nl)

2.3 Indian Ocean Dipole

Prior to the late 1990’s all significant climate variability in the Indian Ocean region was believed to be closely associated with the Pacific Oceans’ ENSO without any form of oscillatory influence from the Indian Ocean itself. The Indian Ocean Dipole, defined as an oscillating mode observed through SST variations between designated east and west regions in the tropical Indian Ocean, was first described by Saji et al. (1999). Based on a 40yr record of observational data, their research used Empirical Orthogonal Function calculations to
determine that the IOD, distinct from ENSO, was responsible for 12% of tropical Indian Ocean SST variability. Through this same method, ENSO was shown to possess a 30% correlation with SST variation and to thus be the dominant, but distinctly separate, influence (Saji et al. 1999).

The Indian Ocean Dipole (IOD) is a zonally, or east-west, occurring coupled ocean-atmosphere dipole system in the tropical and equatorial Indian Ocean (BOM 2011b, Saji et al. 1999). It is quantified using an index termed the Dipole Mode Index (DMI) or Indian Ocean Dipole Mode (IODM) which compares Sea Surface Temperature anomalies in a specified zone in the eastern equatorial Indian Ocean, between 90°-110°E and 10°-0°S, and a zone in the western equatorial Indian Ocean, between 50°-70°E and 10°S-10°N (BOM 2011b, Saji et al. 1999). These regions are illustrated in Figure 3. Although the Index is determined solely by SST comparisons this is significantly influential for climatic fluctuations as 60-80% of climate variability between the tropics is forced by this SST (Ummenhofer et al. 2008).

The IOD is measured using SST but affects many additional parameters including temperature, thermocline, wind strength and direction, and rainfall relative to mean conditions (Saji & Yamagata 2003, Meyers et al. 2007).

Figure 3: Indian Ocean and surrounding landmasses showing positions of the east and west poles of the IOD.
Two distinct phases in the Dipole Mode Index, a positive phase and a negative phase, have been noted in the SSTs of the tropical Indian Ocean and have been shown to correlate strongly with anomalous trends in other properties such as surface wind and thermocline dynamics (Saji & Yamagata 2003). By subtracting SSTs from the eastern ‘pole’ from those in the western, the resultant DMI is positive when SSTs are warmer in the west and a negative DMI occurs when SSTs are warmer in the east. During an IOD positive phase the SSTs are anomalous, relative to the mean range of variability, with negative anomalies in the east and positive in the west which influences the east-west SST gradient of the Indian Ocean tropics (Saji & Yamagata 2003). The IOD negative phase is essentially the opposite occurrence with negative SST anomalies in the west and positive in the east. The east-west SST oscillations between the two phases are evident in Images a and b of Figure 4 which show annual mean conditions for known positive and negative IOD years, 1994 and 1958 respectively. An IOD event occurs when the three-month running mean of the Dipolar Mode Index exceeds half of the standard deviation calculated for the whole record (Saji et al. 2005). The Index anomalies for the east and west poles must also be of opposite sign for the three months. Events are classed by Abram et al. (2008) as moderate events (>1.5σ) and strong events (>3σ). Drawing on this definition, the IOD events between 1924 and 1992 are tabulated below in Table 1.

Table 1: Event years calculated from the Dipole Mode Index (DMI) record between 1924-1992, as having a 3-month running mean of a DMI >1.5σ (CSIRO 2011b, Saji et al 2005).

<table>
<thead>
<tr>
<th>IOD event phase</th>
<th>Year (1924-1992)</th>
</tr>
</thead>
</table>
Figure 4: Monthly anomalies averaged over 12 months with positive IOD and no ENSO, 1994, in the left column and a negative IOD year with no ENSO, 1958, in the right. Plots a) and b) depict SST anomalies (Kaplan reconstruction), plots c) and d) depict land precipitation anomalies (GPCC V5 analysis). Distinct differences can be noted between the conditions in a positive year relative to a negative year. (Figures compiled using climexp.knmi.nl)

Studies have applied the Bjerknes hypothesis to explanation of the Indian Ocean Dipole oscillations, and the inherent ocean-atmosphere interactions involved, as it is similarly applied to ENSO explanation (Meyers et al. 2007, Saji et al. 2006, Schott et al. 2009). Deser et al. (2010) described this mechanism as an ‘east-west seesaw’ involving oscillating SSTs, wind anomalies and upwelling-downwelling thermocline trends across the tropics of the Indian Ocean. As research into Indian Ocean processes continues these explanations will no doubt be better described and understood.
CHAPTER THREE : Indian Ocean Sea Surface Temperature variability

3.1 Sea Surface Temperature

Sea Surface Temperature (SST) is the temperature of the thin film of water on the sea surface which forms the sea-atmosphere interface and is detectable through remote sensing (NSIDC 2011). The term is commonly applied, however, to the temperature of the top few metres of water and is thus also applicable to in situ instrumental measurements which inherently measure below the sea surface itself. SST is influenced by both oceanic and atmospheric processes and is consequently one of the key parameters associated with large-scale climate oscillations. It is also significant for its influence on atmospheric factors. The SST of the tropical Indian Ocean has been variable and inconsistent over the last century. The record shown in Figure 5 illustrates both annual oscillations and longer term variability in SST of the Cocos (Keeling) Islands in the eastern Indian Ocean derived from the GOSTA Global SST and Ice Concentration record.

![Figure 5: Sea Surface Temperature record for 96.5°E - 12.5°S, from 1924 to 1992, constructed by GOSTA gisst22 (IRI 2011).](image)
3.2 El Niño Southern Oscillation influence

3.2.1 ENSO as the foremost influence on Indian Ocean SST

It has been shown that the Pacific Ocean’s El Niño Southern Oscillation (ENSO) phenomenon is the foremost influencing factor on SST variation in the tropical Indian Ocean. This has been demonstrated previously through statistical analysis of SST records, derived from in situ, remote and proxy measurements (Cai et al. 2005, Meyers et al. 2007, Saji & Yamagata 2003). It is highly likely that ENSO thus exerts a fundamental influence over local SSTs of the Cocos (Keeling) Islands in the eastern Indian Ocean. More topical is whether it is also ENSO which forces other less dominant cycles, with various lags, determined within the Indian Ocean’s SST record.

3.2.2 Influence on Indian Ocean SST via an Atmospheric Bridge

It has been suggested that less dominant cycles in the Indian Ocean SST record may be lagged manifestations of the ENSO influence (Klein et al. 1999, Alexander et al. 2002, Deser et al. 2010). The ‘atmospheric bridge’ concept has been used to explain lagged relationships between climatic and oceanic conditions in the Pacific and Indian Oceans, accounting for the dominant, and numerous subsequent, cycles in Indian Ocean SSTs (Klein et al. 1999, Deser et al. 2010). ENSO-induced changes in atmospheric circulation and tropical convection in southern latitude tropics result in cloud cover, air temperature and wind variations and associated changes in evaporation, humidity and absorbed solar radiation in other oceans including the Indian (Klein et al. 1999, Alexander et al. 2002). Through more complex atmospheric dynamics, ENSO may induce changes in the Walker Circulation which causes wind stress over the Indian Ocean (Saji et al 2006) and the formation of off-equatorial Rossby waves in turn which disturb the thermocline and influence SST (Saji et al. 2006).

Klein et al. (1999) proposed that this atmospheric bridge was responsible for 3 month lagged cloud cover fluctuations and 5-6 month lagged SST variability in the tropical Indian Ocean. In further support of the atmospheric bridge concept, studies by Alexander et al. (2002) and Deser et al. (2010) found the Indian Ocean SSTs to warm with El Niño at a 3-6 month lag. Alexander et al. (2002) additionally found SSTs of the Indian Ocean to vary significantly across longer temporal scales coherent with ENSO. Similar statistical analysis, looking specifically at the second most prominent cycle within Indian Ocean SST variation,
suggested that the SST signal varied with ENSO at leads and lags of 9-10 months (Allan et al. 2001). Proof of lagged influence does not, however, provide conclusive support for the atmospheric bridge as other modes of influence may exist.

**3.2.3 Influence on Indian Ocean SST via the Indonesian Through Flow**

Direct oceanic impacts of ENSO may transmit to the Indian Ocean via the Indonesian Through Flow (ITF) which flows through Indonesia and the Timor Sea, north of Australia (Bernal-Baquero et al. 2001). The Through Flow carries relatively warm and fresh water from the North Pacific Ocean, through the Indonesian archipelago, into the Indian Ocean and down the west coast of Australia (Lee 2002). The dominant flow directions of the Indonesian Through Flow are illustrated in *Figure 6*. The impact of ENSO on this current and its effect on circulation and water characteristics in the Indian Ocean are not fully understood due, in part, to the challenges of studying the flow through so many channels (Lee 2002). The ITF is known to weaken during an El Niño event when the major equatorial currents of the Pacific Ocean are directed eastwards (Saji et al. 2006). Abram et al. (2007) proposed, based on simulations, that SST fluctuations in the tropical Indian Ocean, distinct from ENSO, may be initially influenced by the Pacific Ocean due to interaction via this Through Flow.

*Figure 6:* Ocean circulation diagram showing major currents of the Indonesian Through Flow from the Pacific Ocean to the Indian Ocean. Arrow direction indicates direction of flow.
Another aspect of interaction between the Pacific Ocean and the Indian Ocean through the Indonesian Through Flow is the progression of Rossby Waves westward between the tropics of each Ocean (Schwarzkopf & Boning 2011). This plays a role in raising the thermocline in the southern tropical Indian Ocean which causes cooling at 100-300m depth and a resulting decline in sea surface height (Schwarzkopf & Boning 2011). Research in this field has not yet linked the Rossby waves with ENSO events so it is possible that there is a correlation yet to be discovered.

3.3 Indian Ocean Dipole influence

3.3.1 Debate surrounding the IOD - supporting evidence

The IOD, its autonomy from ENSO, and its influence on Indian Ocean SST have become topical and fiercely debated concepts within the realm of contemporary climatic studies (Allan et al. 2001, Damassa et al. 2006, Kayanne et al. 2006).

Since Saji et al. (1999) there has been growing support for the existence of the IOD, an internally-forced coupling in the tropical Indian Ocean which was shown to be responsible for 12% of tropical Indian Ocean SST variability (Loschnigg & Webster 1999, Saji et al. 1999). In particular, studies have used the temporal nature of positive and negative IOD events, to illustrate the IODs’ independence from ENSO in influencing SST (Abram et al. 2007, Abram et al. 2008, Kayanne et al. 2006, Saji et al. 1999). The events have been shown by Abram et al. (2008) to occur episodically at a frequency which varies significantly across time; from ~7yr frequency demonstrated in the 19th Century to the ~20yr and ~4yr frequencies identified for the early and late 20th Century respectively. This contrasts ENSO frequency and suggests that the IOD occurs, and has an effect on SSTs, independently of ENSO.

Numerous studies have determined the rate of coincident IOD events and ENSO events. Some IOD events, such as that in 1994, have occurred concurrently with El Nino however 39% of all IOD events between 1846 and 2007, including the strong 1961 occurrence, have taken place during a neutral ENSO phase, and one event, in 1967, coincided with a La Nina phase (Abram et al. 2007, Abram et al. 2008, Kayanne et al. 2006, Saji et al. 1999). Saji and Yamagata (2003) address this inconsistency by suggesting that the
tropical Indian Ocean SST is subject to the influence of both lagged, ENSO-driven changes in the mixed layer of the entire Indian Ocean basin and, additionally, strong east-west anomalies in the equatorial regions which explains the occurrence of IOD events both with and without simultaneous ENSO events. Disregarding the potential for lagged ENSO influence, research by Kayanne et al. (2006) showed that, though ENSO and IOD occasionally fall into phase, the frequent independence of events demonstrates the distinctness of the two phenomena. Similarly, a study of IOD variability since the middle Holocene, by Abram et al. (2007), suggested that the temporal nature of sea-surface temperature fluctuations and drought peaks were inconsistent with ENSO and, consequently, not driven by ENSO. It is likely that the tropical Indian Ocean, with the right conditions, can be triggered to commence a Bjerknes feedback and subsequent IOD event (Saji et al. 2006). The trigger for such events may be ENSO related but in other instances they could be triggered by alternative circumstances such as monsoonal variations, intra-seasonal variability, or the Southern Annular Mode (Saji et al 2006).

Research has also considered the intra-annual temporal characteristics of the proposed IOD. Initially undertaken by Li et al. (2003) and supplemented by others (Cai et al. 2005, Meyers et al. 2007) this field of study has concerned the development and evolution of individual IOD events in comparison to the life-cycle of ENSO events. IOD events have been shown to develop in May-June, reach peak strength in September-October and terminate rapidly towards the December-January monsoon season, in a seasonally determined temporal pattern quite unique from ENSO. Meyers et al. (2007) analysed this evolution by studying both the SST anomalies and the vertical thermocline upwelling and downwelling patterns in the east and west IOD regions defined by Saji et al. (1999). These parameters were also used by Cai et al. (2005) who termed the season-based evolution a ‘seasonal phase-locking feature’ and concluded that, although ENSO may potentially be a triggering factor for some of the events, the stark differences between IOD and ENSO life-cycles promotes the IODs’ autonomy.

More recently, modelling has been used to study the associations between IOD phases and the climate in the west and east of the tropical Indian Ocean. A Coupled General Circulation Model of the Indian Ocean atmosphere-ocean dynamics, run by Bracco et al. (2005), showed the Indian Ocean to display some independent variability fitting the
original Saji et al. (1999) IOD definition. In contrast, however, while modelling the seasonal development of the IOD Cai et al. (2005) were unable to make decisive conclusions regarding the IODs’ independence from ENSO due to complexity of interactions across the Indonesian Through-Flow. Taking a different approach, using a General Ocean Circulation Model driven with wind observations, Shinoda et al. (2004) showed that tropical Indian Ocean SSTs were most strongly forced by ENSO variability; however, the thermocline was most strongly forced by an Indian Ocean dipole.

A number of studies have looked specifically at linking IOD events and recent climate phenomena. Webster et al. (1999) focused on climate anomalies of 1997, particularly severe Indonesian drought and high east African rainfalls, to suggest that the Indian Ocean SST anomalies were independent of the Pacific Ocean’s influence. The abnormal climatic events were shown to correspond with, and indeed result from, the strong positive IOD phase which occurred during that year. Other studies have similarly drawn on the events of 1997 and reinforced the importance of understanding the evolution of Indian Ocean SSTs, separate from ENSO, for earlier prediction of climate events in eastern Africa (Goddard & Graham 1999). If positive IOD phases could be linked to climatic conditions, by understanding the frequency of the IOD occurrence it may be possible to forecast the onset of similar climatic events in the future and the adverse effects resulting from such events could be mitigated.

3.3.2 Debate surrounding the IOD – contradicting evidence

Despite evidence in support, the existence of the independent Indian Ocean Dipole, and its subsequent effect on SST variation, remains a contentious concept. Following the initial proposal of the IOD by Saji et al (1999) there has been some research contradicting its existence.

A number of alternative climatic patterns have been suggested. Though not ruling out the independence of the IOD, Marshall & McCulloch (2001) found an unequivocal relationship to exist between ENSO and the IOD as determined through corals from Christmas Island. In addition, this article rejected the Saji et al. (1999) designation of an IOD, suggesting that the defined east and west poles are not significantly correlated and that they are thus not valid indicators of climatic oscillation in the tropical Indian Ocean.
Others have suggested that a weak, yet autonomous, Indian Ocean dipolar mode does exist and has climatic influence however it is measurable only through atmospheric process (Annamalai et al. 2003, Bernal-Baquero et al. 2001). A study by Bernal-Baquero et al. (2001) showed SSTs in the Indian Ocean, and thus the IOD, to be remotely forced by ENSO via Indonesian Through Flow interactions. Rather than discarding the notion of an independent Indian Ocean Dipole, however, they suggested the existence of a zonally-oscillating dipole in the Indian Ocean which is primarily atmospherically driven rather than based on SSTs. Annamalai et al. (2003), similarly proposed the existence of a dipole-like variable, the Indian Ocean Zonal Mode (IOZM), which is an atmospherically driven dipole appearing only weakly when independent of ENSO. It is suggested that intensification of the IOZM may be triggered by ENSO through changes to the Walker Circulation over the Pacific Ocean and subsequent teleconnection (Annamalai et al. 2003).

### 3.3.3 Current IOD research

In ongoing research within the Saji et al. (1999) IOD paradigm, studies have touched on IOD-climate change interaction. Recent research by Cai et al. (2009) shows that the frequency of IOD events is increasing, with four events of the early 20th Century surpassed by ten events in the past 30 years. Climate modelling undertaken by these researchers to explain the apparent trend showed a 17% increase in IOD event frequency when modelled with climate change forcing relative to when modelled without. They propose that global warming may cause faster land heating and therefore a stronger monsoon. This may in turn shoal the thermocline in the east of the Indian Ocean and promote positive IOD events (Cai et al. 2009, Zheng et al. 2010). Further study into the impact of global warming has suggested that global warming-induced SST increase is greater in the western, rather than eastern, Indian Ocean which may change the periodicity and magnitude of IOD events from that in the past (Nakamura et al. 2009). A study by Zheng et al. (2010) contradicts this, however, and explains that event frequency remains unchanged with warming due to reducing atmospheric responses. With further study into the IOD palaeoclimatic records the implications of climatic change may become clearer.

Although the most recent publications appear to favour the existence of an IOD, as defined by Saji et al. (1999), the debate surrounding its distinction from ENSO remains unresolved. Proponents of the autonomous IOD infer significant climate influences related
to the events and, in this view, further debate over its existence may constrain potentially beneficial research into prediction. There is therefore a need for future research into the IOD, and its relation to ENSO, is undertaken. This research project assumes the existence of an IOD, separate from ENSO, and concerns whether this IOD signal is distinguishable in coral geochemistry from the Cocos (Keeling) Islands site. To discern a signal at this site would be to support this line of thinking and to bolster knowledge of the eastern pole.

3.4 Significance of the Indian Ocean Sea Surface Temperature Variability

The SST conditions of the tropical Indian Ocean are significant in determining climatic trends over the Ocean itself as well as across surrounding terrestrial regions. The development of a sound knowledge of the influences on Indian Ocean Climate, including the Indian Ocean Dipole and its interaction with ENSO, may assist in future forecasts of climate conditions within and surrounding this region.

The IOD has the capacity to influence or induce interannual climate anomalies in regions surrounding the Indian Ocean (Yamagata et al. 2004). The positive IOD event is believed to be associated with decreased winter rainfall over central and southern Australia and severe drought in the Indonesian region (Abram et al. 2007, BOM 2011b, JAMSTEC 2008, Meyers et al. 2007, Yamagata et al. 2004). This is evident, with particular clarity, in Figure 4 through the terrestrial rainfall patterns shown in Images c and d. This may link to severe south-east Australian bushfires as 11 of the 21 major fires between 1950 and 2000, including the infamous Ash Wednesday and Black Saturday events, followed positive IODs (Cai et al. 2009b). Likewise, the pronounced positive IOD event in 1997 aligned with severe wildfires in Indonesia (Schott et al. 2009). To the west of the Indian Ocean, positive IOD events cause heavy rainfall in eastern Africa as well as in India, Bangladesh and Vietnam (JAMSTEC 2008, Yamagata et al. 2004, Zinke et al. 2004). In 1997, during a positive IOD, record rainfalls and severe floods impacted Somalia, Ethiopia, Kenya, Sudan and Uganda (Schott et al. 2009). Although more difficult to determine, the positive phase has also been linked to decreased rainfall, as well as hotter summer conditions, in Europe, Japan, Korea, eastern China and Brazil (Saji & Yamagata 2003, Yamagata et al. 2004).
Negative IOD events result in increased precipitation over areas of Australia, particularly in the southwest, and Indonesia however the extent of this change is less pronounced than those of the positive events. In the west of the Indian Ocean a negative event causes a drier climate however is less pronounced than the positive IOD effects.

Although undoubtedly still an area of ongoing research, modelling has confirmed that the SSTs of the Indian Ocean are correlated with monsoonal circulation and rainfall (Clark et al. 2000, Ashok et al. 2001, Abram et al. 2007). Positive IOD events have been shown to increase monsoon rainfall and both Ashok et al. (2004) and Nakamura et al. (2009) concluded that IOD events causes relative weakening of the ENSO-monsoonal relations as both poles of the IOD make a contribution on the monsoon. The annual Asian monsoon circulation influences billions of people and unanticipated variations and anomalies in its occurrence subsequently have the capacity to cause severe social and economic consequences (Clark et al. 2000).
4.1 Climate proxies

Palaeoclimatic reconstructions can be based on a variety of climate proxies depending on the spatial context of the climate being investigated. In high latitudes, ice-cores provide various climatic proxies while other sources, such as speleothems and tree-rings, preserve mid- and low-latitude terrestrial proxies and deep-ocean sediment cores providing strong climate proxies in some marine environments. In low latitude marine settings corals have proven to be important sources of palaeoclimatic proxies and can often produce highly temporally resolved reconstructions of past climates (McGregor et al. 2011). The suitability of such proxies, at a specific site, as indicators of climate pre-dating instrumental datasets can be determined by analysing modern proxies in relation to recent instrumental records.

4.1.1 Coral

The term ‘coral’ describes marine organisms (Phylum Coelenterata, Class Anthozoa) with sac-like bodies which secrete calcium carbonate exoskeletons (Veron 2011). Coral are usually found growing in colonies and, given time, the progressive build-up on calcium carbonate skeletons often develops into a ‘coral reef’ structure. *Porites* corals are the dominant coral type that is used for palaeoclimatic reconstructions. These massive corals are abundant throughout the Indian and Pacific Oceans and have a growth rate of 8-24mm yr$^{-1}$ which enables sampling at a high temporal resolution (Marshall & McCulloch 2001, Watanabe et al. 2003). Living *Porites* can generally be accurately dated with banding, can provide a proxy at interannual resolution over a potential duration of 100-400 years, and contain an array of geochemical tracers (Abram et al. 2007, Gagan et al. 2000, Linsley et al. 2000, Watanabe et al. 2003, Zinke et al. 2005). The variability of density and luminescence within coral aragonite skeletons represents local or larger-scale changes in environmental parameters and generally illustrates annual signals which can be used in chronological analysis (Marshall 2000). The chemical composition of each band of coral is related to the
chemical conditions of the ambient sea water when the coral’s aragonite skeleton was formed (Felis et al. 2003, NASA EO 2011). Analysis of geochemical and structural composition can determine abiotic conditions of the past and, particularly, the nature of environmental conditions during skeletogenesis. Corals can, consequently, be used as effective proxies of past SST ($\delta^{18}$O and Sr/Ca), Sea Surface Salinity ($\delta^{18}$O), precipitation ($\delta^{18}$O), upwelling events ($C^{14}$ and Ba/Ca), and river runoff (luminescence) amongst other parameters (Gagan et al. 2000, Zinke et al. 2004).

Historical data for sea surface conditions in the Indian Ocean was collected discontinuously prior to the 1800s using instrumental analysis from ships and buoys. More recently, major research efforts have been undertaken to develop the spatial resolution of oceanographic records, including the World Ocean Circulation Experiment (WOCE) and the Indian Ocean Experiment (INDOEX) in 1990 and 1999 respectively (Schott & McCreary 2001). Since 1999 autonomous ARGO floats have been deployed throughout the world’s oceans to monitor temperature, salinity and current data in each of the worlds oceans and provide high resolution, real-time, data to researchers (ARGO 2011). Remote sensing is now also used to collate data on various sea surface parameters. As modelling and reanalysis are applied to contemporary Indian Ocean studies it is necessary to attain more continuous data of past sea surface conditions at higher temporal resolution than historical records afford. Coral geochemical analysis may enable scientists to establish or extend records of atmospheric data and oceanic data where instrumental records, generally ship or buoy founded, are often sparse (Kuhnert et al. 1999, McGregor et al. 2011).

4.2 Oxygen-18 isotope analysis of corals

In 1947 Urey showed that temperature-dependant oxygen fractionation occurred during carbonate precipitation. More extensive work was done with corals in 1972 when Weber and Woodhead further investigated the dependency between the $\delta^{18}$O recorded in aragonitic coral skeletons and the local SST at the time when the coral was formed (Weber & Woodhead 1972, Yu et al. 2005). Even at this early stage, it was forecast that coral isotope ratios might prove to be valuable to the study of coral reef development and environmental conditions (Weber & Woodhead 1972). True to the forecast, isotopic
records in scleractinian, or hard-skeleton, coral have since proven to be indicative of seasonal and interannual changes in SST and precipitation and thus very useful palaeoclimate proxies (Linsley et al. 2000). The $\delta^{18}$O level in seawater refers to the ratio of the heavier $^{18}$O isotopes to the lighter and more abundant $^{16}$O to the within the H$_2$O molecule and is influenced most prominently by evaporation and condensation processes (NASA 2011b, Pfeiffer et al. 2004). The H$_2$O molecules with the lighter $^{16}$O isotope are more readily evaporated and thus of higher abundance in atmospheric water vapour however any heavier $^{18}$O H$_2$O molecules which are evaporated are the most readily condensed and initial precipitation is thus generally $^{18}$O enriched. This process of weight-dependant isotope separation, termed fractionation, is shown in Figure 7. In very cold global climate conditions some of the water precipitated on land remains there in the form of snow and ice whereas in warmer conditions this precipitation is cycled back into the oceans. As a result of this, lower $\delta^{18}$O in sea water is assumed to indicate fresher water and warmer conditions on a global scale as the lighter molecules are more abundant in the oceans rather than locked up in freshwater icecaps, and may reflect heavy rainfall on a more local scale. (Linsley et al. 2000, NASA 2011b).

The isotope signal transcribed in coral records is often at slight, constant, disequilibrium with seawater due to metabolism processes which have a greater effect, depleting $^{18}$O values, in corals with below-average growth rates (Gagan & Abram 2011). McGregor et al. (2011) reassessed the extent to which coral isotope records, specifically from atolls, are indicative of climate variables. Their study, based on Porites coral from Kiritimati Island in the Pacific Ocean, showed significant correlations between $\delta^{18}$O and local and large-scale climate variability, predominantly SST, at a range of temporal scales. Though generally reflecting precipitation, non-SST related $\delta^{18}$O change may too be influenced by other sources of freshening.

Calibration between $\delta^{18}$O in corals and SST generally uses a conversion of ~1°C increase per 0.22-0.24‰ decrease in $\delta^{18}$O (Cole et al. 2000, Marshall 2000). Most coral records, including those from this study, reflect a longterm trend towards lighter $\delta^{18}$O values across the past century as consistent with the increase in temperature over this duration (Marshall 2000).
Figure 7: Diagrammatic representation of Oxygen isotope fractionation. In warmer climates, $^{16}\text{O}$ is recycled between ocean, atmosphere and land. In colder climates, $^{16}\text{O}$ is trapped on land and the ocean is relatively $^{16}\text{O}$ depleted and $^{18}\text{O}$ enriched.

As oceanic $\delta^{18}\text{O}$ is influenced by both evaporation-precipitation levels and local SSTs, analysis of $\delta^{18}\text{O}$ provides a proxy record of the combined variability of these two parameters which both fluctuate with oscillations such as ENSO and the IOD (Marshall & McCulloch 2001). These records will herald further insight into the existence of an IOD signal and an ENSO signal in this region and the interaction between the two over time in addition to proving the suitability of corals from the given site for palaeoclimate proxy use. This
research is based on samples taken from modern *Porites* coral in the Cocos (Keeling) Islands which reside in the tropical Indian Ocean 2° south of the eastern Indian Ocean Dipole region defined by Saji et al. (1999).

### 4.2.1 Previous Indian Ocean $\delta^{18}$O Research

Previous research involving the reconstruction of palaeoclimatic variation in the Indian Ocean from coral isotopes, has been completed for several sites on the western margin of the Indian Ocean including Tanzania (Damassa et al. 2006), Kenyan islands (Cole et al. 2000, Kayanne et al. 2006), Madagascar (Zinke et al. 2004, Zinke et al. 2005), the Chagos Archipelago (Zinke et al. 2005), Seychelles (Charles et al. 1997, Zinke et al. 2005), Reunion (Zinke et al. 2005), and Mayotte (Zinke et al. 2009). To date there has been relatively less research of this nature with proximity to the eastern margin of the Indian Ocean as is evident in Figure 8. Sites of research in the eastern Indian Ocean include Ningaloo Reef (Kuhnert et al. 2000), Houtman Abrolhos Island (Kuhnert et al. 1999), Christmas Island (Marshall & McCulloch 2001) and Sumatra (Susanto et al. 2001). Notably, Kuhnert et al. (1999) were successful in producing a $\delta^{18}$O record of 200 year duration from a modern coral specimen of the Houtman Abrohlos Islands, Western Australia, which exceeds the length of others from the Indian Ocean. Quintessential to better understanding the Indian Ocean climate and to developing a case for, or against, the existence of the IOD is the pursuit of further data in the eastern tropical Indian Ocean. This research project will analyse monthly $\delta^{18}$O records from coral of the Cocos (Keeling) Islands in the eastern Indian Ocean. It will complement previous work done in the Indian Ocean and contribute to data collation for the Indian Ocean palaeorecord as a whole.
4.3 Strontium-Calcium analysis of corals

The ratio between Strontium and Calcium concentrations (Sr/Ca) in coral can also be used as a proxy for SST. The correlation between skeletal Sr/Ca in Scleractinian corals, such as *Porites*, and local temperature variability has been known since the early 1970s (Weber 1973). Following its discovery the methodology surrounding its use has been developed further and the proxy has been successfully applied to the study of tropical sea surface temperatures since the last interglacial maxima (Shen et al. 1996). This method is often used to complement Oxygen isotope studies as, unlike the Oxygen isotopes, this proxy is unaffected by precipitation and seawater freshening and thus only reflects temperature variability alone (Villiers et al. 1995, Marshall & McCulloch 2001). By combining the two proxies the precipitation or salinity component of the $\delta^{18}O$ may be seen and the sea surface conditions will be better understood.
Strontium and Calcium both have long residence times in the world’s oceans, $5.1 \times 10^6$ years for Sr and $1.1 \times 10^6$ years for Ca (Broecker & Peng 1982), meaning that their average concentrations and the ratio between them has remained virtually constant across scales of $10^5$ years and particularly across the 1900s with which this study is most concerned (Beck et al. 1992). The aragonite secreted by corals, such as the Porites, incorporates both Strontium and Calcium from seawater (Beck et al 1992) and, as the oceanic elemental ratio is virtually unchanging, any variability in the Sr/Ca of coral must result from other factors.

Research has shown that variability in the skeletal uptake of Strontium and Calcium in corals is primarily dependent on the temperature of the seawater in which the skeleton aragonite was secreted (Beck et al. 1992). The initial work of Weber (1973) which proposed this mechanism was followed by early research which supported the Sr/Ca-SST covariability (Houck et al. 1977, Smith et al. 1979) as well as research which found no such correlation (Thompson & Livingston 1975). More recent research, using improved methods, has shown general support for the proxy (Beck 1994, Villiers et al. 1995, McGregor et al. 2011) while still noting limitations such as biological variance and inaccurate SST data which may affect the geochemistry-temperature covariance at some sites. Previous analysis of Sr/Ca of corals of the Cocos (Keeling) Islands has shown some covariance between the geochemistry and SST records but suggests a partial breakdown in this relationship potentially due to stress (Marshall & McCulloch 2002). A linear relationship has been determined between the skeletal Sr/Ca of Porites coral and the ambient SST at time of skeleton formation for most sites (Smith et al 1979). As such, with appropriate correlation calculations the skeletal Sr/Ca from Porites coral can therefore be applied as a proxy for the high resolution reconstruction of SST changes over the period of growth (Villiers et al. 1995).

This method assumes that; SST is the primary control on the skeletal Sr/Ca uptake, biological controls are negligible and that the Sr/Ca ratio in sea water is constant over the period of coral growth (Villiers et al. 1995). There are small shifts in Sr/Ca from variations in river water flux across long time scales and significant changes in the Carbon Compensation Depth could also have an influences however, in the lifespan of a modern Porites coral these changes can be assumed insignificant (Beck et al. 1992). The method also assumes that the SST record used for calibration, from a local sampling station, is representative of SST changes at the given coral site (Shen et al. 1996). Different water masses have unique Sr/Ca
ratios which needs to be accounted for when analysing as spatial variability on the ocean water can account for 2°-3°C difference in Sr/Ca derived SST (Marshall & McCulloch 2002). This can be done with one of two approaches. The ratio can be normalised against a standard or the distribution coefficient can be used (Shen et al. 1996). The distribution coefficient compares the Sr/Ca concentration in coral to that in seawater at the given location with the equation:

\[ D \left( \frac{Sr}{Ca} \right) = \frac{\left[ \frac{Sr}{Ca} \right]_{\text{coral}}}{\left[ \frac{Sr}{Ca} \right]_{\text{seawater}}} \]

This distribution coefficient (Marshall & McCulloch 2002, Shen et al. 1996) has been found to be close to unity for most corals. The relationship between Sr/Ca in coral and the SST at precipitation is not notably impacted by the coral growth rate (Smith et al. 1979). For corals with growth rates between 18 and 23mm/year this biogenic factor has little effect on the Sr/Ca ratio (Shen et al. 1996).

Beck et al. (1992) were the first to conduct high-precision and high resolution Strontium-Calcium analysis of coral using modern isotope dilution mass spectrometry methods to establish the relationship between the skeletal ratio and temperature in Porites coral (McCulloch et al. 1994). A study by Zinke et al. (2004) attained Sr/Ca ratio using an inducted coupled plasma atomic emission spectrometer which enabled the respective elements to be measured simultaneously and this method has been widely used since.

### 4.4 Significance of Indian Ocean coral proxies

There is a clear significance to understanding the Indian Ocean SST variability, as shown in Chapter 3.4, however as satellite and in situ measurement become common practice it is necessary to also reinforce the significance of analysing Indian Ocean coral proxies. Although measurement has been taking place for decades, to best understand the future behaviour of Indian Ocean climate requires a solid record of past variability beyond the past few decades which is not readily available for most regions. By determining the relationship between coral isotopic records and known SST in recent years we can gauge the potential for determining past climate variation from coral records which pre-date
instrumental climate data. The significance of conducting further research into the nature of, and influences on, Indian Ocean SST variability as shown through coral isotopes is hence the potential for improving and extending knowledge of past climate variation. As a result we will be better able to forecast future climatic characteristics thus enabling a better chance of mitigating or preparing for any resulting impacts as discussed in Chapter 3.4.
CHAPTER FIVE : Methodology

5.1 Site

This study uses a coral record obtained from the Cocos (Keeling) Islands. Specifically, the data is derived from a *Porites* microatoll at site PP30 located on the reef flat near Pulu Pandan on the eastern side of the atoll, as depicted in Figure 9.

The Cocos (Keeling) Islands are an Australian territory located in the eastern Indian Ocean, 2950km northwest of Perth and 900km west of Christmas Island, at 96°48’-56°E and 12°04’-13°00’S shown in Figure 9. This location has close proximity to, but is not within, the eastern IOD region specified by Saji et al. (1999) which extends south only as far as 10°S. The Islands were first discovered by Europeans in 1609 and were settled in 1826 (Woodroffe & Berry 1994). They consist of a circular lagoon, fringed by several smaller reef islands, forming a horseshoe-shaped atoll (AGD 2010, Searle 1994, Woodroffe & Berry 1994). The lagoon is 10km wide from east to west and 12km from north to south. The southern side is the most shallow, some areas regularly exposed at low tide, and the northern end is the deeper reaching depths of around 15m (Searle 1994). The lagoon is exposed to the Indian Ocean through two major, relatively deep, channels on either side of the northern Horsburgh Island as well as through numerous shallow inter-island passages to the south and east. The water in the lagoon and reef flats is thus totally flushed and generally assumed to be homogenous with the surrounding ocean water. There is some evidence to suggest the occurrence of events in the past in which lagoon water has lost ocean homogeneity and become temporarily stagnant possibly due to anomalous northwest winds (Marshall & McCulloch 2002, Woodroffe 2011). The Islands, which lie on the Cocos Rise section of the Venning-Meinesz Seamount Range (Smithers 1997), have previously been the subject of geomorphological analysis and studies into sea-level change (Woodroffe et al. 1994, Smithers & Woodroffe 2001).
In 1994, Falkland published an extensive study into instrumental records of the Cocos (Keeling) Islands climate which commenced in 1952. The Islands are located in the Humid Tropical climatic zone and on the western extension of the Pacific marine biogeographic province, and experience the dominant influence of Southeast trade winds throughout 85% of the year. Annual rainfall is between 850 and 3300mm, average temperatures range between 18C and 32C, and humidity averages around 75% (Falkland 1994, Woodroffe & Berry 1994).

Figure 9: The Cocos (Keeling) Islands showing location of site PP30 on a reef flat of the eastern margin.

The Cocos (Keeling) Islands hold historical significance as the only atoll Darwin visited and hence where he sought evidence in support of his theory of coral atoll development in 1836 (Woodroffe & Berry 1994). The islands hosted numerous visits from proponents and opponents of Darwin in subsequent years (Forbes 1879, Woodroffe & Berry 1994). Coral
records from sites like the Cocos (Keeling) Islands provide insight into atmospheric conditions which are not influenced by local topography in the way that terrestrially derived proxies, including the other eastern Indian Ocean sites, are (Pfeiffer et al. 2004). Due to the isolation and limited size of the Islands, lying 1000km from any significant river runoff or major continentally-derived pollutants or influence.

The most notable work previously undertaken at this site, relevant to this study, was completed within a PhD thesis by Marshall (2000) who analysed $\delta^{18}$O and Sr/Ca from two heads of domed *Porites* from the western lagoon at the Cocos (Keeling) Islands. He had found, through analysis methods similar to those undertaken within this study, that there was some identifiable annual banding in *Porites* coral samples from the Cocos (Keeling) Islands but that correlations with climate records beyond this were limited. The study had concluded that the coral oxygen isotopic records at the site had been severely and non-uniformly impaired by a form of ongoing and spatially extensive stress, potentially related to catastrophic climatic events, and that they were thus unusable in oceanic and atmospheric studies. The Sr/Ca records were, similarly, found to be partially degraded due to localised stresses potentially related to weakened circulation of ocean water through the lagoon during northwest winds (Marshall & McCulloch 2002, Woodroffe 2011). No additional research of this nature has been published based on the Cocos (Keeling) Island site until now and it is thus currently accepted that the results of Marshall’s study are representative of the current stance of data from the location.

5.2 Coral preparation

In 1992, coral slabs had been sawn across the living *Porites* microatoll on the eastern side of the Cocos (Keeling) Islands atoll using standard handsaws as part of the study into microatoll growth and upper surface morphology (Smithers & Woodroffe 2001). Slices of 6mm thickness had also been cut from the slabs parallel to the growth axis. X-radiography and U-V luminescence scans of the slices were undertaken to identify annual banding and growth axes.

One of the benefits of using coral as a palaeoclimate proxy is the ease and accuracy with which a chronology can often be inferred. The two primary methods of analysis are;
measurement of density bands using x-radiography, and the use of index bands formed with natural or artificial skeletal markers. The density bands occur in couplets of high density and low density bands. The high density bands correspond with slow rates of skeletal extension, tissue growth, and calcification, whereas low density bands correspond to faster rates. These rates are often cited as being positively correlated with light intensity and water temperature, as well as showing links to sedimentation, turbidity, nutrient availability, hydraulic energy and endogenic processes (Swart 1983, Damassa et al. 2006), however the cause of annual growth rate oscillation at the Cocos (Keeling) Islands remains unclear.

Luminescence, or fluorescence, banding in coral can sometimes be revealed with long-wave Ultra-Violet exposure (Cole et al. 2000) and is proposed to result from humic acids and oceanic organics interacting with the coral skeleton architecture (Islade 1984, Nakamura et al. 2009). These luminescent components are generally incorporated into the coral skeleton at different intensities depending on the season (Matthews et al. 1996). Previous analysis of coral microatolls from the Cocos (Keeling) Islands revealed a distinct annual pattern of coupled dull and bright green banding in which bright UV-illuminated bands were found to align with the x-ray illuminated bands of low density (Smithers 1997, Smithers & Woodroffe 2001). For this study, coral luminescent banding had been used to establish chronology as it was found to be better defined annually than density. In addition, a distinctive stress band in 1983, potentially related to anomalous ENSO-induced wind patterns and resulting coral death, was used as an index marker.

A ledge of 2mm thickness was milled from the coral, aligned with the growth axis, using a micro-drill. The slices were cleaned with an ultrasonic probe in Milli-Q water to ensure that any surface contamination and saw cuttings were removed and were then oven dried at 40°C. Based on the number of years in each section of coral, identified from the luminescent banding, twelve equidistant samples were extracted from each annual band in the coral sample. A low-speed dental drill was used to mill every ‘odd’ month and every ‘even’ month was left intact and then removed before being manually ground. Using linear interpolation methods in Analyseries software and excel it was possible to better select the isotopic values for each calendar month, as is recommended by Cahyarini et al. (2009), rather than assuming consistent growth across all months.
All aforementioned coral preparation was completed by others prior to commencement of this research.

5.2.1 Oxygen Isotope measurement
The Oxygen isotope measurement, for monthly samples from 1924 to 1992, was undertaken in the 1990s on mass spectrometers at the University of Wollongong and at the Australian National University (ANU). Cross-checks were subsequently completed to ensure the integrity of the results from the two facilities and this data is included as Appendix 1. This data was attained prior to this research commencing and was supplied for statistical analysis which had not previously been undertaken.

5.2.2 Strontium-Calcium measurement
Strontium and Calcium analyses were undertaken, as part of this study, when initial analysis of the Oxygen isotope data indicated that further investigation of SST may be needed. The measurement of Sr/Ca concentrations was undertaken on the same coral samples which were collected for Oxygen isotope analysis.

To minimise risk of contamination, plastic 10ml centrifuge vials acid were cleaned before use. The vials were filled with 1% HNO₃, lids were secured, the vials were inverted a number of times to ensure that the inner-lid surface was thoroughly coated, and they were subsequently left to soak overnight. The vials were then rinsed three times with Milli-Q water and placed in a 58°C drying oven for a number of hours.

For each monthly sample, from 1935 to 1992, 1.60-2.00 milligrams of the sample were weighed into the prepared vials and the exact weight was recorded in milligrams to 2 decimal places and the vials were sealed. 25 samples were weighed twice as repeat samples for precision checks and a standard, JCP-1, was analysed at both the beginning and the end of each analysis run.

To dissolve the powdered coral samples, 1% v/v HNO₃ acid was added to each vial using a pipette. The volume of acid added to each vial was dependant on the exact sample mass and the volume needed to attain a Calcium concentration of 68-82 ppm, see Appendix 2 for sample weight to acid volume conversions. Each sealed vial was placed in a 40°C ultrasonic bath to maximise dissolution of the coral sample in acid.
The Strontium-Calcium measurement was undertaken at ANSTO using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). In this instrument, when the sample solution is introduced into the system it is atomised and transported, with Argon gas as a carrier, into an Argon plasma at ~7000°C. The high temperature excites electrons of the elements within the sample and as the excited electrons return to ground state they release light photons which can subsequently be separated into wavelength components. Photomultiplier detectors are used to measure the relative intensities of the various wavelengths emitted and this can be correlated to the relative concentrations of elements, such as Strontium and Calcium, within a sample (USGS 2009).

The final results were checked for anomalous Calcium concentrations and those samples were then re-run. The data was interpolated, using excel, to better align the samples to their corresponding months.

5.3 Time series

Data for the Indian Ocean Dipole was obtained from the Dipole Mode Index record (Jamstec 2008). The dataset was recorded in degrees Celsius, acquired through the standard east-west subtraction method (Saji et al. 1999), at monthly resolution from 1871 to 1998 which included both satellite and instrumental records. The linear trend, obtained from GISST (Global sea-Ice and Sea-Surface Temperature) records, was subtracted from the raw SSTs before the index was calculated. The ENSO data used for this research was the Kaplan NINO3.4 index made available online by the International Research Institute (IRI) for Climate and Society (IRI 2011). Sea Surface Temperature data was from the GOSTA Global SST and Ice Concentration record, ‘GOSTA gisst22’, for 96.5°E and 12.5°S and is, like the ENSO record, available through IRI. The record is at monthly resolution from 1903 to 1994 and anomalies were calculated relative to the mean of the total dataset unless indicated otherwise (IRI 2011b). The Precipitation dataset provides a record of millimetres per day precipitation, averaged monthly, for 96.25°E, between 11.25° and 13.75°S. The data, available through IRI, is derived from NOAA NCEP CPC analysis which combined rain gauge observations, satellite records, and numerical model predictions for the years between 1979 and 2004 (IRI 2011c). The websites for all datasets are listed in Table 2.
Table 2: Names of datasets used for each data type and the URLs from which they were each obtained.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Name</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOD</td>
<td>Dipole Mode Index</td>
<td><a href="http://www.jamstec.go.jp/frsgc/research/d1/iod/">http://www.jamstec.go.jp/frsgc/research/d1/iod/</a></td>
</tr>
<tr>
<td>ENSO</td>
<td>Kaplan NINO3.4</td>
<td><a href="http://iridl.ldeo.columbia.edu/">http://iridl.ldeo.columbia.edu/</a></td>
</tr>
<tr>
<td>SST</td>
<td>GOSTA gisst22</td>
<td><a href="http://iridl.ldeo.columbia.edu/">http://iridl.ldeo.columbia.edu/</a></td>
</tr>
<tr>
<td>Precipitation</td>
<td>NOAA NCEP CPC</td>
<td><a href="http://iridl.ldeo.columbia.edu/">http://iridl.ldeo.columbia.edu/</a></td>
</tr>
</tbody>
</table>

The climate datasets, referenced in Table 2, and both the $\delta^{18}$O and Sr/Ca datasets are provided as Appendix 3.

5.4 Spectral Analysis

With the development of isotopic analysis methods there has been a simultaneous improvement of analytical software and cyclostratigraphy methodologies which detect cycles in layered depositions. An array of time-series analysis tools, designed to statistically analyse data variability and cycles across a time series, are available for application to climatic records. These tools generally consider time-series data to contain evidence of both regular cycles and irregular oscillations attributable to environmental conditions (Weedon 2003). Cycles can be discriminated from each other on the basis of their amplitude, wavelength, and phase, although analysis of cycles commonly disregards the latter. Analysis tools assume a degree of noise contribution in each signal and provide either automatic filtering or user-selected noise-filter options to enable the oscillatory signal components of interest to be read without this interference. At the core of most analytic methods is Fourier’s Theorem which uses sets of sine and cosine functions, termed Orthogonal Functions, as a means of reconstructing and describing any given time-series (Weedon 2003).

Spectral analysis, which employs Fourier’s Theorem, is a tool used to extract frequency domain information from one or more time series and its application to coral isotope data has been well demonstrated through numerous studies (Schulz & Statteggar 1997). Spectral Analysis is essentially an umbrella term which includes specialised methods such as Singular Spectral Analysis, Cross-Spectral Analysis and the Multi-Taper Method. Wavelet analysis, an alternative method, deconstructs a time series into oscillations present over shorter time frames.
The analysis structure is outlined in Figure 10, below, which shows the key relationships to be determined between climate and geochemistry components. Specifically, the analysis should determine the impacts of the IOD and ENSO on each SST and precipitation, then the impacts of SST and precipitation on each \(\delta^{18}O\) and Sr/Ca, and through these relationships it should determine the impacts, via SST and precipitation, of the IOD and ENSO on each \(\delta^{18}O\) and Sr/Ca. The cycles occurring in each climate and geochemical component of the figure are to be determined individually and will then be compared between levels of the flow chart to establish relationships.

\[ \text{Figure 10: A flow chart of the climate and geochemical components being investigated in this study and the relationship links between them which will be investigated.} \]

5.4.1 Singular Spectral Analysis

Singular Spectral Analysis (SSA) is a form of statistical approach to the detection of regular cycles in a time series with each cycle uniquely characterised by frequency, phase and power, which is the wave amplitude squared (Smith et al. 2008). This would enable individual isotopic records to be deconstructed into defined trend, oscillation and noise components, thus providing detailed information regarding their variability (Boiseau et al. 1999). Although Multi-Taper Method analysis is the primary tool used for detection of persistent cycles, SSA is undertaken to confirm that the same results are achieved with different statistical approaches.
The use of SSA-MTM Toolkit software to complete the SSA analysis was based on its suitability for analysing palaeoclimate data sets, for which it was specifically designed, and its user-friendly interface. The alternative Analyseries software, initially developed by Paillard et al. in 1996 based on the SPECMAP group in the 1980s, was also trialled but was found to be less expedient (Paillard et al. 1996). The settings chosen for SSA analysis, using the SSA-MTM Toolkit, are given in Appendix 4.

5.4.2 Cross-spectral analysis
Cross-spectral analysis methods are used to determine, statistically, correlations between the individual spectral signals of multiple time series, within the same temporal range. Using this method, reflecting a technological advancement on the traditional visual assessment method, both the coherency spectra and the phase spectra can be attained (Smith et al. 2008). The coherency spectra produce a measure of the similarity of amplitude variations, one reflecting perfect coherency and zero reflecting no detectable coherency, at particular frequencies in the two datasets (Weedon 2003). This method has been used by researchers such as Asami et al. (2005) and Cole et al. (2000) to identify significant correlation between δ¹⁸O and other data sets such as ENSO records and sea surface characteristics. Asami et al. (2005), in particular, applied cross-spectral analysis to discover significant periodicity between isotope data from the western Pacific Ocean and both Sea Surface Temperature anomalies and Sea Surface Salinity anomalies. The phase spectra, also achieved through cross-spectral analysis, shows the average difference between two time-series which occur at different frequencies (Weedon 2003).

The ARAND software package, originally developed for Spectral mapping within the SPECMAP project, has been made publically available for use on personal computers by P. Howell of Brown University. The software, which complements SSA-MTM Toolkit as the software of choice for many similar coral isotope studies, has been used in this research project for its user-friendly Cross-Spectral analysis tool. Analysis was done using 250 lags, a final frequency of 6.0, full linear detrend and an 80% confidence level, with the exception of those analyses involving the shorter Precipitation time series which used 144 lags.

5.4.3 Multi-Taper Method
The Multi-Taper Method (MTM) has also been widely applied to coral isotope analysis. To analyse a dataset of finite length with relation to continuous cycles requires the
application of tapers which minimise problems of spectral leakage and discontinuities (KSpectra Toolkit 2009). Analysis with the Multi-Taper Method involves multiplying the time-series by a selected number of fixed-shape orthogonal tapers, which have a value of one at the centre and taper to zero at the ends, and the average of the independent power spectrum estimates of each taper are used to detect the variable modes contained within a high spectral resolution and output a final spectral estimation and signal reconstruction (Boisseau & Ghil 1999, Felis et al. 2000, KSpectra Toolkit 2009). The confidence level of each spectral peak identified with this method needs to be accounted for to ensure that the cycles denoted by the peaks are statistically distinguishable from background noise (Weedon 2003). Cole et al. (2000) used the Multi-Taper Method to account for temporal persistence in their Kenyan δ¹⁸O record and can be compared to its application in analysis of Red Sea corals by Felis et al. (2000) who used MTM to provide a robust estimate of spectral properties and analyse teleconnections with ENSO and the North Atlantic Oscillation. Multi-Taper Method has also been used by Gischler et al. (2009) who analysed the growth characteristics of corals from Florida relative to ENSO using Analyseries software.

MTM, for this research, was conducted with the SSA-MTM Toolkit, described in 5.4.1. The specific settings and options selected when analysing are described in Appendix 5.

5.4.4 Wavelet Analysis

Wavelet analysis is a method of time-series analysis which is used to determine localised power variability within a time series (Torrence & Compo 1998). It is applied to data with changing variance, or cycles of numerous time frequencies, over time (Asami et al. 2005, Weedon 2003). In cyclostratigraphy, the technique is most commonly used with Mortlet wavelets which employ plane waves, with Gaussian-modification, at wave types suitable for climatic data (Weedon 2003). Pfeiffer et al. (2004) applied this method to normalised, detrended, isotope records in their study of Chagos Archipelago corals and Bush (2007) used it to analyse trends in the Nino-3.4 index. Likewise the technique has been used to evaluate ENSO teleconnections in Europe and the Middle East, based on Red Sea coral, and whether the frequency of cycles has changed over a period of time (Rimbu et al. 2003).
Wavelet analysis was undertaken using Interactive Wavelet Plot, available for use online at http://paos.colorado.edu/research/wavelets/, which was developed by Torrence and Compo (1998).
CHAPTER SIX : Results

This chapter examines the results of the data analyses of both the Oxygen isotope data and the Strontium-Calcium data, in addition to the climatic time series, for the Cocos (Keeling) Islands, 1924 to 1992.

6.1 Oxygen isotopes

6.1.1 Visual Analysis
Raw datasets were plotted to enable visual observation of their respective variability and detection of any visible covariance or trends. Visually evident in the SST and $\delta^{18}O$ datasets, shown in both Figure 11 and Figure 12, is the presence of distinct annual oscillations. In Figure 12, which shows a shorter temporal portion of the data from 1979 to 1992, shading has been used to highlight the last five peaks in the $\delta^{18}O$ record, noting that the $\delta^{18}O$ axis is inverted such that peaks indicate lower values which correspond with warmer temperatures. The shaded bands intercept the last five peaks in the SST and, to a less defined extent, the precipitation which visually indicates some level of annual correlation. Although the timing of the annual signals appear to align, the relative amplitude of the signals, in most cases, do not. In 1987 and 1992, for example, the Oxygen isotopes exhibit significant peaks relative to adjacent years whereas the SST and precipitation signals are relatively constant.

The IOD and NINO3.4 records each exhibit considerable variability, however, no ongoing correlations are visually discernable between these two datasets and either the SST or $\delta^{18}O$. By comparing prominent years in the IOD or ENSO records with each the SST and the $\delta^{18}O$ records, Figure 11, any obvious relationships should be detected. The pronounced El Niño events of 1941 and 1982, for example, can be visually aligned with distinct peaks in SST and a less defined change in the $\delta^{18}O$ record. Other oscillations in the $\delta^{18}O$ signal, such as a trough in ~1953, do not visually appear to have any correlation with changes in other
timeseries. Based on this visual analysis it would seem that some ENSO events appear to align with prominent variations in the $\delta^{18}$O signal whereas others do not.

The $\delta^{18}$O record trends towards marginally decreasing values across the duration of the timeseries which is made more visible with a trendline, shown in Figure 13. The trend begins at mean isotopic values of around -5.12‰ in 1924 and decreases to values less than -5.18‰ in 1992 which is generally indicative of sea water freshening or warming. Assuming the correlation 0.18‰/ 1°C change (McGregor et al 2011), the ~0.06‰ decrease visible in Figure 13 should align with a ~0.35°C temperature increase, if there is no precipitation influence. Visual analysis of the SST data, shown in Figure 13, confirms a gradual temperature increase from 1924 to 1992. The mean temperature increase of ~0.17°C seen in the data is less than predicted based on the $\delta^{18}$O change. Assuming the same correlation ratio, the temperature change indicates only a 0.031‰ isotopic change. As the changes in $\delta^{18}$O and SST values can’t be fully explained using the given correlation it is possible that freshening or warming, not reflected solely by local SST data, may play a role.
Figure 11: Timeseries of $\delta^{18}O$ record from the Cocos (Keeling) Islands with SST, IOD and NINO3.4 datasets used for this study. All datasets are restricted to the period 1924-1992 as this is the span of the $\delta^{18}O$ record.
Figure 12: Timeseries of $\delta^{18}O$ record from the Cocos (Keeling) Islands with SST, and precipitation datasets used for this study. All datasets are restricted to the period 1979-1992 as the precipitation record is only available from 1979. Shading indicates the last five peaks (note inverted axis) in the $\delta^{18}O$ record.
Figure 13: Timeseries showing a) raw isotope dataset and b) sea surface temperature dataset, for the Cocos (Keeling) Islands, 1924-1992. Black line indicates linear trend in each.
6.1.2 Singular Spectrum Analysis

Singular Spectrum Analysis was used to determine key features in the $\delta^{18}$O time series. The results are shown in Figure 14. In the upper plot, which shows the data Empirical Orthogonal Functions (EOFs) separated by frequency, the error bars at 95% confidence show the null-hypothesis range with points outside of these error bars of interest. The only values observed to occur outside of these bars are at sub-annual frequencies of 2.5-3.5 and 5.5-6.0 cycles per year. The significance of these values, and lacking significance of other values, is confirmed in the lower plot which uses null-hypothesis EOFs, rather than the data EOFs, separated by frequency. The analysis variables used are detailed in Appendix 4.

Figure 14: Singular Spectrum Analysis output for the $\delta^{18}$O isotope record from the Cocos (Keeling) Islands with a) data EOFs and b) Null-hypothesis EOFs, each separated by frequency. Red markers occurring above or below the confidence bars indicate the frequencies of significant cycles. Boxes highlight frequencies with significance. Analysis was undertaken using the SSA-MTM Toolkit.
6.1.3 Multi-Taper Method analysis

The results of the Multi-Taper Method, shown in Figure 15, illustrate the key cycles occurring within the time series data between 1924 and 1992. The $\delta^{18}O$ anomaly data used for MTM analysis shown in Figure 15, plot a), was calculated by subtracting the monthly values from the mean of the entire dataset. The $\delta^{18}O$ anomaly dataset shows a number of cycles occurring at >90% confidence with periodicities ranging from subannual to 2.83 years.

Due to the seasonal nature of relevant climatic events, such as monsoons and the IOD, it was of interest to also investigate month-based anomalies. Means were calculated for each calendar month, across the span of the timeseries, and anomalies were derived by subtracting each dataset value from its respective monthly mean, rather than from the overall mean. The results of Multi-Taper Method analysis on this subsequent $\delta^{18}O$ month-anomaly dataset are shown in Figure 15, plot b). There is no notable variation between the interannual cycles determined in this month-anomaly dataset and those determined in the standard anomaly dataset which implies that detected variability is not due to seasonal variation. The IOD dataset, too, contained numerous cycles of >90% confidence with two at well above 99% as shown in Figure 15 plot c). These signals ranged in periodicities from subannual to multi-decadal with a number of these components occurring at periodicities higher than those in the $\delta^{18}O$ anomaly record. The results of MTM conducted on the ENSO time series, shown in plot d) of Figure 15 exhibited significant oscillations at 5.2 years, 3.57 years, and 2.43 years- 3 years periodicities in addition to more frequent oscillations. Based on knowledge of ENSO events the 3 to 7 year oscillations are expected.

MTM analysis was also completed on both the precipitation record and the SST record for the Cocos (Keeling) Islands region to determine the major oscillations evident in each. The precipitation MTM results, plot e) of Figure 15, showed only a signal of approximately annual frequency to occur with greater than 90% confidence. In contrast to this, the results of the SST analysis in Figure 15 plot f), determined numerous sub-annual and interannual to decadal signals in addition to the pronounced annual cycle. Significant cycles were shown to occur every 17 years and every 4.45 years in addition to numerous cycles oscillating at less than two years.
a) $\delta^{18}$O anomaly

b) $\delta^{18}$O month-anomaly

c) IOD

d) ENSO
6.1.4 Wavelet analysis

Wavelet analysis was undertaken to determine whether the cycles of significant power have occurred at different frequencies across the time series records. The $\delta^{18}O$ dataset, when analysed with wavelet analysis, showed an annual cycle to be persistent, at relatively high power levels, for the duration of the record – see Figure 16. In addition, a high power cycle of around six year frequency is evident from the mid 1940’s to 1960 and another of around 16 year frequency from the mid 1960’s until 1980.
Figure 16: (a) $d_{18}o$ anomaly. (b) The wavelet power spectrum. 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.

Figure 17: (a) iod. (b) The wavelet power spectrum. 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.
The wavelet results for the IOD dataset, Figure 17, showed cycles of the greatest spectral power to be evident between the 1940’s and 1970’s. From the 1940s to the 1960s the cycles of around 16 year periodicities were most prominent however, during the late 1950’s, another frequency of relatively high power was also evident, occurring at around 4 year periods, which became the dominant signal after the mid 1960’s. Figure 17 also suggests that a cycle of 2 year frequency was evident in the 1960’s. Prior to the 1940’s, and after the 1970’s, cycles of various frequencies occurred with lower spectral power.

As is evident in Figure 18, the NINO3.4 dataset exhibits a high power cycle every 4 to 8 years for most of the analysed record. For a number of years around 1960 this signal occurs with lower power and at a marginally higher frequency.
Figure 19: (a) Precipitation (b) The wavelet power spectrum. 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.

Figure 20: (a) SST. (b) The wavelet power spectrum. 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.
The key temporal patterns of cycles in the precipitation and sea-surface temperatures, for the Cocos (Keeling) Islands location, were also analysed with Wavelet Analysis. The precipitation record, 1979 to 1992, exhibited an annual cycle of relatively high power which waned slightly at both ends of the record and in the mid 1980s but was otherwise relatively consistent. Shown in Figure 19, the wavelet analysis results did not indicate any other significant cycles in the precipitation record. Analysis of the SST record, 1924 to 1992, similarly showed a consistent annual cycle – see Figure 20. The analysis also detected a cycle of 4 year periodicity in the 1940s and a 16 year cycle from the 1950s until the 1980s.

6.1.5 Cross-Spectral analysis

Cross-spectral analysis was undertaken on SST and IOD datasets and SST and ENSO datasets to determine whether the SST record for the Cocos (Keeling) Islands region has been influenced by either climatic cycle across the duration of the $\delta^{18}O$ time series. The SST and IOD cross-spectral results, shown in Figure 21, demonstrate significant correlations (>80% coherence) at interannual frequencies of 8.33 years, 4.17 years, 2.53 years and 1.52 years. As IOD events are suggested to have occurred at a range of frequencies, from 20 year to 4 year cycles, in the past century both the 4.17 year and, more likely, the 8.33 year cycles could be indicative of SST varying with the influence of IOD events.

The cross-spectral analysis of SST and ENSO, shown in Figure 22, also demonstrated significant, and very similar, correlations at interannual frequencies. The ENSO-SST correlations occur at 8.33 year, 4.17 year and 1.19 year cycles. The 4.17 year cycle correlation, in particular, aligns with the known frequency of ENSO events and the local SST of the Cocos (Keeling) Islands can hence be assumed to vary with ENSO cycles. The similarities between the SST-IOD and SST-ENSO cross-spectral results are of interest but these may also result from the low temporal resolution of output from the ARAND software which prevents interannual cycles of frequencies a few years apart from being discerned.

Following analysis of the climate data it was subsequently of interest to determine, with cross-spectral analysis, whether the SST changes are reflected in the coral $\delta^{18}O$ record from the Cocos (Keeling) Islands between 1924 and 1992. Cross-spectral analysis of the $\delta^{18}O$ record with the SST dataset, Figure 23, showed an 8.33 year cycle and an annual signal, in addition to some subannual cycles, to correlate at above 80% coherence. Of particular
interest, the significant correlation with the SST record at 8.33 year periodicity aligns with the SST-IOD and SST-ENSO results in the interannual temporal range and could reflect an SST-mediated influence of either. The precipitation record was also cross-spectrally analysed with the δ¹⁸O dataset and showed an annual but no interannual cycle correlation. These results are shown in Figure 24.

The direct cross-spectral analysis of the ENSO and δ¹⁸O anomaly records showed a number of cycles to exist between the two which correlated with >80% coherence levels. The results are shown in Figure 25. In the interannual frequencies, the two time series correlated at 2.2 year cycles, 1.2 year cycles and annual cycles. As ENSO events have occurred at frequencies of around four years (NOAA 2011) over the last century the absence of correlations at this frequency indicates that the δ¹⁸O dataset does not show the ENSO signal.

Unlike the cross-spectral results between δ¹⁸O anomalies and the other analysed time series, when analysed with the IOD signal there was no correlation at an annual cycle. Within the interannual frequencies one correlation with high coherence was evident at 1.85 year frequency. IOD events are suggested to have occurred at frequencies ranging from 20 years to 4 years across the last century (Abram et al. 2008). In a similar case to the ENSO correlation, shown in Figure 25, this IOD correlation, in Figure 26, implies that the IOD is not significantly depicted in the δ¹⁸O coral record from the Cocos (Keeling) Islands.

Figure 21: Results of cross-spectral analysis; IOD-SST anomalies(1924-1992). The upper chart shows relative normalised spectral power for IOD (blue) and SST anomalies(red) at various frequencies. The lower chart shows corresponding coherence levels; 80%(orange) and 95%(green). a- 8.33yrs, b- 4.17yrs, c- 2.53yrs, d- 1.52yrs.
Figure 22: Results of cross-spectral analysis; ENSO-SST anomalies (1924-1992). The upper chart shows relative normalised spectral power for ENSO (blue) and SST anomalies (red) at various frequencies. The lower chart shows corresponding coherence levels; 80% (orange) and 95% (green). a - 8.33 yrs, b - 4.17 yrs, c - 1.19 yrs.

Figure 23: Results of cross-spectral analysis; SST-$\delta^{18}$O anomalies (1924-1992). The upper chart shows relative normalised spectral power for SST (blue) and $\delta^{18}$O anomalies (red) at various frequencies. The lower chart shows corresponding coherence levels; 80% (orange) and 95% (green). a - 8.3 yrs, b - 1.1 yrs, c - subannual.
Figure 24: Results of cross-spectral analysis; precipitation-δ¹⁸O anomalies (1979-1992). The upper chart shows relative normalised spectral power for precipitation (blue) and δ¹⁸O anomalies (red) at various frequencies. The lower chart shows corresponding coherence levels; 80% (orange) and 95% (green). a- annual.

Figure 25: Results of cross-spectral analysis; ENSO-δ¹⁸O anomalies (1924-1992). The upper chart shows relative normalised spectral power for ENSO (blue) and δ¹⁸O anomalies (red) at various frequencies. The lower chart shows corresponding coherence levels; 80% (orange) and 95% (green). a- 2.08 yrs, b- 1.19 yrs, c- annual, d- subannual.
Figure 26: Results of cross-spectral analysis; IOD-$\delta^{18}$O anomalies (1924-1992). The upper chart shows relative normalised spectral power for IOD (blue) and $\delta^{18}$O anomalies (red) at various frequencies. The lower chart shows corresponding coherence levels; 80% (orange) and 95% (green). a-1.85yrs, b-g subannual.

6.2 Strontium-Calcium Results

The Strontium-Calcium data has been plotted against the SST dataset, in Figure 27, to enable visual comparison of their relative variability. When visually compared, relative to SST, the Sr/Ca data shows considerable variability with oscillations appearing to be frequent and irregular, varying primarily between values of 8.6 and 9.0. These frequent oscillations are periodically interrupted with an anomalously high value of >9.0 but are not interrupted by any low values of <8.6. Compared visually to the SST dataset for the same time period, July 1934 to December 1991, the Sr/Ca variability does not clearly align with the SST variability which is, by comparison, far more regular on an annual cycle. In particular, the anomalously high values, >9.0, in the Sr/Ca time series do not align with anomalous peaks or troughs in the respective SST record.
To allow for a clearer visual comparison of the variability of the Sr/Ca dataset, relative to the SST dataset, single decades were plotted in individual time series. The 1980-1990 plot is shown in Figure 28, below, and the four decades from 1940 to 1980 are provided as decadal plots in Appendix 6. The decades, when compared visually, further support that the Sr/Ca record contains more frequent and apparently irregular variability than the SST which is dominated by regular annual cycles. There does appear to be, however, some alignment with the annual peaks and troughs of the SST record and the most pronounced peaks and troughs amongst the Sr/Ca oscillations which suggests that an annual component may be reflected in the Sr/Ca data. The anomalously high values contained in the Sr/Ca record shows no alignment with anomalies in the SST record.

Figure 28: Time series graph showing Sr/Ca in blue (inverted axis) and SST in red. Monthly resolution from 1980 to 1990.
Analysis of the Sr/Ca record using the Multi-Taper Method was undertaken to determine statistically the cyclic components of the time series and specifically those occurring at periodicities of greater than one year. The results, shown below in Figure 29, found a 25 year cycle at 90% confidence, a 3.13 year cycle at 95% confidence and a 2.19 year cycle at 95% confidence, in addition to a very distinct annual cycle at well above 99% confidence. There are numerous cycles in the sub-annual time scale however these are less relevant to a study of this nature and have not been further analysed.

![MTM - Sr/Ca](image)

**Figure 29:** Plot showing results of Multi-Taper Analysis of the Sr/Ca dataset, with confidence levels, restricted to interannual frequencies (<1 cycle/yr). A- 25 years, b- 3.13, c- 2.19, d- annual. Confidence; blue- 99%, purple- 95%, green- 90%.

Wavelet analysis of the Sr/Ca record was employed to determine whether any significant cycles occurred at relatively high spectral power at different time periods through the time series which may not have been persistent enough, across the entire duration, to register as significant with MTM analysis. The Sr/Ca wavelet, shown in Figure 30, was found to contain a ~16 year cycle which was of high spectral power from 1960 to the late 1980s, a 3 year cycle of high power around 1945 to 1955, and cycles of less than 2 year periodicities occurring during the 1950s.
**Figure 30:** (a) Sr/Ca. (b) The wavelet power spectrum. 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.

To determine statistically the extent of coherence between the Sr/Ca record and the local SST record for the site Cross-Spectral Analysis methods were used, the results of which are shown in Figure 31. Correlations of above 95% were found, between the two records, at 1.19 years and at an annual cycle, in addition to various sub-annual cycles. No other correlations in the interannual range were found to occur with above 80% confidence.
Figure 31: Results of cross-spectral analysis; Sr/Ca-SST (1934-1992). The upper chart shows relative normalised spectral power for SST (blue) and Sr/Ca (red) at various frequencies. The lower chart shows corresponding coherence levels; 80% (orange) and 95% (green). a- 1.19 yrs, b- annual.

Finally, in an effort to ascertain any common variability between the Sr/Ca and $\delta^{18}\text{O}$ records the two were plotted for visual comparison, shown in Figure 32. This analysis was of interest as the two records may both be varying with local SST at the corals exact position which itself may not be reflected in the SST used for this study which has been derived from remote sensing of a larger spectral area. As was done for the SST-Sr/Ca comparison, the individual decades were also plotted for more effective visual analysis. The Sr/Ca time series and the $\delta^{18}\text{O}$ time series for 1980 to 1990 is given in Figure 33, below, and the remaining decades from 1940 to 1980 are given as Appendix 7.
**Figure 32:** Time series graph showing the Sr/Ca record (blue, upper) and the $\delta^{18}O$ record (red, lower) for July 1934 to December 1991.

**Figure 33:** Time series graph showing Sr/Ca in blue and $\delta^{18}O$ in red. Monthly resolution from 1980 to 1990.
The results obtained in this study, for both Oxygen isotopes and Strontium-Calcium analysis, reveal the nature of dominant cycles evident within each time-series and enable comparisons and correlations to be made between them. Five key analysis methods have been presented in Chapter Six to deconstruct the spectral morphology of the geochemical and climatic datasets; visual analysis, singular spectral analysis, cross-spectral analysis, Multi-Taper Method analysis and wavelet analysis. Each method engages with a slightly different aspect of the data and, considered together, they contribute to a thorough and well-supported understanding of the temporal relationships between cycles in original geochemical and existing climatic data. This may determine the suitability of these relationships as a basis for palaeoclimatic insight.

7.1 Annual Cycle

Spectral characteristics of the various timeseries were analysed visually to identify any obvious trends, correlations or characteristics. Previous studies at the Cocos (Keeling) Islands, within Marshall’s PhD Thesis (2000), detected some degree of annual banding in raw coral δ¹⁸O data from the locality. This was confirmed visually within this study as the δ¹⁸O record exhibits a highly significant and unequivocal annual cycle, shown Figure 11 and Figure 12. The presence of an annual cycle is also evident statistically as a cycle of one year frequency occurring with greater than 99% confidence, shown to be temporally persistent, made clear through the results of MTM in Figure 15 and wavelet analysis in Figure 16. This annual δ¹⁸O banding aligns temporally with the SST record and, to a lesser extent, with the precipitation record such that lower δ¹⁸O values align with higher temperature and precipitation values annually. Statistically, cross-spectral analysis shows the same alignment of annual cycles between δ¹⁸O and both SST and precipitation, respectively, shown in Figure 23 and Figure 24. The relative amplitudes of the maximum and minimum values, however,
misalign between the records. Years with notably higher or lower δ\(^{18}\)O values, for instance, do not necessarily correlate to particularly higher or lower SST or precipitation values.

The Strontium-Calcium record, when analysed visually from 1935 to 1992, did not appear to contain a clear annual signal when observed relative to the SST record in Figure 27. With visual analysis of the Sr/Ca record on decadal time periods, however, some extent of an annual signal appeared to be evident amongst the frequent and erratic oscillations as shown in Figure 28 and Appendix 6. Through statistical methods, however, an annual cycle is shown to be apparent in the Sr/Ca time series and is significantly coherent with that in the SST record. The MTM analysis results, Figure 29, show this signal to occur with greater than 99% confidence and are complemented by the Cross-Spectral Analysis results, Figure 30, which show correlations of greater than 95% between the Sr/Ca and the SST at an annual frequency.

Previous research, within Marshall’s PhD Thesis (2000), concluded that δ\(^{18}\)O of coral from the Cocos (Keeling) Islands site is not useful for correlation with regional climatic conditions as the annual banding wasn’t strong and no further signals were detected. The very clear annual oscillations revealed in the results of this study suggest that the coral may be more strongly influenced by climate than previously suspected and warrants more extensive research. Further evidence for annual banding of this particular coral sample is the annual C\(^{14}\) evident after 1950. Good agreement has been found between annual C\(^{14}\) oscillations in the Cocos (Keeling) Island coral and records from the western Indian Ocean (Hua et al. 2005). In the case of Sr/Ca from coral of the Cocos (Keeling) Islands, Marshall and McCulloch (2002) had suggested that the geochemical signal was partially degraded due to localised stresses such as decreased oceanic flow through the lagoon during northwest winds. These results make clear that, despite proposed stresses, an annual cycle is still evident in the coral geochemistry and is likely a response of seasonal SST changes. If the evidence for longer-term oscillations were able to match the clarity of the annual oscillations, the coral geochemistry of the Cocos (Keeling) Islands could prove a valuable proxy for gaining knowledge of palaeoclimatic conditions in the eastern Indian Ocean.
7.2 Interannual Cycles: Oxygen

Additional cyclic patterns or climatic influences beyond the annual are difficult to discern using visual observation and it is hence necessary to rely on statistical analysis. Foremost, it is important to consider the temporal nature of the major interannual atmospheric-oceanic cycles influencing the Indian Ocean, the IOD and ENSO, as depicted through spectral analysis. The Indian Ocean Dipole dataset contains a number of interannual cycles, at confidence levels of greater than 95%, determined through MTM analysis. These include cycles at 21.23 year, 12.13 year and 4.72 year periodicities, shown in Figure 15. Wavelet analysis, shown in Figure 17, illustrated that across the time-series the cycles of highest power occurred at 16 year and 4 year periodicities between the 1940s and 1970s. The inconsistency between cycles determined with each spectral analysis method suggests that, although the MTM-detected cycles are persistent throughout the entire time-series, stronger but less persistent cycles have dominated over certain periods of time. The 4.72 year and ~4 year cycles, detected with MTM and Wavelet respectively, may represent the same oscillatory pattern. The ENSO dataset, conversely, demonstrated significant cycles at 5.2 years, 3.57 years and around 3 years using MTM analysis, Figure 15, which was supported in the wavelet analysis which showed that cycles of high power have occurred at periodicities of around 4-8 years for most of the time-series duration, see Figure 18. The strong evidence for a ~4 year cycle over time in the ENSO dataset implies significance to this component. The presence of roughly 4 year cycles, in each the IOD and ENSO results, invokes questions of the IODs independence. This data supports the idea that the IOD is likely influenced by ENSO and subsequently has a component of similar frequency however the additional cycles detected in the IOD suggest that it is distinct from ENSO.

With an understanding of the nature of the major climatic influences on the eastern Indian Ocean it is necessary to establish whether these signals are detectable in the SST and precipitation records for the Cocos (Keeling) Islands region. The SST record has shown 4 and 16 year cycles to occur with significant power over selected time intervals and persistent cycles occur with similar 17 year and 4.45 year periodicities, shown in Figure 15 and Figure 20. As the frequency of IOD oscillation is known to have changed over the period of study, ranging from 4 to 16 cycles, the influence of the IOD on SST could be shown through cycle correlation within this frequency range. The cross-spectral analysis of the IOD and SST
anomaly records, in Figure 21, showed correlations of >80% coherence to occur at 8.33 year, 4.17 year and 2.38 year cycles. Although the temporal nature of IOD event occurrences has not been consistent over time, it is likely that these correlations, particularly the 8.33 years, may represent the IOD influence on the SST record. The ENSO dataset was also shown, in Figure 22, to correlate with SST at multiple interannual cycles including 8.33 year and 4.17 year periodicities. As ENSO events occur roughly every four years, evident in both the MTM and wavelet results, the correlation at 4.17 years can be confidently assumed to represent the ENSO influence on SSTs in the Cocos (Keeling) Island locality. This same frequency correlation in the SST-IOD results likely represents the ENSO influence on IOD oscillation. The precipitation record exhibits no significant interannual signal, as supported by both Figure 15 and Figure 19, and further cross-spectral surveys were not, subsequently, undertaken. Longer term relationships between precipitation and Oxygen isotopes are inherently difficult to determine with certainty due to the limited span of most instrumental precipitation records for the Indian Ocean region (Burns et al. 2002).

Interannual oscillations are most of interest in the detection of climatic cycles influencing this area of the eastern Indian Ocean and their recording in coral geochemical records. The δ¹⁸O anomaly dataset from the Cocos (Keeling) Islands exhibits a number of interannual cycles, occurring at >90% confidence, all with periodicities of less than 3 years, shown in Figure 15. As previously described, the factors influencing δ¹⁸O are SST, at 4 and 16 year cycles, and precipitation, which shows no interannual cycles. The major influences on the eastern Indian Ocean SST, the Pacific Oceans ENSO and the Indian Oceans IOD, likewise exhibit cycles with periodicities of greater than 4 years. The results hence imply that the coral δ¹⁸O record from modern corals of the Cocos (Keeling) Islands does not vary systematically with these influences. Over shorter time segments in the δ¹⁸O data, cycles of relatively high power occurred at 6 year periodicities, from the 1940s to the 1960s, and 16 year periodicities, from the 1960s to the 1980s, as shown through wavelet analysis in Figure 16, however these timings don’t align with similar cycles in other datasets. When analysed cross-spectrally with the SST, the δ¹⁸O aligned at an 8.3 year periodicity. As cycles at ~8.3 years were not detected in the individual MTM analysis of either dataset on their own and this can probably be explained as a cycle which is insignificant in either record but which correlates to a significant extent between the two.
This would not be the first instance of an apparent inconsistency between Oxygen isotopes in modern coral skeletons and localised SST and precipitation conditions. A 2009 study, for instance, found the ratio of isotopic signal to noise was low in many studies and thus presented challenges to the identifying cycles and patterns (Ault et al. 2009). Through analysis of 23 modern coral Oxygen isotope records they further concluded that isotopic covariability with interannual SST variations could only be reliably reconstructed from a very limited number of records (Ault et al. 2009). Although most analysis software is designed to minimise noise interference it is possible that this could have affected the detection of any cycles apparent at low amplitudes or spectral power.

Various alternative explanations have previously been suggested to account for the trends in modern coral isotopes which are not able to be completely explained through SST and precipitation alone. Specific to the Cocos (Keeling) Islands, recent palaeoclimatic research using bivalve geochemistry at the site has found reasonable evidence to suggest that upwelling may influence the sea surface water chemistry. In particular, Elliot et al. (2009) use trace element concentrations, such as Barium, to study variability during the late 1900s. More generally, the long-term cyclic temperature effects on isotopic composition in coral may be obscured by changes in water composition and by subsequent physiological effects on coral (Allison et al. 1996). It has previously been found, on shallow lagoon platforms, that the δ¹⁸O levels are highly variable with local tides, weather and cloud cover which may impact the coral isotope ratios within this environment but would not be reflected fully in SST and precipitation records for the region thus preventing covariance between SST or precipitation records and the δ¹⁸O (Swart et al. 1983). Variation in growth and calcification rates of coral is commonly cited as a contributor to coral δ¹⁸O records that may be non-uniformly offset from ambient water temperatures (Allison et al. 1996, Linsley et al. 1999, Felis et al. 2003, Leder et al. 1996, Tanzil et al 2009). Comparison between slower and faster growing portions of a coral colony in Florida have shown evidence of marginal δ¹⁸O differences between the two (Leder et al. 1996). Variability between corals at the same location can be up to 0.2-0.4‰. Faster growth rates may decrease the Oxygen-18 concentration in the skeleton indicating temperatures that are colder than reality (Allison et al. 1996, Felis et al. 1996, Villiers et al. 1995). Changes in water acidity, and the effect of this on calcification rates, has also been investigated for its impacts on Oxygen isotope records.
in *Porites* coral (Tanzil et al. 2009, Krief et al. 2010). In a 6-14month observation it was found that a 0.1pH unit decrease resulted in an additional -0.08‰ change in coral $\delta^{18}O$ levels (Krief et al. 2010) which is significant for global change as increasing atmospheric CO$_2$ is likely to induce ocean acidification and localised pH variability. Based solely on the SST and precipitation records, however, it is difficult to make an assessment of the likelihood of these changes in water composition.

Based on the results in Chapter 6, which presented the statistical deconstructions of each geochemical and climatic dataset, it is possible to discuss the Indian Ocean Dipole and the contention surrounding its autonomous existence, distinct of ENSO. Their independence is particularly in question as the two exhibit the same correlations with SST, at 8.3 years and 4.17 years, using cross-spectral analysis and each has a “~4 year cyclic component with MTM analysis. The use of Multi-Taper Method analysis enables key cycles of individual datasets to be considered in terms of their frequency irrespective of when they occur in time. As such, lagged signals should be detected as cycles of equal frequencies in their respective data sets without regard for the time period between their occurrences. The IOD was found, in Figure 15, to have cycles of greater than 99% significance at 4.72 years and 2.07 years which are very similar to, but not a mirror of, the significant cycles detected in the ENSO data set. The wavelet analysis results show the 4.72 year cycle to be most powerful in the IOD data during the 1960s yet the persistent 3-5 year signals of ENSO are weakest during this time. These results would suggest that, although key oscillations across the entire record occur at frequencies similar to those in the ENSO record, the IOD is not solely a lagged mirror of ENSO. The ENSO may have an significant influence on the IOD record which would have the most effect on a four-year cycle, however, this does not confirm that the oscillations are related. The presence of additional cycles, at greater than 95% significance, in the IOD data at 21 year and 16 year periodicities, not evident in the ENSO data, is further testimony to this point.

### 7.3 Interannual Cycles: Strontium-Calcium

The relative concentrations of Strontium and Calcium in the aragonite skeletons of *Porites* coral is generally a function of local SST (Weber 1973). As discussed in Chapter 6, the SST record for the Cocos (Keeling) Islands exhibited significant cycles occurring every 17
years and every 4.45 years in addition to numerous cycles oscillating at less than two years, shown with MTM analysis in Figure 15. Wavelet analysis had also shown the SST record to contain a cycle of 4 year periodicity in the 1940s and a 16 year cycle from the 1950s until the 1980s, determined with wavelet analysis in Figure 21. By comparing the cycles within the Sr/Ca record to those in the SST record the extent of covariance between the two data sets can be ascertained.

When analysed with the Multi-Taper method, Figure 29, the Sr/Ca time series was shown to exhibit persistent, significant, cycles occurring every 25 years, 3.13 years and 2.19 years. Using wavelet analysis to determine any significant cycles occurring at different time periods the Sr/Ca record was shown, in Figure 30, to contain a ~16 year cycle which was of high spectral power from 1960 to the late 1980s, a 3 year cycle around 1950 and cycles of less than 2 year periodicities during the 1950s. The cycles in the Sr/Ca record determined with MTM do not align with those detected in the SST record however the ~16 year cycle detected using wavelet analysis does appear to overlap with that found in the SST time series. The Cross-Spectral Analysis of the SST and Sr/Ca records, shown in Figure 31, did not find a common cycle of ~16 years to occur with above 80% confidence between the two. Beyond the annual, the two records were once found to be coherent, with high confidence, in a 1.19 year cycle which suggests that the Sr/Ca record for the Cocos (Keeling) Islands coral is not considerably dependent on the SST and hence does not exhibit close covariance with the SST time series.

7.4 Trends

Of interest in the visual analysis results are the gradual increase and gradual decrease trends evident in the SST and δ¹⁸O records respectively. Based on temperature-isotope correlation equations the change in SST between 1924 and 1992 is not sufficient to fully explain the change in δ¹⁸O across the same span of time. The SST increase in regional records can be used to explain half of the measured isotopic change however the rest of the trend is likely to be attributable to alternative mechanisms such as seawater freshening unrelated to temperature. The low and decreasing isotope values, observed through visual analysis, are unlikely to be a reflection of changing rainfall patterns in the Cocos (Keeling) Islands region and may reflect yet another source of freshening.
7.5 Limitations

Within all fields of research, particularly recently developing fields such as palaeoclimate, it is imperative to recognise the limitations inherent in the techniques and results. This study was limited most prominently by sample size. As only one coral sample was analysed for geochemical characteristics in this study it is possible that this one specimen represents an anomalous organism amongst an atoll of coral with contrasting properties. It was also limited in the scope of tests conducted. With a greater range of geochemical parameters analysed it would have been possible to determine whether the coral, as a whole, was unresponsive to SST and precipitation or whether it was only the isotopic component.

In regards to statistical relationships, a longer record would have provided greater opportunity to identify cycles however the climatic data itself, particularly the precipitation record, is also limited temporally and imposed further restrictions. The locality of climatic data used for this study posed an inherent and unavoidable limitation as an ideal study would use SST and precipitation records from the exact position of the coral site. It is not known whether the climate records used in this study are a true reflection of the conditions experienced by the coral itself.
8.1 Once upon a coral...

The primary objective of this research was to identify the nature of the atmosphere-ocean dynamics expressed in the coral records of the Cocos (Keeling) Islands, in the eastern Indian Ocean, and the dominant processes influencing these dynamics. Well-defined annual oscillations were exhibited in both the Sea Surface Temperature and, to a less defined extent, in the precipitation record. Both the Oxygen isotope record and the Strontium-Calcium record from modern Porites coral sampled for this study were found to correlate with this annual cycle which extended, more definitively, previous research at the site. At an interannual time scale, statistical analysis indicated that the Indian Ocean Dipole and the El Niño Southern Oscillation are each influential over oscillations in the local Sea Surface Temperatures of the Cocos (Keeling) Islands but not in the precipitation record. Neither the Sea Surface Temperature nor the precipitation was found to be significantly correlated with cycles in the Oxygen isotopic record at frequencies deemed significant in the isotopic dataset. It can be concluded that the δ^{18}O isotopic record from modern coral in the Cocos (Keeling) Islands exhibits significant oscillations of less than three year periodicities and that these dominant cycles do not statistically reflect the influence of Precipitation, Sea Surface Temperature, the IOD or ENSO on interannual timescales. Likewise, the Strontium-Calcium record did not significantly correlate with the local Sea Surface Temperature data at any notable periodicities and cannot be shown to strongly reflect variability of climate and ocean conditions. The Oxygen isotope and Strontium-Calcium geochemistry of this Porites coral at the Cocos (Keeling) Islands do not, therefore, appear to be suitable for use as palaeoclimate proxies.

If to no further avail this research does, at least, bring to the fore the fragility and uncertainty of coral records and the inherent need to verify the suitability of each coral proxy as a palaeo-thermometer before assuming its accuracy as such.
8.2 Benefits
The scientific benefits of this research include:


2. Highlighting the need to continue to check more modern proxies from a site against instrumental records before assuming their correlation with climatic parameters in the past.

3. Demonstrating the influence of both Pacific and Indian Ocean oscillations on sea surface temperatures of the eastern Indian Ocean.

8.3 Further Research
In light of this study it is evident that further research is needed into the climatic and atmospheric influences in the tropical eastern Indian Ocean particularly at sites in proximity of the identified Indian Ocean Dipole eastern ‘pole’. This is necessary for gaining an understanding of the relative influence and interdependence of oscillatory patterns and to better comprehend and predict Indian Ocean Dipole events. The geochemistry of the coral of the Cocos (Keeling) Islands showed no apparent correlation with the Indian Ocean Dipole however the very existence of such a Dipole remains controversial and disputes continue to persevere within the scientific community. This indicates that a further body of palaeoclimatic reconstructions and measurements within and surrounding the Indian Ocean is needed in the future.

Future research efforts at the Cocos (Keeling) Islands could consider other influences on the Oxygen-18 isotope and Strontium-Calcium variability in its modern corals and the primary biotic or abiotic factors from which this may result. The vast majority of related studies conducted at other sites throughout each Ocean have found a strong correlation to exist between Oxygen isotope ratios and sea surface temperatures or precipitation in modern corals. Future research needs explain whether the anomalous results of this study are representative of coral at the Cocos (Keeling) Islands and, if so, what is causing such results. Additional palaeoclimate proxies attainable from coral, such as Barium-Calcium,
Magnesium-Calcium and Uranium-Calcium ratios (Marshall & McCulloch 2002), could also be used to better support the results.

The records analysed within this study extended only to 1992 and future research efforts would benefit from analysing post-1992 geochemical records, from the same site, at the Cocos (Keeling) Islands. A major benefit of analysing the most recent coral records is that the corresponding modern climatic records, with which they can be compared, have been measured using improved technologies and are potentially more accurate than earlier years. In addition, IOD and ENSO events of the 1990’s were well measured and are known to have been very pronounced, particularly in 1994 and 1997, and the variability of geochemical records for these years would be of interest to study.

Finally, there is a reasonable possibility that the satellite grid data for climate parameters such as SST, in the Cocos (Keeling) Island region, doesn’t accurately reflect the true local conditions at the site. The results of this study suggest that the installation of data-logger systems to take in situ measurements of SST and other ocean and climate properties at the Cocos (Keeling) Islands could produce more site-specific data than that currently available.
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## Appendices

### Appendix 1:

Data from repeat runs conducted on Mass Spectrometers at UOW and ANU.

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| ANU & UOW average of runs - d18O

- Graph showing d18O per mil from Dec-86 to Jan-88.
**Appendix 2:**

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Appendix 4:

Singular Spectral Analysis using SSA-MTM Toolkit; Variables and options used for analysis.

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<td>SSA Components</td>
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<td>Significance Test</td>
<td>Chi-squared</td>
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<td>Covariance</td>
<td>Vautard &amp; Ghil</td>
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Appendix 5:

Multi-Taper Method Analysis using SSA-MTM Toolkit; Variables and options used for analysis.

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<td>Robust</td>
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Appendix 6:

**Appendix 7:**