1-1-2011

# Paleoclimate from corals

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## Recommended Citation

McGregor, Helen V.: Paleoclimate from corals 2011, 777-785.
https://ro.uow.edu.au/scipapers/1124

# Paleoclimate from corals

## Abstract

Ocean- atmosphere interactions in the tropics have farreaching conscqucnccs for climate variabi lity across the globe. The tropics drive heat transfer to the poles, and tropical inter-annual oscillations such as the El Nino-Southern Oscillation (ENSO) and Indian Ocean dipole (IOD), via atmospheric tcleconncctions, affcct rain rail patterns and climate conditions in arcas far bcyond the tropics (Ropelewski and Halpert, 1987), causing major socioeconomic impacts. Monitoring eIT0l1s have focused on improving obscrvations and undcrstanding of tropical climate variability, with the view to refining modeling or the tropical oceans and atmosphere. Despite these efforts, most instrumcntal records span only the past few decades and do not capture the full range of tropical climate variability, limiting Ollr ability to modcl futurc changcs. Coral paleoclimatology offers the prospect to extend instrumental rccords of tropical climate variability and can provide unique insights into tropical ocean- atmosphere interactions.

## Keywords

paleoclimate, corals, GeoQUEST

## Disciplines

## Publication Details

McGregor, H. V. (2011). Paleoclimate from corals. In D. Hopley (Eds.), Encyclopedia of Modern Coral Reefs:Structure, Form and Process (pp. 777-785). Netherlands: Springer.

the Bahamas, the separate phases of dune accumulation are bounded by prominent red palaeosols. A lesser interruption in dune accretion is marked by a less well-developed soil horizon known as a protosol, or a hard layer of calcrete.

Palaeosols formed during periods when the dunes were stabilized by vegetation. Despite an early view that the fossil dunes formed during periods of low sea level, such as the last glacial maximum, it is now known from extensive dating on many eolianite islands that most dunes accumulated during sea-level highstands. The clay-rich palaeosols mark those periods during which the sea was lower, the glaciations. Prominent in many palaeosols are fossils of land snails, such as *Cerion* in the case of the Bahamas, and *Placostlyus* on Lord Howe Island. Also widespread are the bones of seabirds, as well as rich assemblages of other fossils. Identification and dating of palaeosols and their correlation across islands enables discrimination of the intervening fossil dune formations. These sequences have been particularly effectively mapped and researched on the island of Bermuda.

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### Cross-references

Calcrete/Caliche
Eolianite
Soils of Low Elevation Coral Structures

## PALEOCLIMATE FROM CORALS

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### Synonyms

Coral-climate proxies; Coral palaeoclimatology/paleoclimatology; Paleoceanography; Past climates from corals

### Definition

*Coral paleoclimatology* is the use of geochemical records from the skeletons of fossil or modern corals to reconstruct tropical climate variability during the time the coral lived.

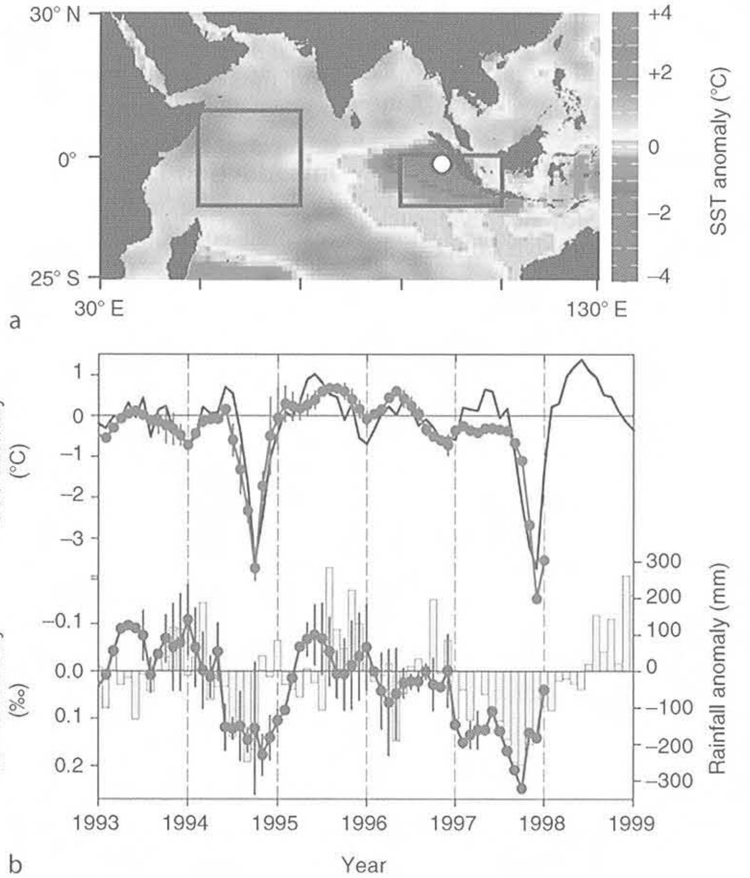
### Introduction

Ocean–atmosphere interactions in the tropics have far-reaching consequences for climate variability across the globe. The tropics drive heat transfer to the poles, and tropical inter-annual oscillations such as the El Niño-Southern Oscillation (ENSO) and Indian Ocean dipole (IOD), via atmospheric teleconnections, affect rainfall patterns and climate conditions in areas far beyond the tropics (Ropelewski and Halpert, 1987), causing major socio-economic impacts. Monitoring efforts have focused on improving observations and understanding of tropical climate variability, with the view to refining modeling of the tropical oceans and atmosphere. Despite these efforts, most instrumental records span only the past few decades and do not capture the full range of tropical climate variability, limiting our ability to model future changes. Coral paleoclimatology offers the prospect to extend instrumental records of tropical climate variability and can provide unique insights into tropical ocean–atmosphere interactions.

Long-lived, massive corals record climate changes in the geochemistry of their skeletons. As corals grow, they deposit an aragonitic (calcium carbonate) skeleton, usually as one high and low density band per year, visible by x-ray of the coral skeleton (Barnes and Lough, 1993). Incorporated in the coral skeletons are varying proportions of geochemical elements, depending on the prevailing environmental and climatic conditions in the ambient seawater in which the corals live, and on the coral's own physiology (see "*Stable Isotopes and Trace Elements*"). The geochemical, or the so-called "proxy," records derived from the coral skeletons can be measured at sub-annual resolution and can be empirically related to a given climate parameter (e.g., Figure 1). Widely used coral proxies include the ratio of strontium to calcium (Sr/Ca), a proxy for sea surface temperature (SST), and the coral oxygen isotope ratio ($\delta^{18}O$). The coral $\delta^{18}O$ is a function of SST and the $\delta^{18}O$ of seawater, where the $\delta^{18}O$ of seawater correlates with changes in sea surface salinity (SSS), which in turn may respond to changes in rainfall. Using the Sr/Ca SST proxy, the SST component of the coral $\delta^{18}O$ signal can be removed leaving the oxygen isotope residual ($\Delta\delta^{18}O$) a SSS-only proxy (McCulloch et al., 1994; Gagan et al., 1998; Gagan et al., 2000). With the most commonly used coral genus *Porites* often living for a century or more, measurement of the coral skeletal geochemistry can provide quantitative, seasonally resolved, century-length records of climate variability for the time the coral lived.

### Reconstructing climate records from corals

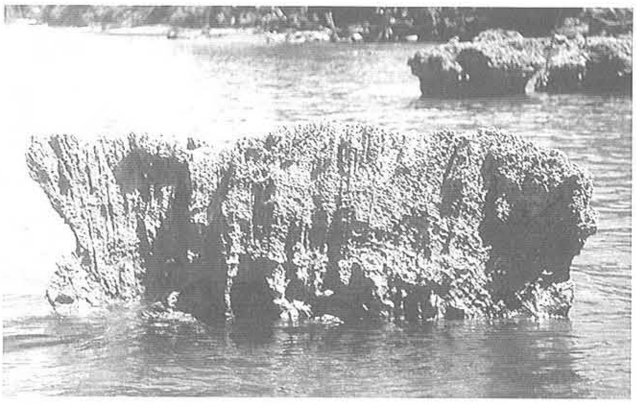
*General approach*. There are two main approaches to reconstructing past climates from corals using modern or



**Paleoclimate from Corals, Figure 1** IOD climate anomalies. (**a**) SST anomalies during November of the 1997 IOD event (Reynolds and Smith, 1994), when anomalous cooling in the east and warming in the west produced a reversal of the equatorial SST gradient across the Indian Ocean. *Boxes* mark the eastern and western sectors used to define the dipole mode index (Saji et al., 1999), and the *white circle* shows the location of the Mentawai Islands. (**b**) In the Mentawai Islands the strong IOD events of 1994 and 1997 were characterized by cool SST anomalies (*black curve*; Saji et al., 1999) and drought (*gray bars*; Xie and Arkin, 1996). These distinct IOD SST and rainfall anomalies are preserved, respectively, in coral Sr/Ca SST (*red circles* and *curve*) and $\Delta\delta^{18}O$ (*blue circles* and *curve*) anomalies (Gagan et al., 1998). Coral time series between July 1993 and February 1997 are based on the average of two coral records, with error bars showing the difference between the coral records for each monthly data point. (Reprinted by permission from Abram et al. [2007].)

fossil corals. The most common approach is to collect a core from a live coral on a reef. The chronology is provided from the coral density growth bands and/or the seasonal cycle recorded in the coral geochemical records. Annual coral density bands can be counted; beginning at the tissue layer at the uppermost surface of the coral, the paired high and low density bands, revealed by x-ray of the coral, are counted back in time. Coral density bands are not always well defined, so alternatively the annual peaks or troughs in the coral geochemical climate proxies can themselves be counted. Using either method, or a combination of the two, it may be possible to count back several centuries with errors of 1 or 2 years (Lough and Barnes, 1997; Guilderson and Schrag, 1999; Hendy et al., 2002; Hendy et al., 2003). The advantage of using a modern coral for climate reconstruction is that the start age is known and the coral geochemical proxies can be directly calibrated against climate parameters as measured in the instrumental records increasing the robustness of the reconstruction. In addition, replicate coral cores can be taken from different coral heads from the same reef, enhancing reproducibility. The disadvantage is that the reconstructed record is limited by the length of time the coral lived, usually no longer than a few centuries. Dating errors may increase further back in time. There are now significant numbers of modern coral records extending back several centuries from the present day from various locations throughout the tropics such that the records are being combined to examine the climate connectivity of the tropical oceans (Kaplan et al., 1998; Evans et al., 2000; Hendy et al., 2002; Charles et al., 2003; Wilson et al., 2006).

An emerging alternative approach is to use well-preserved fossil corals to reconstruct climate further back



**Paleoclimate from Corals, Figure 2** Fossil *Porites sp.* coral from Muschu Island, Papua New Guinea. The coral, once living underwater on the reef, has been uplifted by tectonic activity and is now preserved as an isolated coral head within the intertidal zone, and is exposed at low tide. Note the concentric growth bands in this coral and that the top of the coral has been planed flat.

in time (Figure 2). The age of the fossil coral can be precisely determined using radiocarbon or U-series dating, and the proxy climate record from the coral skeleton provides a "snapshot" of past variations (e.g., Beck et al., 1997; Gagan et al., 1998; Tudhope et al., 2001; Woodroffe et al., 2003; Corrège et al., 2004; Felis et al., 2004; McGregor and Gagan, 2004; Abram et al., 2007). It is also essential to analyze a modern coral that overlaps instrumental record to quantify the coral geochemistry–climate parameter relationship since the same climate proxies are used for the fossil and modern corals. In this case, the modern records for calibration need not extend back several centuries. The major advantage of using fossil corals is that it is possible to look at climate variations further back in time when the climate boundary conditions were different from today, giving a perspective on the range of possible, natural climate modes. The disadvantage of using fossil coral proxy records is that they are almost inevitably disjointed. However, an exciting new development has been to use high-precision U-series dating of multiple fossil coral and look for age overlaps (Cobb et al., 2003; Zhao et al., 2009). Age dating errors are typically +/−0.5%, equivalent to less than a decade for Holocene-aged corals, and where individual fossil corals overlap in age their proxy records can be pieced together, where the climate "wiggles" from each individual coral are matched, to produce a longer record (Cobb et al., 2003).

*Coral-climate signals and reproducibility.* For both fossil and modern coral studies, it is essential to establish the climate factors controlling the signal at a given location, quantify this relationship, and determining the magnitude of associated errors. For example, the commonly use $\delta^{18}O$ proxy reflects changes in both SST and SSS. However at some locations, such as in PNG in the western tropical Pacific SSS changes dominate the signal (Tudhope et al., 2001; McGregor, 2004), whereas at locations such as the central Pacific SST exerts the major control (Evans et al., 2000; Woodroffe and Gagan, 2000). In addition, the aim for coral paleoclimatology is often to be able to use the coral proxy record from a single location to infer regional climate variability. Thus, the climate factors that control the coral proxy climate signal must be quantifiably related to regional climate variations (Guilderson and Schrag, 1999). Some locations appear to be "nodes" for particular tropical climate oscillations (e.g., ENSO or the North Atlantic Oscillation), and coral records from these locations can be representative of climate variability over very large spatial areas. One example of this is where coral-climate records from Kiritimati Island were used to construct a coral-C INDEX, equivalent to the NINO3.4 Index used to define ENSO events (Evans et al., 1998). From this point of view, corals from well-flushed reef settings are preferred. For in situ fossil corals it is usually possible to establish the paleo-reef morphology; however, for transported corals (dislodged either by storm activity or post-uplift erosion) establishing provenance is almost impossible (Cobb et al., 2009).

Several studies have suggested that proxy climate signals from corals living on the same reef may show higher between-coral (inter-reef) differences than that expected from climate variability alone (Guilderson and Schrag, 1999; Linsley et al., 1999; Cohen et al., 2002; Felis et al., 2003). The origins of these offsets are not well understood, and, in addition, there are studies that suggest minimal between-coral offsets (Gagan et al., 1998; Hendy et al., 2002; Stephans et al., 2004). But between-coral differences appear to affect the coral oxygen isotope ratios more than Sr/Ca. Coral growth form, growth rate, reef setting, and diagenesis have all been suggested as possible causes of offsets (Cobb et al., 2009). Corals can also show within-coral variations (McConnaughey, 1989; de Villiers et al., 1995; Alibert and McCulloch, 1997; Cohen and Hart, 1997). Regardless of the origin and magnitude of between-coral and within-coral offsets, reproducing proxy climate signals from the same location, using at least two corals, will reduce uncertainty and quantify errors in climate reconstructions from both modern and fossil corals (Lough, 2004; Stephans et al., 2004; Abram et al., 2009).

*Diagenesis.* An underlying assumption in the use of corals to reconstruct climate is that the corals are pristine, that is, that original coralline aragonite is preserved. However, coral skeletons are susceptible to a process known as diagenesis. Diagenesis is the precipitation of secondary aragonite or calcite in skeletal voids, or the replacement of skeletal aragonite, usually with calcite. If even a small amount of diagenetic material is included in a sample, then the resulting climate reconstruction may be rendered inaccurate. This is because isotopes and trace elements are exchanged and removed during the diagenetic transformation, changing the geochemistry of the coralline matrix. For example, secondary calcite can lead to "warm" SST artefacts (SST appears warmer than was the case), particularly in Sr/Ca SST reconstructions, of 1°C or more

(McGregor and Gagan, 2003). Secondary aragonite, typical for early marine diagenesis of modern corals, causes considerable alteration of coral geochemistry and creates "cool" SST artefacts (Bar-Matthews et al., 1993; Enmar et al., 2000; Müller et al., 2001; Lazar et al., 2004; Müller et al., 2004; Allison et al., 2007). Dissolution was shown to create "cool" anomalies in a range of trace element SST proxies (Hendy et al., 2007). Diagenesis has been observed in living corals and corals just a few decades old (Enmar et al., 2000; Müller et al., 2001; Hendy et al., 2007; Nothdurft et al., 2007); however, fossil corals are more susceptible to diagenetic processes as they are exposed to seawater, sea spray, rainfall, and/or groundwater for centuries to millennia or longer.

Numerous studies have called for screening for diagenesis in modern and fossil corals to become standard procedure (McGregor and Gagan, 2003; Gagan et al., 2004; Quinn and Taylor, 2006; Allison et al., 2007; Hendy et al., 2007; Cobb et al., 2009). Diagenesis that produces an addition of ~10% or more secondary material to the skeletal bulk density can be detected in coral density profiles, X-radiographs, and UV luminescence photos (Hendy et al., 2007). However, just 1% calcite diagenesis would alter the coral climate signal (McGregor and Gagan, 2003). X-ray diffraction (XRD) has been the most commonly used diagenesis screening method in coral paleoclimate studies. However, XRD detects secondary calcite, not secondary aragonite or dissolution, and the XRD detection limit is effective down to around the 1% calcite (McGregor and Gagan, 2003; Allison et al., 2007). For lower levels of diagenesis, thin section is proving a highly effective means of screening samples for all types of diagenesis (McGregor and Gagan, 2003; McGregor and Abram, 2008; Cobb et al., 2009). One thin section per 20–30 years of coral growth is recommended (Cobb et al., 2009) and a guide has been developed to assist coral paleoclimatologists in screening using thin sections (McGregor and Abram, 2008). Scanning electron microscopy (SEM) is also a highly effective tool for diagenetic screening (Nothdurft et al., 2007).

## Coral paleoclimate records

One of the major strengths of corals as paleoclimate archives is their ability to record monthly or finer resolution (e.g., weekly) climate information. This level of resolution means corals are ideally suited to investigating inter-annual climate phenomena, such as the El Niño-Southern Oscillation and the Indian Ocean Dipole. Approximately 90 coral proxy records based on corals that were alive at the time of collection have been published, with around 30 of those extending from the late twentieth century back prior to 1900 (Jones et al., 2009). These longer coral records are able to provide a wealth of information on multidecadal to centennial timescale variability. At least one coral record exists from every tropical ocean, with the vast majority of records from the tropical Pacific. There are significantly fewer records from older fossil corals. Coral paleoclimatology has made a significant contribution to understand a number of facets of tropical climate variability and a snapshot of these contributions will be discussed in the following sections.

## Interannual and multi-decadal variability in the tropical Pacific: variations past and present

A key focus of coral paleoclimate research has been in extending records of the El Niño-Southern Oscillation system. ENSO, with its origins in the equatorial Pacific, is the largest source of interannual climate variability across the planet. It is a coupled climate system between the atmosphere and the ocean, and it oscillates irregularly on a timescale of 2–7 years. The average state of the equatorial Pacific Ocean involves strong easterly trade winds pushing warm water to the west, which then brings (upwells) cool subsurface water in the east. This sea surface temperature gradient then reinforces the easterly winds. A La Niña event is an enhancement of the average state, where the easterly winds and temperature gradient strengthen. In an El Niño event, the easterly winds slacken and reduce the ocean temperature gradient, allowing warm water to flow back to the central and eastern Pacific. Atmospheric convection and precipitation follows the warmest water, and in an El Niño, above average rainfall is deposited over the central Pacific. El Niño events have become stronger and more frequent since the mid-1970s (McPhaden et al., 2006). However, there is debate about whether strengthened El Niño is a result .of global warming or whether the 1970s intensification resulted from a decadal or longer-term cycle of ENSO variability (Fedorov and Philander, 2000; Cane, 2005; McPhaden et al., 2006). The relatively short instrumental record does not give a complete picture of ENSO behavior, and models are unable to simulate ENSO fully, limiting our ability to predict future ENSO scenarios.

Corals from optimal locations across the equatorial Pacific are able to capture the SST and rainfall/SSS variations that result from ENSO oscillations (Cole et al., 1993; Dunbar et al., 1994; Evans et al., 1998; Urban et al., 2000), and have complemented and extended instrumental records of ENSO variability. Spectral analysis of one of the earliest published coral $\delta^{18}O$ records, that from Tarawa Atoll, western Pacific, showed changing dominance of seasonal and interannual variability through the twentieth century, suggesting a change in the ENSO "pulse" (Cole et al., 1993). Further analysis of the Tarawa $\delta^{18}O$ record and comparison with a 155 year $\delta^{18}O$ record from Maiana Atoll, just south of Tarawa, revealed, among other things, that the 1976 shift in ENSO variability coincided with changes in the mean background climate of the tropical Pacific, with the ENSO period shifting from 2.9 to 4 years across the 1976 change (Urban et al., 2000). The record also revealed that during the late nineteenth century, ENSO cycles lasted 10–15 years. These results are significant because they show that the length of the ENSO cycle varies with small changes in tropical climate.

Furthermore, the results suggest that there is substantial natural variability in ENSO, but that the most recent period may be unique in that the changes in the mean climate due to anthropogenic greenhouse gases may also influence ENSO (Dunbar, 2000).

The network of coral-climate records from across the Pacific, although still sparse, does appear to capture large-scale, multi-decadal climate variance, and in combination with coral records from other ocean basins, is revealing ocean–atmosphere connections right across the tropics. Consensus is emerging for significant decadal variability in tropical Pacific SSTs at the 9–14 year period (Cobb and Charles, 2001; Holland et al., 2007; Ault et al., 2009). The decadal variability displays an ENSO-like spatial and temporal pattern suggesting that the Pacific decadal-scale variance is directly related to ENSO (Urban et al., 2000; Holland et al., 2007; Ault et al., 2009). Decadal-scale variability appears to be stronger in the late nineteenth century, and analysis based on only twentieth century records may underestimate decadal-scale variability (Ault et al., 2009). Synthesis of coral SST records spanning the whole tropics suggests that the late twentieth century is the warmest period for the past 250 years, which can be explained by the increase in anthropogenic greenhouse gases in the atmosphere (Wilson et al., 2006). A consistent antiphased correlation between the South Pacific Convergence Zone, a low pressure trough extending from around the Solomon Islands to French Polynesia, and the decadal variability in the central equatorial Pacific has been documented back to 1650 AD (Linsley et al., 2008). At the decadal-scale the Atlantic Ocean may be directly influenced by SST anomalies in the central tropical Pacific (Cobb and Charles, 2001), and central equatorial Pacific SSTs also correlate on a variety of timescales with Indian Ocean coral oxygen isotope records, suggesting a decadal-scale connection between these ocean basins (Cobb and Charles, 2001; Charles et al., 2003).

The longest, continuous coral proxy record published to date, based on eight coral cores from the Great Barrier Reef (GBR), sampled at 5-yearly resolution and totaling 420-years from present back to 1565 AD, showed that corals can also record centennial-scale shifts in tropical climate (Hendy et al., 2002). This study was unique in its approach in that it combined records in a similar manner to the approach used in tree-ring studies to extract the robust "common signal" of low-frequency SST and SSS variability in the records. The resulting common GBR SSS anomaly record showed increased salinity between 1565 and 1870, around the time of the Little Ice Age (LIA) in the northern Hemisphere (Hendy et al., 2002). The SST anomaly results, along with other long records from the tropical Pacific, suggest a stronger latitudinal temperature gradient during the LIA, enhancing wind-driven evaporation, giving rise to the high salinity anomalies. The authors suggest that the high evaporation equated to a net export of moisture from the tropics contributing to glacial advance during the LIA (Hendy et al., 2002).

Also, drawing on approaches adapted for tree-ring studies, Cobb et al. (2003) pieced together numerous fossil and modern corals from ENSO-sensitive Palmyra Atoll, central Pacific, to give the first picture of ENSO variability for the past millennium. Their landmark reconstruction was based on dislodged coral heads deposited on Palmyra during storms events. The corals were precisely dated by the U-Th method to identify periods of overlap, and then the monthly resolved $\delta^{18}O$ records were "wiggle matched" together. In total, this resulted in 430 years of monthly resolved record, for five intervals across the past millennium. The record showed a surprising degree of variability in ENSO strength, independent of changes in solar or volcanic forcing. In addition, ENSO strength does not appear to relate to changes in Northern Hemisphere climatic periods such as the Little Ice Age or Medieval Warm Period (Cobb et al., 2003). ENSO strength seemingly switches modes in a matter of decades, and the late twentieth century ENSO, although strong, is not unprecedented over the length of the record (Cobb et al., 2003). The results suggest that ENSO can change its character on its own, and in future, may shift with or without an additional push from anthropogenic greenhouse gases (Cobb et al., 2003; Tudhope and Collins, 2003). This presents a challenge for modeling future ENSO behavior, and testing global climate models against past ENSO variability provides a means to refine and improve these models.

Coral paleoclimate reconstructions have been instrumental in understanding the origin and long-term evolution of ENSO (Hughen et al., 1999; Corrège et al., 2000; Tudhope et al., 2001; Woodroffe et al., 2003; Kilbourne et al., 2004; McGregor and Gagan, 2004; Sun et al., 2005). A major discovery from Indonesian and Papua New Guinea (PNG) fossil corals has been that ENSO has been a component of the tropical climate system for at least 130,000 years (Hughen et al., 1999; Tudhope et al., 2001), and has varied significantly in strength through glacial and interglacial cycles (Tudhope et al., 2001). Tudhope et al. (2001) proposed that ENSO strength varied as a result of changes in tropical Pacific seasonality related to the Earth's orbital cycles (orbital forcing) plus dampening of ENSO strength during glacials. Further work on coral from PNG, and additional coral records from the central Pacific, are providing a more detailed picture of the evolution of ENSO for the most recent Holocene period (10,000 years ago to present; Corrège et al., 2000; Tudhope et al., 2001; Woodroffe et al., 2003; Gagan et al., 2004; McGregor and Gagan, 2004; Sun et al., 2005). These studies suggest that ENSO was less active compared to today, although still present, and may have been more active around 2,000 years ago.

A key component of ENSO and the tropical Pacific climate system is the Indo-Pacific Warm Pool (IPWP). The IPWP is the warmest body of ocean water in the world having an average temperature of >28°C, and coupled ocean–atmosphere interactions in the IPWP are not only thought to trigger El Niño events, but also deliver large amounts of heat to the atmosphere via the global atmospheric Hadley-Circulation (Webster, 1994). Much coral evidence for the evolution of ENSO originates from the IPWP and coral data has also provided important information on the long-term climate variability of the warm pool. Sea surface temperature estimates, based on corals from Vanuatu, PNG, GBR, and Indonesia and utilising a revised coral Sr/Ca SST calibration, suggest that the early Holocene IPWP was ~1–3°C cooler than present (Gagan et al., 2004 and references therein). Temperatures had reached modern values by ~8.5 ka, in general agreement with planktonic foraminifera Mg/Ca and alkenone SST estimates, and mid-Holocene SSTs were 0.5–1°C warmer than present (Gagan et al., 2004). A more detailed picture of IPWP SST variations, based on 48 fossil corals from Indonesia and PNG, suggested that the southern margin of the IPWP cooled and warmed periodically through the mid-Holocene, associated with an expansion and contraction of the warm pool as the Asian summer monsoon weakened and strengthened, respectively, and points to the fundamental importance of the warm pool in propagating climate change (Abram et al., 2009).

## Interannual modes in the Atlantic and Indian Ocean

Understanding the influence of the tropical Pacific and ENSO on the Indian Ocean has been recognised as an important issue and corals have played a role in better characterising the interactions. For the past few decades, SSTs in the Indian Ocean have been associated with ENSO and the Asian monsoon via complex multifeedbacks (Webster et al., 1998). As with the tropical Pacific, however, a major limit in understanding climate variability in the tropical Indian Ocean, and the Indian, East African, and southeast Asian monsoons, on which millions of people are dependent for life-giving rain, has been the absence of records of more than a few decades in length. Multi-century coral oxygen isotope records from the central and western Indian Ocean however, reveal a clear ENSO teleconnection, whereby during El Niño events western Indian Ocean SSTs are warmer (Charles et al., 1997; Cole et al., 2000; Zinke et al., 2005; Pfeiffer and Dullo, 2006). The western Indian Ocean SSTs also display decadal-scale ENSO-like variability (Cole et al., 2000; Pfeiffer and Dullo, 2006), which may be linked to the Pacific decadal oscillation (Crueger et al., 2009).

Although there may be a generally consistent teleconnection between the western Indian Ocean and ENSO, new perspectives from coral records from the eastern Indian Ocean show a changing ENSO–Indian Ocean–monsoon interaction, with potentially negative consequences for SE Asian rainfall under global warming scenarios (Abram et al., 2007). Recently identified IOD events are defined by a reversal of the equatorial Indian Ocean east–west SST gradient and zonal winds from their mean climatological state (Saji et al., 1999; Figure 1), resulting in drought for western Indonesia and southern Australia (Overpeck and Cole, 2007). IOD events were reconstructed back to 1846 using a suite of corals from the eastern and western Indian Ocean (Abram et al., 2009). The coral IOD index showed an increase in the strength and frequency of IOD events through the twentieth century (Figure 1). The results also showed that despite the historical influence of ENSO in triggering IOD events, the twentieth century IOD intensification was a direct result of IOD–monsoon feedbacks, with consequences for rainfall distribution (Abram et al., 2009).

Coral reconstructions of Holocene IOD events have likewise revealed changes in the IOD–monsoon–ENSO relationship over time (Abram et al., 2007). The results are significant, their strength being that they provide information on monthly scale timing and duration of individual IOD events (Figure 1), and show that ~6,500 years ago IOD SST cooling lasted 5 months, up from 3 months for the present day. They also reveal that long-duration IOD events result in drought peaking later in the calendar year than for the present day, coinciding with what would normally be the maximum monsoon rainfall in western Indonesia. The mid-Holocene enhanced IOD cooling and drying is thought to result from strengthened Asian monsoon, and future Asian monsoon–IOD strength may extend drought through Australasia (Abram et al., 2007).

Coral records are making a significant contribution to our understanding of the Atlantic Multidecadal Oscillation (AMO), hurricane activity, and the North Atlantic Oscillation/Arctic Oscillation (NAO/AO). The AMO is a decadal- to multidecadal-scale variation in SSTs across the Atlantic and may be related to hurricane activity in the northern tropical Atlantic (Goldenberg et al., 2001). A 440-year growth rate SST reconstruction from the Bahamas suggests that multidecadal variability may only be significant after 1730, limiting the accuracy of decadal climate forecasts (Saenger et al., 2009). In a related study, luminescence lines from Caribbean corals were used in combination with a marine sediment core proxy record to investigate hurricane frequency, vertical wind sheer, SST, and the AMO for the past 270 years (Nyberg et al., 2007). The results suggest that vertical wind sheer is more important than SST in controlling hurricane frequency, and controversially, that increased hurricane frequency since 1995 is not unusual compared to other periods of high hurricane activity in the record (Elsner, 2007; Nyberg et al., 2007; Neu, 2008; Nyberg et al., 2008).

Coral records, particularly those from fossil corals, have made key inroads into our understanding of the NAO/AO. The NAO/AO is the dominant interannual atmospheric mode in the North Atlantic influencing the climate of much of Europe via its modulation of the strength of the subpolar westerlies (Hurrell, 1995; Thompson and Wallace, 2001). Oxygen isotopes in corals from the northern Red Sea reflect the influence of the NAO/AO and ENSO on the climate of the region (Felis et al., 2000). Sr/Ca SST records from 125,000 year old fossil corals show increased temperature seasonality

(Felis et al., 2004). In an innovative approach, combining the seasonal-resolution coral data with coupled atmosphere–ocean model simulations, the results suggest that a more positive NAO/AO operated 125,000 years ago contributing to the increased seasonality in the Red Sea coral record, as a response to insolation changes from differences in Earth's orbital configuration at that time (Felis et al., 2004). Such studies help to disentangle natural climate variability and will help us better understand the response of interannual climate oscillations to anthropogenic greenhouse warming.

## Summary

Corals are proving an invaluable source of quantitative data on past climate variability across the tropical oceans, and over a range of timescales from seasonal, interannual, decadal to centennial and millennial. Community wide efforts to extract records from undersampled time periods, such as the LGM and deglaciation (Expedition 310 Scientists, 2006; Webster et al., 2009), and locations, and further integration of coral data and climate model output will continue to see coral paleoclimatology contribute to understanding natural climate variability.

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## Cross-references

Aragonite
Calcite
Corals: Biology, Skeletal Deposition, and Reef-Building
Corals: Environmental Controls on Growth
Diagenesis
El Niño, La Niña, and ENSO
Microatoll
Mid Holocene
Radiocarbon ($^{14}$C): Dating and Corals
Sclerochronology
Stable Isotopes and Trace Elements
Uranium Series Dating

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# PATCH REEFS: LIDAR MORPHOMETRIC ANALYSIS

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## Setting

Alina Reef is one of several thousand patch reefs that lie across the shallow carbonate platform seaward of Hawk Channel off the northern Florida Keys. The site is near the northern latitudinal fringe of the late Holocene western Atlantic coral reef distribution (Figure 1). The area is covered by calcareous sand and discontinuous *Thalassia testudinum* seagrass meadows and is studded with numerous scattered Holocene patch reefs. Most of the patch reefs are found in water depths of 2–9 m, are subcircular, elliptical, or irregular in plan view, and range up to about 8 m in vertical relief and 700 m in width. Coring has demonstrated thicknesses of 4.5–6 m and has revealed frameworks built by large, massive head corals.

## Lidar surveys

In August 2002, the Experimental Advanced Airborne Research Lidar (EAARL) system was used by NASA and the U.S. Geological Survey to survey the submarine topography of the broad swath of the reef tract seaward of Elliot Key and within Biscayne National Park (Figure 1). The NASA – USGS Airborne Lidar Processing System (ALPS) was used to interpret the EAARL laser soundings to create a spot-elevation data set that was subsequently subjected to triangulation and gridding to create a digital-elevation model (DEM) at 1-m cell resolution. Next, a 1-m-resolution slope map was constructed from the lidar-derived DEM based upon