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WHAT CORALS CAN TELL US ABOUT CLIMATE CHANGE

TEMPERATURE VARIABILITY OVER MILLENNIA

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Introduction

We are constantly being informed that the world is in the midst of a climate crisis and that current atmospheric temperatures are unprecedented. However, it is very important to consider the present situation in the context of what has occurred in the past. The public and politicians appear to have been conditioned to associate the term "climate change" with the destructive behaviour of generations of humans since the onset of the industrial revolution about 130 years ago. However, the scientific literature informs us that climate change is a natural phenomenon that has occurred over thousands of years and there is no reason to believe that this process is not ongoing. Studies of corals can contribute to our knowledge and understanding of these natural processes that are contributing to current climate change and also enable us to quantify the contribution from human activities.

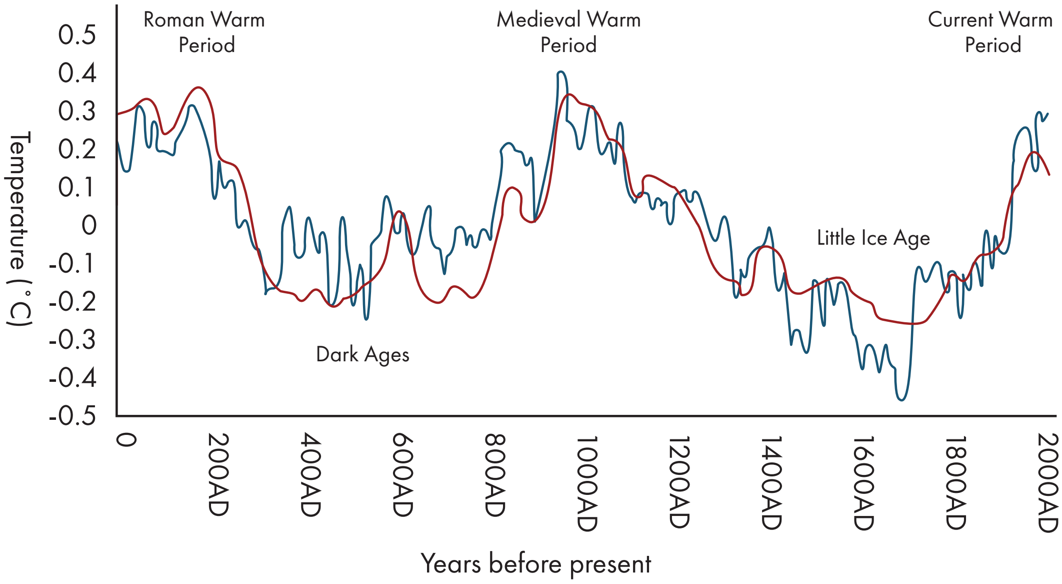
Records of past temperatures

Instrumental temperature records measured with thermometers are, at best, limited to about the past 200 years, and are available for only a few European locations. Paleoclimatology is the study of the weather and climate from past ages. The word is derived from the Greek root word "paleo-," which means "long ago" combined with "climate". Paleoclimate records can give us valuable information about climatic conditions on earth over hundreds, thousands and millions of years. These records have been derived from a wide variety of natural sources including tree rings, marine sediments, lake sediments, ice cores, speleothems (stalagmites and stalactites found in caves) and corals. The data that can be derived from these sources are referred to as proxy-records. The scientific literature now has hundreds of published paleoclimate studies from many locations around the world, many focussing on temperatures, with particular emphasis on the past 1,000 to 2,000 years.

Individual proxy temperature records correspond to specific locations such as might be obtained from individual trees in a forest or stalagmites from a particular cave. The duration of the proxy record generated from a study is very variable and may range from a few hundred years to thousands of years. An important objective is to generate reliable continuous records of temperature for a region, a hemisphere or globally over the past 1,000 to 2,000 years. Individual proxy records presently available do not uniformly cover the earth's surface. The majority are terrestrial temperature records from the northern hemisphere and are concentrated in certain regions, particularly Europe, North America and China. Combining the available individual records representing an unevenly distributed input of geographical and temporal temperature data is complex and has led to some notable divergences in the interpretation of results obtained and published during the past two decades (Christiansen and Ljungqvist, 2017).

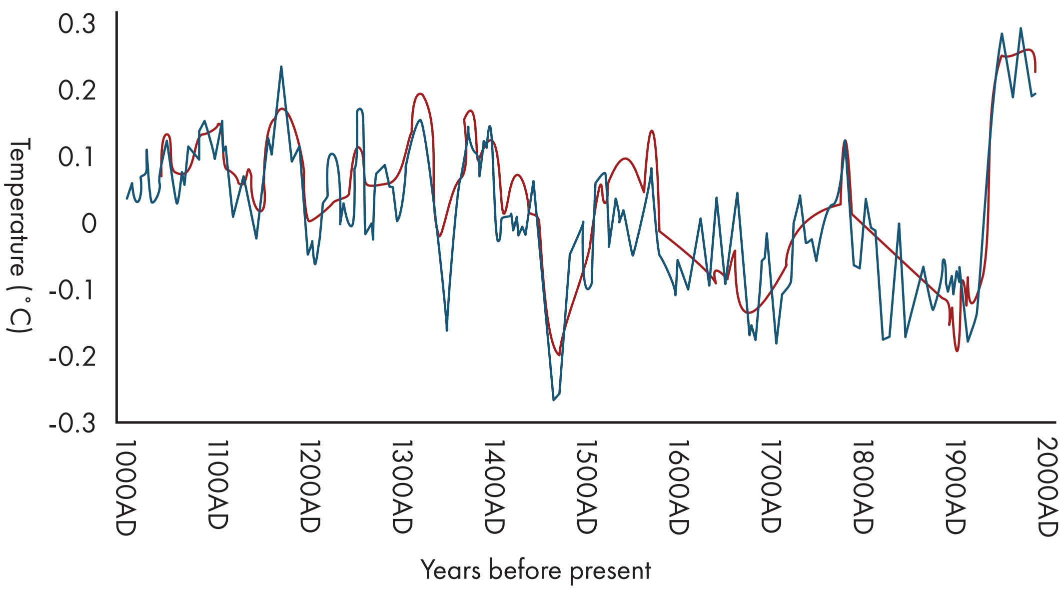
As an illustration, Figure 1 is based on composite proxy temperatures published by Ljungqvist in 2010 using extra-tropical temperature information from a combination of historical documentary records, seafloor sediment records, lake sediment records, speleothem records, ice-core records, varved thickness of sediment records, tree-ring widths and maximum latewood density records. The proxy temperature record extends over the past 2,000 years and clearly shows the Current Warm Period (CWP), the Little Ice Age (LIA), the Medieval Warm Period (MWP), the Dark Ages (DA) and the Roman Warm Period (RWP). Maximum temperatures reached during the CWP appear comparable to those in MWP and RWP and are not unprecedented in the past 2,000 years.

Figure 1. Proxy temperature profile for the northern hemisphere using results from Ljungqvist.



Studies by Mann, Bradley and Hughes and others during the past two decades (Mann et al., 1999) have generated an alternative representation of global and northern hemisphere temperatures that have been widely publicised and colloquially often referred to as "the hockey stick", illustrated in Figure 2. These reconstructions exhibit a slow long-term cooling trend downward trend from about 1000 AD (the ice hockey stick) to about 1900 AD, followed by relatively rapid warming in the 20th century (the blade), with the instrumental temperature record by 2000 AD exceeding earlier temperatures during the previous 1,000 years. According to the temperature profile in Figure 2, current temperatures exceed those at any time during the past 1000 years. The rapid rise in temperature since 1900 has been attributed mainly to anthropogenic factors, primarily greenhouse gas emissions.

Figure 2. Proxy temperature profile generated using results from Mann et al., showing an example of the hockey stick profile.



Part of the controversy has focussed on whether there are clearly identifiable features such as the LIA and the MWP in climate records, how extensively these were experienced across the globe, and whether current temperatures are comparable to those in MWP. Another linked issue is to what extent there are repeating natural cycles in the climate records. If there are indeed repeating natural cycles, these may explain, at least part, the rise in temperature seen over the past century. (Abbot, 2021)

Global- and regional-scale climate reconstructions of last millennium's temperature changes are largely based on terrestrial paleoclimate proxy data such as tree rings and ice cores. However, 70% of the Earth's surface area is ocean, and changes in oceanic circulation and associated latent and sensible heat fluxes cause and respond to global-scale climate variations. Reconstructions of climate derived from marine paleoclimate data are therefore very important in assessing climate variations associated with the ocean and providing more reliable records of temperature profiles for the whole planet. Climate records, including temperatures generated from studies of corals are therefore very important in contributing to this information.

Corals and coral reefs

Coral reefs are formed by colonies of very small animals known as coral polyps that secrete the structural material composed of the minerals calcite or aragonite which are forms of calcium carbonate $CaCO_3$, available to the polyps in the oceanic waters (Russel, 2020). Each polyp has a stomach with an opening, called the mouth, surrounded by a circle of tentacles. The polyp uses these tentacles for defence, to capture small animals for food, and to clear away debris. Food enters the stomach through the mouth and waste products are expelled through the same opening. Most corals feed at night, capturing their food by using stinging cells called nematocysts located in the polyp's tentacles and outer tissues.

With the passage of time, the coral polyps migrate towards the surface of the reef so that it expands by adding successive layers of calcite. Most stony corals have small polyps between 1 to 3 millimetres in diameter, but entire colonies can grow very large, weighing several tonnes. The skeletons of stony corals are secreted by the lower portion of the polyp. This process produces a cup in which the polyp sits. Periodically, a polyp will lift off its base and secrete a new basal plate above the old one, creating a small chamber in the skeleton. While the colony is alive, $CaCO_3$ is deposited, adding partitions and elevating the coral. As they grow, these reefs provide structural habitats for hundreds to thousands of different vertebrate and invertebrate species.

The coral polyps have a symbiotic relationship with a type of algae that depends on sunlight for photosynthesis (Russel, 2020). Corals that build reefs can survive in a rather narrow range of environmental conditions, requiring the warm ocean waters found in the tropics and sub-tropics and clear shallow water that permits enough sunlight to penetrate to allow the algae to grow. As coral reefs are only found in low-latitude oceans, proxy records from corals compliment records from other sources such as ice cores and tree rings that are available for high-latitude locations. In addition to stony, shallow-water corals that build reefs and have been extensively studied in the context of climate change, there are also soft corals and deep water corals that live in dark cold waters.

Annual growth rates of coral

Massive stony corals of the genera *Porites*, *Pavona*, and *Montastraea* are most commonly used for paleoclimatic studies because they form large mounding colonies with distinct annual bands and they can grow for several hundred years. Annual growth rates of corals can be inferred from the annual density-band pattern and can provide a paleoclimatic record. Coral growth rates can reflect diverse environmental parameters including temperature, nutrient or food availability, water transparency, and sediment input. Although the annual banding patterns are sometimes evident through visual inspection, in many cases X-ray imaging is required in order to clearly differentiate the bands.

Obtaining climate and environmental records from corals can be a costly and time-consuming exercise. Continuous records of past climate are obtained by extracting a core from an individual massive coral along its major axis of growth. The first requirement is to locate suitable large corals and extract a sample, using specialized coral coring equipment and suitably qualified scuba divers,

Typically, this involves drilling a corer through the top centre of the coral head to its initial point of growth. The extracted core is cut along its length into slabs about 1 cm in thickness, cleaned with water, dried, and then X-rayed. X-ray images reveal the banding patterns that are used to establish a chronology for the coral. In some cases, the X-rays serve as environmental proxies in and of themselves. In a few cases, composite records have been made by using multiple cores to extend the record length beyond that available from a single core.

Three coral growth characteristics that can be measured non-destructively are linear extension rate, average annual skeletal density and, the product of these, the mass of calcium carbonate skeleton deposited per year or calcification rate.

Environmental variables from examination of the coral core

It is possible to obtain a diverse range of environmental variables from the coral core by measuring different characteristics of the samples. Although replication is fundamental to generating reliable proxy climate records, it is often difficult to locate many similar-sized large coral colonies on a particular reef. This can be contrasted with obtaining samples from land-based trees for analysis of growth rings where many trees are often readily available within an accessible area. Table 1 shows examples of environmental variables potentially available from studies of coral and the chemical or physical measurements with which they have been associated (Eakin, 2006).

Table 1: Environmental variables potentially available from coral proxies.

Environmental variable	Proxy
Ratios of isotopes	
Sea surface temperature, sea surface salinity	ratio of stable isotopes oxygen-18 (^{18}O) and oxygen-16 (^{16}O) ($\delta^{18}O$)
Light	ratio of stable isotopes carbon-13 (^{13}C) and carbon-14 (^{14}C) ($\delta^{13}C$)
Ocean ventilation	Change in radiocarbon ^{14}C levels ($\Delta^{14}C$)
pH	boron isotope ratio ($^{11}B/^{10}B$) $\delta^{11}B$
Ratios of trace elements	
Sea surface temperature	strontium/calcium (Sr/Ca)
Sea surface temperature	uranium/calcium (U/Ca)
Sea surface temperature	*magnesium/calcium (Mg/Ca)*
Wind anomalies, upwelling	manganese/calcium (Mn/Ca)
Upwelling	cadmium/calcium (Cd/Ca)
Upwelling, river outflow	barium/calcium (Ba/Ca)
Skeletal properties	
Sea surface temperature, light (seasonal changes), stress, water motion, sedimentation,	Skeletal growth bands
River outflow	Luminescence

During the 1970s it was discovered that there was a regular seasonal alternation in the density of calcium carbonate of coral skeletons leading to studies generating records of coral skeletal growth (sclerochronology) to show the variations in environmental conditions. The discovery of alternating dense and less dense bands in such massive corals and their demonstration as annual (Knutson et al., 1972) opened the door to the 'vast storehouses of information about chemical and physical waters in which they grew' (Moore and Krishnaswami, 1974).

Although sclerochronology continues to be used for some applications, most paleoclimatic investigations of coral now rely on geochemical analysis, particularly through measuring ratios of trace elements and isotopes (Eakin, 2006). Current paleoclimatic records are based on $\delta^{18}O$, Sr/Ca, or $\Delta^{14}C$ determinations in modern corals and do not extend back beyond the year 1500 AD. This is due to the fact that most still growing massive corals which can be found in the modern reefs are not older than about 100 to 500 years.

Sea surface temperatures from coral cores

Large corals suitable for paleoclimatic reconstructions are usually limited to depths of about 20m so that these records reflect near-surface ocean conditions. Sea surface temperatures (SSTs) can be reconstructed from coral using each of the three categories shown in Table 1, ratios of isotopes, ratios of trace elements and the skeletal growth of the bands.

Isotopic ratios, particularly $\delta^{18}O$ have been used in conjunction with various proxies to measure past temperatures., including ice cores, spleothems and corals. The isotopic ratio $\delta^{18}O$ represents the ratio of the oxygen isotopes oxygen-18 (^{18}O) and oxygen-16 (^{16}O). Oxygen-16 is a stable isotope of oxygen, having 8 neutrons and 8 protons in its nucleus. Oxygen-16 is the most abundant isotope of oxygen and accounts for 99.76% of this element's natural abundance. Oxygen-18 is a natural, stable isotope of oxygen having 10 neutrons and 8 protons.

The isotopic ratio $\delta^{18}O$ has the longest history as a temperature proxy from corals (Grottoli and Eakin 2007). Unfortunately, coral skeletal $\delta^{18}O$ is influenced by both water temperature and salinity, and is therefore not a pure indicator of temperature. This confounding influence is minimized when the relative contribution from either salinity or temperature variability is low or the two variables combine to increase the change in coral $\delta^{18}O$. In contrast, elemental Sr/Ca ratios are not influenced by salinity, and fortunately, improvements in instrumentation have made the application of strontium to calcium ratios (Sr/Ca) in coral skeletons a practical alternative to $\delta^{18}O$.

Examples of SST reconstructions from corals

Many examples of measurements coral characteristics have been made available at the NOAA database, some of which have been interpreted as proxy temperature records. Most of these records extend back only for 100-200 years and are based on measurements from samples from live corals. For example, Zinke et al (2015) used elemental analysis (Sr/Ca) to construct a SST record for the past 200 years based on coral samples from several sites along the Western Australian coastline including Bundegi Ningaloo Reef, Clerke Reef, Imperieuse Reef and Mermaid Reef. As illustrated in Figure 3, this shows a trend of increasing SST from 1790 through to 2010. It is apparent that the rate of temperature increase between 1790 and 1890 AD is similar to that between 1890 and 2010AD suggesting the rate of change has not increased significantly with the onset of the industrial era.

Figure. 3. Variation in SST during the period 1795-2010 AD constructed using corals from coastal Western Australia also showing the trend of increasing temperature.

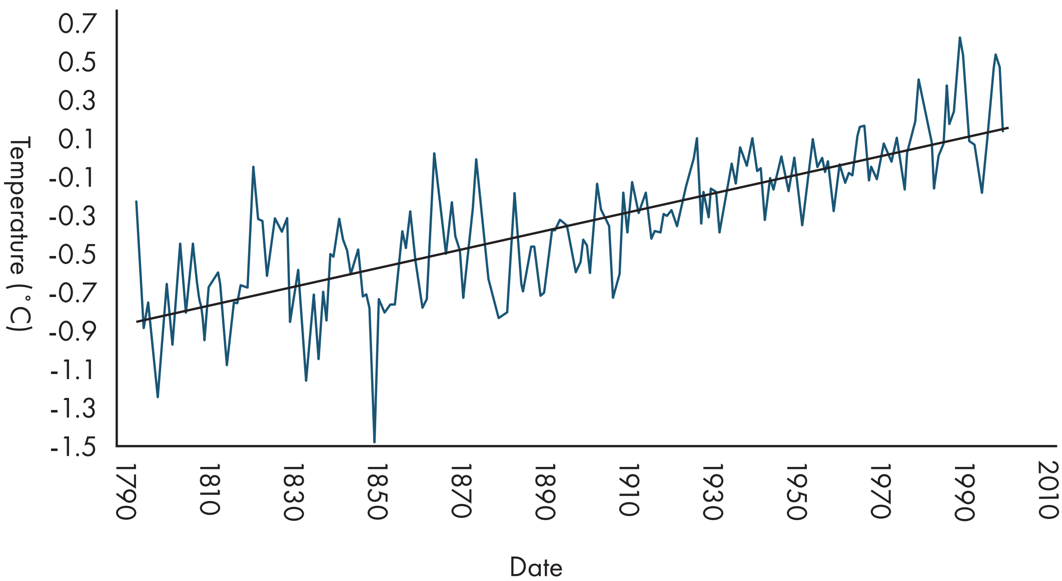
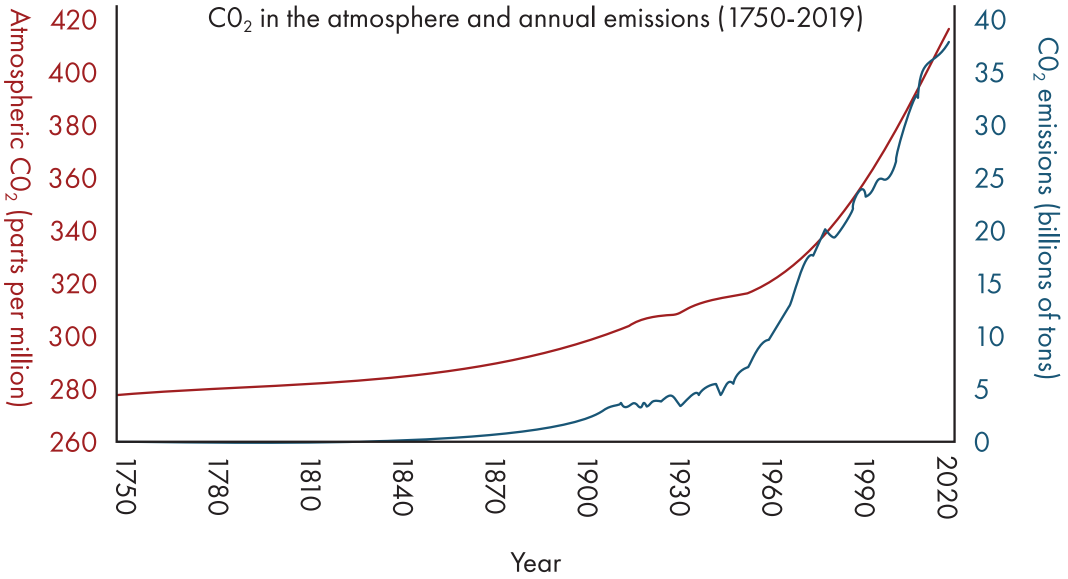


Figure 4 shows the concentrations of atmospheric carbon dioxide, the major greenhouse gas, and annual emissions between 1750 and 2019 AD. Between 1790 and 1890 AD atmospheric carbon dioxide increased only by about 10ppm, whereas between 1890 and 2010 AD it increased by about 115ppm. Influences other than carbon dioxide would appear to be causing SST increase in the pre-industrial era. Also, the exponential rate of growth in atmospheric CO_2 is not reflected in an increasing rate of SST increase during the industrial era.

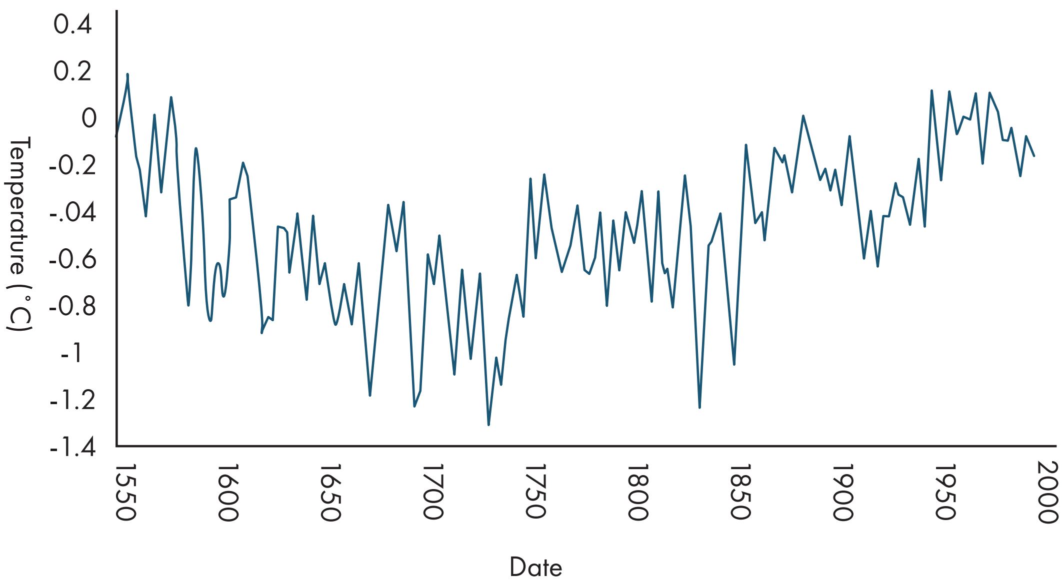
Figure 4. Atmospheric carbon dioxide levels between 1750 and 2019 (Lindsey, 2020).



NOAA Climate.gov. Data: NOAA, ETHZ, Our World in Data.

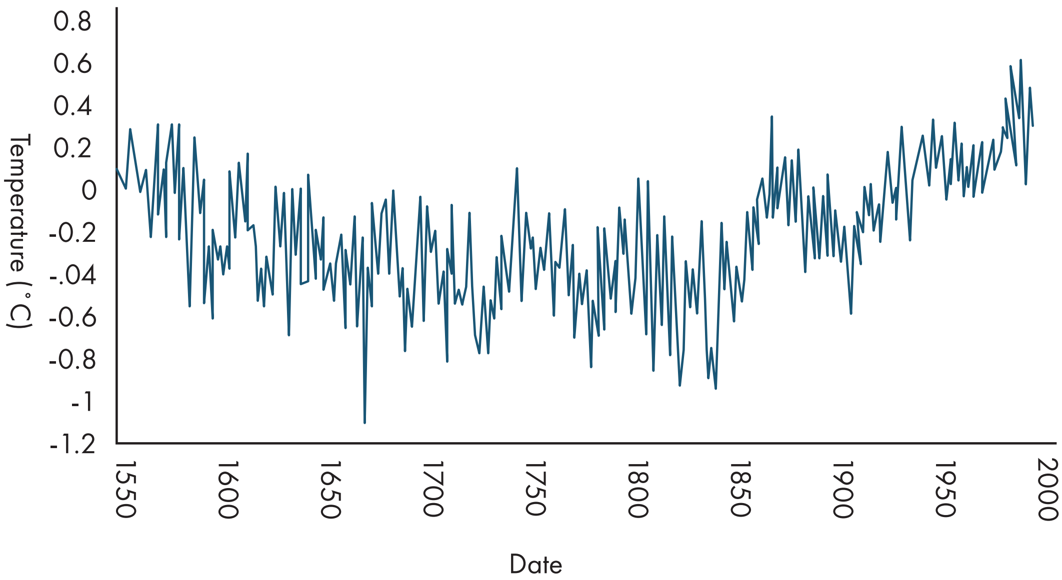
Saenger et al (2009) have presented a continuous annually resolved proxy record of Atlantic SST spanning several centuries from 1550 AD by examination of a massive *Siderastrea siderea* coral collected from the Bahamas in 1991. Using computed axial tomography (CAT) imaging, they quantified temperature-dependent variations in the annual growth of the coral. They first established the relationship between skeletal band growth and SST for this coral over the full instrumental record (1857–1991). Figure 5 shows the variation in SST with time using data made available at the NOAA database. The temperature profile is consistent with falling SST from 1550 reaching a minimum around 1750 during the Little Ice Age, then increasing moving towards the Current Warm Period.

Figure 5. Variation in SST since 1550 AD using massive *Siderastrea siderea* coral from the Bahamas.



Tierney et al. (2015) generated a SST record for the tropical western Atlantic using nine records derived from coral including samples from the Bahamas and coastal Florida. The record spans the period from 1552 to 2009 using elemental (Sr/Ca), isotopic ($\delta^{18}O$) and skeletal growth rates. The proxy record shows a decreasing temperature to about 1800 AD, then increasing SST as shown in Figure 6. Again the temperature profile shown is consistent with falling SST from 1550 AD moving into the LIA, then increasing from about 1800AD moving into the Current Warm Period.

Figure 6. Variation in SST since 1550 AD using coral from the tropical Western Atlantic



Evidence for MWP and LIA in coral records

In considering whether Figure 1 (Ljungqvist) or Figure 2 (Mann) is a better representation of northern hemisphere temperatures, an important consideration is whether there are clearly identifiable MWP and LIA features in temperature records during the past 1,000 years (Broecker, 2001). A review in 2003 by Soon and Baliunas of proxy climatic and environmental changes of the past 1,000 years examined more than 120 examples published between 1975 and 2002. These included regional and worldwide proxy records for both northern and southern hemispheres. A total of 107 studies indicated there was a discernible climatic anomaly during the MWP (800 AD–1300 AD) in the proxy record, whereas only six indicated this was absent. 123 studies indicated there an objectively discernible climatic anomaly during the LIA interval (1300 AD–1900 AD) in the proxy record, whereas only one reported this was absent. Continuous records of temperature from corals generally extend back a few hundred years. However, Figures 3, 4 and 5 show a minimum which can be identified with LIA.

It is possible to investigate SST variations over much longer periods of time than illustrated above, where only live corals were studied to generate proxy temperature records of up to several hundred years. This can be achieved by also including fossil corals in the study. For example, in a study by Deng et al. (2017) one modern coral and four fossil coral cores were extracted using an underwater pneumatic drill from five *Porites lutea colonies*, with diameters of 0.5–1.5 m, from water depths of 4–6 m on fringing reefs at Qionghai in the northern South China Sea. Fossil coral samples were dated in the ranges 1129–1255 AD and 1063–1087 AD, corresponding to the Medieval Warm Period, and 1628–1657 AD, and 1702–1772 AD corresponding to the Little Ice Age. SSTs were derived from geochemical records from coupled elemental Sr/Ca and isotopic $\delta^{18}O$ measurements. The average long-term annual SST during the LIA was about 1.58°C lower than that of the CWP in the northern South China Sea. The results indicated that temperatures of the Medieval Warm Period (900–1300 AD) was similar to that of the Current Warm Period.

Corals also provide evidence for variations in SST on a much longer time scale through a large part of the Holocene, which extends back over the past 12,000 years (Felis and Pätzold, 2003). Skeletal elemental Sr/Ca and isotopic $^{18}O/^{16}O$ ratios in corals from the Great Barrier Reef indicate that the tropical ocean surface ~5,350 years ago was 1°C warmer than present (Gagan et al., 1998). A coral from Vanuatu which grew ~4,150 calendar years ago provides a 47-year record of SST variability based on coral elemental ratios Sr/Ca and U/Ca (Corrège et al. 2000) suggesting that SSTs in the southwest tropical Pacific during the mid-Holocene were comparable to modern SSTs.

Oscillatory behaviour in temperature records

Records of past temperatures can be represented by sets of oscillations that can occur on decadal, centennial and millennial time scales (Abbot and Marohasy, 2017). For example, the multi-proxy temperature profile in Figure 1 can be decomposed into a set of sine waves comprising a dominant millennial oscillation (1,230 years), centennial oscillations (383, 149, 128 and 106 years) and decadal oscillations (81, 76 years). Oscillations with decadal periodicities (70 year and 22 years) have been identified in coral records extending over several centuries (Felis and Pätzold, 2003). Spectral analysis of the SST record for the Bahamas in Figure 5 showed evidence for oscillations with centennial (468, 182 and 106 years) and decadal (62 and 19 years) periodicities.

Identification of persistent oscillations in temperature records is important as it can enable forecasts of temperature into the industrial era based on oscillatory patterns in the pre-industrial era dominated by natural phenomena influencing climate. For example, based on analysis of oscillatory patterns prior to 1880 AD extending though the previous 1,000 to 2,000 years it can be shown that temperature increases during the past 100 years are likely to be primarily a continuation of natural cycles. It is important to further investigate these oscillatory processes using information from corals to advance the representation and understanding of temperature changes in the oceans.

Conclusion

Studies of corals can contribute important information on recent and past climatic conditions. An evolving area of investigation has been the use of corals in different parts of the world to provide records of past temperatures. These records can reveal the changes in sea surface temperatures, particularly in the tropical regions. Records show that SST temperatures have been increasing since about 1790 AD after a period of decline of at least several centuries. This fits with temperature profiles that show evidence for the Little Ice Age, approximately during the period of 1600-1800 AD, following a relatively warm period called the Medieval Warm Period around 1000 AD, which had maximum temperatures similar to the present.

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About the author

John Abbot is a Senior Fellow with interests in environmental issues, including climate change, at the IPA.

He has a BSc in chemistry from Imperial College, London, an MSc from the University of British Columbia, Canada, a Master of Biotechnology from the University of Queensland and a PhD in chemistry from McGill University, Canada. He has spent more than 20 years as a research scientist in universities and industry working in areas of industrial chemistry, particularly relating to petroleum refining and pulp and paper production. He successfully supervised a group of about 20 PhD and Honours students at the University of Tasmania and has published more than 100 papers in the peer-reviewed scientific literature.

He obtained a Juris Doctor Law degree from the University of Queensland in 2003 and was admitted as a solicitor in Queensland. He worked for a period at Welfare Rights dealing with Centrelink issues, and also disability discrimination. He also obtained an LLM degree from the University of Queensland, specialising in intellectual property law. He has published a number of papers in legal journals, including several relating to Freedom of Information law in the context of public access to environmental information from government agencies.

During the period 2009 – 2015 Dr Abbot had an appointment at Central Queensland University as a Professorial Research fellow. A number of projects in the environmental area were undertaken, including re-examination of the evidence for an influence of pesticides on biota in rivers, and the use of diatoms to determine the salinity history of Lake Alexandrina. Other projects undertaken included the application of artificial intelligence using neural networks for medium-term rainfall forecasting. This work was initiated following the devastating flooding in Queensland during the 2010-11 summer, where flooding of Brisbane has been linked to poor dam management practices and inadequate official rainfall forecasts. These projects resulted in about 20 papers – published in the peer reviewed literature. His work at CQU was wholly funded by the B. Macfie Family Foundation, which now supports his research at the IPA.

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