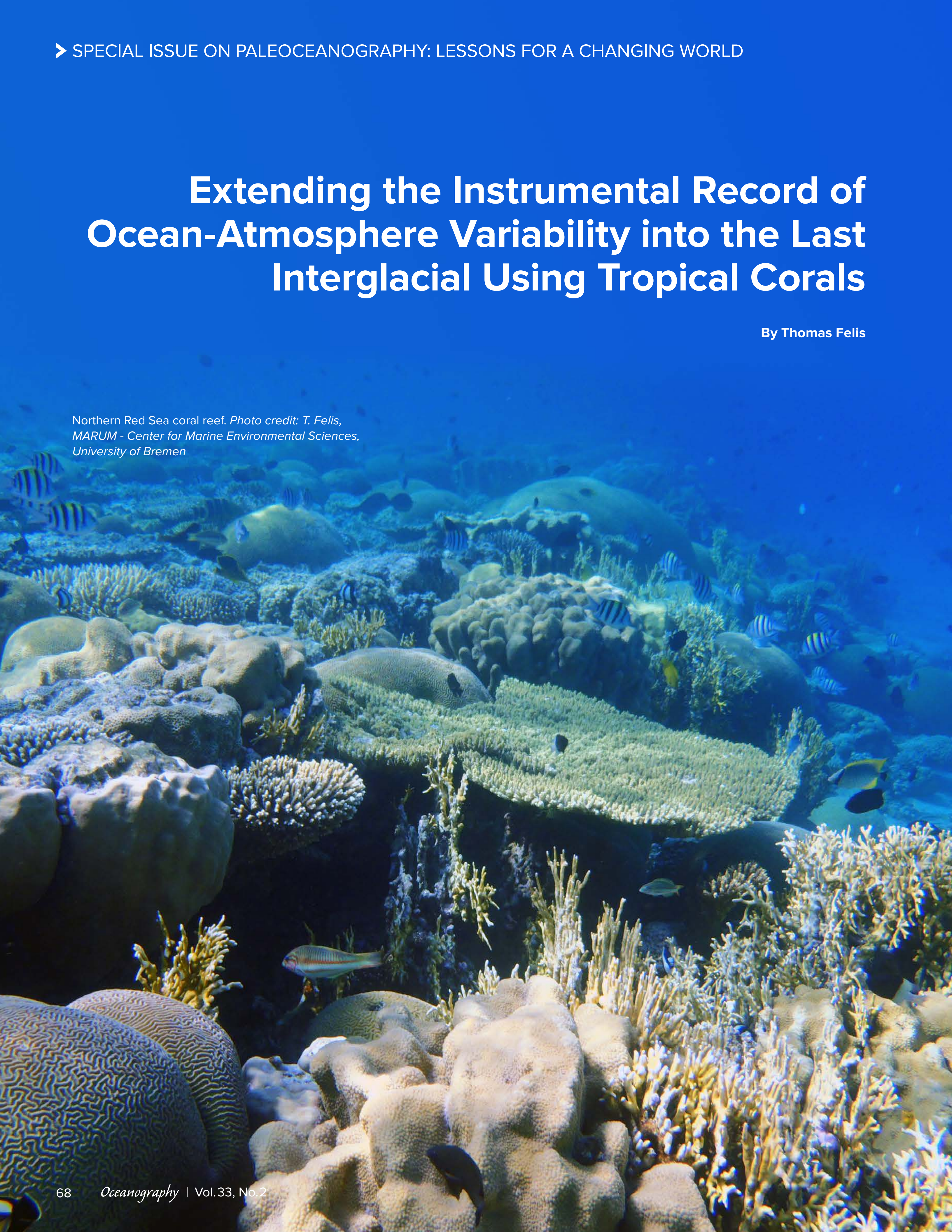
Extending the Instrumental Record of Ocean-Atmosphere Variability into the Last Interglacial Using Tropical Corals

By Thomas Felis



Northern Red Sea coral reef. *Photo credit: T. Felis, MARUM - Center for Marine Environmental Sciences, University of Bremen*

ABSTRACT. The interaction of warm tropical ocean surface waters with the overlying atmosphere on seasonal, interannual, and decadal timescales is the source of climate extremes throughout the tropics and beyond. Tropical cyclones, heatwaves, flash floods, droughts, and El Niño have severe effects on ecosystems and societies globally. Projecting their amplitude and frequency changes in a warming climate requires knowledge of how the tropical ocean-atmosphere system operated in the past. Tropical shallow-water corals have great potential for extending the short and rather sparse instrumental record of sea surface observations at monthly resolution. Coral records deliver quantitative information about the fluctuations of sea surface temperature and hydrology on seasonal, interannual, and decadal timescales, with precise chronology. They provide a paleo-observational constraint on climate model simulations of past and future tropical ocean-atmosphere variability. This article highlights selected recent achievements in coral-based reconstructions of surface ocean conditions during recent centuries, the Holocene, the last deglaciation, and the last interglacial period. Future work combining ultrahigh-resolution coral reconstructions, novel analytical techniques, advanced statistical methods, and Earth system modeling will contribute to improved projections of tropical marine climate variability and the fates of coral reef ecosystems.

INTRODUCTION

Tropical marine climate variability is an important component of the Earth system. The variability of tropical sea surface temperature and related hydrological changes have substantial climatic impacts throughout the tropics and beyond. The interaction of warm tropical ocean surface waters with the overlying atmosphere modulates global rainfall patterns and climate extremes through atmospheric teleconnections. Climate extremes originating from the tropical ocean include interannual internal climate oscillations such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) as well as tropical cyclones and hurricanes, marine heatwaves, flash floods, and severe droughts. These climate extremes have severe effects on societies, economies, infrastructures, and marine and terrestrial ecosystems globally and are broadly thought to intensify in amplitude and frequency in a warming climate.

Our current understanding of the tropical ocean-atmosphere system and related climate extremes is limited by the shortness of the instrumental record of observations. Systematic monitoring of tropical surface ocean conditions by ocean observing systems and satellites began less than 40 years ago, in the 1980s. Measurements of sea surface temperature by ships of opportunity extend back to the late to mid-nineteenth century, but they are mostly located along major shipping lanes and are sparse in key regions of intense tropical ocean-atmosphere interaction such as the equatorial Pacific. Furthermore, these ship-based observations usually do not include sea surface salinity far back in time, limiting our knowledge of surface ocean hydrological changes. Understanding tropical marine climate variability and improving insights into its responses to recent and future climate changes require a long-term perspective beyond the short instrumental record. In particular, warm climate intervals in Earth's recent geologic history as well as periods of substantial or rapid warming are of interest here. Examples of past climate conditions warmer than those of the pre-industrial (~1850 Common Era, CE) can be found during the Holocene thermal maximum (~11,000 to 5,000 years ago) and the last interglacial period (~129,000 to 116,000 years ago). Although these past warm intervals are not strict analogues for future warming because they were orbitally forced and not a result of anthropogenic change, such periods can provide insights into regional climate responses under future warming, and thus provide a paleo-observational constraint on projections of future climate change impacts (Fischer et al., 2018). Similarly, the last deglaciation (~18,000 to 11,000 years ago), an interval of changing climate following the last glacial period, can be considered a partial analogue for modern warming.

During the last decade, tropical corals have continued to evolve into a powerful archive that extends the instrumental record of oceanic sea surface observations into the pre-instrumental period. These corals grow in shallow waters of warm tropical to subtropical ocean regions. Their massive aragonitic carbonate skeletons commonly reveal annual density banding patterns similar to tree rings. Along with their growth rates of about one centimeter per year or more, these corals can create huge dome-shaped colonies with life spans that may last for centuries. Their continuous growth throughout the year allows precise analysis, using isotopic and geochemical proxies, of their carbonate skeletons for temperature and hydrology at seasonal to monthly resolution. This ultrahigh temporal resolution usually reveals annual cycles in the isotopic and geochemical proxies and enables construction of precise chronologies that can be supported by the annual density banding. Importantly, coral proxy records retrieved from living colonies overlap the instrumental record. Thus, they can be calibrated with instrumental time series of climate parameters of the tropical ocean-atmosphere system. Quantitative proxy records derived from large living coral colonies can extend the instrumental record of tropical marine climate variability back in time for centuries at monthly resolution, with associated uncertainties of reconstructed variables and based on precise chronology.

Most tropical corals have life spans of a few decades to centuries, which limits the use of living ("modern") colonies for extending the instrumental record of tropical marine climate throughout the last millennium and beyond. Using dead ("fossil") corals, for example, from the Holocene or the last interglacial is possible, but requires careful examination of their skeletal preservation. Under rare circumstances, splicing of coral proxy records derived from living and fossil colonies allows generation of longer records. More commonly, "floating" time windows are derived from fossil corals. These records provide snapshots of past ocean-atmosphere variability with precise internal chronology. The absolute age of fossil corals is established by radiometric methods such as uranium-series dating.

The seasonal to monthly resolution of coral proxy records is exceptional for a marine climate archive. The resolution of coral proxy records, along with their time span of up to centuries, permit us to truly reconstruct tropical marine climate variability in interannual to decadal ranges. Tropical climate variability plays an important role on these timescales in regional projections of recent and future climate change impacts. Furthermore, the seasonal to monthly resolution allows us to truly reconstruct tropical marine climate variability during specific seasons of the year and with respect to changes in the amplitude of the annual cycle. Tropical corals grow throughout remote regions of the tropical oceans, from equatorial waters up to the subtropics, where they provide an important source for insights into past interactions between the tropical ocean-atmosphere system and mid-latitude climate variability (Felis et al., 2004; Felis and Rimbu, 2010). This article highlights selected contributions of tropical corals to the field of paleoceanography during the last 10 years and their unique potential for extending the instrumental record of tropical marine climate observations into the more distant past. Particular emphasis is given on proxy records of tropical sea surface temperature and hydrology from paired strontium/calcium (Sr/Ca, for temperature) and oxygen isotope ($\delta^{18}O$, for temperature and hydrology) measurements in fossil corals of the Holocene, the last deglaciation, and the last interglacial period. For more comprehensive, traditional reviews of various aspects of coral paleoclimatology, see Lough (2010), Sadler et al. (2014), and Saha et al. (2016).

TROPICAL SEA SURFACE TEMPERATURE, EL NIÑO, IOD, AND MARINE HEATWAVES

Tierney et al. (2015) reconstruct tropical sea surface temperatures at annual resolution for the past four centuries from an extensive network of modern coral records. This study, conducted within the Past Global Changes (PAGES) Ocean2K project, suggests that the tropical oceans were cooling until modern warming began around the 1830s CE, especially during the early 1800s CE when there was an exceptionally cool period in the Indo-Pacific region. This coral-based reconstruction of tropical sea surface temperatures was key to the finding of the relatively early onset of industrial-era warming across the ocean and continents (Abram et al., 2016). Decadal-scale variability was determined to be a quasi-persistent feature of all tropical ocean basins, but no evidence was found that either natural or anthropogenic forcings have altered ENSO-related interannual variability in tropical sea surface temperatures (Tierney et al., 2015).

Coral-based reconstructions of Pacific sea surface temperature seasonality and ENSO strength provide fundamental constraints on tropical climate dynamics and may ultimately lead to improved climate model projections of ENSO-related climate extremes under greenhouse warming (Emile-Geay et al., 2016). The two major El Niño event types differ in their impacts on regional temperature and precipitation extremes at a global scale. A higher frequency of central Pacific El Niño events and fewer but more intense "traditional" eastern Pacific El Niño events in recent decades relative to the past four centuries were detected in a tropical coral network by exploiting the seasonal resolution of the coral proxy records (Freund et al., 2019). Climate model simulations suggest sensitivity of ENSO to large volcanic eruptions via aerosol forcing. However, records of modern and fossil corals of the central equatorial Pacific do not reveal a consistent ENSO response to volcanic forcing over the last millennium, suggesting that some models may overestimate the forced response relative to natural ENSO variability (Dee et al., 2020). An extension of the ENSO proxy record over the past 7,000 years using snapshots provided by modern and fossil corals of the central equatorial Pacific (Cobb et al., 2013) suggests that ENSO variability over the last five decades was stronger than during the preindustrial era and relatively weak between 3,000 and 5,000 years ago (Grothe et al., 2019). During this mid-Holocene interval of weak ENSO variability, an enhanced annual cycle and delayed seasonal growth was found in a 175-year-long coral record from the central equatorial Pacific from ~4,300 years ago (McGregor et al., 2013).

The Pacific trade winds are an important component of the tropical ocean-atmosphere system and ENSO. These trade winds can modulate global temperatures. Seasonally resolved records of manganese/calcium (Mn/Ca) in tropical Pacific corals from atolls with west-facing lagoons were shown to offer a promising proxy for westerly wind strength, and suggest that early twentieth-century warming was linked to weakening of tropical Pacific trade winds (Thompson et al., 2015). The relationship between trade winds, tropical Pacific temperature, and global temperature may allow reconstructions of tropical Pacific wind strength from coral Mn/Ca to provide important constraints on projections of global temperature evolution under greenhouse warming (Thompson et al., 2015).

The western Indian Ocean has been warming faster than any other tropical ocean during the twentieth century and is the largest contributor to the rise in global mean sea surface temperature. An annually resolved reconstruction of sea surface temperature from a set of western Indian Ocean coral records shows that a methodological bias, the so-called World War II bias, is the main reason for the differences between the various products of instrumental sea surface temperature observations and that it affects western Indian Ocean as well as global mean temperature trends (Pfeiffer et al., 2017). Such multi-coral reconstructions may help in evaluation of different sea surface temperature products as they are truly independent from historical ship-based observations (Pfeiffer et al., 2017).

The IOD causes hydrological extremes in regions surrounding the Indian Ocean. A proxy record of the IOD over the last millennium based on snapshots provided by modern and fossil corals of the eastern equatorial Indian Ocean demonstrates that extreme positive IOD events were rare before 1960 CE, but that at least one event larger than the most extreme event observed in the instrumental record occurred during the seventeenth century (Abram et al., 2020). The identification of extreme IOD variability, persistent tropical Indo-Pacific climate coupling, and a tendency toward clustering of positive IOD events in the reconstruction may improve projections at seasonal and decadal timescales that will help to improve management of the climate risks associated with future IOD variability in a warming world (Abram et al., 2020).

Increasing intensity of marine heatwaves has caused widespread mass coral bleaching events. An annually resolved reconstruction of sea surface temperature for the past two centuries from multiple southeastern Indian Ocean corals demonstrates the important role of coupling between the western and central Pacific in amplifying thermal stress in the southeastern Indian Ocean (Zinke et al., 2015). Multi-century coral reconstructions provide a long-term perspective on the regional impacts of large-scale climate coupling between ocean basins, which may lead to improved projections of extreme heatwaves and their ecological impacts on coral reef ecosystems at regional scales (Zinke et al., 2015).

The monsoon systems are of critical importance to the densely populated areas of South Asia as they control the amount and intensity of precipitation as well as the severity of winters in some regions. An annually resolved reconstruction of the East Asian Monsoon based on radiocarbon measurements in a coral of the South China Sea suggests a long-term decline in both summer and winter monsoon variability since the sixteenth century (Goodkin et al., 2019). Coral proxy records from the rim of continental Asia, for example, the South China Sea (Goodkin et al., 2019) and the northern Red Sea (Felis and Rimbu, 2010), have the potential to provide insights into past interactions between tropical marine and higher latitude continental climate variability.

> "Ultrahigh-resolution coral proxy records provide a powerful tool for reconstructing past tropical marine climate and environmental variability and for understanding the temporal response of corals and coral reefs to ongoing climate and environmental changes."

Most centuries-long coral records are based on $\delta^{18}O$, a proxy that reflects both the temperature and the $\delta^{18}O$ of the surrounding seawater. This dual control can complicate the interpretation of coral $\delta^{18}O$ records in terms of temperature through space and time. Furthermore, although seawater $\delta^{18}O$ is thought to be closely related to salinity, the two variables have a complicated relationship that can vary with time and location. Proxy system models, also known as proxy forward models (Dee et al., 2015; Lawman et al., 2020), can improve the interpretation of coral $\delta^{18}O$ records and better quantify their uncertainties. Paired with isotope-enabled climate model simulations, they can be used to investigate the dynamics of seawater $\delta^{18}O$ and salinity variations in relation to coral $\delta^{18}O$ in different climate regimes (Dee et al., 2015; Stevenson et al., 2018).

Centuries-long coral records based on Sr/Ca, a proxy thought to solely reflect temperature, are becoming increasingly available (DeLong et al., 2012). Other temperature proxies that are increasingly analyzed in coral skeletons for longer time intervals include uranium/calcium (U/Ca; Felis et al., 2009), lithium/calcium (Li/Ca) and lithium/magnesium (Li/Mg; Hathorne et al., 2013a), as well as a combination of the Sr/Ca and U/Ca proxies termed strontium-uranium (Sr-U; DeCarlo et al., 2016). When paired with coral $\delta^{18}O$ measurements, temperature proxies such as Sr/Ca and U/Ca provide tools for reconstructing changes in seawater $\delta^{18}O$ in the surface ocean (Felis et al., 2009), a hydrologically relevant variable that reflects oceanic processes as well as variations in hydroclimate. Such coral-based seawater $\delta^{18}O$ reconstructions are considered to be an important source of information on hydroclimatic changes for the vast areas of the tropical to subtropical oceans during the pre-instrumental period. They can be used, in combination with terrestrial hydroclimate archives and climate model simulations, to constrain future hydroclimatic risks estimated from climate model projections (PAGES Hydro2k Consortium, 2017).

SURFACE OCEAN FRESHENING DURING THE LAST CENTURIES

Annually resolved reconstructions of seawater $\delta^{18}O$ changes over recent centuries derived from paired coral Sr/Ca and $\delta^{18}O$ records provide indications for transitions toward fresher surface conditions since the mid-nineteenth century in regions of the tropical to subtropical Indo-Pacific

(PAGES Hydro2k Consortium, 2017). In the subtropical northern Red Sea (Ras Umm Sidd) and western North Pacific Ocean (Ogasawara), apparent regime shifts toward fresher conditions occurred relatively abruptly within about five years after 1850 CE and 1905 CE, respectively (Felis et al., 2009, 2018; **Figure 1**). At both sites, an increase in regional precipitation could be excluded as a cause of the reconstructed surface ocean freshening. While a change in surface evaporation driven by a reorganization of the atmospheric circulation over Europe at the end of the putative Little Ice Age provides a likely explanation for the arid northern Red Sea (Felis et al., 2018), a change in the Kuroshio Current system and associated westerly winds likely played a role in the western North Pacific (Felis et al., 2009). Reconstruction of seawater $\delta^{18}O$ changes from paired measurements of $\delta^{18}O$ and Sr/Ca, U/Ca, or other element/Ca temperature proxies in corals can provide unprecedented insights into the past dynamics of surface ocean hydrology at annual and higher resolution. These reconstructions have the potential to reveal surprises regarding abrupt changes and unexpected trends even during the last century for which instrumental observations of hydrologically relevant variables such as salinity are sparse. In tandem with corresponding temperature reconstructions (Felis et al., 2010), seawater $\delta^{18}O$ reconstructions may provide a comprehensive understanding of ocean-atmosphere variability at seasonal and interannual to decadal timescales, including the dynamics of ocean to land moisture transport and related hydrological extremes. The PAGES CoralHydro2k

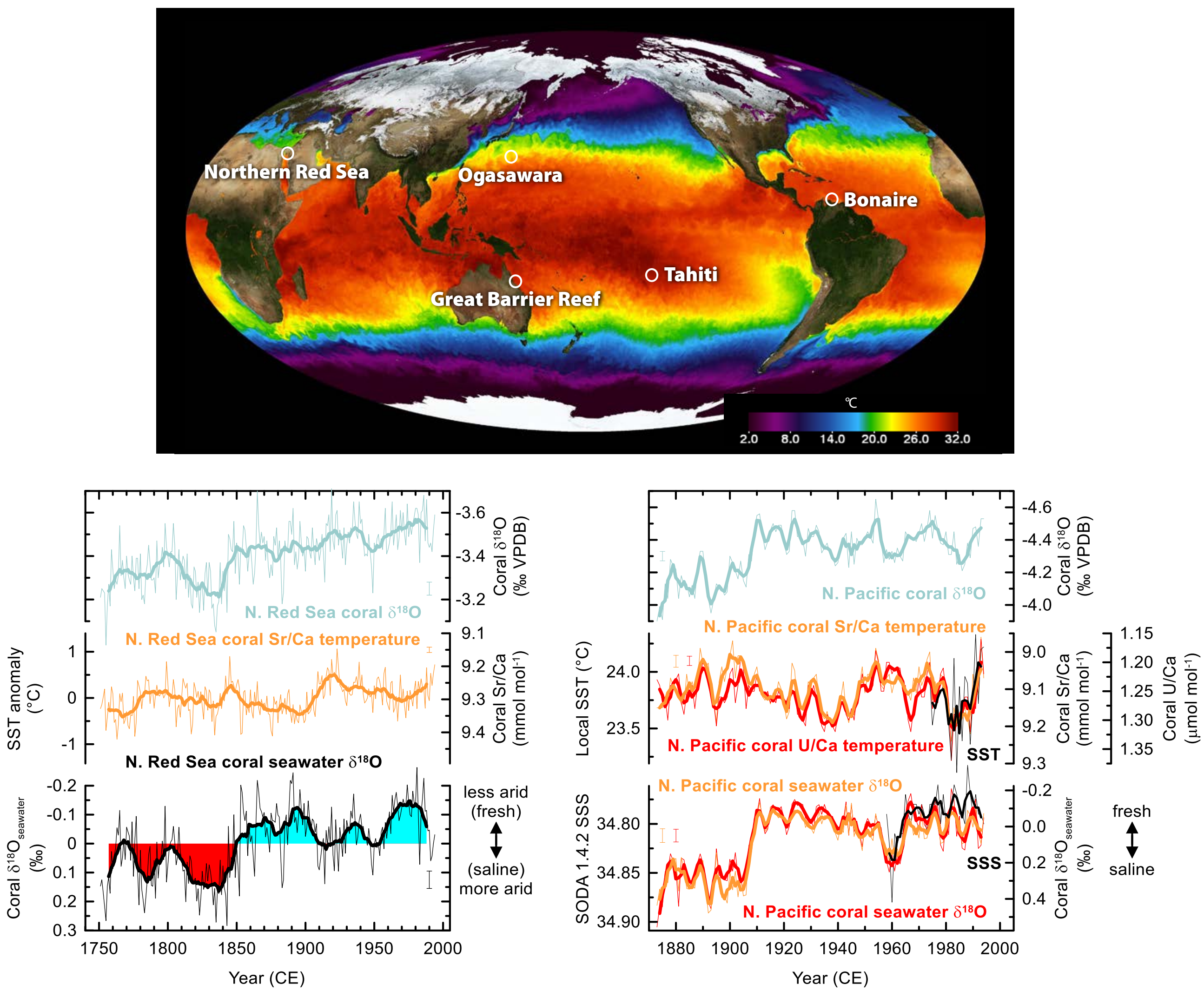


FIGURE 1. (top) Selected tropical and subtropical sites of coral paleoclimate work in the Indo-Pacific and Atlantic Oceans discussed in this paper are indicated on a map showing the multi-scale ultrahigh-resolution (MUR) sea surface temperature (SST) analysis from NASA/Goddard Space Flight Center (downloaded from https://svs.gsfc.nasa.gov/30008). The graphs show annual average proxy records of subtropical sea surface temperature and hydrology during recent centuries derived from bimonthly resolved Sr/Ca (and U/Ca) and $\delta^{18}O$ measurements in modern corals (*Porites* spp.) of (bottom left) the northern Red Sea (Ras Umm Sidd; Felis et al., 2018) and (bottom right) the western North Pacific (Ogasawara; Felis et al., 2009). The corresponding seawater $\delta^{18}O$ reconstructions suggest abrupt shifts toward fresher conditions after 1850 CE and 1905 CE. Bold lines are 13-year (northern Red Sea) and three-year (western North Pacific) running averages. *Modified from Felis et al. (2009) and Felis et al. (2018)*

project is a new initiative toward encouraging employment of paired Sr/Ca and $\delta^{18}O$ measurements in corals for reconstructing tropical ocean hydroclimate and temperature during recent centuries (Hargreaves et al., 2020).

HOLOCENE AND LAST INTERGLACIAL TROPICAL ATLANTIC TEMPERATURE VARIABILITY

The tropical Atlantic Ocean plays a fundamental role in the modulation of ocean-atmosphere variability on interannual to decadal timescales throughout the basin and adjacent continental areas. The tropical Atlantic is the source of severe climate extremes such as hurricanes, floods, and droughts. Proxy records of tropical North Atlantic sea surface conditions for time intervals back to the mid-Holocene and during the last interglacial provided by fossil corals of the southern Caribbean (Bonaire) allow unprecedented insights into the pre-instrumental period at monthly resolution (Giry et al., 2012, 2013; Felis et al., 2015; Brocas et al., 2016, 2018; Wu et al., 2017). The paired coral Sr/Ca and $\delta^{18}O$ records indicate pronounced interannual to decadal variability as well as longer-term trends in tropical Atlantic sea surface temperature and hydrology during the late to mid-Holocene and the last interglacial (Figure 2). The records show some tendency for a positive relationship on these timescales when interpreted as temperature and salinity variations. Quasi-biennial variability is a persistent feature in many records. Pronounced interannual variability at typical ENSO periods ~2,350 years ago could be indic-

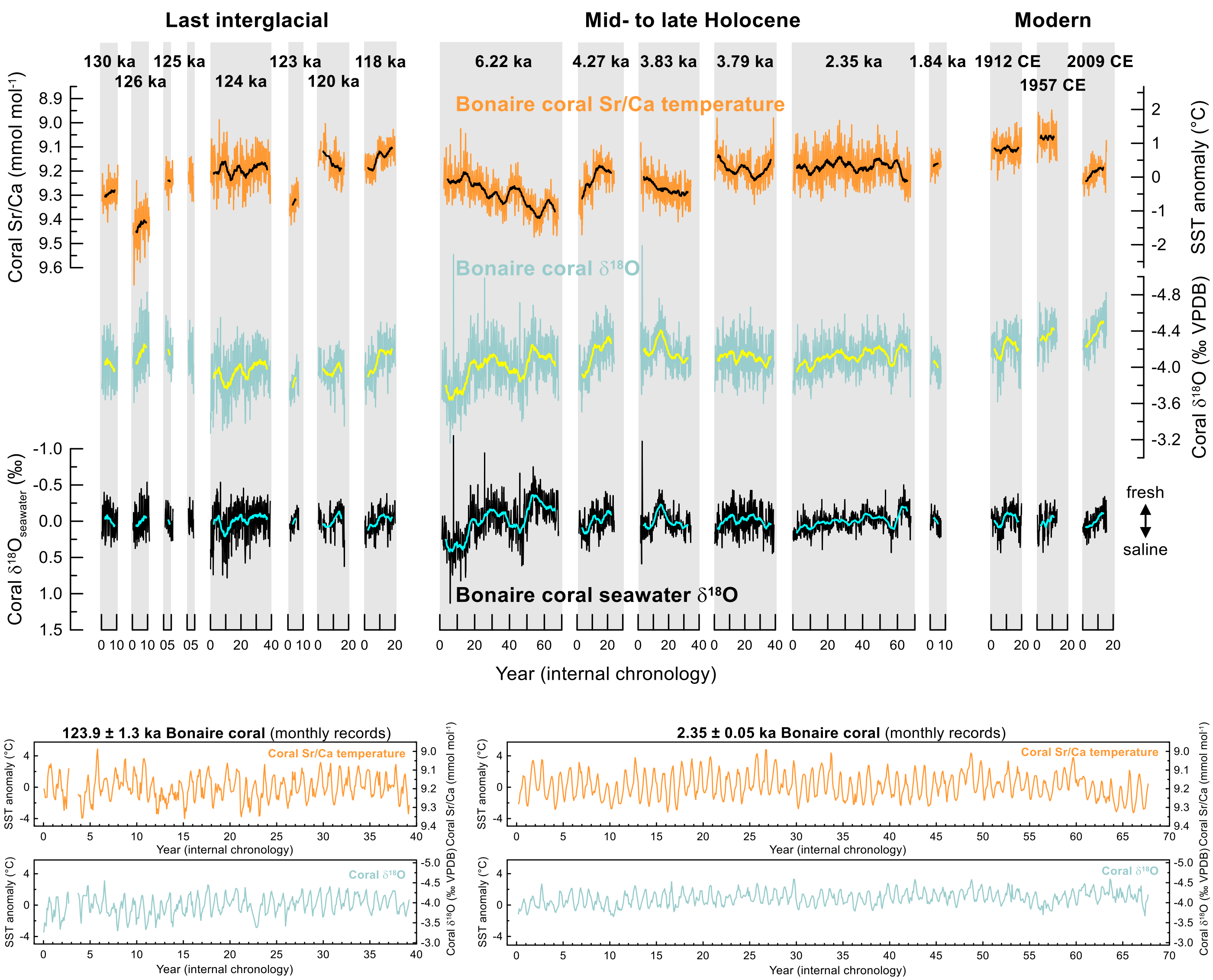


FIGURE 2. (top) Monthly resolved proxy records of tropical Atlantic sea surface temperature (SST) and hydrology for time intervals during the last interglacial (~130,000 to 118,000 years ago) and since the mid-Holocene (~6,000 years ago) derived from Sr/Ca and $\delta^{18}O$ measurements in modern and fossil corals (*Diploria strigosa*) of the southern Caribbean Sea (Bonaire; Giry et al., 2012, 2013; Felis et al., 2015; Brocas et al., 2016, 2018). The corresponding seawater $\delta^{18}O$ reconstructions are shown. Bold lines are 51-month running averages. (bottom) Enlargement of monthly coral Sr/Ca and $\delta^{18}O$ records for time intervals around 124,000 and 2,350 years ago. *Modified from Giry et al. (2012, 2013), Felis et al. (2015), and Brocas et al. (2016, 2018)*

ative of a stronger influence of Pacific climate variability on the tropical Atlantic basin at that time (Giry et al., 2012, 2013). Indications for prominent decadal variability in sea surface temperature at a period of ~12 years identified during the peak of the last interglacial ~124,000 years ago (Brocas et al., 2016) are noteworthy. Similar decadal variability has been a typical feature in North Atlantic surface temperatures during the period of instrumental observations.

The monthly resolved Bonaire coral Sr/Ca records indicate that the seasonality of surface ocean temperature in the tropical North Atlantic during the Holocene and the last interglacial was controlled mainly by insolation changes on orbital timescales (Giry et al., 2012; Felis et al., 2015; Brocas et al., 2016). The reconstructed temperature seasonality closely follows the temporal evolution of orbitally controlled changes in insolation seasonality between ~130,000 and 118,000 years ago and from ~6,000 years ago until the present day (**Figure 3**). The maximum temperature seasonality relative to today reconstructed for 126,000 years ago, during the peak of the last interglacial, is temporally consistent with a corresponding maximum in insolation seasonality at this latitude and in line with climate simulations using a coupled atmosphere-ocean general circulation model (Brocas et al., 2016). It is notable that a time interval of anomalously increased temperature seasonality reached peak last interglacial amplitudes during the late Holocene ~2,350 years ago and cannot be explained by an orbital forcing of insolation seasonality (Giry et al., 2012). Along with pronounced interannual variability at typical ENSO periods, this anomalous time interval might provide a paleo-observational constraint for substantial modulation of tropical Atlantic temperature seasonality through internal variability of the climate system, such as strengthened interactions between the Pacific and Atlantic basins via atmospheric teleconnections (Giry et al., 2012; Felis et al., 2015). Given the important role of tropical surface ocean seasonal temperature changes in the development of hurricanes, floods, and droughts, a better understanding of the dynamics behind such anomalous time intervals of the past might lead to improved projections of future climate extremes and their impacts on the tropical Atlantic region and adjacent continental areas.

The evolution of tropical ocean temperatures at sub-basin to regional scales during the Holocene and the last interglacial is still not well known. A noteworthy result based on the Bonaire coral records is a reconstructed cooling in the tropical North Atlantic relative to today during the mid-Holocene ~6,000 years ago (Giry et al., 2012) and especially during the peak of the last interglacial ~126,000 years ago (Brocas et al., 2019), with both time intervals accompanied by apparently fresher sea surface conditions (Giry et al., 2013; Brocas et al., 2019). That the tropical Atlantic Ocean did not warm during the peak of the globally warmer-than-pre-industrial last interglacial is at first glance counterintuitive (Brocas et al., 2019). However, this result is consistent with other proxy reconstructions and climate model simulations of the tropical oceans and with the annual orbital forcing of insolation during this time interval (Fischer et al., 2018). This highlights the potential for corals to shed more light on the temperature evolution of the tropical oceans during warm periods of the past.

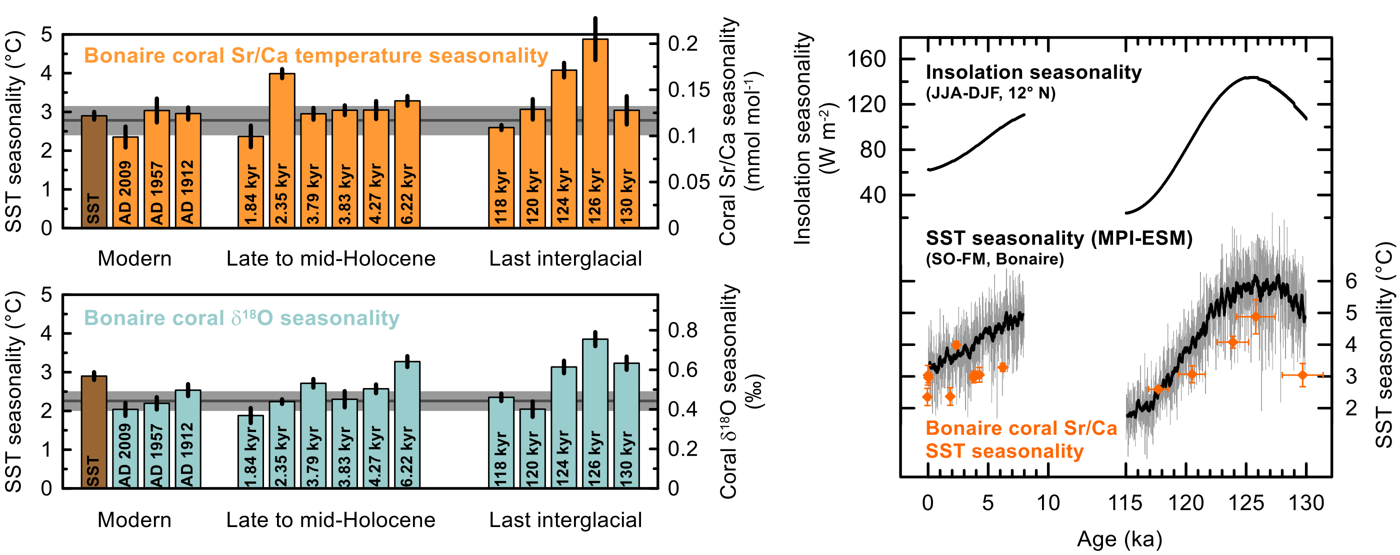


FIGURE 3. (left) Evolution of tropical Atlantic sea surface temperature (SST) seasonality during the last interglacial (~130,000 to 118,000 years ago) and since the mid-Holocene (~6,000 years ago) derived from monthly Sr/Ca and $\delta^{18}O$ measurements in modern and fossil corals (*Diploria strigosa*) of the southern Caribbean Sea (Bonaire; Giry et al., 2012, 2013; Felis et al., 2015; Brocas et al., 2016, 2018). Deviations of coral $\delta^{18}O$ seasonality from coral Sr/Ca-temperature seasonality arise from hydrological effects. (right) Reconstructed coral Sr/Ca-temperature seasonality closely follows orbitally controlled changes in insolation seasonality at this latitude and regional SST seasonality from a climate model simulation. *Modified from Giry et al. (2012, 2013), Felis et al. (2015), and Brocas et al. (2016, 2018)*

LAST DEGLACIAL TEMPERATURES, EAST AUSTRALIAN CURRENT, AND THE GREAT BARRIER REEF

The last deglaciation (~18,000 to 11,000 years ago) is a time interval of substantial global warming and sea level rise following the cold last glacial maximum that culminated 20,500 years ago with a sea level of about 125 m to 130 m lower than today (Yokoyama et al., 2018). Submerged shallow-water reefs that grew during the last deglaciation, however, are difficult to access. In the Great Barrier Reef, along the path of the southward flowing East Australian Current, tropical Pacific corals that grew during the last glacial maximum were successfully recovered for the first time using a mission-specific platform on Integrated Ocean Drilling Program (IODP) Expedition 325 (Felis et al., 2014; Webster et al., 2018; Yokoyama et al., 2018). Average Sr/Ca values of fossil corals from two IODP drilling sites separated by about 3° of latitude indicate a considerably steeper meridional sea surface temperature gradient than that of the present day between ~20,000 and 13,000 years ago, and is supported by the corresponding coral $\delta^{18}O$ data (Felis et al., 2014; Figure 4). The result was interpreted as an indication for the northward expansion of cooler subtropical waters along the eastern Australian coast during the last glacial maximum and the last deglaciation due to a weakening of the East Australian Current (Felis et al., 2014), the western boundary current of the South Pacific subtropical gyre. These findings also suggest a northward contraction of the southern boundary of the Western Pacific Warm Pool during the last glacial maximum and the last deglaciation. Furthermore, the reduction in the transport of warm tropical waters poleward due to a weakened East Australian Current may have played an important role in dampening the amplitude of cooling in the Western Pacific Warm Pool during the last glacial maximum (Felis et al., 2014). From an ecosystem perspective, the coral-based temperature reconstructions (Felis et al., 2014) along with the sea level reconstructions (Yokoyama et al., 2018) of IODP Expedition 325 provide the basis for the conclusion that the Great Barrier Reef has been more resilient to past temperature (Felis et al., 2014) and sea level changes than previously thought (Webster et al., 2018), but there is little evidence for resilience during the next decades given the current rates of change (Webster et al., 2018).

The reconstruction of last deglacial temperature gradients at a regional scale from a large number of corals analyzed for Sr/Ca in multiple laboratories within the international context of an IODP expedition is a challenge. Next to analytical precision, this reconstruction requires well-characterized reference material that is appropriate for the high Sr content of coral skeletons and the corresponding coral matrix. The coral paleoclimatological work arising from IODP Expedition 310 to Tahiti strengthened the need for a direct comparison of coral Sr/Ca temperature proxy data generated in different laboratories (Asami et al., 2009; Hathorne et al., 2011; Felis et al., 2012). The Geological Survey of Japan's JCp-1 coral reference material was identified as appropriate and characterized in an interlaboratory study for coral Sr/Ca and other element/Ca ratio measure-

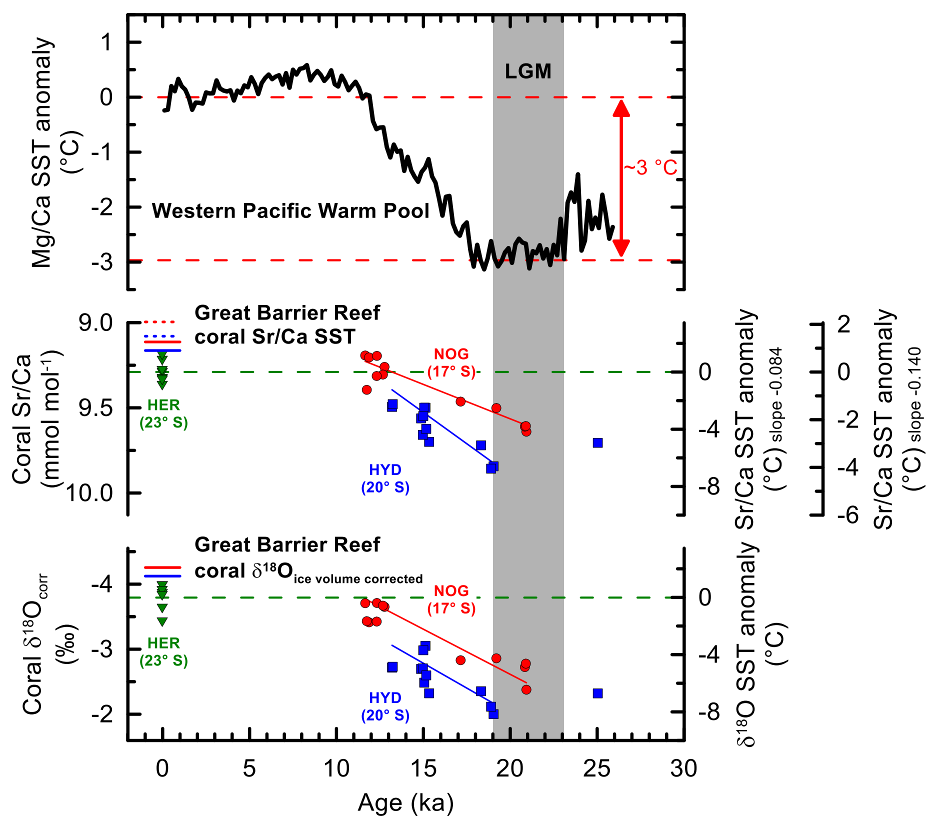


FIGURE 4. Evolution of tropical South Pacific sea surface temperature (SST) during the last deglaciation and last glacial maximum (LGM) derived from average Sr/Ca and $\delta^{18}O$ values of fossil corals (*Isopora palifera/cuneata*) drilled by Integrated Ocean Drilling Program (IODP) Expedition 325 to the Great Barrier Reef (Felis et al., 2014). Reconstructed coral Sr/Ca temperatures from northern (NOG) and southern (HYD) sites indicate a steeper meridional SST gradient than at present day between ~20,000 years ago and 13,000 years ago, supported by the coral $\delta^{18}O$ data. The coral Sr/Ca SST anomalies are not adjusted for changes in seawater Sr/Ca, and thus provide upper estimates of the magnitude of cooling. Deviations of coral $\delta^{18}O$ from coral Sr/Ca temperatures arise from hydrological effects. Coral data for a modern reference site (HER) and scaled relative SST at IODP sites are shown for comparison (short blue and red horizontal lines: solid = Sr/Ca-SST slope –0.084 mmol mol^{-1} per °C; dashed = Sr/Ca-SST slope –0.140 mmol mol^{-1} per °C). Warm Pool SST data are from Linsley et al. (2010). *Modified from Felis et al. (2014)*

ments (Hathorne et al., 2013b). It was suggested that future studies reporting coral element/Ca data should also report the average value obtained for a reference such as the JCp-1 (Hathorne et al., 2013b), a procedure that was followed in coral work of subsequent IODP expeditions (Felis et al., 2014) and other studies (Giry et al., 2012; Felis et al., 2015; Zinke et al., 2015; Brocas et al., 2016; DeCarlo et al., 2016; Wu et al., 2017).

TROPICAL PACIFIC TEMPERATURE VARIABILITY DURING HEINRICH STADIAL 1

Fossil corals recovered in the tropical South Pacific at Tahiti by IODP Expedition 310 provide monthly resolved snapshots of sea surface temperature variability during the last deglaciation that coincide with key periods of Northern Hemisphere climate change such as the Younger Dryas cooling, the Bølling-Allerød warming, and the Heinrich Stadial 1 cold interval (Asami et al., 2009; Hathorne et al., 2011; Felis et al., 2012). Average coral Sr/Ca values suggest relative cooling at Tahiti during the Younger Dryas at 12,400 years ago compared to 14,200 years ago during the Bølling-Allerød, which could indicate the reflection of a Northern Hemisphere-type pattern of deglacial warming at ~17°S in the central tropical South Pacific (Asami et al., 2009).

During the early last glacial termination, the Heinrich Stadial 1 interval (~18,000 to 14,600 years ago) was characterized by intense North Atlantic cooling and weak overturning circulation. Heinrich Stadial 1 was accompanied by a disruption of global climate, but its impact on interannual climate variability in the tropical Pacific is not well known. A monthly resolved Tahiti coral Sr/Ca record indicates pronounced interannual variability in tropical South Pacific sea surface temperatures at typical ENSO periods around 15,000 years ago (Felis et al., 2012), different from today when ENSO influence on Tahiti sea surface temperatures is weak (**Figure 5**). The results indicate that ENSO was active during Heinrich Stadial 1. Furthermore, greater ENSO influence in the South Pacific at this time is suggested as potentially resulting from a southward expansion or shift of ENSO-related sea surface temperature anomalies (Felis et al., 2012). Such coral proxy evidence of tropical Pacific sea surface temperature characteristics in an extreme climate of the past, at the end of the last glacial period, might help to constrain climate model projections of future climate change.

OUTLOOK

Proxy records derived from tropical shallow-water corals have great potential for extending the instrumental record of sea surface observations into the past throughout the tropical to subtropical oceans. The monthly resolution of coral proxy records provides quantitative information on the fluctuations of sea surface temperature and hydrology on seasonal, interannual, and decadal timescales during the pre-instrumental period, with associated uncertainties and precise chronology. This information can be derived from $\delta^{18}O$ measurements in modern and fossil corals, paired with analysis of temperature proxies such Sr/Ca and U/Ca (Felis et al., 2009), Li/Ca

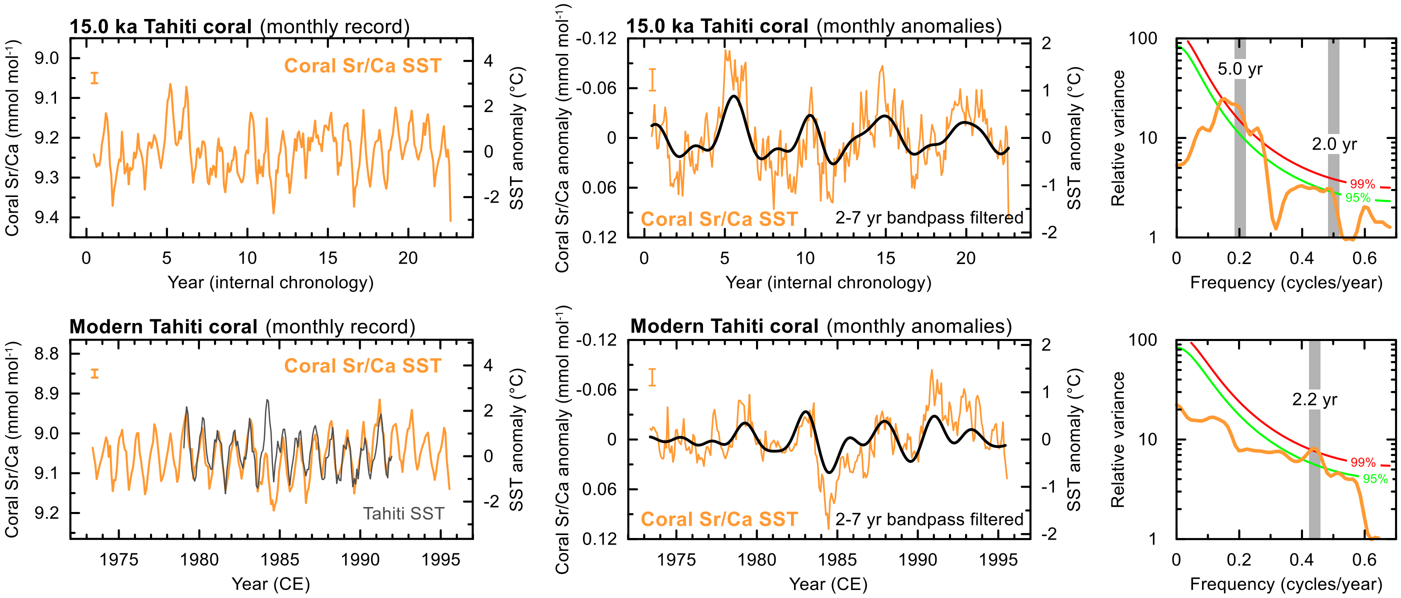


FIGURE 5. (left) Monthly resolved proxy records of tropical South Pacific sea surface temperature (SST) for a time interval during the Northern Hemisphere's Heinrich Stadial 1 cold interval (~18,000 to 14,600 years ago) derived from Sr/Ca measurements in a fossil coral (*Porites* sp.) drilled by IODP Expedition 310 off Tahiti (Felis et al., 2012). (center) Corresponding monthly coral Sr/Ca-SST anomaly records (annual cycle removed) filtered in the two- to seven-year band. (right) Results of spectral analysis. Pronounced interannual variability in tropical South Pacific SST at typical El Niño-Southern Oscillation (ENSO) periods is indicated around ~15,000 years ago, which is different from today when the ENSO influence on Tahiti SST is weak. Modern Tahiti coral data is from Cahyarini et al. (2008). *Modified from Felis et al. (2012)*

and Li/Mg (Hathorne et al., 2013a), and Sr-U (DeCarlo et al., 2016) and clumped isotopes (Saenger et al., 2012). Multi-proxy approaches involving Sr/Ca and Li/Mg show potential for improving coral-based temperature reconstructions (D'Olivo et al., 2018), whereas other emerging proxies such as calcium isotopes ($\delta^{44/40}Ca$) reveal only a weak temperature dependence (Pretet et al., 2013). Specially designed micromilling techniques for skeleton sampling need to be applied to corals other than the commonly used *Porites* of the Indo-Pacific, such as Atlantic brain corals (Giry et al., 2010). The use of fossil corals requires rigorous screening for potential effects of diagenesis (Hathorne et al., 2011; Felis et al., 2012) as well as identification of appropriate skeletal elements for precise uranium-series dating (Obert et al., 2016).

Paired coral proxy records of sea surface temperature and hydrology are of great importance for better assessment of ongoing and future changes in the tropical ocean-atmosphere system and related climate extremes. They can be used, in combination with proxy system models and isotope-enabled climate models (Dee et al., 2015; Brocas et al., 2018; Stevenson et al., 2018; Lawman et al., 2020), to investigate the fundamental dynamics of tropical ocean-atmosphere variability, investigations that will ultimately lead to a better understanding of how this important component of the Earth system works. Following paleoclimate data reporting and archiving standards agreed on by the scientific community (Khider et al., 2019), the growing network of coral records can serve synthesis studies on various aspects of past tropical marine climate (Tierney et al., 2015; Abram et al., 2016).

Other proxies that are beginning to be frequently analyzed in coral skeletons include boron isotopes ($\delta^{11}B$) and boron/calcium (B/Ca) for identifying the long-term effects of ocean acidification on coral calcification (McCulloch et al., 2017), nitrogen isotopes ($\delta^{15}N$) in skeleton-bound organic matter that provide information about the oceanic nitrogen cycle and the influence of anthropogenic nitrogen on the open ocean (Wang et al., 2018), and barium isotopes ($\delta^{138/134}Ba$) as a potential proxy for oceanic barium cycling (Liu et al., 2019). The combination of element/Ca and boron isotope records shows promise for detecting the response of coral calcification and calcifying fluid to thermally induced bleaching stress (D'Olivo and McCulloch, 2017), which might contribute to the reconstruction of past bleaching events and a better understanding of coral resilience under current and future warming. These new proxies are important because systematic coral reef monitoring started only a few decades ago and is still absent in many remote reef areas. Consequently, in addition to paleoceanographic and paleoclimatic information, coral reconstructions can provide a long-term perspective on the responses of coral reef ecosystems to environmental stresses. Together, such reconstructions provide the potential for insights into the effects of large-scale oceanographic and atmospheric processes on coral reef ecosystems (Zinke et al., 2015; Felis and Mudelsee, 2019).

Key regions for future coral-based paleoclimatic research include the area of highest ENSO variability in the equatorial Pacific Ocean, including the Western Pacific Warm Pool; the tropical Atlantic Ocean as a source for climate extremes affecting the Americas, Africa, and downstream Europe; and the Indian Ocean, where warming is occurring faster than in any other tropical ocean and whose related climate extremes affect the adjacent continental areas of Africa, Asia, and Australia. Furthermore, subtropical Northern Hemisphere sites that were affected by warming during the last interglacial period are of interest. In addition to the last interglacial, the Holocene thermal maximum is of primary interest as another period warmer than the preindustrial, as is the Common Era of the last 2,000 years as a time interval immediately preceding the period of instrumental observations. Older interglacials that represent time intervals of substantial warming might also provide well-preserved fossil corals, as might the last deglaciation and earlier deglaciations that are of interest to studies of tropical marine climate variability during periods of rapid warming.

In summary, ultrahigh-resolution coral proxy records provide a powerful tool for reconstructing past tropical marine climate and environmental variability and for understanding the temporal response of corals and coral reefs to ongoing climate and environmental changes. Used in conjunction with advanced statistical methods and Earth system modeling, these data can improve projections of tropical climate variability and the fates of coral reef ecosystems.

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