Climate Records from Corals

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Abstract: In many regions instrumental climate records are too short to resolve the full range of decadal- to multidecadal-scale natural climate variability. Massive annually banded corals from the tropical and subtropical oceans provide a paleoclimatic archive with a seasonal resolution, documenting past variations in water temperature, hydrologic balance, and ocean circulation. Recent coral-based paleoclimatic research has focused mainly on the tropics, providing important implications on the past variability of the El Niño-Southern Oscillation (ENSO) phenomenon and decadal tropical climate variability. However, new records from some of the rare subtropical/mid-latitude locations of coral growth were shown to reflect aspects of dominant modes of Northern Hemisphere climate variability, e.g. the North Atlantic Oscillation (NAO). This natural mode has important socio-economic impacts owing to its large-scale modulation of droughts, floods, storms, snowfall, and fish stocks at timescales relevant to society. Coral records extending over several centuries from key locations (e.g. northern Red Sea, Bermuda) provide the opportunity to assess recent shifts in the NAO with respect to the natural variability of the pre-instrumental period. Providing a better understanding of NAO dynamics, such paleoclimatic records, together with those derived from other paleoclimatic archives, are essential for the predictability of future European climate.

Introduction

Instrumental climate records are too short to resolve the full range of decadal- to multidecadal-scale natural climate variability. Banded corals, tree rings, ice cores, and varved sediments provide paleoclimatic archives which can be used to reconstruct past climate variability in the pre-instrumental period in annual resolution. These proxy climate indicators provide paleoclimatic records which are important for the assessment of perturbations to the natural climate variability by anthropogenic forcing, for climate predictability and for a better understanding of the dominant modes of the global climate system, e.g. the El Niño-Southern Oscillation (ENSO) phenomenon of tropical Pacific origin, the Asian and African monsoon, the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), and the mechanisms of decadal climate variability. These natural modes have important socio-economic effects owing to their large-scale modulation of droughts, floods, storms, snowfall, or fish stocks at timescales relevant to society.

Massive "stony" (scleractinian) corals from the modern and fossil reefs of the tropical and subtropical oceans provide an important archive of past climate and ocean variability. These corals build skeletons of aragonite ($CaCO_3$) and grow at rates of millimeters to centimeters per year. During growth, annual density bands are produced in the skeleton that can be used for the development of chronologies. As corals grow they incorporate isotopic and elemental tracers reflecting the environmental conditions in the ambient seawater during skeleton secretion, e.g. water temperature, hydrologic balance (evaporation, precipitation, runoff), and ocean circulation. Compared to other paleoclimatic archives corals provide a clear seasonal resolution. Modern corals from living reefs provide continuous climate

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records extending several centuries back from the present. Well-preserved fossil corals from emerged or submerged reef terraces provide information on climate variability during time-windows throughout the late Quaternary. The most commonly used corals in paleoclimatology are those of the genus *Porites* which are ideally suited for sub-annual sampling owing to their dense skeletons and rapid growth rates (about 1 cm per year).

Most reef-building (hermatypic) corals live in the upper ~40 m of the ocean where there is sufficient light for the photosynthetic activity of the coral's endosymbiotic algae (zooxanthellae). Furthermore the development of coral reefs is restricted to warm water temperatures. Most corals are located in regions where mean annual temperatures are around 24°C and/or mean winter minimum temperatures are not below 18°C, i.e. roughly between 23-24°N and S latitude. Therefore recent coral-based paleoclimatic research has focused mainly on the tropics providing important implications on past variability of the ENSO phenomenon and decadal tropical climate variability (e.g. Cole et al. 1993; Charles et al. 1997; Cole et al. 2000; Urban et al. 2000). However, some ocean currents transport warmer tropical waters to higher latitudes leading to coral growth also at some rare subtropical/mid-latitude locations. These locations have provided the opportunity for coral records from up to ~29°S in the southeastern Indian Ocean (Kuhnert et al. 1999); ~32°N in the North Atlantic (Pätzold and Wefer 1992; Pätzold et al. 1999; Berger et al. 2002), and ~28°N in the northern Red Sea (Felis et al. 2000). These paleoclimatic records were generated from living corals covering the past centuries. In contrast, fossil corals have revealed important aspects on climate variability during time-windows of up to decades length throughout the Holocene (Beck et al. 1997), especially the Mid-Holocene (Gagan et al. 1998; Corrège et al. 2000; Moustafa et al. 2000), and the last interglacial warm period (Hughen et al. 1999).

Coral-based paleoclimatic records from Bermuda and the northern Red Sea were shown to reflect aspects of dominant modes of Northern Hemisphere climate variability, in particular the oceanic (Bermuda) and atmospheric (northern Red Sea) signature of the NAO (Pätzold et al. 1999; Felis et al. 2000). The NAO has a strong influence on large-scale variations in the atmospheric circulation over the North Atlantic and its surrounding continents, controlling European winter climate (Hurrell 1995). Coral records of several centuries length from such key locations provide the opportunity to assess recent shifts in the NAO with respect to the natural variability of the pre-instrumental period. Providing a better understanding of NAO dynamics, such paleoclimatic records, together with those derived from tree rings, ice cores, and varved sediments, are essential for the predictability of future European climate.

An additional source of annual- to seasonal-resolution paleoclimatic records from the marine environment with relevance to European climate are the shells of the long-lived mollusc *Arctica islandica* (Weidman et al. 1994; Marchitto Jr. 2000). This annually-banded bivalves inhabit the continental shelves and slopes of the northern North Atlantic covering a geographic region where no warm-water corals grow. Individual *Arctica islandica* specimens are commonly living for about 100 years. Therefore the splicing of several accurately dated fossil shell records has the potential to provide continuous or near-continuous composite records covering the past 1000 years (Weidman and Goodfriend 1999).

In summary, coral records are successfully used since nearly a decade for seasonal-resolution reconstructions of tropical climate and ocean variability during the past centuries but also during periods of time with boundary conditions different from today. Future research should exploit the potential of corals from rare subtropical/mid-latitude locations (e.g. Bermuda, northern Red Sea) to better understand past mid-latitude climate variability which is important with respect to present and future European climate.

Annual density banding and age model

As corals grow, new skeleton is generated within the living tissue layer which always remains as a thin band (of several millimeters width) at the outermost surface of a colony. Centuries-old coral colonies can become several meters high considering typical growth rates for *Porites* of about 1 cm per year. Such large living corals are usually sampled by drilling a core vertically from the top to the bottom of a colony along the major axis of growth.

In general, coral skeletons reveal a density banding pattern of alternating bands of high- and low density, with each year being represented by a pair of such bands. The density variations result from changes in a coral's rate of calcification and/or growth. The preliminary age model of a coral chronology is usually based on counting the annual density-band pairs. The counting starts at the top of a coral core within the tissue layer whose age is known from the date of collection of the core, provided a living colony was drilled. The preliminary age model based on banding is then refined using the seasonal cyclicity of isotopic or elemental tracers in the coral skeleton that reflects the seasonal cycle of temperature or light.

Well-preserved fossil corals can be dated either using radiocarbon or the ^{230}Th/^{234}U method. The ^{230}Th/^{234}U method is applied to date corals which are older than 30,000 to 45,000 years which is the limit of the ^{14}C method. Furthermore, ^{230}Th/^{234}U ages can be considered as absolute ages compared to ^{14}C ages, which are influenced by ocean reservoir effects and variations in the ^{14}C level of the atmosphere. The dating of a fossil coral provides a floating chronology for which top and bottom ages are known only approximately.

Climate tracers in corals

Annual growth rates

The annual growth rates of corals can be inferred from the annual density-band pattern and can provide a paleoclimatic tracer. Coral growth rates can reflect several environmental parameters such as temperature, nutrient or food availability, water transparency, and sediment input. An 800-year record of coral growth from Bermuda in the North Atlantic was shown to reflect temperature variability, probably as a result of enhanced coral growth during periods of increased wind-induced vertical mixing resulting in cooler but nutrient richer surface waters (Pätzold and Wefer 1992; Pätzold et al. 1999; Berger et al. 2002). However, due to the dependence on several environmental factors growth rate variations in most corals are difficult to interpret in climatic terms.

Oxygen isotopes

The ratios of the isotopic species of oxygen (^{18}O/^{16}O) incorporated in coral skeletons during growth, reported as δ^{18}O, are primarily influenced both by the temperature and the δ^{18}O of the ambient seawater during skeleton precipitation. In localities where one of these two environmental factors dominates the other, coral δ^{18}O records can therefore provide information either on variations in water temperature or in δ^{18}O of the seawater with the latter being related to the hydrologic balance.

As temperature increases, there is a decrease in the δ^{18}O (depletion in ^{18}O) of the coral skeletal aragonite. Near-weekly resolution calibrations of Porites coral δ^{18}O variability suggest a temperature dependence of 0.18‰ per 1°C (Gagan et al. 1994). This ratio is supported by a regression of several long annually-averaged Indo-Pacific Porites coral δ^{18}O records against local SST anomaly which indicates a ratio of 0.19‰/°C (Evans et al. 2000).

Variations in the δ^{18}O of the seawater can result from evaporation (enrichment in ^{18}O), precipitation (enrichment in ^{16}O), or runoff (enrichment in ^{16}O), i.e. such variations reflect the hydrologic balance. Water mass transport can also play a role. High evaporation results in both an increase in the δ^{18}O of the seawater and a higher salinity; high precipitation or runoff has opposing effects. Because of this, salinity variations, if driven through evaporation, precipitation, or runoff, covary with variations in the δ^{18}O of the seawater.

The environmental interpretation of the ratios of the stable isotopic species of carbon (^{13}C/^{12}C) incorporated in coral skeletons, reported as coral δ^{13}C, is complicated because of interactions with physiological processes such as symbiont photosynthesis and respiration. The coral δ^{13}C signal is therefore difficult to apply in paleoclimatic research. In cases, a strong signal can emerge. For example, we found that a coral δ^{13}C record from the northern Red Sea documents interannual events of extraordinarily large plankton blooms caused by deep vertical water mass mixing in certain winters. We think this is a result of changes in the coral's food uptake, i.e. increased heterotrophic feeding on zooplankton during the periods of high plankton availability (Felis et al. 1998).

The strontium/calcium ratio

Because of the dependence of coral $\delta^{18}O$ on both temperature and seawater $\delta^{18}O$, with the latter covarying with salinity, there is the need for additional proxies either solely reflecting temperature or salinity, respectively. Concentrations of some of the various trace elements incorporated in coral skeletons during growth were shown to be dependent on the temperature of the ambient seawater during skeleton precipitation.

Sr/Ca ratios in corals were shown to provide a promising proxy for water temperature variability (Beck et al. 1992; McCulloch et al. 1994; Alibert and McCulloch 1997; Gagan et al. 1998). The slopes of the calibration equations show a strong similarity. However, there are still differences in the temperature calibrations between different studies. The average of several coral Sr/Ca calibrations suggests a temperature dependence of 0.062 mmol/mol per 1°C (Gagan et al. 2000), but it is not known whether this coral Sr/Ca-temperature relationship is generally valid for *Porites*.

Coral Sr/Ca ratios are influenced by the Sr/Ca ratio of the ambient seawater during skeleton precipitation. Due to the long residence times of Sr and Ca in the ocean the Sr/Ca ratios of seawater are supposed to be constant on glacial-interglacial timescales. However, some works indicate that seawater Sr/Ca ratios can vary significantly between sites (de Villiers et al. 1994) as well as at the same location over the annual cycle. Seawater Sr/Ca ratios were shown to be correlated with nutrient variability, e.g. at upwelling sites (de Villiers et al. 1994). Furthermore it was suggested that during glacial conditions the Sr/Ca ratio of seawater could have been significantly different due to the weathering and dissolution of Sr-enriched aragonitic carbonates exposed on the continental shelves (Stoll and Schrag 1998).

Other temperature-sensitive trace elements incorporated in coral skeletons are Mg and U. Recent studies revealed that U/Ca ratios in corals could provide a temperature proxy comparable in accuracy to Sr/Ca (Corrège et al. 2000) whereas Mg/Ca ratios probably do not (Schrag 1999).

Combined oxygen isotopes and Sr/Ca

Combined determinations of $\delta^{18}O$ and Sr/Ca in corals can provide information on $\delta^{18}O$ seawater as well as temperature variability, through removing the temperature component of the coral $\delta^{18}O$ variations which is derived from the coral Sr/Ca signal (McCulloch et al. 1994; Gagan et al. 1998). The residual coral $\delta^{18}O$ can be used to reconstruct variations in the hydrologic balance because variations in the $\delta^{18}O$ of seawater reflect evaporation, precipitation, and runoff, which in turn can be related to changes in atmospheric moisture transport. Water mass transport effects can also play a role. If the relationship between $\delta^{18}O$ of seawater and salinity is constant over time, the double-tracer technique of coupled $\delta^{18}O$ and Sr/Ca measurements in corals can be used to reconstruct past variations in ocean surface salinity.

Radiocarbon

Radiocarbon (^{14}C) incorporated in coral skeletons during growth reflects the ^{14}C content of the dissolved inorganic carbon (DIC) of the ambient seawater during skeleton precipitation and provides a useful tracer for ocean circulation and upwelling. The ^{14}C content of the surface ocean is controlled by the ^{14}C level of the atmosphere (equilibration time about a decade) and by mixing with waters which have a different ^{14}C signature. The latter can result from changes in the depth of the mixed layer or thermocline or changes in the rate of vertical mixing and upwelling which brings radiocarbon-depleted waters to the surface. Another factor is the horizontal advection of surface waters with a different ^{14}C signature from other oceanic source regions (e.g. Druffel and Griffin 1993). The ^{14}C content is reported as $\Delta^{14}C$ (‰), which is the $^{14}C/^{12}C$ ratio relative to 19th-century wood.

The atmospheric testing of nuclear weapons in the 1950s and early 1960s increased the $\Delta^{14}C$ of the surface ocean. During this time of rapidly increasing bomb ^{14}C in the atmosphere air-sea exchange was the primary controller on surface ocean $\Delta^{14}C$. This increased the natural $\Delta^{14}C$ gradient between surface and subsurface waters and makes coral $\Delta^{14}C$ records from the surface ocean very sensitive to changes in upwelling, but also to changes in the horizontal advection of water masses which upwelled elsewhere (e.g. Guilderson and Schrag 1998; Guilderson et al. 1998). Because the rate of biological processes on $\Delta^{14}C$ DIC as well as radioactive decay are negligible relative to surface water dynamics and the timeframe of interest, respectively, $\Delta^{14}C$ in surface waters is a quasi-conservative, passive advective tracer (Guilderson et al. 1998; Guilderson et al. 2000).

Climate records from corals

Past centuries

Current paleoclimatic records which are based on $\delta^{18}O$, Sr/Ca, or $\Delta^{14}C$ determinations in modern corals do not extend back beyond the year 1600. 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 350 years. Furthermore, these centuries-old coral colonies are usually quite rare in most reef environments. Most long coral-based paleoclimatic records are the result of extensive surveys to discover the biggest colony of an area.

The generation of century-long coral stable isotope records in annual resolution started in the 1980s (Pätzold 1986). The longest coral stable isotope time series available is a 347-year record from Galápagos (Dunbar et al. 1994). More recent studies exploit the clear seasonal resolution which corals can provide. However, of the published coral records which are currently archived in the World Data Center-A for Paleoclimatology only 8 which have seasonal or higher resolution extend beyond 1850 (Fig. 1). These coral records are based on $\delta^{18}O$ with the exception of the Rarotonga record which is based on Sr/Ca (Linsley et al. 2000). The latter was generated by applying a newly developed method for rapid analysis of high-precision Sr/Ca ratios in corals (Schrag 1999). These coral records cover a latitudinal range of ~28°N to ~29°S in the Indian and Pacific Oceans (Fig. 2). Most of these records are correlated with local and regional climate variability but also reflect aspects of large-scale climate phenomena. Many of them indicate decadal-scale climate variability.

The Ras Umm Sidd coral $\delta^{18}O$ record from the northern Red Sea (Sinai, Egypt) (Felis et al. 2000) is correlated with instrumental observations of climate in the Middle East. The mean annual coral $\delta^{18}O$ signal apparently reflects varying proportions of both sea surface temperature (SST) and $\delta^{18}O$ seawater variability which in turn are related to large-scale aspects of Middle East climate variability on interannual and longer timescales. In conjunction with instrumental observations of climate the coral record suggests that colder periods are accompanied by more arid conditions in the northern Red Sea but increased rainfall in the southeastern Mediterranean, whereas warmer periods are accompanied by decreased rainfall in the latter and less arid conditions in the northern Red Sea.

The coral time series extending back to 1750 is dominated by a ~70-year oscillation (Fig. 3a). A comparable oscillation has been related to variations in the intensity of the thermohaline circulation in the North Atlantic (Delworth and Mann 2000). Interannual to interdecadal variability in the coral time series is correlated with instrumental indices of the NAO (Fig. 4), ENSO, and North Pacific climate variability. Apparently these modes consistently contributed to Middle East climate variability since at least 1750, preferentially at a period of ~5.7 years. These coral-based results suggest that atmospheric forcing by large-scale primarily Northern Hemisphere Pacific- and Atlantic-based climatic modes plays an important role in the northern Red Sea/Middle East region.

Another prominent mode in the coral time series is an oscillation with a period of 22-23 years. A similar oscillation has recently been identified as the most prominent mode in a tree-ring based reconstruction of the PDO (Biondi et al. 2001) which represents climate variability in the North Pacific region. The bidecadal oscillations in the Ras Umm Sidd coral record and in the PDO reconstruction are roughly in phase since about 1850 (Fig. 3b). This may suggest coherent bidecadal climate variability over large parts of the Northern Hemisphere extratropics for nearly 150 years. Recent results based on field correlations with sea level pressure

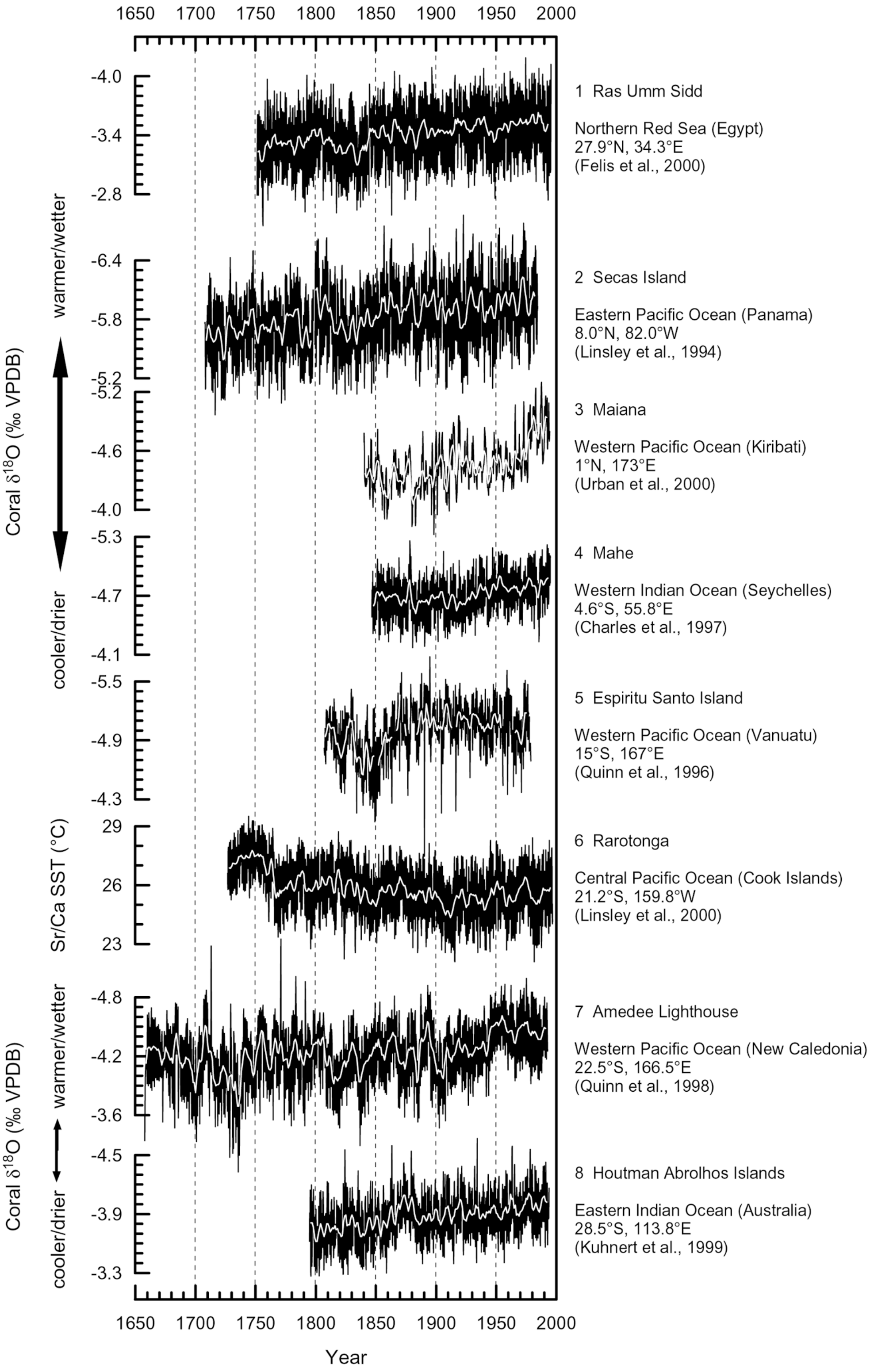


Fig. 1. Coral $\delta^{18}O$ and Sr/Ca records in seasonal or higher resolution extending back beyond 1850 which are archived at the World Data Center-A for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/corals.html). Thick white lines represent 3-year running means.

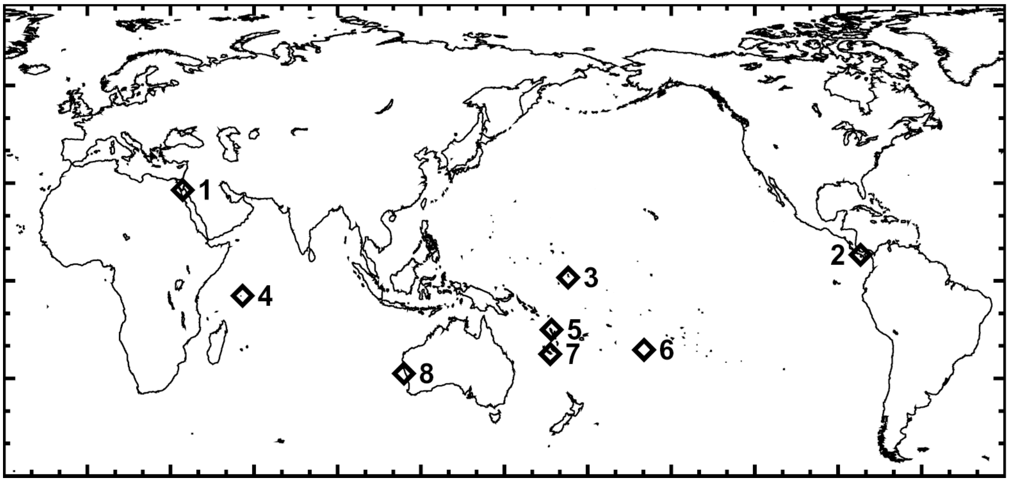
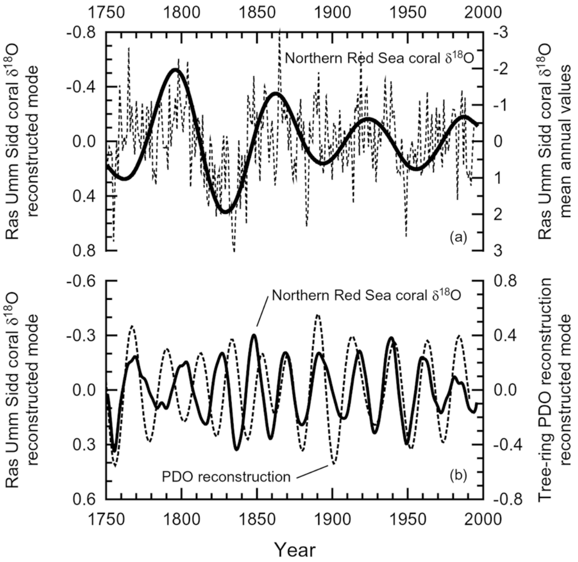


Fig. 2. Map showing locations of long high-resolution coral records as shown in Figure 1.



left: Fig. 3. a) The most prominent mode in the Ras Umm Sidd coral δ^{18}O record from the northern Red Sea has a period of ~70 years (solid line) (Felis et al. 2000) and is probably related to climate and ocean variability in the North Atlantic (Delworth and Mann 2000) Also shown is the detrended normalized mean annual coral δ^{18}O time series (dashed line). **b)** The second prominent mode in the coral record has a period of 22-23 years (solid line). The comparison with a tree-ring based reconstruction of the Pacific Decadal Oscillation (PDO) (dashed line) (Biondi et al. 2001) may suggest coherent bidecadal climate variability in the northern Red Sea/Middle East and the North Pacific during since about 1850.

suggest that the winter coral time series is linked to the Arctic Oscillation phenomenon, the Northern Hemisphere's dominant mode of atmospheric variability (Rimbu et al. 2001).

The Secas Island coral δ^{18}O record from the eastern Pacific Ocean (Panama) (Linsley et al. 1994) primarily reflects δ^{18}O seawater variability which is controlled by changes in precipitation. The precipitation pattern in this part of Central America is related to seasonal and interannual variability in the latitudinal position of the Intertropical Convergence Zone. The coral time series extending back to 1707 is dominated by strong decadal variability.

Coral δ^{18}O records from the western equatorial Pacific primarily reflect δ^{18}O seawater variability mainly driven by changes in precipitation with minor contributions from relatively small changes in SST. During El Niño events increased precipitation associated with the eastward migration of the Indonesian Low and advection of fresher

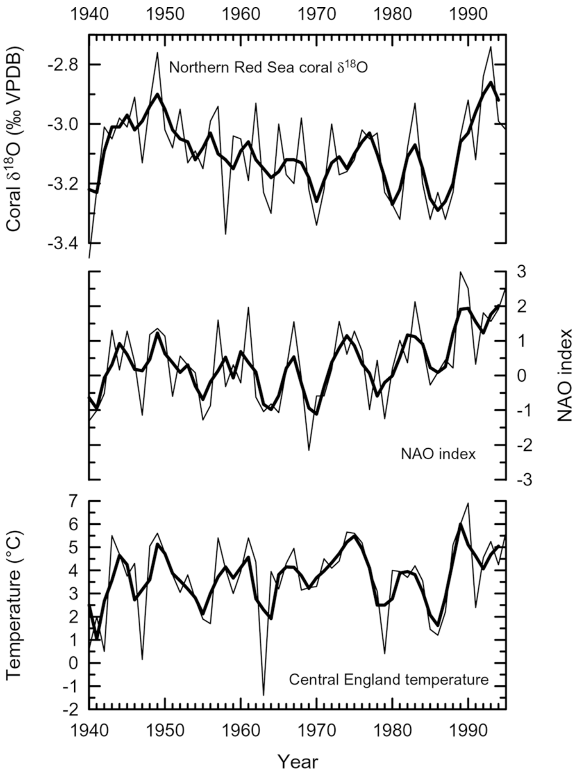


Fig. 4. The winter Ras Umm Sidd coral $\delta^{18}O$ record from the northern Red Sea (Felis et al. 2000) and the winter index of the North Atlantic Oscillation (NAO) (Jones et al. 1997) show common variability. A similar variability is indicated by the winter time series of Central England temperatures (Parker et al. 1992) suggesting that both Central England temperatures and northern Red Sea coral $\delta^{18}O$ are influenced by the NAO. Coral $\delta^{18}O$ and Central England temperatures are for January-February; the NAO index is for December-March. Thick lines represent 3-year running means.

and slightly warmer surface waters resulting from the eastward expansion of the western Pacific warm and fresh pool combine to generate strong coral $\delta^{18}O$ anomalies. Relatively cool and dry conditions during La Niña events produce coral $\delta^{18}O$ anomalies of opposite sign. Therefore corals from this region are excellent recorders of ENSO variability (Cole et al. 1993; Urban et al. 2000).

The Maiana coral $\delta^{18}O$ record from the western equatorial Pacific (Kiribati) (Urban et al. 2000) is strongly correlated with instrumental indices of ENSO variability (Fig. 5). This coral-based reconstruction of ENSO extending back to 1840 provides evidence that variability in the tropical Pacific is linked to the region's mean climate. Cooler and drier background conditions during the mid to late 19th century when anthropogenic greenhouse forcing was absent were accompanied by prominent decadal variability and weak interannual variability. During a gradual transition towards warmer and wetter conditions in the early 20th century variability with a period of ~2.9 years intensified. Between 1920 and 1955 2-4 year variability was attenuated. With an abrupt shift towards warmer and wetter conditions in 1976 variability with a period of about 4 years becomes prominent. The results suggest that changes in the tropical Pacific mean climate and its variability have occurred during periods of natural as well as anthropogenic climate forcing.

The Mahe coral $\delta^{18}O$ record from the western equatorial Indian Ocean (Seychelles) (Charles et al. 1997) primarily reflects variations in SST. Interannual variability in the coral time series is correlated with Pacific climate records suggesting a

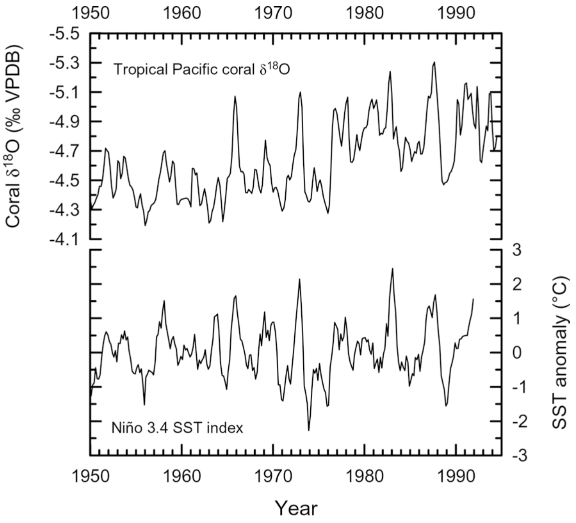


Fig. 5. The Maiana coral $\delta^{18}O$ record from the western equatorial Pacific and the Niño 3.4 sea surface temperature (SST) index, a commonly used measure of the state of the El Niño-Southern Oscillation, are strongly correlated (Urban et al. 2000). SSTs are from (Kaplan et al. 1998).

consistent influence of ENSO on Indian Ocean SSTs for over a century. However, the coral time series extending back to 1846 is dominated by strong decadal variability which was suggested to be characteristic of the Asian monsoon system, implying important interactions between tropical and mid-latitude climate variability. This has been questioned recently by presenting evidence for a tropical Pacific forcing of decadal SST variability in the western equatorial Indian Ocean inferred from an annual-resolution coral δ^{18}O record from Malindi (Kenya) (Cole et al. 2000).

The Rarotonga coral Sr/Ca record from the central subtropical South Pacific (Cook Islands) (Linsley et al. 2000) provides an excellent proxy for SST variability. The coral time series extending back to 1726 is dominated by decadal variability. Several of the largest-scale SST variations at Rarotonga a coherent with SST regime shifts in the North Pacific, as indicated by the index of the PDO over the past 100 years. Because of this hemispheric symmetry it was suggested that tropical forcing may play an important role in at least some of the decadal variability which is observed in the Pacific Ocean.

The Amedee Lighthouse coral δ^{18}O record from the western South Pacific (Quinn et al. 1998) is correlated with variations in SST. The coral time series extending back to 1657 shows prominent decadal fluctuations, especially in the early 18th and early 19th century. Interannual-scale cooling events in the coral record coincide within 1 year with known volcanic eruptions (Crowley et al. 1997), e.g. 1808 (unknown source), 1813-1821 (several eruptions including Tambora 1815), 1835 (Coseguina), 1883 (Krakatau), and 1963 (Agung).

The Houtman Abrolhos Islands coral δ^{18}O record from the eastern subtropical Indian Ocean (Australia) (Kuhnert et al. 1999) is correlated to local SST variability. The location is influenced by the Leeuwin Current which is coupled to the Indonesian throughflow. The coral time series extending back to 1795 shows prominent pentadal and decadal variability.

The longest coral-based Δ^{14}C time series available is a 323-year record from the Great Barrier Reef which has a biannual resolution (Druffel and Griffin 1993). More recent studies on Pacific corals provide seasonal to higher resolution records which give information on the seasonal to interannual variability in the surface circulation and thermocline structure in the Pacific basin (Fig. 6).

The Galápagos coral Δ^{14}C record from the eastern equatorial Pacific (Ecuador) (Guilderson and Schrag 1998) documents the seasonal upwelling of low Δ^{14}C subsurface waters. The interannual variability of the coral time series is dominated by ENSO. During El Niño events the depth of the thermocline increases and the upwelling of low Δ^{14}C water is reduced. The coral record shows that Δ^{14}C values during the upwelling season increased abruptly after the El Niño event of 1976. This suggests a reduction in the contribution of

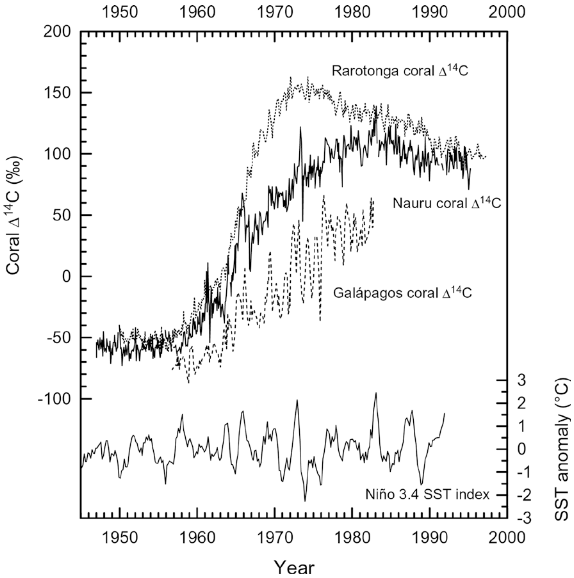


Fig. 6. Coral based Δ^{14}C records from different locations in the Pacific Ocean. Rarotonga, subtropical South Pacific (Guilderson et al. 2000); Nauru, western equatorial Pacific (Guilderson et al. 1998); Galápagos, eastern equatorial Pacific (Guilderson and Schrag 1998). The long-term trend in the coral Δ^{14}C records reflects the uptake of bomb ^{14}C in the ocean. Interannual variability in the equatorial records reflects changes in upwelling and surface circulation which in turn are related to the El Niño-Southern Oscillation (ENSO) phenomenon. The Niño 3.4 sea surface temperature index, a commonly used measure of the state of ENSO, is also shown. SSTs are from (Kaplan et al. 1998).

deeper, lower $\Delta^{14}C$ water to the upwelling since 1976, and together with a simultaneously occurring shift in upwelling season SSTs was interpreted as a shift in the vertical thermal structure of the eastern tropical Pacific towards a deepened thermocline.

The Nauru coral $\Delta^{14}C$ record (Guilderson et al. 1998) documents the interannual redistribution of surface waters in the western equatorial Pacific which is the result of mixing between waters of subtropical origin (higher $\Delta^{14}C$) and water upwelled in the eastern equatorial Pacific (lower $\Delta^{14}C$) then advected zonally by equatorial currents. The interannual variability in the coral time series is dominated by ENSO. During El Niño events coral $\Delta^{14}C$ values increase, reflecting the reduction of low $\Delta^{14}C$ water upwelling in the eastern Pacific and the invasion of high $\Delta^{14}C$ subtropical water into the western equatorial Pacific.

Holocene

Most modern corals are usually not growing for more than 100 to 350 years, but fossil corals provide an opportunity to reconstruct climate variability during time-windows throughout the Holocene. Well-preserved fossil corals can provide records of climate variability comparable in resolution and quality to those derived from modern corals. However, the longest Holocene time series available from a fossil coral is a 47-year record from Tasmaloum (Vanuatu) in the western South Pacific (Corrège et al. 2000). Most records based on fossil Holocene corals only cover periods of 5 to 20 years. This is due to the fact that finding a fossil coral that provides a century-long record is even more difficult than finding a comparable modern coral in the living reefs. Fossil corals are collected from uplifted or submerged reefs mostly by drilling. The chance to recover a long record along the major growth axis of a coral by drilling into a fossil reef is rather small. Direct collection of individual fossil colonies might provide a better solution but is also a matter of luck.

The Eilat coral $\delta^{18}O$ records from the northern Red Sea (Israel) show a higher seasonal amplitude for time-windows during the Mid-Holocene compared to modern corals (Moustafa et al. 2000). The records of up to 18 years length were derived from corals which grew around 6000 to 4500 ^{14}C years before present (BP). The results suggest a higher seasonal cycle in SSTs and changes in the seasonal cycle of precipitation and/or evaporation during the mid-Holocene compared to now (Fig. 7). A possible explanation could be the occurrence of summer rains in this region of the Middle East during these times.

Coral Sr/Ca records from the southwest tropical Pacific provide information on the temperature variability during time-windows of up to 6 years during the early- to mid-Holocene (Beck et al. 1997). The corals grew around 10,300 to 4,200 calendar years BP and the Sr/Ca signal suggests that SSTs during the early Holocene in this part of the tropics (~16°S) were about 6.5°C cooler than today, but increased abruptly during the following 1500 years.

A coral from Tasmaloum (Vanuatu) which grew around 4150 calendar years BP provides a 47-year record of SST variability based on coral Sr/Ca and U/Ca (Corrège et al. 2000). Composite coral Sr/Ca and U/Ca derived temperatures suggests that SSTs in the southwest tropical Pacific during the mid-Holocene were comparable to modern SSTs with respect to the mean as well as typical ENSO variability. However, the variability in the seasonal amplitude as well as interannual SST variability during the mid-Holocene were considerably stronger than today. The coral time series shows several prominent interannual cooling events occurring at decadal-scale intervals as well as a decadal-scale modulation of the seasonal cycle (Fig. 8). The results could be interpreted in a way that phase shifts in the ENSO mode similar to today also occurred during the mid-Holocene but probably with stronger exchanges between the tropics and the extratropics.

Combined $\delta^{18}O$ and Sr/Ca records derived from Great Barrier Reef corals (Australia) provide important information on the temperature and surface-ocean hydrologic balance during the mid-Holocene (Gagan et al. 1998). Coral Sr/Ca ratios indicate that the tropical western Pacific was 1°C warmer ~5350 calendar years BP ago. The residual coral $\delta^{18}O$ signal as derived from the difference between the Sr/Ca and $\delta^{18}O$ records indi-

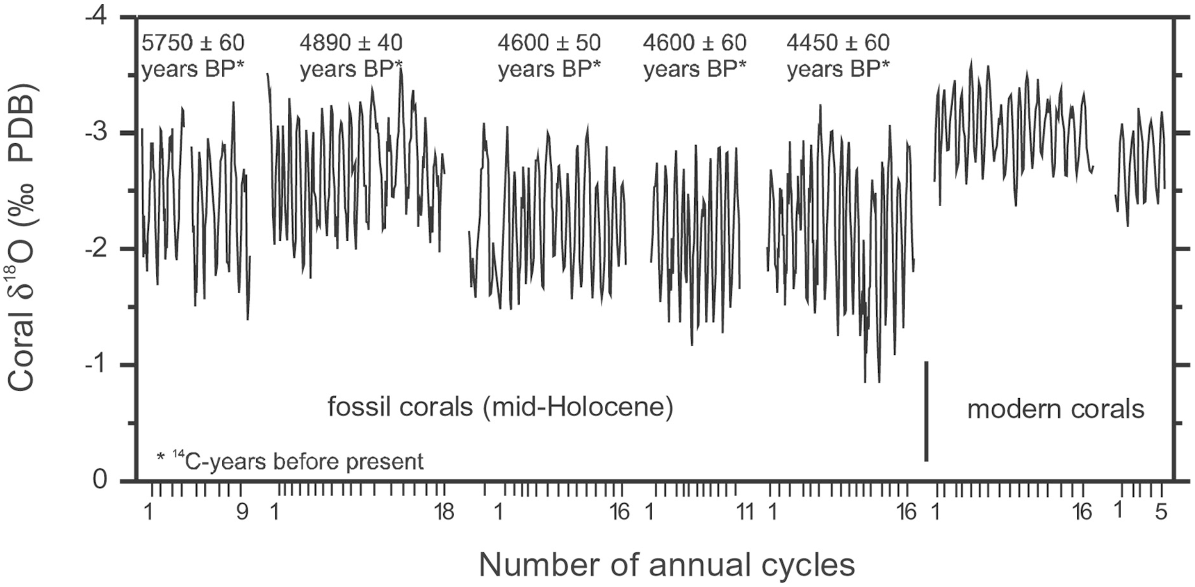


Fig. 7. Eilat coral $\delta^{18}O$ records from the northern Red Sea (Moustafa et al. 2000). Compared to modern corals the seasonal amplitude in corals which grew during the mid-Holocene is higher. This suggests a higher seasonal cycle in sea surface temperatures and changes in the precipitation and evaporation regime in this part of the Middle East compared to today.

cates that the $\delta^{18}O$ of the surface water was 0.5‰ higher relative to modern seawater. The results suggest that the higher temperatures increased the evaporation resulting in higher $\delta^{18}O$ seawater. This $\delta^{18}O$ seawater anomaly may have been sustained by transport of part of the additional water vapor to extratropical latitudes.

Pleistocene

Because the growth of reef-building corals is restricted to the surface ocean the dating of fossil corals from uplifted or submerged Pleistocene reefs can provide a record of sea-level fluctuations (Bard et al. 1990). Well-preserved fossil corals can provide records of climate variability during time-windows of the Pleistocene comparable in resolution and quality to those derived from modern corals. Next to the difficulties in finding a long-lived fossil colony, corals from uplifted Pleistocene reef terraces are often affected by diagenesis making them not suitable for paleoclimatic reconstructions based on stable isotopes or trace element.

Coral $\delta^{18}O$ and Sr/Ca records derived from cores recovered from the submerged Barbados offshore reefs indicate that SSTs in the western equatorial Atlantic were 5°C colder than present values during the last glacial maximum (LGM) 18,000 to 19,000 years ago (Guilderson et al. 1994), a finding in conflict with the CLIMAP reconstructions (CLIMAP Project 1976, 1981).

Coral $\delta^{18}O$ and Sr/Ca records derived from a fossil colony collected on an uplifted reef terrace on Bunaken Island, North Sulawesi (Indonesia), reflect interannual variability in precipitation and SST in the western equatorial Pacific during the last interglacial period 124,000 years ago (Hughen et al. 1999). The 65-year long coral time series reveals ENSO variability similar to the modern instrumental record. This indicates that ENSO was robust during the last interglacial, a time when global climate was slightly warmer than Holocene. However, changes in ENSO magnitude and frequency after 1976 appear different with respect to the earlier instrumental and last interglacial records. The results were interpreted to support the hypothesis that ENSO behavior in recent decades is anomalous with respect to natural variability.

A fossil coral from the uplifted reef terraces of the Huon Peninsula (Papua New Guinea) provides

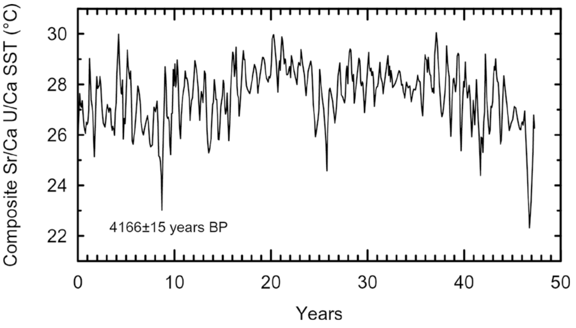


Fig. 8. The Tasmaloum composite sea surface temperature record derived from Sr/Ca and U/Ca analysis of a fossil coral from the southwest tropical Pacific (Corrège et al. 2000). Compared to today (not shown) the time series suggests a stronger SST variability with respect to seasonal amplitude and interannual variability as well as several prominent interannual cooling events during the mid-Holocene.

a record of SST from the western equatorial Pacific during the penultimate deglaciation around 130,000 years ago when sea level was 60 to 80 m lower than today (McCulloch et al. 1999). Coral $\delta^{18}O$ and Sr/Ca values indicate that SSTs were 6°C colder during the penultimate deglaciation than either last interglacial or present-day temperatures in this region of the tropics. The results again raise the question whether the tropics underwent significant cooling during glacial periods.

Deep-sea corals

In analogy to warm-water corals, solitary corals from the deep-sea can provide records of past climate and ocean variability. These non-reef-building (ahermatypic), non-photosynthetic corals usually live at depth of 500 to 2000 m. They are usually collected from the ocean floor by dredging. Therefore deep-sea corals provide one of the rare proxies to document past changes in intermediate and upper deep water masses which in turn can be related to changes in the surface ocean and the atmosphere (Smith et al. 1997; Adkins et al. 1998; Mangini et al. 1998).

Coupled ^{14}C and $^{230}Th/^{234}U$ dates from deep-sea corals can provide information about deep-water ventilation rates. Subtracting the $^{230}Th/^{234}U$-age (which represents the true age) from the ^{14}C-age (which represents the coral's age plus the age of the deep water) gives the age of the deep water at the time of coral skeleton precipitation. This age represents the time since the deep water had last contact to the air at the ocean surface, i.e. the deep-water ventilation age (Mangini et al. 1998). Multiple ^{14}C dates throughout the life span of a deep-sea coral can provide information about variations in the deep-water ventilation rate (Adkins et al. 1998). This method revealed that the ventilation rate of the North Atlantic upper deep water varied greatly during the last deglaciation and provided evidence that the deep ocean changed on decadal-centennial time scales during rapid changes in the surface ocean and the atmosphere 15,400 years ago (Adkins et al. 1998). Another method suggests that paleotemperatures can be estimated from the stable isotopic composition of deep-sea corals (Smith et al. 1997).

Open problems

Oxygen isotope signals

Coral skeletons are depleted in ^{18}O and ^{13}C with respect to isotopic equilibrium with the ambient seawater, i.e. compared to inorganically precipitated aragonite. This isotopic disequilibrium or vital effect is most likely biologically mediated and attributed to so-called "kinetic" isotope effects which apparently result from discrimination against the heavy isotopes of oxygen and carbon during the hydration and hydroxylation of CO_2 (Mc Connaughey 1989a). The isotopic disequilibrium appears to be constant over time along the major growth axis of an individual coral colony, where growth and calcification rates are at their maximum (McConnaughey 1989a; Guilderson and Schrag 1999; Linsley et al. 1999). Samples for stable isotope analysis are therefore taken along the major axis of coral growth following single fans of corallites.

The mean isotopic disequilibrium offset from seawater can vary significantly for individual corals living in the same environment (Guilderson and Schrag 1999; Linsley et al. 1999), even within the same species of *Porites* (Linsley et al. 1999). Apparently it cannot solely be attributed to intercolony differences in average growth rates. The reported differences of 0.2 to 0.4‰ for coral $\delta^{18}O$ equal 1-2°C in terms of temperature interpretation. Therefore, caution is required when quantifications about mean climatic conditions are being made by comparing $\delta^{18}O$ records from individual corals which grew at different locations or during different periods of time. Coral $\delta^{18}O$ provides an excellent proxy for variability but should not be considered as an absolute proxy for SST or $\delta^{18}O$ of seawater.

It has been speculated that at least some of the low-frequency variability observed in individual coral $\delta^{18}O$ records may originate not directly from climatic influences but from variations in the mean disequilibrium offset through time as a result of complex biological or ecological processes (Evans et al. 2000). Differences between seasonal and mean annual SST-coral $\delta^{18}O$ calibrations have also been reported implying a larger interannual to decadal coral-derived SST variability than indicated by the instrumental SSTs. Changes in sea surface salinity on these timescales have been suggested as one possible explanation (Quinn et al. 1998; Felis et al. 2000). However, long salinity time series to test this assumption are usually rare. A recent study using 40 years of salinity observations from the Fiji area showed that on the seasonal timescale coral $\delta^{18}O$ in this region is driven by changes in SST whereas on the interannual timescale it is almost exclusively affected by sea surface salinity variations (Le Bec et al. 2000).

Sr/Ca signals

In analogy to stable isotopes, Sr/Ca ratios in coral skeletons show a vital effect that produces disequilibrium with the ambient seawater compared to inorganically precipitated aragonite. Similar to kinetic effects on coral stable isotopes this vital effect was shown to be partly biologically controlled, e.g. responding to growth rate variations (de Villiers et al. 1994). However, as for stable isotopes, it was shown that the effects of growth and calcification rates on coral Sr/Ca can be neglected when sampling follows a major growth axis along single fans of corallites (Alibert and McCulloch 1997).

Apparently the coral Sr/Ca-temperature calibrations do not vary significantly for individual corals living in the same environment, not even between different species of *Porites* and colonies with different growth and calcification rates, provided sampling follows optimal growth regions (Alibert and McCulloch 1997). This could imply an advantage in using Sr/Ca compared to using coral $\delta^{18}O$ to reconstruct changes in absolute mean temperatures at a given location.

There are notable differences in the temperature calibrations between studies from different sites which remain to be solved. The difference in the offsets between the regression lines (not the slopes!) from these studies can lead to differences of up to 3.5°C in absolute temperature estimates (Gagan et al. 2000). The difference in the Sr/Ca ratio of the seawater as measured at modern oligotrophic reef sites in the Pacific and Atlantic can represent an uncertainity of 1.2°C in the Sr/Ca thermometer (de Villiers et al. 1994), and seawater Sr/Ca variations over the annual cycle can correspond to temperature variations of 0.7 °C. Seawater Sr/Ca changes during glacial conditions were suggested to result in potential errors of up to 1.5°C (Stoll and Schrag 1998). All this is critical to the applicability of coral Sr/Ca ratios as an absolute proxy of past SST variations.

Future directions

More multicentury coral records in seasonal or higher resolution from tropical and subtropical locations are necessary to provide a more complete picture on the global patterns of decadal- and longer-scale climate variability during the past centuries. Such proxy records are the only marine archive to understand climate variations on these timescales. Apparently a bimonthly sampling resolution for corals seems to be a good compromise with respect to significant detection of interannual and decadal variability as well as laboratory expenditure (e.g. Felis et al. 2000; Urban et al. 2000). Applying the double tracer technique of coupled $\delta^{18}O$ and Sr/Ca determinations which until now has been only used for short periods to such bimonthly-resolution coral records will provide insights into the variability of temperature and hydrologic balance at key locations of the global climate system during the past centuries. Similar to other fields of paleoclimatology a multi-proxy approach is recommended for coral research. The combination of different proxies will reduce analytical errors and improve paleo estimates for environmental parameters.

A promising trend is the reconstruction of SST fields based on multicentury coral records. Work on the reconstruction of the SST field in the Pacific basin by using available coral $\delta^{18}O$ data sets has already started (Evans et al. submitted). In this first appoach only the leading modes of large-scale variability which are both evident in instrumental climate data and coral $\delta^{18}O$ records are being reconstructed.

Another trend is the splicing of accurately dated fossil coral records of several decades length to create longer records covering parts of the last millennium (Cobb et al. 1999). However, this is a difficult task considering vital effects and other difficulties, e.g. the lack of significant event years which could provide tie points as well as the precipitation of secondary aragonite leading to slight dating uncertainties.

Another promising trend is the generation of decades- to century-long records from fossil corals collected from uplifted or submerged reefs. Such records will provide information on climate variability during the last interglacial, the last glaciation, the last deglaciation, and the Holocene comparable in resolution and quality to those derived from modern corals. This will enable the assessment of natural climate variability during periods with boundary conditions different from today. Fossil corals from the Pacific basin will provide new insights into the ENSO phenomenon (e.g. Hughen et al. 1999). Fossil corals from the northern Red Sea where modern corals were shown to be related to prominent modes of Northern Hemisphere climate variability (Felis et al. 2000; Rimbu et al. 2001) will provide information on the existence of North Pacific- or North Atlantic-based atmospheric teleconnections on Middle East climate variability, e.g. the NAO, during these periods of time. It is an intriguing question whether the NAO was active during the entire Holocene or during the last interglacial. Seasonal resolution coral records from the northern Red Sea could provide some answers.

Future coral studies should proceed along the frontiers of coral reef distribution. These areas seem to be quite sensitive to environmental change, since different limiting factors affect coral growth. Ocean areas that have not been extensively covered include the tropical eastern and western Atlantic. Coral reefs develop along the western boundary of the Atlantic from the Caribbean down to about 20°S on the Abrolhos platform, Brazil. The reef distribution along the eastern Atlantic is rather limited but reaches up to the Cape Verde Islands. Tropical coral records from both sides of the Atlantic basin are potential sources to reconstruct the history of tropical Atlantic climate variability (Chang et al. 1997). Future research should also exploit the potential of corals from rare subtropical/mid-latitude locations (e.g. Bermuda, northern Red Sea) to better understand past mid-latitude climate variability which is important with respect to present and future European climate. In addition, further coral research in the Indian Ocean will help to detect modes of ocean climate variability on the decadal scale. Recently, a dipole mode linking the eastern and western tropical Indian ocean has been suggested (Saji et al. 1999; Webster et al. 1999). Current research in deep-sea coral reefs will provide informations about the potential of non-zooxanthellate corals in climate research (Freiwald et al. 1997), especially along the European margin of the North Atlantic.

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