Climate Reconstructions from Annually Banded Corals

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Abstract. Instrumental observations are too short to resolve the full range of natural climatic and environmental change. Massive, annually banded corals from the tropical and subtropical oceans however, provide a means to reconstruct climatic conditions prior to the instrumental record. Isotopic and elemental tracers, incorporated into the carbonate skeletons of these corals during growth, provide proxies of past environmental variability of the surface ocean. Here we give an overview of the most frequently used coral based proxies reflecting variations in sea surface temperature (Sr/Ca, U/Ca, δ18O), hydrologic balance (δ18O), ocean circulation and upwelling (Δ14C), and terrestrial runoff (Ba/Ca) at seasonal resolution. We present coral based reconstructions of climatic and environmental change for the last few centuries, the last millennium, the Holocene, and the Pleistocene; with a focus on seasonal, interannual, and decadal scale climate variability. Finally, future directions in coral-based paleoclimatology are discussed.

Keywords: coral paleoclimatology, interannual variability, ENSO, AO/NAO, δ18O, Sr/Ca

1. INTRODUCTION

Instrumental climate records are too short to resolve the full range of seasonal, interannual, and decadal-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 Arctic Oscillation (AO)/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.

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 (CaCO₃) and grow at rates of millimetres to centimetres 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 precipitation, 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 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 subannual 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 a 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 not below 24°C and/or mean winter minimum temperatures are not below 18°C, i.e., roughly equatorwards of 23–24° 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, 2000; Charles *et al.*, 1997; Urban *et al.*, 2000; Cobb *et al.*, 2001). 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 to study 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; Kuhnert *et al.*, 2002), and ~28–29°N in the northern Red Sea (Felis *et al.*, 1998; Felis *et al.*, 2000; Rimbu *et al.*, 2001, 2003). 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 several decades throughout the last millennium (Kuhnert *et al.*, 2002; Cobb *et al.*, 2003a), the Holocene (Beck *et al.*, 1997; Gagan *et al.*, 1998; Corrège *et al.*, 2000; Moustafa *et al.*, 2000; Tudhope *et al.*, 2001; Abram *et al.*, 2003), and the last interglacial warm period (Hughen *et al.*, 1999; Suzuki *et al.*, 2001; Tudhope *et al.*, 2001).

The paper is organized as follows. In Section 2 the construction of the age model for coral chronologies is described. In Section 3 the main climate tracers which are used in coral-based paleoclimatology are introduced. In Section 4 important coral-based climate reconstructions are presented. Finally, in Section 5 recent directions in coral-based paleoclimatology are discussed. This paper is an updated version of two previously published review papers on the same topic (Felis and Pätzold, 2003, 2004). Its main intention is to provide scientists from
other fields (e.g., paleoclimatologists working on other climate archives, climate modellers) with basic information for a more efficient interpretation of coral-based climate reconstructions. Therefore, only the most commonly used isotopic and elemental tracers in coral-based climatology are described in detail. Criteria for the coral-based reconstructions presented here are their length and paleoclimatic implication as well as a seasonal resolution.

2. 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 millimetres 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 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 linear extension. The preliminary age model of a coral chronology is usually based on counting the annual density-band pairs, which are revealed by X-radiography. 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. Sometimes, seasonal cycles in measured variations of density (Lough and Barnes, 1997) or luminescence (Isdale *et al*., 1998) are also used for the development of an age model. Furthermore, characteristic patterns of distinct luminescent lines in coral skeletons associated with freshwater influx at some locations were used to improve the chronological control of coral records and to develop a master chronology (Hendy *et al*., 2003).

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 (Yokoyama and Esat, 2004). Because of this, the $^{230}$Th/$^{234}$U method was also applied to date young fossil corals from the last millennium (Edwards *et al*., 1988; Kuhnert *et al*., 2002; Cobb *et al*., 2003a, b). The dating of a fossil coral provides a floating chronology for which top and bottom ages are known only approximately.

3. CLIMATE TRACERS IN CORALS

3.1 Annual growth rates

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

The average annual calcification rate of several centuries-long coral records
from the Great Barrier Reef (Australia) was shown to provide a proxy for sea
surface temperature (SST) for the period 1746–1982 (Lough and Barnes, 1997).
One of these records extends back to the year 1479. The density variations were
measured by gamma densitometry and provided data for average annual density
and annual extension rate. These were used to estimate average annual calcification.
The calcification rate is the product of the linear extension rate and the average
density at which skeleton was deposited in making that extension. Interestingly,
the annual calcification rate was more strongly correlated with SST variations
compared to the annual extension rate (Lough and Barnes, 1997).

3.2 Oxygen isotopes

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

As temperature increases, there is a decrease in the $\delta^{18}$O (depletion in $^{18}$O)
of the coral skeletal aragonite. Near-weekly resolution calibrations of Porites
coral $\delta^{18}$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 $\delta^{18}$O records against local SST
anomaly which indicates a ratio of 0.19‰/°C (Evans et al., 2000).

Variations in the $\delta^{18}$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 also can play a
role. High evaporation results in both, an increase in the $\delta^{18}$O of the seawater and
a higher salinity; high precipitation or runoff have opposing effects.

Coral skeletons are depleted in $^{18}$O 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
(McConnaughey, 1989; Adkins et al., 2003). The isotopic disequilibrium is
assumed 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, 1989; Guilderson and Schrag, 1999; Linsley et al., 1999). However, long-term trends reported in some coral $\delta^{18}O$ based studies are consistent in sign but too large to be explained by observed changes in SST, seawater salinity, or rainfall over contemporaneous intervals, as emphasized by Evans et al. (2000). Therefore, it has been speculated that at least some of the low-frequency variability and long-term trends 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).

The mean isotopic disequilibrium offset from seawater can vary significantly for individual corals living at the same location (Guilderson and Schrag, 1999; Linsley et al., 1999; Felis et al., 2003). Therefore, caution is required when past mean climate conditions are estimated based on comparison of mean $\delta^{18}O$ values of modern and fossil corals even from the same area. Coral $\delta^{18}O$ provides an excellent proxy for variability but should not be considered as an absolute proxy for SST and/or $\delta^{18}O$ of seawater.

### 3.3 Stable carbon isotopes

The environmental interpretation of the ratios of the stable isotopic species of carbon ($^{13}C/^{12}C$) incorporated in coral skeletons, reported as coral $\delta^{13}C$, is complicated because of interactions with physiological processes such as symbiont photosynthesis and respiration (e.g., Grottoli and Wellington, 1999). Therefore the application of the coral $\delta^{13}C$ signal as a climate proxy has been hampered, despite the fact that $\delta^{18}O$ and $\delta^{13}C$ values are routinely produced together by mass spectrometry.

Several coral records indicate a long-term trend towards lower $\delta^{13}C$ (depletion in $^{13}C$) during the past centuries (e.g., Nozaki et al., 1978; Pätzold, 1986; Quinn et al., 1998). This trend most likely reflects the $\delta^{13}C$ of the dissolved inorganic carbon (DIC) of the seawater and is usually attributed to a corresponding trend in the $\delta^{13}C$ of atmospheric CO$_2$ owing to an increased anthropogenic release of $^{13}C$-depleted CO$_2$. However, the slopes of the trends differ among coral records even for individual corals from the same location (e.g., Guilderson and Schrag, 1999).

On the seasonal timescale coral $\delta^{13}C$ variations are thought to be mainly controlled by the photosynthetic activity of the coral’s endosymbiotic algae, and are therefore attributed to the seasonal light cycle, cloudiness or water column transparency (Fairbanks and Dodge, 1979; Pätzold, 1984; McConnaughey, 1989; Wellington and Dunbar, 1995). Periods of higher photosynthesis lead to higher $\delta^{13}C$ values in coral skeletons (Fairbanks and Dodge, 1979; Swart, 1983; McConnaughey, 1989). Therefore, the seasonal cyclicity in coral $\delta^{13}C$ is sometimes used for age model improvements of corals records where a clear cyclicity in coral $\delta^{18}O$ is absent due to local environmental conditions (e.g., Cole et al., 1993; Guilderson and Schrag, 1999; Urban et al., 2000).
At some locations, strong coral $\delta^{13}C$ signals with paleoceanographic implications can emerge. For example, a coral $\delta^{13}C$ record from the northern Red Sea documents interannual events of extraordinarily large plankton blooms caused by deep vertical water mass mixing in certain winters. This was attributed to 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).

3.4 The strontium/calcium (and uranium/calcium) ratio

Sr/Ca ratios in corals were shown to provide a promising proxy for water temperature variability (Beck et al., 1992; Mc Culloch et al., 1994; Alibert and McCulloch, 1997; Gagan et al., 1998). As temperature increases, there is a decrease in the Sr/Ca ratio of the coral skeletal aragonite. Apparently the coral Sr/Ca-temperature calibrations do not vary significantly for individual corals living in the same area (Alibert and McCulloch, 1997), but this has to be confirmed for other locations. However, there are still differences in the temperature calibrations between studies from different sites. The average of several coral Sr/Ca calibrations suggests a temperature dependence of 0.062 mmol/mol per 1°C (Gagan et al., 2000) and a more recent compilation shows a similar average slope (0.0597 mmol/mol per 1°C) of the calibration equations (Marshall and McCulloch, 2002). However, it is not known whether this coral Sr/Ca-temperature relationship is generally valid for Porites. Other temperature-sensitive trace elements incorporated in coral skeletons are Mg (Mitsuguchi et al., 1996) and U (Min et al., 1995; Shen and Dunbar, 1995). Recent studies revealed that U/Ca ratios in corals could provide a temperature proxy comparable in accuracy to Sr/Ca (Corrège et al., 2000; Corrège et al., 2001; Hendy et al., 2002) whereas Mg/Ca ratios probably do not (Schrag, 1999).

Sr/Ca ratios in coral skeletons show a vital effect that produces disequilibrium with the ambient seawater compared to inorganically precipitated aragonite. This vital effect was suggested to be partly biologically controlled (de Villiers et al., 1994) but can be probably neglected along the major growth axis of individual corals (Alibert and McCulloch, 1997). However, 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 (millions of years) the Sr/Ca ratios of seawater are supposed to be constant on glacial-interglacial timescales (e.g., Guilderson et al., 1994). In contrast, 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 (Shen et al., 1996). 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). All this is critical to the applicability of coral Sr/Ca ratios as an absolute proxy of past SST.
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; Hendy et al., 2002; Ren et al., 2002). 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.

3.5 Radiocarbon

Radiocarbon ($^{14}$C) incorporated in coral skeletons during growth reflects the $^{14}$C content of the 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 (e.g., Rodgers et al., 1997). 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 a standard.

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 recent 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 rates 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 tracer for advection (Guilderson et al., 1998; Guilderson et al., 2000).

3.6 The barium/calcium ratio

Ba/Ca ratios in corals can provide records of suspended sediment loads and hence in the nutrients entering reef areas as a result of river floods (McCulloch et al., 2003). Ba is desorbed from fine-grained suspended particles (clays) in the low-salinity region of the estuarine mixing zone. Thereafter Ba behaves as an essentially conservative dissolved tracer, being advected with the flood plume and incorporated into the coral skeleton in proportion to the ambient seawater concentration (McCulloch et al., 2003). Earlier studies used coral Ba/Ca to reconstruct the variability in upwelling of nutrient rich waters in the equatorial Pacific (Lea et al., 1989; Shen et al., 1992).
4. CLIMATE RECORDS FROM CORALS

4.1 Last centuries

Current paleoclimatic records which are based on $\delta^{18}O$, Sr/Ca, U/Ca, or $\Delta^{14}C$ determinations in modern corals do not extend back beyond the mid-16th century. 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 200 to 400 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 stable isotope records in annual resolution started in the 1980s with a coral from the Philippines (Pätzold, 1986). The longest coral stable isotope or trace element time series available are a 347-year record from Galápagos (Ecuador) (Dunbar et al., 1994) and a composite 420-year record from the Great Barrier Reef (Australia) (Hendy et al., 2002) with annual and 5-yearly resolution, respectively. Most recent studies exploit the clear seasonal resolution that corals can provide. However, of the published coral records which are currently archived in the World Data Center for Paleoclimatology only 8 have seasonal or higher resolution beyond 1850 (Fig. 1). The records in Fig. 1 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).

Subsequently, a $\delta^{18}O$ time series was generated from the Rarotonga record (Ren et al., 2002) which is not shown in Fig. 1. These coral records cover a latitudinal range of $\sim28^\circ$N to $\sim29^\circ$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 bimonthly resolution Ras Umm Sidd coral $\delta^{18}O$ record from the northern Red Sea (Sinai, Egypt) (Felis et al., 2000) extends back to 1750 and is correlated with instrumental observations of Middle East climate which in turn is related to large-scale Northern Hemisphere atmospheric variability. On interannual to multidecadal timescales the coral $\delta^{18}O$ variations apparently reflect varying proportions of both SST and $\delta^{18}O$ seawater variability. The narrow northern Red Sea represents a relatively continental setting which is strongly influenced by mid-latitude climate and is very sensitive to atmospheric processes due to a relatively weak stratification of the water column. Northern Red Sea SST and coral $\delta^{18}O$ variability are controlled by a high-pressure anomaly over the Mediterranean Sea associated with the AO/NAO which favours an anti-cyclonic flow of surface winds in the eastern Mediterranean, resulting in an advection of relatively cold air from southeastern Europe (Rimbu et al., 2001). Colder and more arid conditions in the northern Red Sea correspond to a high index state of the AO/NAO and vice versa (Fig. 3) (Felis et al., 2000; Rimbu et al., 2001). Strong correlations between the coral record and instrumental indices of AO/
Fig. 1. Coral δ¹⁸O and Sr/Ca records in seasonal or higher resolution extending back beyond 1850 which are archived at the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/corals.html). Thick white lines represent 3-year running means.
NAO, North Pacific climate variability, and ENSO are evident at interannual periods of 5–6 years (Felis et al., 2000). Further dominant oscillations in the coral time series with periods of about ~70 years and 22–23 years are probably related to variations in the North Atlantic thermohaline circulation (Delworth and Mann, 2000) and in the PDO (Mantua et al., 1997; Biondi et al., 2001), respectively. Large-scale Northern Hemisphere atmospheric variability is most strongly documented in the winter time series (January–February) of the Ras Umm Sidd coral $\delta^{18}O$ record (Rimbu et al., 2001), which contains also important information on the non-stationarity in the ENSO teleconnections over Europe and the Middle East during the pre-instrumental period (Rimbu et al., 2003).

The Secas Island coral $\delta^{18}O$ record (10 samples/year) from the eastern Pacific Ocean (Panama) (Linsley et al., 1994) primarily reflects $\delta^{18}O$ 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 $\delta^{18}O$ records from the western equatorial Pacific primarily reflect $\delta^{18}O$ 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 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 bimonthly resolution 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. 4). This coral-based reconstruction of ENSO extending back to 1840 suggests 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 monthly resolution Mahe coral δ^{18}O record from the western equatorial Indian Ocean (Seychelles) was suggested to primarily reflect variations in regional SST (Charles et al., 1997). Interannual variability in the coral time series is correlated with Pacific climate records suggesting a 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 δ¹⁸O record from Malindi (Kenya) (Cole et al., 2000).

A seasonally-resolved coral δ¹⁸O record from Espirito Santo Island (Vanuatu) in the western South Pacific (Quinn et al., 1996) documents the combined effects of SST and rainfall-induced salinity changes since the year 1807. The coral time series is dominated by decadal variability but unfortunately has several gaps.

The monthly resolution Rarotonga coral Sr/Ca record from the central subtropical South Pacific (Cook Islands) (Linsley et al., 2000) was suggested to provide a proxy for regional 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 the decadal variability which is observed in the Pacific Ocean (Linsley et al., 2000; Evans et al., 2001).

The seasonal resolution Amedee Lighthouse coral δ¹⁸O record from the western South Pacific (New Caledonia) (Quinn et al., 1998) is correlated with variations in local and regional 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 bimonthly resolution Houtman Abrolhos Islands coral δ¹⁸O 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. A coral Sr/Ca, U/Ca, and δ¹⁸O record from the Great Barrier Reef (Australia) with 5-yearly resolution provides information on SST and salinity variations in the southwestern Pacific since the year 1565 (Hendy et al., 2002). The composite 420-year coral time series indicates that SST and salinity were higher in the 18th century than in the 20th century. An abrupt freshening accompanied by a cooling is observed after 1870. These findings are supported by other coral-based reconstructions from the southwestern Pacific (Druffel and Griffin, 1993; Quinn et al., 1996, 1998; Linsley et al., 2000). It was suggested that the reconstructed higher salinities during the period 1565–1870 were due to the combined effect of advection and wind-induced evaporation as a result of a stronger latitudinal temperature gradient and intensified circulation during the so-called Little Ice Age (Hendy et al., 2002).
The longest coral-based $\Delta^{14}C$ 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. 5).

The Galápagos coral $\Delta^{14}C$ record from the eastern equatorial Pacific (Ecuador) (Guilderson and Schrag, 1998) documents the seasonal upwelling of low $\Delta^{14}C$ 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 $\Delta^{14}C$ water is reduced. The coral record shows that $\Delta^{14}C$ values during the upwelling season increased abruptly after the El Niño event of 1976. This suggests a reduction in the contribution of 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.

A coral Ba/Ca record provides information on the sediment flux to the inner Great Barrier Reef (Australia) as a result of river floods for the period 1750–1998 (McCulloch et al., 2003). The coral time series has an approximately weekly resolution and was generated by using laser ablation inductively coupled plasma mass spectrometry specifically adapted for coral studies. Following the beginning of European settlement a substantially increase in the delivery of sediments is recorded after about 1870. This was attributed to land-use practices associated with European settlement leading to degradation of the semi-arid river catchments.

4.2 Last millennium

Because modern corals are usually not growing for more than 200 to 400 years, fossil corals provide an opportunity to reconstruct climate variability during time-windows throughout the last millennium. However, fossil corals from the early- and mid-last millennium that provide records of several decades or more are quite rare. One possible reason could be that, in the living reefs, most dead corals are rapidly affected by bioerosion.

A seasonal-resolution coral $\delta^{18}O$ and Sr/Ca record from Bermuda in the subtropical North Atlantic provides information on regional SST variability for an 84-year time window during the 16th century (Kuhnert et al., 2002). This record was generated from a dead coral which has been subsequently overgrown by a living coral. The dead section was dated with the $^{230}Th/^{234}U$ method and covers the period 1520–1603 (±15 years). An oscillation in this 16th-century
coral $\delta^{18}O$ time series with a period of ~7.8 years is also observed in regional SSTs during the last century where it is associated with the AO/NAO. The results suggest that similarly to present-day the AO/NAO was influencing Bermuda SSTs at interannual to decadal timescales during this period of the Little Ice Age.

Monthly resolved coral $\delta^{18}O$ records from Palmyra Island provide information on climate variability in the central tropical Pacific and ENSO for time windows during the last 1100 years (Cobb et al., 2001, 2003a). Next to a record of a modern coral these records were generated from storm-derived deposits of fossil corals collected from ocean-facing beaches. The individual fossil corals provide time windows of 30–90 years. Based on high-precision $^{230}\text{Th}/^{234}\text{U}$ dates (Cobb et al., 2003b) and high coral-to-coral reproducibility the splicing of overlapping coral $\delta^{18}O$ sequences provided four time windows of up to 150 years starting in the year 928. The coral records indicate relatively cold and dry mean climate conditions during the 10th century and increasingly warmer and wetter conditions in the 20th century. However, the behaviour of ENSO is poorly correlated with these estimates of mean climate, with the most intense ENSO activity occurring during the mid-17th century. The Palmyra coral records imply that the majority of ENSO variability over the last millennium may have arisen from dynamics internal to the ENSO system itself (Cobb et al., 2003a).

4.3 Holocene

Well-preserved fossil corals can provide records of climate variability comparable in resolution and quality to those derived from modern corals for time-windows throughout the Holocene. However, finding a fossil Holocene coral that provides a century-long record is even more difficult than finding a comparable modern coral in the living reefs. Fossil corals are usually collected from uplifted or submerged reefs mostly by drilling. The chance to recover a long core along the major growth axis of a single coral by drilling into a fossil reef flat is rather small. Direct collection or coring of individual fossil colonies in the field might provide a better solution but is possible only at some rare locations.

The nearly monthly resolved Eilat coral $\delta^{18}O$ records from the northern Red Sea (Israel) show an increased seasonality 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 $^{14}\text{C}$ years before present (BP). The results suggest an increased SST seasonality and/or changes in the seasonal cycle of evaporation and/or precipitation relative to present-day during periods of the mid-Holocene.

Monthly-resolved coral Sr/Ca records from the southwest tropical Pacific (Vanuatu) 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 ($\sim 16^\circ S$) were about 6.5°C cooler than today, but increased abruptly during the following 1500 years. However, this result needs verification.
A coral from Tasmaloum (Vanuatu) which grew around 4150 calendar years BP provides a monthly resolved 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. 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 δ¹⁸O and Sr/Ca records in fortnightly resolution 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 δ¹⁸O signal as derived from the difference between the Sr/Ca and δ¹⁸O records indicates that the δ¹⁸O 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 δ¹⁸O seawater. This δ¹⁸O seawater anomaly may have been sustained by transport of part of the additional water vapor to extratropical latitudes.

Fortnightly to weekly resolved coral Sr/Ca- and δ¹⁸O-based SST reconstructions from western Sumatra (Indonesia) document anomalous upwelling events during periods of the mid-Holocene associated with the so-called Indian Ocean Dipole (IOD). The reconstructed mid-Holocene IOD events exceed the strong 1997 event in magnitude (Abram et al., 2003). However, coral reef mortality as observed during this modern event is not documented for the past 7000 years, as inferred from the absence of growth unconformities in a suite of 48 coral cores.

4.4 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; Gallup et al., 1994; Chappell et al., 1996; Stirling et al., 2001; Yokoyama et al., 2001; Lambeck et al., 2002; Cutler et al., 2003). Furthermore, 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 elements.
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 4.5–5°C colder than present values during the late glacial and the last glacial maximum (LGM) 18,000 to 24,000 years ago (Guilderson et al., 1994, 2001), a finding in conflict with the CLIMAP reconstructions (CLIMAP Project, 1976, 1981).

A suite of fossil corals from the uplifted reef terraces of the Huon Peninsula (Papua New Guinea) provides information on ENSO-related rainfall and SST variations in the western Pacific Warm Pool for time windows of several decades during the last 130,000 years (Tudhope et al., 2001). The bimonthly to monthly resolved coral $\delta^{18}O$ records suggest that ENSO was active at interannual timescales even during periods of high latitude glaciation and substantially lower global sea level (38,000–42,000, 85,000, 112,000, and 130,000 years ago). The coral records suggest that ENSO variability was relatively weak during the mid-Holocene but strongest during the 20th century with respect to the past 130,000 years. A combined effect of ENSO dampening during glacial conditions and ENSO forcing by precessional orbital variations was suggested to explain the observed changes in amplitude (Tudhope et al., 2001). Coral Sr/Ca values of one of these corals 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 (McCulloch et al., 1999). This result again raises the question whether the tropics underwent significant cooling during glacial periods. However, the coral Sr/Ca values may overestimate the cooling by 1–3°C (Tudhope et al., 2001) due to proposed glacial-interglacial changes in oceanic Sr/Ca (Stoll and Schrag, 1998).

Monthly resolved 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 behaviour in recent decades is anomalous with respect to natural variability.

A coral $\delta^{18}O$ record of a fossil colony from Ryukyu Islands (Japan) in the northwest Pacific indicates an increased seasonality during the last interglacial (127,000 years ago) relative to modern corals from the region (Suzuki et al., 2001), most likely resulting from SST changes. This increased seasonality, which is also observed in the $\delta^{13}C$ data of the 10-year long coral time series, was attributed to an enhanced seasonal cycle of insolation on the Northern Hemisphere at that time, resulting from changes in the Earth’s orbital parameters.

It was suggested that the atmospheric $\Delta^{14}C$ is linked to abrupt changes in oceanic ventilation which occurred during the last deglaciation, and that these
variations can be reconstructed from fossil corals cross-dated by radiocarbon and the $^{230}$Th/$^{234}$U method (Bard, 1998). The $\Delta^{14}C$ of fossil corals from Huon Peninsula (Papua New Guinea) was used to reconstruct changes in atmospheric radiocarbon during periods of the Pleistocene (Yokoyama et al., 2000; Yokoyama and Esat, 2004). Peaks of coral $\Delta^{14}C$ which are related to episodes of sea-level rise and reef growth at Huon Peninsula appear to be synchronous with Heinrich events and concentrations of ice-rafted debris in North Atlantic sediments. It was suggested that the connection factor between these events is the interruption of the North Atlantic thermohaline circulation following periodic partial disruptions of the Laurentide ice sheet.

5. DIRECTIONS IN CORAL-BASED PALEOClimATOLOGY

More multicentury coral records in at least seasonal resolution are necessary to provide a more complete picture on global patterns of seasonal, interannual, and decadal-scale climate variability during the last millennium. Apparently a bimonthly sampling resolution for long coral cores seems to be a good compromise with respect to significant detection of climate variability on these timescales as well as laboratory expenditure (e.g., Felis et al., 2000; Urban et al., 2000). Applying the double tracer technique of combined $\delta^{18}O$ and Sr/Ca (or U/Ca) determinations to multicentury coral records will provide insights into the variability of temperature and hydrologic balance at key locations of the global climate system during the past millennium (e.g., Linsley et al., 2004).

Most multicentury coral records are from sites in the equatorial or subtropical southern Pacific, and have provided the opportunity for a coral $\delta^{18}O$-based reconstruction of SST fields in the Pacific basin for the period 1607–1990 (Evans et al., 2002). The network of multicentury coral records in the Indian and especially the Atlantic Ocean is still sparse but work is in progress. Recent work from the northernmost Red Sea, one of the rare subtropical/mid-latitude locations of coral growth has shown the potential of multicentury coral records to provide information on past AO/NAO-related atmospheric variability over the Northern Hemisphere (Felis et al., 2000; Rimbu et al., 2001, 2003).

The advantage of coral records compared to other natural climate archives is a clear seasonal resolution. The disadvantage is that records generated from living corals usually extend back for a few centuries only, with a maximum of 420 years reported for a climate reconstruction from the Great Barrier Reef (Hendy et al., 2002). One approach to solve this problem is splicing together records of fossil corals from the last millennium (Cobb et al., 2003a), but this will probably be possible only at some rare sites. Another approach is to use slow-growing corals that have the potential to provide continuous climate records spanning up to 1000 years (Watanabe et al., 2003). However, ongoing work on such slow-growing corals in the Atlantic Ocean, where fast-growing corals are relatively rare, has shown that the extraction of climatic information can be complicated.

Decades- to century-long records of fossil Holocene and Pleistocene corals can provide information on seasonal to interannual climate variability for time
windows during glacial-interglacial cycles (Tudhope et al., 2001). This enables the assessment of natural variability of the climate system on these timescales during periods with boundary conditions and forcings different from present-day, and is critical for evaluating and improving climate models (Trenberth and Otto-Bliesner, 2003).

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