Annually-banded corals as climate proxies.

'White Paper' for Trieste Meeting, 9-11 June 2008

Kim Cobb, Julie Cole, Janice Lough and Sandy Tudhope

UNDERLYING RATIONALE: As they grow, corals record in the chemistry and structure of their skeletons information about the temperature and composition of the water in which they live. This attribute, combined with rapid growth rates (commonly 10-20mm/year), the presence of annual skeletal banding, the longevity of individual colonies (commonly >100 years, exceptionally >200 years), the fact that the skeletons are suitable for high-resolution ^{14}C and U-series dating, and the multiple geochemical climate proxies that can be applied to coral aragonite make corals exceptional archives of tropical climate information, with the potential to produce ~ monthly resolution records back into the late Quaternary. Here we focus on uncertainties in the climatic interpretation of coral records, and suggest some strategies for reducing these uncertainties.

CORALS USED FOR PALAEOCLIMATE RECONSTRUCTION: To date, most coral palaeoclimatology has focussed on the skeletons of massive (dome-shaped) reef-building corals belonging to the genus *Porites*. Most of the following discussion relates to these *Porites*-based records. However, there is considerable potential to develop the use of other long-lived (but often slower-growing and less abundant) coral genera (see recommendations below).

I. CORAL CHRONOLOGICAL UNCERTAINTIES:

Annual banding: The massive reef-building corals typically used for palaeoclimate reconstruction have annual banding in the structure and composition of their skeletons. In areas of strong seasonality this banding (e.g., in skeletal density, geochemistry and/or luminescence) is often very clear, allowing robust annual chronologies to be developed. However, in regions with little or no seasonality, the annual banding may be muted, leaving considerable scope for uncertainty in the establishment of an annual chronology. In such cases, researchers must rely on detecting seasonality in geochemical and/or isotopic timeseries. Most coral researchers tie their chronologies to the instrumental record back to 1850, looking for characteristic climate events such as large El Nino's, etc. Prior to 1850, the potential to add and/or drop years increases significantly, such that chronological uncertainties accumulate at an approximate rate of up to 2-3 years per century (i.e. a coral band-counted date of 1800AD might be anywhere from 1797 to 1803). The potential to date coral sequences with high-precision U/Th dates exists, and could improve such chronological uncertainties (U/Th dates could deliver a date of 1800AD +/- 1yr). Cross-dating between modern coral records has great potential, as most Indo-Pacific sites contain similar records of large ENSO activity. Such an exercise has not been attempted, however, largely because it has been difficult to estimate real-world chronological uncertainties for modern coral records (most researchers maintain that their older records are absolutely-dated, implying zero age errors).

A further source of uncertainty stems from the fact that while most corals grow year-round, those that grow in locations marked by strong seasonality may exhibit seasonal growth-rate variations (usually faster growing in summer and slower in winter). Therefore, strategies need to be developed to convert proxy records to equivalent 'monthly' records (i.e., to avoid over-representation of high-growth rate conditions).

ADDITIONAL SOURCES OF CHRONOLOGICAL UNCERTAINTY: In addition to the aforementioned problems with corals in areas of little or no seasonality, uncertainties arise in establishing robust chronologies from corals with complex growth forms, corals that have experienced partial mortality (and subsequent re-growth over a formerly dead area of skeleton), and around borings of organisms that live within the growing coral (some bivalves, shrimps and polychaete worms). This is particularly problematic for fossil corals, whose quality has been eroded by extended exposure to bio-erosion and/or mechanical erosion.

STRATEGIES FOR REDUCING CHRONOLOGICAL UNCERTAINTIES: The most important tool for reducing uncertainties in coral chronologies is via replication and cross-dating, borrowing from proven techniques in dendro-chronology. Cross-dating could be pursued on either a site-by-site basis or a regional multi-site basis. Secondary recommendations include: avoid corals with borings and complex growth forms; in areas where the annual nature of banding is unproven, use vital staining (e.g., alizarin) over a few-year period to establish the timing of band formation; where applicable (typically at sites marked by significant terrigenous input), use distinctive patterns of luminescent banding to establish and cross-check chronologies between nearby corals.

Floating chronologies and cross-dating with sub-fossil corals: High precision U-series dating can yield absolute ages of corals with a 2-sigma age uncertainty close to 0.5% of the age, e.g., ±5 years at 1000 years old. Therefore, old dead corals may be used to extend the record of climate into the late Quaternary. The dated records may be used as floating chronologies with associated age uncertainties, or in the case of abundant corals closely spaced in time, extended absolute chronologies (age uncertainties approach zero years when multiple corals are overlapped, as in tree ring dendrochronology) may be established through matching distinctive inter- and intra-annual banding patterns in geochemistry and/or luminescent banding between corals. These approaches have been successfully demonstrated, but require considerable commitment of resources.

II. UNCERTAINTIES IN CLIMATE RECORDS FROM CORAL SKELETAL CHEMISTRY:

The most commonly used climate proxies in corals are the stable oxygen isotopic composition of the skeleton, and the trace and minor element composition. Here we focus on the oxygen isotopic composition ($\delta^{18}O$) and Sr/Ca ratios of coral skeletal aragonite, which are proxies for SST/hydrology and SST, respectively Skeletal Mg/Ca and U/Ca have also been proposed as SST proxies, but significant uncertainties still surround the true environmental significance of these elements. Other trace and minor elements and isotopes are potentially useful for reconstructing terrestrial inputs (e.g., Ba/Ca), upwelling (e.g., Ba/Ca), ocean circulation (e.g., ^{14}C), and pH (e.g., boron isotopes), but are beyond the scope of this White Paper which focuses on temperature and hydrological ("precipitation") proxies.

Climate records from coral skeletal $\delta^{18}O$: Variations in the $\delta^{18}O$ (oxygen isotopic) composition of coral aragonitic skeletons are closely related to changes in the temperature of the water, and changes in the isotopic composition of the water. ***Temperature*:** Despite the fact that the coral skeleton is several permil offset from the equilibrium values of $\delta^{18}O$ in aragonite (see below), many empirical studies have demonstrated that the slope of the temperature-dependent oxygen isotopic fractionation between sea water and coral aragonite is close to the non-biogenic fractionation of about -0.2 ‰ /°C. ***Water composition:*** On short (seasonal –interannual) timescales, the oxygen isotopic composition of seawater is mainly controlled by the local evaporation-precipitation balance and the isotopic composition of the rainfall. On this basis, coral $\delta^{18}O$ records from areas of little SST variation have been used to reconstruct qualitative changes in rainfall. However, mixing and lateral and horizontal advection in the near surface ocean, and changes in water vapour transport between ocean basins, likely play more important roles in controlling water composition on longer (e.g., decadal-millennial) timescales. (Changes in global land-based ice volume become important on still-longer timescales).

Climate records from coral skeletal Sr/Ca:
The coral skeletal Sr/Ca ratio is considered to be a more direct measure of water temperature, an interpretation which is based on temperature dependent changes in the Sr/Ca of inorganic aragonite and an ever-growing body of empirical coral-based calibrations. Although this relationship appears to

be strong and robust in some cases, the mechanisms responsible for the temperature relationship remain relatively poorly understood, and some non-temperature-related artefacts have been noted.

SOURCES OF UNCERTAINTY IN $\delta^{18}O$ AND Sr/Ca-BASED CLIMATE RECONSTRUCTIONS:

- ***Analytical uncertainty:*** The 2-sigma uncertainty on a single $\delta^{18}O$ analysis is less than 0.1 ‰, i.e., less than 0.5° C equivalent. Likewise, the analytical uncertainty in a single Sr/Ca measurement is generally less than 0.5°C equivalent. With multiple measurements (e.g., replicate analysis of the same sample, or combining the results of analyses of 'monthly' growth increments to produce a seasonal average) this analytical uncertainty is easily reduced still further. Thus, analytical uncertainty is not the limiting factor for coral palaeoclimate reconstructions.
- ***Between-coral offsets:*** For reasons that remain poorly understood, the absolute $\delta^{18}O$ composition of coral colonies from the same island has been found to differ by up to about 0.3 ‰, far larger than can be explained by the relatively small differences in either water $\delta^{18}O$ composition and/or temperature that generally exist in open ocean reef settings. This is equivalent to a temperature uncertainty of about 1.5 °C. Some of this reported between-coral difference in absolute $\delta^{18}O$ could potentially be related to the following three factors.
- ***Coral growth location:*** Corals collected from areas of restricted access to the open ocean, for example from lagoons or from intertidal/very shallow subtidal reef flats, may well record environmental conditions that are not representative of the regional climate (the usual 'target' for palaeoclimate reconstruction). For example, poor mixing with the open ocean could result in seawater $\delta^{18}O$ anomalies that are several tenths of per mil offset from open ocean values, due to an excess of precipitation and/or evaporation. Most researchers make every effort to collect modern corals from open ocean settings. Where fossil corals are *in situ* it is often possible to estimate the palaeo-setting in terms of water depth and location on the reef based on growth form, species composition and reef morphology. However, it is impossible to know the palaeo-setting of dislodged and transported fossil corals.
- ***Growth form and coral growth-rate:*** empirical studies have indicated that the most robust climate records are retrieved from analysis of material sampled along the vertical axis of maximum growth. If material is sampled from the sloping sides of corals or from areas representing deep depressions on the former surface of the coral, then the $\delta^{18}O$ composition can sometimes be affected by up to a few tenths permil $\delta^{18}O$ (isotopically heavier on the sides). Sr/Ca values are also sometimes affected. The reasons for these differences are not well understood. One study has also shown that 'scars' around parrot fish bites can alter bulk $\delta^{18}O$ composition of the coral skeleton, although this is not a common problem. Growth rate also impacts coral $\delta^{18}O$ and Sr/Ca composition, particularly when growth rates dip below 5-10mm/yr. Most coral reconstructions are conducted on faster-growing corals with extension rates between 10 and 20 mm/yr, so this pitfall is typically easily avoided.
- ***Post-depositional alteration of the skeleton:*** Diagenesis can alter the bulk skeletal $\delta^{18}O$ and Sr/Ca by adding phases (often secondary aragonite or calcite cements) with a different isotopic and Sr/Ca composition. Diagenesis has been documented in living coral colonies that are <50 years old, but is far more common in fossil corals, which have been exposed to precipitation and/or seawater for centuries to millennia. In extreme cases diagenesis can result in artefacts equivalent to well over 1°C; Sr/Ca is particularly susceptible to even small amounts of diagenesis. Very few researchers take the trouble to thin-section their corals prior to analysis, which while not 100% fool-proof, represents the best way to detect early diagenesis of the coral skeleton. This is particularly problematic in old corals that extend back beyond 1900AD, and most likely has impacted the magnitude and shape of secular trends in some published coral $\delta^{18}O$ and Sr/Ca records, as it has gone largely undetected.
- ***Temperature reconstruction:*** To date, there are relatively few long (>100 year) records of coral skeletal Sr/Ca from which to derive SST reconstructions. Therefore, most coral-based temperature reconstructions are based on skeletal $\delta^{18}O$. The largest source of uncertainty in reconstructing monthly-centennial timescale changes in sea surface temperature from coral $\delta^{18}O$ is related to potential changes in seawater $\delta^{18}O$ composition. 'Local' calibration and verification of coral skeletal $\delta^{18}O$ against instrumental-based records of SST can provide an empirical

approach to address the problem, but has some significant drawbacks. In particular, although the relationship between changes in SST and water composition may be relatively stable and robust on short (e.g., seasonal – interannual) timescales in those parts of the tropical oceans where rainfall amount is closely related to SST, these relationships will not necessarily hold on longer timescales (e.g., decadal-centennial) where other processes such as ocean mixing and advection may be more important. Thus, while it may be possible to distinguish seasonal to interannual changes in SST vs. hydrology by combining coral $\delta^{18}O$ records with instrumental SST, it is impossible to reconstruct the magnitude of SST trends from coral $\delta^{18}O$ alone, given the large errors associated with trends in the instrumental SST databases.

STRATEGIES TO REDUCE TEMPERATURE RECONSTRUCTION UNCERTAINTIES:

- ***Replicate coral cores:*** many of the aforementioned sources of uncertainty can be significantly reduced by the simple strategy of ensuring replication of coral records within sites. This allows the quantification of uncertainties related to within- and between-coral differences (e.g., growth form effects, un-correlated diagenetic artefacts; chronological uncertainties), as well as uncertainties in the climate variable being reconstructed (through calibration and verification with instrumental data).
- ***Avoid corals from restricted locations**:* Because coral records from any kind of restricted environment bring with them an additional and poorly constrained uncertainty in how well they record regional-scale climate information, they should be avoided if at all possible. Where they are used, this must be clearly recorded in the accompanying metadata (see below).
- ***Combine Sr/Ca and $\delta^{18}O$ analyses*** to yield separate estimates of SST and seawater $\delta^{18}O$. Because coral Sr/Ca is not affected by hydrological processes, it can be used to quantify the SST contribution to coral $\delta^{18}O$, thus allowing for the quantification of the hydrological contribution to coral $\delta^{18}O$. This is particularly important for the reconstruction of low-frequency temperature trends (i.e. decadal to secular trends). Furthermore, given the increasing focus on hydrological shifts associated with climate changes, knowledge of low-frequency hydrological variations from the coral network would be particularly important.
- ***Instrumentation:*** Deploy instruments at coral coring sites to continuously record temperature and (ideally) conductivity (~salinity) over 5-10 year periods to quantify the relationship between conditions at the coral and the more regional-scale climate parameters of interest. Additionally, few seawater $\delta^{18}O$ samples have been collected across the tropical oceans, such that the relationship between seawater $\delta^{18}O$, salinity, and large-scale climate changes is difficult to study. Such information is critical to placing better constraints on existing long coral $\delta^{18}O$ reconstructions, almost all of which do not have Sr/Ca counterparts.
- ***Metadata:*** The utility of coral records would be greatly enhanced through the systematic collection and reporting of appropriate metadata. *Field data should include:* precise location; water depth wrt tidal datum; reef environment; angle of core (usually vertical); any instrumental data or data from analysis of water samples collected in the vicinity. *Lab-based data should include:* X-radiograph and natural light photographs of the slabbed coral cores showing the sampling trace for geochemical analysis; an overlay of these photographs indicating the chronology (and a description of how this was arrived at); thin section and SEM photographs of representative sections of the core to establish the potential for diagenetic artefacts; and the location and with whom the coral core is stored.
- ***Screen for diagenesis*** including routine SEM and thin section analysis, as well as XRD. Such analyses should be conducted at regular intervals down-core (ideally every 20-30 years).

III. UNCERTAINTIES IN CLIMATE RECORDS FROM CORAL GROWTH RATES:

The annual density banding visible in x-rays of coral slices can be used to extract three measures of coral growth: a) linear extension rate, which, where clearly present, can be simply measured from the x-rays, b) annual skeletal density, which requires either gamma or optical densitometry and is, therefore, less commonly measured, and c) calcification rate, the multiple of average density and linear extension. Average *Porites* linear extension and calcification rates are strongly linearly related

(84% variance explained) to average annual sea surface temperatures (SSTs) when examined spatially across Indo-Pacific reef sites. The temporal relationship between coral extension and calcification rates and SSTs is much weaker, ~30% variance explained or less. Thus coral growth rates on their own are not particularly good proxies for reconstructing past SSTs. This is partly attributed to difficulties in obtaining accurate annual growth measurements (see below) and that the $CaCO_3$ skeleton is the integrated result of many biological and environmental factors affecting the coral.

The geochemical tracers (discussed above) are, therefore, likely to provide more reliable environmental and climatic proxies than obtainable from coral growth rates. At the same time, coral growth rates can modulate the climatic/environmental signals in the geochemical tracers, e.g. equally-spaced sampling can be compromised by faster growth rates in summer compared to winter etc. It would, therefore, be a useful adjunct to geochemical analyses to routinely measure and report coral growth rates (at the very least, linear extension rates).

It should also be noted that historical information about coral calcification rates is growing in importance. This is due to the projected effects of progressive ocean acidification (due to oceanic absorption of ~ 30% excess atmospheric CO_2) on the ability of marine calcifying organisms, such as corals, to form their calcium carbonate skeletons.   There is, therefore, an ongoing need to capture historical and current trends in massive coral growth rates as there is already some disturbing evidence of declining coral growth rates despite continued ocean warming.

SOURCES OF UNCERTAINTY IN USING CORAL GROWTH RATE FOR ENVIRONMENTAL RECONSTRUCTION:

- Several factors are known to impact on coral growth rate including physical variables (e.g., temperature, light, water turbulence and turbidity), chemical variables (e.g., carbonate ion saturation) and other factors such as disease and state of reproduction. Therefore, it is not possible to use changes in growth rate alone to unambiguously reconstruct any single variable.
- X-rays and densitometry are typically applied to coral slices ~7mm thick which, in the commonly used Indo-Pacific massive *Porites*, includes several individual coral polyps. As a consequence of this "averaging" through the thickness of the slice, these growth variables are commonly distorted by changes in coral architecture and orientation of the growth axes. Caution is, therefore, required in interpreting these growth records at interannual or higher-resolution time scales.
- Even within on site, there are relatively large inter- and intra-colony differences in growth rate such that it is not possible to use measurements from single cores to extract useful environmental information.

STRATEGIES FOR REDUCING UNCERTAINTY IN USING CORAL GROWTH RATE FOR ENVIRONMENTAL RECONSTRUCTION:

- sample replication is key to obtaining reliable measures of coral growth rates.

IV. UNCERTAINTIES IN CLIMATE RECORDS FROM CORAL LUMINSCENCE:

When placed under ultra-violet light some corals show bright luminescent lines that have been shown to be related to freshwater flood events and can, therefore, provide a proxy for river flow and rainfall in tropical environments. These luminescent lines have been most successfully applied to climate reconstructions in the highly seasonal and highly variable rainfall regime of northeastern Australia. Visually the banding can be exceptionally clear and show a very high degree of reproducibility amongst different coral samples, thus allowing very reliable reconstructions. Much can be obtained from visual assessment of the occurrence and intensity of the lines. Routine measurement procedures are, to date, very limited in application.

SOURCES OF UNCERTAINTY IN CORAL LUMISCENCE-BASED RECONSTRUCTIONS OF CLIMATE:

- Although luminescent banding in inshore corals is clearly related to rainfall and runoff events in northeastern Australia, in other areas coral luminescent banding is independent of rainfall and runoff and may be associated with incorporation of marine humic compounds.
- There is also some evidence of long-term decline in measured luminescence that can compromise the interpretation of reconstructions. The causes of this measured decline are, as yet, unclear and not clearly related to, for example, degradation of humic acids (the likely cause of coral luminescent lines) through time (for which the trend, would be an increase towards the younger part of the skeleton).

STRATEGIES TO REDUCE UNCERTAINTY IN CORAL LUMINESCENCE-BASED RECONSTRUCTIONS OF CLIMATE:
- Replication and quantification of records
- At each site/region, a systematic assessment of the relationship between coral luminescence and environmental variables.

DEVELOPING A SAMPLING AND ANALYTICAL STRATEGY FOR REGIONAL-TROPICAL CLIMATE RECONSTRUCTION:

Several studies have already demonstrated the potential of using a network of coral records to reconstruct regional-tropical SST. There remains great potential to expand this approach in space and time through a co-ordinated approach. This approach should include:

- careful consideration of the spatial density of records required to achieve robust reconstruction of a region or feature of the climate system. This may be achieved through analysis of the instrumental record and through use of climate models. Use of fully coupled climate models with oxygen isotopes included as tracers could further help in the interpretation of, and quantification in uncertainty of records based of coral $\delta^{18}O$.
- recognition that longer coral records are likely to come from locations with relatively cooler average annual SSTs than in the warmest parts of the tropical oceans. Tapping this resource will help reduce uncertainty in 15th-18th century climate reconstruction where the number of records available is currently the main limiting factor.
- develop other long-lived but slower-growing annually-banded coral genera as climate proxies to replicate and extend *Porites*-based records.
- combined with the above, careful consideration of the degree of replication (with two cores/site considered the bare minimum of replication requirements) required within each site to achieve the desired precision and chronological accuracy in the reconstructed parameter, and to enable the quantification of uncertainties (i.e. move coral palaeoclimatology towards a dendroclimatology model)
- an efficient and co-ordinated strategy to replicate key coral records and quantify temperature vs. hydrological contributions to these key coral records (through paired analysis of Sr/Ca and $\delta^{18}O$)
- an efficient and internationally co-ordinated strategy for the field collection of samples that ensures collection of appropriate metadata, appropriate handling and storage of the samples, systematic deployment of appropriate environmental loggers and collection of water samples, and efficient use of ship-time resources to maximise value for money.
- the systematic analysis of all coral records (published and underway) for diagenetic alteration, and the archiving of such results alongside coral proxy data (if not in the publication itself).
- the development of a coral database that includes all appropriate metadata associated with published coral records (water depth, X-rays, chronological information, sampling transects, diagenesis-related studies, etc)