

Dendroclimatology underwater: Australian coral records from 1565AD

E.J. Hendy

Lamont Doherty Earth Observatory, Columbia University, Palisades NY 10964, USA

Email: ejhendy@ldeo.columbia.edu

Introduction

Replication of records from within individual trees, between multiple trees, and between sites, is fundamental to dendroclimatology because it allows explicit quantification of the strength of common growth forcing and chronology confidence (Fritts 1976). The same approach is applied in this study of multi-century records replicated between coral colonies, which demonstrates the reproducibility of coral-based tracers and reveals the common environmental signals on decadal to century timescales. The massive aragonitic skeleton formed by coral colonies of *Porites* sp. accumulates at ~1 cm/year and archives physiological, isotopic and elemental tracers that vary with changes in sea surface temperature (SST), salinity, rainfall and river runoff, sediment input, upwelling and/or shifts in water mass circulation. Sub-annual sampling also allows the reconstruction of short-term events e.g. individual river floods, in continuous records that can span many centuries. The development of such high resolution, multi-century, tropical ocean surface climate reconstructions is critical to understanding the role of the tropical ocean and atmosphere in global climate variability. Global climate anomalies originating from the tropics include high frequency perturbations like the El Niño Southern Oscillation (Allan et al. 1996), to the Pacific Decadal Oscillation (Latif and Barnett 1994, Trenberth and Hurrell 1994, Power et al. 1999) and millennial scale impacts (Cane and Clement 1999, Clark et al. 2002).

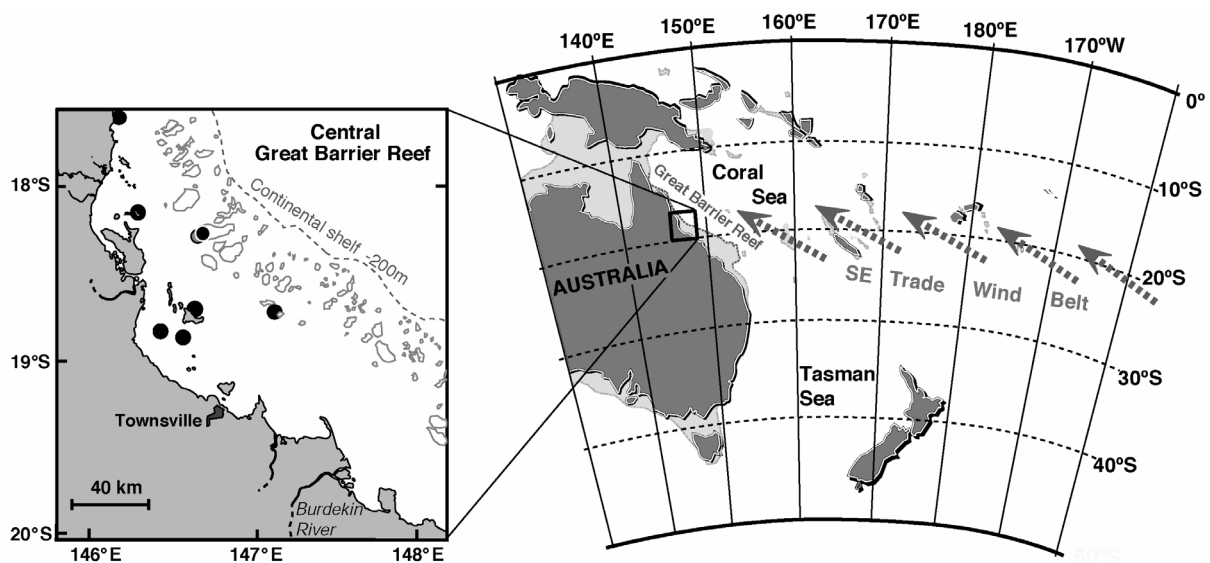


Figure 1: The reef locations of the eight coral cores used in this study, from the Central Great Barrier Reef, Australia.

Study outline

Accurate error estimates need to be established for coral-based climate reconstructions, and to do this requires the examination of fundamental issues including:

- (1) age control
- (2) signal reproducibility, and
- (3) tracer behaviour, and therefore interpretation, over the timescale to be reconstructed.

This study addressed all of these issues by adapting dendroclimatological approaches to coral reconstructions with particular attention to low frequency variability. The study used eight cores taken from *Porites* sp. colonies growing within a 60km radius in the Great Barrier Reef, Australia (Fig. 1). The coral cores spanned the period 1565 to 1985 AD (Fig. 3A).

Age control of coral records: cross-dating, historical die-offs and rainfall extremes.

Absolute age control was critical for parts 2 and 3 of this study. The accuracy of traditional methods of assigning years to coral proxy-climate records, such as counting skeletal density bands, had not been previously established, but typical error estimates are quoted as 1-2 years per century. In this study, UV luminescent lines caused by annual river floods and associated with the Australian summer monsoon, were used as a second marker to assign years to the eight multi-century coral cores. Cross-dating techniques were adapted from dendrochronology and applied to characteristic patterns of luminescent lines visible in the coral skeleton under UV light (e.g. Fig. 2, full details in Hendy et al. 2003a). The timing, width and intensity of the luminescent bands correlate strongly with summer monsoonal rainfall and the magnitude of coastal discharge from Queensland's largest river, the Burdekin (Isdale 1984, Lough 1997, Isdale et al. 1998).

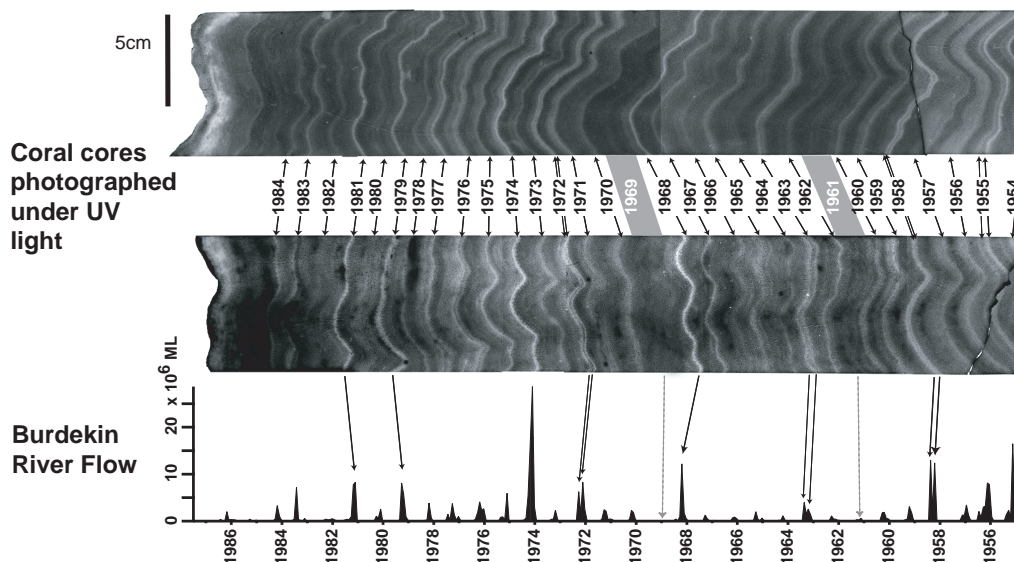


Figure 2: Black and white photomontage of luminescent lines in two coral core slabs under UV light, compared with the Burdekin River discharge record (1955-1985). The two cores were collected from inshore central GBR reefs, 120 km (top core) and 170 km (lower core) north of the Burdekin River mouth (Fig. 1).

Following methods developed in tree-ring studies, skeleton-plots of luminescent banding were produced for each core and combined into a master luminescence chronology giving annual and absolute precision back to 1615 AD. A 373-year cross-dated chronology was developed (Fig. 3B), despite gaps between core sections, growth hiatuses and patches of complex growth orientation within individual cores. Discrepancies of up to 15 years relative to previously published chronologies for these cores (e.g. Lough and Barnes, 1997, Isdale et al. 1998) demonstrate the need for a more rigorous dating approach in coral research. Cross-dating also highlighted sampling errors where a core section had been inverted before labeling. Problems inherent in dating a single coral core, such as difficult growth orientation, skeletal discontinuities and breaks between core sections, were also resolved by cross-dating, for example a 3-year gap was identified between two sections of one core.

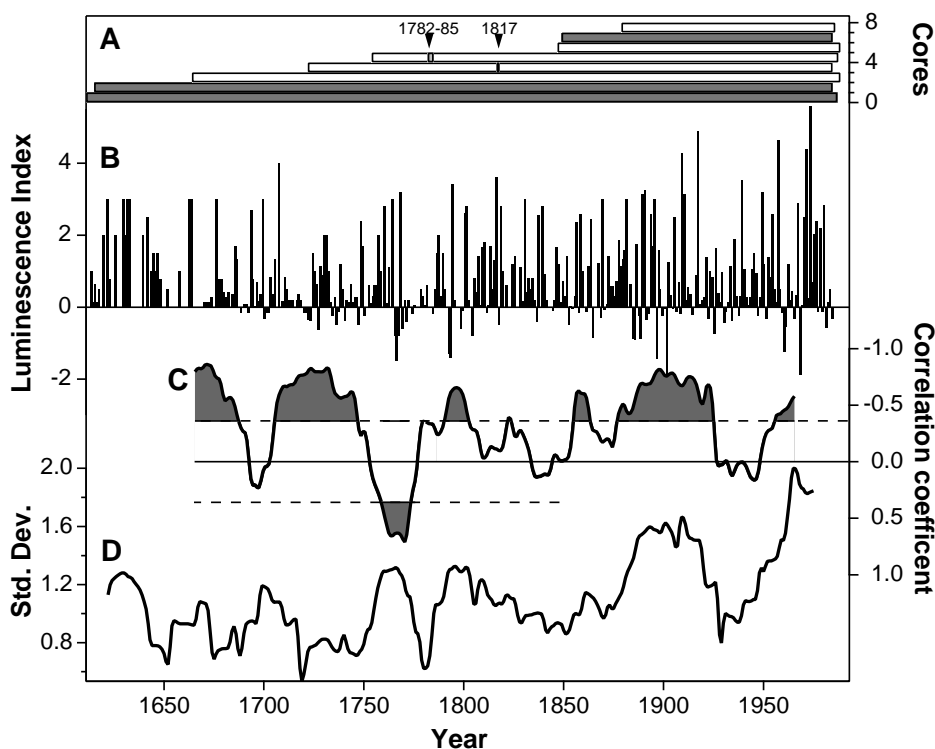


Figure 3: (A) The number of coral cores contributing to the study through time separated into inshore reef locations (white) and midshelf reefs (shaded dark grey). Growth hiatus scars are also marked. (B) Luminescence master chronology for the central Great Barrier Reef, 1612-1850 AD. (C) Cross correlations between the luminescence master series and NINO3 SST reconstruction (Mann et al., 2000) for 30-year sliding windows (shaded areas are where the relationship is significance at 0.05 level). (D) Interannual variability of the luminescence master series expressed as the standard deviation of the series calculated over a 20-year sliding window. Further details are given in Hendy et al. 2003a and 2003b.

The luminescent master chronology provides a reconstruction of regional rainfall and river runoff. It was significantly correlated with the instrumental record of Burdekin River flow ($r=0.82$, 1894-1985 extended using rainfall records, Isdale et al. 1998), and Lough's (1997) index of Queensland summer rainfall ($r=0.65$, 1891-1985). The master luminescence chronology also provides evidence for the non-stationary nature of ENSO teleconnections

with the Australian Monsoon (Hendy et al. 2003a). Years with a marked absence of luminescence coincide with many historical drought records from the western Pacific and these often occur during ENSO events. However, the relationship between ENSO events occurring in the equatorial Pacific and climatic anomalies in ENSO-sensitive regions, like NE Australia, is non-stationary. For example, during the 1920s to 1950s ENSO activity was reduced, ENSO teleconnections with sensitive regions were weak to non-existent, and Australia experienced prolonged drought conditions with reduced interannual rainfall variability (Allan et al. 1996). The off-on relationship between NE Australian rainfall and ENSO can be observed in the shifting correlation between the luminescence master chronology and the Mann et al. (2000) NINO3 reconstruction (Fig. 3C). For much of the period from the 1650s to 1800s, 1870s to 1920s and 1950s onwards ENSO-related teleconnections were a dominant factor in NE Australian rainfall variability. The relationship breakdown recognized in the instrumental record for the 1920s-50s is reproduced, and an analogous period is highlighted from the 1800s to 1870s (Fig. 3C). As in the 1920s-1950s, there is a reduction in interannual and interdecadal variability between 1800 and 1870 (Fig. 3D). The positive trend in interannual variability towards the present suggests an increasing number and amplitude of extreme rainfall events. This long-term trend, however, is biased prior to 1750 because the earlier period is dominated by less sensitive records from midshelf sites, which only experience the more extreme river floods.

Reproducibility of low frequency variability in multi-century coral records

A suite of geochemical tracers was measured from each of the eight cores, including oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotopes, and trace element ratios, strontium/calcium, uranium/calcium and barium/calcium (Hendy 2003). Measurements were made in 5-year increments, and where possible samples of the same time period were duplicated within cores by taking contemporaneous samples from different growth axes. A basic principle of dendroclimatology, the aggregation of a number of records into one common master series to enhance common environmental signals (Cook and Kairiukstis 1989), was applied in the construction of master records for each coral geochemical tracer (e.g. Sr/Ca and $\delta^{18}\text{O}$ records in Fig. 4). This was the first quantitative analysis of coral tracer reliability over decadal-to-centennial timescales, and the results highlight that it is critical to replicate information from multiple coral colonies in order to reliably reconstruct the paleoclimate signal (Hendy et al. 2002). For example, the variability between individual Sr/Ca records was large in comparison to the desired signal on interdecadal to century timescales, and for this reason a single core on average accounted for only a third of the variance contained in the master Sr/Ca record. The $\delta^{18}\text{O}$ records were more consistent between cores in terms of relative trends on both decadal and century scales, and on average a single record reconstructed over 70% of the composite record. Anomalous periods when $\delta^{18}\text{O}$ records did not reproduce were valuable markers of artifacts (e.g. skeletal diagenesis or unusual growth). Confidence estimates for each of the composite records were used to demonstrate the reproducibility of coral tracer signals over multi-decadal to century timescales and show that coherent regional-scale information is being replicated between coral colonies (Fig. 4).

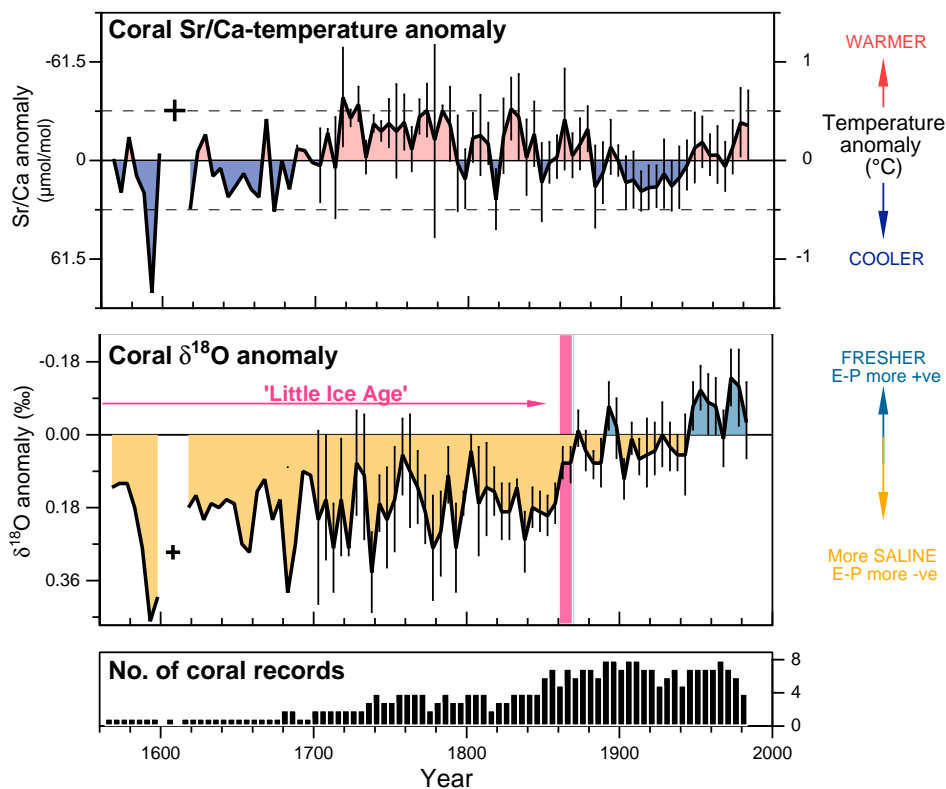


Figure 4: The Sr/Ca (upper panel) and $\delta^{18}\text{O}$ (middle panel) composite master records with 95% confidence envelope. A temperature slope calibration of $-62 \mu\text{mol/mol Sr/Ca per } ^\circ\text{C}$ (Alibert and McCulloch 1997, Gagan et al. 1998) is used to convert Sr/Ca anomalies (left axis) to sea surface temperature anomalies (right axis). The number of coral cores contributing to each 5-year average are given in the lower panel. More details are provided in Hendy et al. 2002.

Verification of the coral palaeo-environmental reconstructions on decadal to century timescales

The interpretation of proxy records is complicated because tracers can respond to a number of environmental variables, and different variables can dominate over different timescales. In addition, the climate-related mechanism that produces the coral geochemical signal is often uncertain. The master records for each geochemical tracer were verified against local and regional-scale instrumental records using previously published calibrations developed from short high-resolution records. For example, the Sr/Ca record (Fig. 4 upper panel) successfully reconstructs the 0.7°C warming (1905-1985) observed in the local ($146^\circ\text{E } 18^\circ\text{S}$) GISST2.2 series (Rayner et al. 1996, $r=0.68$, $p<0.005$).

Through the measurement of multiple geochemical tracers it is possible to separate competing environmental influences on tracer variability. For example, coral $\delta^{18}\text{O}$ records are difficult to interpret because $\delta^{18}\text{O}$ is influenced by both salinity and SST, but the replication of multiple tracers allows a comparison of the proposed sea surface temperature-tracers (Sr/Ca, U/Ca, $\delta^{18}\text{O}$) and the freshwater flux tracers ($\delta^{18}\text{O}$, Ba/Ca and luminescence). The similarity of the freshwater flux signals between $\delta^{18}\text{O}$, Ba/Ca and luminescence, and the poor correlation between parallel Sr/Ca and $\delta^{18}\text{O}$ records (Fig. 4) demonstrated that the $\delta^{18}\text{O}$ was

dominated by changes in the evaporation-precipitation balance on decadal-century timescales, not by temperature.

The last five centuries: the demise of the 'Little Ice Age' and the 20th century warming

In global and hemispheric-scale composite reconstructions of palaeotemperature the anomalous warmth of the 20th century contrasts dramatically with the millennium-scale cooling trend that culminated in the 'Little Ice Age' (LIA) between the 15th and late 19th centuries (Bradley, 2000, Jones et al., 2001, Mann et al. 2000). Glacial advances in both hemispheres (Grove, 1988) and enhanced polar atmospheric circulation (Kreutz et al., 1997) suggest that the LIA was a global-scale event, though cooler conditions were possibly restricted to higher latitudes (Rind, 1998, 2000). Coral provide one of the few tropical climate reconstructions of this period.

The GBR coral proxy records of SST anomalies (from Sr/Ca, Fig. 4 top panel) and sea surface salinity anomalies ($\delta^{18}\text{O}$, Fig. 4 middle panel) suggest that a dramatic shift occurred in the tropical ocean-atmosphere system at the end of the LIA (Hendy et al., 2002). The striking 0.2‰ shift in $\delta^{18}\text{O}$ from the 1850s to modern values in the 1870s indicates an abrupt shift to lower salinities, and this signal is seen simultaneously in coral $\delta^{18}\text{O}$ records across the Pacific and Indian Oceans from latitudes within the trade wind belts (e.g. Druffel and Griffin 1993, Quinn et al. 1993, Linsley et al. 1994, Quinn et al. 1998, Kuhnert et al. 1999). The late 19th century abrupt transition in the ocean-atmosphere freshwater flux coincides with a sudden weakening of atmospheric circulation, including the trade winds, and surface driven ocean currents. At the same time, the glacial retreat signaling the end of the LIA occurs during a recovery to warmer conditions at the higher latitudes, but tropical cooling according to coral SST records (Linsley et al. 2000, Hendy et al. 2002). These results support the scenario that a stronger latitudinal temperature gradient and intensified Hadley circulation occurred during the LIA. Evaporation and condensation processes are extremely effective mechanisms for transporting and redistributing energy on all scales. Increased salinities from 1565 to 1870 in sites within the trade-wind belt are consistent with an intensified Hadley circulation impacting E-P and enhancing poleward moisture transport. More tropical palaeoclimate reconstructions are required to improve our understanding of the nature of the LIA and possible role of the tropics. This study shows how a replicated coral-based multi-tracer approach, and the application of lessons learnt from dendroclimatology, can provide paleoclimate information on multiple components of the tropical ocean-atmosphere system.

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