Coral microatoll reconstructions of El Niño-Southern Oscillation: New windows on seasonal and interannual processes

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***Porites* coral microatolls show $\delta^{18}O$ signal reproducibility and fidelity comparable to more conventional coral growth forms. Longer-lived and fossil microatolls, which grow in suitably flushed environments, contain $\delta^{18}O$ signals that can significantly extend instrumental records of the El Niño-Southern Oscillation.**

Porites corals are the most commonly used genus for reconstructing El Niño-Southern Oscillation (ENSO). This hermatypic coral is found in all tropical reef environments (Veron 2000) with a variety of growth forms. Climate reconstructions of a century or more have been obtained from the most common, dome-shaped *Porites* growth form, whereby the colonies, beginning from the substrate, grow outward and upward towards the ocean surface (Knutson et al. 1972). Domed structures, however, are not the only *Porites* growth form.

Coral microatolls

Porites coral microatolls are found on shallow reefs where reef topography enables individual colonies to grow up to the average spring low tide level. Further upward growth is limited due to exposure of the upper coral surface at low tide (Stoddart and Scoffin 1979). At this point, the coral then grows laterally, resulting in a flat-topped discoid growth morphology termed "microatoll" (Fig. 1).

Coral microatolls can live for decades to many centuries (McGregor et al. 2011a), are distributed broadly across the Indo-Pacific region (Scoffin and Stoddart 1978), and their preservation potential is particularly high due to the possibility for rapid burial beneath sand and coral rubble through storm ridge or beach deposition. Microatolls provide information about past water levels, from which sea level, climatic, or tectonic histories have been derived (Natawidjaja et al. 2004; Sieh et al. 2008; Smithers and Woodroffe 2001; Taylor et al. 2008, 1987; Woodroffe and McLean 1990; Woodroffe et al. 2012; Zachariasen et al. 1999). Microatolls also have the advantage of sampling a narrow depth range over long periods of time, which is desirable when reconstructing depth-dependent, ENSO-related variables, such as sea surface temperature (SST) and sea surface salinity (SSS), together with changes in ocean dynamic height, in the tropical Pacific.

Studies of domed *Porites* show that there can be significant differences in skeletal $\delta^{18}O$ on the sides and tops of the corals and this is equally a concern for laterally-growing microatolls (e.g. Cohen and Hart 1997; McConnaughey 1989). However, testing of $\delta^{18}O$ variability within and between *Porites* sp. microatolls living on reef flats around Kiritimati (Christmas) Island in the central Pacific ocean, demonstrates no significant differences between $\delta^{18}O$ records from different growth orientations within a single microatoll, or between records from microatolls in different reef settings (McGregor et al. 2011b). Moreover, $\delta^{18}O$ records from microatolls and from conventional domed *Porites* from elsewhere on the atoll (Evans et al. 1998b; Nurhati et al. 2009) also show similar patterns and magnitude of variability. Together, the results show that *Porites* microatolls can be used interchangeably with dome-shaped corals to reconstruct tropical climate variability.

ENSO and $\delta^{18}O$ in modern microatolls at Kiritimati Island

Kiritimati Island is optimally located (Evans et al. 1998a) for reconstructions of ENSO. The island lies within the dry equatorial zone of the central Pacific, and in the NINO3.4 index region where SST variations define ENSO events (Bjerknes 1969; Ropelewski and Halpert 1987). In this region El Niño events result in marked positive SST anomalies of up to 3°C in the boreal winter, whereas La Niña events produce negative SST anomalies of 1-2°C (Wyrtki 1975; Fig. 2a). Rainfall also shows a dominant ENSO signal with higher annual precipitation during El Niño years.

Porites microatolls from Kiritimati register these climatic variations. Variations in a composite (stacked) monthly microatoll $\delta^{18}O$ record spanning the years 1978-2007 show a strong inverse correlation of r = -0.71 with SST and records major El Niño events (McGregor et al. 2011b; Fig. 2a). This is similar to findings for domed-*Porites* from Kiritimati where 70% of the variance is shared with SST (Evans et al. 1999). The stacked microatoll $\delta^{18}O$ record

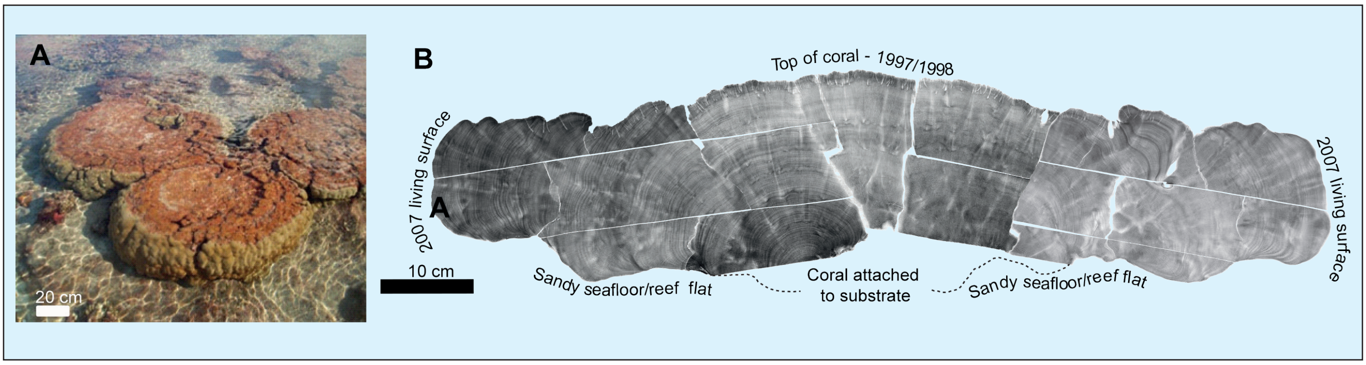

Figure 1: Porites coral microatoll image and X-radiograph. ***A)*** *Porites coral microatolls on a reef flat at low tide.* ***B)*** *Positive X-radiograph cross- section through a Porites microatoll. Dark and light bands are the high and low-density bands, respectively, that form as the coral grows. Starting from the center, the coral grows upwards until further upward growth is constrained by exposure during the minimum low water level (in this case, 1997/1998). Lateral growth then ensues resulting in a discoid microatoll structure. The location of the living surface in 2007 when the coral was collected is indicated. Dashed lines indicate the outline of coral pieces not X-rayed.*

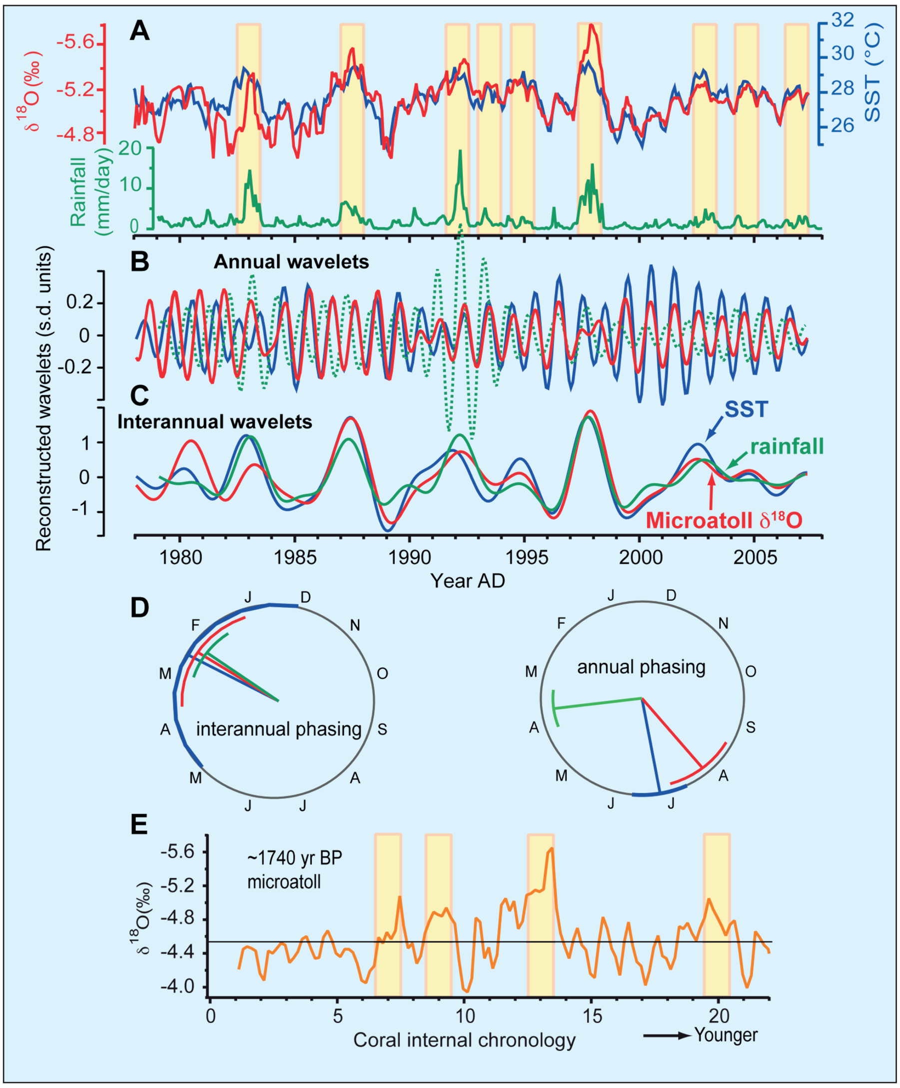

Figure 2: Variability of Kiritimati Island records. ***A)*** *Comparison of the stacked microatoll δ18O record (red line) with Kiritimati SST (blue line) and monthly rainfall (green line). The stacked δ18O is a composite of three microatoll records from Kiritimati. The microatoll δ18O record is strongly anti-correlated with Kiritimati SSTs (r = -0.71) and is sensitive to El Niño events (yellow bars).* ***B)*** *Annual-scale and* ***(C)*** *interannual-scale wavelets for the stacked microatoll δ18O (red, y-axis inverted), SST (blue), rainfall (green).* ***D)*** *The circular phase plots show the calendar month (and 95% confidence intervals) when, on average, the wavelets in B) and C) reach their maximum value. In general the microatoll δ18O record tracks SST variations. The rainfall is in phase with the SST and coral δ18O data at the interannual scale, but is out of phase at the annual scale.* ***E)*** *Profile of a δ18O microatoll from Kiritimati dated at ~1740 yr BP, placed on a new floating age scale (unpublished data) that shows El Niño events (yellow bars) similar to those of the past few decades. Black horizontal line is the mean δ18O. Figure modified after McGregor et al. (2011b), and Woodroffe and Gagan (2000). SST and rainfall data from ERSSTv3b (Smith et al. 2008) and GPCPv2 (Adler et al. 2003), respectively.*

also corresponds with anomalously high rainfall years (Fig. 2a); annual mean coral δ18O values of less than -5.3‰ are found only in years when total annual rainfall is above 1800 mm. In addition to local SST and rainfall, the microatoll δ18O signal is also negatively correlated with both SST and precipitation amount over a broad area of the equatorial Pacific (McGregor et al. 2011b). Since most of the covariance between δ18O, SST and precipitation is due to ENSO, the spatial correlations reflect the characteristic ENSO pattern.

ENSO and seasonal cycle variance patterns

Understanding ENSO annual and interannual cycle variance and interactions can provide important information on ENSO processes (Guilyardi et al. 2009). ENSO variance is recorded in the stacked microatoll δ18O record. The record (Fig. 2b,c) tracks SST variability at interannual (ENSO; 53% of the δ18O variance) and annual timescale (14%), consistent with existing analyses of instrumental tropical Pacific SSTs (Chiu and Newell 1983). Changes at annual and interannual scales at Kiritimati are reminiscent of the climate signal of the eastern equatorial Pacific (Chen et al. 1994; Mitchell and Wallace 1992).

ENSO events occur irregularly every 2-8 years, yet individual events show a distinctive SST pattern tied (or "phase-locked") to the seasonal cycle, such that El Niño SST anomalies peak during the boreal winter (DJF). The interannual component of SST and rainfall records for Kiritimati Island show maxima in February, as does microatoll δ18O (Fig. 2d). At the annual scale, the microatoll δ18O, which peaks in July-August, varies predominantly in-phase with SST, rather than with rainfall. The annual maximum in Kiritimati rainfall occurs in March-April, due to the position of the Intertropical Convergence Zone (ITCZ) (An and Choi 2010; Horel 1982; Mechoso et al. 1995; Waliser and Gautier 1993). That the microatoll δ18O tracks SST at the annual and interannual scale is important; SST variations in the NINO3.4 Index region are used to define ENSO variations. Accordingly, microatoll δ18O from the NINO3.4 region, such as Kiritimati Island, can be used to reconstruct past ENSO variations at multiple timescales.

ENSO signal in fossil microatoll δ18O

Fossil *Porites* microatolls, which were growing in well-flushed environments, offer opportunities to reconstruct tropical SST and ENSO variability beyond the limits of the instrumental record. Initial studies confirm reduced ENSO variability during the middle Holocene (Woodroffe et al. 2003). Individual ENSO events in the late Holocene (Fig. 2e) however, appear at least as intense as those experienced in the past two decades (Woodroffe et al. 2003). One particular El Niño event from 1740 yr BP (Fig. 2e) shows a negative δ18O excursion to ~5.6‰, which suggests substantial addition of 18O-depleted rainfall (Woodroffe and Gagan 2000). The stronger ENSO in the late Holocene may represent tighter coupling in the Pacific between the more southerly ITCZ, the east Pacific cold tongue and the Southern Oscillation, which could amplify ENSO precipitation variability and associated teleconnections. Such a scenario is consistent with terrestrial paleoclimate records indicating a marked increase in El Niño activity from ~3000 yr BP. We are undertaking further analysis of fossil coral microatolls and their annual and interannual variability to test this scenario.

Note

Data are archived at WDC-paleoclimatology http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:4336223539645946::::P1_STUDY_ID:12278

Selected references

Full reference list online under:
http://www.pages-igbp.org/products/newsletters/ref2013_2.pdf

Evans MN, Kaplan A, Cane MA (1998a) *Paleoceanography* 13: 502-516

Mitchell TP, Wallace JM (1992) *Journal of Climate* 5: 1140-1156

McGregor HV et al. (2011b) *Geochimica et Cosmochimica Acta* 75: 3930-3944

Woodroffe CD, Gagan MK (2000) *Geophysical Research Letters* 27(10): 1511-1514

Woodroffe CD, Beech MR, Gagan MK (2003) *Geophysical Research Letters* 30, doi: 10.1029/2002GL015868