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Mayotte coral reveals hydrological changes in the western Indian Ocean between 1881 and 1994

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[1] We reconstruct the hydrologic history of the tropical western Indian Ocean by calculating the $\delta^{18}\text{O}_{\text{seawater}}$ from coupled coral Sr/Ca and $\delta^{18}\text{O}$ measurements in a massive *Porites* coral from Mayotte (Comoros) between 1881 and 1994. We found that the precipitation-evaporation balance varies naturally on time scales of 5–6 years and 18–25 years. High (low) SSTs are associated with positive (negative) $\delta^{18}\text{O}_{\text{seawater}}$ implying that atmospheric variability is linked with remote climate modes in the Indian Ocean and the tropical/extratropical Pacific Ocean. Warm El Niño-Southern Oscillation events are associated with a negative freshwater balance at Mayotte. This case study demonstrates that a much denser network of $\delta^{18}\text{O}_{\text{seawater}}$ reconstructions is crucial for understanding the spatial patterns of hydrological conditions. **Citation:** Zinke, J., M. Pfeiffer, O. Timm, W.-C. Dullo, D. Kroon, and B. A. Thomassin (2008), Mayotte coral reveals hydrological changes in the western Indian Ocean between 1881 and 1994, *Geophys. Res. Lett.*, 35, L23707, doi:10.1029/2008GL035634.

1. Introduction

[2] Future global warming will trigger significant changes in surface temperature and the hydrological cycle, with both combined leading to uncertain societal and environmental consequences. For the Indian Ocean and the adjacent continents the IPCC's latest AR4 projections show a large spread [Annamalai *et al.*, 2007]. Precipitation over the oceans has a complex spatial structure and often differs from trends in underlying sea surface temperature (SST) [Kumar *et al.*, 2004]. Over the western Indian Ocean, instrumental data is too sparse to investigate the rainfall/temperature response over the ocean on interannual to multidecadal time scales [Annamalai *et al.*, 1999; Deser *et al.*, 2004]. Satellite-borne rainfall measurements, which provide high spatial coverage over the oceans, are not available before 1979, a period too short to reduce the uncertainty in the trend estimates.

[3] However, the stability of the ocean-atmosphere coupling in a changing climate is important for future climate

projections. Long proxy records with sufficient temporal resolution are the only alternative to assess the stability of such connections.

[4] The close link between SST and the El Niño-Southern Oscillation (ENSO) in the western Indian Ocean north of 10°S is confirmed by a number of coral records [Charles *et al.*, 1997; Cole *et al.*, 2000; Timm *et al.*, 2005; Zinke *et al.*, 2005; Pfeiffer *et al.*, 2006], while the response of the hydrological cycle is not well understood. Pfeiffer *et al.* [2006] find positive rainfall excursions during El Niño years north of 10°S. Rainfall data from southern Africa, however, suggests that El Niño events may lead to pronounced droughts south of 10°S [Richard *et al.*, 2000].

[5] In this study we investigate long-term hydrological changes over the western Indian Ocean south of 10°S using a 113 year long, bimonthly resolved record of $\delta^{18}\text{O}$ and Sr/Ca from a *Porites solida* coral drilled at Mayotte (12°39'S, 45°06'E; Comoro Archipelago; for methodology see auxiliary materials).¹ The combination of Sr/Ca as a temperature proxy with $\delta^{18}\text{O}$ as an independent proxy for SST and $\delta^{18}\text{O}_{\text{seawater}}$ can provide simultaneous information on SST and hydrological changes [Cahyarini *et al.*, 2008, and references therein]. Our coral $\delta^{18}\text{O}_{\text{seawater}}$ series is the first of its kind from the western Indian Ocean. We will use a range of hydrological data ($\delta^{18}\text{O}_{\text{seawater}}$ and salinity measurements, rainfall and precipitation-evaporation data) collected at and around Mayotte to demonstrate that our coral proxy data can expand the current understanding of the hydrological cycle.

2. Climatic Setting of the Study Area

[6] Air Temperature (AT) and rainfall for Mayotte are available between 1949 to present and 1933 to present, respectively (NOAA GHCN monthly Weather Station at Pamandzi/Dzaoudzi, 12.80°S, 45.28°E). An inferred local SST record (hereafter SSTi) back until 1949 is derived from linear regression of *in-situ* lagoonal SST with local air temperature for the calibration period 1999–2002 (equation: $\text{SST} = 0.8535 \cdot \text{AT} + 4.7733$; $r^2 = 0.85$). Regional precipitation minus evaporation (P-E) and outgoing longwave radiation (OLR) data are taken from NCEP/NCAR reanalysis [Kalnay *et al.*, 1996] averaged over 10–15°S, 40–45°E. Monthly gridded sea level pressure (SLP) data are taken from the Met Office of the Hadley Centre of the UK [Allan and Ansell, 2007].

[7] SST and rainfall show an unimodal distribution with highest temperatures and rainfall between December to April (Figure S1). We investigated the relationship between

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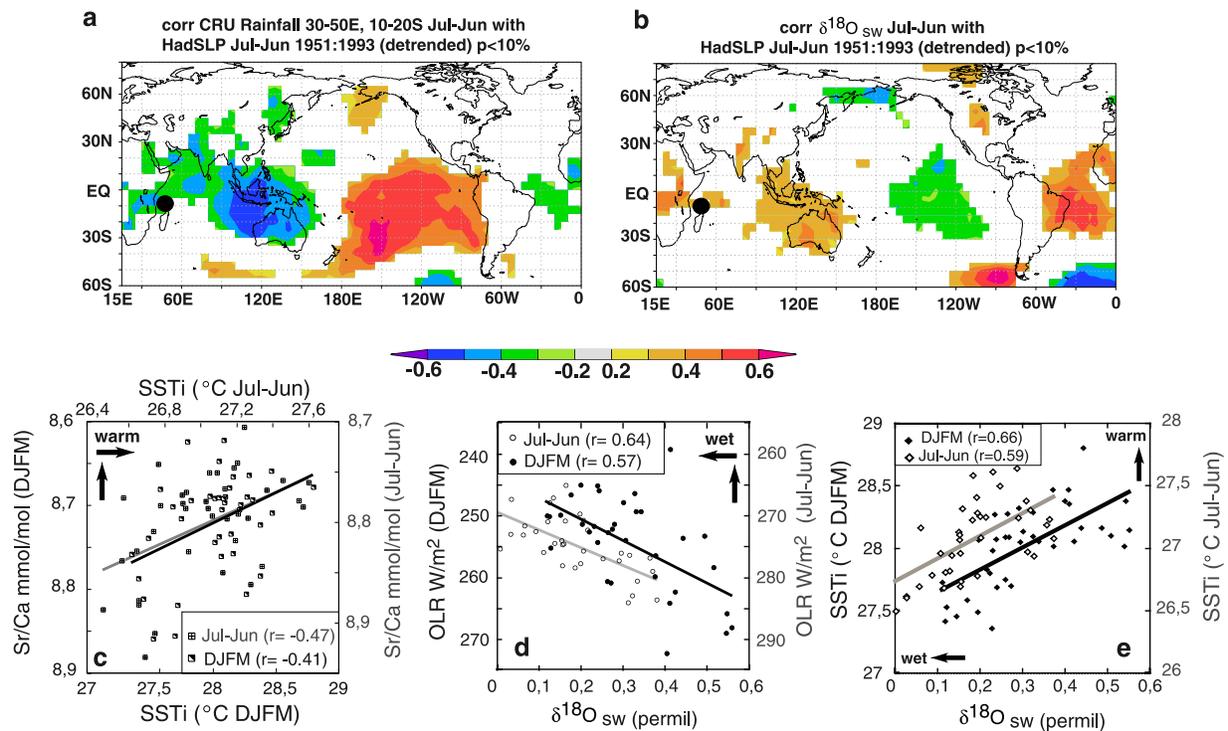


Figure 1. Spatial correlation of mean annual averages (July to June) of (a) rainfall data averaged between 30–50°E and 10–20°S including Mayotte (black circle) and (b) of $\delta^{18}\text{O}_{\text{seawater}}$ ($\delta^{18}\text{O}_{\text{sw}}$) with gridded sea level pressure (HadSLP) [Allan and Ansell, 2007]. Shading represents confidence of 90% and greater. Red shading indicates positive correlations and blue negative correlations. (c) Linear regression between mean annual and December to March averaged Sr/Ca ratios with local sea surface temperatures, (d) same as in Figure 1c but for $\delta^{18}\text{O}_{\text{seawater}}$ ($\delta^{18}\text{O}_{\text{sw}}$) with outgoing longwave radiation (OLR) [Kalnay et al., 1996] for the period 1958 to 1993 and (e) same as in Figure 1d but for local sea surface temperatures. Correlation coefficients are indicated. Correlations are significant at the 5% level.

(i) annual mean regional rainfall in the region of Mayotte (averaged between 30–50°E, 10–20°S) and the global SLP field (Figure 1a), and (ii) seasonal mean (December–March, hereafter DJFM) AT/SSTi from Mayotte with the global SST field between 1951 and 1993 (Figure S2). The correlation maps indicate the typical global ENSO SLP (Figure 1a) and SST (Figure S2) pattern. At Mayotte, negative rainfall and positive SST anomalies occur during El Niño events (Table S1).

3. Local Hydrology and Seawater Oxygen Isotopic Variations

[8] In the Mayotte region $\delta^{18}\text{O}_{\text{seawater}}$ is modified by (i) rainout of isotopically depleted rainfall from warm air masses over deep convective regions (the so-called amount effect [Dansgaard, 1964]) during the intense rainy season, (ii) isotopic fractionation during evaporation and (iii) freshwater surface runoff.

[9] A detailed hydrological study at Mayotte for 1993 (dry year) versus 1994 (normal year) revealed that evaporation contributed 45–60% to the annual freshwater balance and was 15% higher under drier conditions in 1993 (Figure S3) [see also Lapègue, 1999]. For the given example years, evaporation contributes significantly to $\delta^{18}\text{O}_{\text{seawater}}$. The NCEP/NCAR reanalysis data for Mayotte further indicates that evaporation intra/interannual variability is of the same order as the precipitation variability.

[10] We monitored $\delta^{18}\text{O}_{\text{seawater}}$ for several months during the dry and wet season in 2002 and between September 2004 and August 2005 (Figure S3). Our $\delta^{18}\text{O}_{\text{seawater}}$ shows a maximum seasonal amplitude of 1.13‰, ranging between 0.26‰ and 1.38‰. The cause of the high values in September and October 2004 is unknown since we lack salinity data. The maximum $\delta^{18}\text{O}_{\text{seawater}}$ amplitude is reduced to 0.51‰ when September and October 2004 are not considered. The negative $\delta^{18}\text{O}_{\text{seawater}}$ values observed between August and October 2002 are related to low salinities in the lagoon (Figure S3). River runoff shows considerable interannual variability and this runoff may potentially influence $\delta^{18}\text{O}_{\text{seawater}}$ in the Mayotte lagoon (Figure S1). For 2002, minimum salinity in the lagoon lags maximum river flow by 1 month (Figure S3). This implies that the integral effect of P-E over the length of the intense rainy season and freshwater runoff into the lagoon of Mayotte resulted in a strong signal in $\delta^{18}\text{O}_{\text{seawater}}$ that persists into austral winter of 2002.

4. Results and Discussion

4.1. Calibration, Calculation of $\delta^{18}\text{O}_{\text{seawater}}$ and Error Estimates

[11] Bimonthly coral Sr/Ca ratios primarily reflect SST; linear regression yields a slope value of -0.058 mmol/mol per 1°C in agreement with published relationships [Corrége, 2006]. Mean annual Sr/Ca ratios show a statistically signif-

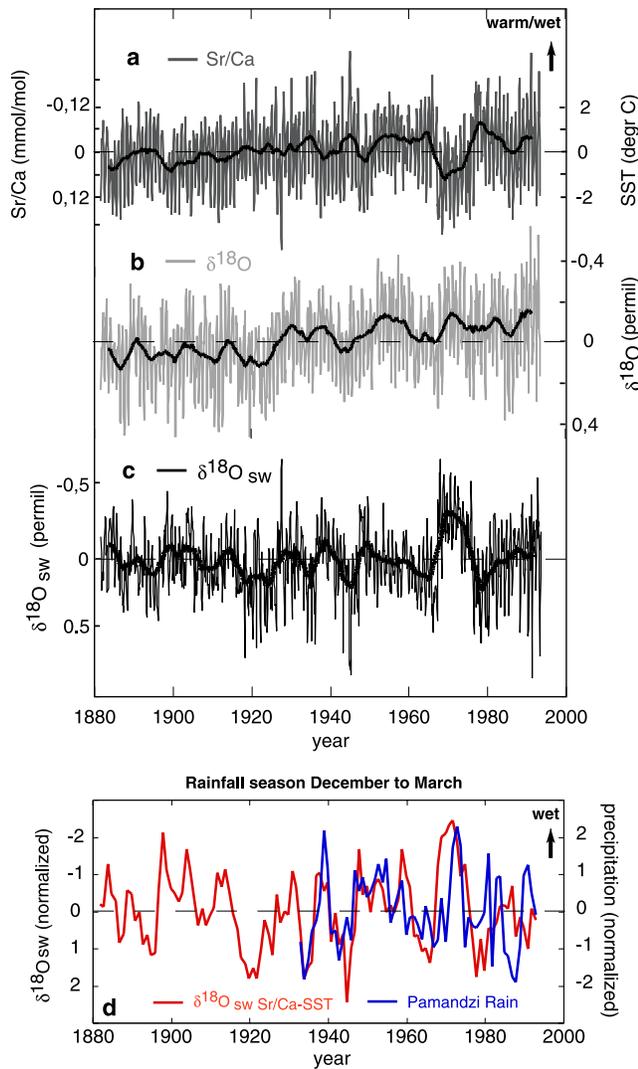


Figure 3. Coral proxy data for the period 1881 to 1994, shown as anomalies relative to their mean. (a) Sr/Ca, (b) oxygen isotopes and (c) reconstructed $\delta^{18}\text{O}_{\text{seawater}}$ ($\delta^{18}\text{O}_{\text{sw}}$; bottom). Sr/Ca has been scaled so that -0.058 mmol/mol corresponds to 1°C (see 4.1. for discussion). Bold lines indicate 11-year running mean. (d) Comparison of reconstructed $\delta^{18}\text{O}_{\text{seawater}}$ ($\delta^{18}\text{O}_{\text{sw}}$; in red) for the main rainfall season (December to March) with local rainfall from the Mayotte weather station (in blue). Both time series were detrended and normalized.

28.16°C between 1951–1961, and 28.06°C between 1975 and 1998). Assuming a local thermodynamic relationship between SST and atmospheric convection over Mayotte, we would expect mean SSTs $> 28^\circ\text{C}$ to be associated with increased convection and a more positive freshwater balance [Timm *et al.*, 2005, and references therein]. However, the reverse is the case. This implies that remotely forced, large-scale atmospheric variability influences the hydrological balance at Mayotte (see 4.3.).

4.3. Large-Scale Climate Teleconnections of $\delta^{18}\text{O}_{\text{seawater}}$

[18] The instrumental SST and Sr/Ca records of Mayotte are strongly related to ENSO (Figure S7). Here, we use our

$\delta^{18}\text{O}_{\text{seawater}}$ reconstruction as a proxy for changes in the hydrological balance to test for ENSO influences (Table S1 and Figure S2). Correlation maps of seasonal and mean annual values for the period 1950 to 1993 between $\delta^{18}\text{O}_{\text{seawater}}$ and global SLP show similar, but weaker correlation patterns as with regional-scale rainfall data from the western Indian Ocean south of 10°S (Figures 1a, 1b, and S2) resembling the ENSO SLP pattern. We observe an enrichment of $\delta^{18}\text{O}_{\text{seawater}}$ in response to ENSO warm events on both seasonal and mean annual scales (Figure S7). This is in contrast to the findings from central Indian Ocean corals (Chagos Archipelago) where $\delta^{18}\text{O}$ indicates a positive freshwater balance in response to ENSO warm events over the last 30 years [Pfeiffer *et al.*, 2006]. However, our results agree with earlier studies, in which the western Indian Ocean south of 10°S shows an opposite ENSO response compared to the equatorial Indian Ocean/East Africa [Hastenrath *et al.*, 1993; Richard *et al.*, 2000; Zinke *et al.*, 2004]. The western pole of maximum rainfall anomalies during warm ENSO events is located between 10°S – 10°N , 50 – 70°E which would favor moisture convergence equatorwards of 10°S and a possibly dryer atmosphere to the south [Neelin *et al.*, 2003]. The correlation with the Niño3.4 Index is significantly higher in the period 1975–1994 ($r = 0.61$, $p < 0.006$) than between 1951–1974 ($r = 0.29$, $p < 0.19$; Figure S7). This is consistent with results from the Chagos Archipelago where the ENSO correlation increased after 1975 [Pfeiffer *et al.*, 2006]. However, the El Niño response at Mayotte (drier) and Chagos (wetter) oppose each other. This agrees with the expected rainfall pattern across the Indian Ocean from remote ENSO forcing. Our findings add to the growing evidence of a strengthening of the ENSO signal in Indian Ocean rainfall since 1975 [Richard *et al.*, 2000; Pfeiffer *et al.*, 2006; Zubair and Ropelewski, 2006].

[19] The correlation map also indicates high correlations of the instrumental and $\delta^{18}\text{O}_{\text{seawater}}$ record with the extratropical North and South Pacific SST and SLP resembling the Pacific Decadal Oscillation (PDO) pattern (Figures 1a, 1b, and S2). The PDO is the dominant mode of interdecadal variability in Indo-Pacific SST/SLP [Deser *et al.*, 2004, and references therein]. Mayotte is located in the region of most significant correlations with the PDO [Deser *et al.*, 2004; Crueger *et al.*, 2008]. Linear least squares regression indicates a strong relationship between our $\delta^{18}\text{O}_{\text{seawater}}$ record and the PDO between 1950–1994 on mean annual and seasonal time scales ($r = 0.6$, $p < 0.003$; Figure S8). The observed periodicity in the $\delta^{18}\text{O}_{\text{seawater}}$ record ranges between 18–25 years, adding further evidence for an atmospheric bridge between the North Pacific and the Indian Ocean.

5. Conclusions

[20] We developed a 113 year long, bimonthly resolved coral record of $\delta^{18}\text{O}_{\text{seawater}}$ from Mayotte (south-western Indian Ocean). The $\delta^{18}\text{O}_{\text{seawater}}$ record indicates that the precipitation-evaporation balance varies on time scales of 5–6 years and 18–25 years. We observe a warm/dry (cool/wet) relationship between SST and $\delta^{18}\text{O}_{\text{seawater}}$, suggesting that atmospheric variability is remotely forced by large-scale climate anomalies in the Indian Ocean and the

tropical/extratropical Pacific Ocean. The observed interdecadal variability of $\delta^{18}\text{O}_{\text{seawater}}$ and its spatial signature indicate a possible link to the Pacific Decadal Oscillation, while interannual variability is clearly related to the El Niño–Southern Oscillation. Warm ENSO events are associated with a negative freshwater balance. The ENSO correlation increases after 1975. This agrees with coral data from the Chagos Archipelago (central Indian Ocean) where the ENSO correlation also increased after 1975. However, the El Niño response at Mayotte (drier) and Chagos (wetter) oppose each other. This agrees with the expected rainfall pattern across the Indian Ocean from remote ENSO forcing. Our case study demonstrates that a much denser network of $\delta^{18}\text{O}_{\text{seawater}}$ reconstructions is crucial for the understanding of spatial patterns in hydrological conditions.

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