Paired coral Sr/Ca and δ18O records from the Chagos Archipelago: Late twentieth century warming affects rainfall variability in the tropical Indian Ocean

Miriam Pfeiffer*  Leibniz Institut für Meereswissenschaften, IFM-GEOMAR, Wischhofstrasse 1-3, 24148 Kiel, Germany
Oliver Timm  International Pacific Research Center, University of Hawaii, POST Building 413, 1680 East West Road, Honolulu, Hawaii 96822, USA
Wolf-Christian Dullo  Leibniz Institut für Meereswissenschaften, IFM-GEOMAR, Wischhofstrasse 1-3, 24148 Kiel, Germany
Dieter Garbe-Schönberg  Institut für Geowissenschaften, Ludewig-Meyn-Strasse 10, 24118 Kiel, Germany

ABSTRACT

Understanding the relationship between sea surface temperature (SST) and precipitation is a significant challenge for climate models, particularly for the tropics. Here we present a new monthly coral Sr/Ca record from the tropical Indian Ocean (Chagos Archipelago) that extends from 1950 to 1995. The coral Sr/Ca ratio shows a stationary relationship with local SST, and documents a warming of 0.3 °C since 1950. Previous work has shown that the δ18O values measured in the same coral core provide a proxy record of precipitation in the tropical Indian Ocean. The coral δ18O record shows a non-stationary relationship with local SST, and a correlation between δ18O and SST only emerges in the 1970s. It was proposed that this nonstationary behavior is due to an increase in mean SSTs in the tropical Indian Ocean. During the 1970s, SSTs reached a critical threshold (28.5 °C) beyond which small SST anomalies can have a significant impact on atmospheric convection. As a result, the covariance between SST and precipitation in the tropical Indian Ocean increased. Our new Sr/Ca data confirm that the warming of the Indian Ocean during the late twentieth century affects atmospheric convection and rainfall variability. Moreover, our proxy data show that the relationship between SST and precipitation is nonlinear and characterized by threshold behavior.

Keywords: Porites, paleoclimate, precipitation, trace elements, Indian Ocean, sea surface temperature, climate.

INTRODUCTION

In the past few years, tropical Indian Ocean sea surface temperature (SST) variations have received considerable attention. The Indian Ocean shows a pronounced secular warming trend since 1950, which could be associated with global warming (Hoerling et al., 2001, 2004). This warming has been linked to changes in atmospheric circulation that alter boreal winter precipitation (e.g., Hoerling et al., 2001, 2004; Hurrell et al., 2004), affecting large-scale climate phenomena such as the North Atlantic Oscillation (Hoerling et al., 2001, 2004; Bader and Latif, 2003; Hurrell et al., 2004). However, instrumental SST data from the central Indian Ocean are sparse and are associated with errors that are as large as SST anomalies across a range of time scales (Annamalai et al., 1999); satellite-based precipitation data prior to 1979 are not available (Xie and Arkin, 1996).

Geochemical parameters measured in coral aragonite have provided robust records of environmental changes in the Indian Ocean on interannual to multidecadal time scales (e.g., Charles et al., 1997; Cole et al., 2000; Zinke et al., 2005; and others). The oxygen isotope composition (δ18O) of the coral skeleton is the most widely used tool in coral paleoecology and is a function of both SST and the isotopic composition of seawater (δ18Owater). In oceanic regions such as the West Pacific Warm Pool, where precipitation variability is larger than SST variability, coral δ18O records the associated changes in δ18Owater (e.g., Tudhope et al., 1995).

A coral δ18O record from the Chagos Archipelago (71°45'E, 5°15'S) correlates with boreal winter precipitation in the equatorial Indian Ocean, but only shows a significant relationship with local SST and the El Niño–Southern Oscillation after the 1970s (Pfeiffer et al., 2004; Timm et al., 2005). Timm et al. (2005) proposed that this reflects an increase in the covariance between SST and rainfall beginning in the 1970s, when tropical Indian Ocean SSTs reached a critical threshold beyond which small SST anomalies can have a significant impact on tropical convection (e.g., Zhang, 1993).

Here we apply the coral Sr/Ca temperature proxy (e.g., Marshall and McCulloch, 2002) to the Chagos coral to reconstruct SST in the central Indian Ocean from 1950 to 1995. By comparing the new coral Sr/Ca record with the existing δ18O record and to instrumental time series of SST and precipitation in the western tropical Indian Ocean, we find that central Indian Ocean precipitation anomalies increased after 1970, when ocean temperatures surpassed ~28.5 °C. Our results are consistent with the hypothesis put forward by Timm et al. (2005), and highlight the nonlinear relationship between ocean temperature and regional precipitation patterns.

DATA AND METHODS

The δ18O data were obtained from core GIM, a coral core drilled from a Porites solida colony growing in the lagoon of Peros Banhos Atoll (Chagos Archipelago, 71°46'E, 5°15'S) in a water depth of 3 m. The coral was drilled in February 1996. Coral δ18O was measured in 2 mm intervals, at approximately bimonthly resolution. A detailed description of the analytical procedures used for the δ18O measurements was given in Pfeiffer et al. (2004). For Sr/Ca analysis, powdered samples were taken at 1 mm intervals (approximately monthly resolution) along a sampling transect parallel to the previously measured δ18O. The distance between the two sampling transects is ~1 mm. Coral Sr/Ca was measured with an inductively coupled plasma–optical emission spectrophotometer (for details, see the GSA Data Repository1).

The age model of core GIM presented here is based on the seasonal cycle in Sr/Ca. We assigned the positive Sr/Ca extremes to August 15 of every year, which is, on average, the coldest month, and interpolated linearly between these anchor points for all other age assignments. We then used the same anchor points for coral δ18O. In a second step, the Sr/1GSA Data Repository item 2006233, Table DR1 (sampling locations of the three Chagos cores), Table DR2 (correlation of Sr/Ca with SST and air temperature), and Figure DR1 (reproducibility of coral Sr/Ca records), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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Ca ($\delta^{18}O$) series was interpolated to 12 equidistant points per year to obtain a monthly (6 bimonthly) time series. We did not find any significant differences between monthly and bimonthly resolved time series of coral Sr/Ca.

Note that the age model of core GIM presented here is different from the age model presented in Pfeiffer et al. (2004) and Timm et al. (2005), as the anchor points are based on Sr/Ca and set to August 15 (the coldest month), while in Pfeiffer et al. (2004) the anchor points are based on the $\delta^{18}O$ record and set to February 15 (the wettest month). For the results presented in this paper, it is important that the age model of Sr/Ca and $\delta^{18}O$ is consistent, because the subseasonal time scale error ($\pm$1 month) introduced by data interpolation could accumulate when setting the anchor points to different months.

Annual mean values of coral Sr/Ca ($\delta^{18}O$) were computed from the 12 monthly (6 bimonthly) values of each year (January to December averages, with the year labeled according to January). The results presented in this study do not depend on the months chosen for the computation of annual average values.

RESULTS

Figure 1 compares the bimonthly coral $\delta^{18}O$ and the monthly coral Sr/Ca time series measured in core GIM. The correlation between the two proxy time series is low and not significant ($r = 0.21$; $p = 0.16$ for annual means). Coral $\delta^{18}O$ shows a series of large negative anomalies since ca. 1970, indicating warmer and wetter conditions. The largest anomalies occur in the El Niño years of 1972–1973, 1982–1983, 1987, 1992, and 1994–1995 (Fig. 1A). Mean coral Sr/Ca values indicate a shift toward lower values (i.e., warmer SSTs) in the period 1976–1995 (Fig. 1B). The magnitude of this shift is 0.017 mmol/mol, corresponding to a warming of 0.21–0.42 °C based on published coral Sr/Ca–SST relationships that range from 0.04 to 0.08 mmol/mol/°C (e.g., Marshall and McCulloch, 2002). The local SST record (Fig. 1B) shows a warming of 0.32 °C, consistent with the Sr/Ca data. The reproducibility of coral Sr/Ca, including the shift in the 1970s, is confirmed by two other monthly coral Sr/Ca records from the Chagos Archipelago that cover the same time period (Tables DR1 and DR2; Fig. DR1; see footnote 1).

We have computed scatter plots of annual mean coral Sr/Ca and $\delta^{18}O$ versus local SST for two different time periods, 1950–1969 and 1970–1995 (Figs. 2A, 2B; Table 1). Figure 2A clearly shows that Sr/Ca is well correlated with local SST, and that the coral Sr/Ca–SST relationship is stable in both time periods. Different tables and figures are omitted here for brevity.

TABLE 1. LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS BETWEEN ANNUAL MEAN CORAL $\delta^{18}O$ (Sr/Ca) AND LOCAL SEA SURFACE TEMPERATURE

<table>
<thead>
<tr>
<th>Time period</th>
<th>Regression equation</th>
<th>$r$ (r²)</th>
<th>$p$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta^{18}O$</td>
<td>1950–1995: $\delta^{18}O = -0.10 \pm 0.06 \times$ SST = 1.96 (±1.64)</td>
<td>0.24</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>1950–1969: $\delta^{18}O = -0.05 \pm 0.07 \times$ SST = 3.30 (±1.91)</td>
<td>0.16</td>
<td>0.5</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>1970–1995: $\delta^{18}O = -0.23 \pm 0.12 \times$ SST + 1.86 (±3.46)</td>
<td>0.38</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>Sr/Ca</td>
<td>1950–1995: Sr/Ca = −0.050 (±0.01) $\times$ SST + 10.15 (±0.35)</td>
<td>0.52</td>
<td>$&lt;0.001$</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>1950–1969: Sr/Ca = −0.067 (±0.02) $\times$ SST + 10.62 (±0.63)</td>
<td>0.57</td>
<td>$&lt;0.05$</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>1970–1995: Sr/Ca = −10.33 (±0.62)</td>
<td>0.47</td>
<td>$&lt;0.05$</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Note: Sea surface temperature, SST, is taken from the Extended Reconstructed SST data set, version 2 (ERSST, Smith and Reynolds, 2003), centered at 70°E, 6°S.
ferences in the regression equations of annual mean Sr/Ca with local SST for the 1950–1969 and the 1970–1995 time period are within the uncertainty range of the linear regression (Table 1). In contrast, $\delta^{18}O$ does not correlate with local SST prior to 1970 (Fig. 2B; Table 1). Note, however, the negative $\delta^{18}O$ values occurring in the 1970–1995 period, at SST values of $-28.5$ °C (Fig. 2B).

Previous work has shown that coral $\delta^{18}O$ of core GIM correlates well with precipitation over the central and western tropical Indian Ocean ($r = -0.78, p < 0.001$; see Pfeiffer et al., 2004). Over oceanic areas, however, direct measurements of precipitation are made by satellites (Xie and Arkin, 1996). These data sets are only available for the time period from 1979 to present; therefore, we cannot confirm the reliability of our coral $\delta^{18}O$ record prior to 1970 because direct rainfall measurements are lacking. Here we use total cloudiness data from the Comprehensive Ocean Atmosphere Data Set (COADS, Woodruff et al., 1998) as a qualitative proxy record of precipitation. To obtain a continuous time series that extends back until 1950, we average the cloudiness data over the western and central equatorial Indian Ocean (50–80°E; 2–8°S). In this region, the correlation between total cloudiness and satellite-derived precipitation (Xie and Arkin, 1996) is high ($r = 0.74, p < 0.001$ for annual means, 1979–1997). Figure 3 compares the annual mean time series of coral $\delta^{18}O$ and total cloudiness from COADS. The correlation between the two time series is high and statistically significant. More important, the correlation remains stable in the time period of 1950–1969 (Fig. 3), suggesting that coral $\delta^{18}O$ of core GIM is a robust proxy for precipitation. Subtracting the SST contribution inferred from coral Sr/Ca from the $\delta^{18}O$ record confirms that the SST contribution to coral $\delta^{18}O$ is very small: the correlation between annual mean coral $\delta^{18}O$ and the residual $\delta^{18}O_{\text{seawater}}$ signal (not shown) is high ($r = 0.82; p < 0.001$), and the two time series are almost identical.

Figure 4A shows a running correlation analysis between total cloudiness from COADS and SST at the Chagos. The correlation is nonstationary, and a significant correlation only appears in the 1970s. A running correlation analysis between coral $\delta^{18}O$ and SST (Fig. 4B) shows the same low-frequency modulations, and a significant correlation also emerges only in the 1970s. In contrast, coral Sr/Ca shows a stationary and statistically significant relationship with local SST from 1950 to 1995 (Fig. 4C).

The results confirm that the Sr/Ca of core GIM records SST, while the $\delta^{18}O$ records precipitation changes in the central Indian Ocean. The increase in the correlation between coral $\delta^{18}O$ and SST in the 1970s reflects an increase in the covariance between precipitation and SST.

**DISCUSSION**

In the tropics, precipitation is associated with deep convection, which is very sensitive to the background SST, moisture convergence, and the large-scale atmospheric circulation (Graham and Barnett, 1987; Laut et al., 1997). These factors influence the covariance between SST and precipitation. Based on a statistical analysis of the $\delta^{18}O$ record of core GIM, Timm et al. (2005) proposed that the recent warming of the tropical Indian Ocean led to an increase in the covariance between SST and precipitation. The warming raised SSTs to near $28.5$ °C in boreal fall (September–November), the early phase of the main rainy season that lasts from October to March. SSTs of $-28.5$ °C are believed to form a critical threshold level that is needed to charge the lower atmosphere with moist static energy before deep convection reaches the tropopause (Graham and Barnett, 1987; Zhang, 1993; Sud et al., 1999). At this threshold level, a small variation in SST ($-0.5$ °C) can have a large impact on moisture availability and tropical convection (Zhang, 1993). Thus, after the 1970s, the small SST anomalies that occur in the Indian Ocean during El Niño events ($-0.5$–$1$ °C; Reason et al., 2000) may raise SSTs above the threshold level and are more likely to cause positive rainfall anomalies.

However, coral $\delta^{18}O$ and Sr/Ca can be influenced by nonclimatic processes such as growth-related effects or secondary diagenetic alterations that may lead to severe biases of the records (e.g., McConnaughey, 1989; de Villiers et al., 1995; McGregor and Gagan, 2003). Measuring coral Sr/Ca at the same coralline core is ideal for the validation of the thresh-
We have demonstrated that coral Sr/Ca measured in core GIM shows a stationary correlation with local SST from 1950 to 1995 (Figs. 2A and 4B; Table 1). Also, the slope of the coral Sr/Ca–SST relationship is consistent with published estimates that range from \(-0.04 \text{ to } -0.08 \text{ mmol/mol°C} \) (e.g., Marshall and Mc Culloch, 2002), confirming the reliability of our coral record. Coral Sr/Ca correctly recorded a shift toward warmer SSTs, closer to the anticipated threshold value of \(28.5 °C \) in 1976. Using total cloudiness data from COADS, we have confirmed that coral \(\delta ^{18}O \) is a robust proxy for precipitation in the western and central equatorial Indian Ocean from 1950 to 1995 (Fig. 3). The most negative coral \(\delta ^{18}O \) values occur after the 1970s, at SSTs of \(-28.5 °C \) (Fig. 2B). The nonstationary relationship between coral \(\delta ^{18}O \) and SST reflects the nonstationary relationship between precipitation and SST in the equatorial Indian Ocean (Figs. 4A, 4B). The strengthening of the correlation between coral \(\delta ^{18}O \) and SST in the 1970s is due to an increase in the covariance between precipitation and SST, rather than an enhanced correlation between coral \(\delta ^{18}O \) and SST. Thus, by combining coral \(\delta ^{18}O \) with Sr/Ca measurements, we can confirm the threshold hypothesis of Timm et al. (2005). Also, our results highlight the nonlinear relationship between SST and precipitation in the tropical Indian Ocean, and show that the recent warming has had an impact on atmospheric convection and precipitation patterns, as suggested by Hoerling et al. (2001) and Hurrel et al. (2004). This will have important implications for long-range weather forecasts as ocean temperatures continue to rise. The results presented here clearly illustrate how paired coral \(\delta ^{18}O \) and Sr/Ca records can help to improve regional precipitation forecasts in the tropics.

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