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Nonstationary ENSO-precipitation teleconnection over the equatorial Indian Ocean documented in a coral from the Chagos Archipelago

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[1] This study proposes a mechanism that explains the marked shift in the correlation between the El Niño/Southern Oscillation (ENSO) and the isotopic composition ($\delta^{18}O_c$) of a *Porites* coral from the Chagos Archipelago (71°E/5°S). Only after the mid-1970s a strong ENSO signal emerges in the $\delta^{18}O_c$ during the analyzed period 1950–1994. In the 1970s, the increasing sea surface temperature (SST) shifted the mean SST closer to the deep convection threshold at about 28.5°C. ENSO-related SST variability largely controls the deep convection and precipitation in the central equatorial Indian Ocean (CEIO) when the SST is at this critical level. The anomalies in the precipitation induce changes in the isotopic composition of the surface ocean waters. The precipitation signal amplifies the SST signal in the coral $\delta^{18}O_c$ and raises the correlation to ENSO. The presented results have important implications for the reconstruction of ENSO indices from corals within the Indian Ocean. **Citation:** Timm, O., M. Pfeiffer, and W.-C. Dullo (2005), Nonstationary ENSO-precipitation teleconnection over the equatorial Indian Ocean documented in a coral from the Chagos Archipelago, *Geophys. Res. Lett.*, *32*, L02701, doi:10.1029/2004GL021738.

1. Introduction

[2] Skeletal oxygen isotopic compositions of corals ($\delta^{18}O_c$) have been used in many studies as a proxy for local SST and/or precipitation. Pacific coral proxies have been successfully applied in the reproduction and reconstruction of ENSO variability, for example, by *Cole et al.* [1993] and *Cobb et al.* [2003]. The success of their reconstructions was ensured by the predominance of ENSO in the local climate variability either in terms of SST or precipitation anomalies. Likewise, corals from the Indian Ocean can record ENSO signals [*Charles et al.*, 1997]. The interaction between ENSO and climate in the Indian Ocean sector has been subject of many studies [e.g., *Cadet*, 1985; *Reason et al.*, 2000]. Positive (negative) SST anomalies are observed during warm (cold) ENSO periods in western and central parts of the Indian Ocean. Zonal shifts in the Walker Circulation cause dipole-like precipitation anomalies over the Indian Ocean with wetter (drier) conditions in the western (eastern) sector during El Niño events. In addition, advective processes associated with ENSO can affect coral $\delta^{18}O_c$ [*Pfeiffer et al.*, 2004b].

[3] The temporal stability of these teleconnection patterns is vital for the interpretation of coral proxies. *Rimbu et al.* [2003] showed that the nonstationary teleconnection patterns in the Middle East led to time-varying correlations between a Red Sea coral record and ENSO. In the Indian Ocean sector, for example, *Kumar et al.* [1999] found evidence for a weakened teleconnection between ENSO and the Indian Monsoon. However, *Kinter et al.* [2004] demonstrated that the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis used by the former authors have their limits due to changes in the assimilated data stream in the reanalysis.

[4] Recently, *Pfeiffer et al.* [2004a] found some new coral-based evidence for a major shift in the teleconnection between precipitation anomalies in the central equatorial Indian Ocean and ENSO during the 1970s. In that study the authors invoked atmospheric changes associated with shifts in the Walker Circulation because SST and deep convection appear to be uncorrelated in the northern tropical Indian Ocean [*Webster et al.*, 1998]. The objective of the present study is to examine the physical mechanisms leading to the observed shift in the relationship between the $\delta^{18}O_c$ of the Chagos corals and ENSO. Therefore, the spatiotemporal variability of SST, precipitation, and $\delta^{18}O_c$ is investigated and compared with ENSO. It is proposed that the Indian Ocean SST warming contributed to the observed climate shift over the CEIO sector by a nonlinear linkage between SST and deep convection.

2. Data

[5] The $\delta^{18}O_c$ data stem from a coral of the Chagos Archipelago (71°46′E/5°15′S) [*Pfeiffer et al.*, 2004a]. This record spans the period 1876–1996 and has bimonthly resolution. The basic relationship between $\delta^{18}O_c(t)$ and local climate variability is given by the equation

$$\delta^{18}O_c(t) = \delta^{18}O_T(t) + \delta^{18}O_w(t) + \epsilon(t), \qquad (1)$$

where the index t denotes the time dependence. The coral oxygen isotopic composition $\delta^{18}O_c(t)$ is the sum of temperature-dependent variability $\delta^{18}O_T(t)$, variations in the ambient seawater composition $\delta^{18}O_w(t)$, and a noise component $\epsilon(t)$. The noise is assumed to be independent of the climatic variability and includes for example site-specific environmental and/or metabolic effects [*McConnaughey*, 1989a, 1989b]. Because the isotopic fractionation in coral aragonite is linearly related to ambient temperature, the first term on the right hand side of equation (1) is proportional to sea surface temperature [*Ren et al.*, 2002]. The second term is closely related to freshwater flux (evaporation-

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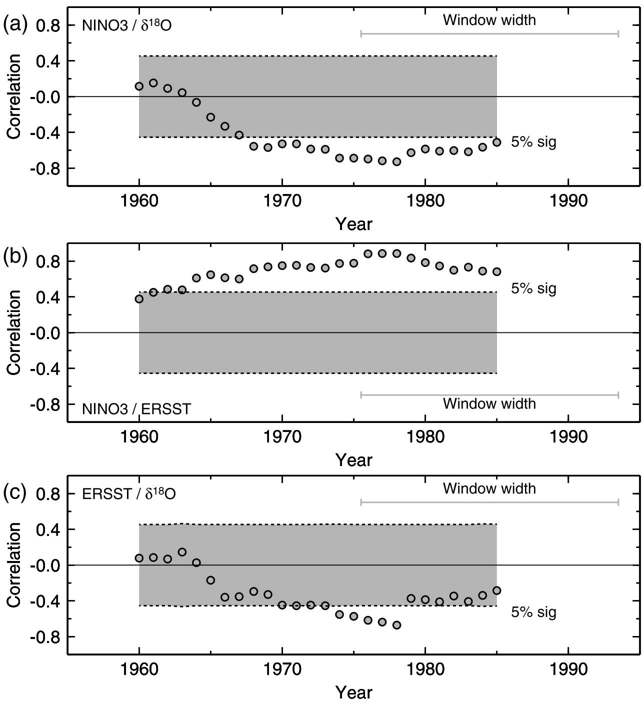

Figure 1. Running correlation analysis between (a) NINO3 (NDJF) index and $\delta^{18}O_c$ (ANN) [*Pfeiffer et al.*, 2004a], (b) NINO3 (NDJF) and Chagos SST (ANN), (c) Chagos SST (ANN) and $\delta^{18}O_c$ (ANN) over the period 1950–1994. Window width is 19 yr and two-sided significance test niveau is 5%. Significance test accounts for serial correlation. Correlations are assigned to the center year of the data window.

precipitation) [*Delaygue et al.*, 2000]. To quantify the influence of precipitation in the Chagos coral, the convective precipitation from the European Centre for Medium Range Weather Forecasts (ECMWF) 40-year reanalysis was analyzed. The SST data were taken from *Smith and Reynolds* [2003]. The grid point nearest to the coral location was chosen as a local SST time series. The NINO3 index from *Kaplan et al.* [1998] was chosen as an index for ENSO variability. The monthly data were reduced to the bimonthly resolution of the $\delta^{18}O_c$. Further, seasonal and annual averages were calculated. Primary focus is on the boreal winter season (November through February, hereafter NDJF) and annual averages (September–August means with the year labeled according to January, hereafter ANN). The transition season (boreal fall September–November, hereafter SON) is considered when we focus on the ENSO-precipitation relation and its mechanism in the discussion.

3. Results

[6] The starting point of the statistical analysis, which motivated this study, is shown in Figure 1a. The running correlation between annual $\delta^{18}O_c$ and NINO3 during NDJF shows low-frequency variability. Only the last decades of the 20th century indicate significant negative correlations. Negative anomalies in $\delta^{18}O_c$ (i.e., wetter and/or warmer conditions at the Chagos) correspond to anomalous high SSTs in the NINO3 region. Although there is a chance that this transition could be an artefact of the running correlation procedure [*Gershunov et al.*, 2001], there is ample independent evidence suggesting a major shift in tropical climate occurred in the 1970s [e.g., *Kumar et al.*, 1999; *Kinter et al.*, 2002]. We believe that the Chagos coral is predisposed to record changes in atmospheric teleconnection between the Indian Ocean climate and ENSO. Comparing the running correlation between ENSO and the SST from Chagos (Figure 1b), no significant changes took place in the ENSO-Indian Ocean relation during the last 50 years. If $\delta^{18}O_c$ recorded SST variability only, one would expect a constant correlation between $\delta^{18}O_c$ and ENSO. Instead, $\delta^{18}O_c$ and local SST have the same shift in the linear relationship as $\delta^{18}O_c$ and ENSO (Figure 1c). By analyzing a second coral core from another site at the Chagos, *Pfeiffer et al.* [2004a] have shown that the coral $\delta^{18}O_c(t)$ signal is reproducible back until 1962. Thus, the 1970 shift recorded by the coral cannot be attributed to biological or other site-specific effects. If the variance of the noise component $\epsilon(t)$ remained unchanged, then the covariance between $\delta^{18}O_T(t)$ and $\delta^{18}O_w(t)$ must have changed according to equation (1). Because these terms are closely related to SST and precipitation, respectively, their covariance must have increased in the recent decades. In the tropics, precipitation is associated with deep convection, which is very sensitive to the background SST, moisture convergence and large-scale circulation [*Graham and Barnett*, 1987; *Lau et al.*, 1997]. These effects can modify the covariance between SST and precipitation. The teleconnection between ENSO and convective precipitation is investigated below.

[7] The annual mean convective precipitation of the reanalysis highlights a significant change in the precipitation fields over the Indian Ocean. Figure 2a depicts the difference in convective precipitation between El Niño years and La Niña years during the period 1958–1971 (years are tabulated in Table 1). In this period the impact of ENSO on rainfall is restricted to the Pacific Ocean. The pattern resembles those found by *Dai and Wigley* [2000]. In the CEIO region, ENSO had no effect on the convective rainfall. In the later period (1972–1994) El Niño years are accompanied by anomalously high rainfall compared to La Niña events over the CEIO (Figure 2b). To test the significance of the differences between both periods, a resampling procedure was applied. The composite analysis was repeated 300 times by generating random subgroups of all El Niño years and all La Niña years listed in Table 1. The random selections replaced the groups of the pre and post 1970s eras in the composite calculation. The standard deviation of the randomly generated differences was estimated and provided a test for the local significance of the differences. The positive anomalies over Chagos are significant at the 10% level. Similar results have been obtained with the NCEP/NCAR precipitation rates on a 5% significance level (not shown).

4. Discussion

[8] The statistical results suggest that prior to the 1970s the influence of ENSO on the central Indian Ocean climate was restricted to SST anomalies. Deep convection and precipitation was independent from ENSO. After the early 1970s, positive (negative) SST anomalies during El Niño (La Niña) years were accompanied by positive (negative)

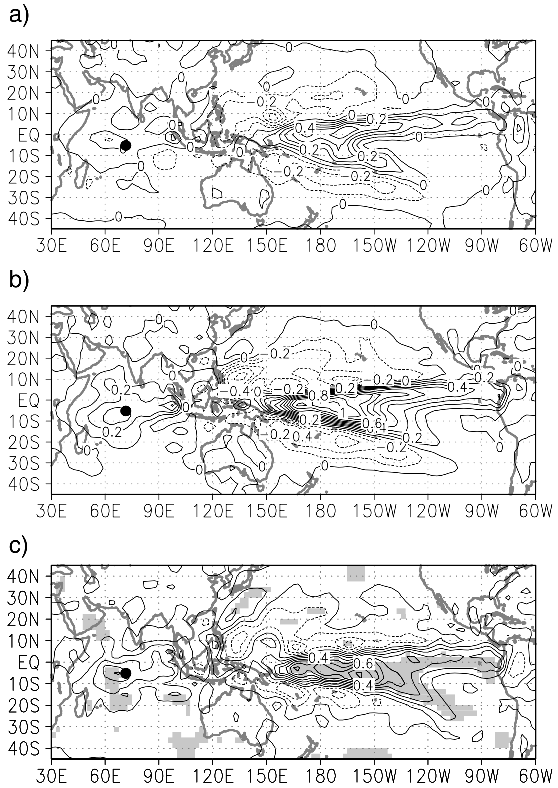

Figure 2. Precipitation anomalies El Niño minus La Niña years for (a) the period 1957–1974 and (b) the period 1975–1994. Contour interval is 0.1 mm/6h. The difference 1975–1994 minus 1958–1974 is shown in (c). Significant (10%) differences are shaded gray.

convective precipitation anomalies over the CEIO. Our results are supported by earlier studies [*Reverdin et al.*, 1986; *Richard et al.*, 2000] and provide further evidence of a large scale shift in the tropical climate [*Kumar et al.*, 1999; *Kinter et al.*, 2002].

[9] Since statistics should be supported by physical reasoning we propose a mechanism in which the recent warming of the Indian Ocean is responsible for the nonstationary character of the relationship between ENSO, precipitation, and $\delta^{18}\mathrm{O}_c$. In the CEIO, SST is near to the anticipated threshold of 27.5–28.5°C that is needed to charge the lower atmosphere with moist static energy before deep convection reaches the tropopause [*Graham and Barnett*, 1987; *Sud et al.*, 1999]. During the 1970s the secular warming trend raised SST closer to this critical value during boreal fall (SON). The cumulative distributions of the CEIO SST data for the periods 1950–1971 and 1972–2002 reveal a remarkable increase in occurrences of SSTs above the threshold level (Figure 3). Simply assuming that deep convection is turned on at SST above 28.5°C and turned off below 27.5°C, the shift towards a warmer SST increases the chance that positive SST anomalies (related to El Niño) are accompanied with anomalously high rainfall. Thus, the early stages of the El Niño development have also produced a pronounced effect on rainfall in the last decades. According to equation (1), the ENSO signal in the Chagos coral is amplified by the synchronized SST and precipitation anomalies. The raised signal-to-noise ratio is reflected in an increased (i.e., significant) correlation between NINO3 and $\delta^{18}\mathrm{O}_c$ (Figure 1).

[10] We are aware that the proposed mechanism is only one possible explanation of the observed nonstationary statistical relationship between ENSO and $\delta^{18}\mathrm{O}_c$ of the Chagos coral. Recent results of *Neelin et al.* [2003] suggest that moisture advection is a crucial factor in the tropics. Their model results contradict our findings that El Niño induces positive rainfall anomalies over the CEIO. However, the former authors noted that a precise moisture gradient representation is needed for an accurate localization of the "upped-ante" mechanism. Changes in the upper-level wind divergence by large scale circulation also produce precipitation anomalies [*Lau et al.*, 1997]. Finally, the results concerning the physical linkage between ENSO and precipitation in the Indian Ocean strongly depend on the data sets in use [*Kinter et al.*, 2004] and the season analyzed [*Misra*, 2003]. Nonetheless our results demonstrate that corals from the Indian Ocean need a careful interpretation. This is both a blessing and a curse: while individual paleoclimatic reconstructions are difficult to interpret in

Table 1. Ten Strongest El Niño and La Niña Years during the 1958–1994 Period[a]

Associated Period	El Niño years	La Niña years
1958–1974	1958	1963
	1966	1965
	1969	1968
	1970	1971
	1973	1972
		1974
1975–1994	1977	1976
	1983	1985
	1987	1986
	1988	1989
	1992	

[a] The years have been selected from the boreal winter season (NDJF) NINO3 index. The ten most positive and negative NINO3 index values have been selected.

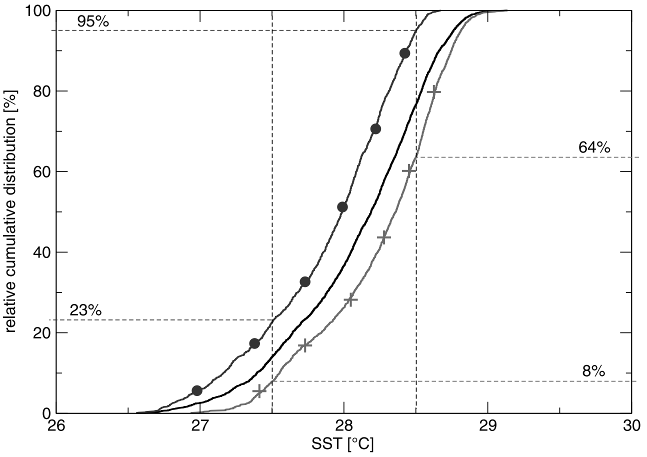

Figure 3. Relative cumulative distribution of the SST in the CEIO area (60–80°E, 10–0°S) for the season SON: 1950–1971 (blue line with circles), 1972–2002 (red line with crosses) and 1950–2002 (black solid line). Vertical dashed lines mark the critical SST range (see text) and horizontal dashed blue (red) lines denote the associated cumulative value in the SST distribution for the pre (post) 1971 period. See color version of this figure in the HTML.

terms of global climate phenomena like ENSO, similar large-scale climate shifts may be traced back into preindustrial centuries, provided that the Indian Ocean corals are combined with corals from the central Pacific or other reliable records of past ENSO variability.

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