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SPCZ migration and ENSO events during the 20th century as revealed by climate proxies from a Fiji coral

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[1] Instrumental sea surface temperature (SST) and sea surface salinity (SSS) records since 1975 have indicated that migrations of the South Pacific Convergence Zone (SPCZ) are strongly related to El Niño-Southern Oscillation (ENSO) events. To reconstruct independent SSS and SST time series for the past century and document this SPCZ and ENSO relationship prior to 1975, we apply a neural network analysis to seven climate proxies derived from a coral skeleton collected in Fiji. These reconstructions suggest that five SPCZ migrations linked to ENSO occurred between 1908 and 1970 while as many migrations occurred during the last three decades, highlighting the recent enhanced frequency of ENSO occurrence. **Citation:** Juillet-Leclerc, A., S. Thiria, P. Naveau, T. Delcroix, N. Le Bec, D. Blamart, and T. Corrège (2006), SPCZ migration and ENSO events during the 20th century as revealed by climate proxies from a Fiji coral, *Geophys. Res. Lett.*, *33*, L17710, doi:10.1029/2006GL025950.

1. Introduction

[2] The western Pacific Warm Pool (WPWP), characterized by sea surface temperature (SST) warmer than 28°C and sea surface salinity (SSS) fresher than about 35, plays a key role in ocean-atmosphere interactions associated with El Niño Southern Oscillation (EN) events. The WPWP is not symmetrical about the equator. On average, it extends from ~10°N to 18°S, and from Indonesia to the dateline near the equatorial band and from Australia to French Polynesia in its southern portion [*Wyrtki*, 1984]. There is a zonal front in SSS near the equator at the eastern edge of the WPWP, which moves eastward during EN events, and westward during La Niña events [*Vialard and Delecluse*, 1998; *Picaut et al.*, 2001]. In the southern portion of the WPWP is a major regional atmospheric feature, the South Pacific Convergence Zone (SPCZ). The location of the SPCZ varies systematically with EN-related expansion and contraction of the WPWP [*Trenberth*, 1984]. It creates in southwestern part another SSS front. This front migrates in the opposite sense of the previously noted front at the equator during El Niño/La Niña events [*Gouriou and Delcroix*, 2002].

[3] The average location of the southern limit of the SPCZ lies near Fiji islands. Here, the SPCZ moves further to north during El Niño (EN) events, hence causing lower rainfall and further south during La Niña events, causing higher rainfall. In situ observations, available since 1975 in the Southwestern Tropical Pacific clearly show the influence of EN on regional SST and SSS variability [*Gouriou and Delcroix*, 2002]. Before 1975 *in situ* observations are too sparse to infer possible changes in the regional SPCZ impact and EN signature. Here, we use proxy SST and SSS records obtained from a massive coral to examine these ocean-atmosphere interactions in the southwest Pacific prior to 1975.

[4] One of the most commonly measured tracers in corals is oxygen isotope ratio ($\delta^{18}O$) [*Gagan et al.*, 2000]. $\delta^{18}O$ in coral can reflect changes in SST, SSS or a mixed signal, depending on the location [*Gagan et al.*, 2000]. Previous analyses of $\delta^{18}O$ over the period 1960 to 1997 from a *Porites* from Yasawa, a Fiji island, show a linear relationship between coral $\delta^{18}O$ and SSS on inter-annual time scales [*Le Bec et al.*, 2000]. In contrast, the Sr/Ca (a commonly used SST proxy measured in corals [*Gagan et al.*, 2000]) from other Fiji coral cores (*Porites* and *Diploastrea* spp) is not always linearly related to SST at inter-annual time scales [*Linsley et al.*, 2004; *Bagnato et al.*, 2004]. While SST and SSS fluctuations were not clearly separated, *Porites* $\delta^{18}O$ and Sr/Ca records were in good agreement with records of a *Disploastrea* coral [*Bagnato et al.*, 2004], the coral $\delta^{18}O$ matching well with the Pacific Decadal Oscillation Index, based on SST variations in the North Pacific [*Linsley et al.*, 2004]. It suggests that classical linear regressions cannot be applied to Fiji coral climate proxies because interdecadal changes in Sr/Ca are likely affected by other factors than SST. We, therefore, use a Neural Network (NN) approach to several coral climate tracers measured in the *Porites* collected at Yasawa to obtain proxy SST and SSS records. We demonstrate that NN allows SST and SSS to be separately estimated from seven proxies including stable isotopes, trace elements and density.

[5] A massive coral colony of *Porites sp.* (2.6 m long) was drilled in July 1998 in Yasawa Island (16°48′S–177°27′E) on the western side of the Fiji archipelago, during the Paleofiji cruise of the French Institut de Recherche pour le Développement (IRD) (Figure 1). We collected an average of 15 samples per annual band along the main growth axis. Each sample was subsampled to analyze the isotopic and trace element/Ca ratios. To quantify the density the core was X-rayed by computerized tomography [*Bessat and*

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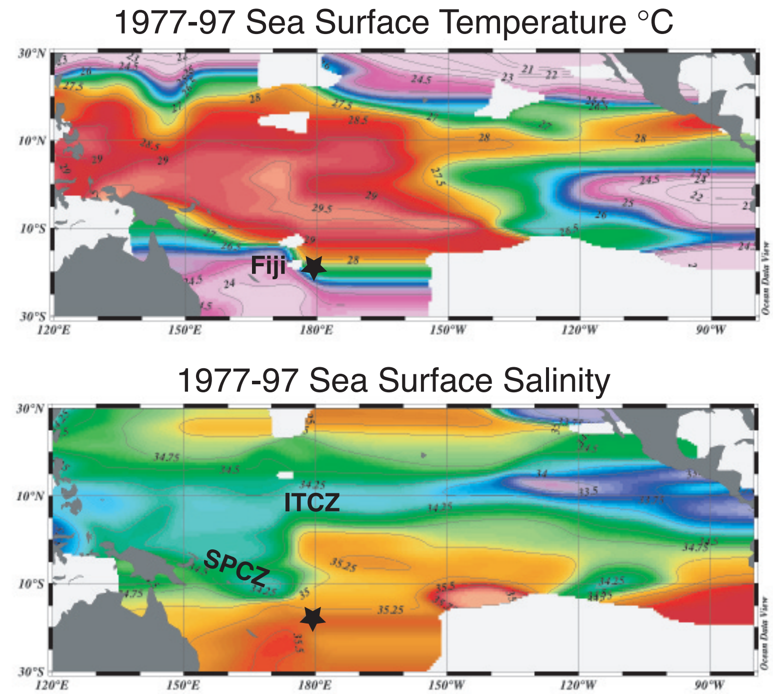

Figure 1. Annual average SST and SSS from the WOCE "Upper Ocean Thermal Programme" for the tropical Pacific Ocean during the 1977–97 period. SSS is in practical salinity units. The convergence zones ITCZ and SPCZ are indicated, underlined by low salinity.

Buigues, 2001]. The chronology was based on peak matching between δ^{18}O and trace elements.

[6] Seven monthly time series were interpolated using the AnalySeries software [*Paillard et al.*, 1996] over the 90 year period 1908–1997: δ^{18}O, δ^{13}C, Sr/Ca, Mg/Ca, U/Ca, Ba/Ca and density (Figure 2). After a preliminary study [Le Bec et al., 2000], we decided to remove variations equal to shorter than one year in using a 25 months Hanning filter. The Multi-Layered Perceptons, a particular class of NN, basically corresponding to a multi-dimensional nonlinear regression algorithm [*Bishop*, 1995] was then applied on the time-series. The shortness of the instrumental records of SSS and SST necessitated using small NN architectures. More details are given in the auxiliary material[1].

2. SST and SSS Reconstructions Over 1961–1997

[7] NN is calibrated using the 1961–1997 filtered original SST and SSS time series [*Reynolds and Smith*, 1994; *Delcroix*, 1998] shown in Figure 3. EOF and few ship opportunities furnished SSS data series in 60's and 70's. Data from ships are more numerous in 70's than in 60's. SST is a predominant external factor affecting all the proxies even Ba/Ca and Mg/Ca because the largest correlation coefficient between measured and calculated SST is obtained with the seven proxies. To reconstruct SSS, we considered only four data series: δ^{18}O, δ^{13}C, Sr/Ca and density. The precision of reconstructed SST and SSS, 0.09°C and 0.15 respectively is calculated by cross validation. These reconstructions were correlated with the revised *Trenberth* [1984] SOI data series (http://www.cgd.ucar.edu/cas/catalog/climind/SOI.signal.annstd.ascii). They are also compared with EN3, an index derived from SST of the eastern tropical Pacific (http://ingrid.ldeo.columbia.edu/SOURCES/.Indices/.nino/.KAPLAN/.NINO3/). The largest significant correlation coefficients are obtained by incorpo-

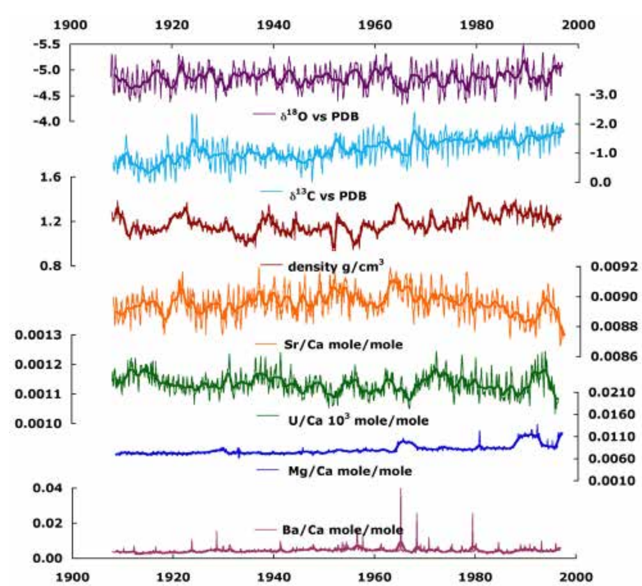

Figure 2. Monthly values of δ^{18}O (‰ vs PDB), δ^{13}C (‰ vs PDB), density (g/cm^3), Sr/Ca (mole/mole), Mg/Ca (mole/mole), U/Ca (10^{3}mole/mole) and Ba/Ca (mole/mole). The thicker curves denote the 25-month Hanning filtered signals.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL025950.

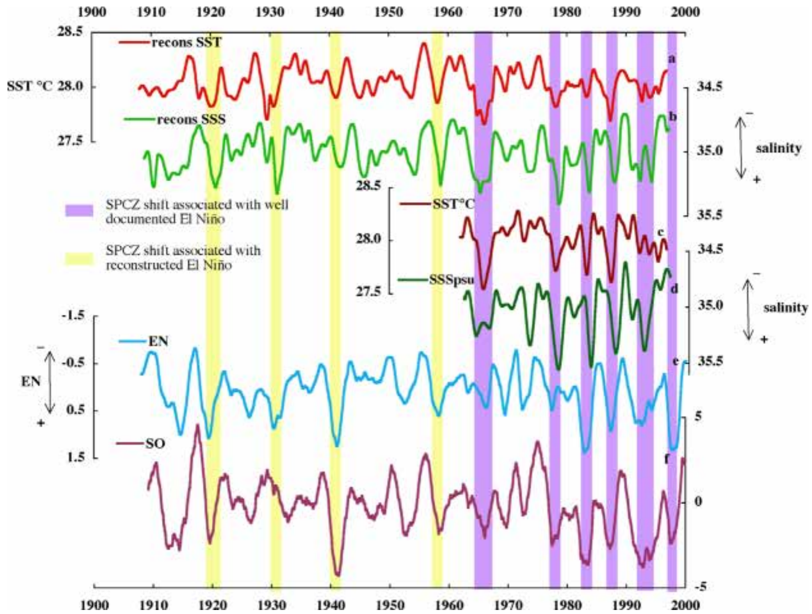

Figure 3. Monthly values of 25-month Hanning filtered time series nearby Fiji. From top to bottom are (a and b) the reconstructed SST and SSS, (c and d) the observed SST and SSS in a grid centered on 16°S–175°E, (e) the SST anomalies in the NINO3 box, and (f) SOI (Southern Oscillation Index). Details are given in the main text.

rating a 2-month delay between the SOI indices and the SST-SSS time series (Table 1). Noteworthy, there is a progressive SSS decrease from 1978 to 1990. SSS values given by *Delcroix* [1998] indicate a freshening of −0.27 between 1978 and 1997, and the decrease derived from our SSS reconstruction is −0.25. This suggests a drastic modification of the regional hydrological cycle.

[8] The reconstructed time series clearly show SST and SSS anomalies associated with El Niño (1965/66, 1972/73, 1976/78, 1982/83, 1986/87, 1991/94) and La Niña (1967/68, 1973/75, 1988/89 and 1996) events [*Quinn et al.*, 1987]. Compared to the instrumental records [*Reynolds and Smith*, 1994; *Delcroix*, 1998], some differences in amplitude are evident (Figure 3).

[9] The regional relationships between SST, SSS and EN were already documented for the 1978–97 period for the SW Pacific [*Gouriou and Delcroix*, 2002]. Our reconstructed SST and SSS time series confirm the main regional features highlighted by [*Gouriou and Delcroix*, 2002]. In Fiji, the SSS changes depend on the SPCZ location and related precipitation changes. The concomitant positive SSS and negative SST anomalies recorded during EN in Fiji (Figure 3) support the role of horizontal advection of high salinity waters by anomalous horizontal oceanic currents already stressed by *Gouriou and Delcroix* [2002].

3. SST and SSS Reconstructions During the Early 20th Century

[10] Figure 3 shows that the amplitude of reconstructed SST and SSS signals appearing in the first half of the twentieth century is of the same order as observed during 1960–1997, SST ranges within 27.5–28.5°C and SSS within 34.5–35.5.

[11] The overall reconstructed signals indicate a less frequent occurrence of high SSS/low SST values (1918/19, 1930, 1940 and 1960), possibly associated with EN-related SPCZ migration, during the first half of the century than during the 2nd half. Conversely, low SSS/high SST values happened during the La Niña events in 1916/17, 1942/43, 1955/56 (Figure 3). During the whole century, the higher SSS values can only be explained by an advection of salty waters from the East. In 1913 and 1925, SSS does not record a positive peak as pronounced as with the EN indices. Between 1930 and 1960, (a period of reduced EN activity and associated teleconnection [*Folland et al.*, 2002]) there is only one event in the early 1940's

Table 1. Correlation Coefficient R Calculated During 1961–1997 Period Between the Monthly Filtered Data Series, EN Indices, and Reconstructed SST and SSS[a]

	Reconstructed SST	Reconstructed SSS	SST	SSS
Reconstructed SST				
Reconstructed SSS	−0.62			
SST	0.80	−0.49		
SSS	−0.55	0.78	−0.54	
SOI	0.61	−0.43	0.58	−0.49
EN 3	−0.50	0.50	−0.50	0.61

[a]Data take into account the two month delay.

corresponding to the record of weak SST and SSS signals, while the 1943 and 1955/56 low SSS values (less than 34.8) correspond to La Niña. Between two successive SST and SSS peaks, conditions remained constant with continuous precipitation like between 1921–1930 or 1931–1940 or less rainy as between 1942–1955. Two negative peaks of SSS corresponding with La Niña surround the 1957 El Niño event. Decreasing SSS trends show up during 1908–1925 and during 1975–1997 as discussed above. Increasing SSS trend shows up from about 1930 to 1970.

4. Discussion

[12] Usually, the responses of $\delta^{18}O$ and Sr/Ca to environment forcing are supposed linear. Two methods have been proposed to calculate SST and SSS from the paired $\delta^{18}O$ and Sr/Ca data series [*McCulloch et al.*, 1994, *Ren et al.*, 2003]. However, in the WPWP where the interannual and interdecadal fluctuations are essentially due to SSS, Sr/Ca variability cannot be only explained by SST changes [*Linsley et al.*, 2004]. We conclude that climatic record in coral skeleton is more complex than earlier supposed and it is probably not linear. More often, the factors responsible of the fluctuations remain ignored and such anomalies are attributed to "vital effect".

[13] We call vital effect the biological impact on climate proxies. The same biological filter, specific to one colony, modifies every proxy measured on one core. Thus, the response of each of them results of embedded environmental and biological influences. We expect that NN is capable to recognize the unique and common filter from a set of data series. After learning the geochemical responses to an external factor (SST and SSS) during the calibration period, NN is supposed to separate biological influence and every external effect. The robustness of NN approach would depend on the consistency of the set of proxies. We note that separated SST and SSS reconstructions allow SSS error to be lowered, as compared to other methods.

[14] As a cautionary note, it is worth noting that the learning process of the neural network approach was undertaken in using proxies and environmental parameters during 1960–97 period. Specific features marked this period: higher SST than during the previous decades, more frequent EN events [*Fedorov and Philander*, 2000]. Thus, we checked that the reconstruction does not provide specific SST and SSS characteristics of 1960–97 years to the early 20th century. Firstly, we noted that prior to mid-70's, SPCZ displacements associated with EN are less frequent than after (Figure 3). Secondly, reconstructed SST does not show any long trend, even the warming related with the greenhouse effect that we could expect as it was recorded every where else.

[15] However, significant tendencies are observed on SSS curve (Figure 3). Fiji being located on the front between subtropical waters and the WPWP, the SSS trend recorded during the last decades (Figure 3), could reproduce the variability of the WPWP size. A similar SSS decrease has been derived from coral $\delta^{18}O$ collected around Vanuatu [*Kilbourne et al.*, 2004]. However, if we suppose that the SSS decrease is related to the WPWP size change, we would observe both SSS and SST variation. But no noticeable variability affects SST reconstruction, and this SSS trend could be a regional feature. Another SSS decrease of 0.23 was observed from 1908 to 1928 followed by a progressive increase of 0,1 from 1930 to 1970 (Figure 3). The latter interdecadal variation could be due to local changes in coherence with the SPCZ index from *Deser et al.* [2004], which indicates a rainfall episode from 1930 to 1940 turning to a dry episode until the late 1970s. These hydrological changes might correspond with a displacement of the SPCZ.

[16] The comparisons with other interannual records over this period are limited because up to now investigations were essentially focused on interdecadal fluctuations [*Linsley et al.*, 2004; *Folland et al.*, 2002]. During the last decades, almost all EN events were associated with SPCZ migration (Figure 3) except 1969/70 and 1972/73 events. Prior to 1970, among the EN listed by earlier reconstructions [*Quinn et al.*, 1987], only stronger events are associated with migrations of SPCZ. The strong EN indicated by SOI and EN3 in 1912/14 is not recorded on our SSS and SST. During this period SST remains at about 28°C and salinity lower than 35. No SST and SSS peak appear during the moderate event of 1925/26. In contrast, after 1930, SSS and SST changes indicate a SPCZ migration in good agreement with EN3 but earlier than the SOI index. Our curves indicate a short episode of SSS increase and low SST during the strong EN signaled by the indices in 1941/42. But the peak recorded in 1943 showing a strong influence of SPCZ both on Fiji SST and SSS is not corresponding to a clear Niña event on indices curves. After ten years marked by moderate to low SST and moderate salinity from 1944 to 1955, the consequences of an incursion of the SPCZ over Fiji is followed by a rapid SPCZ migration. These convergence zone displacements are corresponding to peaks on SOI and EN3: the indices show a strong La Niña in 1956 followed by an El Niño event in 1958. The low SST decreases and SSS increases recorded in 1945 and 1953/54 cannot be considered as real SPCZ migrations. Therefore, SSS and SST reconstructions in Fiji indicate that SPCZ migrated only five times between 1908 and 1970 in phase with strong EN. For precision about direction of migration we need records from surrounding islands.

[17] Between the 1920–1940 period, the "normal" condition corresponded with fresh water, supposing an active and constant convective activity of the SPCZ. Then, the climatic conditions prevailing during the period between two SPCZ southward displacements could be influenced by El Niño-like conditions (SSS > 35 and SST < 28°C as found between 1943 and 1953) or La Niña-like regime (SSS < 35 and SST > 28°C as found between 1923 and 1928, 1932 and 1940 and 1969 and 1977). We note that a clear regime shift occurred in 1977. After this date, EN events are so frequent than we observe rapid and alternate conditions. The curious regime recorded at the beginning of 90's could be regarded as mainly influenced by an El Niño-like regime.

5. Conclusion

[18] In an area where classical interpretation of proxies from coral skeleton to reconstruct SST and SSS is tricky, the NN approach provides an attractive alternative to the linear methods. It could signify that the assumptions on which the

previous interpretations were based need to be revised and that coral remains the promised tropical ocean archive.

[19] Our reconstructed SST and SSS are probably slightly underestimated in term of magnitude but they clearly indicate that in this portion of WPWP, the fluctuations of the two parameters are always associated during the 20th century. In contrast with other Pacific areas we do not reconstruct a SST increase from the beginning of the last century corresponding with the global warming. SSS fluctuations being essentially due to SPCZ migrations, their reconstruction reveals that during the 1900-mid 70's period five SPCZ displacements were associated with EN of strong amplitude while five shifts (including the migration associated with the 1997–98 event) occurred after 1977.

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