A 170-year Sr/Ca and Ba/Ca coral record from the western Pacific warm pool:

2. A window into variability of the New Ireland Coastal Undercurrent

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[1] A *Porites* coral from New Ireland (2.5°S, 150.5°E), at the heart of the Pacific warm pool, records variations of Ba/Ca back to the early 1820s. The New Ireland Coastal Undercurrent, which flows along the north coast and transports high-nutrient thermocline waters, is thought to be the main source of the Ba enrichment observed in the coral during El Niño. Between the 1850s and the 1960s, frequent large Ba peaks indicate that nutrients were available during both phases of El Niño–Southern Oscillation (ENSO). During La Niña, Ba could be advected along the South Equatorial Current. Also during this period, clusters of Ba/Ca peaks at nearly decadal timescale generally coincide with the return time of a strong El Niño, in accord with the high decadal variance of NINO3 sea surface temperatures. Ba enrichment in this coral primarily reflects the stratification in the thermocline that controls vertical mixing. The coral records long-term changes in those properties affecting nutrients in surface waters, with reduced Ba after the 1960s, and even less between 1823 and 1850. These reductions are tentatively attributed to the high rate of warming at the end of the Dalton Minimum and since the mid-20th century. An ensuing weakening of the trade winds may have produced a more stratified equatorial thermocline, hindering the transport of Ba and nutrients from the undercurrent to the shallow coastal waters north of New Ireland.

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1. Introduction

[2] In part 1 of this study [Alibert and Kinsley, 2008] the Sr/Ca and Ba/Ca compositions of the top ~50 years of a *Porites* coral from the New Ireland province of Papua New Guinea (2.5°S, 150.5°E) [see Alibert and Kinsley, 2008, Figure 1] were assessed as tracers of sea surface temperature (SST) and nutrients, respectively. In this second part, we report on the entire coral record back to ~1823. Sr/Ca and Ba/Ca were analyzed at high resolution by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). The application of this technique to coral analysis was first reported by Sinclair *et al.* [1998] and McCulloch *et al.* [2003] produced a multicentury record of Ba/Ca for an inner Great Barrier Reef coral influenced by the flood plumes and sediment load of the Burdekin River. For the coral studied here, however, the observed Ba enrichment cannot be attributed to river runoff. In part 1, we have interpreted this enrichment as being related to advection processes along the upper ocean currents north of New Ireland.

[3] Climate variability in the western Pacific warm pool is mainly related to ENSO and is opposite in character to that observed in the central east Pacific, with relatively cooler SST, higher sea level pressure (SLP) and shallower thermocline during El Niño [Mayer and Weisberg, 1998; Wang and Picaut, 2004]. During the recent 1997/1998 El Niño, the TAO buoys west of 156°E indicate that the 20°C isotherm shoaled by ~30 m, with an even greater shoaling reported for the New Guinea Coastal Undercurrent (NGCU) [Ueki *et al.*, 2003]. The New Ireland Coastal Undercurrent (NICU) flows equatorward along the north coast of New Ireland, following closely the steep bathymetry. As this undercurrent is dynamically similar to the NGCU [Butt and Lindstrom, 1994], it is also expected to shoal during El Niño.

[4] ENSO is an irregular climate oscillation whose properties have changed during the past decades [e.g., Torrence and Webster, 1999]. The origin of these decadal-multiperennial variations remains a subject of intense debate (see the recent review by Wang and Picaut [2004]). There is a consensus that the interaction between SSTs in the central eastern Pacific, winds and the tilt of the equatorial thermocline (Bjerknes' positive ocean-atmosphere feedback mechanism) is central to ENSO dynamics. Low-frequency variations of ENSO amplitude have been attributed to changes of the tropical climate mean state [Fedorov and

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Philander, 2000; *Wang and An*, 2002] or a nonlinear mechanism associated with ocean dynamics [*Timmermann*, 2003]. The additional role of the mean zonal thermocline depth anomaly is now recognized, as it carries the memory necessary to produce an oscillation. A recharge and discharge of the warm water volume above the 20°C isotherm has been proposed as a mechanism to explain the transition between El Niño and La Niña [*Jin*, 1997; *Meinen and McPhaden*, 2001]. Of particular interest is the nonlinearity revealed by the asymmetry of the anomaly patterns between El Niño and La Niña (the amplitude of the warm anomaly in the eastern Pacific during El Niño is greater than that of the cold anomaly during La Niña) [*Burgers and Stephenson*, 1999; *Hannachi et al.*, 2003]. Long-term changes of this nonlinear component of ENSO have been suggested by analyses of historical data sets such as HadISST, but remain poorly reproduced by coupled climate models [*Cai et al.*, 2004; *Monahan and Dai*, 2004; *Rodgers et al.*, 2004].

[5] Long-lived corals from the equatorial Pacific have the potential to document changes in the decadal modulation of ENSO. The coral record presented here provides a western Pacific warm pool perspective of these changes. As seawater Ba is normally depleted in the surface layer, the coral skeleton enrichment in Ba is interpreted as primarily reflecting the efficiency of mixing processes above the NICU and their response to changes in background winds and vertical temperature structure of the upper ocean.

2. ENSO Events in the Coral Record Between 1950 and 1823

2.1. Coral Data and Climatic Data Sets

[6] The 2.1 m long coral core reported here, and designated as NEP, was collected off the northeast pass, ~8 km north of Lavongai island. Sampling and protocols for LA-ICPMS analyses are described in part 1 [*Alibert and Kinsley*, 2008]. Although Sr/Ca in the NEP coral depends not only on water temperature, but also to a significant degree on vital effects, we have utilized the large apparent sensitivity of Sr/Ca to temperature as a guide in establishing the chronology. Sr/Ca variations were compared (Figure S6¹) with the SST reconstruction from the Hadley Center (HadISST v. 1.1, at the grids 2.5°S, 150.5–156.5°E) [*Rayner et al.*, 2003]. The El Niño events can be recognized in Figure S6 by cooler than normal SST, with a winter minimum around 28–28.5°C. As indices of ENSO, we used NINO3,4, which is the central east Pacific SST (5°N–5°S, 120–170°W), extracted from the HadSST2 data set [*Rayner et al.*, 2006], and sea level pressures (SLP) from Darwin (back to 1882) and Jakarta (back to 1866) [*Können et al.*, 1998]. All three indices have been calculated as anomalies relative to 1961–1990 (SLP and the Equatorial Islands Rainfall indices are available on the Web site of the University of Washington at http://jisao.washington.edu/data_sets).

[7] Knowledge of El Niño events before the advent of reliable SST data, which cover only the past five decades for the warm pool region, depends on proxy records and historical reports of severe droughts/floods in regions

strongly impacted by ENSO. Although *Kaplan et al.* [1998] show a reconstruction for the 1868 El Niño, based on sparsely sampled observations along the American coast, the first well-documented El Niño event is that of 1877/1878 [*Kiladis and Diaz*, 1986]. We used an account by the Australian Bureau of Meteorology of major El Niño events since 1900 and their impact on the Australian climate (available at http://www.bom.gov.au/climate/enso/australia_detail.shtml). The role of ocean currents in transporting nutrients to the Kavieng region has been assessed from analyses of ocean surface currents by Ants Leetmaa (NOAA) (available at <http://iridl.ldeo.columbia.edu/SOURCES/IGOSS/leetmaa>), and also from the OSCAR project (available at the NOAA/NESDIS Web site at <http://www.oscar.noaa.gov/datadisplay/>).

[8] The analytical transects for Sr/Ca and Ba/Ca are shown in detail for each of the three individual pieces of the coral core, at approximately weekly resolution, in Figures S3, S4, and S5. These analytical transects have been averaged to produce a composite record at monthly resolution (Figure 1 and Data Set S1).

2.2. Chronology of Coral Growth and Interpretation of Ba/Ca Peaks in the Coral Record

[9] The chronology for the entire NEP coral follows the same lines as described for the top core in part 1 [*Alibert and Kinsley*, 2008]: tie-points were established between the SST record and the coral trace element record. These were preferably taken at distinctive Sr/Ca maxima, hence cold SST, often coinciding with El Niño, or at Sr/Ca minima corresponding to seasonally high SSTs in May or November. Tie-points are indicated as arrows in Figures S3, S4, and S5 and are labeled on X-ray positives of the coral skeleton in Figure S2. The consistency between the resulting extension rate (Figures S3, S4, and S5) and that determined from density bands on X-ray images was carefully monitored so that Sr/Ca and Ba/Ca maxima in the coral record are not artificially forced to fit known El Niño events. As described in part 1, biannual or multiple thin high-density bands are common, for example during the 1990s, 1920s, or 1840s (Figure S2). They correspond closely with Sr/Ca maxima (cold temperature) and limit the use of density banding for age determination. When some uncertainty remained in the identification of a tie-point, the chronology was tested by adding ±1 year, and the most satisfactory solution was retained. The smoothness of the long-term variations of the inferred extension rate was also used as a guide. This value of ±1 year is a realistic estimate for the error in the coral chronology.

[10] The coral Ba/Ca record shows frequent enrichments by up to almost an order of magnitude over background values. Large peaks (>20 μmol/mol) over several successive years, particularly prior to 1950 (Figure 1), suggest that Ba enrichment occurs during both phases of ENSO, as defined according to NINO3,4 SST and Darwin/Jakarta SLP indices (Figure 2). Some successive Ba/Ca peaks form clusters, as in 1876–1879, 1913–1915, or 1923–1927, indicating long-lasting nutrient enrichment in surface waters. Features such as the shape and magnitude of the Ba/Ca peaks, together with the time of the year and associated Sr/Ca, hence SST, appear to be characteristic of processes related to vertical and horizontal advection of nutrients. This is

¹Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/jc/2007JC004263>. Other auxiliary material files are in the HTML.

illustrated in Figure 3 for two decades showing particularly large Ba enrichments.

[11] Ba/Ca spikes of short duration (<1 month), usually preceding a steep fall of temperature, have been interpreted as tracers of a transient enrichment associated with coastal upwelling during westerly wind bursts (WWBs). Similar upwelling occurs along the northern coast of Papua New Guinea influenced by the NGCU [Ueki *et al.*, 2003]. The largest Ba/Ca spikes are found in 1986, 1963 (multiple events), 1952, 1930, 1918, and 1859 (Figures S3–S5). Others can be seen in early 1850, in 1896, 1902, 1914, or 1925. Some of these occur at the start of a second El Niño year, indicating that upwelling above an elevated thermocline is more conducive to entrainment of cold water and nutrients from the upper part of the NICU. Other similar narrow peaks coinciding with a major Sr/Ca cooling, as in 1858 or 1890, or with decreasing Sr/Ca (rising SSTs) as in 1915 or 1943, suggest different processes. Large Ba peaks of 2–3-month duration, with a rather symmetrical shape and steep sides, coinciding with the winter minimum SST (Sr/Ca maximum), for example in mid-1972, 1925, 1885, 1880, and 1858, are inferred to reflect nutrients brought up by vertical advection, owing to the enhanced shoaling of the NICU during El Niño. A large number of these peaks include large spikes (in 1877, 1880, 1896, 1925, or 1963) suggesting WWBs, or show a broad base (1930, 1940, 1946, or 1948) (Figures 3, S4, and S5).

[12] Most Ba peaks during La Niña show a more irregular shape or a skewed decay, suggesting a patchy or slowly declining nutrient supply. These peaks rather occur early or late in the year. Large Ba peaks interpreted in this manner can be seen in 1942, 1943, 1949, or 1879 (Figure 3). Nutrients, including Ba-rich detritus from plankton blooms, could be advected along subbranches of the SEC or accumulate in regions of convergence such as the eastern edge of the warm pool. The South Equatorial Current (SEC) is strongest in February–April around 165°E [Johnson *et al.*, 2002]. An intensification of westward near-surface currents between New Ireland and the equator is also frequently seen during this season, particularly during La Niña years (NOAA ocean surface currents). Maes *et al.* [2004] have reported large displacements of the eastern edge of the warm pool during the ENSO cycle, and observed it as far west as 140°E during La Niña. Furthermore, Lehodey *et al.* [1997, 2003] found a close relation between the movements of skipjack tuna, the displacements of the edge of the warm pool, and the accumulation of tuna forage (secondary production) along this frontal region. Consequently, Ba peaks during La Niña may also be associated with a cooling indicating a westward penetration of Cold Tongue waters. Similar Ba enrichment occurring shortly after El Niño mature phase, as in the early part of the years 1878, 1897, 1915, 1926, 1949, and 1983, is more likely to reflect equatorial upwelling to the north of New Ireland, owing to persisting shallow thermocline and anom-

Figure 1. Sr/Ca and Ba/Ca ratios for the NEP coral, at monthly resolution, with a 5-year running mean highlighting decadal-scale variations. Ba peaks frequently occur over successive years, forming clusters around 1858, 1877, 1890, 1914, 1925, 1947, 1962, 1972, and 1986.

alously strong northeasterlies in the warm pool region. Such conditions were observed in early 1998, coinciding with the reestablishment of the SEC at the end of the very strong 1997/1998 El Niño [McPhaden, 1999; Murtugudde *et al.*, 1999].

[13] There is sufficient variability in peak shapes such that not all peaks conform to the generalized descriptions given here. Differences can be subtle, as seen in Figure 3, and do not always permit a clear or unique interpretation, particularly before 1877 when ENSO indices are not available. For instance, the large Ba peaks during the La Niña years of 1890 and 1924 are similar to those found during El Niño, while the 2-month duration of the Ba spikes of 1918 and 1930 exceeds that of single WWBs. Nevertheless, the decadal to longer-term changes observed in the coral Ba enrichment remain significant.

2.3. Early El Niño Events Recorded by the NEP Coral

[14] During the period of sparse instrumental SSTs in the 1940s, the very strong and prolonged El Niño of 1940/1941 was well under way by October 1939 [Brönnimann *et al.*, 2004], which may explain below average Sr/Ca-derived temperatures and significant Ba peaks for three consecutive years from 1939 to 1941 (Figure 3). Other large Ba peaks in 1944, 1946, and 1948 also suggest El Niño events, in accord with above average SLP at Darwin and Jakarta during 1944 and 1946 (Figure 2), and above average rainfall in the central equatorial Pacific (Rainfall Index) for 1946 and 1948. The high Ba/Ca background observed between 1944 and 1949 coincides with a downward trend of Sr/Ca-derived temperatures but may also reflect the high frequency of Ba enrichment events. For the other period of sparse observations between 1914 and 1918, Ba peaks related to El Niño are found for the two consecutive years of 1913–1914 and also 1918–1919 (Figure S4). At the beginning of the century, ENSO indices indicate strong El Niño events in 1896, 1899/1900, 1902, and 1904–1905. There are reports of severe Australian drought during all these years, in particular the 1895–1902 “Federation Drought.” SSTs (Figure S6) suggest colder than average SST during the winters of 1902, 1904, and 1905. The coral Sr/Ca shows a stronger cooling in 1904 (Figure S4), additional Ba peaks during the summer of 1904/1905 being suggestive of WWBs.

[15] Between 1877 and 1891, anomalously cold SSTs indicate El Niño conditions in 1877, 1880, 1885, and 1888 (Figure S6). ENSO indices suggest that the two events of 1877/1878 and 1888 were the strongest, in agreement with reports of severe drought in Australia for 1888. Coral Ba/Ca peaks for 1877, early 1878, 1880, 1885, and 1888 are

Figure 2. Coral Ba/Ca (green, right scale) is compared with several indices of ENSO (sea surface temperature (SST) and sea level pressure (SLP) anomalies, left scale): NINO3,4 (blue), Darwin (red), and Jakarta (orange). These have been smoothed from monthly data, using a 5-month running mean. Ba/Ca is also shown as a 3-year running mean to highlight ENSO timescale variations. Some significant enrichment is observed during each El Niño and also some La Niña events, but there is a marked decrease of amplitude of the Ba/Ca peaks after ~1963.

Figure 3. Coral Sr/Ca (red) and Ba/Ca (green) for the two periods of 1939–1950 (top) and 1870–1881 (bottom). Ba/Ca is shown at ~weekly resolution for three transects, while Sr/Ca is averaged at monthly resolution. Sr/Ca is scaled as temperature ($\text{Sr/Ca} = 0.0156 - 0.00023 \times T$) with an additional offset down by 0.5°C for 1870–1891 for comparison with SSTs (blue). Ba peaks during El Niño are associated with a midyear Sr/Ca maximum (below average SST) and generally show a sharp decline. Such peaks during mid-1877, 1880, or in 1939, 1940, and 1941 coincide with well-known El Niño events. Others in the 1940s (1944, 1946, and 1948) are less well documented. Ba peaks during La Niña, or shortly after El Niño, are often offset relative to the winter SST minimum. Such peaks can be seen in 1878, 1879, 1942, 1943, 1947, and 1949. The large peaks of 1943, early 1949, and late 1879 show a slow decrease of Ba. Along these lines, 1870, 1874, and 1875 may also be La Niña years.

consistent with these El Niño events, but show a larger signal for 1880 than for 1888 or 1877 (Figure S5). Prior to 1877, Quinn [1992] noted El Niño events for 1874, 1871, 1868, 1864, 1857–1858, 1850, and 1844–1846. There were reports of severe drought in Australia in 1865–1869, 1857–1859, 1855, 1849–1852, and 1846–1847 [Nicholls, 1992]. The coral shows two large Ba peaks in 1858 and early 1859 suggesting a strong El Niño event and smaller El Niño-like peaks in 1873, 1868, 1865, 1855, 1856, 1850, and 1845–1846. The association of the large peak of 1871 with El Niño or La Niña is uncertain. Before 1846, Quinn [1992] inferred El Niño events in 1824, 1828, 1832, and 1837. Historical droughts in Queensland and southeast Australia have been reported for 1824, 1827–1829, 1833, 1837–1839, and 1842–1843 [Nicholls, 1988, 1992; Blainey, 1983]. The coral record indicates lessened nutrient supply, with only small Ba/Ca peaks ($<10 \mu\text{mol/mol}$) possibly

related to El Niño events in 1823, 1833, and 1837. The base of the core is dated as 1823 within ± 2 years.

3. Decadal to Long-Term Variations in the Ba/Ca Coral Record

[16] The entire NEP record is shown in Figure 1 at monthly resolution. The 5-year running mean highlights the near-decadal frequency of the high-amplitude Ba/Ca peaks. There is no systematic correlation between periods of high Ba enrichment and cooler SSTs. Each Ba cluster generally corresponds to the return date of a strong El Niño. From 1875 to 1920, the amplitude modulation of these clusters is similar to the 2–7-year wavelet variance of NINO3 SST [Torrence and Webster, 1999]. The Ba clusters between 1857 and 1860 and 1923–1927 suggest that this decadal modulation of ENSO was present back to the 1850s and continued until about 1930.

[17] There are three distinct periods: Ba peaks are small and less frequent prior to ~ 1850 ; of large amplitude and often found during both phases of ENSO between 1850 and 1963; and again smaller after 1963 and mainly associated with El Niño. This transition does not correspond to any significant change of amplitude of ENSO, as seen in Figure 2, where Ba/Ca is shown with a background subtracted in order to better compare the amplitude of each Ba peak against individual ENSO events. The value subtracted is the minimum Ba/Ca measured in a 5-year running window. Between 1870 and 1940, El Niño-related Ba/Ca maxima of $\sim 10 \mu\text{mol/mol}$ correspond to a NINO3,4 SST anomaly of $\sim 1.5^\circ\text{C}$ (see 1877, 1896, 1904, 1911, 1913–1914, 1925, 1940–1941), although the Ba enrichment is relatively smaller than NINO3,4 amplitude in 1888, 1902, or 1918, and larger in 1880. After 1940, however, the coral shows much larger variations in the amplitude of the Ba peaks, and after 1963, the Ba signal is markedly reduced relative to NINO3,4 (about a factor of 2 less than for 1870–1940).

[18] Ba enrichment during La Niña is also variable between events and not correlated with NINO3,4 in a simple way. This indicates that the NEP coral Ba/Ca record cannot be used as a proxy for ENSO amplitude. The long-term variations in the Ba record reflect instead changes in vertical mixing above the NICU. The higher Ba enrichment observed between the 1850s and the 1960s points to more efficient turbulent mixing and entrainment of cold water and nutrients at the top of the NICU, thereby implying a decreased stratification (higher Richardson number) in the thermocline compared to the present-day gradient of $\sim 5^\circ\text{C}/50 \text{ m}$ in the western equatorial Pacific.

3.1. Periods of High Ba/Ca Variability Between the 1850s and the 1960s

[19] The 1870s show a sequence of large Ba/Ca peaks of comparable amplitude during both La Niña and El Niño. The Jakarta SLP index suggests that ENSO was rather skewed toward La Niña, except for the very strong El Niño of 1877/1878. This indicates energetic ENSO conditions, with sufficiently high available potential energy in the system to sustain strong La Niñas [Goddard and Philander, 2000], and a Cold Tongue penetrating far westward into the warm pool. According to Fedorov and Philander [2001], background conditions including strong wind stress, a relatively deep mean zonal thermocline, and an ENSO period of 3–4 years indicate that the delayed oscillator was the dominant mode. The 3-year running mean through Ba/Ca (Figure 2) shows that the large Ba clusters often correspond to more than one El Niño–La Niña cycle, for example during the 1870s, 1910s, or mid-1920s. The two successive El Niño events of 1877/1878 and 1880 are particularly interesting, as there is only a short interval between La Niña in late 1879 and the recharge of the warm water volume in early 1880 (warmer than average SSTs and accordingly low Sr/Ca in Figure S6). This suggests some ocean memory across the two events. This also appears to be the case for the two strong El Niños of 1913/1914 and 1918/1919, followed by a strong and weak La Niña, respectively. Such prolonged active ENSO suggests a strong role for the delayed oscillator (or recharge) mechanism, in a similar way as documented by the analysis of energetics by Goddard and Philander [2000] for the sequence 1970–1975. In contrast, Kessler [2002] found that

since 1980, the El Niños show no such persistence across a La Niña break.

[20] The 1930s have long been singled out by weak SST anomalies in the Pacific and weak SOI variations. Long-lasting La Niña-like conditions have been inferred for 1932–1938, on the basis of sparse SST observations [Rayner *et al.*, 2003; see also Schubert *et al.*, 2004, Figure 2]. During the 1930s, the coral shows multiple intra-annual cooling episodes and comparatively small Ba peaks difficult to interpret. Larger peaks during the 1940s suggest that El Niño occurs every 2 years. Fedorov and Philander [2001] identify this ENSO mode as a westward propagating local mode, which is an enhancement of the annual cycle favored by a relatively shallow mean zonal thermocline. What causes these fluctuations of the basin-scale thermocline depth remains uncertain. If the trade winds are sufficiently strong, the Cold Tongue can extend far westward. In the New Ireland region, horizontal advection could be the predominant source of nutrients for the small but cyclic Ba peaks observed in the NEP coral during the 1930s. Higher-amplitude Ba peaks after ~ 1940 suggests a strengthening of the equatorial easterlies and a more important role for the delayed oscillator mode. Although Fedorov and Philander [2001] propose that the local mode prevailed during the 1940s and 1950s, the coral record rather suggests the period 1930–1950.

3.2. Ba/Ca Decline Around the 1960s

[21] Neither Ba/Ca nor Sr/Ca ratios show a clear change in the mid-1970s when large changes in the subsurface ocean temperature structure were reported in the Pacific Ocean [e.g., Stephens *et al.*, 2001]. In contrast, this shift to higher SSTs is recorded by corals from the eastern Pacific, for example at Clipperton Atoll (Figure 4) [Linsley *et al.*, 2000]. Ba/Ca peaks in the NEP coral record show a significant reduction of amplitude and frequency after ~ 1950 . There is also less Ba enrichment during the cold phase of ENSO, which could be related to the expansion eastward of the warm pool and a reduced westward advection of cold water in the western Pacific. These are patterns of change observed and simulated for El Niño-like global warming [e.g., Huang and Liu, 2001]. A steep increase of SSTs in the Southern Hemisphere has occurred since the 1950s [Rayner *et al.*, 2006] and Australian annual temperatures equally show a 1°C warming [Karoly and Braganza, 2005] (also at <http://www.bom.gov.au/climate/change/amtemp.shtml>). McPhaden and Zhang [2002] have reported a large decrease of transport in the Subtropical Cells (STCs) since 1950, mainly after the 1970s climate shift, however, recent models show a weaker decrease [Schott *et al.*, 2007; Merryfield and Boer, 2005]. These authors found that global warming may have contributed to that decline of transport, and decreased Ekman divergence is a major contributor, implying weaker equatorial upwelling since the 1950s.

[22] There is also evidence of weakening, since ~ 1950 , of the gradient of sea level pressure between the western Pacific-Indonesian region and the eastern tropical Pacific, which suggests a weakening of the Walker circulation as well as the equatorial Pacific trade winds [Zhang and Song, 2006; Vecchi *et al.*, 2006]. Using an ocean GCM, Liu and Philander [1995] showed that a reduction of the subtropical wind stress curl leads to increased stratification by cooling the lower thermocline. Large-scale ocean circulation

Figure 4. The NEP Sr/Ca record is compared with oxygen isotope coral records from the Pacific and Indian Oceans, and from the Red Sea, tracing mainly SST variations. These corals are from Urvin Bay, Galapagos Islands [Dunbar *et al.*, 1994], Clipperton Atoll (10.3°N, 109.2°W) [Linsley *et al.*, 2000], Malindi, Kenya [Cole *et al.*, 2000], Ras Umm Sidd (RUS-95), Red Sea [Felis *et al.*, 2000], New Caledonia [Quinn *et al.*, 1998], and Abrolhos Island, Western Australia [Kuhnert *et al.*, 1999]. Yearly data have been smoothed with a 5-year running mean to highlight decadal variability. Anomalously cold temperatures during the Dalton Minimum (gray shaded area), and later between 1830 and 1845, are recorded in all these corals. The NEP coral does not cover the DM period but shows a significant cooling during the mid-1830s and no long-term trend.

changes in the past 50 years [Johnson and Orsi, 1997; Schaffer *et al.*, 2000; Gille, 2002; Levitus *et al.*, 2005] are all consistent with a weaker wind-driven circulation in the South Pacific. Modeling studies indicate that the waters reaching the Equatorial Undercurrent via the western boundary originate from a window of subduction west of 140°W, around 20–25°S [e.g., Lu *et al.*, 1998; Wang and Huang, 2005]. The NICU core waters, with a potential density range of 25–26 kg.m⁻³ [Butt and Lindstrom, 1994], may originate from further east than those reaching the NGCU through the Coral Sea [Tsuchiya *et al.*, 1989]. It is therefore plausible that decadal to long-term changes in those pathways could have some impact on the amount of nutrients carried along the diverse branches forming the low-latitude western boundary currents.

3.3. Ba/Ca Low Variability Before 1850 and Sr/Ca-Derived Cooling During the 1830s

[23] Following 1833, a year identified as an El Niño event (± 1 year), below average temperatures ($\sim 0.6^\circ\text{C}$) are indi-

cated by the coral Sr/Ca record, with a return to average temperature around 1845 (Figure 1). The slightly lower Ba/Ca background, around 2 $\mu\text{mol/mol}$ during 1832–1845 suggests lower seawater Ba concentration. Although the magnitude of this cooling is possibly enhanced by vital effects, it is not caused by diagenesis, as the skeleton appears pristine (Figure S2) and both Mg/Ca and U/Ca remain consistent with Sr/Ca and display recognizable annual cycles. This prolonged cooling could be related to the two volcanic eruptions of Babuyan Claro, Philippines, in 1831 and Coseguina, Nicaragua, in January 1835. A similar cooling of $\sim 0.5^\circ\text{C}$ between 1835 and 1839 has been documented in the Bahamas [Chenoweth, 1998] and attributed to the Coseguina eruption. This period follows the Dalton Minimum (DM), a period of low solar activity circa 1795–1825 [Lean *et al.*, 1995]. During this last pulse of the Little Ice Age, the radiative cooling was reinforced by strong volcanic eruptions such as Tambora in 1815. In the Australian region, there are historical reports of successive

severe droughts between 1796 and 1804 and 1813–1820 [Nicholls, 1988] coinciding with the DM. As already noted, there were also severe droughts in Australia during the late 1830s. Accordingly, between 1820 and 1860, corals from inshore Great Barrier Reef show only a few flood-related luminescent bands [Isdale *et al.*, 1998; Hendy *et al.*, 2003; Lough, 2001] and Ba peaks [Hendy, 2003; McCulloch *et al.*, 2003], further documenting rather cold and dry conditions.

[24] In a simulation of the Little Ice Age, Crowley [2000] was the first to point to the important role of volcanism relative to solar forcing. Wagner and Zorita [2005] also found that the cooling during the second half of the DM (1810–1820) had a strong volcanic imprint and a global impact, and obtained a lesser cooling during the 1830s. These models suggest a high rate of warming during the recovery period following the DM. Accordingly, five $\delta^{18}\text{O}$ coral records from Western Australia, Red Sea, New Caledonia, Kenya, and Galapagos Islands (Figure 4) show two successive cooling episodes during the DM and the mid-1830s, followed by a long-term warming until ~1850. As the warm pool region is less sensitive to solar forcing than subtropical and high-latitude regions [Cubasch *et al.*, 1997], a preferential positive solar forcing in the subtropical and central east equatorial Pacific is expected to decrease the SST gradient across the equatorial Pacific. These conditions would produce relatively weaker trade winds, keeping the system in a rather low-energy mode (El Niño-like background conditions). Although the NEP Sr/Ca record does not cover the DM period, such a change in background winds could explain the smaller Ba/Ca peaks observed between ~1823 and 1850.

4. Conclusion

[25] In this second paper on the NEP coral, we have focused on the significance of Ba/Ca, which appears to be a more robust tracer of environmental conditions than Sr/Ca. The coral shows cyclic transient enrichments in Ba/Ca interpreted as reflecting a nutrient supply modulated by ENSO. As warm pool surface waters are largely oligotrophic, and in the absence of continental fluvial runoff, the main source of nutrients is likely to be the New Ireland Coastal Undercurrent, shoaling during the growing phase of El Niño. Ba enrichment is also observed during some La Niña episodes, which could be derived from the horizontal advection of nutrients along the South Equatorial Current.

[26] The long-term Ba/Ca record displays a markedly different character during 1850–1960, with more substantial Ba enrichment occurring during both phases of ENSO, in contrast to earlier or later periods. The high Ba enrichment observed around 1855–1860 denotes a previously little known period of energetic ENSO.

[27] Although the variability of Ba/Ca in the NEP coral primarily reflects the local environment, the involvement of the NICU and SEC as sources of nutrients has implications at a larger scale, perhaps even involving the source regions of these currents. Nevertheless, a major factor that can affect biological productivity in the euphotic zone of the equatorial western Pacific is the stratification of the thermocline, which acts as a barrier to mixing processes. A sharper thermocline, possibly linked to a weakening of the trade

winds, could explain the apparent decrease of nutrient availability since the 1960s and between 1823 and 1850.

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