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Does the El Niño–Southern Oscillation control the interhemispheric radiocarbon offset?

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Abstract

Since the 1970s it has been recognised that Southern Hemisphere samples have a lower radiocarbon content than contemporaneous material in the Northern Hemisphere. This interhemispheric radiocarbon offset has traditionally been considered to be the result of a greater surface area in the southern ocean and high-latitude deepwater formation. This is despite the fact that the El Niño–Southern Oscillation (ENSO) is known to play a significant role in controlling the interannual variability of atmospheric carbon dioxide by changing the flux of 'old' CO_2 from the tropical Pacific. Here we demonstrate that over the past millennium, the Southern Hemisphere radiocarbon offset is characterised by a pervasive 80-yr cycle with a step shift in mean values coinciding with the transition from the Medieval Warm Period to the Little Ice Age. The observed changes suggest an ENSO-like role in influencing the interhemispheric radiocarbon difference, most probably modulated by the Interdecadal Pacific Oscillation, and supports a tropical role in forcing centennial-scale global climate change.
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Keywords: ENSO; Interdecadal Pacific Oscillation; Little Ice Age; Medieval Warm Period; Pacific Decadal Oscillation; Tree-rings

Introduction

The global atmospheric radiocarbon content is controlled by several factors, including changes in climate and oceanic circulation, solar output and geomagnetic variability (Stuiver et al., 1991; Broecker, 1998; Hughen et al., 2004). Embedded within the reconstructions of past global radiocarbon content (Reimer et al., 2004), however, are subtle but measurable variations in regional atmospheric radiocarbon content over at least the past millennium. Due to the poor atmospheric mixing across the equator, pre-industrial Southern Hemisphere radiocarbon samples are typically several decades older than Northern Hemisphere counterparts. Numerous studies have demonstrated that Southern Hemisphere samples have lower ^{14}C contents (e.g. Lerman et al., 1970; Vogel et al., 1993). Although the precise mechanism(s) for the origin of the older CO_2 signal remain uncertain, the difference is considered to be due to the larger ocean surface area in the Southern Hemisphere and associated atmospheric–ocean CO_2 exchange (Braziunas et al., 1995), the latter possibly driven via deep water formation at high latitudes.

One phenomenon that has been largely ignored with regards to its potential impact on atmospheric radiocarbon content is the El Niño/Southern Oscillation (ENSO) (Feely et al., 2002; McKinley et al., 2004). Major climatic perturbations associated with the ENSO phenomenon are known to have taken place at a range of different timescales, including over the last glacial–interglacial cycle (Tudhope et al., 2001; Turney et al., 2004; Rein et al., 2005), and through much of the Holocene, including the past millennium (Quinn et al., 1987; Whetton and Rutherford, 1994; Fowler et al., 2000; Gagan et al., 2000; Mann et al., 2000; Larkin and Harris, 2002; Moy et al., 2002; Cobb et al., 2003; Gagan et al., 2004; D'Arrigo et al., 2005). Here we discuss the known impact of contemporary ENSO variability on atmospheric carbon-dioxide content and then investigate its potential effect on the interhemispheric radiocarbon offset.

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ENSO and the carbon cycle

As a result of the upwelling of CO_2-rich deepwater, the tropical Pacific Ocean is the single largest, geographically constrained source of carbon dioxide to the atmosphere (Feely et al., 1999, 2002; Schimel et al., 2001). Of the 0.7–1.5 PgC yr^{-1} ($\times 10^{15}$ g carbon yr^{-1}) emitted from the equatorial oceans, up to 72% emanates from the tropical Pacific (Feely et al., 1999). Under El Niño conditions, the thermocline in the eastern equatorial Pacific is depressed by eastward propagating Kelvin waves generated by anomalous westerly wind-flow originating in the western Pacific (McPhaden et al., 1998). The depression of the thermocline prevents the upwelling of CO_2-rich water to the surface in the eastern Pacific (Guilderson and Schrag, 1998; McKinley et al., 2004). Accompanying this, anomalous warming occurs within the central equatorial region, forming a warm cap of seawater that has a low partial pressure of CO_2 in a region that typically exhibits upwelling of carbon dioxide-rich waters (Feely et al., 2002). As a result, during an El Niño event, anomalous warming between 10°S and 10°N in the equatorial Pacific can lead to a 90% reduction in the CO_2 flux (Chavez et al., 1999; Feely et al., 1999; McKinley et al., 2004). The location of these changes is critical because the principal mechanism for restricting gaseous exchange between the hemispheres is the Inter-Tropical Convergence Zone (ITCZ), which forms a major convergence of surface (and divergence at high altitude) atmospheric flow in the equatorial region between approximately 8°N and 15°N (i.e. north of the changes in CO_2 flux to the atmosphere). At a global level, biogeochemical oceanic models indicate ENSO to be the primary driver of the worldwide variability in the air–sea flux of carbon (±0.5 PgC yr^{-1}), while the North Atlantic air–sea CO_2 flux variability is negligible (McKinley et al., 2004).

Hydrographic observations indicate that the upwelling CO_2-rich cold water in the central and eastern tropical Pacific originates from the eastward flowing Equatorial Undercurrent; the latter is believed to originate from Antarctic surface waters that have been resubducted into the South Pacific thermocline before being equilibrated with the atmosphere (Toggweiler et al., 1991). Following several centuries or more of isolation since deepwater formation at high latitude, the resulting upwelling CO_2 in the eastern equatorial Pacific is relatively ^{14}C depleted compared to the atmosphere (Toggweiler et al., 1991).

Over the equatorial Pacific, the ITCZ remains relatively stationary throughout the year, although during El Niño events the boundary moves equatorwards (Diaz and Kiladis, 1992). Under non-El Niño conditions, therefore, upwelling of ^{14}C-depleted CO_2-rich water will dilute the atmospheric radiocarbon content south of the ITCZ, generating older Southern Hemisphere ages. During El Niño periods, however, the reduced flux of 'old' CO_2 to the atmosphere and the equatorwards migration of the ITCZ contribute to a significant decrease in the interhemispheric radiocarbon difference. In the Southern Hemisphere, the growing season typically extends over the period October to March. Modern El Niño events show a significant tendency to peak towards the end of the calendar year (Tziperman et al., 1998), potentially exaggerating the sensitivity of South Pacific wood to the changing flux of 'old' CO_2 into the atmosphere (Manning et al., 2003).

Interhemispheric radiocarbon during the past millennium

The recent publication of absolutely-dated and high-precision radiocarbon-dated paired wood samples of UK oak (*Quercus petraea*) and New Zealand cedar (*Libocedrus bidwillii*) or silver pine (*Lagarostrobos colensoi*) provides a decadally resolved interhemispheric radiocarbon difference record for the period AD 950 to 1850 (Fig. 1; Hogg et al., 2002). Due to the decadal sampling of the UK and New Zealand wood samples for ^{14}C it is not presently possible to resolve the interannual variability in the interhemispheric radiocarbon difference. Nevertheless, we can explore the cyclic nature of the interhemispheric radiocarbon offset at greater than decadal timescales. An advantage of such an approach over conventional dendroclimatic methods is that the inferred environmental changes have been passively recorded in the wood, rather than being an active record based on ring widths where other competing growth influences have to be taken into consideration (i.e. filtered).

The reconstruction of the interhemispheric difference demonstrates that the offset is not constant but varies around a mean of 40±13 yr, with a range of between 7 and 83 yr (Fig. 1). Intriguingly, however, there appears to be a stepped change in the offset from the Medieval Warm Period (MWP) to the Little Ice Age (LIA) (Grove, 1988; Broecker et al., 1999; Moberg et al., 2005), with mean values of 49 and 35 yr, respectively.

The MWP and LIA have been proposed to be associated with changes in deepwater formation (Broecker, 2000; Broecker et al., 1999). Although not a significant contributor to the variability of contemporary atmospheric CO_2 concentration levels (McKinley et al., 2004), a shift in mean interhemispheric

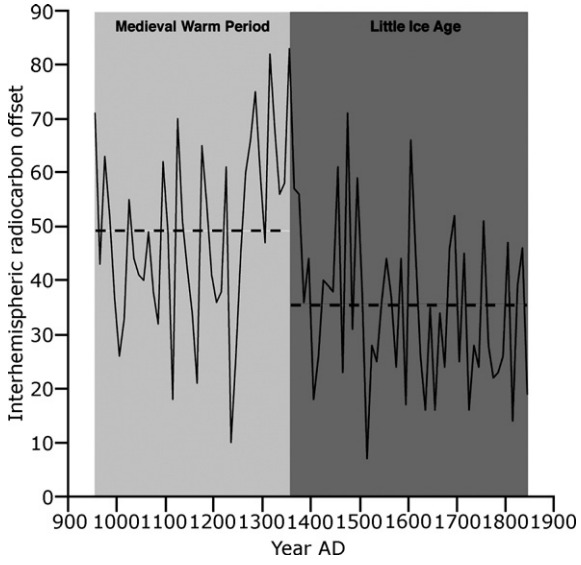


Figure 1. The interhemispheric radiocarbon offset for the past millennium using UK oak (*Quercus petraea*), New Zealand cedar (*Libocedrus bidwillii*) and silver pine (*Lagarostrobos colensoi*) (Hogg et al., 2002). The Medieval Warm Period and Little Ice Age are as defined by Grove (1988) and Broecker et al. (1999). Dashed lines represent mean values of 49 and 35 years, respectively.

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radiocarbon difference would be anticipated under a scenario of changing deepwater dominance. The proposed changes in deepwater formation, however, should produce the opposite change in hemispheric radiocarbon activity to that observed here. A decrease in deepwater formation increases the atmospheric radiocarbon content, largely because of a reduction in the transfer of ^{14}C into the ocean (Hughen et al., 2004). Extrapolated to regional differences in deepwater formation dominance, a decrease of deepwater formation in the North Atlantic (and an increase in Southern Ocean water formation) during the LIA should therefore increase the interhemispheric radiocarbon difference, instead of reducing it as observed in Figure 1.

An alternative scenario is that during the MWP and LIA there were two different pervasive states of ENSO activity across the Pacific region (e.g., Hendy et al., 2002; Cobb et al., 2003; Cook et al., 2004). The MWP could have been characterised by persistent La Niña conditions, maintaining a relatively high interhemispheric radiocarbon offset, while the LIA may have been dominated by El Niños, capping the upwelling of 'old' CO_2 and resulting in elevated ^{14}C activity in the Southern Hemisphere. Indirect evidence for this has been reported by Cook et al. (2004), who demonstrated pervasive drought conditions in the western USA during the MWP that appeared to be associated with cool sea surface temperatures (SST) in the eastern Pacific, suggesting persistent La Niña conditions. Pervasive La Niña conditions have also been proposed for the MWP in the eastern (Rein et al., 2005) and central (Cobb et al., 2003) Pacific. In contrast, the LIA appears to have been characterised by wetter conditions in the western USA (Cook et al., 2004), associated with a warmer El Niño state (Cobb et al., 2003; Rein et al., 2005). Similarly, Hendy et al. (2002) demonstrated that the LIA was characterised by warmer Pacific SST on the Great Barrier Reef (GBR) and that its termination coincided with a reduction in sea temperatures. Coincident with the SST changes observed across the Pacific, shifts in $\Delta^{14}C$ are also recorded within marine records. In banded coral series from Abraham Island, GBR (Druffel and Griffin, 1993), persistent low-radiocarbon waters entered the region during the LIA (typical of El Niño conditions) with the latter terminating in elevated-radiocarbon waters, consistent with a long-term shift in ENSO activity.

Changing ENSO activity during the MWP and LIA does not preclude a change in deepwater formation dominance, but the latter clearly did not dominate the interhemispheric radiocarbon offset during these periods. Such a scenario raises a fascinating possibility that climatic periods such as the MWP and LIA were driven by pervasive La Niña and El Niño conditions in the tropics and did not originate in the North Atlantic. For instance, unambiguous warmer temperatures have been reported across the Northern Hemisphere and New Zealand during the MWP (Broecker, 2001; Cook et al., 2002; Moberg et al., 2005), while glacial advances have been recorded in both regions through the LIA (Grove, 1988). The proposed persistent El Niño conditions during the LIA would increase moisture delivery to the high northern latitudes (Hendy et al., 2002) while in the south produce a high-pressure anomaly over southern Australia (Hooker and Fitzharris, 1999), resulting in enhanced south-westerly airflow and precipitation over New Zealand, thereby driving glacier advances in both hemispheres. Although it is believed that glacial advances were experienced globally during the LIA, it is by no means certain that it was significantly cooler throughout the world. The reconstructions from the tropics and Southern Hemisphere have largely failed to identify a cold period synchronous with the Northern Hemisphere (Jones et al., 2001; Hendy et al., 2002). One possibility is that the Northern Hemisphere cooling associated with the LIA was restricted to high latitudes (Rind, 2000).

We spectrally analyzed the published interhemispheric dataset (Hogg et al., 2002) using the high-resolution Multi-Taper Method (MTM; Thomson, 1982) available through AnalySeries (Paillard et al., 1996). The MTM plot of the offset over the past millennium (Fig. 2) identifies two prominent peaks centred on 850 and 80 yr. To test for periodicity, a statistical *F*-test was performed on the MTM amplitude, of which these peaks were identified with 91 and 94%, respectively. The peak centred on 850 yr is intriguingly similar to Holocene climate cycles previously identified (Bond et al., 2001; Russell et al., 2003; Turney et al., 2005) and most probably reflects the cyclic nature of the MWP and LIA discussed above. Unfortunately, however, due to the relatively short length of the dataset, the period spanning the MWP is not fully represented, and this is reflected in the relatively low *F*-test value. In contrast, the 80-yr cycle appears robust and periodic through the dataset.

On the multidecadal timescale, variations in ENSO are connected across the Pacific Ocean via changes in oceanic and atmospheric conditions, including SST and sea-level pressure (Zhang et al., 1997; Barnett et al., 1999; Minobe, 1999; Cane, 2005). Of critical importance is the Interdecadal Pacific Oscillation (IPO) (Power et al., 1999), which is sometimes referred to as the Pacific Decadal Oscillation (Minobe, 1997) although the latter term tends to be associated with just the North Pacific region. Changes in the IPO generate ENSO-like

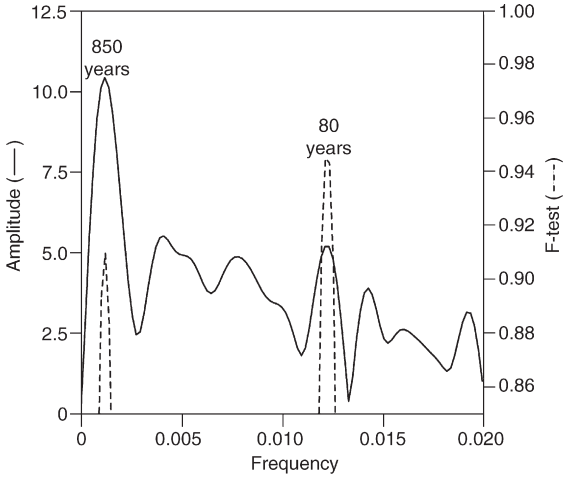


Figure 2. Spectrum of the interhemispheric radiocarbon offset (Hogg et al., 2002) using the high-resolution Multitaper Method (MTM; Thompson, 1982). The left axis is the estimated MTM amplitude and the right axis is the statistical *F*-test.

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patterns across the Pacific with a negative phase resulting in positive SST anomalies over the North and South Pacific, while producing negative anomalies over the tropical Pacific (Gershunov and Barnett, 1998; Power et al., 1999; Salinger et al., 2001). Although there is some debate as to whether the IPO modulates or is influenced by ENSO (Cane, 2005; Verdon and Franks, 2006), a robust relationship does appear to exist between phase changes in the IPO and changing frequency of El Niño and La Niña events (Power et al., 1999; Verdon and Franks, 2006). When the IPO is in a negative phase, there is a greater propensity for La Niña events; during a positive IPO phase there are more El Niños.

The 80-yr cycle recognised in the interhemispheric difference is close to the multidecadal periodicity recognised in the historical time series for the IPO (Minobe, 1997, 1999; Power et al., 1999). Furthermore, a recent reconstruction of past El Niño variability (Rein et al., 2005) proposed the strongest events recurred with a 60- to 80-yr periodicity, supporting the contention that the IPO influences ENSO activity and that together they significantly impact upon the interhemispheric radiocarbon difference.

Past ENSO activity

To investigate the above requires absolutely dated reconstructions from regions highly sensitive to ENSO, of which the highest resolved sequences tend to preserve only 'floating' century-length records of activity. Nevertheless, the biannual reconstruction of $\Delta^{14}C$ from Abraham Island, GBR (Druffel and Griffin, 1993) and the recent publication by Cobb et al. (2003) from Palmyra Island in the central Pacific provide the most comprehensive compilation of coral records representing several centuries of ENSO activity. We have used these datasets in combination with a historical reconstruction of 5-yr-long 'warm' ENSO events dating back to the seventeenth century based on contemporary teleconnection observations (Mann et al., 2000) (Figs. 3A–C).

The ENSO reconstructions (Figs. 3A and B) indicate cold mean SSTs in the late 12th century and the mid-14th century, with moderate SSTs associated with more frequent/sustained warm ENSO events in the early 13th century, the 14th-15th century boundary, the mid-18th century and early 19th century. A period of exceptionally warm SSTs is clearly observed in the central Pacific corals of Palmyra in the mid-17th century and coincides with sustained low radiocarbon waters entering the GBR, suggesting sustained/more frequent El Niños at this time. These periods of variable ENSO activity recognised in the corals and historical records are all associated with changes in the Southern Hemisphere radiocarbon offset (Fig. 3C), consistent with an El Niño control on the CO_2 flux to the atmosphere.

In contrast to the coral and historical records, however, the interhemispheric radiocarbon difference provides a complete continuous record and when taken over the full 1000 yr, clear trends in the intensity and/or frequency of ENSO can be identified at the decadal and multidecadal timescale. For instance, although the interhemispheric radiocarbon dataset and corals identify sustained changes in ENSO activity during the mid-17th century, more extreme periods are indicated by the trees. During the periods centred on AD 1235 and 1515 (with Southern Hemisphere offsets of 10 and 7 yr, respectively), more

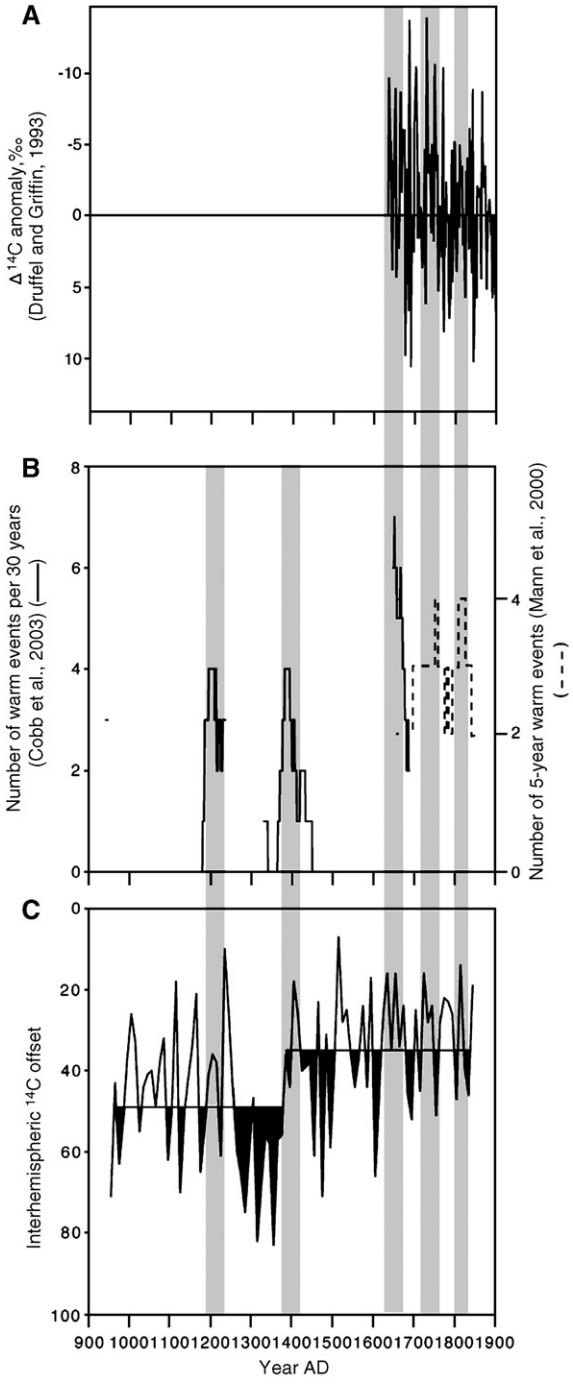


Figure 3. Comparison between published reconstructions of ENSO activity represented by changes in (A) radiocarbon waters reaching Abraham Island on the Great Barrier Reef (Druffel and Griffin, 1993), (B) number of 'warm' ENSO (El Niño) events (Mann et al., 2000; Cobb et al., 2003), and (C) the interhemispheric radiocarbon offset for the past millennium (Hogg et al., 2002). The $\Delta^{14}C$ record from Abraham Island has been calculated as an anomaly relative to the expected ocean mixed-layer values (Hendy et al., 2002). Grey zonation denotes correlation between historical and coral-recognised periods of sustained/more frequent ENSO activity and the interhemispheric offset dataset. Note the inversion of the radiocarbon axes.

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intense events are inferred. These are periods not currently covered by the corals or historical reconstructions.

A sustained period of high interhemispheric radiocarbon offset values is identified between AD 1250 and 1380 (Fig. 3C), falling at the end of the MWP and immediately prior to the LIA. During this period, the Southern Hemisphere offset reached a maximum of 83 yr in AD 1355. The values suggest a sustained period of outgassing of old CO_2 in the Southern Hemisphere (relative to the North). An ENSO control on the interhemispheric radiocarbon offset would suggest this was an extraordinary sustained period of La Niña-like conditions in the tropical Pacific. If so, it is unclear what may have disrupted the 80-yr ENSO–IPO coupling over this period of time.

The timing of sustained La Niña conditions at the end of the MWP appears to coincide with major archaeological activity in the region. For instance, Polynesian settlement of New Zealand is believed to have been undertaken from remote Oceania (centred on the Cook and Society Islands) (Sutton, 1994; Matisoo-Smith and Robins, 2004) during the period AD 1200 and 1400 (McGlone and Wilmshurst, 1999), shortly after the Kaharoa eruption of AD 1314±12 (Hogg et al., 2004). Traditionally, it has been assumed that the Polynesian landfall took place after travelling against the prevailing winds, thereby insuring being able to return to the point of origin if the voyage was unsuccessful (Irwin, 1992). Reaching New Zealand, however, involved a complex voyage, travelling across the trade winds and possibly into westerly airflow. Under sustained La Niña conditions identified here during the period of colonisation, atmospheric circulation would have been dominated by northeasterly airflow (Bhaskaran and Mullan, 2003; Fitzharris, 2003) providing more stable conditions for New Zealand colonisation from remote Oceania. With the identification of a continuous record of ENSO–IPO spanning the last millennium, its role in changing behaviour on human occupation and cultural collapse throughout the Pacific (e.g., Sandweiss et al., 1999; Rolett and Diamond, 2004; Kirch and Sharp, 2005; Hunt and Lipo, 2006) and climatic change around the globe (Moberg et al., 2004) can be investigated more fully.

Conclusions

The interhemispheric radiocarbon offset for the past millennium is characterised by a step shift in mean values associated with the transition from the MWP to the LIA and a pervasive 80-yr cycle. The long-term difference in values is not consistent with changing high-latitude deepwater formation dominance. Here we propose that these changes imply an ENSO role in influencing the interhemispheric radiocarbon offset (most probably modulated by the Interdecadal Pacific Oscillation) by changing the flux of 'old' CO_2 to the atmosphere from the tropical Pacific. This interpretation provides an opportunity to reconstruct a decadally resolved record of ENSO–IPO activity for the past millennium and implies a significant role in regional (and potentially global) climatic, environmental and archaeological change. Furthermore, the results have major implications for the calibration of Southern Hemisphere radiocarbon ages and investigating the rise and fall of ancient cultures beyond the last millennium for which no continuous absolute-dated record of ENSO exists. Future work investigating annual radiocarbon differences in paired interhemispheric wood samples can potentially provide a detailed record of ENSO–IPO at the interannual timescale over the past millennium.

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