Radiocarbon, Vol 58, Nr 1, 2016, p 37–53 DOI:10.1017/RDC.2015.4

UPWELLING OF PACIFIC INTERMEDIATE WATER IN THE SOUTH CHINA SEA REVEALED BY CORAL RADIOCARBON RECORD

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ABSTRACT. Annual radiocarbon from a massive *Porites lutea* coral collected from Hon Tre Island, Vietnam, South China Sea (SCS) was analyzed over a ~100-yr-long period from AD 1900 to 1986. The pre-bomb results from 1900–1953 show a steady $\Delta^{14}C$ value of –54.4 ± 1.8‰ ($n = 60$). These values are similar to coral records located in the central and southern SCS and from Indonesian waters, but are lower than those from Japan. Following the input of anthropogenic bomb ^{14}C, our results show a sharp increase in $\Delta^{14}C$ from 1960, reaching a peak value of 155.3‰ in 1973. The Hon Tre Island post-bomb $\Delta^{14}C$ values are lower than those of other corals located in the SCS and Japan, but higher compared to those in the Indonesian Seas. This study infers a seasonal input of upwelled water depleted in ^{14}C from the deeper SCS basin that originates from the tropical Pacific via the Luzon Strait. The bifurcation of the North Equatorial Current feeds the surface and intermediate currents in the SCS and Makassar Strait region. However, unlike the Makassar site, this study's coral $\Delta^{14}C$ does not receive lower ^{14}C water from the South Pacific Equatorial Current. The Vietnam record therefore represents a unique oceanographic position, reflecting the seasonal influence of older, deeper SCS waters that upwell periodically in this area and have modified the surface waters locally in this region over the last 100 yr.

KEYWORDS: *Porites*, South China Sea, ^{14}C, Sr/Ca, stable oxygen isotopes, Asian monsoon, post-bomb, pre-bomb.

INTRODUCTION

The calcium carbonate skeletons of marine calcifiers such as foraminifera, bivalves, and corals contain a useful array of geochemical proxies that have been used to improve our understanding of past climate, ocean circulation, and atmospheric to surface ocean processes (Smith et al. 1979; Beck et al. 1992; Gagan et al. 1998; Elderfield and Ganssen 2000; Schöne et al. 2004; Lynch-Stieglitz 2006). Coral carbonate reflects the $\Delta^{14}C$ of surface seawater during the time and place of calcification because coral calcification uses dissolved inorganic carbon (DIC) from surrounding seawater, incorporating the radiogenic isotope ^{14}C proportionally (Goreau 1977; Erez 1978; Druffel and Suess 1983; Druffel 1987, 1997; Swart et al. 1996; McConnaughey et al. 1997; Reynaud-Vaganay et al. 1999).

Over the last 50 yr, the atmosphere and surface ocean $\Delta^{14}C$ increased by nearly 100% and 20%, respectively, due to nuclear weapons testing in the late 1950s and early 1960s. ^{14}C records in marine carbonates in surface waters lag those in the atmosphere, due to long equilibration times (~10 yr) and regional oceanographic features caused by the global thermohaline circulation, local upwelling, stratification, and freshwater impact (Southon et al. 2002; Hua et al. 2004). A single oceanographic measurement is therefore not representative of the entire global ocean (Guilderson et al. 1998). The differences between $\Delta^{14}C$ records of marine carbonates therefore allow the investigation of local and regional ocean circulation and thus can be used for testing and improving ocean circulation models (Reimer et al. 2013), adjustment of fossil marine sample ages, and allowing for the investigation of oceanographic processes in specific regions.

This article presents a new $\Delta^{14}C$ record, analyzed at annual resolution from a massive *Porites lutea* coral located at Hon Tre Island, Vietnam, in the South China Sea (SCS) to investigate the regional influence of atmospheric versus ocean circulation processes. We show the pre-bomb

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and post-bomb record from AD 1900–1986, and compare to six records around the SCS region. Our Hon Tre Island post-bomb ^{14}C record shows values in between other coral records located in the SCS and Indonesian Seas and suggests influence of upwelled water from the Pacific North Equatorial Current (NEC).

OCEANOGRAPHIC SETTING

The SCS and surrounding region are marginal seas strongly influenced by the Asian monsoon, which is considered the most important factor for the formation and variation of the seasonal circulation (Hu et al. 2000). The primary exchange with the Pacific Ocean is in the northeast, via the Luzon Strait. This strait has the deepest sill, ~1900 m, allowing the surface waters of the NEC to enter the SCS periodically via the Kuroshio Intrusion (KI) (Figure 1). In general, the summer monsoon begins in May and ends in September, with the winter monsoon period starting in November and ending in February. Summer monsoon winds flow weakly from the southwest towards the northeast and vice versa in winter, leading to anticyclonic and cyclonic basin circulation,

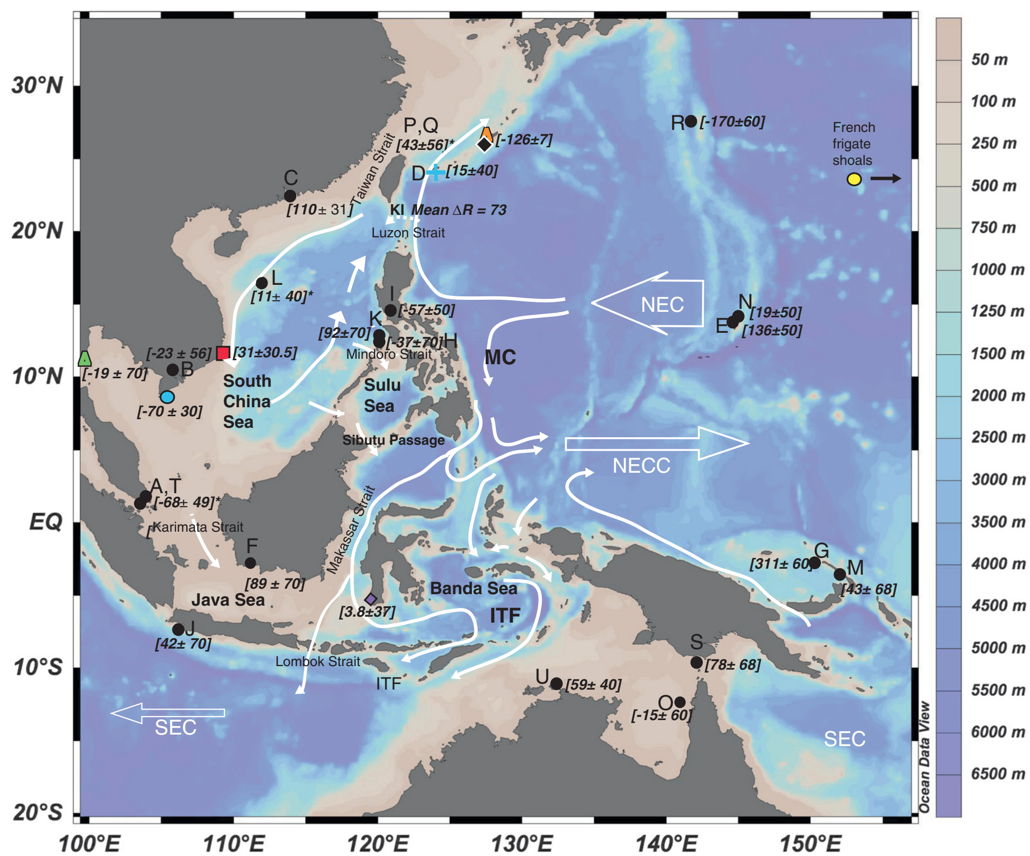

Figure 1 Bathymetric map (depth in meters on right axis) of the South China Sea and surrounding region. Mean annual circulation (white arrows) and marine reservoir corrections (black and colored symbols) are shown with errors where available (ΔR). The red square indicates this study's data (year = 1950) to closely match the data from Vietnam reported in Dang et al. (2004) (blue circle). Other symbols indicate location of studies used for comparison (see Figure 2). Black circles indicate the locations of ΔR values obtained from the marine reservoir correction database (http://calib.qub.ac.uk/marine/); see also Appendix 3. Asterisks indicate averaged records from the same location. NEC = North Equatorial Current; NECC = North Equatorial Counter Current; SEC = South Equatorial Current; ITF = Indonesian Throughflow; KI = Kuroshio Intrusion; MC = Mindoro Current. This figure was drawn using Ocean Data View (Schlitzer 2002).

respectively, in which water flows along the east coasts of Indo-China and the western Philippines following the direction of the monsoon winds (Xu et al. 1982; Fang et al. 2005) (see Figure 1). The local bathymetry and stratification of the water column result in Ekman pumping and transport, which are important in the generation of summer upwelling offshore of the Vietnamese coast and of an offshore jet at ~12°N further from the coast (Kuo et al. 2000; Dippner et al. 2007; Hein 2008; Chen et al. 2012; Wang et al. 2013; Zhang 2014). In the southern SCS, surface water seasonally circulates via the Karimata Strait while some is transported through the Sibutu Passage, returning to the Indian Ocean through the Makassar Strait via the Indonesian Throughflow (ITF) (Gordon et al. 2012).

MATERIAL AND METHODS

In March 2011, two *Porites lutea* corals were drilled from Hon Tre Island, Vietnam (12°12′49.90″N, 109°18′17.51″E). Hon Tre Island sits on a shallow ~100-m coastal shelf and the corals are located at the northeastern tip of the island. The two corals, To Nhat (TN) and Bai Bans (BB), were sampled using an underwater hydraulic drill, producing 4.6-m-long and 2.4-m-long cores, respectively. Each core was sectioned and then cleaned ultrasonically in deionized water, dried, and then X-rayed to reveal annual density bands. The Sr/Ca ratios from previous work confirm that darker bands (on an inverted X-ray) are formed during the winter and lighter bands during the summer (Bolton et al. 2014). A diamond-tipped drill bit mounted on a Dremel® tool was used to drill annual bands from 1900 to 1986 from the longest coral (TN). In addition, one year (1969) was drilled at subannual resolution, by drilling parallel to growth axis in 1-mm increments to produce ~7 samples/yr. These subannually drilled bands were used to examine seasonal variability for that year. Subsamples of ~200 µg were analyzed for Sr/Ca by completely dissolving in 2 mL of 5% HNO_3 and analyzing on an inductively coupled plasma optical emission spectrometer (ICP-OES) at the Marine Geochemistry Research Facility at Nanyang Technological University. Solution standards were used to correct for drift and matrix effects from varying Ca concentrations (Schrag 1999). The international coral standard JCp-1 was used as an internal standard, with a consensus Sr/Ca value of 0.01932 ± 0.0002 ppm (Hathorne et al. 2013). Our measurements of JCp-1 yielded an average value of 0.01932 ± 0.000068 ppm (1σ) (relative standard deviation = 0.36%, n = 1620).

For ^{14}C analysis, 7–8 mg of coral powder were acidified with 85% phosphoric acid to convert the aragonite to CO_2 gas. The resultant CO_2 was reduced to graphite on iron powder using the zinc reduction method (Xu et al. 2007). The graphite was then analyzed for ^{14}C on an accelerator mass spectrometer (AMS) at the Keck Carbon Cycle AMS laboratory, using standard techniques (Southon et al. 2004; Santos et al. 2007). Sample backgrounds were subtracted, based on measurements of ^{14}C-free calcite. We report ^{14}C measurements as age-corrected (or decay-corrected) $\Delta^{14}C$ (Δ term of Stuiver and Polach 1977). Total uncertainty of 2.4‰ was determined from the propagated error from averaged coral standards and duplicate samples measured. The data were not corrected for the Suess effect, the depletion of ^{14}C from fossil fuel emissions (Suess 1953).

MARINE RESERVOIR AGE AND CORRECTIONS

The ^{14}C marine reservoir age (R) reflects the difference between the atmospheric modeled ^{14}C age and the conventional ^{14}C age of our coral samples, here expressed as the difference between the terrestrial calibration curve IntCal13 (Reimer et al. 2013) and our coral ^{14}C conventional age such that:

$$R = {}^{14}C_{coralage} - {}^{14}C_{INTCAL13age} \tag{1}$$

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where $^{14}C_{coralage}$ is the age of the coral sample and $^{14}C_{INTCAL13age}$ is the age as estimated by the IntCal13 model (Reimer et al. 2013) for that same year. This value may also be different to the modeled R of the global surface oceans, e.g. Marine13 (Reimer et al. 2013), which is expressed as the regional marine reservoir correction or ΔR (Stuiver and Braziunas 1993) such that

$$\Delta R = {}^{14}C_{coralage} - {}^{14}C_{MARINE13age} \tag{2}$$

where $^{14}C_{coralage}$ is the ^{14}C age of the coral for any particular year and $^{14}C_{MARINE13age}$ is the ^{14}C age as estimated by the Marine13 model (Reimer et al. 2013) for that same year. The R and ΔR of our pre-bomb samples were compared to other corals in the SCS and surrounding region from previous studies.

RESULTS AND DISCUSSION

The Hon Tre Island pre-bomb (1900–1953) $\Delta^{14}C$ and associated R and ΔR values are summarized in Appendix 1. The pre-bomb $\Delta^{14}C$ values range from –60.8 to –48.8‰ with an overall decrease of –0.13‰/yr, as estimated using a linear least-squares regression. Because the $\Delta^{14}C$ values are corrected for known age of formation, the decrease is assumed to be due to environmental changes including the Suess effect. Post-bomb annual (1954–1986) and seasonal (1969) $\Delta^{14}C$ values are reported in Appendix 2. Between 1954 and 1986, the Hon Tre Island annual $\Delta^{14}C$ has a range of 198.8‰, from a low of –43.6‰ in 1953 to a high of 155.3‰ in 1973 (n = 29). The $\Delta^{14}C$ values begin to rise in the early 1950s, and increase rapidly from 37.6‰ in 1962 to 74.5‰ in 1963 (Figure 2). Following the $\Delta^{14}C$ high in 1973, which occurs approximately 10 yr after the 1963 atmospheric bomb peak (Nydal 2000), $\Delta^{14}C$ values have been decreasing at a rate of ~1.1‰/yr. Using Equations 1 and 2, we calculated that our Hon Tre Island coral yields a R (from 1900 to 1950) of 342 ± 19 yr and ΔR of 18 ± 29 yr. The seasonal data in 1969 have a $\Delta^{14}C$ range of 18 ± 1.7‰ with the lowest values (138.4‰) occurring during spring and the highest (156.5‰) in the summer. The Sr/Ca maxima (SST minima) are 9.195 mmol/mol in late summer and 8.861 mmol/mol at the beginning of the year. The seasonal ^{14}C trend therefore increases towards the summer with a coeval shift in Sr/Ca that reflects a change in SST from warmer to cooler temperatures (see Figure 2 inset).

Pre-Bomb 1900–1953

The SCS generally shows a distinct pre-bomb north to central/south variability in surface $\Delta^{14}C$ owing, presumably, to the well-equilibrated source waters that enter from the western Pacific (Konishi et al. 1981) (Figure 1). Pacific (NEC) water enters the SCS via the KI, which occurs when the Kuroshio Current flowing from the tropical Pacific north past Japan intrudes into the SCS (Wu et al. 1998; Chu et al. 1999; Xie et al. 2003; Xue et al. 2004). The data in Figure 1 represent a compilation of pre-bomb ΔR values from other carbonate fossil material collected from the SCS and surrounding areas (see Appendix 3). The data show that the ΔR values within the central and southern SCS and those located south in the Indonesian Seas are equal (within 2σ). The R and the regional ΔR for the SCS are estimated to be 281 ± 84 yr and − 23 ± 52 yr, respectively (Southon et al. 2002; Dang et al. 2004) and are within 2σ of the data from this study. Continuous pre-bomb records from the SCS and surrounding areas are scarce. However, Figure 2 shows available pre-bomb $\Delta^{14}C$ from the Andaman Sea (–60.6 ± 4‰, n = 1, AD 1935) and Makassar Strait (Langkai Island, –55.0 ± 3.5‰, n = 467, AD 1900–1950), which share similar pre-bomb $\Delta^{14}C$ values with Hon Tre Island (–54.3 ± 1.9‰, n = 57, AD 1900–1950). However, the annual trends in $\Delta^{14}C$ are not consistent with this pattern. For example, there are some years when $\Delta^{14}C$ in the Langkai Island (Makassar Strait) coral are higher

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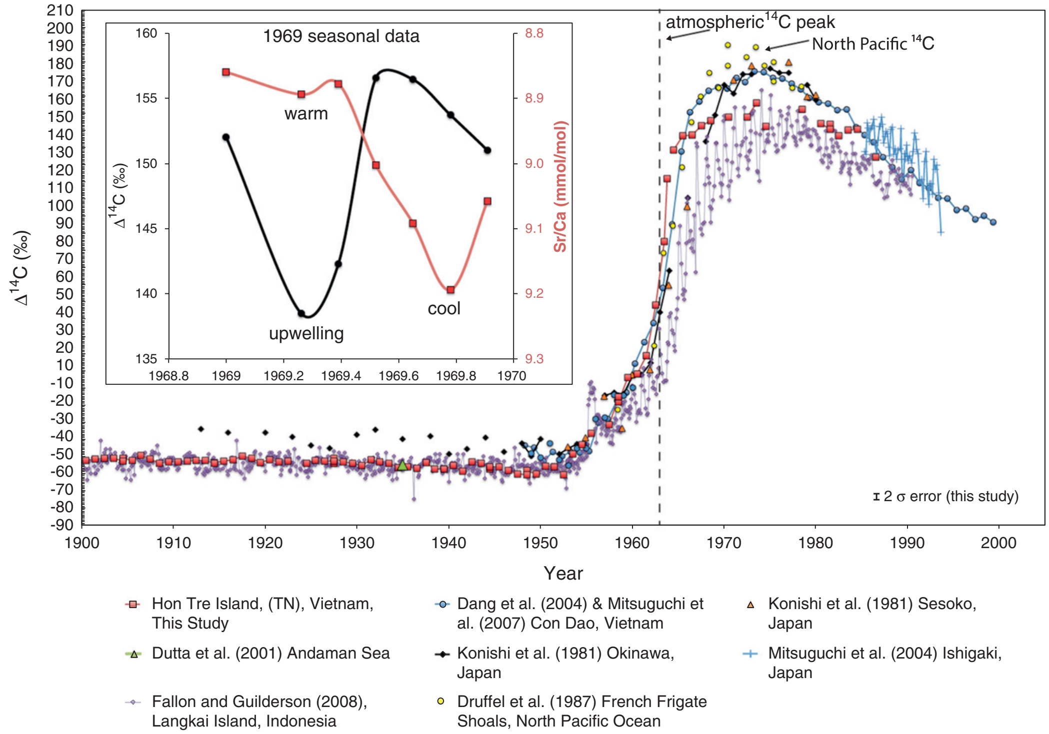

Figure 2 Annual coral $\Delta^{14}C$ (‰) data from this study versus those of other SCS and tropical coral records from the Pacific and Indonesian Oceans. Inset: Seasonal $\Delta^{14}C$ (black filled circles) and Sr/Ca (red filled squares) for 1969 to 1970.

(and vice versa) than our coral record. Some of this can be explained by the seasonality of the Langkai coral when compared to our annually resolved record; the former shows much higher variability. Both corals are also influenced by different monsoon systems. We discuss these in detail in the following sections.

Post-Bomb Period 1954 to 1986

Large differences appear when we compare the post-bomb $\Delta^{14}C$ data from corals in the SCS and those from the surrounding bodies of water. During this increased input of anthropogenic ^{14}C, there are distinct differences in each of the coral records. Around the bomb peak, corals from Japan (i.e. NEC waters) are consistently higher in $\Delta^{14}C$ (up to 179‰ in 1977 at Sesoko), with North Pacific corals from the French Frigate Shoals showing even higher values that peak earlier (189‰ in 1970), whereas the Langkai Island coral's highest value is 163‰ in 1974. Generally, these differences shown in Figure 2 agree well with the circulation of the SCS. Well-equilibrated water enters through the NEC via the KI, with the main throughflow moving surface water south along the Vietnam coast during the NE monsoon and flowing out through the Java Sea and into the ITF. In the Makassar Strait, the seasonal mixing of surface waters is complex but reflects the relative contribution of source waters from (1) the Indonesian Throughflow (ITF) originating from NEC and South Equatorial Current (SEC) surface and subsurface water, and (2) the South China Sea Throughflow, that enters the SCS from the Luzon Strait and exits it through the straits to the south (Qu et al. 2004, 2006). The relative contribution of these two source waters alternate during the SE and NW monsoon

(Gordon et al. 2012). Alternating mixing from tidal and Ekman pumping is extensive in the Indonesian Seas and changes the relative influence of NEC and SEC source waters that are transported through the Makassar Strait seasonally.

In the earlier part of the post-bomb Langkai Island record, a prominent but small peak in $\Delta^{14}C$ is seen at around 1955, which was explained by Fallon and Guilderson (2008) as resulting from nuclear fallout from early bomb testing in the Marshall Islands in 1953. It is likely, however, that this peak is not detected in other records due to the proximity of the sites (i.e. lack of direct fallout) and/or smoothing from annual sampling. The Hon Tre Island post-bomb values rise rapidly from 37.6‰ in 1962 to 74.5‰ in 1963 and peak at 155.3‰ in 1973 (Figure 2). The closest geographical $\Delta^{14}C$ record to our site is from Con Dao Island in southern Vietnam. $\Delta^{14}C$ at this location begins to increase sharply between 1963 and 1965 and reaches a peak of 173.8‰ in 1973. The relative difference in timing of these two records could be due (1) our site experiencing more rapid exchange of CO_2 compared to the Con Dao record, overprinted by an upwelling signal, and/or (2) temporal changes in upwelling intensity, e.g. ENSO, that may also enhance or reduce gas exchange in particular years.

However, from 1966 onwards, the Con Dao Island record is consistently higher in $\Delta^{14}C$ compared to our Vietnam record, almost matching the values in corals from Japan. Dang et al. (2004) and Mitsuguchi et al. (2007, 2008) have attributed this early rise and the enriched values to the shallow location of the coral on the Sunda shelf. Indeed, its location is isolated as it lies ~300 km from the deeper SCS basin. The possible mechanisms for lower $\Delta^{14}C$ values at the Hon Tre Island coral site include (1) riverine input, (2) lateral advection, and (3) upwelling.

Freshwater rivers may contain lower $\Delta^{14}C$ owing to the dissolved inorganic carbon (DIC) from ancient carbonates, known as the freshwater effect (Philippsen 2013). We assume that riverine influence is negligible at our site due to the relatively small size of the nearest river (Cai) and the distance from this river to our coral site (~12 km). However, we cannot discount small amounts of riverine input during periods of extreme rainfall (e.g. during La Niña events). Depending on the monsoon season, lateral surface water advection could lower (or increase) coral $\Delta^{14}C$ values as evinced by the pre-bomb north to central/south variability in surface $\Delta^{14}C$ (Figure 1).

Intrusion of ^{14}C-depleted water that reaches Hon Tre Island (but not Con Dao Island) must therefore originate from the south, as NEC/KI waters indicate higher $\Delta^{14}C$ values (Konishi et al. 1981; Mitsuguchi et al. 2004). While northward flowing low-$\Delta^{14}C$ water could be present during the summer monsoon (Dale 1956; Wyrtki 1961; Guilderson et al. 2009), it cannot explain the higher $\Delta^{14}C$ values found in the coral from Con Dao, which presumably would also be bathed in the same northward flowing water mass.

During the summer, there is a northeastward flow in the SCS and shallow coastal upwelling occurs at ~12°N (Xu et al. 1982; Shaw and Chao 1994; Chao et al. 1996; Xie et al. 2003). This has been observed in numerous satellite, physical oceanographic, and model simulations (Pohlmann 1987; Kuo et al. 2000; Dippner et al. 2007; Barthel et al. 2009). ^{14}C measurements from intermediate and deep water in the SCS reported by Broecker et al. (1986) are significantly lower, ranging from –106‰ at 420 m to –204‰ at 4170 m. The summer upwelling from Ekman transport is thought to be weak and limited to the upper 100 m of the water column (Dippner et al. 2007; Barthel et al. 2009). At the same time, wind stress is enhanced in the central SCS. The curl is positive in the northwestern SCS and negative in the southeast, with the strongest curl found off the coast of central Vietnam (Hein 2008). Dynamical upwelling, from the clockwise rotation of the northward undercurrent or stretching deformation-induced upwelling from this general circulation pattern in the SCS is thought to result in stronger upwelling (Dippner et al. 2007). This upwelled water is driven east and would therefore not reach the coral site at Con Dao Island.

The similarity of the post-bomb values in Langkai and the Hon Tre Island corals may initially suggest some connection between the upwelling rates and sources of the upwelled water (Figure 3). Both records have consistently lower $\Delta^{14}C$ values compared to other corals located in the SCS with the Langkai Island coral having the lowest $\Delta^{14}C$ values. The Langkai Island coral exhibits a clear seasonal signal with a range of 15 to 65‰ (Fallon and Guilderson 2008), whereas our seasonally resolved samples have a range of 18‰. This range is similar to coral $\Delta^{14}C$ values at Ishigaki Island, which exhibits a seasonal range of 15 to 40‰ (Mitsuguchi et al. 2004). The lowest $\Delta^{14}C$ values at Langkai and Ishigaki Islands are observed during

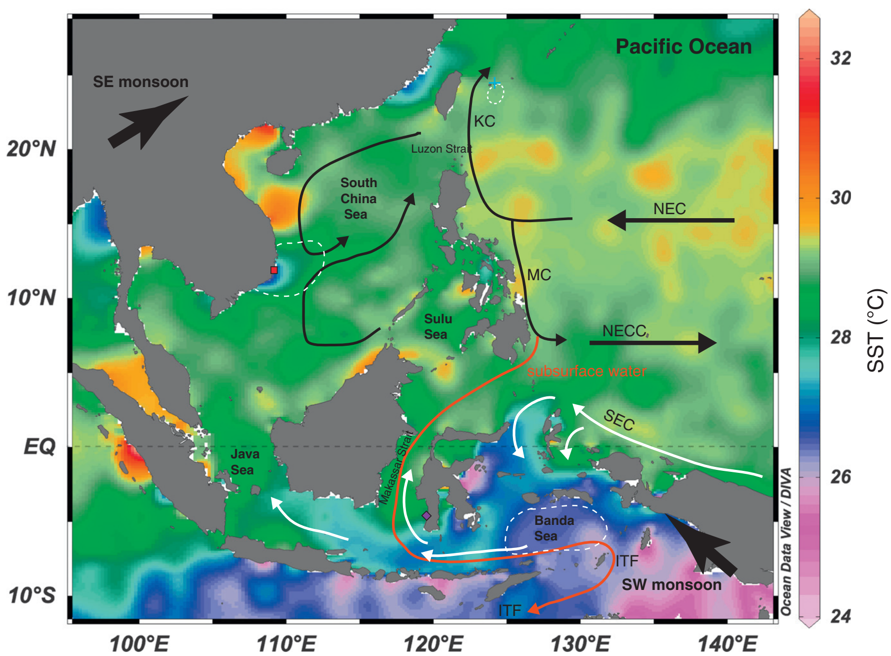

Figure 3 Ocean circulation and average sea surface temperature for August (1955–2012) in the South China Sea and adjacent seas. The red square indicates this study's site, and the purple filled diamonds indicate the coral location of Fallon and Guilderson (2008) at Langkai Island and the blue cross Ishigaki Island (Mitsuguchi et al. 2004). Black arrows illustrate the main surface circulation of the SCS including the basin-scale cyclonic summer gyre (modified from Wang and Li 2009) and source waters from the Pacific Ocean (North Equatorial Current). White arrows indicate the surface ocean currents originating from the South Equatorial Current and red arrows indicate subsurface currents for the same months (modified from Fallon and Guilderson 2008). In general, during May-September, the monsoon winds in the Northern Hemisphere move from the southeast towards the northeast leading to anticyclonic basin-wide circulation in the northern half of the SCS. Ekman pumping and transport generate upwelling offshore of the Vietnamese coast (white dotted area) with the northeasterly flow diverting offshore at ~12°N further from the coast (Kuo et al. 2000; Dippner et al. 2007; Hein 2008; Chen et al. 2012; Wang et al. 2013; Zhang et al. 2014). During the same months in the Southern Hemisphere, in the region of the Indonesian Seas, the winds blow from the southwest towards the northeast. At the same time, the Banda Sea experiences intense vertical mixing, leading to lower surface seawater ^{14}C content (Ffield and Gordon 1996; Cresswell and Luick 2001). NEC = North Equatorial Current; NECC = North Equatorial Counter Current; SEC = South Equatorial Current; ITF = Indonesian Throughflow; KC = Kuroshio Current; MC = Mindoro Current. This figure was drawn using Ocean Data View (Schlitzer 2002) using SST data from the World Ocean Atlas 2013 (Locarnini et al. 2013).

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the boreal summer/austral winter (August) around the same time that upwelling can occur at our coral site. If upwelling is the main reason for our lower $\Delta^{14}C$ values, then we also expect there to be similar seasonal variation, lowest during the boreal SW summer monsoon and highest during the boreal NE winter monsoon. Although we only have data for one subannually resolved year, the $\Delta^{14}C$ values show a distinct range that suggests upwelling during this year is occurring in the spring, with Sr/Ca data indicating warm, but not maximum, sea surface temperatures. The Sr/Ca is the lowest towards late autumn, which matches a sharp rise in $\Delta^{14}C$ that slowly decreases towards the winter. This observation in our record is intriguing and requires further investigation. However, *prima facie*, the seasonality observed in our record is similarly in phase with the Langkai and Ishigaki Islands seasonal cycle, although our SST proxy does not perfectly match up with the $\Delta^{14}C$, an observation also noted in the Ishigaki study. Mitsuguchi et al. (2004) hypothesized that the seasonality of their $\Delta^{14}C$ values was related to the monsoon-induced local upwelling. Higher North Pacific $\Delta^{14}C$ values are observed here, with the SSW-S monsoon during spring and summer inducing Ekman transport. The offshore transport of surface water leads to coastal upwelling of ^{14}C-depleted subsurface water.

Fallon and Guilderson (2008) attributed the lower $\Delta^{14}C$ values at Langkai Island to extensive upwelling occurring in the Banda Sea (East Indonesian Seas). The Banda Sea water has inputs from the South Pacific Equatorial Water, which is lower in $\Delta^{14}C$ than that of NEC water. This would explain the overall lower $\Delta^{14}C$ values compared to Hon Tre Island record. Although more data are required, our post-bomb $\Delta^{14}C$ record also hints at seasonal input of upwelled water. This upwelled water appears to be a consistent feature that mixes significantly low $\Delta^{14}C$ water from below the mixed layer with the surface waters in the region of Hon Tre Island. The source of this upwelled water is from the deeper SCS basin that originates from intermediate water fed from the Pacific via the Luzon Strait. The same NEC waters also influence the corals in the Makassar Strait and off the southern Sumatran coast, but consist of a mixture of both NEC and SEC water, the latter of which is more depleted in ^{14}C.

CONCLUSIONS

We present a new annual $\Delta^{14}C$ record for the years 1900 to 1986 and one subannual record of $\Delta^{14}C$ and Sr/Ca (1969), from Hon Tre Island, Vietnam, extending the southern SCS $\Delta^{14}C$ record. Our pre-bomb coral $\Delta^{14}C$ record, along with other pre-bomb records from the southern part of the SCS, show a low marine reservoir effect, and are significantly lower than those from Japan. Following the input of bomb ^{14}C, our coral showed $\Delta^{14}C$ values that lie in between those from corals bathed in NEC waters and those in the path of the ITF in the Makassar Strait. The data suggest that upwelling at both sites is controlled by different mechanisms under a boreal summer monsoon regime—the combination of Ekman transport and the basin-wide gyre system in the SCS affect upwelling rates at Hon Tre Island—whereas the strength of the Southern Hemisphere SE monsoon affects upwelling rates in the Banda Sea and subsequent advection of water in corals in the ITF. The Langkai coral record represents the relative mixing rates between NEC and SEC intermediate source waters entering the Indonesian Seas; the lower $\Delta^{14}C$ values in the Langkai record reflect more seasonal influence of modified, upwelled NEC and SEC water. Our Hon Tre Island record represents only seasonal NEC sourced intermediate SCS waters that enter through the Luzon Strait and are periodically upwelled at our study site.

ACKNOWLEDGMENTS

We thank two anonymous reviewers for their helpful comments. We also thank to K Hughen and J Ossolinski from Woods Hole Oceanographic Institution and the Nha Trang Institute of Oceanography for assistance with coral identification and collection. We also thank Ng

Sin-Hwee for her assistance in subsampling the coral. This study was funded by the National Research Foundation Singapore under its Singapore NRF Fellowship scheme awarded to N F Goodkin (National Research Fellow Award No. NRF-RF2012-03), as administered by the Earth Observatory of Singapore and the Singapore Ministry of Education under the Research Centres of Excellence initiative.

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https://doi.org/10.1017/RDC.2015.4 Published online by Cambridge University Press

APPENDICES

Appendix 1 Annual pre-bomb $\Delta^{14}C$ (1900–1953) and calculated marine reservoir age (R) and marine reservoir correction (ΔR) from Hon Tre Island, Vietnam.

ID	UCID#	Year (AD)	Coral $\Delta^{14}C$ (‰)	±1σ	Coral ^{14}C age (BP)	±1σ	Atmospheric modeled ^{14}C age (BP)	±1σ	Marine modeled $\Delta^{14}C$ (‰)	±1σ	Marine modeled ^{14}C age (BP)	±1σ	R (Yr)	ΔR (Yr)
TN6A-3	UCID16782	1953	–48.75	2.1	400	20								
TN6A-4	UCID16783	1952	–60.83	2.0	500	20								
TN6A-5	UCID16784	1951	–56.31	2.2	465	20								
TN6A-6	UCID16785	1950	–55.7	2.2	460	20	199	8	–56.7	2.7	469	23	261	−9
TN6A-7	UCID16786	1949	–60.5	2.2	500	20	188	8	–55.6	2.7	464	23	312	36
TN6A-8	UCID16787	1948	–58.6	2.3	485	20	188	8	–55.6	2.7	464	23	297	21
TN6A-8 (Duplicate)	UCID16832	1948	–60.8	2.2	505	20	188	8	–55.6	2.7	464	23	317	41
TN6A-9	UCID16788	1947	–60.5	2.4	505	25	188	8	–55.6	2.7	464	23	317	41
TN6A-10	UCID16789	1946	–58.3	2.2	485	20	188	8	–55.6	2.7	464	23	297	21
TN6A-11		1945					188	8	–55.6	2.7	464	23		
TN6B-1	UCID18314	1944	–57.7	2.0	485	20	172	8	–54.5	2.7	460	23	313	25
TN6B-2		1943					172	8	–54.5	2.7	460	23		
TN7-01	UCID16790	1945	–56.4	2.3	470	20	188	8	–54.5	2.7	464	23	282	6
TN7-02	UCID16791	1944	–56.3	2.2	470	20	172	8	–54.5	2.7	460	23	298	10
TN7-03	UCID16792	1943	–54.1	2.2	455	20	172	8	–54.5	2.7	460	23	283	−5
TN7-04	UCID16793	1942	–53.6	2.2	450	20	172	8	–54.5	2.7	460	23	278	−10
TN7-05	UCID16794	1941	–58.7	2.0	495	20	172	8	–54.5	2.7	460	23	323	35
TN7-06	UCID16795	1940	–55.6	2.2	470	20	172	8	–54.5	2.7	460	23	298	10
TN7-07	UCID16796	1939	–57.7	2.1	490	20	154	8	–54.5	2.7	457	23	336	33
TN7-07 (Duplicate)	UCID16833	1939	–57.7	1.8	487	20	154	8	–53.6	2.7	457	23	333	30
TN7-08	UCID16797	1938	–57.7	2.1	490	20	154	8	–53.6	2.7	457	23	336	33
TN7-09	UCID16798	1937	–53.8	2.2	455	20	154	8	–53.6	2.7	457	23	301	−2
TN7-10	UCID16799	1936	–57.2	2.3	485	20	154	8	–53.6	2.7	457	23	331	28
TN7-11	UCID16800	1935	–56.5	2.1	480	20	154	8	–53.6	2.7	457	23	326	23

TN7-12	UCID16801	1934	–56.6	2.2	485	20	152	8	–53.6	2.7	454	23	333	31
TN7-13	UCID16802	1933	–54.4	2.3	465	20	152	8	–52.7	2.7	454	23	313	11
TN7-14	UCID16803	1932	–53.5	2.2	460	20	152	8	–52.7	2.7	454	23	308	6
TN7-15	UCID16804	1931	–52.3	2.2	450	20	152	8	–52.7	2.7	454	23	298	−4
TN7-16	UCID16805	1930	–55.4	2.2	480	20	152	7	–52.7	2.7	454	23	328	26
TN7-17	UCID16806	1929	–54.1	2.2	465	20	132	7	–52.7	2.7	451	23	333	14
TN7-18	UCID16807	1928	–53.4	2.2	460	20	132	7	–51.7	2.7	451	23	328	9
TN7-19	UCID16808	1927	–51.4	1.6	445	15	132	7	–51.7	2.7	451	23	313	−6
TN7-19	UCID16884	1927	–54.1	1.2	470	15	132	7	–51.7	2.7	451	23	338	19
TN7-19 (Triplicate)	UCID17254	1927	–52.9	1.6	460	15	132	7	–51.7	2.7	451	23	328	9
TN7-20	UCID16809	1926	–52.9	1.6	460	15	132	7	–51.7	2.7	451	23	328	9
TN7-21	UCID16810	1925	–52.5	1.6	460	15	132	6	–51.7	2.7	451	23	328	9
TN7-22	UCID16811	1924	–54.0	1.5	470	15	129	6	–51.7	2.7	449	23	341	21
TN7-23		1923					129	6	–50.9	2.7	449	23		
TN7-24	UCID16813	1922	–53.1	1.5	465	15	129	6	–50.9	2.7	449	23	336	16
TN7-25	UCID16814	1921	–53.3	1.6	470	15	129	6	–50.9	2.7	449	23	341	21
TN7-26	UCID16815	1920	–52.1	1.7	460	15	129	7	–50.9	2.7	449	23	331	11
TN7-27	UCID16816	1919	–53.8	1.6	475	15	104	7	–50.9	2.7	449	23	371	26
TN7-28	UCID16817	1918	–51.3	1.6	455	15	104	7	–50.2	2.7	448	23	351	7
TN7-29	UCID16818	1917	–49.9	1.6	445	15	104	7	–50.2	2.7	448	23	341	−3
TN7-30	UCID16819	1916	–52.0	1.5	460	15	104	7	–50.2	2.7	448	23	356	12
TN7-31	UCID16820	1915	–53.0	1.6	470	15	104	7	–50.2	2.7	448	23	366	22
TN7-32	UCID16821	1914	–53.8	1.5	480	15	99	7	–50.2	2.7	448	23	381	32
TN7-32 (Duplicate)	UCID16834	1914	–54.3	1.5	485	15	99	7	–49.7	2.7	448	23	386	37
TN7-33	UCID16822	1913	–52.7	1.5	470	15	99	7	–49.7	2.7	448	23	371	22
TN7-34	UCID16823	1912	–52.8	1.6	470	15	99	7	–49.7	2.7	448	23	371	22
TN7-35	UCID16824	1911	–53.1	1.5	475	15	99	7	–49.7	2.7	448	23	376	27
TN7-36	UCID16825	1910	–53.5	1.6	480	15	99	7	–49.7	2.7	448	23	381	32
TN7-37	UCID16826	1909	–53.2	1.6	480	15	84	7	–49.7	2.7	449	23	396	31
TN7-38	UCID16827	1908	–54.2	1.5	490	15	84	7	–49.2	2.7	449	23	406	41
TN7-39	UCID16828	1907	–51.9	1.5	470	15	84	7	–49.2	2.7	449	23	386	21
TN7-40	UCID16829	1906	–49.6	1.6	450	15	84	7	–49.2	2.7	449	23	366	1

Appendix 1 (*Continued*)

ID	UCID#	Year (AD)	Coral $\Delta^{14}C$ (‰)	±1σ	Coral ^{14}C age (BP)	±1σ	Atmospheric modeled ^{14}C age (BP)	±1σ	Marine modeled $\Delta^{14}C$ (‰)	±1σ	Marine modeled ^{14}C age (BP)	±1σ	R (Yr)	ΔR (Yr)
TN7-41	UCID16830	1905	–52.7	1.7	480	15	84	7	–49.2	2.7	449	23	396	31
TN7-42	UCID16831	1904	–51.1	1.6	465	15	70	7	–49.2	2.7	454	23	395	11
TN7-42 (Duplicate)	UCID16835	1904	–52.8	1.5	481	15	70	7	–49.2	2.7	454	23	411	27
TN8-1	UCID16841	1903	–51.1	1.3	465	15	70	7	–49.2	2.7	454	23	395	11
TN8-2	UCID16842	1902	–51.2	1.2	470	15	70	7	–49.2	2.7	454	23	400	16
TN8-3	UCID16843	1901	–51.7	1.2	475	15	70	7	–49.2	2.7	454	23	405	21
TN8-4	UCID16844	1900	–52.4	1.3	480	15	70	7	–49.2	2.7	454	23	410	26

Appendix 2 Annual post-bomb $\Delta^{14}C$ (1954–1986) and seasonal (1969) $\Delta^{14}C$ and Sr/Ca ratios, Hon Tre Island, Vietnam.

ID	UCID#	Year (AD)	Coral $\Delta^{14}C$ (‰)	± 1σ (‰)	Coral ^{14}C age (BP)	±1σ (BP)	Sr/Ca (mmol/mol)
TN3-11	UCID18644	1986	123.8	2.8			
TN3-13	UCID18663	1984	140	2.9			
TN3-14	UCID18632	1983	139.54	2.9			
TN4-1	UCID18633	1982	136.19	2.9			
TN4-2	UCID18634	1981	142.81	2.9			
TN4-2 dup of 18634	UCID18668	1981	140.02	2.9			
TN4-3	UCID18635	1980	143.34	2.9			
TN4-5	UCID18636	1978	151.49	2.9			
TN4-7 OS	UCID18914	1974	141.58	2.4			
TN4-9 OS	UCID18915	1972	146.94	2.5			
TN4-10	UCID18637	1973	155.28	2.9			
TN4-12 OS	UCID18916	1970	147.12	2.3			
TN4-14.7	UCID19189	1969.91	150.92	1.7			9.059
TN4-14.6	UCID19188	1969.78	153.64	1.7			9.195
TN4-14.5	UCID19187	1969.65	156.35	1.7			9.093
TN4-14.4	UCID19186	1969.52	156.47	1.7			9.004
TN4-14.3	UCID19185	1969.39	142.22	1.9			8.879
TN4-14.2	UCID19184	1969.26	138.44	1.7			8.896
TN4-14.1	UCID19183	1969	151.95	1.7			8.861
TN4-15	UCID18638	1968	144.9	2.9			
TN4-16	UCID18639	1967	142.05	2.9			
TN4-17	UCID18640	1966	136.6	2.9			
TN4-18	UCID18641	1965	136.47	2.9			
TN4-19	UCID18642	1964	128.09	2.9			
TN5-1	UCID17052	1963.8	111.14	2.1			
TN5-2	UCID17053	1963	74.51	1.8			
TN5-3	UCID17054	1962	37.59	2.1			
TN5-4	UCID17055	1961	8.26	1.9			
TN5-5	UCID17056	1960	–2.41	1.8	10	15	
TN5-6	UCID17057	1959	–4.28	1.6	25	15	
TN5-7	UCID17058	1958	–18.45	1.7	140	15	
TN5-7 (Duplicate)	UCID17059	1958	–15.65	1.8	120	15	
TN5-8	UCID17060	1957	–31.92	1.5	255	15	
TN6A-1	UCID16780	1955	–36.58	2.1	295	20	
TN6A-2	UCID16781	1954	–43.56	2.3	355	20	

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Appendix 3 Compilation of ^{14}C ages from marine carbonates samples from the SCS and surrounding regions. Data obtained from the Marine Reservoir Correction database (see http://calib.qub.ac.uk/marine/).

Symbols as per Figures 1 to 3, Letters as per Figure 1	Reference	Sample type	Year (AD)	Location	Lat (°N)	Long (°E)	^{14}C age (yr)	^{14}C age error (yr)	Reservoir age (yr)	Reservoir age error (yr)	ΔR (yr)	ΔR error (yr)
Blue circle	Dang et al. 2004	Coral (*Porites* spp.)	1952	Con Dao Island, Vietnam	8.7	106.5	398	30	190	35	–70	30
Red square	This study	Coral (*P. lutea*)	1950	Hon Tre Island, Vietnam	12.2	109.2	465	20	266	22	–4	30
Purple diamond	Fallon and Guilerson 2008	Coral (*P. lutea*)	1950	Langkai Island, Indonesia	5.0	119.0	473	27	274	28	4	35
A	Southon et al. 2002	Bivalve	1945	Singapore	2.9	103.8	448	38	260	39	–15	38
B	Southon et al. 2002	Bivalve	1945	Saigon, Vietnam	10.8	106.8	440	56	252	57	–23	56
C	Goodkin et al. 2011	Coral (*P. lutea*)	1942	Hong Kong	22.2	114.1	570	20	392	22	110	31
Green triangle	Dutta et al. 2001	Bivalve	1935	Andaman Sea	13.0	92.6	469	34	458	4	11	35
D	Hideshima et al. 2001	Coral (*P. lutea*)	1931	Ishigaki, Japan	24.6	124.3	470	40	318	40	15	40
E	Athens 1986	Gastropod	1930	Guam	13.4	144.7	590	50	438	51	136	50
Orange triangle	Konishi et al. 1982	Coral (*P. lutea*)	1927	Okinanwa, Japan	26.4	127.8	326	7	186	10	–126	7
F	Southon et al. 2002	Gastropod	1925	South Borneo, Indonesia	–3.0	111.5	540	70	391	71	89	70
G	Petchey et al. 2004	Gastropod	1919	New Ireland, Papua New Guinea	–2.6	150.8	760	60	629	61	311	60
H	Southon et al. 2002	Gastropod	1916	Mona Islands, Philippines	12.0	120.0	410	70	301	70	–37	70
I	Southon et al. 2002	Gastropod	1916	Luzon Strait, Philippines	13.8	120.9	390	50	281	50	–57	50
J	Southon et al. 2002	Gastropod	1910	Java, Indonesia	–7.0	106.5	490	70	362	71	42	70
K	Southon et al. 2002	Gastropod	1908	Mindoro Strait, Philippines	12.5	120.5	540	70	447	70	92	70
L	Southon et al. 2002	Coral (*P. lutea*)	1906	Paracel Islands	16.7	112.3	460	40	375	41	11	40
M	Petchey et al. 2004	Gastropod	1905	St. Georges Channel, Papua New Guinea	–4.2	152.4	492	68	372	68	43	68

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N	Southon et al. 2002	Gastropod	1903	Guam	13.5	144.8	470	50	392	50	19	50
O	Rhodes et al. 1980	Gastropod	1903	Gulf of Carpentaria, Australia	–12.0	141.0	436	60	316	60	–15	60
P	Yoneda et al. 2007	Gastropod	1896	Suao, Taiwan	24.0	121.5	443	59	367	59	–15	64
Q	Yoneda et al. 2007	Gastropod	1896	Suao, Taiwan	24.0	121.5	559	43	483	43	101	49
R	Southon et al. 2002	Gastropod	1884	Bonin Island, Japan	27.0	142.0	300	60	198	60	–170	60
S	Gillespie and Polach 1979	Bivalve	1875	Torres Strait, Australia	–10.0	143.0	553	85	391	69	78	68
T	Southon et al. 2002	Bivalve	1860	Singapore	1.3	103.9	360	60	241	60	–121	60
U	Southon et al. 2002	Bivalve	1841	Raffles Bay, Australia	–11.3	132.4	549	40	388	41	59	40