GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L21602, doi:10.1029/2005GL023882, 2005

Radiocarbon in corals from the Cocos (Keeling) Islands and implications for Indian Ocean circulation

Quan Hua,[1] Colin D. Woodroffe,[2] Scott G. Smithers,[3] Mike Barbetti,[4] and David Fink[1]

Received 28 June 2005; revised 25 September 2005; accepted 29 September 2005; published 2 November 2005.

[1] Annual bands of a *Porites* coral from the Cocos (Keeling) Islands, eastern Indian Ocean, were analysed by radiocarbon for 1955–1985 AD. A rapid oceanic response of the site to bomb ^{14}C is found, with a maximum Δ^{14}C value of 132‰ in 1975. This value is considerably higher than those for the northwestern Indian Ocean, suggesting that surface waters reaching Cocos are not derived from the Arabian Sea. Instead, Δ^{14}C values for Cocos and those for Watamu (Kenya) agree well over most of the study interval, suggesting that the South Equatorial Current carries ^{14}C-elevated water rather than ^{14}C-depleted water westward across the Indian Ocean. This implies that oceanic upwelling in the northwestern Indian Ocean is spatially confined with little contribution to the upper limb of the global thermohaline circulation. **Citation:** Hua, Q., C. D. Woodroffe, S. G. Smithers, M. Barbetti, and D. Fink (2005), Radiocarbon in corals from the Cocos (Keeling) Islands and implications for Indian Ocean circulation, *Geophys. Res. Lett.*, *32*, L21602, doi:10.1029/2005GL023882.

1. Introduction

[2] Corals provide an unaltered record of radiocarbon in dissolved inorganic carbon (DIC) of surrounding sea waters at the time of accretion of their calcium carbonate skeletons. Radiocarbon in oceanic DIC is mainly controlled by changes in ocean circulation rather than by air-sea exchange of CO_2, allowing coral ^{14}C records to be utilised to study variations in vertical mixing, horizontal current shifts and changes in thermocline depth [*Druffel*, 1997; *Gagan et al.*, 2000]. Atmospheric nuclear detonations in the 1950s and early 1960s produced an excess of atmospheric ^{14}C, amplifying the contrast in ^{14}C between surface and subsurface waters, thus increasing its effectiveness as a tool to study ocean circulation. Global ocean models currently do not reliably reproduce all of the features of Indian Ocean circulation. Coral bomb ^{14}C records from key locations offer the prospect of further insights into Indian Ocean circulation [*Grumet et al.*, 2005].

[3] Based on ^{14}C measurements of pre-bomb known-age marine shells from the Indian Ocean, *Southon et al.* [2002] reported high regional marine reservoir correction (ΔR) values of ~200 years for the Arabian Sea, 120–190 years for the Red Sea, ~130 years for Sri Lanka, and ~135 years for the Seychelles and northern Madagascar. These values, together with a high ΔR value of 186 years for the Cocos (Keeling) Islands in the eastern Indian Ocean derived from a 1941 coral sample of *Toggweiler et al.* [1991], led Southon et al. to suggest that upwelled, ^{14}C-depleted water in the northwestern Indian Ocean is carried to Cocos by southeast flow from the Arabian Sea. According to the authors, this ^{14}C-depleted water then flows to the Seychelles and northern Madagascar in the western Indian Ocean via the South Equatorial Current (SEC), and eventually returns to the Arabian Sea via the East African Coast Current (EACC) and Somali Current (SC) (Figure 1). Thus, they imply that the influence of monsoon-driven upwelling in the northwestern Indian Ocean is spread throughout the Indian Ocean by major current systems.

[4] In contrast, *Hua et al.* [2004] suggested that Cocos receives ^{14}C-elevated water derived from the far western Pacific, via the Indonesian Through Flow (ITF) based on their re-evaluation of the ΔR value for Cocos at 64 ± 15 years. This revised value is far lower than the previous value of 186 years for Cocos [*Toggweiler et al.*, 1991], but is similar to values for the eastern Indian Ocean and adjacent seas. Watamu (Kenya, 3°S, 40°E) in the western Indian Ocean also has a relatively low ΔR value (37 ± 10 years for 1947–1953) [*Grumet et al.*, 2002a]. The seasonal structure of a coral ^{14}C record for Watamu during the post-bomb period indicated that the site was supplied by ^{14}C-elevated water from the south via the EACC during the southwest monsoon (Figure 1) [*Grumet et al.*, 2002b]. Thus, there is currently conflicting evidence on the influence over the rest of the basin of upwelled waters from the northwestern Indian Ocean. This paper addresses this issue by examining a coral record of bomb ^{14}C from Cocos.

2. Materials and Methods

[5] The Cocos (Keeling) Islands (12°S, 97°E) are an isolated atoll in the eastern Indian Ocean (Figure 1). An annual band chronology covering most of the 20th century has been established for corals from this atoll [*Smithers and Woodroffe*, 2001]. For this study, we used *Porites* microatoll PP30, collected on the eastern side of the atoll from a reef-flat site that is freely connected to the open ocean. The live coral was sampled in 1992 and no recrystallisation has occurred (XRD indicates no calcite in modern or late Holocene Cocos microatolls). Thirty-one single annual bands, representing 1955–1985, were sampled for ^{14}C analysis along the coral's growth axis. The entire high and

---

[1] Australian Nuclear Science and Technology Organisation, Menai, New South Wales, Australia.

[2] School of Earth and Environmental Sciences, University of Wollongong, Wollongong, New South Wales, Australia.

[3] School of Tropical Environment Studies and Geography, James Cook University, Townsville, Queensland, Australia.

[4] ACQUIRE, Richards Building, University of Queensland, Brisbane, Queensland, Australia.

0094-8276/05/2005GL023882

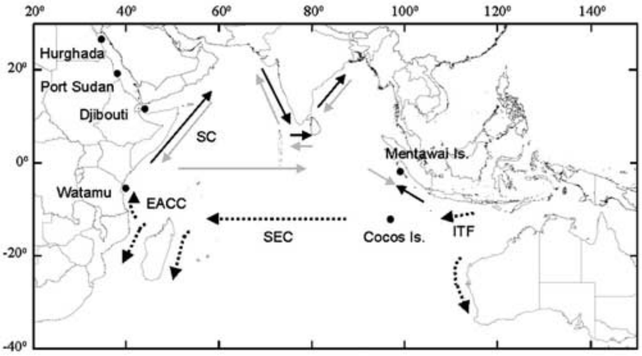

Figure 1. Coral sites discussed in this paper (solid dots) and major current systems in the Indian Ocean (adapted from *Schott and McCreary* [2001]): during the southwest monsoon (dark arrows), during the northeast monsoon (light arrows), and all-year-round currents (dashed arrows).

low density couplet of each annual band was used for ^{14}C measurement.

[6] These samples were washed 3 times with deionised water in an ultrasonic bath to remove any surface contamination. They were then oven-dried at 60°C for 2 days. The cleaned samples were hydrolysed to CO_2 using 85% phosphoric acid, then converted to graphite using the Zn/Fe method [*Hua et al.*, 2001]. AMS ^{14}C measurements were performed using the ANTARES facility at ANSTO [*Fink et al.*, 2004], with a precision of 0.3–0.4%.

3. Results

[7] Our bomb ^{14}C results for Cocos expressed in Δ^{14}C, after corrections for isotopic fractionation using δ^{13}C and radioactive decay, are illustrated in Figure 2 together with coral Δ^{14}C values for Cocos reported by *Toggweiler et al.* [1991] and *Hua et al.* [2004]. There is no significant difference between our data and those from Toggweiler et al. for 1970, 1973 and 1976. For 1972 and 1974, the two data sets diverge by slightly more than 1σ errors. For the pre-bomb period, our Δ^{14}C values ranging from −65.8 to −60.7 ± 2.8‰, are consistently higher than the Toggweiler et al. value for 1941 (−78.2 ± 8.2‰). The Δ^{14}C value for 1953 from Toggweiler et al. (−29.5 ± 9.0‰) is quite high, differing from other coral ^{14}C records for the Indian Ocean (Figure 3). Unfortunately, no 1953 datum for Cocos is available in our study for direct comparison. Due to the limited data available for the pre-bomb period, the exact timing of the rise of bomb ^{14}C in Cocos cannot be accurately determined (Figure 2). Δ^{14}C in Cocos corals starts rising in the early to mid-1950s due to atmospheric nuclear detonations, increases significantly during the early to late 1960s, reaches its maximum of 132‰ in 1975 (~10 years after the bomb peak in the troposphere), then decreases after 1979.

[8] Published Δ^{14}C values in surface waters close to Cocos (10–15°S, 87–107°E) are also plotted in Figure 2. These surface water Δ^{14}C values agree with those in Cocos corals apart from one water sample (13.8°S, 88.2°E) collected in August 1976 [*Nydal*, 1998]. Its Δ^{14}C value of 160 ± 12‰ is much higher than our 1976 Cocos value of 117.9 ± 3.8‰. As the two coral ^{14}C records for Cocos (Toggweiler et al. and this study) agree well for 1976, the single surface water Δ^{14}C value from Nydal may not be representative of mean oceanic conditions within Cocos proximity during that year.

4. Discussion

[9] Figure 3 compares our Δ^{14}C data for Cocos to published Δ^{14}C data from Indian Ocean corals for the period 1945–1990. Cocos Δ^{14}C rises earlier and faster reaching a much higher bomb ^{14}C peak (132‰ in 1975) than that measured at Djibouti (~50‰ in the early to mid-1980s) [*Toggweiler et al.*, 1991]. In contrast, two sites in the Red Sea show a fast response to bomb ^{14}C similar to that seen at Cocos, but not reaching the maximum value observed at Cocos (87‰ in 1975–1977 for Port Sudan and ~103‰ during 1966–1972 for Hurghada [*Cember*, 1989]). These results agree with the observations at these sites for the pre-bomb period [*Hua et al.*, 2004], suggesting strong oceanic upwelling in the northwestern Indian Ocean, but limited influence of oceanic upwelling at Cocos, implying that an Arabian sea water source at Cocos is unlikely.

[10] Cocos Δ^{14}C values are also higher than those for the Mentawai Islands (Sumatra, Indonesia) for most of the study interval, except for 1969–1974 (Figure 3). The Mentawai record starts rising in the late 1950s (at least 3–4 years later than Cocos) and reaches its maximum value of ~120‰ during the early to mid-1970s. The delayed rise and lower maximum bomb ^{14}C value for Mentawai reflect the influence of mild local upwelling and rapid exchange between surface and subsurface waters along the Sumatran coast [*Grumet et al.*, 2004]. Meanwhile, the more elevated Δ^{14}C Cocos data suggest that horizontal transport with little exchange between surface and subsurface waters might dominate ocean circulation at Cocos.

[11] Cocos and Watamu Δ^{14}C values agree well except for 1968–1982 (Figures 3 and 4). The two records have nearly identical pre-bomb Δ^{14}C values for an overlapping year of 1950 (−65.1 ± 2.9‰ for Cocos [*Hua et al.*, 2004], −63.5 ± 0.8‰ for Watamu calculated from data of *Grumet*

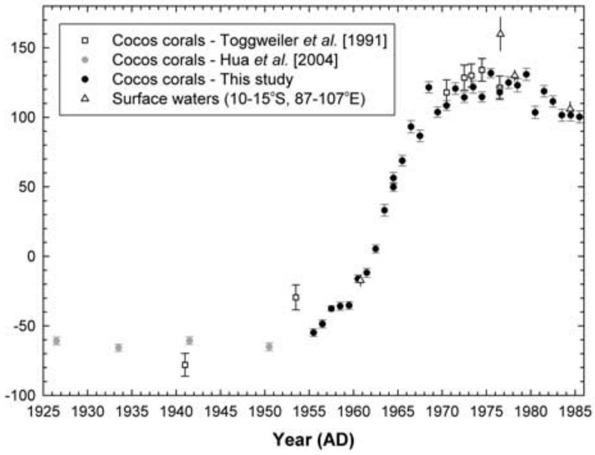

Figure 2. Δ^{14}C values in Cocos corals for 1925–1985 vs those in surface waters close to Cocos [*Bien et al.*, 1965; *Stuiver and Östlund*, 1983; *Nydal*, 1998]. Error bars are 1σ.

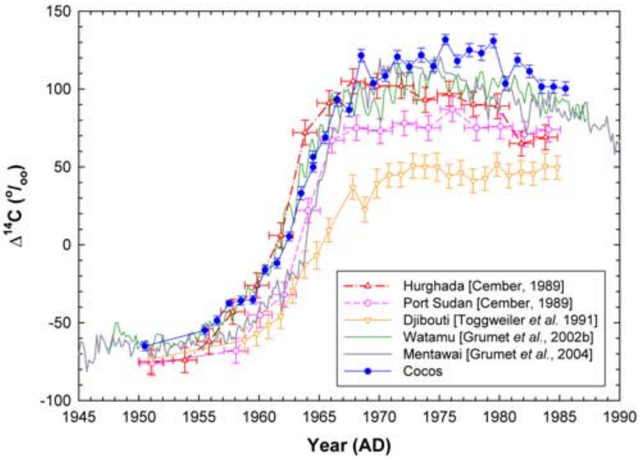

Figure 3. Δ^{14}C values in Cocos corals (this study and *Hua et al.* [2004]) compared to published Δ^{14}C data from corals from the Indian Ocean for 1945–1990. Vertical bars are 1σ errors. Horizontal bars represent 2-year time span.

et al. [2002a]). Both records also have similar ΔR values for the pre-bomb period (64 ± 15 years for Cocos and 37 ± 10 years for Watamu), signs of early invasion of bomb ^{14}C in the early to mid-1950s, and a very similar rate of rise in ^{14}C for 1955–1967. The two records start diverging in 1968, and their Δ^{14}C values continue to rise at different rates reaching their maxima in the mid-1970s (132‰ in 1975 for Cocos compared to 121‰ in 1974 for Watamu). Their Δ^{14}C values then fall at different rates and the two records start converging again during 1983–1985.

[12] In order to determine what might cause the two records to be so similar for most of the study interval, water sources for the two sites need to be examined. Surface waters at Cocos are derived from the Pacific Ocean via the ITF [*Hua et al.*, 2004]. Cocos appears dominated by horizontal transport within the SEC flowing westward between 10–15°S throughout the year (Figure 1), with limited ocean upwelling. By contrast, Watamu, which is dominated by fast lateral transport [*Grumet et al.*, 2002b], receives waters from the SEC via the EACC during the southwest monsoon, and from the SC flowing southward during the northeast monsoon (Figure 1). This pattern of ocean current movement for the SEC provides a possible physical link between Cocos and Watamu at least during the southwest monsoon.

[13] Δ^{14}C values in surface waters within the SEC between 10–15°S across the Indian Ocean and in the western equatorial boundary (4–10°S, 40–55°E), are also plotted in Figure 4. The two data sets for surface waters within the SEC match very well with Δ^{14}C values for Cocos, whereas the other surface water data set agrees well with Δ^{14}C values for Watamu. There is no significant difference between these surface water data for most of the time including the INDIGO (1986) and WOCE (1995–1996) expeditions (note that there are no overlapping data for the early bomb period for comparison). Only during the GEOSECS (1978) survey, is the Δ^{14}C value in waters in the western equatorial boundary significantly lower than those within the SEC. This ^{14}C pattern in water samples is similar to that observed in coral samples from Cocos and Watamu – no difference for most of the time except the late 1960s to early 1980s. This indicates that the divergence/convergence pattern seen in coral Δ^{14}C records from Cocos and Watamu is a real signal, and not an artifact of coral preservation or chronology. In the following section we present a possible explanation for the observed pattern.

[14] For the pre-bomb period, the weak gradient in ^{14}C between the two seasonal water sources to Watamu [*Grumet et al.*, 2002a], causes the lack of seasonal structure in the Watamu Δ^{14}C record and hence its pre-bomb values are similar to those for Cocos. As bomb ^{14}C has augmented the contrast between surface and subsurface water ^{14}C levels, the two seasonal water sources arrive at Watamu with a larger ^{14}C difference as indicated by the initiation of its ^{14}C seasonal variations from 1962 onwards. However, no significant difference is evident between the two Δ^{14}C records for the period of rapid increase in ^{14}C from 1955 to 1967 (their mean yearly difference is 2.2 ± 2.0‰), because the transfer of excess ^{14}C from the atmosphere to the ocean is the dominant process for this period. As a result, upwelled water from the northwestern Indian Ocean is enriched in ^{14}C through air-sea exchange as soon as it reaches the surface and consequently the relative difference in ^{14}C between the two water sources to Watamu is not significant. Also, the northern water source for Watamu is not sufficiently depleted in ^{14}C (as seen in the pre-bomb period mentioned above) to lower and/or delay its rate of rise for the early bomb period. After a period of steep rise from 1955 to 1967 (Figure 4), Watamu Δ^{14}C increases at a slower rate as the air-sea ^{14}C gradient decreases. The contribution of relatively lower Δ^{14}C water from the north thus becomes significant at Watamu after 1967, as indicated by more pronounced seasonal ^{14}C variations for the late 1960s to late 1970s with an amplitude (from peak to trough) up to 25‰

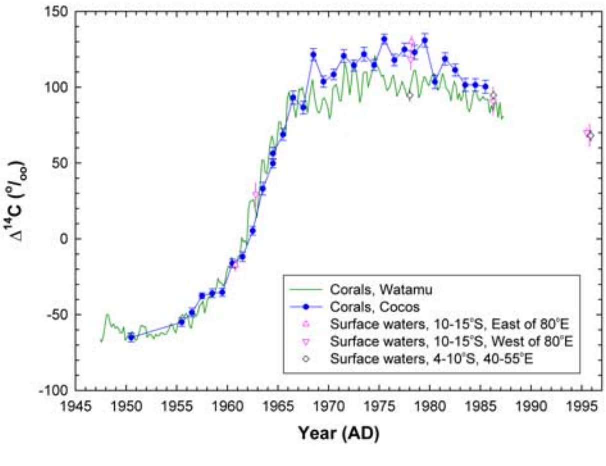

Figure 4. Δ^{14}C values in Cocos corals (this study and *Hua et al.* [2004]) compared to those from Watamu and values in surface waters for regions: 10–15°S, east of 80°E (triangles); 10–15°S, west of 80°E (inverted triangles); and 4–10°S, 40–55°E (diamonds) [*Bien et al.*, 1965; *Stuiver and Östlund*, 1983; *Östlund and Grall*, 1991; *Nydal*, 1998; *Key and Quay*, 2002]. Δ^{14}C values in surface waters for October 1960 and October 1962 are from individual samples. The other values for 1978, 1986 and 1995–1996 are average Δ^{14}C values of more than one individual sample. Error bars are 1σ.

(Figure 4). This results in a lower Δ^{14}C level for Watamu for 1968–1982 (Cocos is 16.8 ± 2.4‰ higher than Watamu). As bomb ^{14}C penetrates deeper into the subsurface ocean, surface ocean Δ^{14}C values at Watamu fall and its seasonal amplitude also decreases ($\sim$15‰) since the late 1970s. Upwelled waters from shallow depths may therefore have higher Δ^{14}C values than those at the surface, reducing the seasonal amplitude in the Watamu record [*Grumet et al.*, 2002b] and consequently causing the convergence of the Cocos and Watamu records during 1983–1985 (their difference is reduced to 8.9 ± 2.7‰).

5. Conclusions

[15] Our results show a rapid response of Cocos to bomb ^{14}C with a maximum Δ^{14}C value markedly above those for the northwestern Indian Ocean, suggesting that surface waters reaching Cocos might not be derived from the Arabian Sea as previously proposed. Instead, the strong response of Cocos to bomb ^{14}C supports the idea that surface waters around Cocos are derived from the ITF [*Hua et al.*, 2004]. The remarkable agreement between coral Δ^{14}C values from Cocos and Watamu for most of the period 1950–1985 also suggests that the SEC carries ^{14}C-evelvated waters rather than ^{14}C-depleted waters from the tropical southeastern to southwestern Indian Ocean. Divergence between these two records for 1968–1982 reflects seasonal contribution of slightly ^{14}C-depleted water from the northwestern Indian Ocean to Watamu, which is in contrast to its southern water source in terms of ^{14}C during that period. If this is indeed the case, several implications follow. First, ^{14}C-depleted waters around the Seychelles and northern Madagascar in the western Indian Ocean reported by *Southon et al.* [2002] are due to local upwelling near Saya de Malha Bank [*Woodberry et al.*, 1989], mid-ocean upwelling at 5–10°S, 50–90°E [*Schott et al.*, 2002] and local upwelling in northwestern Madagascar [*Schott and McCreary*, 2001], and do not significantly influence the SEC. Second, oceanic upwelling in the northwestern Indian Ocean is spatially confined (not affecting eastern equatorial sites, such as Mentawai and Cocos, and scarcely reaching western equatorial sites such as Watamu). Additional coral ^{14}C records from select regions, such as reefs along the SEC and in the western boundary, would be of value to validate our interpretation.

[16] Our results also have broader relevance to global oceanic circulation patterns as proposed in *Broecker*'s [1991] model of thermohaline circulation (THC). This model argues deep water in the Atlantic Ocean enters the Pacific and Indian Oceans as bottom water, then returns to the surface by upwelling, a significant proportion of which occurs in the northwestern Indian Ocean. Broecker indicated that the upwelled water in the northwestern Indian Ocean contributes to one of the major return flows (the upper limb of the THC) to the Atlantic from the Pacific via the Indonesian archipelago. However, our results imply spatial constraints on upwelling in the northwestern Indian Ocean and we infer that the contribution of this upwelled water to the upper limb of the THC may be very limited.

[17] **Acknowledgments.** We thank Alan Williams and Ugo Zoppi for helping with sample preparation, and δ^{13}C and ^{14}C measurements. We also thank Nerilie Abram and George Burr for their constructive comments which greatly improved the manuscript. We gratefully acknowledge funding from AINSE for AMS ^{14}C measurements (grants 01/207, 02/150P and 04/174).

References

Bien, G. S., N. W. Rakestraw, and H. E. Suess (1965), Radiocarbon in the Pacific and Indian oceans and its relation to deep water movements, *Limnol. Oceanogr.*, *10*, R25–R37.

Broecker, W. S. (1991), The great ocean conveyor, *Oceanography*, *4*, 79–89.

Cember, R. P. (1989), Bomb radiocarbon in the Red Sea: A medium scale gas exchange experiment, *J. Geophys. Res.*, *94*, 2111–2123.

Druffel, E. R. M. (1997), Geochemistry of corals: Proxies of past ocean chemistry, ocean circulation, and climate, *Proc. Natl. Acad. Sci. U. S. A.*, *94*, 8354–8361.

Fink, D., et al. (2004), The ANTARES AMS Facility at ANSTO, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *223–224*, 109–115.

Gagan, M. K., L. K. Ayliffe, J. W. Beck, J. E. Cole, E. R. M. Druffel, R. B. Dunbar, and D. P. Schrag (2000), New views of tropical paleoclimates from corals, *Quat. Sci. Rev.*, *19*, 45–64.

Grumet, N. S., T. P. Guilderson, and R. B. Dunbar (2002a), Pre-bomb radiocarbon variability inferred from a Kenyan coral record, *Radiocarbon*, *44*, 581–590.

Grumet, N. S., T. P. Guilderson, and R. B. Dunbar (2002b), Meridional transport in the Indian Ocean traced by coral radiocarbon, *J. Mar. Res.*, *60*, 725–740.

Grumet, N. S., N. J. Abram, J. W. Beck, R. B. Dunbar, M. K. Gagan, T. P. Guilderson, W. S. Hantoro, and B. W. Suwargadi (2004), Coral radiocarbon records of Indian Ocean water mass mixing and wind-induced upwelling along the coast of Sumatra, Indonesia, *J. Geophys. Res.*, *109*, C05003, doi:10.1029/2003JC002087.

Grumet, N. S., P. B. Duffy, M. E. Wickett, K. Caldeira, and R. B. Dunbar (2005), Intrabasin comparison of surface radiocarbon levels in the Indian Ocean between coral records and three-dimensional global ocean models, *Global Biogeochem. Cycles*, *19*, GB2010, doi:10.1029/2004GB002289.

Hua, Q., G. E. Jacobsen, U. Zoppi, E. M. Lawson, A. A. Williams, A. M. Smith, and M. J. McGann (2001), Progress in radiocarbon target preparation at the ANTARES AMS Centre, *Radiocarbon*, *43*, 275–282.

Hua, Q., C. D. Woodroffe, M. Barbetti, S. G. Smithers, U. Zoppi, and D. Fink (2004), Marine reservoir correction for the Cocos (Keeling) Islands, Indian Ocean, *Radiocarbon*, *46*, 603–610.

Key, R. M., and P. D. Quay (2002), US WOCE Indian Ocean survey: Final report for radiocarbon, *Tech. Rep. 02-1*, Ocean Tracers Lab., Atmos. and Oceanic Sci. Program, Princeton Univ., Princeton, N. J.

Nydal, R. (1998), Carbon-14 measurements in surface water CO_2 from the Atlantic, Indian and Pacific Oceans, 1965–1994, *ORNL/CDIAC-104, NDP-057A,* Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Östlund, H. G., and C. Grall (1991), Indian Ocean radiocarbon: Data from the INDIGO 1, 2, and 3 cruises, *ORNL/CDIAC-41, NDP-036,* Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Schott, F. A., and J. P. McCreary (2001), The monsoon circulation of the Indian Ocean, *Prog. Oceanogr.*, *51*, 1–123.

Schott, F. A., M. Dengler, and R. Schoenefeldt (2002), The shallow overturning circulation of the Indian Ocean, *Prog. Oceanogr.*, *53*, 57–103.

Smithers, S. G., and C. D. Woodroffe (2001), Coral microatolls and 20th century sea level in the eastern Indian Ocean, *Earth Planet. Sci. Lett.*, *191*, 173–184.

Southon, J., M. Kashgarian, M. Fontugne, B. Metivier, and W. W.-S. Yim (2002), Marine reservoir corrections for the Indian Ocean and southeast Asia, *Radiocarbon*, *44*, 167–180.

Stuiver, M., and H. G. Östlund (1983), GEOSECS Indian Ocean and Mediterranean radiocarbon, *Radiocarbon*, *25*, 1–29.

Toggweiler, J. R., K. Dixon, and W. S. Broecker (1991), The Peru upwelling and the ventilation of the South Pacific thermocline, *J. Geophys. Res.*, *96*, 20,467–20,497.

Woodberry, K. E., M. E. Luther, and J. J. O'Brien (1989), The wind-driven seasonal circulation in the southern tropical Indian Ocean, *J. Geophys. Res.*, *94*, 17,985–18,002.

M. Barbetti, ACQUIRE, Richards Building, University of Queensland, Brisbane, QLD 4072, Australia.

D. Fink and Q. Hua, Australian Nuclear Science and Technology Organisation, PMB1, Menai, NSW 2234, Australia. (qhx@ansto.gov.au)

S. G. Smithers, School of Tropical Environment Studies and Geography, James Cook University, Townsville, QLD 4811, Australia.

C. D. Woodroffe, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia.