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

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Abstract
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 14C is found, with a maximum D14C 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, D14C values for Cocos and those for Watamu (Kenya) agree well over most of the study interval, suggesting that the South Equatorial Current carries 14C-elevated water rather than 14C-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.

Keywords
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[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 $\Delta^{14}$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, $\Delta^{14}$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 [Draffel, 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 [Gagan 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 (AR) 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 AR 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 AR 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 AR value (37 ± 10 years for 1947–1953) [Gagan 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) [Gagan 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
cleaned samples were hydrolysed to CO2 using 85% phosphoric acid, then converted to graphite using the Zn/Fe method [Hua et al., 2001]. AMS 14C measurements were performed using the ANTARES facility at ANSTO [Fink et al., 2004], with a precision of 0.3–0.4%.

3. Results

Our bomb 14C results for Cocos expressed in Δ14C, after corrections for isotopic fractionation using δ13C and radioactive decay, are illustrated in Figure 2 together with coral Δ14C 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 Δ14C 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 Δ14C value for 1953 from Toggweiler et al. (−29.5 ± 9.0‰) is quite high, differing from other coral 14C 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 14C in Cocos cannot be accurately determined (Figure 2). Δ14C 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 value of 132‰ 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.

Cocos Δ14C 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 14C 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 Δ14C Cocos data suggest that horizontal transport with little exchange between surface and subsurface waters might dominate ocean circulation at Cocos.

Cocos and Watamu 14C values agree well except for 1968–1982 (Figures 3 and 4). The two records have nearly identical pre-bomb Δ14C 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 et al. [1991] and this study) agree well for 1976, the single surface water Δ14C value from Nydal may not be representative of mean oceanic conditions within Cocos proximity during that year.

4. Discussion

Figure 3 compares our Δ14C data for Cocos to published Δ14C data from Indian Ocean corals for the period 1945–1990. Cocos Δ14C rises earlier and faster reaching a much higher bomb 14C 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 14C 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.

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Figure 2. Δ14C values in Cocos corals for 1925–1985 vs those in surface waters close to Cocos [Bien et al., 1965; Stuiver and Oœstlund, 1983; Nydal, 1998]. Error bars are 1σ.
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 14C in the early to mid-1950s, and a very similar rate of rise in 14C for 1955–1967. The two records start diverging in 1968, and their Δ14C 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 Δ14C values then fall at different rates and the two records start converging again during 1983–1985.

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.

Δ14C 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 Δ14C values for Cocos, whereas the other surface water data set agrees well with Δ14C 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 Δ14C value in waters in the western equatorial boundary significantly lower than those within the SEC. This 14C 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 Δ14C 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.

For the pre-bomb period, the weak gradient in 14C between the two seasonal water sources to Watamu [Grumet et al., 2002a], causes the lack of seasonal structure in the Watamu Δ14C record and hence its pre-bomb values are similar to those for Cocos. As bomb 14C has augmented the contrast between surface and subsurface water 14C levels, the two seasonal water sources arrive at Watamu with a larger 14C difference as indicated by the initiation of its 14C seasonal variations from 1962 onwards. However, no significant difference is evident between the two Δ14C records for the period of rapid increase in 14C from 1955 to 1967 (their mean yearly difference is 2.2 ± 2.0‰), because the transfer of excess 14C from the atmosphere to the ocean is the dominant process for this period. As a result, upwelled water from the northern Indian Ocean is enriched in 14C through air-sea exchange as soon as it reaches the surface and consequently the relative difference in 14C between the two water sources to Watamu is not significant. Also, the northern water source for Watamu is not sufficiently depleted in 14C (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 Δ14C increases at a slower rate as the air-sea 14C gradient decreases. The contribution of relatively lower Δ14C water from the north thus becomes significant at Watamu after 1967, as indicated by more pronounced seasonal 14C variations for the late 1960s to late 1970s with an amplitude (from peak to trough) up to 25‰
(Figure 4). This results in a lower $\Delta^{14}C$ level for Watamu for 1968–1982 (Cocos is 16.8 ± 2.4% higher than Watamu). As bomb $^{14}C$ penetrates deeper into the subsurface, surface ocean $\Delta^{14}C$ values at Watamu fall and its seasonal amplitude also decreases (~15%) since the late 1970s. Upwelled waters from shallow depths may therefore have higher $\Delta^{14}C$ 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 $\Delta^{14}C$ value markedly above those for the northern 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 $\Delta^{14}C$ values from Cocos and Watamu for most of the period 1950–1985 also suggests that the SEC carries $^{14}C$-elevated 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 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%).

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