JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. C6, PAGES 12,359–12,365, JUNE 15, 1997

Coral radiocarbon constraints on the source of the Indonesian throughflow

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Abstract. Radiocarbon variability in *Porites* spp. corals from Guam and the Makassar Strait (Indonesian Seaway) was used to identify the source waters contributing to the Indonesian throughflow. Time series with bimonthly resolution were constructed using accelerator mass spectrometry. The seasonal variability ranges from 15 to 60‰, with large interannual variability. $\Delta^{14}C$ values from Indonesia and Guam have a nearly identical range. Annual mean $\Delta^{14}C$ values from Indonesia are 50 to 60‰ higher than in corals from Canton in the South Equatorial Current [*Druffel*, 1987]. These observations support a year-round North Pacific source for the Indonesian throughflow and imply negligible contribution by South Equatorial Current water. The large seasonality in $\Delta^{14}C$ values from both sites emphasizes the dynamic behavior of radiocarbon in the surface ocean and suggests that $\Delta^{14}C$ time series of similar resolution can help constrain seasonal and interannual changes in ocean circulation in the Pacific over the last several decades.

Introduction

Intense surface heating along the equator combined with the mean easterly flow of the tradewinds causes warm surface waters to accumulate in the western Pacific Ocean. Although most of this water is recirculated within the Pacific, some enters the Indonesian Seaway and flows into the Indian Ocean (Figure 1). This throughflow is driven by the difference in sea level between the two oceans (about 16 cm) and is primarily restricted to the upper 200 m [*Wyrtki*, 1987]. Tracer studies indicate that the throughflow results in the net transfer of surface waters from the Pacific to the Indian Ocean [*Fine*, 1985]. Recent estimates of mean throughflow, based on observations and modeling studies, are 10–20 Sverdrups (1 Sv = 10^6 m^3 s^{-1}) [*Ffield and Gordon*, 1992; *Macdonald*, 1993; *Lukas et al.*, 1996]. The very few direct observations indicate flows of 0.5–4.0 Sv at the Lombok Strait [*Murray and Arief*, 1988] and 3.4–5.3 Sv at the Timor Strait [*Molcard et al.*, 1996]. Recent geostrophic estimates from hydrographic data along a section from Bali (Indonesia) to Port Hedland (Australia) reveal substantial seasonal and interannual variability in the throughflow, with transports of 18 ±7 Sv westward in August 1989 (an El Niño-Southern Oscillation (ENSO) cool phase) and 2.6 ±9 Sv eastward in February 1992 (an ENSO warm phase) [*Fieux et al.*, 1996]. Throughflow is inferred to increase during ENSO cool phases and decrease during ENSO warm phases by about 5 Sv [*Bray et al.*, 1996; *Meyers*, 1996]. Recent studies of the Indonesian throughflow are reviewed in *Lukas et al.* [1996] and *Godfrey* [1996].

The Indonesian throughflow is an important component in the global ocean circulation system because it results in a significant net export of tropical Pacific heat [*Hirst and Godfrey*, 1993; *Macdonald*, 1993; *Wajsowicz*, 1993a], on the order of 5 × 10^{13} W Sv^{-1} [*Godfrey*, 1996]. However, the relative contribution of North Pacific and South Pacific source waters to the throughflow is not fully understood: Sverdrup theory (even as modified by *Godfrey's* [1989] island rule) predicts a South Pacific source, yet observational evidence suggests a predominantly North Pacific source [*Lukas et al.*, 1996]. Identifying the source supply for Indonesian throughflow and characterizing its seasonal and interannual variability is important since the South Pacific source comprises the core of the warm pool region, whereas the North Pacific source does not. Examination of archived hydrographic data for the Indonesian Seaway yields ambiguous conclusions because of the strong effects of monsoonal rain on water properties. During the dry season (SE Monsoon), salinity and dissolved oxygen data indicate that most of the throughflow is supplied by the North Equatorial Current and that the principal throughflow path is via the Makassar Strait [*Ffield and Gordon*, 1992] (Figure 1). During the rainy season (NW Monsoon), high precipitation erases differences in surface water salinity characteristics [*Godfrey et al.*, 1993]. This allows for the possibility that an important throughflow path is via the Halmahera Strait with the throughflow supplied by the South Equatorial Current and derived from a South Pacific source [*Godfrey et al.*, 1993; *Wajsowicz*, 1993a, b]. Direct observations of western boundary current patterns as they relate to throughflow are limited; Western Equatorial

Paper number 97JC00590
0148-0227/97/97JC-00590$09.00

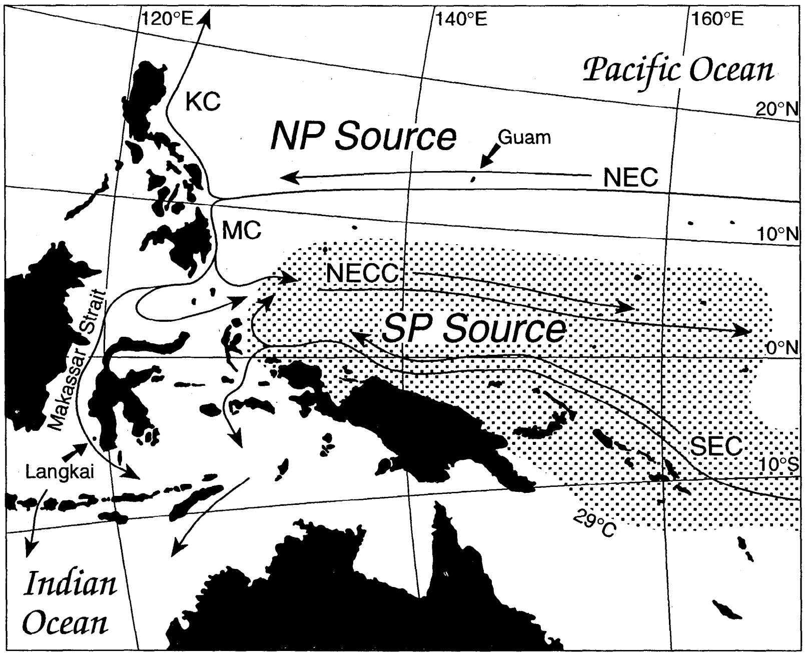

Figure 1. Schematic showing western boundary currents [*Lukas et al.*, 1991] and throughflow routes [*Ffield and Gordon*, 1992] during the SE Monsoon, and the mean annual position of the 29°C SST isotherm [*Levitus*, 1982]. The North Equatorial Current (NEC) bifurcates at the Philippines, with the northward branch supplying the Kuroshio Current (KC) and the southward branch supplying the Mindanao Current (MC) and the North Equatorial Countercurrent (NECC). The South Equatorial Current (SEC) retroflects in the vicinity of Halmahera, also supplying the NECC. Throughflow routes are via the Makassar Strait and the Halmahera Strait. Coral core localities indicated by arrows.

Pacific Ocean Circulation Study (WEPOCS III) drifter buoys launched off of Mindanao in July entered the Makassar Strait and measured current velocities between 50–80 cm s^{-1}, suggesting a residence time of about one month [*Lukas et al.*, 1991].

Radiocarbon as a Tracer of Indonesian Throughflow

The distribution of radiocarbon (^{14}C) in the surface ocean is a sensitive indicator of ocean circulation. Radiocarbon is produced in the atmosphere from collisions of nitrogen atoms with thermal neutrons produced naturally by cosmic rays or artificially by atmospheric nuclear bomb testing. Approximately 1 in 10^{12} carbon atoms is ^{14}C, and these decay back to ^{14}N with a 5730 year half-life. Atomic ^{14}C is rapidly oxidized to $^{14}CO_2$ and becomes well-mixed in the atmosphere. Gas exchange of CO_2 enriches the surface ocean in ^{14}C at an invasion rate of approximately 20 moles m^{-2} yr^{-1}. The flux of radiocarbon to the deep ocean is accomplished by convective processes and by settling of particulate matter. Because the residence time of water in the deep ocean is long enough to allow for significant radioactive decay, the deep ocean is depleted in ^{14}C relative to the surface ocean. Since the 1950s, excess production of ^{14}C from nuclear weapons testing, and its subsequent invasion into the surface ocean, has augmented the difference between the surface and the deep ocean. The concentration of ^{14}C is reported as Δ^{14}C, which is the difference between measured ^{14}C /^{12}C ratios for a sample and a preindustrial standard, in parts per thousand (‰) and normalized to a constant ^{13}C/^{12}C ratio.

In the early 1970s, the Geochemical Ocean Sections Study (GEOSECS) provided the first picture of the spatial distribution of radiocarbon in the surface ocean [*Broecker et al.*, 1985; *Östlund and Stuiver*, 1980], identifying a contrast in Δ^{14}C between North and South Equatorial Current waters in the Pacific Ocean of approximately 100‰. A common interpretation is that this distribution results from upwelling of low-radiocarbon water from the lower thermocline in equatorial region off Peru, with migration of ^{14}C-rich surface water toward higher latitudes [*Broecker and Peng*, 1980; *Quay et al.*, 1983; *Toggweiler et al.*, 1991]. Based on this observed contrast, we hypothesized that high-resolution accelerator mass spectrometry (AMS) Δ^{14}C measurements on a coral from the Indonesian Seaway could identify seasonal differences in source waters contributing to Indonesian throughflow.

Shallow water corals are an important archive of information about how the radiocarbon content of the tropical surface ocean has varied through time. Corals that construct massive colonies in shallow reef environments (e.g., *Porites*) typically have growth rates of more than a centimeter per year and can attain ages of 200–400 years. Radiocarbon in the coral's aragonite skeleton reflects seawater radiocarbon content at the time of deposition. Measurements of annual skeletal density bands in such corals have yielded reconstructions of the annual mean radiocarbon content of the surface ocean back to prebomb and preindustrial values [*Nozaki et al.*, 1978; *Konishi et al.*, 1981; *Druffel*, 1982, 1987; *Druffel and Griffin*, 1993].

The first suggestion that radiocarbon might vary seasonally in the surface ocean was made by *Broecker and Peng* [1980].

More recent studies have identified seasonal and interannual variability in surface ocean radiocarbon by making multiple measurements within the annual density bands of massive corals. *Druffel* [1987] observed seasonal variability between 10 and 25‰ in radiocarbon records from Canton Island (3°S, 172°W) and Fanning Island (4°N, 159°W), although the 3–6 month sampling resolution was not high enough to accurately measure the amplitude. The development of AMS has made possible still higher resolution studies by reducing the amount of coral material required to less than 10 mg; this represents a significant improvement over beta counting methods which require 20 g or more. AMS allows for higher resolution studies on massive corals, similar to those carried out for stable isotopes and trace metals at monthly resolution [*Shen et al.*, 1987, *Cole et al.*, 1993]. In a pioneering study, *Brown et al.* [1993] made 16 AMS measurements on a coral from the Galapagos Islands over four annual bands (1970–1973), observing seasonal Δ^{14}C variability of 35–50‰. They favored a similar explanation to *Druffel* [1987] that the seasonal radiocarbon variability is due to seasonal changes in horizontal flow patterns of water in the tropical Pacific. In this study, we compare AMS radiocarbon measurements from a coral in the Makassar Strait in the Indonesian Seaway with data from the North and South Equatorial Currents to identify the major source of the Indonesian throughflow and to evaluate whether the source region changes through seasonal and interannual cycles.

Table 1. Coral Radiocarbon Time Series from Langkai Island (5°02'S, 119°04'E)

Date	Depth, mm	Δ^{14}C, ‰	Date	Depth, mm	Δ^{14}C, ‰
1970.33	300	110.0 ±6.0	1978.08	180	152.9 ±7.5
1970.58	297	99.3 ±7.3	1978.33	177	153.0 ±6.1
1970.83	294	107.9 ±6.4	1978.67	174	133.3 ±6.0
1971.08	291	144.7 ±6.6	1978.92	171	115.2 ±7.3
1971.33	288	115.8 ±6.6	1979.17	168	158.1 ±7.7
1971.58	285	122.0 ±6.7	1979.33	165	163.5 ±6.0
1971.75	282	102.4 ±6.5	1979.50	162	148.7 ±8.0
1972.00	279	108.4 ±6.4	1979.75	159	158.9 ±5.8
1972.25	276	160.3 ±9.1	1979.92	156	150.9 ±5.8
1972.33	273	138.6 ±6.6	1980.08	153	151.5 ±5.8
1972.50	270	125.8 ±7.9	1980.33	150	144.7 ±5.8
1972.67	267	131.9 ±7.5	1980.58	147	164.5 ±7.8
1972.83	264	112.4 ±5.7	1980.75	144	155.4 ±5.8
1973.00	261	133.1 ±6.5	1981.00	141	134.1 ±6.5
1973.17	258	160.0 ±8.5	1981.25	138	145.9 ±6.9
1973.33	256	151.2 ±6.5	1981.33	135	135.2 ±5.9
1973.58	252	125.8 ±6.4	1981.50	132	139.0 ±6.6
1973.83	249	112.8 ±6.4	1981.67	129	130.2 ±8.4
1974.00	246	128.3 ±6.4	1981.83	126	141.4 ±6.4
1974.17	244	163.3 ±8.5	1982.00	123	143.2 ±9.3
1974.25	243	137.4 ±6.6	1982.17	120	155.7 ±7.4
1974.42	240	137.9 ±5.1	1982.33	117	143.1 ±6.4
1974.58	237	130.0 ±6.3	1982.50	114	153.0 ±5.3
1974.83	234	127.1 ±6.3	1982.58	111	120.5 ±7.2
1975.00	231	134.5 ±6.6	1982.75	108	118.9 ±6.3
1975.25	228	156.5 ±6.5	1982.92	105	130.3 ±6.3
1975.42	225	142.4 ±6.4	1983.08	102	146.6 ±8.3
1975.67	222	123.7 ±5.6	1983.25	99	131.0 ±8.6
1975.83	219	127.0 ±6.4	1983.50	96	119.2 ±7.9
1976.00	216	131.1 ±6.4	1983.67	93	133.1 ±6.4
1976.25	213	129.7 ±6.4	1983.83	90	136.3 ±6.8
1976.50	210	139.1 ±6.4	1984.00	87	125.1 ±6.4
1976.67	207	133.9 ±6.4	1984.17	85	150.4 ±6.9
1976.92	204	124.2 ±5.7	1984.25	84	119.5 ±9.9
1977.17	201	138.4 ±6.6	1984.42	81	120.0 ±7.0
1977.33	198	147.0 ±6.6	1984.58	78	112.2 ±5.3
1977.42	195	141.8 ±6.6	1984.75	75	101.4 ±5.7
1977.58	192	136.3 ±6.8	1985.00	72	126.5 ±6.5
1977.67	189	131.9 ±7.4	1985.17	69	129.9 ±7.6
1977.83	186	138.9 ±5.0	1985.33	66	127.1 ±6.5
1977.92	183	147.0 ±6.8			

Table 2. Coral Radiocarbon Time Series from Guam (13°21'S, 144°39'E)

Date	Depth, mm	Δ^{14}C, ‰	Date	Depth, mm	Δ^{14}C, ‰
1978.83	170	121.7 ±6.7	1981.42	134	160.4 ±7.3
1979.08	167	144.2 ±8.1	1981.58	131	145.6 ±5.5
1979.25	164	137.7 ±6.5	1981.83	128	142.6 ±6.7
1979.42	161	154.5 ±6.6	1982.00	125	154.3 ±6.7
1979.58	158	117.4 ±7.2	1982.25	122	123.0 ±6.5
1979.83	155	126.3 ±6.7	1982.42	119	136.2 ±9.3
1980.08	152	134.6 ±6.7	1982.67	116	138.3 ±7.2
1980.42	149	128.3 ±7.2	1982.83	113	148.6 ±5.6
1980.67	146	135.2 ±7.6	1983.00	110	144.7 ±9.2
1980.83	143	125.3 ±7.8	1983.17	107	134.9 ±7.7
1981.08	140	129.5 ±7.6	1983.42	104	119.4 ±5.9
1981.25	137	137.3 ±7.4	1983.58	101	133.9 ±6.2

Methods

Cores were drilled from large *Porites lutea* colonies growing in shallow water (4 m) at Taelayag Reef on the west coast of Guam (13°21'N, 144°39'E), and at a fringing reef on the south coast of Langkai Island (5°02'S, 119°04'E). Langkai Island is situated at the edge of the continental shelf in the southern Makassar Strait, 35 km west from mainland Sulawesi. A single 9 mm thick slab was cut lengthwise from each core. The slabs were sampled at 3 mm increments along a transect parallel to the coral's axis of growth by drilling several holes in series perpendicular to the transect (i.e. same time horizon) with a 1.5 mm diameter bit. An aliquot (10 mg) of each sample was dissolved under vacuum with 85% phosphoric acid, and the carbon dioxide was reduced to graphite [*Vogel et al.*, 1987] for radiocarbon assay by AMS at the Center for Accelerator Mass Spectrometry-Lawrence Livermore National Laboratory (CAMS-LLNL) [*Davis et al.*, 1990].

Radiocarbon measurements are reported as Δ^{14}C (‰) as defined in *Stuiver and Polach* [1977], and are corrected using measured $^{13}C/^{12}C$ ($\delta^{13}C$) ratios. Error based on reproducibility of standard calcite is ±7‰. For the Indonesian coral, 81 AMS Δ^{14}C determinations were made on skeleton deposited during 1970–1985. For the Guam coral, 24 AMS Δ^{14}C determinations were made on skeletal material deposited during 1979–1983. The Δ^{14}C time series are presented in Tables 1 and 2; each time series has a resolution of approximately 2 months.

Additional samples of the corals were taken every millimeter for stable carbon and oxygen isotope analyses by gas-source mass spectrometry at the Center for Isotope Geochemistry at Lawrence Berkeley Laboratory. Aliquots were sequentially reacted in a common bath of orthophosporic acid at 90°C for 12 min. A laboratory standard of *Porites* spp. aragonite ($\delta^{18}O$ = -5.34‰, $\delta^{13}C$ = -1.30‰) was used throughout. The long-term, raw 1σ precision on the measurement of the laboratory standard was better than 0.08‰ for $\delta^{18}O$ and

0.06‰ for δ^{13}C. Well-established corrections were applied to the data to achieve even higher precision.

The seasonal variability in the coral δ^{13}C has been shown to be controlled at certain locations primarily by seasonal light cycles, such that attenuation of light due to increased cloud cover produces more negative δ^{13}C values [*McConnaughey*, 1989]. The annual δ^{13}C minima appears to mark the peak of the rainy season (the time of maximum cloud cover) at both Langkai (in March) and Guam (in October). This marker was used to establish the timescale for both the Δ^{14}C and δ^{18}O time series.

Results

The most dramatic feature of the 15 year radiocarbon time series from Indonesia (Figure 2a) is the strong seasonal variability. From 1970–1974, the amplitude of the seasonal variations in Δ^{14}C is relatively uniform at approximately 50‰. From 1974–1985, there is large interannual variability, with amplitudes of 15–50‰. The change in the average Δ^{14}C value is primarily a response of the ocean to changes in the Δ^{14}C of the atmosphere due to nuclear testing [*Druffel*, 1987]. To examine the relationship between the observed Δ^{14}C seasonality and the seasonality of surface water conditions in the Makassar Strait, we compare the radiocarbon time series to the stable isotope time series (Figures 2b and 2c). Figure 2B compares the δ^{18}O time series (which tracks variability in surface water conditions due to the prevailing monsoon regime) to the sea surface temperature (SST) anomaly time series for the 3° × 3° region adjacent to the core site (3.5°S–5.5°S, 116.5°E–118.5°E). The SST anomaly time series was computed from monthly averaged 1° × 1° Improved Global Ocean Sea Surface temperature data from the National Meteorological Center (IGOSS NMC), which is derived from ship, buoy, and satellite observations [*Reynolds and Smith*, 1994]. The close match between the dry season δ^{18}O maxima and the SST minima suggests that the Δ^{14}C and δ^{18}O timescale is consistently accurate with a precision no worse than ±2 months.

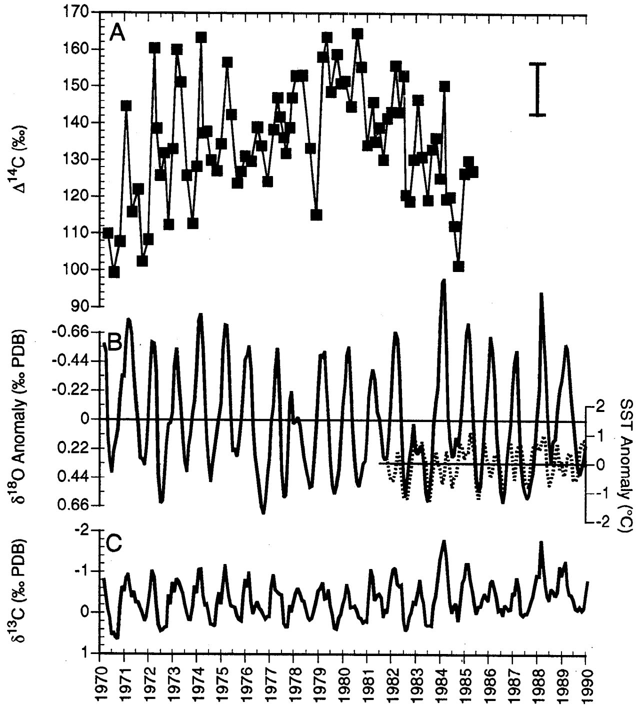

Figure 2. (a) Bimonthly resolution Δ^{14}C time series for the Langkai site, with the 2σ error bar (14‰) indicated. (b) Langkai monthly resolution δ^{18}O anomaly time series (solid line) compared to the IGOSS NMC monthly SST anomaly in the southern Makasssar Strait (dashed line). The δ^{18}O y axis is reversed and scaled so the data correspond directly to the temperature anomaly. (c) Langkai monthly resolution δ^{13}C time series, with the y axis reversed so the data correspond directly to the seasonal attenuation of sunlight associated with the NW monsoon.

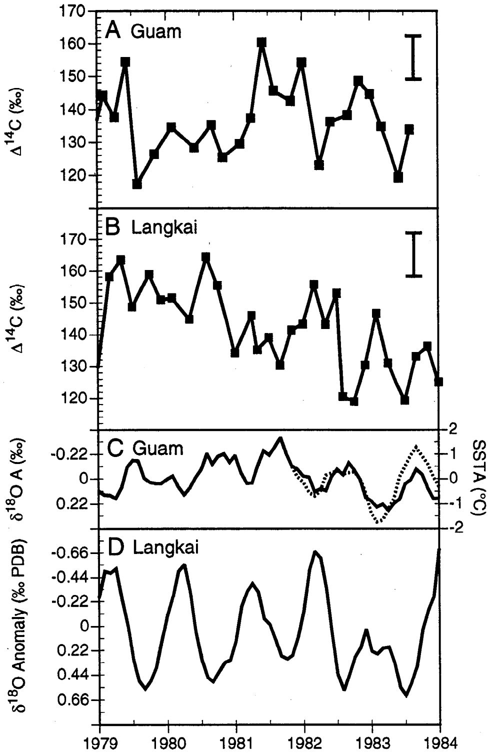

Figure 3. Comparison of (a and b) Δ^{14}C time series and (c and d) δ^{18}O time series for the Guam and Langkai sites. The Δ^{14}C 2σ error bars (14‰) are indicated, and the y axes in δ^{18}O plots are reversed. Dashed line in Figure 3c is the IGOSS NMC monthly SST anomaly for the Guam core site.

The timing of the δ^{18}O maxima and minima is consistent with the surface water variability observed in the Makassar Strait. Low δ^{18}O values correspond to low salinity-high SST conditions which occur during the peak of NW Monsoon rainy season (February–March). Freshwater flux (rainfall and river discharge) dominates the δ^{18}O response during these months. High δ^{18}O values correspond to high-salinity/low-SST conditions which occur during the SE Monsoon dry season (July–August). The interannual δ^{18}O variability is caused chiefly by variability in precipitation and river discharge due to the ENSO-related movements of the Indonesian Low Pressure Cell. The δ^{18}O time series records ENSO warm-phase events as anomalously high values, indicative of drought conditions. The very strong ENSO in 1982–1983 is especially notable: the normally large (about one per mil) rainy season δ^{18}O depletion is attenuated to a small range of relatively enriched values that explain exactly the observed temperature cycle. This is evidence of minimal freshwater input throughout the entire 1983 year.

High radiocarbon values are seen in the winter months, correlated with low δ^{18}O and δ^{13}C values. The timing of high Δ^{14}C in winter during the NW monsoon is consistent through most of the record, although there are notable exceptions such as 1976 and 1980, when the highest radiocarbon values occur in the middle of the year. The most anomalous years in the Δ^{14}C record are 1976 and 1981, which show the smallest increase in Δ^{14}C during winter months.

Radiocarbon and δ^{18}O time series from the Guam and Indonesian corals are compared in Figure 3. The variability in Δ^{14}C values in the Guam coral has the same magnitude as in the Indonesian coral (Figures 3a and 3b). The range of Δ^{14}C values is approximately the same in both records, varying between 120 and 160‰. Figure 3c compares the Guam δ^{18}O time series and the SST anomaly time series for the 3° × 3° region adjacent to the core site (11.5°N–13.5°N, 142.5°E–144.5°E) from the 1° × 1° IGOSS NMC monthly SST data. Precision on the Guam timescale is no worse than ± 2 months, and consistent with climatology, Guam δ^{18}O and Langkai δ^{18}O are 5–6 months out of phase (Figures 3c and 3d).

Discussion

The potential sources of seasonal radiocarbon variability include seasonal changes in the invasion rate of CO_2 from the atmosphere, seasonal changes in carbon flux, local mixing with subsurface waters, and horizontal advection of surface waters. Seasonal changes in the invasion rate of CO_2 from the atmosphere are far too small to produce the observed radiocarbon variability. Seasonal changes in organic carbon flux (due to river discharge or settling of particulate matter) are also small effects and are completely accounted for by the δ^{13}C correction.

At first glance, it might appear that the radiocarbon seasonality can be attributed to effects of local upwelling during the SE monsoon and input of Java Sea water during the NW monsoon, since depleted Δ^{14}C values occur in July–August and enriched Δ^{14}C values occur in February–March. However, unlike the Banda and Arafura Seas in the eastern part of the Indonesian Seaway, the Makassar Strait is not a region of significant upwelling [*Wyrtki*, 1961; *Bray et al.*, 1996, Figure 11b]. Though seasonal shoaling of the Java Sea water-throughflow water discontinuity has been observed for deeper reef sites in the Java Sea [*Roberts et al.*, 1988], it is unlikely that significant amounts of Java Sea water reach the Langkai site. Surface water salinity maps by *Wyrtki* [1961] clearly indicate throughflowing surface waters moving south along the southwestern coast of Sulawesi during the February peak of the NW monsoon.

Vertical profiles of seawater Δ^{14}C might provide some insights about the role of upwelled waters at Langkai and Guam; however, no such data exists near these sites. More important, the large seasonality evident in the coral data suggests that seawater Δ^{14}C profiles are probably subject to temporal aliasing unless stations have been reoccupied on a seasonal basis. We note that it might be possible to retrospectively test for the presence of upwelled waters by comparing the coral Δ^{14}C time series to high-resolution time series of coral Cd/Ca ratios [*Shen et al.*, 1987].

The pattern of interannual Δ^{14}C variability is also not consistent with a local mixing mechanism. Using expendable bathythermograph data, *Bray et al.* [1996] found that thermocline depth in the Flores Sea-Makassar Strait region, Sulawesi sea level and the Tahiti-Darwin Southern Oscillation Index (SOI) are positively correlated. During the 1988 ENSO cool phase, sea level rose by 10 cm and the thermocline in the Makassar Strait was depressed by 10–20 m, while during the 1987 ENSO warm phase, sea level fell by 10 cm and the thermocline shoaled by 10–20 m. Similar elevations of the thermocline occurred during ENSO warm events in 1982 and 1992. If local mixing processes were responsible for the observed radiocarbon variability, given the consistency of *Bray et al.* [1996] SOI-thermocline depth relationship, we would expect a regular pattern of ENSO-related Δ^{14}C variability, with enriched Δ^{14}C during ENSO cool phases and depleted Δ^{14}C during ENSO warm phases. Instead, we see no clear ENSO relationship: during 1972–1973, Δ^{14}C has a strong 50‰ seasonality; during 1976–1977, Δ^{14}C is depleted; during 1980, Δ^{14}C is enriched; during 1982–1983, Δ^{14}C has a 30‰ seasonality. Some of the most depleted Δ^{14}C values occur in 1981, one year prior to the very strong 1982–1983 event. *Bray et al.* [1996] also found little ENSO-related variability in the E–W pressure gradient along the Java Sea-Timor Sea axis; this eliminates the possibility of advection of radiocarbon from the Java Sea as the major source of interannual Δ^{14}C variability. We conclude that the Langkai site is capturing Δ^{14}C variability advected into the Makassar Strait from the Sulawesi Sea by throughflowing surface waters.

Based on the phase relationships between the δ^{18}O and Δ^{14}C, we find it difficult to explain the observed Δ^{14}C variability in the Makassar Strait with a simple source water supply argument. Since the archive data allow the possibility

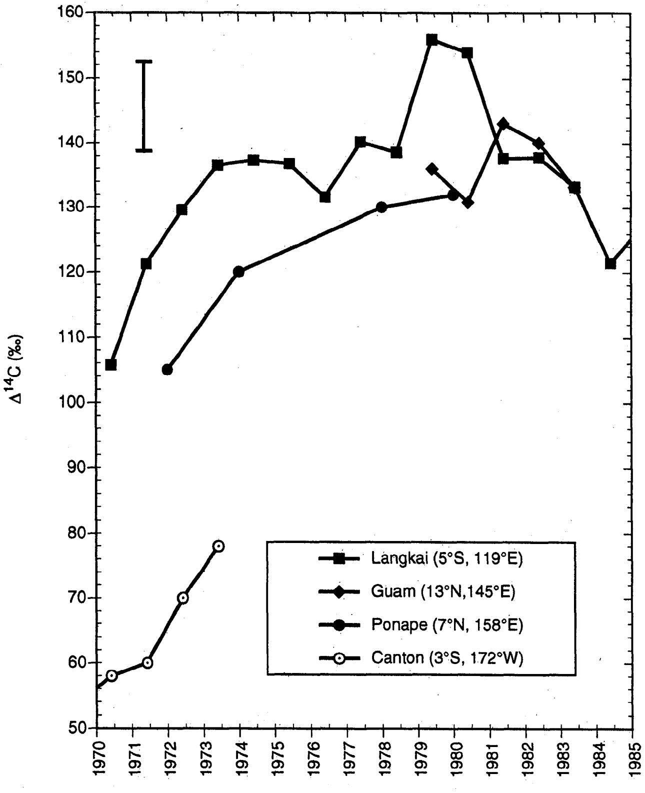

Figure 4. Comparison of time series of annual mean coral Δ^{14}C from Langkai (Indonesian Seaway), Guam (NP source), Ponape (NP source, biannual values) [*Konishi et al.*, 1981] and Canton (SP source) [*Druffel*, 1987]; all data are from *Porites* spp. corals. The Δ^{14}C 2σ error bar (14‰) is indicated.

of South Pacific source water contributing to the Makassar Strait throughflow during the NW Monsoon rainy season, and remembering that the GEOSECS data indicate that the $\Delta^{14}C$ of water supplied by the South Equatorial Current (SEC) is about 50‰ lower than water supplied by the North Equatorial Current (NEC), we might expect to observe low $\Delta^{14}C$ corresponding to the $\delta^{18}O$ minima. Instead, we observe highest $\Delta^{14}C$ values during the NW monsoon, which eliminates the possibility of the SEC contributing to throughflow during this time. We observe lowest $\Delta^{14}C$ during the SE Monsoon, when $\delta^{18}O$ maxima and archived data clearly indicate the Makassar Strait is supplied water from the NEC [*Ffield and Gordon*, 1992].

Radiocarbon data from *Porites* spp. corals collected at Ponape (7°N, 158°E) in the NEC by *Konishi et al.* [1981] and Canton (3°S, 172°W) in the SEC by *Druffel* [1987] are compared to the Langkai and Guam $\Delta^{14}C$ values in Figure 4. To facilitate comparison, the data have been reduced to annual means, with the exception of the biannual Ponape data. The Ponape $\Delta^{14}C$ values are nearly identical to Guam (1979–1980), and 40‰ higher than the Canton means (1972–1974). This interhemispheric disparity in radiocarbon values is consistent with the GEOSECS observations, and cannot be attributed to interspecific differences. The Langkai $\Delta^{14}C$ means are 0–25‰ higher than Guam and Ponape (1972–1983), and 50–60‰ higher than Canton (1970–1973).

The similarities between $\Delta^{14}C$ records from Langkai, Guam and Ponape, and the difference between those records and the data from Canton, strongly support a year-round North Pacific source to Indonesian throughflow in the Makassar Strait. This is consistent with other tracer data and modeling results [*Ffield and Gordon*, 1992; *Godfrey et al.*, 1993; *Lukas et al.*, 1991]. In addition, the Guam data, combined with previous observations [*Brown et al.*, 1993; *Druffel*, 1987] indicate that there is significant seasonal radiocarbon variability in the open waters of the Pacific Ocean, and that the distribution of radiocarbon in the surface ocean is more dynamic than suggested by previous studies. Recent modeling studies by *Rodgers et al.* [this issue] also suggest that strong seasonal and interannual variations in surface water $\Delta^{14}C$ are a widespread feature of open ocean waters.

If the seasonal and interannual radiocarbon variability is indeed caused by changes in the horizontal flow patterns of water in the tropical Pacific, as suggested by *Druffel* [1987], then additional coral time series from different sites across the tropical Pacific may help to constrain the dynamic circulation of water and heat in the Pacific, adding a time dimension to GEOSECS and World Ocean Circulation Experiment (WOCE) radiocarbon studies based on shipboard seawater sampling. For example, analysis of phase differences among coral $\Delta^{14}C$ time series from closely-spaced sites in the major current pathways could provide retrospective observations of surface water transport variability. Our present data are inadequate for this purpose because the time series are short and it is unlikely that a time-varying $\Delta^{14}C$ signature generated in the open W. Pacific could be delivered as far as the Makassar Strait without being modified in transit (the lagged crosscovariance function yields a weak correlation of $r = +0.29$ when Guam leads Langkai by 36 months; though this may be a plausible transport timescale, it is probably a concidental result). There may also be sites in the equatorial Pacific where coral radiocarbon variability is sensitive to large-scale redistribution of surface waters during ENSO warm phases. A coral $\Delta^{14}C$ time series from such a site would provide a proxy record of the magnitude of water mass transfers associated with these events. We can also speculate that if improvements in AMS technology ultimately yield $\Delta^{14}C$ precision better than ±1‰, it would then be possible to extend high-resolution coral radiocarbon studies into the prebomb era.

Summary

High-resolution radiocarbon records from *Porites* spp. corals collected from Guam and the Makassar Strait show seasonal variability between 15 and 50‰ and significant interannual variability. The similar range in $\Delta^{14}C$ values observed at the two sites strongly supports a year-round North Pacific source for Indonesian throughflow in the Makassar Strait. These results emphasize the dynamic behavior of radiocarbon in the surface ocean and suggest the utility of such time series for studying ocean circulation at monthly resolution. Because this approach can provide time series several decades in length, it may be an excellent way to help constrain interannual and decadal changes in surface ocean circulation.

Acknowledgments. We acknowledge the support of L. Wells, G. Shen, C. Meyer, I. Suparka and the Indonesian Institute of Sciences (LIPI). We also thank M. Cane and two anonymous reviewers for insightful comments. Radiocarbon analyses were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory (contract W-7405-Eng-48). Field work and stable isotope analyses were funded under the U.C. Pacific Rim Research Program (FY 1990–1991, 1991–1992, 1992–1993), NSF Climate Dynamics FD9207491, and a Global Change Graduate Fellowship from U.S. Department of Energy, Office of Energy Research, Environmental Sciences Division.

References

Bray, N. A., S. Hautala, J. Chong, and J. Pariwono, Large-scale sea level, thermocline, and wind variations in the Indonesian throughflow region, *Geophys. Res.*, *101*, 12,239-12,554, 1996.

Broecker, W. S., and T.-S. Peng, Seasonal variability in the $^{14}C/^{12}C$ ratio for surface ocean water, *Geophys. Res. Lett.*, *7*, 1020-1022, 1980.

Broecker, W. S., T.-S. Peng, G. Östlund, and M. Stuiver, The distribution of bomb radiocarbon in the ocean, *J. Geophys. Res.*, *90*, 6953-6970, 1985.

Brown, T. A., G. W. Farwell, P. W. Grootes, F. H. Schmidt, and M. Stuiver, Intra-annual variability of the radiocarbon content of corals from the Galapagos Islands, *Radiocarbon*, *35*, 245-251, 1993.

Cole, J. E., R. G. Fairbanks, and G. T. Shen, Recent variability in the Southern Oscillation: Isotopic results from a Tarawa Atoll coral, *Science*, *260*, 1790-1793, 1993.

Davis, J. C., *et al.*, LLNL/UC AMS facility and research program, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *52*, 269-272, 1990.

Druffel, E. M., Banded Corals: Changes in oceanic carbon-14 during the Little Ice Age, *Science*, *218*, 13-19, 1982.

Druffel, E. M., Bomb radiocarbon in the Pacific: Annual and seasonal timescale variations, *J. Mar. Res.*, *45*, 667-698, 1987.

Druffel, E. M., and S. Griffin, Large variations in surface ocean radiocarbon: Evidence of circulation changes in the Southwestern Pacific, *J. Geophys. Res.*, *98*, 20,249-20,259, 1993.

Ffield, A., and A. L. Gordon, Vertical mixing in the Indonesian thermocline, *J. Phys. Oceanogr.*, *22*, 184-195, 1992.

Fieux, M., R. Molcard, and A. G. Ilahude, Geostrophic transport of the Pacific-Indian Oceans throughflow, *J. Geophys. Res.*, *101*, 12,421-12,432, 1996.

Fine, R., Direct evidence of using tritium data for throughflow from the Pacific into the Indian Ocean. *Nature*, *315*, 478-480, 1985.

Godfrey, J. S., A Sverdrup model of the depth-integrated flow for the world ocean allowing for island circulations, *Geophys. Astrophys. Fluid Dyn.*, *45*, 89-112, 1989.

Godfrey, J. S., The effect of the Indonesian throughflow on ocean circulation and heat exchange with the atmosphere: A review, *J. Geophys. Res.*, *101*, 12,217-12,238, 1996.

Godfrey, J. S., A. C. Hirst, and J. Wilken, Why does the Indonesian throughflow appear to originate from the North Pacific?, *J. Phys. Oceanogr.*, *23*, 1087-1098, 1993.

Hirst, A., and J. S. Godfrey, The role of Indonesian throughflow in a global ocean GCM, *J. Phys. Oceanogr.*, *23*, 1057-1086, 1993.

Konishi, K. J., T. Tanaka, and M. Sakanoue, Secular variation of radiocarbon concentration in seawater: A sclerochronological approach, *Proc. Fourth Intl. Coral Reef Symp.*, *1*, 181-185, 1981.

Levitus, S., Climatological atlas of the world ocean, *Prof. Pap., 13, NOAA*, 1982.

Lukas, R., E. Firing, P. Hacker, P. L. Richardson, C. A. Collins, R. Fine, and R. Gammon, Observations of the Mindanao Current during the western Equatorial Pacific Ocean circulation study, *J. Geophys. Res.*, *96*, 7089-7104, 1991.

Lukas, R., T. Yamagata, and J. P. McCreary, Pacific low-latitude western boundary currents and the Indonesian throughflow, *J. Geophys. Res.*, *101*, 12,209-12,216, 1996.

Macdonald, A., Property fluxes at 30°S and their implications for the Pacific-Indian Ocean throughflow and global heat budget, *J. Geophys. Res.*, *98*, 6851-6868, 1993.

McConnaughey, T., ^{13}C and ^{18}O isotopic disequilibrium in biological carbonates, 1, Patterns, *Geochim. Cosmochim. Acta*, *53*, 151-162, 1989.

Meyers, G., Variation of the Indonesian throughflow and the El Niño-Southern Oscillation, *J. Geophys. Res.*, *101*, 12,255-12,264, 1996.

Molcard, R., M. Fieux, and A. G. Ilahude, The Indo-Pacific throughflow in the Timor Passage, *J. Geophys. Res.*, *101*, 12,411-12,420, 1996.

Murray, S. P., and D. Arief, Throughflow in the Indian Ocean through the Lombok Strait, January 1985-January 1986, *Nature*, *333*, 444-447, 1988.

Nozaki, Y., D. M. Rye, K. K. Turekian, and R. E. Dodge, A 200 year record of carbon-13 and carbon-14 variations in a Bermuda coral, *Geophys. Res. Lett.*, *5*, 825-828, 1978.

Östlund, H. G., and M. Stuiver, GEOSECS Pacific radiocarbon, *Radiocarbon*, *22*, 25-53, 1980.

Quay, P. D., M. Stuiver, and W. S. Broecker, Upwelling rates for the equatorial Pacific Ocean derived from bomb ^{14}C distribution, *J. Mar. Res.*, *41*, 796-792, 1983.

Reynolds, R. W., and T. M. Smith, Improved global sea surface temperature analyses, *J. Clim.*, *7*, 929-948, 1994.

Roberts, H. H., P. Aharon, and C. V. Phipps, Morphology and sedimentology of *Halimeda* bioherms from the eastern Java Sea (Indonesia), *Coral Reefs*, *6*, 161-172, 1988.

Rodgers, K. B., M. A. Cane and D. P. Schrag, Seasonal variability of sea surface Δ^{14}C in the equatorial Pacific in an ocean circulation model, *J. Geophys. Res.*, this issue.

Shen, G. T., E. A. Boyle and D. W. Lea, Cadmium as a tracer of historical upwelling and industrial fallout, *Nature*, *328*, 794-796, 1987.

Stuiver, M., and H. A. Polach, Discussion and reporting of ^{14}C data, *Radiocarbon*, *19*, 355-363, 1977.

Toggweiler, J. R., K. Dixon, and W. S. Broecker, The Peru upwelling and the ventilation of the South Pacific thermocline, *J. Geophys. Res.*, *96*, 20467-20497, 1991.

Vogel, J. S., J. R. Southon, and D. E. Nelson, Catalyst and binder effects in the use of filamentous graphite for AMS, *Nucl. Instrum. Methods Phys. Res., Section B*, *29*, 50-56, 1987.

Wajsowicz, R. C., The circulation of the depth-integrated flow around an island with application to the Indonesian throughflow, *J. Phys. Oceanogr.*, *23*, 1407-1484, 1993a.

Wajsowicz, R. C., A simple model of the Indonesian throughflow and its composition, *J. Phys. Oceanogr.*, *23*, 2683-2703, 1993b.

Wyrtki, K., Scientific results of marine investigations of the South China Sea and the Gulf of Thailand, *NAGA Rep. 2*, Scripps Inst. of Oceanogr., Univ. of Calif., San Diego, 1961.

Wyrtki, K., Indonesian throughflow and associated pressure gradient, *J. Geophys. Res.*, *92*, 12,941-12,946, 1987.

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(Received October 13, 1994; revised December 17, 1996;
accepted December 30, 1996)