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Air-sea exchange of CO_2 in the Gulf of Kutch, northern Arabian Sea based on bomb-carbon in corals and tree rings

S CHAKRABORTY, R RAMESH and S KRISHNASWAMI
Physical Research Laboratory, Ahmedabad 380 009

Abstract. Radiocarbon analyses were carried out in the annual bands of a 40 year old coral collected from the Gulf of Kutch (22·6°N, 70°E) in the northern Arabian Sea and in the annual rings of a teak tree from Thane (19°14′N, 73°24′E) near Bombay. These measurements were made in order to obtain the rates of air-sea exchange of CO_2 and the advective mixing of water in the Gulf of Kutch. The $\Delta^{14}C$ peak in the Thane tree occurs in the year 1964, with a value of $\sim 630‰$, significantly lower than that of the mean atmospheric $\Delta^{14}C$ of the northern hemisphere ($\sim 1000‰$). The radiocarbon time series of the coral was modelled considering the supply of carbon and radiocarbon to the gulf through air-sea exchange and advective water transport from the open Arabian Sea. A reasonable fit for the coral data was obtained with an air-sea CO_2 exchange rate of 11–12 mol $m^{-2}\,yr^{-1}$, and an advective velocity of 28 m yr^{-1} between the Arabian Sea and the Gulf of Kutch; this was based on a model generated time series for radiocarbon in the Arabian Sea. The deduced velocity (~ 28 m yr^{-1}) of the advective transport of water between the gulf and the Arabian Sea is much lower than the surface tidal current velocity in this region, but can be understood in terms of net fluxes of carbon and radiocarbon to the gulf to match the observed coral $\Delta^{14}C$ time series.

Keywords. Air-sea interaction; CO_2 exchange; Gulf of Kutch; coral; tree rings; bomb radiocarbon.

1. Introduction

The oceans of the world contain about sixty times as much CO_2 as the atmosphere and regularly exchange CO_2 with it. Thus, they play a significant role in controlling the CO_2 content of the atmosphere and hence the greenhouse warming of our planet (Dickson 1992). The oceanic capacity for uptake of CO_2 is influenced by physical, chemical and biological processes occurring within the sea. One of the aims of the JGOFS (Joint Global Ocean Flux Study), an IGBP core project, is to determine the rate of exchange of carbon dioxide between the atmosphere and the oceans, for a better understanding of the global carbon cycle. The air-sea CO_2 exchange rate (ASCER), has been determined by various investigators in several oceanic regions (Sundquist 1985 and references therein). Such measurements are however meagre in the Arabian Sea, a unique biogeochemical province of the oceans. Realizing the importance of Arabian Sea in the global carbon cycle, detailed JGOFS related studies are planned in this region during the next 2–3 years.

ASCER can be determined by comparing the radiocarbon time histories of the atmosphere and the ocean. The surface water radiocarbon history can be derived from ^{14}C data in dated coral bands, and the atmospheric radiocarbon variation can be obtained by measuring ^{14}C concentrations in tree rings. Druffel and Suess (1983) estimated the ASCER in the northwest Atlantic and eastern tropical Pacific region

Table 1. $\Delta^{14}C$ minimum, maximum and peak shift for different oceanic regions. The minima of $\Delta^{14}C_{coral}$ represent the pre-bomb values. The time difference between the peaks in $\Delta^{14}C$ of the atmosphere and the coral (surface ocean) is termed 'peak shift'. The atmospheric peak was taken to be in the year 1963.

Oceanic region	$\Delta^{14}C_{coral}$ min	$\Delta^{14}C_{coral}$ max	Year of maximum	Peak shift (yr)	Reference
Bermuda 32°N, 65°W	−50	168	1975	12	Nozaki *et al* (1978).
Florida 24°57′N 88°33′W	−55	160	1972	9	Druffel and Linick (1978)
Oahu 21°N, 158°W	—	175	1973	10	Toggweiler *et al* (1991).
Belize 16°50′N 83°48′W	−55	160	1972	9	Druffel (1980).
North Red Sea 12°N, 43°E	−75	105	1967	4	Cember (1989).
South Red Sea 11·5°N, 43°E	−73	~45	1972	>7	Cember (1989).
Tarawa 1°N, 172°E	—	103	1978	15	Toggweiler *et al* (1991).
Galapagos 1°S, 90°W	−72	25	1973	10	Druffel (1981).
Fiji 18°S, 179°E	−70	138	1974	11	Toggweiler *et al* (1991).
Tonga 20°S, 175°W	—	157	1975	12	Toggweiler *et al* (1991).
Gulf of Kutch 22·6°N, 70°E	−65	172	1968	5	This work.

using coralline $\Delta^{14}C$. Cember (1989) estimated the ASCER in the Red Sea following a similar approach. The earlier results are summarized in table 1. We have followed this approach to determine ASCER in the northeast Arabian Sea.

2. Methods

We collected a coral *Favia speciosa* from the Pirotan island of the Gulf of Kutch (GKh, 22·6°N, 70°E), northeastern Arabian Sea, (water depth during low tide at coral location $\leqslant 1$ m) in June 1990 (figure 1). This gulf is a part of the western continental shelf of the Indian coast and supports fringing reefs. Tree rings from a teak tree (*Tectona grandis*) that grew in Thane (19°14′N, 73°24′E) near Bombay was also analyzed for radiocarbon. A disc from the stump and its chronology was provided by Pant and Borgaonkar (1983).

A ~1 cm thick slice of the coral was sectioned along its growth axis using a diamond tipped circular saw. X-radiography revealed clear bands with a mean band thickness of ~4 mm. Oxygen isotope studies showed that these bands were annual in nature,

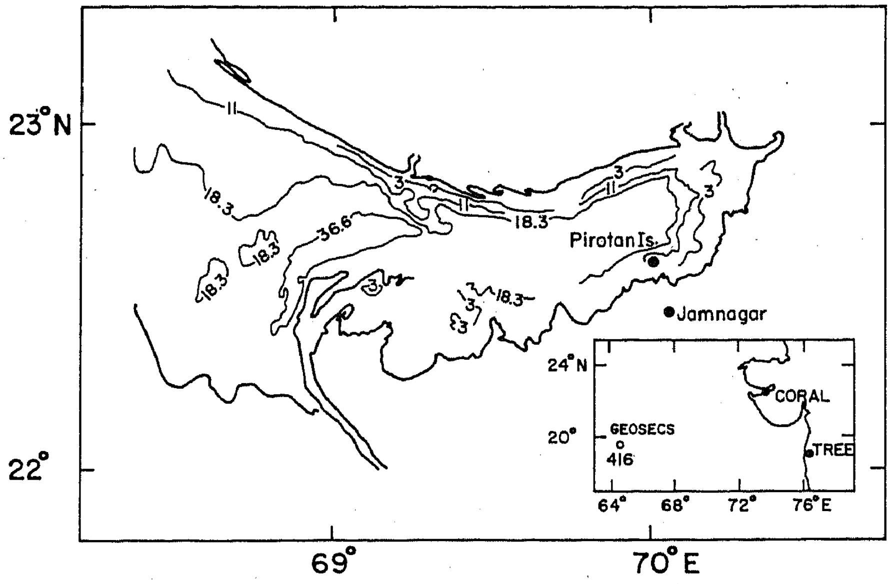

Figure 1. The Gulf of Kutch showing water depth contours (m) and the coral location (Pirotan island). Inset shows the locations for coral, tree and the GEOSECS station 416.

with an average growth rate of $4 \pm 0{\cdot}8$ mm/yr (Chakraborty and Ramesh 1994) for the past 40 years. Because of the low growth rate, 2 or 3 bands were combined for radiocarbon measurements. Radiocarbon measurements were made by the liquid scintillation technique (Chakraborty 1993; Bhushan *et al* 1994) using a TASK benzene synthesizer and a Packard 2250CA Liquid Scintillation Analyzer. The radiocarbon activity is reported as $\Delta^{14}C$ following standard terminology (Stuiver and Polach 1977). Fractionation correction was done using measured $\delta^{13}C$ values, (average of a number of samples per band). The reported $\Delta^{14}C$ values are decay corrected to the year of formation.

For the measurement of radiocarbon in tree rings, wood was powdered and chemically pretreated according to the method of Cain and Suess (1976). Samples were combusted in oxygen to produce CO_2 which was converted to benzene (Noakes *et al* 1965). $\delta^{13}C$ measurements were not made in these tree rings but was done in the cellulose from an adjacent tree (Ramesh *et al* 1989) which shows values in the range of -24 to -26‰. We used a value of -25‰ for $\Delta^{14}C$ calculations. The overall analytical uncertainty in $\Delta^{14}C$ measurement is ± 8‰ (1σ).

3. Features of the data

3.1 *Gulf of Kutch coral*

Figure 2 shows the $\Delta^{14}C$ time-series in the GKh coral for the years 1950–1990. From a value of -60‰ in the year 1950 it steadily increases to a peak value of 170‰ in 1968, after which it decreases monotonically to a value of 55‰ in 1990. The increase in ^{14}C activity since 1950 results from the injection of bomb produced radiocarbon from the atmosphere to the surface ocean via air-sea CO_2 exchange. Moore and Krishnaswami (1974) had reported $\delta^{14}C$ time series for a *Favia* coral in the GKh

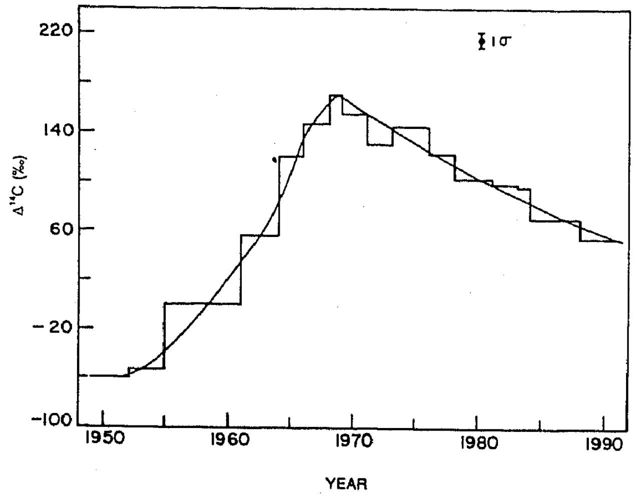

Figure 2. $\Delta^{14}C$ time series in the coral *Favia speciosa* from the Gulf of Kutch, northern Arabian Sea. The continuous curve is an eye fit line to the data.

for the years 1951 to 1973. They obtained a peak value of +230‰ for $\delta^{14}C$ in 1968. This $\delta^{14}C$ when corrected for isotopic fractionation using a $\delta^{13}C$ value of −0·27‰ (our measured average value in the GKh coral) yields a $\Delta^{14}C$ of 169‰, very close to the peak value of 170‰ obtained in this study. Measurements of radiocarbon activity in the water of Pirotan island in 1992 yielded a value of 46 ± 8‰ (Bhushan *et al* 1994) which is consistent with the $\Delta^{14}C$ value (55 ± 7‰) of the coral bands for the years 1988–90.

3.2 *Tree rings*

The $\Delta^{14}C$ profile in the annual rings of the teak tree from Thane is shown in figure 3 along with the northern hemispheric (NH) curve (Nydal and Lövseth 1983; Gupta and Polach 1985). The Thane tree ring samples analyzed cover a time span of 1960 to 1980. The prebomb (1934–43 A.D.) tree ring $\Delta^{14}C$ value was −25 ± 7·9‰ for the same species (*Tectona gradis*) collected from Kerala (9°N, 76°5′E; Kusumgar 1965). This is in agreement with Stuiver and Quay's (1981) prebomb $\Delta^{14}C$ values of −22‰ from tree rings. In the early sixties, the $\Delta^{14}C$ values of the Thane tree rings are indistinguishable from that of the NH values, but the two sets of values differ significantly after mid-sixties through the year 1980. The Thane tree ring $\Delta^{14}C$ reaches a peak value (630‰) during 1964–65, similar to that for air samples from Bombay during 1963–64 (Kusumgar 1965) which yield values of ~700‰. The trend of $\Delta^{14}C$ time series in the Thane teak tree is similar to that of NH curve, but the $\Delta^{14}C$ values at Thane are significantly lower than those of NH. For example the peak $\Delta^{14}C$ value for NH is ~1000‰ compared to 630‰ for Thane. Broecker *et al* (1985) have reported atmospheric $\Delta^{14}C$ time series for three regions: >20°N, 20°N-20°S, and >20°S. The tree analyzed in this study (located at 19°N) belongs to the middle group and its peak $\Delta^{14}C$ value is ~100‰ less compared to that expected from the 20°N-20°S curve. The reason for the consistently lower $\Delta^{14}C$ in the tree could not be due to ^{14}C depleted CO_2 from the Arabian Sea, as pre-bomb values for the same species are in good agreement with global values, as mentioned above. More teak trees should be analyzed to verify the above results.

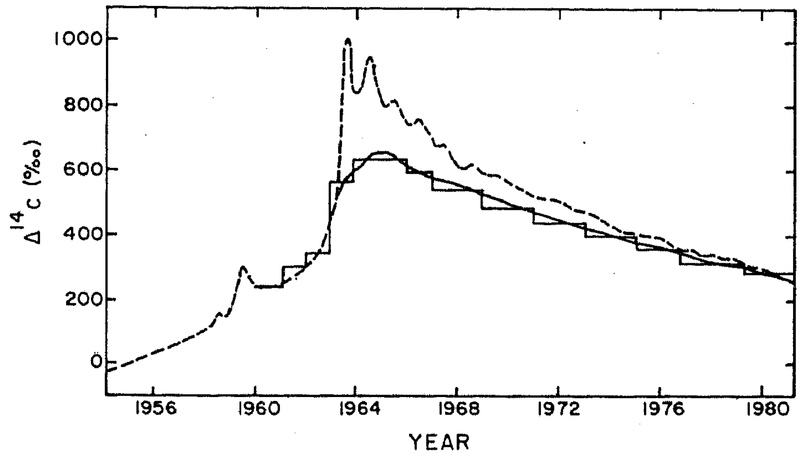

Figure 3. Atmospheric $\Delta^{14}C$ time variations of the Northern Hemisphere (long dashed line, data from Nydal and Lövseth 1983) and Thane (near Bombay, solid line). The Thane data are based on tree ring measurements. The Thane values are significantly lower than the NH curve after 1963. Typical 1σ error in the $\Delta^{14}C$ measurement of tree ring is ± 7‰.

4. Air-Sea CO_2 exchange rate (ASCER) in the Gulf of Kutch

4.1 *Model for calculation of ASCER*

Determination of the CO_2 exchange rate between atmosphere and the surface ocean requires a knowledge of sources and sinks of carbon and radiocarbon in the particular oceanic region. The carbon budget in surface water is controlled mainly by air-sea CO_2 exchange, advective processes (lateral and/or vertical mixing of water masses) and biological productivity. The GKh area is a shallow continental shelf region having a mean water depth of ~ 30 m. It exchanges water with the adjoining Arabian Sea through tidal currents. The speed of these currents vary from 0·5 to 0·76 m/sec and are mainly towards the west and southeast directions (Srivastava and John 1977). The mass balance equations for ^{12}C and ^{14}C in the GKh between supply and removal is given by:

$$\left\{\begin{array}{l}\text{Invasion of } CO_2 + \\ \text{advective transport}\end{array}\right\} = \left\{\begin{array}{l}\text{Evasion of } CO_2 + \text{advective transport} + \\ \text{biological removal.}\end{array}\right\}$$

For ^{12}C this is given by (assuming invasion and evasion of CO_2 are equal)

$$F_{12} + wC_S = F_{12} + wC_G + B \quad (1)$$

$$wC_S = B + wC_G \quad (2)$$

where F_{12} (mol m^{-2} yr^{-1}) is the CO_2 exchange flux, w (m yr^{-1}) lateral advection velocity, C (mol m^{-3}) carbon concentration and B (mol m^{-2} yr^{-1}) is the biological removal rate of carbon. The subscripts S and G refer to the surface Arabian Sea and the GKh respectively. The above equations assume steady state for ^{12}C balance. This assumption is an oversimplification as the CO_2 concentration of atmosphere has been increasing steadily during the past century (Bacastow and Keeling 1981; Siegenthaler and Sarmiento 1993) which would affect the invasion-evasion balance.

The mass balance equation for ^{14}C is of the following form (neglecting the radiocarbon decay term).

$$D_G \frac{dC_G^*}{dt} = F_{12}(R_A - R_G) + w(C_S R_S - C_G R_G) \tag{3}$$

where R is the $^{14}C/^{12}C$ mol ratio in the respective reservoirs. Subscripts A and G stand for the atmosphere and GKh respectively. C_G^* is the radiocarbon concentration in GKh and D_G is the mean depth of GKh (table 2). The formulation of our model is similar to that used by Cember (1989) for deriving ASCER in the Red Sea region. Equation 3 can be written in the standard $\Delta^{14}C$ notation. The first term in the right hand side, the net ^{14}C flux, between the atmosphere and the GKh can be expressed as: $k(\Delta^{14}C_A - \Delta^{14}C_G)F_{12}$, where k is a factor which takes into consideration the $^{14}C/^{12}C$ mol ratio of the NBS oxalic acid standard ($1{\cdot}176 \times 10^{-12}$) and fractionation factor for the inter reservoir carbon transfer (Stuiver 1980). The numerical value of k is $1{\cdot}24 \times 10^{-15}$ (*op cit.*). $\Delta^{14}C_A$ and $\Delta^{14}C_G$ are the atmospheric and Gkh radiocarbon activities. The second term in the right hand side of equation (3) represents the exchange flux of radiocarbon between the Arabian Sea and GKh by advection. This term can be written as:

$$F_{SG} = w\left[m(\Sigma CO_2)_S\left(1 + \frac{\Delta^{14}C_S}{1000}\right) - m(\Sigma CO_2)_G\left(1 + \frac{\Delta^{14}C_G}{1000}\right)\right] \tag{4}$$

Table 2. Symbols, units and values of parameters used in our model.

Symbol	Parameter	Unit	Value	Reference
F_{12}	Air-sea exchange rate of CO_2	$mol\,m^{-2}\,yr^{-1}$	model derived	
C_S, $(\Sigma CO_2)_S$	Total DIC conc. in surface Arabian Sea	$mol\,m^{-3}$	2·11	Stuiver and Östlund (1983).
C_D, $(\Sigma CO_2)_D$	Total DIC conc. of deep Arabian Sea	$mol\,m^{-3}$	2·36	Stuiver and Östlund (1983).
C_G, $(\Sigma CO_2)_G$	Total DIC conc. in GKh	$mol\,m^{-3}$	2·11	Stuiver and Östlund (1983).
R	$^{14}C/^{12}C$ mol ratio	—	variable	
C^*	Radiocarbon conc.	$mol\,m^{-3}$	variable	
D_S	Mixed layer depth of Arabian Sea	m	60	
D_G	Mean depth of GKh	m	30	
$(\Delta^{14}C)_A^0$	Pre-bomb atmospheric $\Delta^{14}C$	‰	−25	Stuiver and Quay (1981).
u	Upwelling velocity	$m\,yr^{-1}$	model derived	
w	Advective velocity Arabian Sea to GKh	$m\,yr^{-1}$	model derived	

where m is a constant which is obtained by multiplying the $^{14}C/^{12}C$ mol ratio of the NBS Oxalic acid standard and the fractionation term between the nineteenth century wood standard and the marine bicarbonate (Stuiver 1980). That is, $m = (1{\cdot}176 \times 10^{-12} \times 1{\cdot}052) = 1{\cdot}24 \times 10^{-12}$. The solution of equation (3) is given by:

$$\Delta\,^{14}C_G(t) = \Delta\,^{14}C_G^0 e^{-Jt} + Ee^{-Jt}\int_0^t e^{J\tau}\Delta\,^{14}C_A(\tau)d\tau + Fe^{-Jt}\int_0^t e^{J\tau}\Delta\,^{14}C_S(\tau)d\tau \tag{5}$$

where $\Delta\,^{14}C_G^0$ is the initial value (pre-bomb) of $\Delta\,^{14}C$ in GKh, J, E and F are constants ($E = F_{12}/D_G\Sigma CO_2, F = W/D_G, J = E + F$). The values of various parameters used in this model are given in table 2.

In equation (3), the term containing F_{12} is always positive as $\Delta\,^{14}C_A > \Delta\,^{14}C_{GK}$ during the period under consideration. In contrast, the term containing w is always negative because $R_G > R_S$ ($C_S = C_G$, we neglect the biological removal B, for simplicity), if the trend seen in 1977 GEOSECS (Östlund *et al* 1987) observations is assumed to hold good for the entire period under consideration. Therefore it is possible to get a number of solutions for equation (3) such that they are consistent with the observed $\Delta\,^{14}C$ in the GKh coral, as long as the ratio F_{12}/w is kept constant. The timing of the maximum in $\Delta\,^{14}C_G$ can be used as a constraint to determine the value of F_{12}/w. At maximum, $dC/dt = 0$ and hence F_{12}/w is given by $[(C_G R_G - C_S R_S)/(R_A - R_S)]_{1968}$. This is numerically equal to $\sim 0{\cdot}4$. Therefore under the assumptions that F_{12} and w are constant during the period of investigation, a number of 'best fit' solutions are possible for equation (3), for the ratio of 0·4 for F_{12}/w. It is difficult to constrain the values of F_{12} and w based only on the model as the $\Delta\,^{14}C$ time series trend is governed by the ratio of F_{12}/w such that $F_{12}/w \sim 0{\cdot}4$. Independent estimates of w are needed to arrive at unique values of F_{12}. As a first step we calculate $\Delta\,^{14}C_G(t)$ using (5) with two simplifications, (i) $[\Sigma CO_2]_S = [\Sigma CO_2]_G$ and (ii) the advective transport process is negligible, i.e. the ^{14}C time variations in the GKh is controlled only by carbon exchange with the atmosphere. Druffel and Suess (1983) also modelled their ^{14}C data in corals from north-west Atlantic and eastern tropical Pacific to derive exchange time scales and CO_2 exchange rate based on a similar simplified model. Equation 3 with $w = 0$ reduces to the model used by Druffel and Suess (1983) i.e. the time derivative of ^{14}C concentration in sea surface water is proportional to the air-sea gradient of $\Delta\,^{14}C$.

Solving (5) with $w = 0$ and for different F_{12} values we obtain a family of curves (figure 4). The curve (a) with $F_{12} = 2\,mol\,m^{-2}yr^{-1}$ shows that the GKh radiocarbon activity increases monotonically through 1980 without a distinct peak. This is not consistent with our coral data (filled circles in figure 4) which show a distinct peak in 1968. The second, third and fourth curves (b), (c) and (d) with $F_{12} = 6, 8$ and $10\,mol\,m^{-2}yr^{-1}$ respectively, though show peaks in the $\Delta\,^{14}C$ time series, they predict much higher radiocarbon concentration in the GKh compared to that observed in the coral. It is clear from these results that the air-sea exchange alone is not able to simulate the observed $\Delta\,^{14}C$ variations in the GKh coral. Therefore carbon and radiocarbon supply to the GKh via advection from the Arabian Sea also needs to be considered, which would 'dilute' the effects of air-sea exchange and thereby provide a better fit to the coral data.

The advective supply of carbon to the GKh could be from the surface layer or

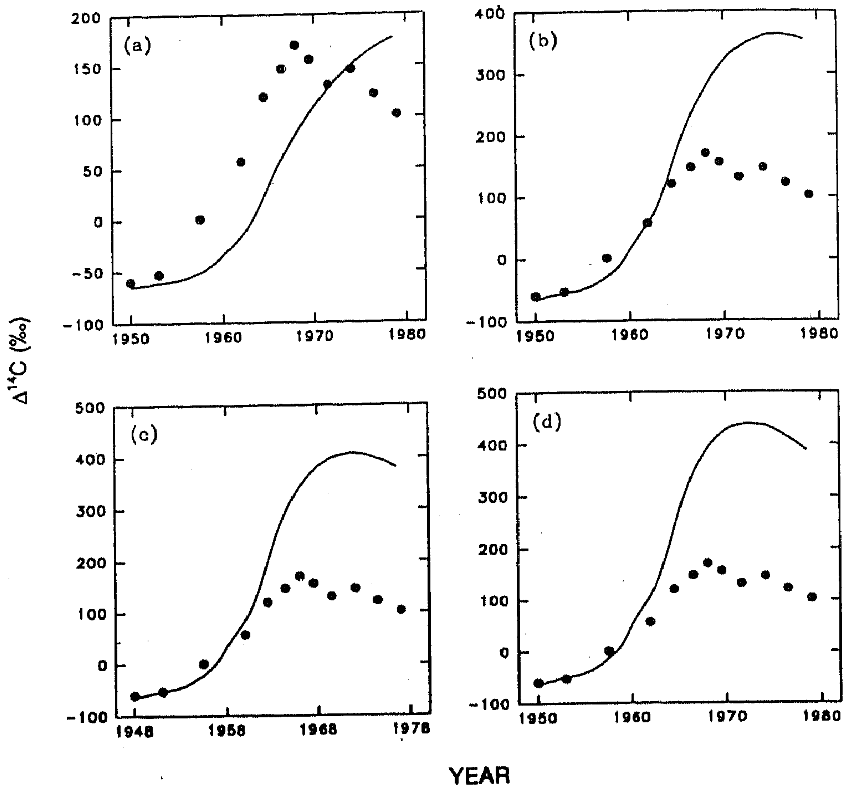

Figure 4. Calculated time variations of radiocarbon activity in the Gulf of Kutch considering only air-sea exchange of CO_2. (a) $F_{12} = 2$, (b) $F_{12} = 6$, (c) $F_{12} = 8$, (d) $F_{12} = 10$ mol m^{-2}yr^{-1}. Solid line: simulated curve; filled circle: coral data.

shallow depths of the Arabian Sea. Solution of (5) requires knowledge of time variations in R_S, $^{14}C/^{12}C$ ratio of the Arabian sea water contributing radiocarbon to GKh. Since there is no data on $\Delta^{14}C$ time series of the surface Arabian Sea, we generated the same for the time period 1953 to 1980 (figure 5), based on input from atmosphere and upwelling from the deep Arabian Sea (the detailed calculations are presented in Chakraborty 1993). The dotted curves in this figure represent the simulated radiocarbon activities, $\pm 20\%$ wrt the solid line which was obtained with $F_{12} = 11$ mol m^{-2} yr^{-1} and u (upwelling velocity in the northern Arabian Sea) = 10·5 m yr^{-1}. Though we constrained this time series with the 1977 mixed layer $\Delta^{14}C$ value of 59‰ (dot in figure 5) based on the GEOSECS (station 416; Stuiver and Ostlund 1983) measurements, the trend of the time series is not necessarily unique, as values for various parameters used were based not on actual measurements but on reasonable assumptions. However the derived time series provides a likely $\Delta^{14}C$ data set for the Arabian Sea.

Now we use the Arabian Sea and the atmospheric $\Delta^{14}C$ time series as the two end members contributing carbon and radiocarbon to GKh to generate the $\Delta^{14}C$ time series in the GKh; we generate a family of curves for different sets of values of F_{12} and w (figure 6). The solid line is the calculated $\Delta^{14}C$ time series for the GKh, appear to fit well. Dashed lines represent the model fit with different F_{12} and w values. The filled circles are our coral data.

It is seen from figure 6 that the rise in $\Delta^{14}C$ of coral during 1953–1960 is faster than that predicted by the model. A factor which would have contributed to this is the

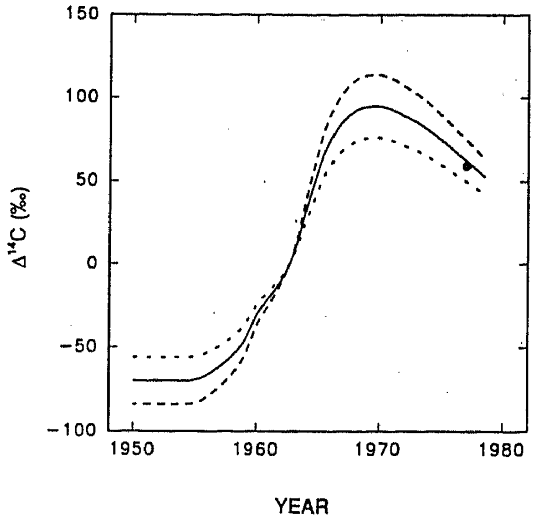

Figure 5. Calculated time variations of radiocarbon activity in the mixed layer of the northern Arabian Sea (GEOSECS Sta 416). See text for explanation. Filled circle is the only data available.

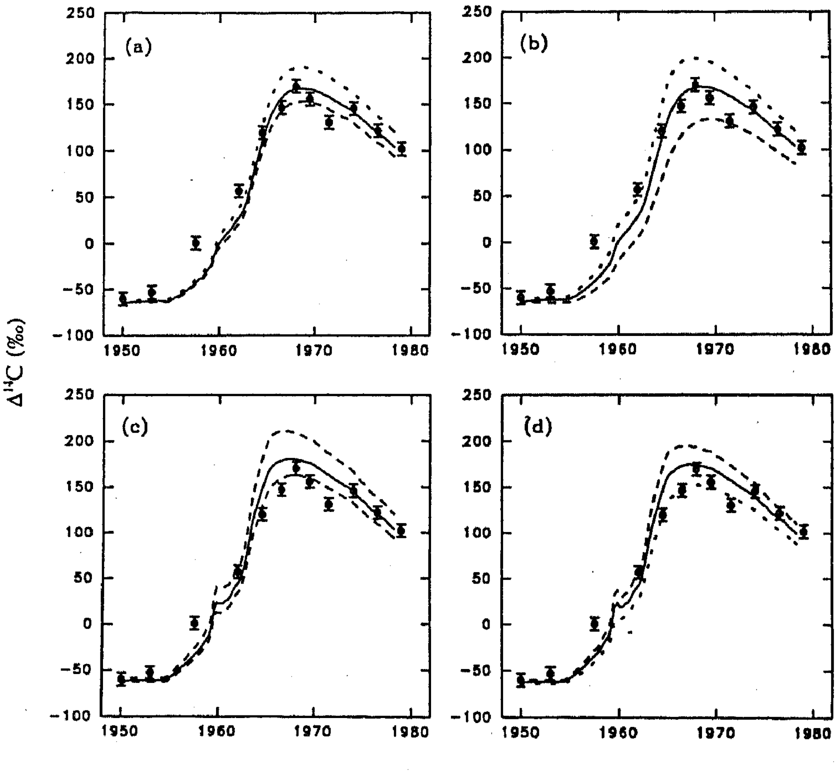

Figure 6. Results of box model calculations. The plots show the simulated radiocarbon time series in the Gulf of Kutch (GKh) for different sets of parameters. (a) constant F_{12} ($= 12\,\text{mol}\,\text{m}^{-2}\,\text{yr}^{-1}$) and varying $w (= 20, 28, 36\,\text{m}\,\text{yr}^{-1})$, (b) constant w ($= 28$) and varying $F_{12} (= 18, 12, 6)$, (c) constant F_{12} ($= 50$) and varying w ($= 70{,}100{,}130$) and (d) constant w ($= 216$) and varying $F_{12} (= 70{,}100{,}130)$. Filled circles represent GKh coral data with $\pm 1\sigma$ errors. Solid lines in each case appears to fit well. Dashed lines represent the model fit with different F_{12} and w values.

averaging effect i.e., the $\Delta\,^{14}C$ plotted for the year 1957.5 is an average for five coral bands 1955–1960. Another possible cause for this discrepancy can be an error in the year assignment for the bands. As we have taken utmost care in sampling and verified the year assignments with the $\delta^{18}O$ data this error is unlikely; however, if at all there is an error it is likely to be ± 1 yr.

Our calculations show that the timing of $\Delta\,^{14}C$ peak in the GKh is controlled more by F_{12}, whereas both F_{12} and w seem to influence the magnitude of the $\Delta\,^{14}C$ peak. A reasonable fit to the coral data can be made using the values of $F_{12} = 12\,\text{mol m}^{-2}\,\text{yr}^{-1}$ and $w = 28\,\text{m yr}^{-1}$ based on the $\Delta\,^{14}C$ time series of the two end members considered. In this case when $F_{12} = 0$ the $\Delta\,^{14}C_G$ approaches $\Delta\,^{14}C_s$ with a time constant of ~ 1 yr and when $w = 0$ the $\Delta\,^{14}C_G$ approaches to that of atmospheric activity with a time constant of about 5 yrs.

Figure 7 shows the simulated $\Delta\,^{14}C$ variations for the gulf. All the curves were plotted with $F_{12} = 12$ and $w = 28$. The input from the Arabian Sea for the solid line was considered with $F_{12} = 11$ and $u = 10{\cdot}5$ (the solid line in figure 5) and those for the dotted lines were plotted considering the inputs from the Arabian Sea which are 20% off the best fit line (dotted lines in figure 5). Filled circles are our coral data.

If the $\Delta\,^{14}C$ values of the Arabian Sea end member contributing radiocarbon to GKh is different from that used in the above model, then the values F_{12} and w for GKh would also differ correspondingly. However, for $< 20\%$ change, there is no significant effect on the coral $\Delta\,^{14}C$ (figure 5). There are no reported results on the circulation and hydrographic properties of the GKh and hence it is difficult at present to constrain our model further to have a unique solution. However it is possible to estimate the exchange rate by some other independent means. One of them is to calculate the exchange rate using the ^{14}C inventory. Broecker *et al* (1985) have calculated the inventory of bomb ^{14}C in station 416 to be $5{\cdot}1 \times 10^9$ atom cm^{-2}. According to Stuiver (1980) the inventory is related to the CO_2 air-sea exchange flux as:

$$Q = 1{\cdot}24 \times 10^{-15} F_{12} \int (\Delta\,^{14}C_A - \Delta\,^{14}C_S - 45)\,dt$$

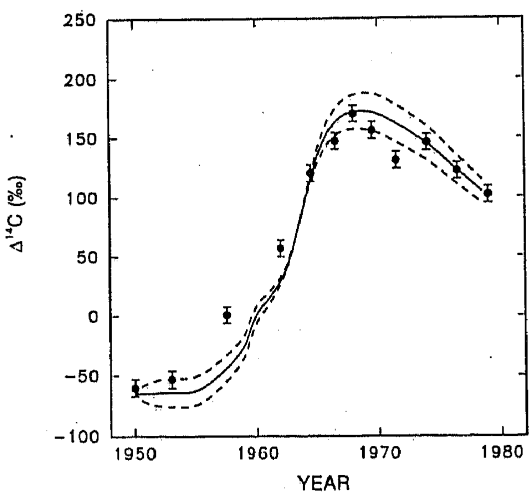

Figure 7. Calculated time variations of the GKh radiocarbon activity considering different inputs from the Arabian Sea. Solid line which appears to fit well was plotted with the Arabian Sea input (solid line in figure 5) and the dotted lines in figure 5 are the corresponding inputs for these two lines.

The value of the integrand between 1953–1977 is ~5500‰yr based on our model derived $\Delta\,^{14}C$ values of the surface Arabian Sea, atmospheric $\Delta\,^{14}C$ values used in this model, and a steady state difference between atmosphere and ocean of about 45‰. This yields a value of $F_{12} = 12\ \mathrm{mol\,m^{-2}\,yr^{-1}}$ for the northern Arabian Sea. This value is similar to that derived for GKh using our model.

Broecker *et al* (1985) have established a relation between the wind speed and the CO_2 invasion flux. Considering a mean annual wind speed in the northern Arabian Sea region as ~6m/s (Esbensen and Kushnir 1981) the CO_2 invasion flux obtained is 13 $\mathrm{mol\,m^{-2}\,yr^{-1}}$. Our calculation is in good agreement with this estimate. The uncertainties in F_{12} and w are ~10%.

5. Conclusions

The air-sea CO_2 exchange rate and the advective transport of water to the Gulf of Kutch were determined by modelling the coral $\Delta\,^{14}C$ time series. The estimated CO_2 exchange rate was found to be 11–12 $\mathrm{mol\,m^{-2}\,yr^{-1}}$ which was in good agreement with that obtained from other evidences. The model results suggest that it is not possible to reproduce the radiocarbon time series in the Gulf of Kutch coral without considering the advective supply of carbon and radiocarbon to the gulf from the Arabian Sea. Further the model also predicts that with the typical CO_2 exchange rate of 8–25 $\mathrm{mol\,m^{-2}\,yr^{-1}}$ the $\Delta\,^{14}C$ in corals would be much higher than commonly observed if not diluted by carbon from other sources. The model derived advective velocity (~28 $\mathrm{m\,yr^{-1}}$) between the gulf and the Arabian Sea is too low compared to the surface current velocity in this region. This could be explained in terms of fluxes of carbon and radiocarbon to the gulf to match the observed coral $\Delta\,^{14}C$ time series.

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