Estimates of upwelling rates in the Arabian Sea and the equatorial Indian Ocean based on bomb radiocarbon

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Abstract

Radiocarbon measurements were made in the water column of the Arabian Sea and the equatorial Indian Ocean during 1994, 1995 and 1997 to assess the temporal variations in bomb 14C distribution and its inventory in the region with respect to GEOSECS measurements made during 1977–1978. Four GEOSECS stations were reoccupied (three in the Arabian Sea and one in the equatorial Indian Ocean) during this study, with all of them showing increased penetration of bomb 14C along with decrease in its surface water activity. The upwelling rates derived by model simulation of bomb 14C depth profile using the calculated exchange rates ranged from 3 to 9 m a⁻¹. The western region of the Arabian Sea experiencing high wind-induced upwelling has higher estimated upwelling rates. However, lower upwelling rates obtained for the stations occupied during this study could be due to reduced 14C gradient compared to that during GEOSECS.

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1. Introduction

Arabian Sea, a part of the Northern Indian Ocean is known for its seasonally reversing summer and winter monsoonal wind patterns and associated upwelling and convective mixing (Wyrtki, 1971; Shetye et al., 1994). These processes contribute to the well-known seasonal oscillation in the biological productivity of these waters (Qasim, 1977, 1982; Lal, 1994; Krishnaswami and Nair, 1996). The upwelling and biological productivity are expected to influence the air–sea exchange of CO2 and its budget in the atmosphere. Detailed measurements of various chemical and biological parameters were made in the Arabian Sea to determine air–sea exchange fluxes of CO2 during the Indian Joint Global Ocean Flux Study (George et al., 1994; Krishnaswami and Nair, 1996; Sarma et al., 1998).

Radiocarbon (14C) is a valuable tracer for studies of ocean circulation and pathways of carbon across various exchangeable carbon reservoirs (Broecker et al., 1985). The atmospheric 14C levels nearly doubled due to the injection of considerable amounts of 14C in the environment by nuclear weapon tests conducted during late 1950s and early 1960s (Nydal and Lövseth, 1983, 1996; Broecker and Peng, 1994). This transient of bomb 14C in the environment during early 1960s provided an opportunity to study circulation in the upper water column of oceans and exchange of CO2 at the air-sea interface processes that take place on decadal time scales (Lassey et al., 1990). The earliest 14C measurements in the water column of the Arabian Sea and Indian Ocean were made during 1977–1978, as part of the GEOSECS expedition (Geochemical Ocean Section Study; Østlund et al., 1980; Stuiver and Ostdlund, 1983).

The equatorial regions are deficient in the bomb radiocarbon content compared to other mid and high latitude oceanic regions. This could be due to lower evasion rates, or due to ventilation of the equatorial zone from the source regions or thinner thermocline. However, none of the hypothesis is able to explain such a large difference in bomb 14C inventory of the equatorial waters. Thus, the only plausible explanation could be ventilation of the surface water by deep cold waters deficient in bomb 14C (Broecker et al., 1978). The Arabian Sea and the equatorial Indian Ocean are regions associated with high wind speed due to seasonally reversing monsoon and climate

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associated wind induced upwelling. The upwelling areas associated with higher productivity are expected to yield higher than average exchange rates. To ascertain the temporal variations in the bomb $^{14}$C distribution in the upper layers of the Arabian Sea and the equatorial Indian Ocean, number of expeditions were made in this region between 1994 and 1999 (Somayajulu et al., 1999; Bhushan et al., 2000, 2003; Dutta, 2001). The present study is aimed to determine the upwelling rates at various locations of the Arabian Sea and at the equatorial Indian Ocean based on temporal variation in bomb $^{14}$C distribution over two decades. Since the Arabian Sea is known to be a region of high upwelling due to seasonal monsoonal winds, an understanding of upwelling rates could provide better insight into the wind driven circulation in its upper layers.

2. Materials and methods

2.1. Seawater sampling

Several depth profiles of $^{14}$C were measured in the Arabian Sea during three expeditions conducted in 1994, 1995 and 1997, onboard FORV Sagar Sampada of Dept. of Ocean Development (DOD), Govt. of India. A total of 10 stations in the Arabian Sea and one in the equatorial Indian Ocean were occupied during this study (Fig. 1). For $^{14}$C analysis, about 10 samples were collected per profile from the selected depths, except in the equatorial Indian Ocean station where 20 depths were sampled. Nearly 120 L of seawater samples was collected from each depth for onboard measurements of nutrients, dissolved inorganic carbon (DIC) and processing for $^{14}$C analysis.

2.2. $^{14}$C measurements

Details of $^{14}$C analysis method in seawater samples followed in this study were described in Bhushan et al. (1994, 2000) and Dutta et al. (2006). Briefly, CO$_2$ was extracted onboard by acidifying ~100 L of seawater in a closed circulation system and trapped in aqueous NaOH solution. In the laboratory, CO$_2$ was liberated from the alkaline solution upon acidification under vacuum and converted to benzene through formation of Li$_2$C,H$_2$ and finally assayed for its $^{14}$C activity using low level Liquid Scintillation Spectrometer. For atmospheric $^{14}$C analysis, CO$_2$ was trapped from the air of marine boundary layer by pumping air through NaOH during the cruises using a greaseless pump and assayed for $^{14}$C as above. The $\delta^{13}$C was measured in an aliquot of CO$_2$ used for benzene synthesis for isotopic fractionation correction of the $^{14}$C results and determination of $\Delta^{14}$C (Stuiver and Polach, 1977). Based on repeat analysis of modern standards, typical precision for $\Delta^{14}$C measurements was $\pm 5\%_{\text{oo}}$.
2.3. Determination of bomb $^{14}$C inventory and air–sea $\text{CO}_2$ exchange rates

Details of exchange rates calculations were described in Bhushan et al. (2000), and revised in this study based on the methods outlined in Dutta (2001) as described below. The $^{14}$C concentration in the upper 1000 m of the ocean is a mixture of natural and bomb components. Its measurements in the water column represents sum of the $^{14}$C contributions from these two sources and to delineate the bomb $^{14}$C component, it is necessary to have precise estimates of pre-bomb $^{14}$C activity (i.e., natural $^{14}$C) in these waters. This requirement, however, is not fulfilled in several areas of the ocean including the Arabian Sea and the Bay of Bengal as no measurements of $^{14}$C were made in these areas during early 1950s. Therefore, indirect approaches based on the distribution of their proxies are used to derive the pre-bomb $^{14}$C profile in the upper ocean. Broecker et al. (1995) observed correlation between silica and the natural $^{14}$C in deep waters (below 1000 m) which are devoid of any bomb $^{14}$C, and established an empirical relation for reconstruction of natural or pre-bomb $^{14}$C ($^{14}$C*) as $^{14}$C* = $^{14}$C - $^{14}$C$_{\text{SiO}_2}$, where $^{14}$C$_{\text{SiO}_2}$ is the concentration of silica. The surface seawater $^{14}$C was constrained by $^{14}$C measurements in pre-bomb surface marine carbonate samples. No silica measurements were made during the present study. Therefore to calculate the bomb $^{14}$C component, pre-bomb curves derived from the GEOSECS silica data have been used for the reoccupied GEOSECS stations. The bomb $^{14}$C ($^{14}$C*) profiles were obtained by subtracting $^{14}$C$_{\text{SiO}_2}$ from the measured $^{14}$C profiles, with uncertainty of $\pm 10\%$. The surface ocean $^{14}$C values were based on Dutta et al. (2001). For the stations occupied during this study which are not reoccupation of earlier GEOSECS stations, a conservative approach of latitudinal dependency of pre-bomb curve is used. Inventories of bomb $^{14}$C were determined from the depth integrated values of $^{14}$C* and the mean $^{14}$C$_{\text{SiO}_2}$ till the depth of penetration of bomb $^{14}$C. The estimated uncertainty of bomb $^{14}$C inventory obtained by this method is about $\pm 10\%$ (Peng et al., 1998).

Based on the bomb $^{14}$C inventories, the air–sea $\text{CO}_2$ exchange rates ($E$) were calculated using the model of Suurva (1980). The exchange rates are calculated assuming that the observed inventory of bomb $^{14}$C is only due to the integrated gradient of $^{14}$C between the atmosphere and oceanic mixed layer, with no lateral transport of $^{14}$C. The values of the integrals for $^{14}$C$_{\text{atm}}$ and $^{14}$C$_{\text{mix}}$ were obtained from $^{14}$C measurements in the atmosphere and in corals (Chakraborty et al., 1994). The input function of atmospheric $^{14}$C used here was based on a model curve, constrained by atmospheric $^{14}$C measurements at Israel, Ethiopia and Madagascar between 1963 and 1978 (Nydal and Lövseth, 1983, 1996), tree-ring $^{14}$C measurements at Thane, India, near the Arabian Sea coast (Chakraborty et al., 1994), and atmospheric $^{14}$C measurements over the Northern Indian Ocean between 1993 and 1997 (Bhushan et al., 1997; Dutta et al., 2006). The model atmospheric $^{14}$C curve rose from $0\%$ in 1954, peaking at $730\%$ in 1964, and dropped to $570\%$ in 1968. From 1968 onward, an exponentially decreasing atmospheric $^{14}$C trend with e-folding time of 17 yr is adopted, fixing the $^{14}$C for the years 1980 and 1999 at $265\%$ and $88\%$, respectively. The model atmospheric $^{14}$C function is shown in Fig. 2, where it is compared with the atmospheric $^{14}$C compilations by Hua and Barbetti (2004) for the latitudes of the Arabian Sea and north of equatorial Indian Ocean (“Northern Hemisphere Zone 3”). The integrated values of atmospheric $^{14}$C between 1994 and 1997 of these two curves differ by about 1%, which is not significant as compared to other uncertainties.

![Fig. 3. $^{14}$C distribution in the upper 1000 m of station SS#152-3846, reoccupation of GEOSECS #448.](image-url)
The overall uncertainty for air–sea CO₂ exchange rates from bomb ¹⁴C profiles is about ±15%.

2.4. Determination of upwelling rates using 1-D model

In this study, upwelling rates are calculated based on the CO₂ exchange rates using one dimensional (1-D) box diffusion model (Oeschger et al., 1975; Broecker et al., 1978). For this model calculation, the upper 1000 m of the water column is subdivided into 40 boxes, each with 25-m thicknesses with the assumption that ¹⁴C concentration within each of these boxes is homogeneous and that the top 100 m is well mixed. The model simulates the bomb ¹⁴C depth profile with the defined CO₂ exchange rate (E), upwelling rate (w) and the vertical eddy diffusivity (K) for a given input function of bomb ¹⁴C from atmosphere to the ocean surface layer. The same atmospheric ¹⁴C input function was used as described in the previous section. The vertical eddy diffusivity (K) and the upwelling rate (w) were varied to generate ¹⁴C depth profiles and the values that provided the best fit to the observed bomb ¹⁴C profile were chosen as the mixing parameters for the station. The fitted values of K range from 0.4 to 0.7 cm² s⁻¹. In our calculation, we have used the CO₂ exchange rates (E) calculated earlier from bomb ¹⁴C inventories for each station. However, for some stations, we also needed to invoke different E to obtain best fit to observed bomb ¹⁴C profiles.

3. Results and discussion

3.1. Bomb ¹⁴C inventory and air–sea CO₂ exchange rates

The bomb ¹⁴C inventory in the Arabian Sea estimated during this study ranged from 3 to 8 × 10⁹ atoms cm⁻² (Table 1). A relatively higher bomb ¹⁴C inventory of 8.0 × 10⁹ atoms cm⁻² was obtained at SS#132-3273 and at the equatorial Indian Ocean station SS#152-3846, where the inventory was 9.5 × 10⁹ atoms cm⁻². Lower inventories at other locations in the Northern Indian Ocean could result either because of weak diffusive gas exchange leading to low ¹⁴C input or processes favoring vertical penetration (e.g., wind speed) were not vigorous. It is known that on an average the wind speed over the Arabian Sea is ≈ 5 m s⁻¹ (Esbensen and Kushnir, 1981), which is less than the global average value. Additionally, the Northern Arabian Sea has various high salinity water masses within the top 1000 m, which could result in stratification of...
the water column leading to shallower penetration of bomb 14C and thereby low bomb 14C inventory in the region. The increase in bomb 14C inventories at the Arabian Sea stations during the period between GEOSECS and the present study is consistent with the model predictions of Toggweiler et al. (1989a). The increases in inventory are ≤30% relative to GEOSECS, which are expected considering the significantly low δ13C values of the atmosphere since GEOSECS (Table 1). The station SS#152-3846, reoccupation of the GEOSECS #448 at equatorial Indian Ocean, shows an increase in bomb 14C inventory of ~95% (Fig. 3), which could be a result of lateral transport of 14C enriched waters. Bard et al. (1988, 1989) observed ~10–90% increase in the bomb 14C inventory after about a decade of GEOSECS at some of the stations near equatorial northwestern Indian Ocean. They attributed this increase to the advection of low salinity waters enriched in 14C from the Indonesian Archipelago along the equator to the 10°S latitudinal belt. The CO2 exchange rates for the Arabian Sea and equatorial Indian Ocean are in the range of 7.5–20.4 mol m⁻² a⁻¹ and are within ±30% of the rates derived for the GEOSECS data (Table 1). Also, the gas exchange rates computed using wind speeds (Wanninkhof et al., 1985; Wanninkhof, 1992) were similar to our values. Toggweiler et al. (1989b) computed CO2 gas exchange rates for various oceanic regions based on a wind speed dependent model, wherein the exchange rates for the Arabian Sea computed as 10–15 mol m⁻² a⁻¹, with highest values near the Somali Basin, a region known for highest wind speeds and exceptionally strong wind-induced upwelling. The exchange rates derived in this study from temporal variation of bomb 14C inventory (Table 1) are in good agreement with the model predicted values (Toggweiler et al., 1989b). In the Arabian Sea, the highest exchange rate of 17.1 mol m⁻² a⁻¹ was obtained for the station SS#123-3273, which is close to the Somali Basin. The highest exchange rate obtained for SS#152-3846 could be due to the lateral inputs of 14C enriched waters (Table 1).

3.2. Upwelling rates

The upwelling rates determined for the Arabian Sea and equatorial Indian Ocean stations occupied during this study ranged from 3 to 9 m a⁻¹ (Table 1). In general, it was noticed that the upwelling rates calculated for the stations occupied during this study are low compared to the GEOSECS stations. However, GEOSECS station #448 and its reoccupation station SS#152-3846 show similar upwelling rates (5 m y⁻¹), with use of higher exchange rate for station SS#152-3846 (Fig. 4). As expected, the western region of the Arabian Sea known for high wind-induced upwelling shows higher upwelling rates. During GEOSECS studies, there were more sampling points in the top 1000 m than this study, thereby constraining the upwelling to give a better fit. Thus, the upwelling rates derived for the present study show lower values than expected for the region. These upwelling rates may be underestimates since this model does not take into consideration the horizontal advection of 14C along the adjoining isopycnal surfaces.

The upwelling rate calculation is dependent on the gradient of bomb 14C in the water column. This gradient is controlled by the atmospheric 14C concentration, its penetration due to vertical mixing, the air–sea exchange rate and upwelling. During the period of this study, atmospheric 14C concentration has almost stabilized since about a decade leading to the reduced gradient of 14C, possible reason for lower estimates of upwelling.

4. Conclusions

The 14C measurements carried out in the Arabian Sea and the equatorial Indian Ocean provide a means to assess temporal variation of 14C distribution since GEOSECS. The surface seawater activity of 14C has decreased since GEOSECS, but the mean penetration depth of bomb 14C has increased since then. The bomb 14C inventory shows only a marginal increase or no significant change between 1978 and 1994, consistent with model predictions. The upwelling rates of 3–9 m a⁻¹ obtained for various stations in the Northern Indian Ocean could be another parameter controlling the exchange of CO2 in this region. The upwelling calculated for the GEOSECS stations is generally higher than those calculated for the stations occupied during this study. The estimated upwelling rates in the Arabian Sea are higher for areas experiencing high wind-induced upwelling. The reduced 14C gradients during this period of study compared to that during GEOSECS could be responsible for the differences observed in calculated upwelling rates.

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References


