Daily variability of dissolved inorganic radiocarbon at three sites in the surface ocean

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Abstract

We report radiocarbon measurements of dissolved inorganic carbon (DIC) in surface water samples collected daily during cruises to the central North Pacific, the Sargasso Sea and the Southern Ocean. The ranges of Δ14C measurements for each cruise (11–30‰) were larger than the total uncertainty (7.8‰, 2-sigma) of the measurements. The variability is attributed to changes in the upper water mass that took place at each site over a two to four week period. These results indicate that variability of surface Δ14C values is larger than the analytical precision, because of patchiness that exists in the DIC Δ14C signature of the surface ocean. This additional variability can affect estimates of geochemical parameters such as the air–sea CO2 exchange rate using radiocarbon.

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1. Introduction

Bomb radiocarbon (14C) was produced in the late 1950s and early 1960s by thermonuclear weapons testing in the stratosphere and caused 14Cl e v e n si nt r o p o s p e r i s C O2 to nearly double by 1964 (Nydal and Lovseth, 1983). After 1965, levels of 14C in the atmosphere have decreased because of gas exchange with CO2 in the surface ocean and incorporation into the terrestrial biosphere. Maximum Δ14C values measured in surface water dissolved inorganic carbon (DIC) were attained in the 1970s, indicating that the turnover time of CO2 in the atmosphere with respect to transfer to the surface ocean is ∼10 years (Druffel and Suess, 1983). Measurements of Δ14C in water column profiles made since 1970 have been used to calculate the inventory of bomb 14C in various oceanic regions (Broecker and Peng, 1994; Duffy and Caldeira, 1995). The timescale of modification of 14C is of the order of years, much longer than that for temperature, which is quasi-conservative over a few weeks. This means that 14C will “remember” a mixing event from a storm, entraining colder, usually lower 14C water for a longer time than will SST.

Daily measurements of surface DIC Δ14C were reported previously for sites in the North central Pacific (NCP) (Druffel et al., 1989) and the Sargasso Sea (SS) (McDuffee and Druffel, 2007). The Δ14C results from the NCP in November 1985 showed more variability after a 4-day storm, but accompanying chemical and physical data were not sufficient to determine the cause of the Δ14C variability. Daily measurements of chemical and physical parameters at the SS site indicated a change in water mass that was coincident with an increase in variability of Δ14C values (McDuffee and Druffel, 2007) half way through the cruise.

We report daily surface DIC Δ14C values obtained for cruises to the NCP and SS sites, and a site in the Southern Ocean. We wanted to determine if the variability of surface Δ14C values was greater than the total uncertainty of the measurements, because of changes in the water mass that occurred during the course of each cruise. Our results highlight the fact that the surface ocean Δ14C signature varies by a larger amount than previously indicated by uncertainties assigned to the individual values (3–4‰). This is relevant because surface radiocarbon values are used to calculate such quantities as air–sea CO2 exchange rate and bomb 14C inventory in the ocean, and additional error in the radiocarbon can impart larger error into these biogeochemical parameters.

2. Methods

Surface water samples were collected from a single site in the North central Pacific (NCP, 31 °N, 159 °W, bottom depth 5220 m) during three
Table 1

| Site    | Cruise | Date       | Days on station | Average Δ14C ± Range Δ14C values | Aver Δ13C ± Range Δ13C values | Average Alk ± Aver [DIC] ± Aver SST ± Aver Salinity ± |
|---------|--------|------------|-----------------|--------------------------------|-------------------------------|------------------------------------------------------|
| NCP     | Alcyone| Nov-85     | 25              | 147.1 ± 6.0   | 17.4 ± 7.4         | 2330 ± 22                       | 2003 ± 4    | 24.7 ± 1.0       | 36.60 ± 0.05       |
| NCP     | Eve    | Jun-87     | 28              | 134.4 ± 7.4   | 24.3 ± 8.4         | 2317 ± 15                       | 2030 ± 5    | 21.6 ± 1.8       | 35.11 ± 0.22       |
| NCP     | Avon   | Jun-99     | 17              | 88.7 ± 6.9    | 29.9 ± 7.8         | 2387 ± 17                       | 2043 ± 6    | 23.8 ± 0.4       | 36.60 ± 0.05       |
| SS      | Hydros | Jun-89     | 25              | 121.8 ± 4.4   | 11.1 ± 12.1        | 2387 ± 17                       | 2078 ± 2    | 24.7 ± 1.0       | 36.60 ± 0.05       |
| SS      | SarC   | Jun-00     | 14              | 80.6 ± 6.4    | 24.2 ± 7.8         | 2291 ± 7                        | 2091 ± 8    | 8.5 ± 0.5        | 34.32 ± 0.09       |
| S. Ocean| Soce   | Dec-95     | 18              | 19.8 ± 7.3    | 25.5 ± 8.5         | 80.6 ± 6.4                      | 24.2 ± 7.8  | 36.60 ± 0.05     |

Fig. 1. Time series of a) Δ14C and b) δ13C measurements of surface water DIC taken during three cruises to the North central Pacific (NCP) (October–November 1985; June 1987; June 1999) and a cruise to the Southern Ocean (December 1995).
variable from days 7–17 (86±5‰, n=12) (Fig. 1a). The δ13C values from days 1–6 averaged 0.96±0.11‰, and were lower and more variable thereafter (0.69±0.32‰) (Fig. 1b). Data from CTD casts made during this cruise showed a shift toward higher surface salinity values between days 8 and 11 (data not shown), which is consistent with a change in Δ14C and δ13C values during this time. Values of [DIC] were constant throughout the cruise and averaged 2043±6 µmol/kg. Alkalinity and salinity measurements are not available.

Previously reported Δ14C measurements from a November 1985 cruise (Alcyone, 25 days on station) to the NCP site (Druffel et al., 1989) averaged 147 ±6‰ (n=12) (Fig. 1a). Values appeared more scattered after day 13, though this trend was not statistically significant. Salinity, alkalinity and SST values were higher during the first half of the cruise (averaging 35.44±0.02‰, 2355±27 µeq/kg, 24.6±0.4 °C) than during the second half (35.31±0.04‰, 2319±8 µeq/kg, 23.4±0.4 °C) (Fig. 2a,b,c). A storm and high winds (~50 kts) occurred during days 10–13 of the cruise, and likely caused increased mixing in the surface water mass (Druffel et al., 1989). Values of [DIC] were constant throughout the cruise and averaged 2003±4 µmol/kg.

3.2. Sargasso Sea

At the Sargasso Sea site in June 1989 (Hydros, 25 days on station), Δ14C measurements averaged 122.4±3‰ (n=7) (Fig. 1a) and were slightly lower during the first part of the cruise (days 1–14, 119±3‰ n=4) than during the second part (days 20–25, 125±3‰ n=3). There were no δ13C analyses of these water samples. Alkalinity, salinity and SST measurements were less variable before day 8 (2399±5 µeq/kg, 36.56±0.01‰, 23.5±0.2 °C) than afterward (2381±19 µeq/kg, 36.61±0.06‰, 25.3±0.6 °C) (Fig. 2a,b and c). There was a general warming trend with time. During the first 7 days of the cruise, the surface waters were more homogenous (i.e., low temperature, constant salinity) than afterward (data not shown). Values of [DIC] were constant and averaged 2078±2 µmol/kg.

McDuffee and Druffel (2007) report Δ14C measurements for the SS site, in June 2000 (SarC, 14 days on station) that averaged 81±8‰ (n=10). Values were high from days 1–8 (87±4‰, n=4) and lower and more variable thereafter (76±8‰, n=6) (Fig. 1a). Similar to the Δ14C values, the δ13C values were more variable during the second half of the cruise (1.05±0.08‰) than during the first 8 days (1.01±0.02‰) (Fig. 1b). The [DIC] measurements averaged 2085±9 µmol/kg (days 1–15) until the last day when an increase of 45 µmol/kg was noted. SST values increased 3 °C over the course of the cruise. Temperature–salinity data from five CTD casts (on days 2, 7, 11, 14 and 16) in the upper 250 m revealed large shifts in salinity between 2 and 25 m depth on days 7, 11 and 16. Temperature values below ~20 m were 2–3 °C warmer after day 7 (McDuffee and Druffel, 2007).

3.3. Southern Ocean

At the Southern Ocean site in December 1995 (SOce, 18 days on station), surface Δ14C results averaged 19±8 (n=17) (Fig. 1a), and values were lowest during days 2–4 (range 5–8‰). The δ13C values averaged 1.8±0.2‰ (n=17) and values were slightly more variable during days 8–11 (1.6±0.3‰) (Fig. 1b). SST values were lower during days 3–6 (7.7±0.6 °C) than afterward (8.7±0.3 °C) (Fig. 2c). Salinity values were variable (34±32µ±0.09‰) during the period for which data was available (days 1–12) (Fig. 2b). The [DIC] and alkalinity values averaged 2091±8 µmol/kg and 2291±7 µeq/kg, respectively, throughout the cruise (Fig. 2a). Data from five CTD casts revealed overall higher salinity values between 30 and 200 m depth on days 1 and 18 of the cruise than on days 3, 10 and 15.

3.4. Implications for surface ocean variability in DIC Δ14C and δ13C

Variability of the six Δ14C time series, as measured by the standard deviation of the averages, ranged from ±4.4‰ (SS 1989) to ±8.4‰ (SS 2000) (Table 1). The range of Δ14C values observed for the cruises was a minimum of 11.1‰ (SS 1989) and a maximum of 29.9‰ (NCP 1999) (Table 1). We note that the two cruises with the largest ranges of Δ14C values, NCP 1999 and S. Ocean 1995 (25.5‰), also had the largest ranges of δ13C values (1.2% and 0.75‰, respectively).

These results illustrate that, during all six cruises, repeated sampling at the same geographic location over the course of 2–4 weeks revealed surface Δ14C values that varied by more than the
total uncertainty of the measurement (7.8%–2-sigma). Changes in the upper water mass were observed during most of these cruises, as determined by temperature–salinity relationships in the CTD data sets. The source(s) of the variability in the isotopic measurements are likely changes in vertical mixing and/or spatial heterogeneity. Fig. 3 displays $\Delta^{13}C$ measurements in samples collected from the upper ocean (0–300 m) during each of the six cruises (Druffel and Bauer, 2000; Druffel et al., 1992) plotted versus density ($\sigma_t$). The average and standard deviation of all surface values for each cruise are plotted as symbols with error bars, whereas $\Delta^{13}C$ values for subsurface samples (10–250 m depth) are plotted as symbols with no error bars. Data from the earlier NCP cruises in 1985 (filled triangles) and 1987 (filled circles) show a larger gradient of $\Delta^{13}C$ values with depth than that from the 1999 cruise (filled squares), in large part because atmospheric $\Delta^{14}C$ values in the 1980s (160–270‰) were higher than in the 1990s (95–150‰). Surface ocean $\Delta^{14}C$ values were lower in 1999 (NCP) and 2000 (SS) (Fig. 3a, b), because more bomb $^{14}C$ had penetrated deeper into the main thermocline, and were replaced by $^{14}C$-poor waters from below, causing a smaller gradient of $\Delta^{14}C$ values with depth.

It seems likely that the variability of surface $\Delta^{14}C$ is the result of sampling of different water masses that are floating by a single geographic location. Most of the subsurface $\Delta^{14}C$ values are slightly lower than their average surface value. The least squares fit through each data set (lines in Fig. 3a,b) suggests an inverse relationship between $\Delta^{14}C$ and $\sigma_t$ for most of the cruises. This inverse relationship suggests that $\Delta^{14}C$ values are higher in surface waters that have limited contact with subsurface water, e.g., areas of little or no upwelling. The exception is the Southern Ocean where mixing with subsurface waters is prevalent. This is illustrative of the concept that mixing in the ocean occurs predominantly along surfaces of constant density. Discreet water sampling provides a snapshot of DIC $\Delta^{13}C$ values at a single point in time. This is in contrast to geochemical proxies, such as shells, corals, forams and varved sediments that integrate $\Delta^{14}C$ values over an extended period of time (weeks to years) depending on the sampling resolution. Most of the DIC $\Delta^{14}C$ data available for the world ocean has been obtained from discreet water samples, e.g., Geosecs, WOCE, TTO. The reported uncertainty for DIC $\Delta^{14}C$ values is based on repeated analyses of the same water sample and generally ranges from ±3–4‰ (Key, 1996; Key, 1997; McNichol et al., 1994; Ostlund and Stuiver, 1980; Stoiber and Ostlund, 1980). Our study shows that for surface samples, the total uncertainty of a DIC $\Delta^{14}C$ value at a given site over a several week period is approximately two times the reported uncertainty (~7‰).

Therefore, depending on the application, users of post-bomb $\Delta^{14}C$ data should consider this short-term variability of surface ocean $\Delta^{14}C$ values and factor this into their analysis. For example, assessment of the bomb $^{14}C$ inventory in the water column requires numerous $\Delta^{14}C$ measurements from a given depth profile (Broecker et al., 1995). Calculation of the bomb $^{14}C$ inventory at our NCP site in 1999 reveals a value of $1.8 \times 10^{14}$ atoms/m$^2$ with an error (based only on the $\Delta^{14}C$ measurement error of ±3.5‰) of ±2.2‰. Using a larger error for $\Delta^{14}C$ values of ±7‰, our uncertainty for the bomb $^{14}C$ inventory increases to ±5‰, which still is not large. Another example is how variability of surface ocean $\Delta^{14}C$ values affect estimates of air–sea CO$_2$ exchange rate. Using a multi-box isopycnal mixing model to calculate the steady state, pre-bomb $\Delta^{14}C$ value (~43.5‰) in the surface waters of the Sargasso Sea (Druffel, 1997), the average air–sea CO$_2$ exchange rate is 18.9 moles/m$^2$/y. To obtain a pre-bomb value one-sigma lower than this (~47%), an air–sea CO$_2$ exchange rate of 9.9 moles/m$^2$/y is needed, and to obtain a value one-sigma higher (~40.0‰) requires an average air–sea CO$_2$ exchange rate of 28.6 moles/m$^2$/y. Doubling the error for pre-bomb $\Delta^{14}C$ values (±7‰) expands the range of air–sea CO$_2$ exchange rate values obtained to 2.3 to 40.4 moles/m$^2$/y. We need to caveat that this example is for a pre-bomb ocean, based on uncertainties from post-bomb surface water masses, though pre-bomb variability is likely to be equally important at locations where different water masses mix — e.g., tropical Pacific and subpolar/temperate boundaries.

Monthly surface $\Delta^{14}C$ values from post-bomb corals displayed a seasonal amplitude that ranged from 30–80‰ in the eastern equatorial Pacific (Guilderson and Schrag, 1998) to 10–20‰ in the subtropical Atlantic and Pacific (Druffel, 1987; Druffel, 1989; Guilderson et al., 2000). Thus, the ranges of daily $\Delta^{14}C$ values (11–30‰) that we measured at our three sites in the NCP, SS and SOce

![Fig. 3. $\Delta^{13}C$ values in upper water samples (0–300 m depth) collected during a) four cruises to the Pacific, and b) two cruises to the Atlantic, plotted versus water density ($\sigma_t$). The average and standard deviation of all surface values for each cruise are shown with error bars and $\Delta^{13}C$ values for subsurface samples (10–250 m depth) are plotted as symbols with no error bars. Data from the earlier NCP cruises in 1985 (filled triangles) and 1987 (filled circles) show a larger gradient of $\Delta^{13}C$ values with depth than that from the 1999 cruise (filled squares), in large part because atmospheric $\Delta^{14}C$ values in the 1980s (160–270‰) were higher than in the 1990s (95–150‰). Surface ocean $\Delta^{14}C$ values were lower in 1999 (NCP) and 2000 (SS) (Fig. 3a, b), because more bomb $^{14}C$ had penetrated deeper into the main thermocline, and were replaced by $^{14}C$-poor waters from below, causing a smaller gradient of $\Delta^{14}C$ values with depth. It seems likely that the variability of surface $\Delta^{14}C$ is the result of sampling of different water masses that are floating by a single geographic location. Most of the subsurface $\Delta^{14}C$ values are slightly lower than their average surface value. The least squares fit through each data set (lines in Fig. 3a,b) suggests an inverse relationship between $\Delta^{14}C$ and $\sigma_t$ for most of the cruises. This inverse relationship suggests that $\Delta^{14}C$ values are higher in surface waters that have limited contact with subsurface water, e.g., areas of little or no upwelling. The exception is the Southern Ocean where mixing with subsurface waters is prevalent. This is illustrative of the concept that mixing in the ocean occurs predominantly along surfaces of constant density. Discreet water sampling provides a snapshot of DIC $\Delta^{13}C$ values at a single point in time. This is in contrast to geochemical proxies, such as shells, corals, forams and varved sediments that integrate $\Delta^{14}C$ values over an extended period of time (weeks to years) depending on the sampling resolution. Most of the DIC $\Delta^{14}C$ data available for the world ocean has been obtained from discreet water samples, e.g., Geosecs, WOCE, TTO. The reported uncertainty for DIC $\Delta^{14}C$ values is based on repeated analyses of the same water sample and generally ranges from ±3–4‰ (Key, 1996; Key, 1997; McNichol et al., 1994; Ostlund and Stuiver, 1980; Stoiber and Ostlund, 1980). Our study shows that for surface samples, the total uncertainty of a DIC $\Delta^{14}C$ value at a given site over a several week period is approximately two times the reported uncertainty (~7‰). Therefore, depending on the application, users of post-bomb $\Delta^{14}C$ data should consider this short-term variability of surface ocean $\Delta^{14}C$ values and factor this into their analysis. For example, assessment of the bomb $^{14}C$ inventory in the water column requires numerous $\Delta^{14}C$ measurements from a given depth profile (Broecker et al., 1995). Calculation of the bomb $^{14}C$ inventory at our NCP site in 1999 reveals a value of $1.8 \times 10^{14}$ atoms/m$^2$ with an error (based only on the $\Delta^{14}C$ measurement error of ±3.5‰) of ±2.2‰. Using a larger error for $\Delta^{14}C$ values of ±7‰, our uncertainty for the bomb $^{14}C$ inventory increases to ±5‰, which still is not large. Another example is how variability of surface ocean $\Delta^{14}C$ values affect estimates of air–sea CO$_2$ exchange rate. Using a multi-box isopycnal mixing model to calculate the steady state, pre-bomb $\Delta^{14}C$ value (~43.5‰) in the surface waters of the Sargasso Sea (Druffel, 1997), the average air–sea CO$_2$ exchange rate is 18.9 moles/m$^2$/y. To obtain a pre-bomb value one-sigma lower than this (~47‰), an air–sea CO$_2$ exchange rate of 9.9 moles/m$^2$/y is needed, and to obtain a value one-sigma higher (~40.0‰) requires an average air–sea CO$_2$ exchange rate of 28.6 moles/m$^2$/y. Doubling the error for pre-bomb $\Delta^{14}C$ values (±7‰) expands the range of air–sea CO$_2$ exchange rate values obtained to 2.3 to 40.4 moles/m$^2$/y. We need to caveat that this example is for a pre-bomb ocean, based on uncertainties from post-bomb surface water masses, though pre-bomb variability is likely to be equally important at locations where different water masses mix — e.g., tropical Pacific and subpolar/temperate boundaries. Monthly surface $\Delta^{14}C$ values from post-bomb corals displayed a seasonal amplitude that ranged from 30–80‰ in the eastern equatorial Pacific (Guilderson and Schrag, 1998) to 10–20‰ in the subtropical Atlantic and Pacific (Druffel, 1987; Druffel, 1989; Guilderson et al., 2000). Thus, the ranges of daily $\Delta^{14}C$ values (11–30‰) that we measured at our three sites in the NCP, SS and SOce.
are comparable to the range of Δ^{14}C values observed seasonally at selected sites.

In summary, our results show that a single measurement of DIC Δ^{14}C in surface seawater has a larger uncertainty than that accounted for by measurement error alone. The true range of Δ^{14}C values that occur over a several day-to-several week period is approximately double the measurement precision. This is due to patchiness that exists in the DIC Δ^{14}C signature of the surface ocean, and the movement of surface water masses relative to geographic location.

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