

TRANSECT ALONG 24°N LATITUDE OF ^{14}C IN DISSOLVED INORGANIC CARBON IN THE SUBTROPICAL NORTH ATLANTIC OCEAN

JEFFREY P. SEVERINGHAUS,^{1,2} WALLACE S. BROECKER,¹ TSUNG-HUNG PENG³ and GEORGES BONANI⁴

ABSTRACT. The distribution of bomb-produced ^{14}C in the ocean provides a powerful constraint for circulation models of upper ocean mixing. We report ^{14}C measurements from an east-west section of the main thermocline at 24°N latitude in the subtropical North Atlantic Ocean in summer 1992, and one profile from the Gulf of Mexico in 1993. Observed gradients reflect the transient invasion of bomb ^{14}C into the thermocline *via* mixing along isopycnals from the poleward outcrop, with progressively more sluggish mixing at greater depths. A slight deepening of the profile is observed over the 20-yr period since the GEOSECS survey at one location where the comparison is possible.

INTRODUCTION

The distribution in the ocean of ^{14}C produced by atmospheric nuclear weapons testing in the 1950s and early 1960s contains useful information about ocean mixing processes (Broecker *et al.* 1985). The penetration of bomb ^{14}C into ever deeper layers of the ocean constitutes a large-scale unintentional transient tracer experiment. According to the widely accepted oceanographic paradigm, the primary mode of entry into the ocean of bomb ^{14}C is mixing along surfaces of constant density (isopycnals) from the point at which these isopycnals intersect the surface wind-mixed layer in cold northern waters, known as the outcrop. Thus, mixing is primarily a horizontal phenomenon rather than a vertical one, and may involve travel of thousands of kilometers. As of 1992, some 30 yr after the peak of atmospheric bomb testing, little bomb ^{14}C had penetrated to the bottom of the main thermocline (that part of the ocean separating warm, less dense, seasonally ventilated shallower waters from cold, denser deepwater). Thus, this particular tracer is well suited at present to studies of mixing in the thermocline.

Our interest in the main thermocline stems from its being the region of the ocean in which most of the anthropogenic CO_2 taken up by the ocean is stored. As the mixed layer is nearly in equilibrium with atmospheric CO_2 , air-sea exchange is relatively unimportant for the rate of ocean uptake of CO_2 . Instead, it is the mixing of shallower and deeper reservoirs within the ocean that limits the rate of uptake (Siegenthaler and Sarmiento 1993), namely the mixing of surface waters along isopycnals with thermocline waters. When physically accurate general circulation models of the thermocline are capable of reproducing the observed ^{14}C distribution, given the known atmospheric ^{14}C boundary condition, the same model's estimates of oceanic uptake of CO_2 can be regarded with confidence. Taken together with other tracers that differ in the boundary condition, such as ^{85}Kr and the chlorofluorocarbons (which have air-mixed layer equilibration times of ~1 month versus ~10 yr for ^{14}C), ^{14}C provides a powerful verification tool for the physical transport in these models.

As an oceanographic contribution to the quincentennial celebration of Columbus's voyage of discovery in 1492, the Spanish naval vessel *Hesperides* made a transatlantic hydrographic and tracer section along Columbus's route at 24°N in July–August 1992 (Parilla *et al.* 1994). We took advantage of this ship of opportunity to take water samples for ^{14}C analysis. Eight density surfaces were

¹Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964 USA

²Present address: Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island 02882 USA

³Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida 33149 USA

⁴ETH/AMS Facility, Institut für Teilchenphysik, Eidgenössische Technische Hochschule Hönggerberg, CH-8093 Zürich, Switzerland

sampled from the main thermocline to depths of ~850 m at nine stations with a regular spacing of ~500 km across the entire Atlantic Ocean. We present results here with no accompanying modeling attempt. It is our hope that modelers will use our results to improve and verify their own models.

METHODS

Samples were drawn from Niskin bottles that were tripped at target density surfaces, and the water was stored in 0.5-liter glass bottles with greased ground glass stopcocks. Samples were poisoned with HgCl_2 to prevent respiratory addition to the dissolved inorganic carbon (DIC) pool. In the laboratory, samples were acidified under vacuum and the CO_2 was collected over liquid N_2 . Samples were graphitized and analyzed by accelerator mass spectrometry (AMS) at the AMS facility in Zürich, Switzerland. Results are reported in the ^{13}C -corrected $\Delta^{14}\text{C}$ in units of per mil (‰), as is customary (Stuiver and Polach 1977). Uncertainty (1σ) is estimated at $\pm 5\text{‰}$.

RESULTS

^{14}C depth profiles from analyses of waters above 1100 m are presented in Figure 1, and all analytical results are given in the Appendix along with density and depth. The first-order feature of the profiles in Figure 1 is the sharp gradient from high, post-bomb values in the upper 200 m to nearly pre-bomb values at 850 m depth. In keeping with the standard oceanographic paradigm, this gradient arises because mixing is less energetic on deeper isopycnals, since wind stress at the surface is the primary energy source for the mesoscale eddies that drive the bulk of the mixing (e.g., Ledwell, Watson and

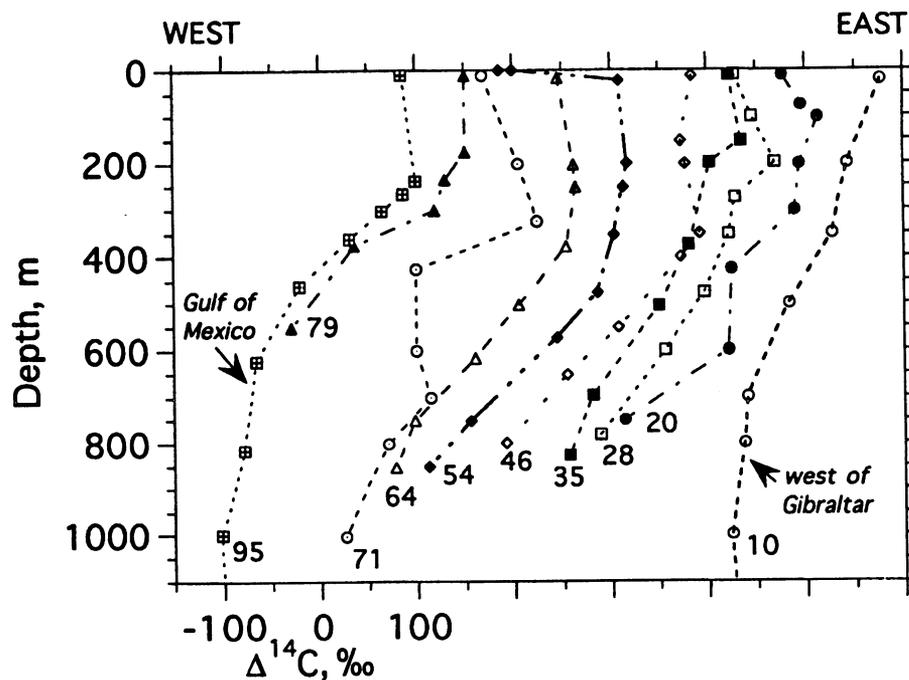


Fig. 1. $\Delta^{14}\text{C}$ along 24°N , Atlantic Ocean. Results of all analyses (except four that were deeper than 1100 m) are arranged by longitude. For clarity, all data sets have been separated by 50‰ , such that each tick mark on the horizontal axis represents the zero for a successive profile. The labeled tick marks correspond to the Gulf of Mexico profile. Numbers near the bottom of each individual profile give the approximate longitude in degrees W.

Law 1993). Thus, at progressively deeper levels less ^{14}C is transported from the outcrop, which may be several thousand kilometers distant for this particular locality (Sarmiento 1983).

Figure 2 shows a “time series” at one station at 54°W longitude for which 1972 GEOSECS (Stuiver and Östlund 1980) data are available. Results at this station are plotted versus density rather than versus depth because the GEOSECS stations are not in the exact same spots as our survey. Because the isopycnals slope considerably in this region, the GEOSECS profiles differ by $\sim 100\%$ when plotted versus depth. In contrast, when plotted versus density the two 1972 profiles are nearly identical, as they should be given that mixing occurs along isopycnal surfaces.

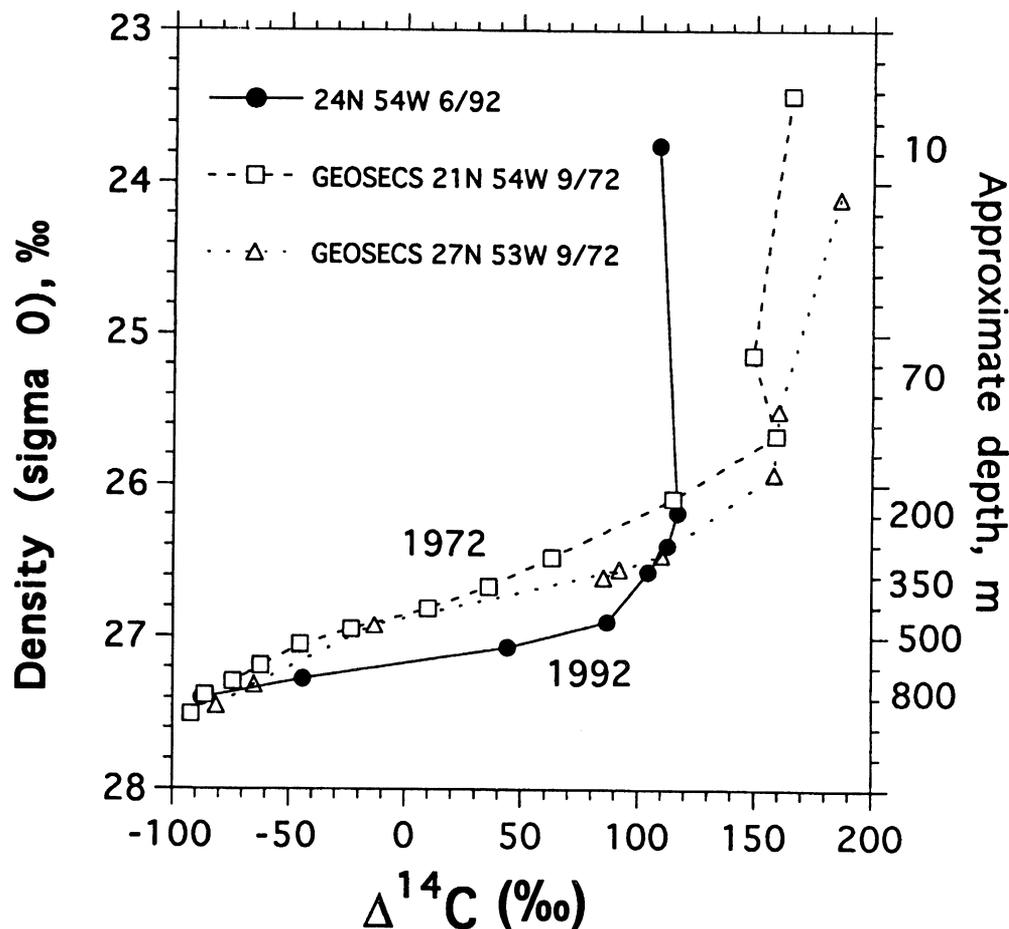


Fig. 2. Penetration of bomb ^{14}C into the main thermocline, 1972–1992. $\Delta^{14}\text{C}$ plotted vs. density at Station 66, 54°W longitude. GEOSECS data from nearby stations plotted for comparison (Stuiver and Östlund 1980). Note the $\sim 200\%$ difference in $\Delta^{14}\text{C}$ across the main thermocline between densities of 26.00 and 27.50. Also note the slight deepening of the profile in 1992 compared with the 1972 GEOSECS profiles.

In Figure 2, note the deepening of the profile that occurred in the 20-yr period spanned by the measurements. Although unsurprising, this deepening is evidence of ongoing mixing along the 26.00‰ to 27.00‰ isopycnals during this period. Also note the slight decrease in ^{14}C of surface waters, as expected from the decrease in the atmosphere over this period (Nydal and Løvseth 1983).

Figure 3 shows longitudinal transects of $\Delta^{14}\text{C}$ on three isopycnal surfaces, obtained by linear interpolation between shallower and deeper data points, as the samples did not fall exactly on these isopycnals. Note that there is a significant slope of the data toward the west, with higher values in the east. Since mixing occurs along isopycnals, these transects ought to be flat if mixing were rapid and complete along a given isopycnal. Instead, bomb ^{14}C might be entering the 24°N section first at the east, and later at the west. There might be an overall flow pattern from east to west at these main thermocline levels, and it would have to be somewhat sluggish for this along-isopycnal gradient to be preserved. Alternatively, outcrop-ward (N-S) along-isopycnal mixing might be more vigorous in the east than in the west, as isopycnals are bowed up closer to the surface in the east by the upwelling off the west coast of Africa, and so are exposed to more energy from wind stress than in the west. A third cause of the higher values in the east might be the injection of Mediterranean outflow water, which is rich in bomb ^{14}C due to the deep haline mixing of the Mediterranean Sea.

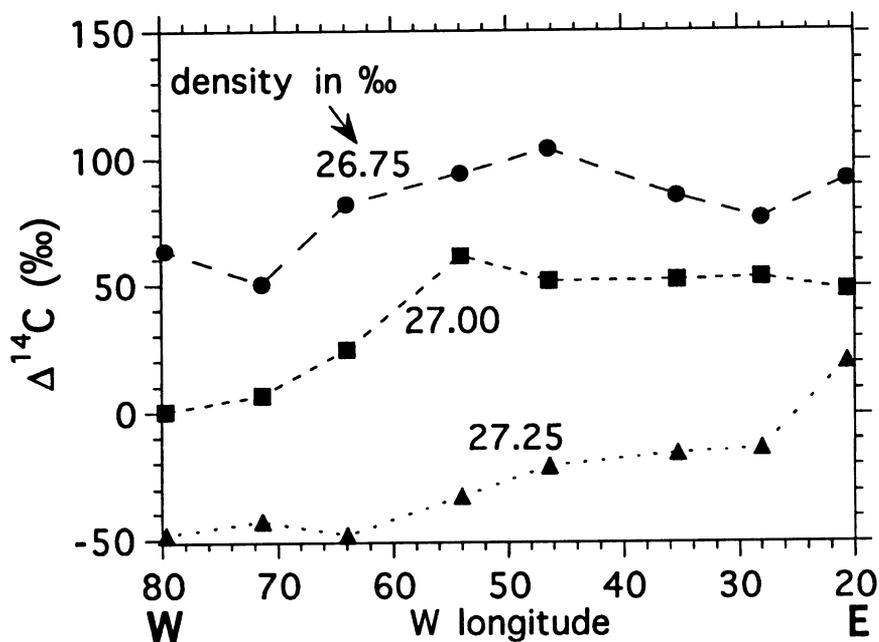


Fig. 3. East-west transects of $\Delta^{14}\text{C}$ along three isopycnal surfaces. Note the slight decrease in values toward the west. This may be due to poorer mixing in the west compared to the east, or to an overall slow east-to-west flow with ^{14}C entering first at the east. Mediterranean water may also contribute a high ^{14}C component to the eastern end of this gradient.

Bomb ^{14}C Inventories

To assess quantitatively the uptake of bomb ^{14}C for the purpose of comparison with models, we calculate the water column inventory of bomb ^{14}C at eight of our nine stations. We do this by subtracting from observed $\Delta^{14}\text{C}$ an estimate of the pre-bomb or natural $\Delta^{14}\text{C}$ using the measured SiO_2 and an empirical SiO_2 -natural $\Delta^{14}\text{C}$ relation (Broecker *et al.* 1995). We then convert to atoms of ^{14}C per cm^2 of ocean surface using the measured hydrographic data and total DIC (TCO_2). Results are given in Table 1.

TABLE 1. Calculated Bomb ^{14}C Inventories along 24°N, Atlantic Ocean

Station	Location (lat., long.)	Sampling date (mo dy yr)	Inventory ($\times 10^9$ atoms ^{14}C)	Estimated surface natural $\Delta^{14}\text{C}$ (‰)
<i>This Study</i>				
13	24.50 -20.65	7 23 92	13.9	-60
24	24.50 -28.00	7 26 92	15.1	-61
35	24.50 -35.32	7 29 92	17.4	-61
53	24.48 -46.40	8 02 92	19.4	-61
66	24.48 -53.98	8 05 92	17.5	-61
81	24.48 -63.98	8 08 92	16.6	-61
92	24.48 -71.32	8 12 92	18.3	-62
107	26.05 -79.65	8 15 92	9.1	-61
<i>GEOSECS</i>				
31	27.0 -53.5	9 22 72	17.6	-44
33	21.0 -54.0	9 26 72	12.0	-50
115	28.0 -26.0	3 15 73	13.0	-43
117	30.7 -39.0	3 20 73	18.8	-41
<i>TTO/TAS</i>				
75	22.8 -37.3	1 12 83	16.8	-49
77	25.3 -34.9	1 14 83	18.3	-46
81	27.3 -29.3	1 16 83	18.3	-44
84	24.7 -26.9	1 18 83	15.1	-47
87	22.4 -24.7	1 19 83	10.3	-49

No clear pattern of variation emerges among the GEOSECS, TTO/TAS (Östlund 1983), and present study surveys of 1972, 1983 and 1992, respectively. We suspect that variations in the depth of isopycnals from station to station explains this, so comparison with earlier surveys is not warranted. However, note that the 1992 inventories show a crude maximum in the center of the gyre at 46°W longitude, as expected from the deeper isopycnals in this portion of the gyre.

Gulf of Mexico Profile

In addition to the 24°N transect, we sampled one station in the Gulf of Mexico on the cruise Gyre 93G01 on Jan 10, 1993 at a location of 26°40'N, 95°00'W. We followed the same sampling and analysis procedures as outlined above. Results are given in the Appendix, and show a pattern similar to the profiles of the 24°N transect.

SUMMARY

We present $^{14}\text{C}/\text{C}$ ratios of DIC in a transect of the main thermocline along 24°N latitude in the Atlantic Ocean taken in 1992. A large gradient of $\sim 200\text{‰}$ is seen between shallower and deeper portions of the thermocline, which we attribute to the transient penetration of the pulse of ^{14}C from atmospheric nuclear weapons testing 30 yr ago and the fact that deeper isopycnal surfaces are not as well ventilated as shallower ones. A comparison with 1972 GEOSECS data at one location reveals an ongoing penetration of the pulse to deeper levels. An decrease from east to west along isopycnal surfaces is suggestive of different mixing properties in the east compared to the west.

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APPENDIX: RESULTS OF ¹⁴C ANALYSES

Station	Date sampled	Location		Depth (m)	Temp (°C)	Density		Comments
		Lat.	Long.			Sigma0 (‰)	Δ ¹⁴ C (‰)	
901	15-Jul-92	34°17'N	9°42'W	20			127	Mediterranean outflow (just west of Gibraltar) "Bio Hesperides VI" test cruise (depths nominal)
				200			93	
				350			77	
				500			33	
				700			-10	
				800			-13	
				1000			-26	
				1200			-19	
				1300			-40	
13	23-Jul-92	24°30'N	20°39'W	11	23.236	25.256	77	Hesperides VI cruise (E-W along 24°N lat)
				76	19.216	26.436	96	
				102	18.871	26.489	113	
				202	16.830	26.697	94	
				301	14.484	26.878	89	
				427	12.165	27.072	25	
				601	9.996	27.265	21	
				750	8.474	27.372	-86	
				24	26-Jul-92	24°30'N	28°00'W	
101	20.792	26.222	96					
199	18.653	26.504	119					
275	16.171	26.709	79					
352	14.320	26.860	72					
476	12.301	27.050	47					
600	10.889	27.192	6					
35	29-Jul-92	24°30'N	35°19'W	782	8.572	27.389	-61	Hesperides VI cruise (E-W along 24°N lat)
				11	25.145	25.288	123	
				153	18.951	26.383	135	
				199	17.698	26.504	103	
				375	14.705	26.824	81	
				504	12.755	27.019	50	
53	2-Aug-92	24°29'N	46°24'W	696	10.465	27.261	-19	Hesperides VI cruise (E-W along 24°N lat)
				827	8.635	27.427	-43	
				12	26.713	24.676	135	
				153	19.155	26.221	123	
				202	18.622	26.329	128	
				351	16.900	26.574	143	
66	5-Aug-92	24°29'N	53°59'W	401	16.189	26.660	123	Hesperides VI cruise (E-W along 24°N lat)
				552	12.859	26.981	58	
				653	11.072	27.166	5	
				800	8.677	27.371	-58	
				23	27.824	23.753	109	
				200	19.707	26.182	117	
				252	18.346	26.402	113	
				353	17.026	26.571	104	
				476	14.578	26.902	87	
81	8-Aug-92	24°29'N	63°59'W	574	12.640	27.070	44	Hesperides VI cruise
				752	9.826	27.277	-44	
				852	8.101	27.399	-88	
				17	28.715	23.470	96	

APPENDIX (Continued)

Station	Date sampled	Location		Depth (m)	Temp (°C)	Density		Comments
		Lat.	Long.			Sigma0 (‰)	$\Delta^{14}\text{C}$ (‰)	
				203	18.865	26.329	112	(E-W along 24°N lat)
				252	18.157	26.445	114	
				379	16.711	26.649	104	
				502	14.656	26.878	55	
				618	12.358	27.061	10	
				751	9.908	27.262	-52	
				853	7.860	27.421	-72	
92	12-Aug-92	24°29'N	71°19'W	11	28.897	23.211	69	Hesperides VI cruise
				202	19.501	26.187	105	(E-W along 24°N lat)
				325	18.941	26.310	124	
				426	18.276	26.414	--	(excluded)
				602	15.283	26.756	--	(excluded)
				702	12.944	26.968	14	
				801	10.691	27.157	-29	
				1004	7.209	27.462	-74	
107	15-Aug-92	26°03'N	79°39'W	11	29.042	23.005	101	Hesperides VI cruise
				175	19.337	26.192	101	(E-W along 24°N lat)
				235	16.686	26.578	80	
				302	15.105	26.727	69	
				376	11.210	27.059	-14	
				551	6.345	27.432	-80	
5G	10-Jan-93	26°40'N	95°00'W	10	23.868	24.742	86	Gyre 93G01 cruise
				238	19.138	26.221	100	Gulf of Mexico
				267	17.672	26.410	87	Depths nominal
				303	16.152	26.599	65	Density values are
				362	13.783	26.839	31	Sigma - theta
				462	11.355	27.031	-21	
				623	8.561	27.227	-66	
				815	6.478	27.410	-79	
				1000	5.350	27.563	-102	
				1600	4.243	27.737	-91	