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

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**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 cholorfluorocarbons (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

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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 $\Delta^{14}C$ in units of per mil (‰), as is customary (Stuiver and Polach 1977). Uncertainty (1 σ) is estimated at ± 5‰.

## 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

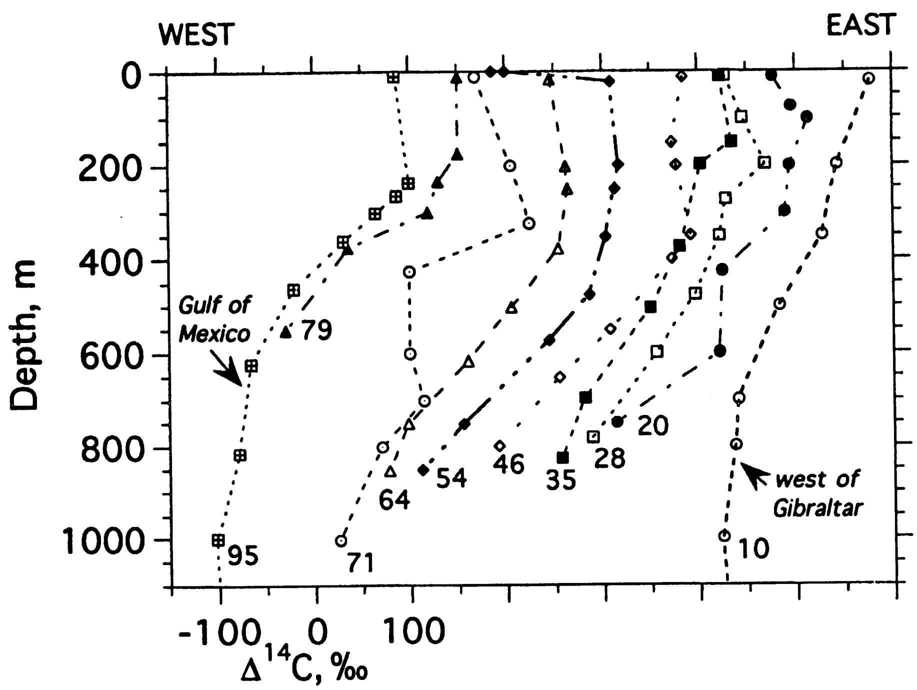


Fig. 1. $\Delta^{14}C$ along 24°N, Atlantic Ocean. Results of all analyses (except four that were deeper than 1100 m) are arranged by longitude. For clarity, all data sets have been separated by 50‰, such that each tick mark on the horizontal axis represents the zero for a successive profile. The labeled 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 ~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.

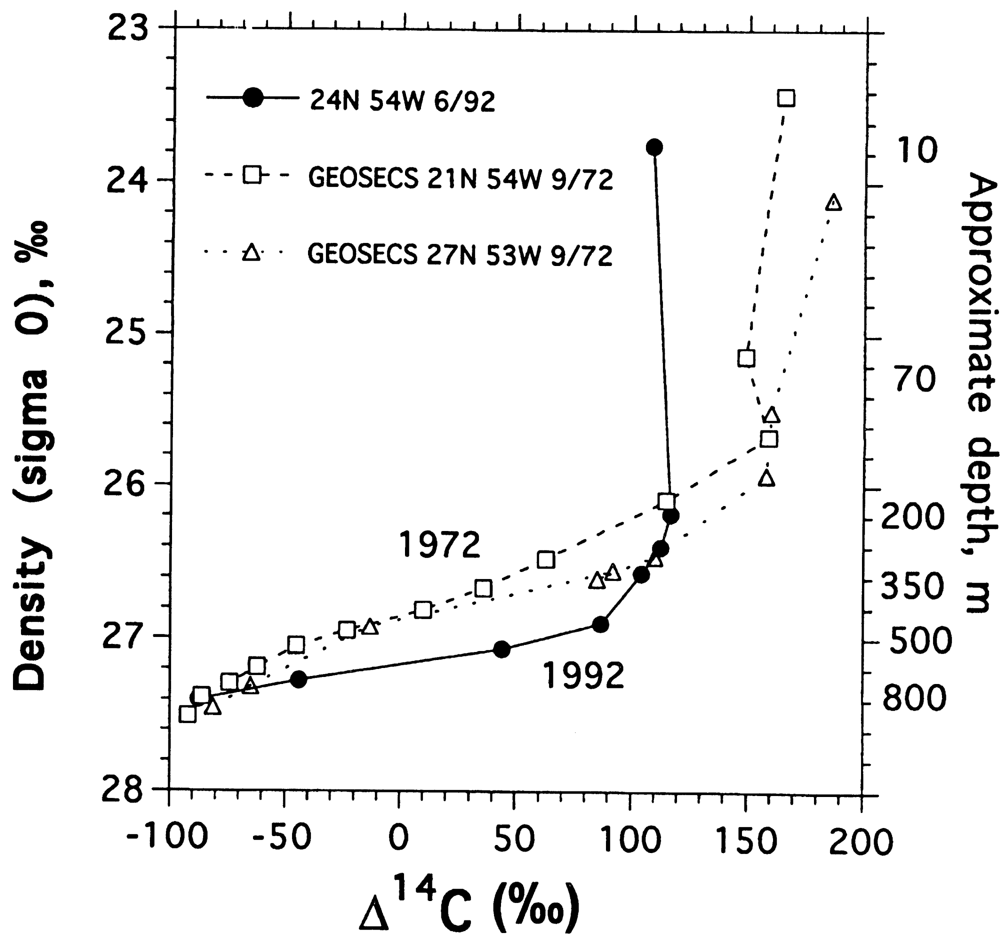


Fig. 2. Penetration of bomb $^{14}C$ into the main thermocline, 1972–1992. $\Delta^{14}C$ plotted *vs.* density at Station 66, 54°W longitude. GEOSECS data from nearby stations plotted for comparison (Stuiver and Östlund 1980). Note the ~200‰ difference in $\Delta^{14}C$ across the main thermocline between 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 $\Delta^{14}C$ 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 Mediterrean Sea.

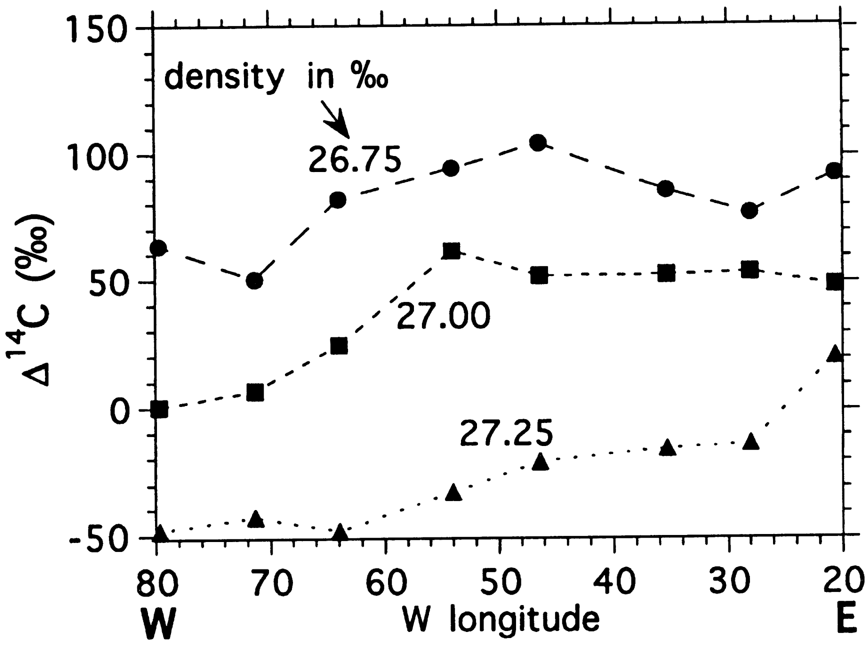


Fig. 3. East-west transects of $\Delta^{14}C$ along three isopycnal surfaces. Note the slight decrease in values toward the west. This may be due to poorer mixing in the west compared to the east, or to an overall slow east-to-west flow with $^{14}C$ entering first at the east. Mediterranean water may 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 $\Delta^{14}C$ an estimate of the pre-bomb or natural $\Delta^{14}C$ using the measured $SiO_2$ and an empirical $SiO_2$–natural $\Delta^{14}C$ 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 $\Delta^{14}C$ (‰) |
|---|---|---|---|---|---|
| *This Study* | | | | | |
| 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 |
| *GEOSECS* | | | | | |
| 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 |
| *TTO/TAS* | | | | | |
| 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 $^{14}C/C$ 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 ~200‰ 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.

## Acknowledgments

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## Appendix: Results of $^{14}C$ analyses

| Station | Date sampled | Location Lat. | Location Long. | Depth (m) | Temp (°C) | Density Sigma0 (‰) | $\Delta^{14}C$ (‰) | Comments |
|---|---|---|---|---|---|---|---|---|
| 901 | 15-Jul-92 | 34°17′N | 9°42′W | 20 | | | 127 | Mediterranean outflow |
| | | | | 200 | | | 93 | (just west of Gibraltar) |
| | | | | 350 | | | 77 | "Bio Hesperides VI" |
| | | | | 500 | | | 33 | test cruise |
| | | | | 700 | | | −10 | (depths nominal) |
| | | | | 800 | | | −13 | |
| | | | | 1000 | | | −26 | |
| | | | | 1200 | | | −19 | |
| | | | | 1300 | | | −40 | |
| | | | | 1600 | | | −52 | |
| 13 | 23-Jul-92 | 24°30′N | 20°39′W | 11 | 23.236 | 25.256 | 77 | Hesperides VI cruise |
| | | | | 76 | 19.216 | 26.436 | 96 | (E-W along 24°N lat) |
| | | | | 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 | 10 | 24.153 | 25.356 | 78 | Hesperides VI cruise |
| | | | | 101 | 20.792 | 26.222 | 96 | (E-W along 24°N lat) |
| | | | | 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 | |
| | | | | 782 | 8.572 | 27.389 | −61 | |
| 35 | 29-Jul-92 | 24°30′N | 35°19′W | 11 | 25.145 | 25.288 | 123 | Hesperides VI cruise |
| | | | | 153 | 18.951 | 26.383 | 135 | (E-W along 24°N lat) |
| | | | | 199 | 17.698 | 26.504 | 103 | |
| | | | | 375 | 14.705 | 26.824 | 81 | |
| | | | | 504 | 12.755 | 27.019 | 50 | |
| | | | | 696 | 10.465 | 27.261 | −19 | |
| | | | | 827 | 8.635 | 27.427 | −43 | |
| 53 | 2-Aug-92 | 24°29′N | 46°24′W | 12 | 26.713 | 24.676 | 135 | Hesperides VI cruise |
| | | | | 153 | 19.155 | 26.221 | 123 | (E-W along 24°N lat) |
| | | | | 202 | 18.622 | 26.329 | 128 | |
| | | | | 351 | 16.900 | 26.574 | 143 | |
| | | | | 401 | 16.189 | 26.660 | 123 | |
| | | | | 552 | 12.859 | 26.981 | 58 | |
| | | | | 653 | 11.072 | 27.166 | 5 | |
| | | | | 800 | 8.677 | 27.371 | −58 | |
| 66 | 5-Aug-92 | 24°29′N | 53°59′W | 23 | 27.824 | 23.753 | 109 | Hesperides VI cruise |
| | | | | 200 | 19.707 | 26.182 | 117 | (E-W along 24°N lat) |
| | | | | 252 | 18.346 | 26.402 | 113 | |
| | | | | 353 | 17.026 | 26.571 | 104 | |
| | | | | 476 | 14.578 | 26.902 | 87 | |
| | | | | 574 | 12.640 | 27.070 | 44 | |
| | | | | 752 | 9.826 | 27.277 | −44 | |
| | | | | 852 | 8.101 | 27.399 | −88 | |
| 81 | 8-Aug-92 | 24°29′N | 63°59′W | 17 | 28.715 | 23.470 | 96 | Hesperides VI cruise |

**APPENDIX** (Continued)

| Station | Date sampled | Location | | Depth (m) | Temp (°C) | Density Sigma0 (‰) | Δ¹⁴C (‰) | Comments |
|---|---|---|---|---|---|---|---|---|
| | | Lat. | Long. | | | | | |
| | | | | 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 | |