Tritium and radiocarbon in the North Atlantic Ocean
An overview

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In the study of large-scale oceanic circulation, tracers of various kinds have always played a large role. Indeed, even temperature and salinity can be considered tracers for this purpose. In the last few decades, dissolved oxygen and nutrients became useful as tracers, since measurement methods were developed that were accurate and reasonably simple to use. Then in the early 60s interest gradually became directed towards radioactivity in the ocean, originating from natural sources and nuclear industry. The first concerted effort to map the field of chemical tracers in the bulk of the ocean was undertaken by the Geochemical Ocean Sections (GEOSECS) programme beginning in 1972. In addition to excellent hydrographic information and data on the nutrients, a considerable effort was spent on two radioactive tracers, the tritium and the radiocarbon. The usefulness of the GEOSECS tracer concept with its world-wide, even if skeletal, data coverage prompted a renewed look at the tracer field through the programme Transient Tracers in the Ocean (TTO). So far, however, this latter programme has only been run in the North Atlantic and Tropical Atlantic regions, and tracer data are just beginning to emerge from the laboratories. At the time of writing this, it is questionable if the renewed mapping process can be continued in this form.

This presentation will deal exclusively with the distribution of radiocarbon and tritium in the North Atlantic Ocean as seen in the GEOSECS and TTO programmes. Other contributions to this symposium report on work with additional tracers like the freons and Kr85. The basis for the use of radiocarbon and tritium as tracers is as follows:

Radiocarbon, or C14, is a beta emitter with a half-life of 5730 years. It is naturally produced in the atmosphere by cosmic radiation, and a global, steady state inventory, at least as a first approximation, has been maintained in the past.

The standard for C14 measurements is the C14/C12 ratio of living wood, unaffected by the fossil fuel CO_2 and nuclear testing. The C14/C12 ratio of a given sample is adjusted for isotope fractionation effects in nature and during treatment by C13 measurement. The corrected C14/C12 ratio is expressed as the deviation, ΔC14, in per mille, from the wood standard. Air/sea exchange transferred radiocarbon as $^{14}CO_2$ to the ocean surface waters, and in pre-nuclear era the ΔC14 value of ocean surface waters in the North Atlantic was between -40 and -70‰, not zero ‰, due to the contribution from resurfacing deep water. When subsurface water is formed by sinking, the air/sea exchange is cut off, and the decay of C14,

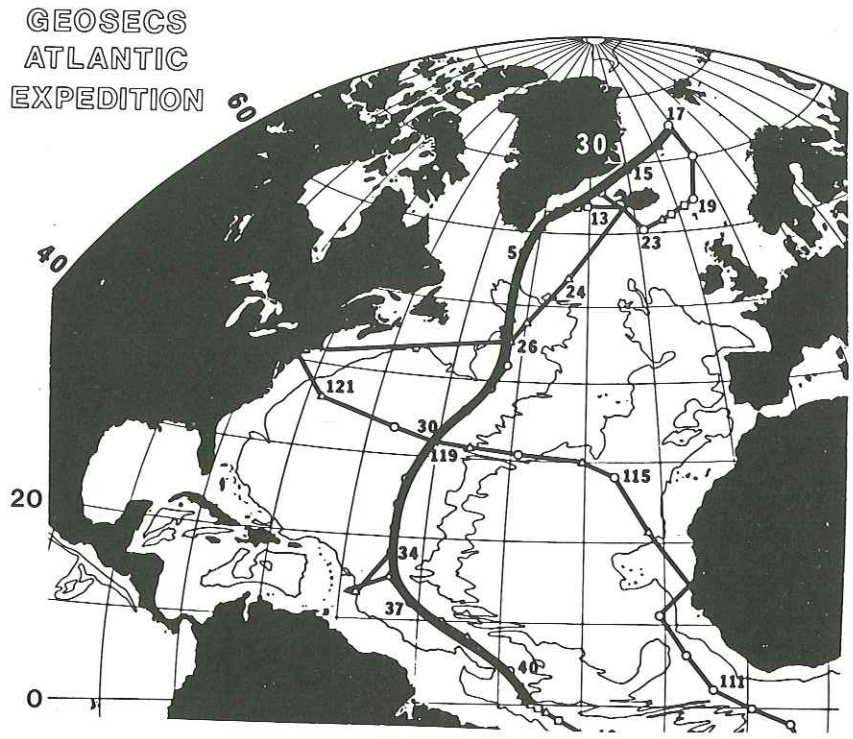

Fig. 1. The Geosecs 1972 cruise track (heavy line).

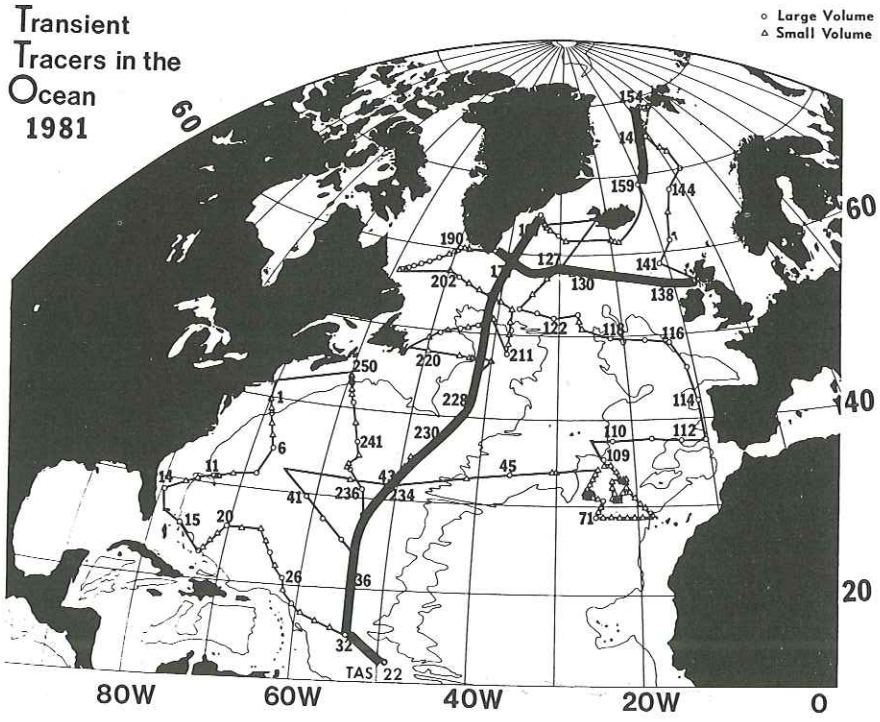

Fig. 2 TTO North Atlantic Study (NAS) and Tropical Atlantic Study (TAS) cruise tracks. Heavy lines: GEOSECS re-occupation and longitudinal section.

1% per 82 years, will cause a deficiency in the C14/C12 ratio that can be interpreted as the "age" of that water, i.e., the time elapsed since it was at the surface. However, as a result of the testing of large nuclear weapons in the atmosphere in the 60s, man-made $^{14}CO_2$ was injected into the atmosphere and is now making its way via the surface waters towards the deep oceans. The "younger" waters contain an excess of C14 and the elevated C14/C12 ratio is going through the ocean as a transient that started around 1960 (see illustrations).

For most practical purposes, the radioactive hydrogen isotope tritium, half-life 12.43 years, a beta emitter, did not exist before the big bomb tests. As a result of these tests, tritium in the form of water, HTO, was laid down on the surface ocean, mainly in the northern hemisphere as a spike in the early and mid-60s. This signal is now, like the bomb C14, proceeding through the oceans. Tritium thus is a transient tracer.

Tritium in the ocean is generally expressed in TU, "tritium units", a somewhat illogical way to name the 10^{18} times abundance ratio $^3H/^1H$, or T/H. Water with 1 TU has an activity of 7.088 dpm/kg H_2O. Since this isotope has a short half-life, it is practical to refer TU values to the same reference date, 1981/01/01, i.e., the tritium ratio the water would have if we had the opportunity to sample it at that time. We call this unit TU81N; N for the use of this new agreement of half-life. In this way tritium becomes a truly conservative tracer, and it is possible to compare samples collected at different times without further age-correction.

Radiocarbon and tritium, sampled in an orderly fashion on the GEOSECS cruises, and measured with a standardized technique, have allowed a multitude of oceanographic studies on large-scale mixing and transports, and processes associated with the fate of fossil fuel CO_2. This presentation will give some of the highlights of the distribution of these tracers in the North Atlantic only and compare that information with what is coming out from the TTO programme ten years later.

The GEOSECS programme in the Atlantic Ocean was primarily an N-S transect in the basins west of the Mid Atlantic Ridge (Fig. 1). The TTO programme in the same area covered the North and Tropical Atlantic much more thoroughly, with some stations selected to offer direct re-occupation of the GEOSECS stations (see TTO cruise track, Fig. 2).

We shall now first look at a direct comparison of the tritium and radiocarbon sections along the northern part of the GEOSECS track and its TTO reoccupation (Figs. 3a-b and 4a-b). The GEOSECS tritium section became a striking illustration of the mechanism of the formation of new deep waters north of Iceland and the transport of those waters into the main Atlantic Ocean, and this section has been quite extensively quoted and reprinted. It shows us some well-known facts, e.g., that the thermocline in the main ocean is a barrier for downward movement of water; that most of the surface waters in the Atlantic move north; and that deep waters of the Atlantic are formed north of 60°N, and are flowing south over the sill in the Denmark Strait out into the abyss. By 1973 the tritium signal at the bottom along the track had reached 36°N. The presence of the North Atlantic Gyre System is causing the tritium not to go far south at mid depths. Other details of the circulation of the upper waters in the North Atlantic can also be seen.

Due to ice conditions in 1981, the TTO section could not exactly reproduce the GEOSECS track, but enough stations are available to show the changes since 1972. This section covers the Greenland Sea better, and the process of deep water overturning is clearly illustrated in the lack of vertical tritium gradient at 75°N in this figure. In the Atlantic proper, the bottom

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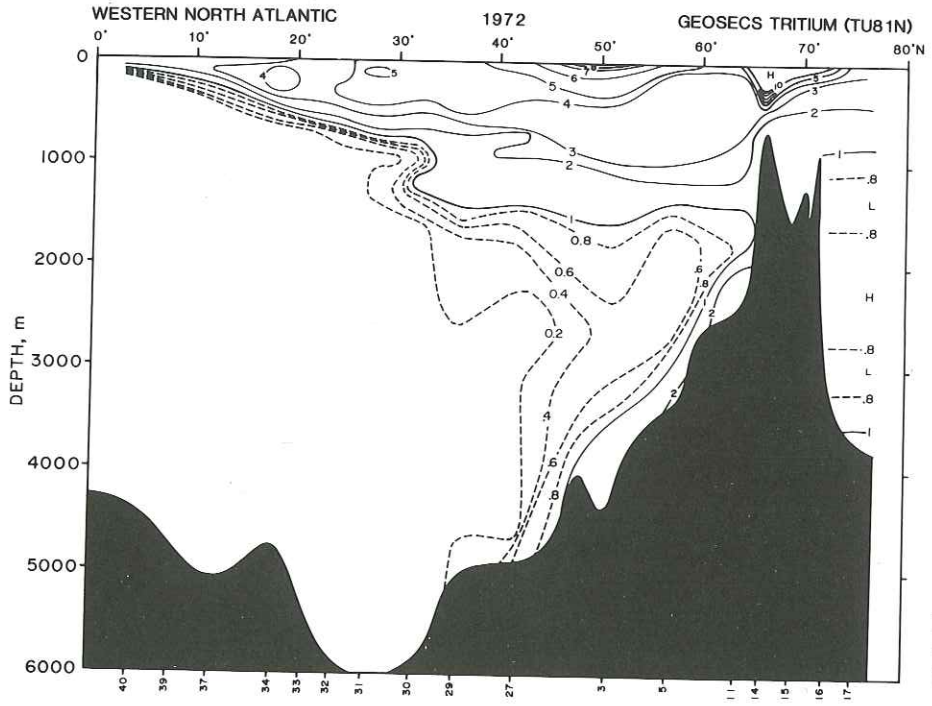

Fig. 3a.
N-S GEOSECS tritium section.

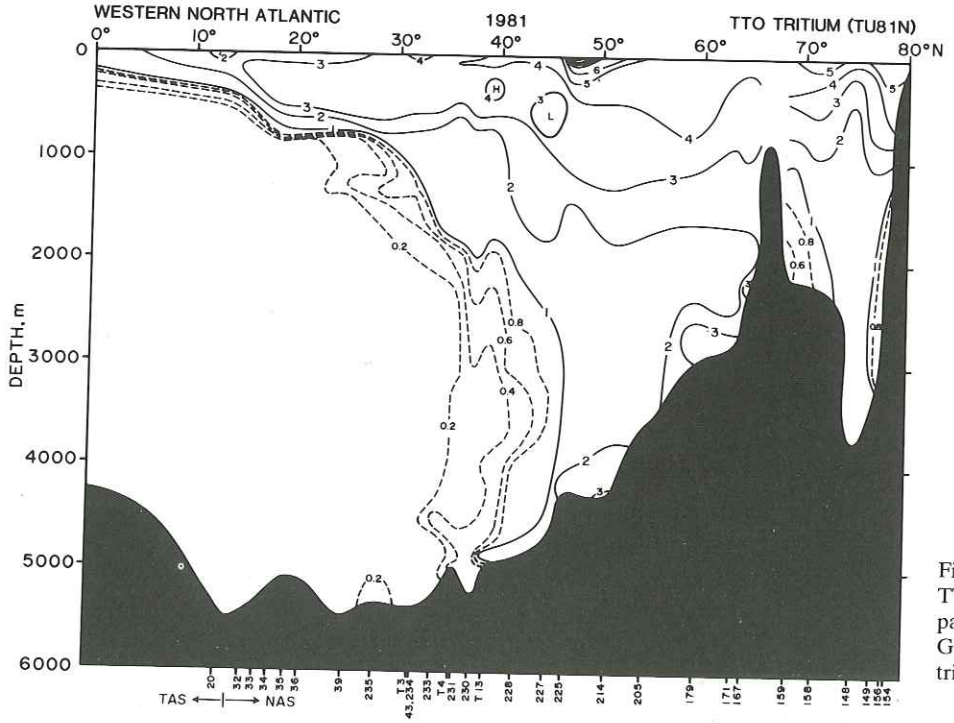

Fig. 3b.
TTO re-occupation of GEOSECS tritium section.

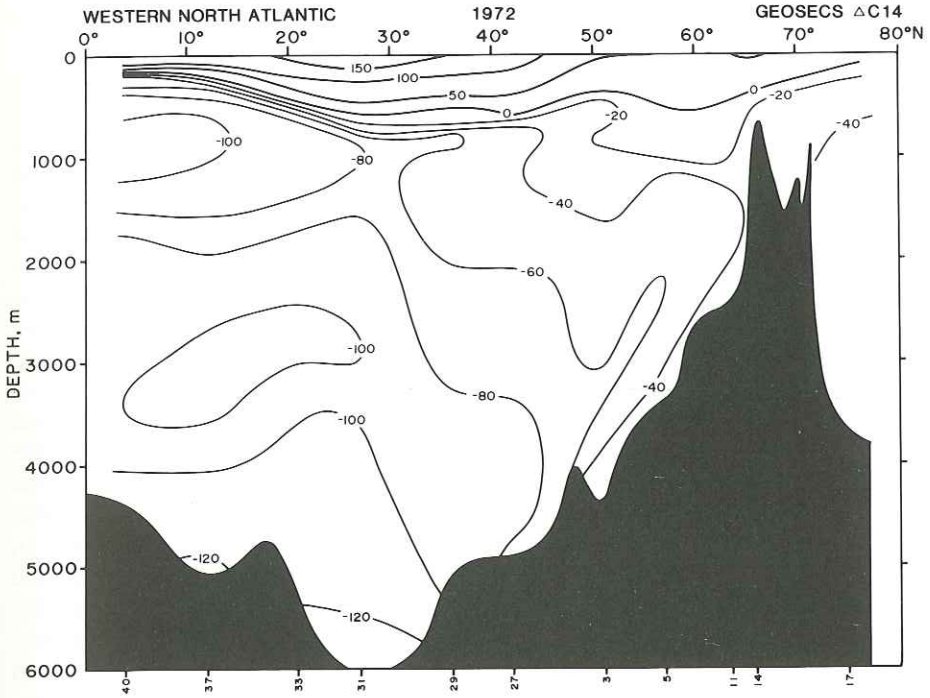

Fig. 4a.
GEOSECS C14
section.

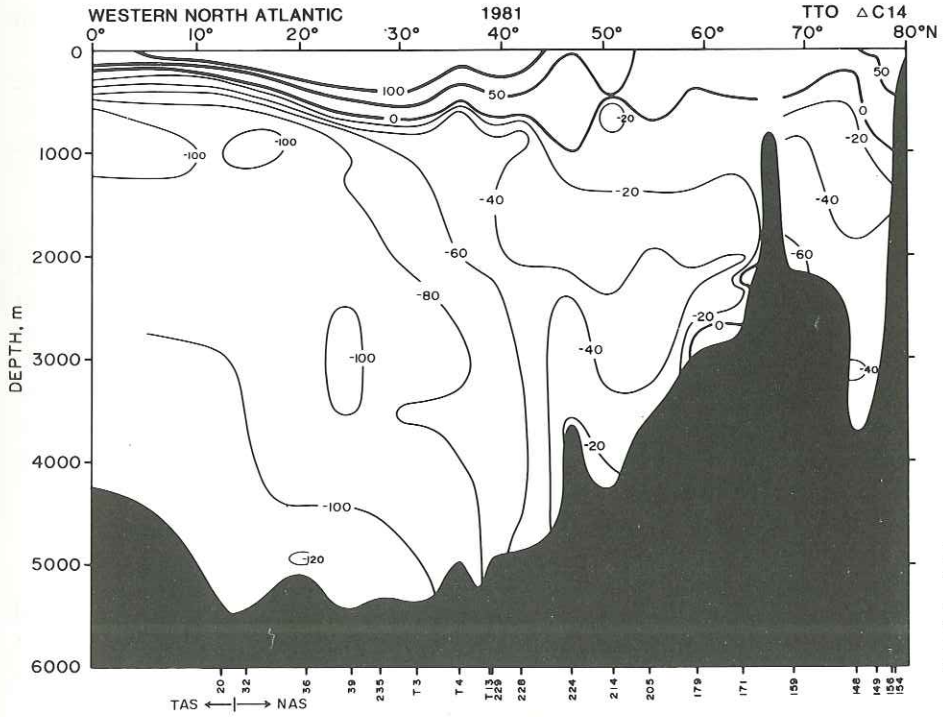

Fig. 4b.
TTO re-occu-
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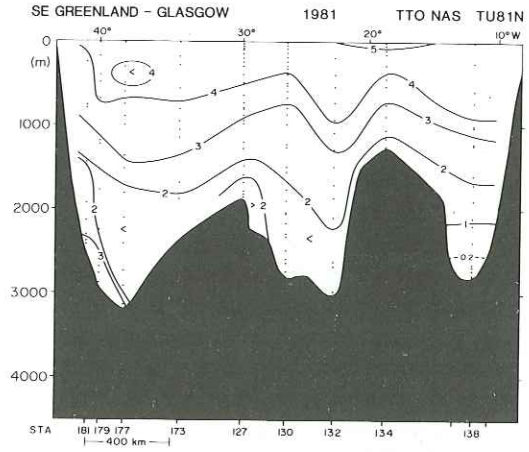

Fig. 5a. TTO tritium E-W section Greenland to Glascow (along about 55°N).

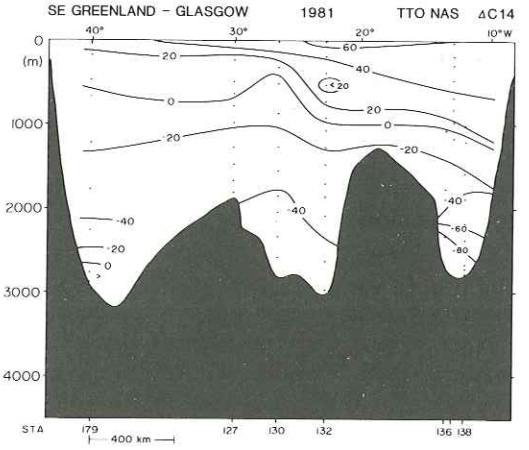

Fig. 5b. TTO E-W C14 section (along about 55°N).

waters with bomb tritium have now proceeded to about 26°N; note that E-W meandering of the current may show up as lack of continuity in the two-dimensional N-S section. The tritium has also worked its way into the mid-depth gyre, and there is some deepening of the tritium layer in the south.

When studying the C14 section, one has to remember that the steady state inventory of C14 before the bomb tests had tagged those waters to a constant level, at about $\Delta C14 = -50‰$. Any value above that indicates presence of post-bomb surface carbonate. A value below -50 indicates decay of C14, i.e., a finite seal-off time, but smaller amounts of bomb C14 can still be present. If so, tritium must also be there, and only as long as there is zero tritium, can one trust the "apparent C14 age" of the water. One shall not take this C14 age as a true value of the seal-off time, since mixing with water masses of other ages may play a role, as does the mode in which one assumes the transport has taken place, e.g., diffusion vs. advection. The iso-C14 lines do, however, give a first rough indication of the time scales involved in the formation of the deeper waters. Clearly at these depths we cannot expect any noticable changes by time until the transient front reaches the area. In the deeper waters in the C14 section, we recognize the various water masses of the North Atlantic Ocean with the northernmost extension of the Antarctic Bottom Water showing up as the oldest layer at the bottom with $\Delta C14$ values around $-120‰$. The North Atlantic deep water coming from the north on a time scale of 100 years or so is also easily seen, and even the Antarcic Intermediate Water in depths between the North Atlantic deep water and the surface water is clearly depicted, the upper $-100‰$ area.

As illustrations of the zonal tracer distributions in the North Atlantic, we present Figures 5a and 5b, the TTO tritium and C14 sections from the southern tip of Greenland to Glascow. Here bomb C14 and tritium are present at all depths except possibly in the bottom waters at 10°W, where heavily diluted Antarctic Bottom Water just barely makes its presence known.

DATA AVAILABILITY

The complete set of GEOSECS C14 and tritium data will be finally listed in the last volume (Vol. 7) of the GEOSECS atlas, estimated to be published in late 1985 by the

U.S. Government Printing Office. In the meantime, the tritium data are available in:

Östlund, H. G. and R. Brescher 1982. GEOSECS Tritium, Tritium Laboratory Data Report No. 12, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, Florida 33149.

Additional Atlantic tritium data from this laboratory are available in:

Östlund, H. G. 1984. NAGS Tritium, North Atlantic Gyre Studies and Associated Projects, Tritium Laboratory Data Report No. 13, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, Florida 33149.

Dr. William Jenkins of Woods Hole Oceanographic Institution is also assembling Atlantic tritium data, especially from the western part of the TTO cruise.

The GEOSECS C14 data are available in:

Stuiver, M. and H. G. Östlund 1980. GEOSECS Atlantic radiocarbon. Radiocarbon 22(1): 1–24.

Östlund, H. G. and M. Stuiver 1980. GEOSECS radiocarbon, Radiocarbon 22(1): 25–53.

Stuiver, M. and H. G. Östlund 1983. GEOSECS Indian Ocean and Mediterranean radiocarbon, Radiocarbon 25(1): 1–29.

A compilation of GEOSECS C14 data is also available in:

Stuiver, M., H. G. Östlund and T. A. McConnaughey 1981. GEOSECS Atlantic and Pacific ^{14}C distribution. In B. Bolin (Ed.), Carbon Cycle Modelling, Scope 16. John Wiley & Sons, New York, pp. 201–221.

Additional C14 data of the atmosphere and from surface ocean are available in:

Nydal, R. and K. Lovseth 1983. Tracing bomb ^{14}C in the atmosphere 1962–1980. J. Geophys. Res. 88(C11): 3621–3642.

A complete set of TTO C14 and tritium data are now being assembled for publication by:

Östlund, H. G., P. Brewer and J. Sarmiento. Radiocarbon and Tritium in the North and Tropical Atlantic, for submission mid-1985.