The Distributions of helium isotopes and tritium along the U.S. GEOTRACES North Atlantic Sections (GEOTRACES GAO3)

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Abstract:

We present the distributions of helium isotopes (in the form of helium isotope ratio anomaly relative to the atmospheric ratio) and tritium along two sections occupied in the subtropical North Atlantic as part of the first U.S. GEOTRACES survey (GEOTRACES GAO3). The general distributions of these isotopes are consistent with the continuing penetration and evolution of bomb-produced tritium and its daughter isotope ^3He in the main thermocline and along the western boundary current system. We combine these two distributions to compute a tritium- ^3He age, which is related to the elapsed time since the water was at the ocean surface. Although it is an indicator biased by the effects of mixing and influenced by the time history and spatial distribution of bomb tritium delivery to the ocean surface, it still remains a useful measure of ventilation time-scales. Aside from the continued propagation of the tritium- ^3He transient into the ocean interior, there are three notable features of interest in these distributions. The first is the clear signature of upwelling in the water column near the coast of Mauritania, characterized by the upward bowing of isochrones in the thermocline and discernable ^3He excess at the ocean surface. A simple ^3He mass balance calculation suggests an upwelling flux of order $1.8 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (1.8 Sv) along the Mauritanian coast. The second is a mid-depth (~1500-2000 m) core of ventilated waters centered over the Mid-Atlantic Ridge, an anticyclonic circulation of waters likely originating in the Labrador Sea. The third notable feature is a volcanic ^3He plume at about 3500 m depth emanating from the TAG Hydrothermal Area that is detectable as much as 500 km away on each side of the Mid-Atlantic Ridge. We estimate a ^3He :heat ratio of $\sim 7 \times 10^{-18} \text{ mol J}^{-1}$ and a ^3He flux from the TAG site of $\sim 15 \text{ mmol y}^{-1}$. Since ^3He is a conserved tracer in the absence of measureable tritium, the correlation of volcanic ^3He with other hydrothermally influenced TEIs (e.g., Fe) can be used as a dilution tracer as probe of non-conservative behavior in the water column. Also, since the regional and global fluxes of volcanic ^3He are known, the correlations can be used as a regional/global flux gauge for hydrothermal input of those TEIs.

1. Introduction:

The GEOTRACES program identified a number of core Trace Elements and Isotopes (TEIs) that are considered key to achieving its main mission (Measures et al., 2007). In addition to those TEIs, it was also recognized that the measurement of other ancillary properties and TEIs would be of value for quantifying the rates and magnitudes of *in situ* processes that support, modify, or transform those primary TEIs. The two isotopes ^3H (tritium) and ^3He prove of value for two reasons. The first is that tritium (Dockins et al., 1965; Giletti et al., 1958; Ostlund and Fine, 1979; Ostlund and Hut, 1984) and ^3He

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are useful transient tracers of ocean ventilation (e.g., Jenkins, 1988, 1998) and have been measured over a wide geographic scale (Jenkins, 1996). The two tracers can be combined to provide a *Tritium-³He Age* that is a measure of the elapsed time since a fluid parcel was in contact with the sea surface. Such an age, depending on location and tritium concentration, responds on timescales from as short as a few months to several decades. The tritium-³He age is biased by mixing and the temporal history and spatial pattern of the bomb tritium injection into the environment (Jenkins, 1980; Wunsch, 2002), but this bias can be accounted for quantitatively using the unique coupling of the two tracers, (Jenkins, 1987, 1988, 1998; Jenkins, 2004).

The second utility is that in the absence of measurable tritium, ³He is a conservative tracer in the water column. Seafloor volcanic activity emits significant amounts of this isotope into the water column (Clarke et al., 1969), producing plumes of volcanic ³He discernable over many thousands of kilometers in the deep ocean (Lupton, 1998; Lupton and Craig, 1981; Lupton et al., 2003), allowing estimates of the global flux of this isotope from newly forming oceanic crust using models of varying sophistication (Bianchi et al., 2010; Craig and Clarke, 1970; Farley et al., 1995). Using observed correlations between ³He and Fe, another hydrothermally augmented TEI, it is possible to make global estimates of hydrothermal Fe fluxes to the deep ocean (Boyle and Jenkins, 2008; Tagliabue et al., 2010). Such calculations assume a globally constant Fe:³He ratio, whereas recent observations suggest a significant difference in this ratio between fast- and slow-spreading ridges (Saito et al., 2013). One objective of the U.S. GEOTRACES North Atlantic sections was to sample ³He and other TEIs at and near another slow-spreading ridge hydrothermal site, the TAG Hydrothermal Site at 26°N on the Mid Atlantic Ridge (Jenkins et al., 1980; Rona et al., 1975; Rona et al., 1984).

Figure 1: GEOTRACES station locations for the 2010 (filled circles) and 2011 (filled squares) campaigns plotted on apparent oxygen utilization on the 26.8 kg m⁻³ neutral surface.

A description of the cruise, station locations, and water mass distributions exists as another paper in this special issue (Jenkins et al, 2014), but for reference we show the station locations in Figure 1, which are plotted against the distribution of apparent oxygen utilization (AOU) on the 26.8 kg m^{-3} neutral surface, estimated using the World Ocean Atlas 2009 climatology (Garcia et al., 2010). Here, the 2010 stations are shown as filled gray circles, and the 2011 stations by darker gray squares. Note the overlap station sampled on both cruises at the TENATSO site ($17.4^{\circ}\text{N } 24.5^{\circ}\text{W}$).

2. Sampling and Measurement Methods

Tritium and helium were sampled at all station locations (see Figure 1). Samples were drawn from a twelve position 30 liter Niskin rosette equipped with a Seabird *SBE9+* CTD, *SBE43* dissolved oxygen sensor, *Seapoint SCF* fluorometer, *Wet Labs C-Star* transmissometer, and *Tritech LPRA-200* altimeter. All bottles were sampled for salinity, dissolved oxygen, and inorganic macronutrients. Helium samples were drawn using TYGON tubing into lengths of 5/8" soft copper refrigeration tubing and hydraulically crimp-sealed using the technique described by Young and Lupton (1983). Tritium samples were drawn using TYGON tubing into especially baked and argon filled 1 liter flint glass bottles sealed with high density polyethylene caps. On shore, about 500 ml of each tritium sample was introduced into 1 liter aluminosilicate glass flasks, degassed, and stored in a shielded underground area (to minimize cosmic ray exposure) for 6-12 months for ^3He ingrowth. The samples were then analyzed mass spectrometrically for the tritiogenic ^3He and the tritium concentrations computed. Results were typically measured to an accuracy of better than 0.5% in quadrature with counting statistics and a detection limit better than 0.005 TU (one standard deviation). Results were corrected for a modest contribution ($0.003 \pm 0.002 \text{ TU}$) from cosmic ray spallation during storage. The helium samples were quantitatively extracted from the $\sim 45 \text{ g}$ water stored in the crimped copper tubes using an all metal high vacuum system and the gases transferred 25 ml aluminosilicate glass ampoules for storage prior to mass spectrometric measurement. The samples were then measured mass spectrometrically for the helium and neon concentration by ion beam manometry, and the helium isotope ratio measured relative to the atmospheric standard (Lott and Jenkins, 1984, 1998). Measurements of the helium and neon concentrations were made to an accuracy of approximately 0.5% (0.3% for helium and 0.55% for neon) and the helium isotope ratio was measured to better than 0.15% (one standard deviation of measurement). Corrections to the latter were made for a modest dependence of the apparent isotope ratio on sample size. The sizes of the corrections were everywhere less than one standard deviation of measurement. A finalized version of this data was submitted to the BCO-DMO and the data are to be included in the GEOTRACES Intermediate Data Product 2014 (Mawji, 2014).

3. A General Description of the Distributions of Helium Isotopes and Tritium

The distributions of these isotopes are shown in Figure 2 (tritium in the upper panel and $\delta^3\text{He}$, the helium isotope ratio anomaly in the lower panel). The sections are presented in a manner identical to the hydrographic and water mass analysis results reported elsewhere in this issue (Jenkins et al, 2014). They are arranged such that an approximately zonal section extending southeastward from Cape Cod, North America to Mauritania, Africa is presented on the left, and an approximately meridional section extending from the Cape Verde Islands northward to Lisbon, Portugal is presented on the right. Where

Figure 2: The distributions of tritium (upper panel in TU) and helium isotope ratio anomaly (lower panel, in percent) along two approximately zonal (left part of the sections) and meridional (right part of the sections). The tritium has been decay corrected to a common date (November 1, 2010).

the two sections meet is indicated by a black vertical line in the right-hand end of the “zonal” section.

Full depth sections appear on the lower half of Figure 2 and an expanded scale for the upper 1000 m of the water column occurs on the upper half. The sample data points, indicated by gray dots in the plots, were objectively mapped onto a 50 km (horizontal) by 50 m (vertical) grid using D.I.V.A. (e.g., see Brasseur, 1996) with horizontal and vertical scale lengths of 1000 km and 500 m respectively. The resultant grids were mapped and contoured using GMT (see Wessel and Smith, 1998). Finally, the northernmost deep portions of the meridional sections (north of $\sim 32^\circ\text{N}$ and deeper than ~ 3000 m) have been masked using a light gray rectangle because they contain no data.

Tritium concentrations are reported in *Tritium Units* (TU), which are defined as 10^{18} times the atom ratio of this isotope relative to the dominant hydrogen isotope. Because sampling was done over the course of two years (October-November 2010 and November-December, 2011) the tritium data in Figure 2 were decay-corrected to a common time (November 1, 2010). In the near surface, tritium is seen to penetrate from the north-eastern corner of the gyre with lower tritium waters apparent in the west. This is the influence of the entrainment of South Atlantic waters into the shallow North Atlantic subtropical gyre (Schmitz, 1995; Schmitz and McCartney, 1993) associated with the northward flowing limb of the planetary scale meridional overturning circulation (MOC). This is most pronounced in the Florida Current and Gulf Stream and influences the western portion of the Subtropical Gyre most strongly (see the shallow band of lower tritium waters in Figure 2 between approximately 55 and 65°W). Southern hemispheric waters are characteristically low in tritium concentrations due to the much lower deposition of this isotope in the southern hemisphere (Butzin and Roether, 2004; Doney et al., 1992; Doney et al., 1993; Weiss and Roether, 1980) and strong upwelling in the southern ocean (Iudicone et al., 2008; Kuhlbrodt et al., 2007; Olbers and Visbeck, 2005) of old, low tritium water. Between 65 and 25°W in the “zonal” section, the tritium concentrations in the upper ~ 600 m appear banded, with 100 km scale variations of ~ 0.100 TU, roughly 10 - 20 times measurement uncertainties (0.005 to 0.010 TU). This is a result of the interaction of the large scale zonal gradient in tritium (higher in the east) and alternating zonal flow. The latter is evident in the circulation scheme for the upper thermocline constructed by Schmitz and McCartney (1993; their Figure 9b). Specifically, near-surface currents just west and east of the Mid Atlantic Ridge along our cruise track derive predominantly from the northeast, while there is an apparent reversal (flow from the west) immediately over the ridge.

The pronounced tongue of higher tritium waters penetrating southward at a few hundred meters’ depth in the meridional section traces the wind- and buoyancy-driven subduction (Federiuk and Price, 1984; Luyten et al., 1983) of higher tritium northern surface waters into the main thermocline, a feature observed also in the North Pacific (Fine et al., 1987; McPhaden and Fine, 1988). This southward penetration appears to detach from the African coast (see shallow maximum between 23 and 25°W in the zonal section), likely due to the influence of Atlantic Equatorial Water from the south (see Jenkins et al, 2014) and upwelling off the Mauritanian coast. Regarding the latter, note the upward bowing of tritium isopleths in the upper 600 m between the Cape Verde Islands and the Mauritanian coast

Deeper in the water column, there is significant penetration of tritium associated with the Mediterranean Water (in the northeast, between 1000 and 1500 m depth) and Labrador Sea Waters (in the northeast between 1500 and 2000 m depth, and in the west between 1000 and 2000 m depth). Note that there is a distinct tritium minimum at around 1000 m depth (visible mostly in the west, but

extending across the entire zonal section) associated with tritium impoverished Antarctic Intermediate Water (AAIW). The minimum is more visible in the west due to contrast with underlying Labrador Sea Water. The contribution of AAIW is actually greater in the southeastern end of the section, but the deeper waters there are essentially tritium-free. Notably, the AAIW is not completely tritium-free; tritium concentrations in the salinity minimum are approximately 0.01 TU in southwestern end of the section. Additionally, there is a tritium maximum centered over the Mid Atlantic Ridge at about 1600 m depth. The water mass analysis presented by Jenkins et al (2014) in this issue labels this water as predominantly Upper and Central Labrador Sea Waters in origin. The circulation scheme for this depth range is characterized by anticyclonic flow that likely acquires significant tritium by cross-frontal mixing with the subpolar gyre to the north.

Although the 0.05 TU isopleth bows upward on both sides of the Mid Atlantic Ridge, the deep and bottom waters west of the Ridge have measureable tritium concentrations, ranging from 0.01 to 0.03 TU below 3000 m depth, with a westward/northward increase. This is consistent with the more rapid ventilation of the western basin by the deep western boundary undercurrents (Doney and Jenkins, 1994; Jenkins and Rhines, 1980; McCartney, 1992; Pickart and Hogg, 1989) that originate in the overflows between Great Britain and Greenland. Northwest of Bermuda, there is a significant tritium signal near the bottom associated with the deep overflow waters (Denmark Straits and Iceland-Scotland). Waters below 2500 m depth east of the Mid Atlantic Ridge are at or below detection limit, which is 0.002 to 0.003 TU. This is because this basin is ventilated from the south by tritium impoverished Antarctic Bottom Water (AABW) flowing through the Romanche Fracture Zone and by slow (century timescale) mixing of Iceland-Scotland Overflow water from the north (Schlitzer, 1987; Schlitzer et al., 1985).

We define the helium isotope ratio anomaly $\delta^3\text{He}$ relative to the atmospheric standard:

$$\delta^3\text{He} = \left(\frac{\left(\frac{^3\text{He}}{^4\text{He}} \right)_X}{\left(\frac{^3\text{He}}{^4\text{He}} \right)_{\text{Air}}} - 1 \right) \times 100\% \quad (1)$$

where the subscript X indicates the measured value. The $\delta^3\text{He}$ distributions seen in Figure 2 (lower panel) are controlled in large part by the penetration of tritium into the water column, with two significant exceptions. The first is the fact that air-sea exchange drives the dissolved helium isotope ratio anomaly toward a solubility equilibrium value of approximately -1.7% (Benson and Krause, 1980; Weiss, 1970) near the sea surface. The one deviation from this occurs off the Mauritanian coast, where the $\delta^3\text{He}$ is elevated by approximately 1% above equilibrium (see Figure 3). This is a surface manifestation of upwelling. We can utilize this observed excess ^3He to estimate upwelling rates by assuming a mixed-layer balance. Using NCEP reanalysis data, a Schmidt number of 125 for He, and the gas exchange formulation proposed by Tsai and Liu (Tsai and Liu, 2003) for surfactant influenced waters, we compute an average piston velocity for the previous 3 weeks of 5.0 m d^{-1} . This implies an ocean-atmosphere ^3He flux of $5 \text{ \%}\cdot\text{m d}^{-1}$. Given that this flux appears to extend $\sim 300 \text{ km}$ off the coast, we estimate a ^3He flux of approximately $1.5 \times 10^6 \text{ \%}\cdot\text{m}^3\text{d}^{-1}$ per m of coast. The maximum $\delta^3\text{He}$ observed in the water column is

~5% at 600 m depth, which is ~6.7% above equilibrium with the atmosphere. From this we can calculate an effective upwelling rate of $2.2 \times 10^5 \text{ m}^3 \text{ d}^{-1}$ per m coastline at that depth. Assuming this to be representative of the coast between Dakkar and Capo Blanco, this amounts to an upwelling of approximately 1.8 Sv for that region.

Figure 3: Measured $\delta^3\text{He}$ in the upper 50 m as a function of longitude along the zonal section. The solid line is the expected isotope equilibrium value, the lower dashed line is the mean value west of 22°W , and the upper dashed line is the mean east of 22°W .

Descending through the thermocline, $\delta^3\text{He}$ increases toward a maximum exceeding 8% at 600 to 900 m depth, generally below the depth at which tritium begins to decline steadily with depth. There is an additional $\delta^3\text{He}$ maximum at intermediate depths (~1800 m) emanating from the western boundary, and is associated with intermediate depth tritium maximum that finds its origin in the Labrador Sea. Further to the south and east, there is a significant intermediate depth (~1500 m) $\delta^3\text{He}$ minimum linked to the incursion of tritium impoverished waters from the south (notably AAIW and Upper Circumpolar Deep Water). West of 65°W below 4900 m, $\delta^3\text{He}$ also increases in association with a bottom tritium increase due to the influence of deep overflow waters from the north.

The second exception and most striking feature, however, is a strong $\delta^3\text{He}$ maximum centered over the central rift valley of the Mid Atlantic Ridge. Here, the isotope ratio anomaly approaches 25% (see Figure 4) at the core of an approximately 500 m thick plume centered around 3300 m depth. Although the

plume in Figure 2 appears to extend beyond the rift valley walls and into the surrounding stations, this is solely an artifact of the mapping/gridding methods. We have plotted the helium isotope ratio anomaly interpolated onto a suitably referenced potential density anomaly surface ($\sigma_{3000} = 41.484 \text{ kg m}^{-3}$ which corresponds to the core of the hydrothermal plume) against longitude in Figure 4.

Note that the vertical axis is logarithmic. A regional trend is sketched in with a dotted line in the figure. The conclusion to be drawn from Figure 4 is that although there is a gradual westward increase in $\delta^3\text{He}$, likely due to the intrusion of tritium and tritiogenic ^3He in the deep western boundary current system (this is more clearly seen in the section shown in Figure 2) the western flank station at around 50°W is clearly elevated by as much as 1% relative to that trend. The fact that the hydrothermal ^3He influence appears only in the western flank station is likely a consequence of beta-plume dynamics associated with buoyancy injection (Stommel, 1982), which drives an inflow from eastern flank and topographically trapped flow along the median valley (Thurnherr et al., 2002). It extends beyond the plume height because the rift valley walls block westward flow and the “escape” of the ^3He to the west is limited to breaks in the wall. There may also be a contribution from shallower hydrothermal sites to the north, although this is purely speculative.

Figure 4: $\delta^3\text{He}$ interpolated on the $\sigma_{3000} = 41.484 \text{ kg m}^{-3}$ potential density anomaly surface plotted as a function of longitude. This horizon corresponds closely to the TAG hydrothermal plume. Stations are connected by solid straight lines, while a dotted line showing the basin scale regional trend is shown for reference. Measurement errors are comparable to the size of the symbols.

The CTD temperature profiles, when plotted against potential density anomaly referenced to 3000 decibars, show elevated temperatures in the Rift Valley compared to the flank stations (Figure 5). The maximum difference approaches 0.038 °C, with the greatest difference just above the seafloor. We interpret this to be the result of diffuse conductive heating through the seafloor as well as direct buoyancy injection. If we attribute approximately two thirds of the temperature increase to the latter process, using a specific heat capacity of $3.9 \times 10^3 \text{ J Kg}^{-1} \text{ C}^{-1}$ we obtain a net heat injection into the plume of $\sim 100 \text{ J kg}^{-1}$ at the plume maximum. Compared to the observed plume ^3He anomaly of $7.3 \times 10^{-16} \text{ mol kg}^{-1}$, this yields a ^3He :heat ratio of $\sim 7 \times 10^{-18} \text{ mol J}^{-1}$. This compares well with other estimates, *e.g.*, ranging from 4×10^{-18} (Lupton et al., 1989) to $9 \times 10^{-18} \text{ mol/J}$ (Jean-Baptiste et al., 2004). Monitoring of the central black smoker complex at the TAG site led Goto et al (2003) to estimate the power output of this field to be approximately 70 MW with some temporal variation. Using our estimated ^3He :heat ratio we compute the ^3He output of this plume area to be $\sim 0.5 \text{ nmol s}^{-1}$, or approximately $\sim 15 \text{ mmol y}^{-1}$. Based on recent estimates of the global ^3He flux (Bianchi et al., 2010), we estimate this constitutes approximately 0.003% of the global input.

Figure 5: A plot of CTD temperature against potential density anomaly referenced to 3000 decibars for a flank station (gray dots) and the TAG plume station (black dots).

Finally, correlating excess TEIs (e.g., Fe) in the plume we can derive an estimate of the “raw” fluxes of these TEIs into the water column. Between 2500 and 3300 m depth a significant excess ^3He signal relative to neighboring stations can be seen on the western flank station (black circles compared to the black squares in Figure 4, left panel). Given the small tritium concentrations observed for these locations and depths ($\sim 0.03 \pm 0.01$ TU), it is unlikely the observed differences ($\sim 1\%$ in $\delta^3\text{He}$) are tritiogenic in origin. Thus it is possible that correlating TEIs with ^3He may be used to estimate regional or even global fluxes of “stabilized” phases of these TEIs, as has been done elsewhere (Boyle and Jenkins, 2008; Saito et al., 2013). This will be the subject of an upcoming paper.

4. The Tritium- ^3He Age

The concentrations of tritium and excess ^3He may be combined to estimate a *Tritium- ^3He Age*, which can be loosely interpreted as the time elapsed since a fluid parcel was last at the sea surface:

$$\tau = 17.763 \log \left(1 + \frac{[{}^3\text{He}]_{\text{Excess}}}{[{}^3\text{H}]} \right) \quad (2)$$

where we use the accepted half-life of tritium (12.31 years, MacMahon, 2006) to compute the mean life in years, and both tritium and excess ^3He are in molar units. To compute the excess ^3He we use

$$[{}^3\text{He}]_{\text{Excess}} = 0.01(\delta^3\text{He} - \delta^3\text{He}^*) R_A C(\text{He}) \quad (3)$$

where $\delta^3\text{He}$ is the helium isotope ratio anomaly expressed in percent, $\delta^3\text{He}^*$ is the solubility equilibrium helium isotope ratio anomaly (Benson and Krause, 1980), R_A is the atmospheric $^3\text{He}/^4\text{He}$ ratio (Clarke et al., 1976), and $C(\text{He})$ is the concentration of helium in molar units. The tritium concentration in TU can be converted to molar units by multiplying by $1.1102 \times 10^{-16} (1 - 0.001S)$, where S is the salinity.

The tritium- ^3He age distributions are presented in Figure 6. The major contour interval is 5 years, but in the shallow (1000 m) sections the 2, 4, 6, and 8 year isochrones are included as thin dotted lines. The age is within errors of zero at the surface with the exception of the Mauritanian upwelling region, where the surface ages are distinctly non-zero, and above 600 m depth the age isochrones bow upward. A feature that we don’t fully understand is that this bowing occurs away from the coast and that the isochrones actually tilt downward into the most shoreward station. We speculate that this may be the influence of an along-shore flow.

Figure 6: *The computed Tritium-³He age distributions.*

Before interpreting the thermocline tritium-³He ages more quantitatively, it is instructive to do a simple model comparison. We force an ensemble of simple box models with ventilation rates ranging from 1 to 100 years (see Jenkins, 1980) using a North Atlantic surface water tritium history proposed by Stanley et al (2012) from an initial condition of 0.5 T.U. at 1950 through 2011. In Figure 7 we compare the tritium-³He age computed from the evolved tritium and ³He concentrations the ensembles in the model year 2011 with the “actual” (box model turnover) age. Although this is a rather crude approximation, analysis of tracer (both CFCs and tritium-³He) distributions and their evolution in the North Atlantic thermocline and in numerical ocean models point to transit time distributions whose characteristic widths are comparable to their spreads (Peacock and Maltrud, 2006; Waugh et al., 2004), a feature that is not unlike our box model behavior for tritium-³He (Stanley et al., 2012).

It is notable that whereas there was a general tendency for the tritium-³He age to be biased low during the early years of the tritium-transient (Doney et al., 1997; Jenkins, 1980), the bias for intermediate time-scales (5-25 years) is now reversed. A rationale for this can be drawn from consideration of the advection-diffusion equations for the tritium-³He age (Jenkins, 1998) and the fact that we are now on the “back porch” of the transient. A broad conclusion to be drawn from this comparison is that the tritium-³He age is accurate to about 10-15% for timescales less than three decades, namely within the rough ventilation time-scales for the main thermocline. Thus it should be possible to use these ages to estimate TEI transformation rates. Clearly a more refined analysis using Transit time Distributions (TTD)

with other transient tracers (CFCs and SF₆) will yield more robust estimates. This will be the subject of a future paper.

Figure 7: A comparison of tritium-³He (solid line) vs. “actual” (dashed line) ages for a simple box model simulation.

Ages increase monotonically downward into and through the main thermocline. One notable geographic trend is the spreading of isochrones in the mode water regions (both the STMW near the western boundary current region and the Madeira Mode water formation area in the east. The ages of the water masses within these regions is consistent with the expected formation time-scales (*i.e.*, the approximate volume of the water mass divided by how much is formed each year) (Joyce et al., 2013; Worthington, 1959).

Below the thermocline, there is a dramatic penetration of mid-depth isochrones in both the northern part of the meridional section (associated with the Mediterranean Water and Labrador Sea Water) and in the western boundary current region (associated with Labrador Seawater). We again remark on the extended age minimum over the Mid Atlantic Ridge at 1500-2000 m depth linked to the tritium maximum with an intermediate depth anticyclonic flow influenced by entrained Labrador Sea Water. Note also the decrease in age with depth below 4500 m west of Bermuda. This is associated with increases in tritium, tritiogenic ³He, and CFCs, likely the influence of the deep overflow waters.

5. Summary and conclusions

We presented the observed distributions of tritium and $\delta^3\text{He}$ along the 2010-2011 U.S. GEOTRACES sections in the North Atlantic, and explain their large-scale characteristics in terms of the evolving bomb-tritium transient in conjunction with what is known about the ventilation and circulation of this ocean basin. The primary features of these distributions are consistent with what is known about North Atlantic circulation and ventilation, but there are a number of notable aspects, including:

- Surface elevated $\delta^3\text{He}$ and upward bowing thermocline isochrones in the Mauritanian upwelling region
- Significant intermediate depth penetration of tritium and tritiogenic ^3He associated with Labrador Sea Waters
- Evidence (including elevated tritium and lower tritium- ^3He age) of an anticyclonic flow centered along the Mid Atlantic Ridge at a depth of 1500-2000 m influenced by Labrador Sea Water
- A strong $\delta^3\text{He}$ plume (approaching 25% in magnitude) over the TAG hydrothermal site, with a characteristic $^3\text{He}:\text{heat}$ ratio of $7 \times 10^{-18} \text{ mol J}^{-1}$, and evidence of a small corresponding anomaly 500 km away on the western flank
- A clear bomb-tritium (and tritiogenic ^3He) signature in the western boundary current region

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