GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.2, PAGES 219-222, JANUARY 15, 1999

The impact of mid-depth recirculations on the distribution of tracers in the North Atlantic

M. Susan Lozier

Division of Earth and Ocean Sciences, Nicholas School of the Environment
Duke University, Durham, North Carolina

Abstract. An interesting feature of the waters carried equatorward by the Deep Western Boundary Current in the North Atlantic is their sharp vertical differentiation in tracer concentration and, accordingly, tracer age. In this work I demonstrate that the structure and lateral extent of the recirculations in the intermediate and deep North Atlantic have substantive differences with depth that can help explain the observed pattern of transient tracers such as tritium, ^{3}He and CFCs. While recirculations are present at all depths spanned by the boundary current, the distinct tracer minimum occurs at the depth where the recirculation extent is maximized. Overall, the effect of the large-scale recirculation at intermediate depths is to lengthen mixing pathways and to provide an alternate route for North Atlantic deep waters to enter the subtropical basin.

Introduction

Key to our understanding of the ocean's role in the global climate cycle is a determination of how climatic signals acquired at deep-water convection sites propagate from high to low latitudes. The extent to which climatic anomalies spread from their source region, and the rapidity of that spreading, determine the effectiveness of the deep ocean as a climatic reservoir. While the origin of high latitude newly-ventilated waters is identifiable by characteristic temperatures and salinities, the chemical signature of these waters yields information on the age of the water, which is defined as the time elapsed since the water was last at the surface. Thus, distributions of anthropogenic tracers, such as tritium, ^{3}He and chlorofluorocarbons (CFCs) introduced into the ocean during the past several decades, have been used extensively to not only map the equatorward spread of deep waters, but to also estimate the spreading rate of newly-ventilated waters through the North Atlantic [e.g., *Doney and Jenkins,* 1994; *Jenkins and Clarke,* 1976; *Jenkins and Rhines,* 1980; *Weiss et al.,* 1985; *Smethie,* 1993; *Molinari et al.,* 1998], where the majority of the global ocean's deep water is produced.

The Deep Western Boundary Current (DWBC) in the North Atlantic is the recognized conduit for tracer-rich newly-ventilated waters from high latitude sources. In an effort to show the continuity of the tracer signal carried by the DWBC, *Doney and Jenkins* [1985] created a composite downstream section of this boundary current from eighteen synoptic cross-sections of the DWBC, principally made as part of the 1981 Transient Tracers in the Ocean-North Atlantic Study [*Brewer et al.,* 1985]. Decay-corrected ages for the waters along the length of the DWBC were calculated from tritium and excess ^{3}He measurements [*Doney and Jenkins,* 1994] (Figure 1a).

Three cores characterize this section; relatively young waters occupy the upper and lower portion of the section, while older waters, centered at 2500 *m* in the western North Atlantic, are sandwiched in between, creating a distinct age maximum in this composite section. The younger waters carried by the deep core (~2-3°C) are believed to derive from the overflow waters of the Greenland-Iceland-Scotland ridge, while the waters carried by the shallow core (~4-5°C) are believed to derive from wintertime convection in the southern Labrador Sea [*Pickart,* 1992]. The tracer minimum water occupies the temperature range (~3-4°C) that is generally attributed to classical Labrador Sea Water [*Pickart,* 1992; *Smethie,* 1993], however, it has also been argued that the waters which display the tracer minimum signal derive from Iceland-Scotland Overflow waters [*Swift,* 1984]. Differences in renewal rates among these various water masses can create the relative age differences that are apparent at the upstream locations in Figure 1a.

Of interest for this paper is the downstream intensification of the tracer age maximum, manifested as a strong age gradient in both the alongstream and vertical direction as the DWBC flows from the Grand Banks to Florida. (The vertical direction in Figure 1a is parallel to the unit normal vector for a surface of constant potential density). An interpretation of this intensification is that the intermediate waters age more rapidly downstream than do the waters carried by the upper and lower cores of the DWBC. Apparently, the most rapid aging occurs at approximately 2500 *m*, where the maximum south of the Grand Banks is observed. Estimates of transit time from source regions that are based on tracer concentrations (~20 years) are much longer than the transit times estimated from direct velocity measurements (~2-4 years) [*Watts,* 1991]. Thus, it has been surmised that the waters at these depths have been either extensively mixed with surrounding waters [Smethie, 1993] or that they have not arrived via a direct route from the North Atlantic deep-water formation sites [*Watts,* 1991]. In this work I demonstrate that the intensified tracer minimum at intermediate depth, as well as the large discrepancy in tracer age, can be explained by recirculations in the horizontal plane.

Linkage between the Horizontal Flow and Tracer Fields

While the effects of recirculations in lengthening transit times and modulating tracer signals have been generally recognized, a determination of exactly how recirculations set the spatial and temporal distribution of tracers has been

Paper number 1998GL900264.
0094-8276/99/1998GL900264$05.00

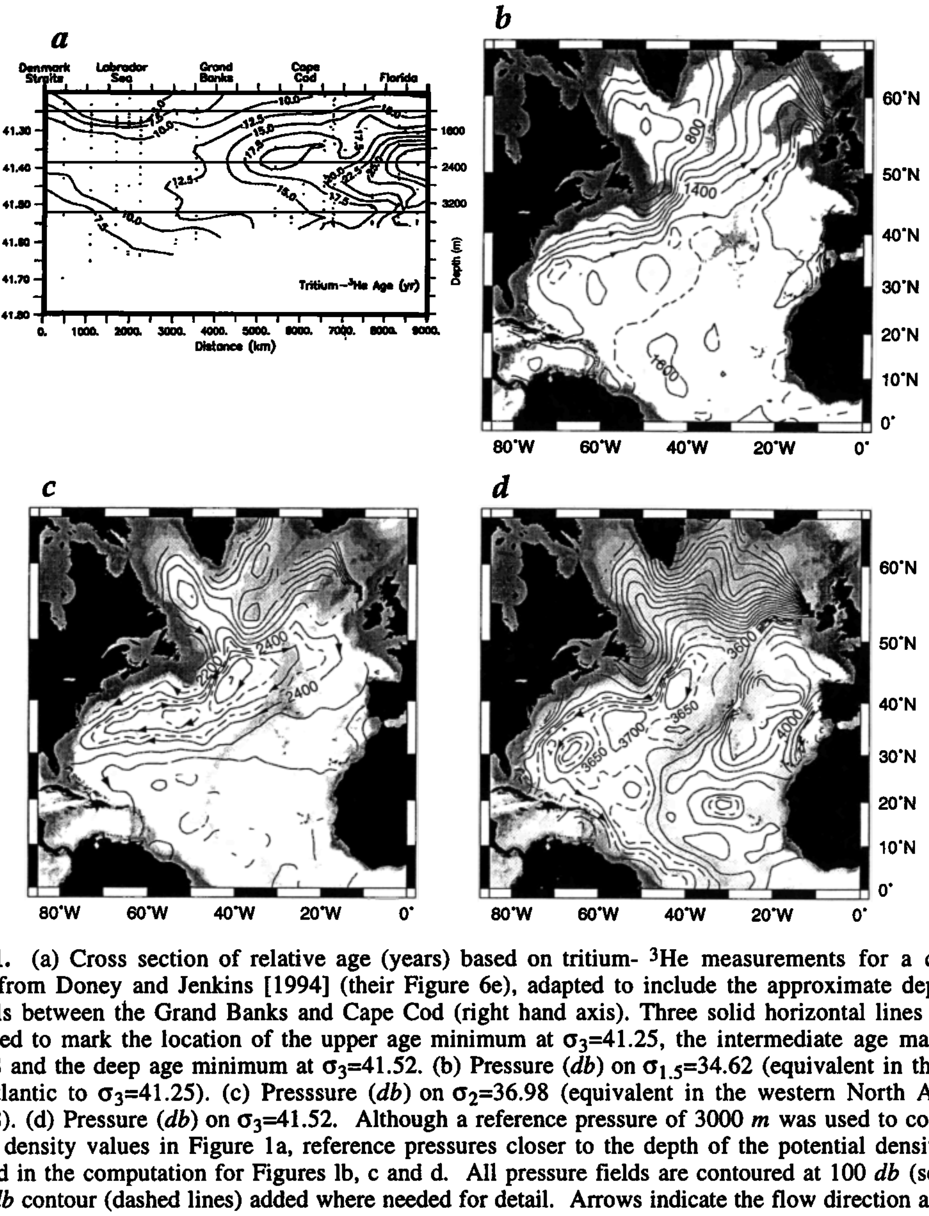

Figure 1. (a) Cross section of relative age (years) based on tritium- ^{3}He measurements for a composite DWBC, from Doney and Jenkins [1994] (their Figure 6e), adapted to include the approximate depth of the isopycnals between the Grand Banks and Cape Cod (right hand axis). Three solid horizontal lines have also been added to mark the location of the upper age minimum at σ_3=41.25, the intermediate age maximum at σ_3=41.38 and the deep age minimum at σ_3=41.52. (b) Pressure (*db*) on $\sigma_{1.5}$=34.62 (equivalent in the western North Atlantic to σ_3=41.25). (c) Presssure (*db*) on σ_2=36.98 (equivalent in the western North Atlantic to σ_3=41.38). (d) Pressure (*db*) on σ_3=41.52. Although a reference pressure of 3000 *m* was used to compute the potential density values in Figure 1a, reference pressures closer to the depth of the potential density surface were used in the computation for Figures 1b, c and d. All pressure fields are contoured at 100 *db* (solid lines) with 50 *db* contour (dashed lines) added where needed for detail. Arrows indicate the flow direction assuming a deep level-of-no-motion for the Gulf Stream, its recirculations and its extension into the North Atlantic Current, and a shallow level-of-no-motion for the DWBC. Bathymetry < 500 *m* and <1000 *m* is shaded dark and medium gray, respectively, for (b), (c) and (d) and bathymetry <2000 *m* is shaded light gray in (c) and (d).

stymied by the lack of information on the location, structure, and extent of recirculations in the western North Atlantic. Recently, however, recirculation patterns in the western North Atlantic have been detailed [*Lozier,* 1997] from an analysis of historical hydrographic data [*Lozier et al.,* 1995]. To illustrate the linkage between tracer extrema and recirculations, the flow fields, approximated by isobars on an isopycnal surface, for each of the three density surfaces that intersect a tracer extrema in Figure 1a are shown in Figures 1b-d. Just as there are three discernible cores to the tracer field of the DWBC, there are three distinct recirculation patterns below the thermocline in the western North Atlantic. It is noted that these recirculations are generally associated with the deep eastward-flowing Gulf Stream and not the DWBC itself. However, the juxtaposition of these two deep currents creates ample opportunity for water and property exchange [*Hogg et al.,* 1986; *Pickart and Smethie,* 1993]. Thus, it is implicitly assumed in this analysis that recirculation of Gulf Stream waters affects the properties carried by the DWBC.

On the upper surface (Figure 1b) the deep Gulf Stream waters extend northeastward into the North Atlantic Current and then further northward into the Norwegian-Greenland Sea, where they serve as source waters for deep-water formation. Recirculations at this depth are confined to small-scale, local gyres associated with the inertial recirculation of the Gulf Stream. In contrast, waters at intermediate depth in the Gulf Stream (~2500 *m*) (Figure 1c) are diverted into the North Atlantic Current, flow eastward over the Mid-Atlantic Ridge, and recirculate anticyclonically southwest of Ireland since their entrance to the northern seas is blocked by sill depths of ~1000 *m*. These waters flow westward back over the Ridge, continue along its western flank, and then turn westward near 37°N to rejoin the Gulf Stream, thus forming a strong, extensive anticyclonic recirculation of the subtropical waters

[*Lozier*, 1997; *Lozier et al.*, 1995]. On the lower surface at 3500 *m* (Figure 1d) recirculations of the deep Gulf Stream are restricted to the western side of the Mid-Atlantic Ridge, since eastward flow at this depth is blocked by the Ridge. The recirculations on the western side are local and not linked to form a large-scale gyre, as is found on the intermediate surface (Figure 1c). Thus, the two age minima in the DWBC are at depths where recirculations are limited in extent, while the age maximum (or tracer minimum) is located at a depth where the recirculation is maximized in extent.

The explanation for the correlation between water age and recirculation extent is twofold. First, as the extent of a recirculation is increased the mixing pathway is lengthened and, as a result, tracer concentrations are diluted. Second, the reach of this mid-depth gyre to the subtropical/subpolar boundary allows for a penetration of newly-ventilated waters from high latitudes along a route other than the DWBC. Tracers carried eastward by the North Atlantic Current can flow southward along either flank of the Mid-Atlantic Ridge [*Saunders*, 1982; *Gana and Provost*, 1993], and thus be entrained into the subtropical basin via a much longer route than the direct pathway provided by the DWBC. As suggested by *Watts* [1991], an indirect pathway could help to explain why the waters are older than expected at this depth in the subtropical waters. Additionally, with such a pathway, the waters in the DWBC would mix with older waters from the same source, minimizing tracer concentrations in the boundary current.

Cross-sections of Potential Vorticity and CFCs

To illustrate that the broad region of the tracer age maximum (Figure 1a) is matched by an equally broad region of recirculating flow, a zonal and meridional section of potential vorticity that cut across the large gyre in Figure 1c are shown in Figure 2. The broad vertical region of nearly uniform potential vorticity that characterizes both sections in Figure 2 is coincident with the depth range over which the large-scale gyre is observed. While previous modeling, theoretical and observational studies have established the homogenization of potential vorticity in the plane of the flow [*Holland and Rhines*, 1980; *Rhines and Young*, 1982; *Lozier*, 1997], large-scale vertical homogenization has not been previously noted. However, supporting evidence for this homogenization in the climatological mean potential vorticity field comes from local, synoptic measurements taken offshore of the DWBC [*Pickart*,1992]. Property homogeneity often indicates the presence of a single water mass. However, local convection at subtropical latitudes does not reach these depths and an analysis of the climatological property fields suggests that this homogenization is not imported from higher latitudes. The remaining supposition is that the homogenization is a result of local processes associated with the recirculating flow field. The homogenization of potential vorticity in these sections not only identifies where the large-scale recirculation resides in vertical space, but also allows the tracer signals to be placed in the context of the recirculation. It is evident from Figure 2 that the upper and lower tracer cores are not within the region of homogenized potential vorticity and that the intermediate core, where tracer concentrations are a minimum, is situated in the middle of this homogenized region.

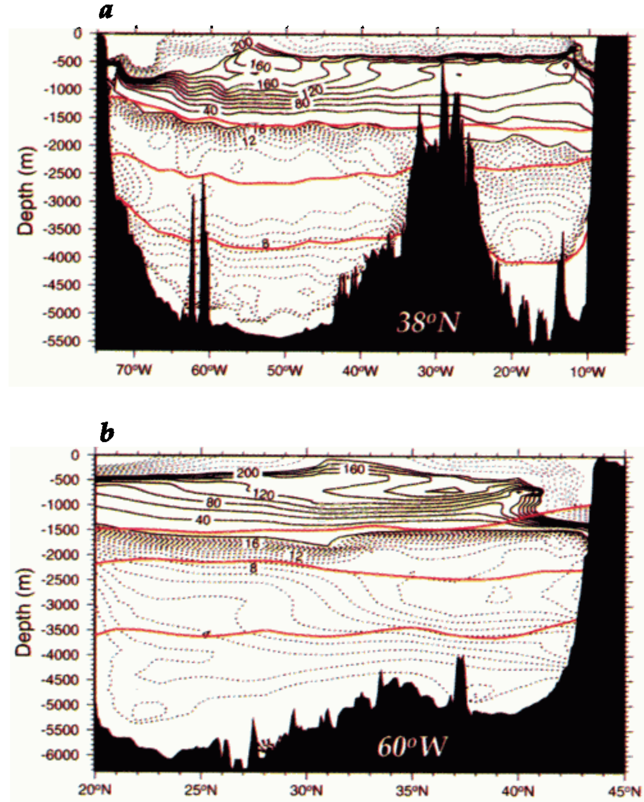

Figure 2. Cross section of potential vorticity (x $10^{-12} m^{-1} sec^{-1}$) at (a) 38°N and (b) 60°W. Potential vorticity is calculated as $f/\sigma_0 \times \partial\sigma_0/\partial z$, where f is planetary vorticity, z is the vertical coordinate, and σ_0 is a constant potential density. The vertical derivative is computed locally over a nominal depth of 100 *m*. Potential vorticity is contoured at 1 x 10^{-12} $m^{-1}sec^{-1}$ (dashed lines in lower portion of panel, 20 x 10^{-12} $m^{-1}sec^{-1}$ (solid lines) and 200 x 10^{-12} $m^{-1}sec^{-1}$ (dashed lines in upper portion of panel). The upper ($\sigma_{1.5}$=34.62), middle (σ_2=36.98) and bottom (σ_3=41.52) red lines are the isopycnal surfaces displayed collectively in Figure 1a and in Figures 1b, c and d respectively.

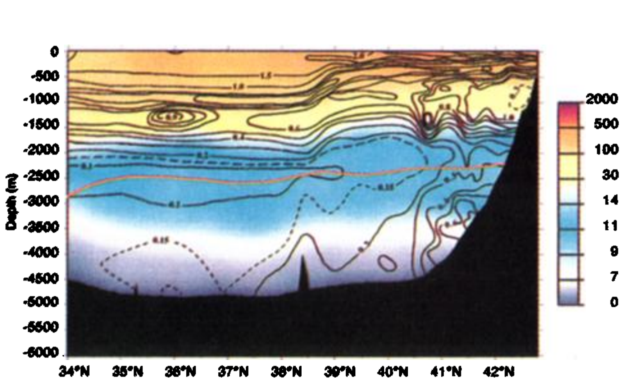

Figure 3. Cross section at 63°30'W of a shaded field of potential vorticity superposed with contours of CFC-11 (*pmol/kg*). The CFC data are from Figure 7 of *Smethie* [1993], while the potential vorticity field was estimated using a climatological database [Lozier et al., 1995]. The orange line is the position of the σ_2=36.98 isopycnal. Blue shading represents the homogenized region of potential vorticity (designated by the 9-12 x 10^{-12} $m^{-1}sec^{-1}$ contours).

To make a more direct association between the tracers in the DWBC and the interior recirculation, a cross section of the climatological potential vorticity field across 63°30'W is shown in Figure 3. This section was chosen because it approximately coincides with a synoptic survey of CFCs conducted in 1985 [*Smethie,* 1993]. Measurements of CFCs for this survey extended over 1000 *km* offshore, past the DWBC and the deep Gulf Stream, into the basin interior at ~34°N. The CFC-11 minimum extends well offshore and is centered within the region of homogenized potential vorticity (Figure 3), indicating that the tracer minimum is embedded within a relatively thick layer of horizontally recirculating flow. As seen in Figure 3, the often-noted offshore deepening of the tracer minimum can be attributed to the deepening of the isopycnal surface in this locale. The tracer field in Figure 3 shows little contrast between the boundary current and the ocean interior, indicating a large degree of exchange between the two. A recent synoptic survey found differences in the property values carried by the DWBC and the ocean interior to be minimized at approximately 3.0°C [*Pickart,* 1992], which lies approximately at the depth of the tracer minimum, and not surprisingly, at the depth of the largest recirculation.

The tracer field in Figure 3 exhibits a minimum at intermediate depths, yet the potential vorticity field, although homogenized, does not have a local extremum in its vertical field. These differences are likely created by the separate and distinct distribution of sources and sinks for each of these tracers. Additionally, differences in their advective/diffusive patterns, perhaps attributable to the difference in how a passive (CFC-11) and active (potential vorticity) tracer mix, can potentially create differences in tracer or property distributions. It is suggested, however, that the vertical homogenization of potential vorticity and the local tracer minimum are both dynamically linked to the large-scale recirculation found in the climatological fields.

Summary

It has generally been recognized that tracer ages represent upper limits on water mass ages due to mixing along the water mass pathways. Thus, tracer ages have often been interpreted as relative ages, with the implicit assumption that mixing along the pathway of a water mass is the same everywhere. However, the demonstrated dependence of the tracer ages on the spatial structure of the flow field belies such an assumption. It has been shown here that estimates of tracer age must account for circulation features in order to produce realistic interpretations of water mass transit times. Because circulation features, such as the large scale recirculation which is the focus of this paper, may change in time, a comparison of tracer ages from one climatic regime to the next must account for differences in circulation strength and pattern.

Acknowledgments. I thank S. Doney and B. Smethie for permission to use their published figures and M. lorga and C. Forbes for graphical assistance. Support from the National Science Foundation (grant OCE-9629489) is gratefully acknowledged.

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M. Susan Lozier, Division of Earth and Ocean Sciences, Nicholas School of the Environment, Box 90230, Duke University, Durham, North Carolina, 27708-0230.

(Received September 4, 1998; revised November 11, 1998; accepted November 18, 1998.)