The Western Boundary Undercurrent off the Bahamas

DONALD B. OLSON AND GOTE H. OSTLUND

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149

JORGE SARMIENTO

Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ 08540

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ABSTRACT

Two tritium sections through the deep western boundary current east of the Bahamas taken in late 1980 and early 1981 are presented. Tritium from the bomb tests in the late 1950s and early 1960s is used to identify recently formed deep waters in the sections. High concentrations are found in the North Atlantic Deep Water. Low tritium values occur in the Labrador Sea Water found above the core of this deep water. This is consistent with the suggestion by Talley and McCartney that this water mass has not been ventilated at the temperatures observed in these sections since the mid-1950s. Tritium in the sections is correlated with maxima in potential vorticity. This is inconsistent with deep convection as a direct source for the water mass. The potential vorticity maxima may be associated with plume dynamics near the overflow regions or with the dynamics of the deep western boundary current. The sections are south of the section discussed by Jenkins and Rhines where high tritium concentrations were found along the topography on the Blake-Bahama Outer Ridge between 3.5 and 4.5 km depth in late 1977. In the sections farther south a similar maximum is found, but it is at a 0.6°C warmer potential temperature and separated from the topography. Tritium is found at the temperature it appears in the Jenkins and Rhines section. In contrast to their concentrated feature, the tritium in the later sections is spread out into a layer which extends into the ocean interior to the limit of the sections in these temperature ranges. This coupled with dynamic height fields suggests that the boundary current feeds an offshore flow into the ocean interior east of the Bahamas. The change in the temperature where the tritium maximum is found implies variations in the formation and spread of North Atlantic Deep Water on fairly short time scales.

1. Introduction

One of the least understood components of the general circulation in the ocean is the thermohaline circulation. Essentially all the physical processes associated with the deep circulation, from convection and mixing in high latitude formation regions to the dynamics of the deep flows through the ocean basins, require further study. The discovery of fairly rapid currents at great depths in the ocean over two decades ago was the first indication of reasonably fast responses along western boundaries of oceans to the formation of dense water masses in polar regions. High velocity currents consisting of waters of polar origin crossing under the Gulf Stream were described by Swallow and Worthington (1961), Barrett (1965), Richardson and Knauss (1971), and Richardson (1977). The existence of these flows supported the picture derived from simple laboratory models and theories proposed by Stommel and Arons (1960a,b). The continuation of this deep western boundary current southward to the Blake–Bahama Outer Ridge was confirmed by Amos et al. (1971). The time scales for these processes were further confirmed by the measurement of bomb derived tritium in the deep western boundary current taken by Jenkins and Rhines (1980, hereafter referred to as JR). A further link between the western boundary undercurrent and the formation areas shows up in the distribution of a potential vorticity minimum associated with Labrador Sea Water (Talley and McCartney, 1982). Farther to the south, at the equator, Weiss et al. (1985) have found freon in the salinity maximum layer associated with the Upper North Atlantic Deep Water. They identify their freon maximum as part of the Labrador Sea Water although the salinity maximum implies some influence of Northeast Atlantic Deep Water which is in turn influenced by the Mediterranean outflow.

Observations of the deep western boundary current show an intermittent flow of dense waters along the North American Slope and Rise north of the Gulf Stream. Some of this fluid is observed to cross under the Stream just off Cape Hatteras (Richardson and Knauss, 1971; Richardson, 1977) although there are examples of fluid entering the subtropical gyre farther east (McCartney et al., 1980). South of Cape Hatteras there is a strong deep current to the south along the edge of the Blake Plateau and Blake–Bahama Outer Ridge (Amos et al., 1971; JR). The section in JR, modified to take into account tritium decay to a date of

1981/01/01 as described below is reproduced in Fig. 1. To facilitate comparison with ours, the JR numbers from August 1977 have been decay corrected by multiplication by 0.852. The section shows a narrow plume of tritiated water following the crest of the Blake–Bahama Outer Ridge at 31°N. Records from current meters deployed in this area of the JR section (Mills and Rhines, 1979; JR) show persistent along bathymetry flow with mean velocities of 0.20 m s^{-1}. The current also appears in deep current measurements just north of the Bahamas at approximately 28°N as reported by Lai (1984). The relatively high speed flow along the boundary has been traced with SOFAR floats at approximately 2000 m by Riser et al. (1978).

The data presented here cover the boundary current farther south along the Bahamas at the separation between the Gulf Stream recirculation and the southern North Atlantic subtropical gyre. An overview of the regional circulation with an emphasis on the upper layers of the water column is given in Olson et al. (1984). Hydrographic stations extending out from the boundary were taken as part of the Navy sponsored Antilles Current Experiment and on Leg II of the Transient Tracers in the Ocean (TTO) program. The sections extend out, normal to the Bahama Island arc, from points at approximately 26° and 22°N. Cruises were in a seven month period starting with R/V *Researcher* and *Iselin* cruises in October–November 1980 and ending with the R/V *Knorr* TTO cruise in April 1981. Tritium samples were collected along the sections and analysed at the University of Miami Tritium Laboratory. Temperature and salinity data were taken with

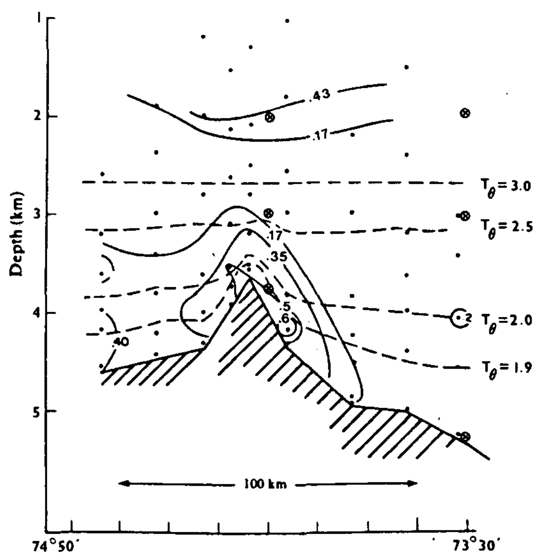


FIG. 1. Tritium and potential temperature for the Jenkins and Rhines (1980) section across the Blake–Bahama Outer Rise at 31°N. The figure is a modification of that in their paper where the tritium values on their contours have been changed to reflect a 1981 standard time for the tritium.

Neil Brown CTDs with support of rosette bottle samples.

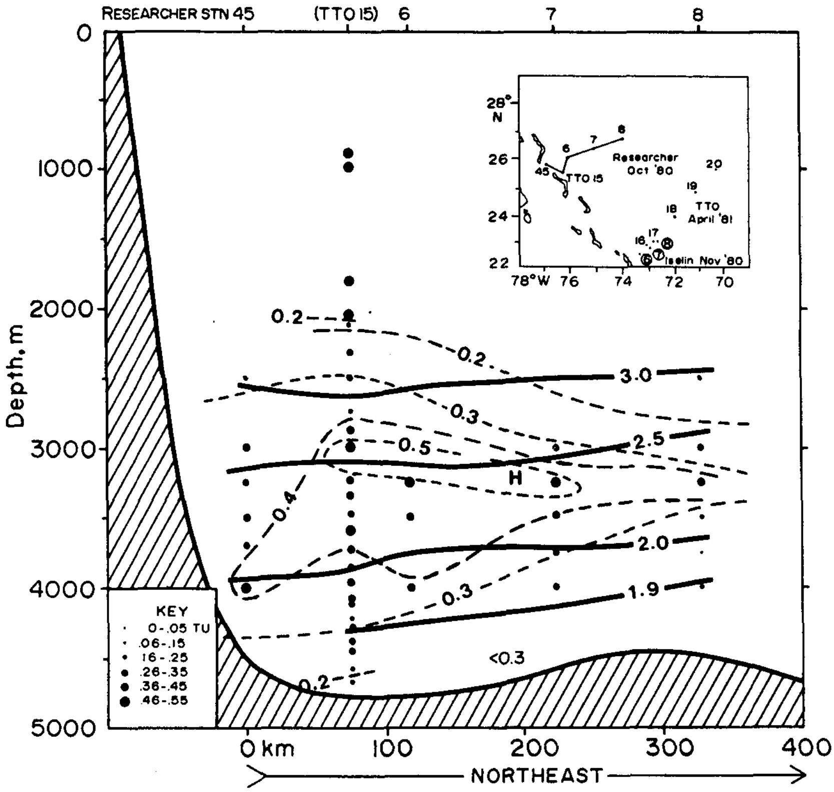
Tritium measurements normally include electrolytic enrichment of 275 ml water to 3.25 ml and subsequent low-level gas proportional counting for 20 hours. The sensitivity and accuracy at very low tritium concentrations are then 0.04 to 0.06 TU [the unit TU is (T/H)10^{18}, abundance ratio]. Due to the importance of resolving very low TU values in this study, most samples were started from 500 ml, and enriched samples counted for 40 hours to give errors of 0.015 to 0.030 TU. Errors quoted are one sigma, all conceivable contributions included. Established blank values for this period of 0.00 to 0.01 TU have been subtracted. Furthermore, in the TU plots the tritium ratios have been recalculated to the date 1981/01/01, with the new recommended half-life of 12.43 years. This unit is named TU81N. On 81/01/01 TU values in the new scale are 3.1% higher than in the old scale. For a comprehensive description of TU scales see Mann et al. (1982).

2. Sections off the Bahamas

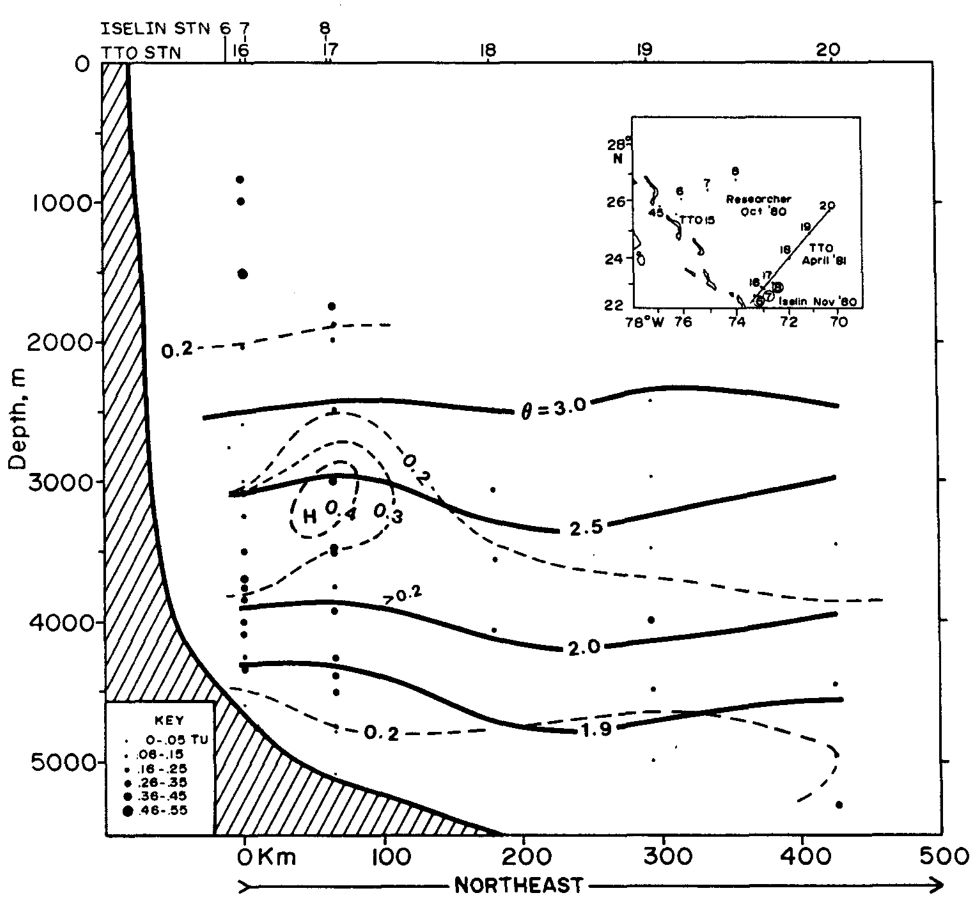
Cross sections of tritium and potential temperature across the western boundary regime along the Bahamas are given in Fig. 2. The northern section, Fig. 2a, extends out of the Northeast Providence Channel from approximately 26°N, 78°W to 27°N, 74°W.This section was occupied by the *Researcher* in October–November 1980 with an additional station shifted slightly off the station line on the TTO cruise in April 1981. The second section, Fig. 2b, extends along a line of moorings deployed as part of the Antilles Experiment (Olson et al., 1984; Zantopp and Leaman, 1984) from approximately 22°N, 73°W out perpendicular to the boundary to 26°N, 70°W. While stations along the sections are separated by up to seven months in time, little difficulty is encountered in contouring the October–November and April data together in the way it is presented.

Both sections show a tritium concentration maximum approximately 100 km from the boundary. This maximum occurs at potential temperatures around 2.5°C in both sections. The corresponding maximum in the JR section converted to TU81N is about the same, 0.5 to 0.6 versus 0.4 or 0.5, but occurs at lower temperatures (1.9°C). Temperatures of 1.9°C correspond to the lower limit of the 0.2 TU81N contour in Fig. 2. In density space the tritium maximum along the Bahamas occurs at sigma-4 (potential density relative to 4000 db, Reid and Lynn, 1971) between 45.80 and 47.86. Relative to a 2000 db reference these maxima are at densities sigma-2 = 37.05 and 37.08. These

FIG. 2. Sections taken off the Bahamas in 1980–81 by the R/Vs *Researcher, Knorr,* and *Iselin.* Tritium (TU81N) and potential temperature are contoured in the figure. The station lines relative to the Bahama Island arc are shown in insets in the figure.



RESEARCHER STN 45
(TTO 15)
6
7
8
Depth, m
0
1000
2000
3000
4000
5000
0 km
100
200
300
400
NORTHEAST
3.0
2.5
2.0
1.9
0.2
0.3
0.4
0.5
H
<0.3
KEY
0-.05 TU
.06-.15
.16-.25
.26-.35
.36-.45
.46-.55
28°
N
26
24
22
78°W
76
74
72
70
Researcher
Oct '80
TTO 15
TTO
April '81
Iselin Nov '80



ISELIN STN 6 7
TTO STN
8
16
17
18
19
20
Depth, m
0
1000
2000
3000
4000
5000
0 Km
100
200
300
400
500
NORTHEAST
θ=3.0
2.5
2.0
1.9
0.2
0.3
0.4
H
>0.2
KEY
0-.05 TU
.06-.15
.16-.25
.26-.35
.36-.45
.46-.55
28°
N
26
24
22
78°W
76
74
72
70
Researcher
Oct '80
TTO 15
TTO
April '81
Iselin Nov '80

levels are also part of the oxygen maximum layer. From this combination of evidence they can be classified as part of what Wust (1935) calls the Middle North Atlantic Deep Water.

The horizontal extent of the tritium plume in these two southern sections is more extensive than the one observed by JR. In the previous measurements at 31°N the core of the tritium plume is only 50 km wide with the 0.17 TU81N contour extending 100 km or so in the horizontal. In fact, if the crest of the Blake–Bahama Outer Ridge is taken as the western boundary under current width to the north, the tritium core in Fig. 1 is less than 50 km wide in the 0.17 contour. In the latter sections to the south the width of the highest contour is 50 to 100 km with the 0.2 contour extending outward across the entire width of the sections, i.e., more than 300 km. Most of the extension of the tritiated fluid out into the center of the basin in Fig. 2 is at somewhat lower temperatures than the tritium maximum. Tritium falls off to levels lower than 0.20 at depths below 4500 m in the southern sections while the maximum in the JR section rests on the topography at depths around 4000 to 4250 m.

In all three sections the deep tritium maximum is separated from the high tritium surface waters by a layer of water with concentrations less than 0.2 TU. This tritium minimum occurs between 3.0 and 3.5°C in waters whose origin is in the Labrador Sea (Talley and McCartney, 1982). The thickness of the minimum is smaller in the 1980–81 sections. The section off Providence Channel (26°N) has only one bottle in TTO station 15 with tritium less than 0.2 TU81N. The details of this tritium minimum and its relationship to the stratification can be seen more easily in individual station profiles.

3. Tritium and potential vorticity

The vertical distribution of tritium as a function of the potential temperature relative to the surface is given in Fig. 3a. Station 15 of the April R/V *Knorr* (TTO) cruise is chosen due to the dense vertical sampling of tritium compared to other stations. The principal features in this station are comparable to those in others along the sections. The stratification is presented as weighted by the Coriolis parameter to form an estimate of potential vorticity in Fig. 3b. The potential vorticity is calculated ignoring the contribution of the relative vorticity and is based on layers 0.02 sigma units apart. The analysis is essentially the same as in Talley and McCartney (1982) with the exception of the deeper reference levels for the density computations (2000 and 4000 as compared to their 1500 db). Rather than carefully compute the isentropic surfaces in the sections using a scheme such as presented in Bray and Fofonoff (1981) two references for the density computation are used. The actual potential vorticity values vary with the reference pressure but the basic features in the profile appear in either computation.

There is a clear relationship between the potential vorticity and the tritium profile. Potential vorticity is at a minimum at 3.75° and 3.00°C while the minima in tritium are at slightly lower temperatures, 3.50° and 2.85°C. The profiles are quite similar with an intervening maximum in both tritium and potential vorticity at 3.25°C. The potential vorticity and the tritium increase sharply in waters warmer than four degrees. The potential vorticity minima with low tritium can both be interpreted as corresponding to the layer identified by Talley and McCartney as Labrador Sea Water. The waters at the lower minimum in potential vorticity are only slightly colder than the level they have being isolated from surface convection after 1956 at OWS Bravo in the Labrador Sea. The low tritium values reinforce this conclusion since the bomb produced tritium entered the system after 1956. The upper tritium and potential vorticity minima are more difficult to place in terms of the Labrador Sea record in Talley and McCartney (1982), who show convection approaching 3.75°C at Bravo in the early 1970s. These waters would have high tritium concentrations and therefore cannot be tied to the layer in Fig. 3. Direct observations of a convective event in the Labrador Sea in 1976 by Gascard and Clarke (1983) show Labrador Sea water formed at 2.9°C. This water is apparently not seen in the section either. The recent discovery of a freon maximum centered around 4°C in the equatorial western boundary layer by Weiss et al. (1985) has been interpreted to be of Labrador Sea origin. This temperature range shows elevated tritium in Fig. 3.

The high tritium concentration waters at 2.5°C are correlated with a potential vorticity maximum. In the logic put forward by Talley and McCartney (1982) this would rule out a direct source of this water through winter convection. This perhaps arises from the formation of this water as a mixture of waters in the ocean interior. Alternatively, the stability maxima might be the result of intrusive plume dynamics in the western boundary current or farther north in the overflow regions which separate the convective source regions of the component waters from the rest of the North Atlantic. Both quantities fall off to low values at the bottom of the profile.

4. The deep western boundary current off the Bahamas

The deep circulation east of the Bahamas can also be discerned from the deep dynamic height patterns. Dynamic heights for 3000/1000 and 4000/2000 m levels along the sections in Fig. 2 and a similar line to the south are shown in Fig. 4. The location of these sections relative to larger scale dynamic height fields from the Levitus (1982) data set are given in Fig. 5. The reference levels in Fig. 4 and 5 are chosen based on year-long

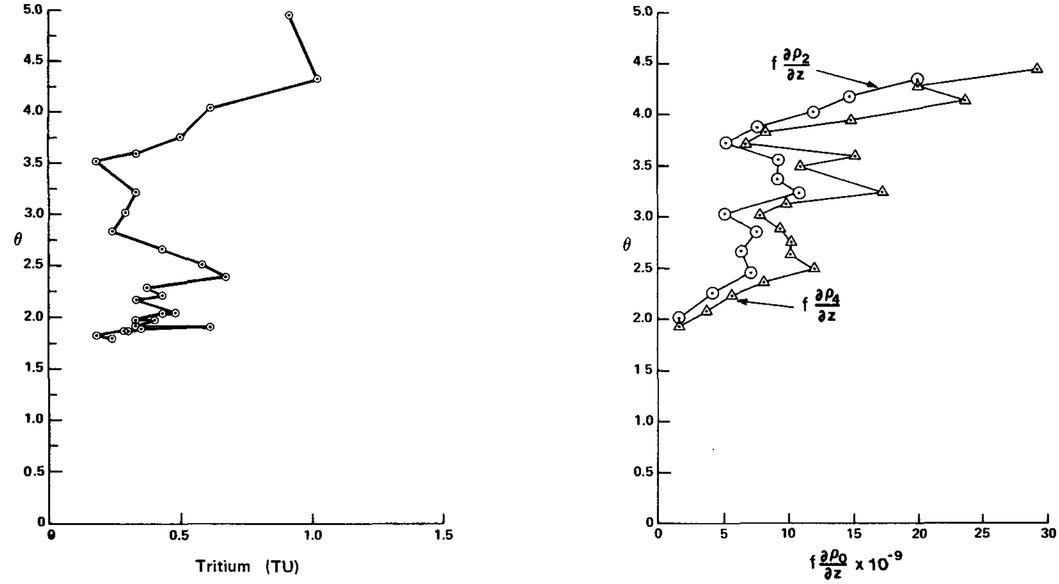


FIG. 3. Tritium and potential vorticity versus potential temperature for R/V *Knorr* TTO Leg II station 15 on the northern section in Fig. 2. The potential vorticity has been computed using profiles of potential density with both 2000 and 4000 db references. Details of the computation are discussed in the text.

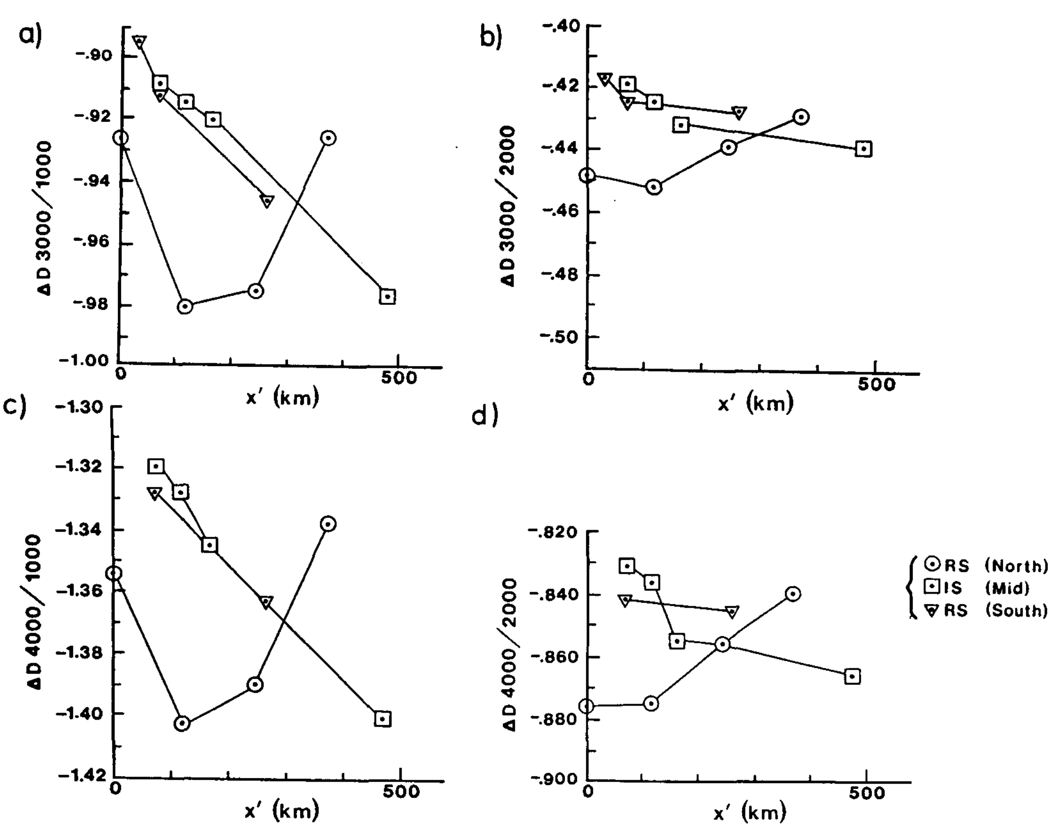


FIG. 4. Dynamic height as a function of distance from the edge of the Bahama platform for three sections occupied in October and November 1980. The locations of the sections are shown in Fig. 5. Symbol notation denotes the sections from north to south and the ship involved, *Researcher* (RS) or *Iselin* (IS). (a) Dynamic height of the 3000 m level relative to 1000 m (3000/1000 m), (b) 3000/2000 m, (c) 4000/1000 m, and (d) 4000/2000 m.

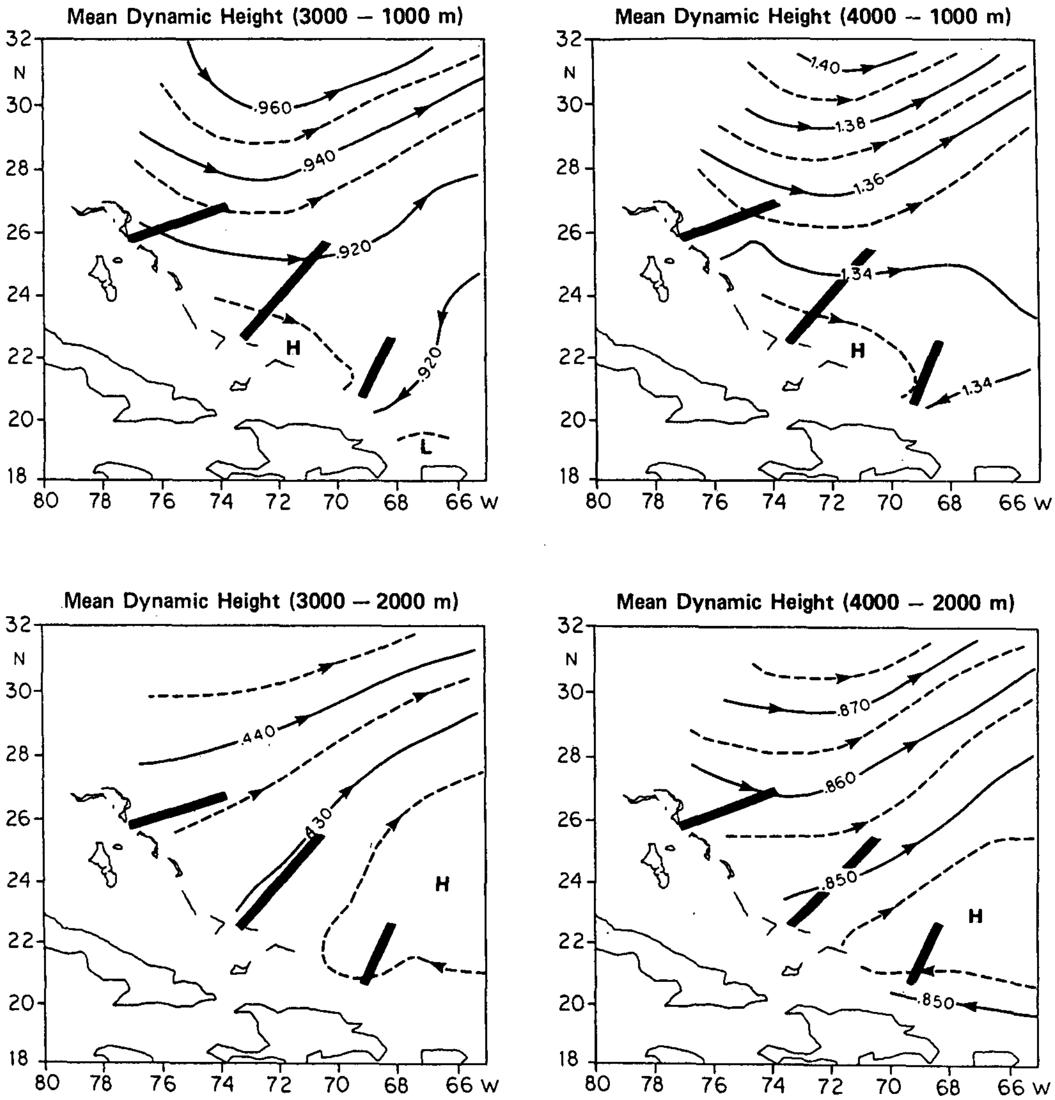


FIG. 5. Dynamic heights for (a) 3000 m and (b) 4000 m relative to a 1000 m reference and the same levels relative to a 2000 m reference (c, d). Data are from the Levitus Atlas (Levitus, 1982). The Levitus (1982) data are derived from historical data with an objective analysis scheme whose smoothing component has a 50% amplitude point at 1200 km. The result is gridded on a one degree grid and made available on tape. Thick lines extending out from the boundary indicate the sections shown in Fig. 4.

current meter measurements in the region between 23° and 27°N by Olson et al. (1984). These mooring data show minimum currents near the 1000 m level along the southern Bahamas and in the interior of the gyre. A mooring along the northern section shows a deeper level of no-motion. All of the moorings show rapid increase in velocity above 1000 m while SOFAR floats at approximately 2000 m show consistent southward flow along the boundary (Riser et al., 1978). This suggests a level of no motion between these two depths. To facilitate interpretation deep dynamic topographies from both the 1000 and 2000 m level are shown in Figs. 4 and 5.

Dynamic heights in Fig. 4 indicate a stronger pressure gradient across all of the sections for a 1000 m level of no motion than for the 2000 m one. The two southern sections have southward flow across the entire section for either choice of reference. A reversal in flow, from southward at the boundary to northward offshore, appears in all the northern computations except the 4000/2000 m case where the flow is northward across the entire width. This feature may be a time dependent reversal in the current, or it may be a deep cyclonic reflection of the anticyclonic eddy, which appears to be a quasi-permanent feature of the near surface circulation in this region (Olson et al., 1984). Comparison of the sections suggests an increase in pressure to the south along the boundary assuming a constant reference or alternatively shoaling of the reference level in this direction. The latter is suggested by current meter records in the area (Olson et al., 1984).

The dynamic height fields in Fig. 5 give a picture of flow into the interior of the gyre from the western boundary. A similar conclusion can be reached from the dynamic height maps in Stommel et al. (1978). The dynamic heights taken along the sections (Fig. 4) show an increase in pressure to the south along the boundary in agreement with the large scale pattern although there is not one-to-one correspondence in values arising from time dependence in the fields and the smoothing of the Levitus data.

The offshore flow is probably responsible for the extension of tritiated water out into the ocean interior as observed in Fig. 2, although the eddy field along the boundary must also play a role. This does not mean there is not a more or less continuous current to the south along the boundary, but rather that this current must be adding flow to the interior to match with the large scale flow. The changes in the tritium cross sections and dynamic height fields from north to south support a change in the character of the deep western boundary current from north to south along the Bahamas. The tendency for the 4000 m flow to be directed offshore relative to the 3000 m flow for either of the reference depths in Fig. 5 is consistent with the extension of the tritium plume offshore at these depths.

5. Discussion and conclusions

The tritium sections in Fig. 2 along with the historical temperature and dynamic height patterns suggest the deep western boundary current becomes less topographically bound along the outer edge of the Bahamas as compared to the JR section. This conclusion is similar to that reached by Tuckolke et al. (1973) and might be anticipated through a consideration of the geometry of the boundary which changes abruptly at the JR section and to the south. From the available data it is not clear whether a plume of tritiated water extends eastward into the gyre interior or if the results in Fig. 2 are indicative of the influence of the eddy field. The dynamic heights in Fig. 5 suggest that part of the tritium extending into the interior is carried out of the boundary layer by the mean flow. A similar flow into the ocean interior is expected from the inertial models of Stommel and Arons (1960a,b). Whatever the exact causes, the evidence suggests variations in the character of the deep western boundary current in space as one proceeds south of the JR section.

The temporal variation implied by the data set presented here are perhaps of greater interest. The absence of tritium in the Labrador Sea Water confirms the observations of deep convection in the Labrador Sea described by Talley and McCartney (1982). The shift in potential temperature of the tritium maximum between the JR section and those presented here also implies a change in North Atlantic Deep Water formation to warmer temperatures. The suggested shift is large, 0.6°C, compared to expectations based on traditional pictures of the deep waters of the world ocean. Comparison of the IGY section at 24°N with a 1981 section by Roemmich and Wunsch (1984) show no change in the vertical temperature structure across the deep western boundary current although there are changes at other depths. Shifts in the properties of the deep waters in the far North Atlantic from later cruises in the TTO program show a freshening of the waters above and below the density and temperature range associated with the tritium plume in the present sections (Brewer et al., 1983). This shift in waters between Labrador and England is not manifested in temperature. The observations presented here may imply a change in the time history of different components of North Atlantic Deep Water rather than an actual long term change in formation of these waters. For example, the mesoscale convection event observed by Gascard and Clarke (1983) may be responsible for variations in the degree of ventilation of the deep water as a function of space and time in the deep western boundary current. Careful analysis of the tracer properties in the North Atlantic should provide a fuller delineation of the variations in deep water formation over the past few decades and an idea of the shorter time and space scale changes in the meridional exchange of these waters.

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