ON THE NORTH ATLANTIC CIRCULATION

William J. Schmitz, Jr., and
Michael S. McCartney

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Abstract. A new, speculative, and, we hope, provocative summary of the North Atlantic circulation is described, including both horizontal currents (wind-driven) and the primarily (thermohaline) meridional flows that involve the transformation of warm to cold water at high latitudes. Our picture is based on a synthesis of a variety of independent investigations that are contained in the literature as opposed to a presentation of the results of one technique or the point of view of one author. We describe a thermohaline cell (the so-called thermohaline conveyor belt) that is concentrated within the Atlantic and Southern oceans (rather than essentially global), with the most important upwelling sites being in the circumpolar and the equatorial current regimes. We concentrate on deep water formation and its replacement relative to intermediate-water formation. It has been pointed out recently that the formation of 13 Sv (1 Sv = 10^6 m^3 s^{-1}) of southward flowing North Atlantic Deep Water is compensated for in the upper ocean by northward cross-equatorial transport. We suggest that this thermocline layer flow passes through the Straits of Florida, transits the Gulf Stream system on its inshore side, and exits through the North Atlantic Current system after recirculation and modification. There is now a clear observational basis for the structure of recirculating gyres on the southern and northern sides of the Gulf Stream. We suggest a recirculation for the North Atlantic Current as well. We also describe a C-shaped component to the southern Gulf Stream recirculation and identify a roughly 10-Sv circulation in the eastern North Atlantic associated with the Azores Current. Recirculations play an important role in deep boundary current regimes and in water mass formation and modification. The transport of the deep western and northern boundary currents in the North Atlantic Ocean may be boosted (roughly doubled or tripled) by counterclockwise recirculating gyres and by additions of modified bottom or intermediate water. While the North Atlantic is the most completely observed ocean, there are still significant gaps in our knowledge of its circulation.

INTRODUCTION

Where does the water come from, where does it go, and what happens along its path? These seemingly simple questions about the oceans' (semi-) permanent circulations are at the heart of physical oceanography. Answers are sought from hydrographic data and direct current observations and tracer measurements, and ideas are dissected with analytical fervor. The North Atlantic Ocean is the most completely observed and extensively studied of all the world's oceans, and yet it still resists thorough description and rationalization. More observations and higher-resolution models using cutting edge supercomputers have helped but have not yielded satisfaction that an accurate picture is at hand. However, it is now possible to present a replacement for the North Atlantic circulation scheme hypothesized by *Worthington* [1976] (hereinafter W76) and resolve many of the transport dilemmas he highlighted. Basically, what we do is describe a general circulation that is compatible with community wisdom as opposed to one author's idea or the results of one approach or method.

The difficulties experienced by W76 and us in producing a circulation scheme arise to a large extent because there are only a few circulation components that are quantitatively tightly constrained. That is, we rarely are able to measure transports very well. Uncertainties in transport estimates are typically at least 5–25%, with the smaller error unique to well-defined channels like the Straits of Florida. Careful treatments of individual basins or smaller regions may not be particularly compatible when merged, even though the individual treatments may each appear "right." For many locations the intensity of the general circulation is obscured by the presence of mesoscale eddies and recirculating gyres, and choice of "reference level" is usually arbitrary. There are, however, a few circulation elements that we feel are well constrained by the observations. The northward transport of the Florida Current through the Straits of Florida is close to 30 Sv, and approximately 45% is from the South Atlantic. The net transformation of warm water to cold water in the North Atlantic is 13 Sv. The rate of production of dense cold overflow waters in the Nordic Seas is 6 Sv. Downstream from the Straits of Florida, the 30 Sv transported as the Florida Current is increased to roughly 100 Sv by recirculating gyres. Our goal is to combine these four circulation elements with what else is known of the distribution of currents and water masses to produce a circulation scheme for the North Atlantic.

Schmitz and Richardson [1991] (hereinafter SR91) re-

8755-1209/93/92RG-02583 *$15.00*

Reviews of Geophysics, 31, 1 / *February 1993*
pages 29–49
Paper number 92RG02583

TABLE 1. Abbreviations for the Water Mass Names Used in the Text

Abbreviation	*Full Name*
AABW	Antarctic Bottom Water
AAIW	Antarctic Intermediate Water
LNADW	Lower North Atlantic Deep Water
LDW	Labrador Deep Water
LSW	Labrador Sea Water
MOW	Mediterranean Outflow Water
NACW	North Atlantic Central Water
NADW	North Atlantic Deep Water
SACW	South Atlantic Central Water
SPMW	Subpolar Mode Water
UNADW	Upper North Atlantic Deep Water

cently have identified the low-latitude path for the water that replaces the surface water lost through convection as deep water is formed in the northern North Atlantic. Here we extend the description of this path to the mid-latitude and northern North Atlantic. *McCartney and Talley* [1984] developed a picture of the formation of the North Atlantic Deep Water that is almost identical in transport magnitude (13–14 Sv; 1 Sv = 10^6 m^3 s^{-1}) to the cross-equatorial contribution to the Florida Current transport as found by SR91. General compatibility of SR91 with other investigations is shown, including a study of the southern South Atlantic by *Rintoul* [1991]. *Hogg* [1992] has developed a picture of the transport of the Gulf Stream system that will be a key element of our circulation scheme. The way in which recirculations (that is, relatively narrow return flows for boundary currents) shape the deep circulation has been elaborated recently by *McCartney* [1993], and we discuss these and other recirculations. For example, we point to a recirculating gyre associated with the North Atlantic Current (NAC), combined with a throughput in the NAC of 12 Sv, as a partial resolution of the "northern gyre" conflict (W76) [*Clarke et al.*, 1980].

There is a classic dilemma concerning the transport in the wind-driven interior or Sverdrup circulation at 24°N and the transport of the Florida Current [*Leetmaa et al.*, 1977; *Leetmaa and Bunker,* 1978; *Roemmich and Wunsch,* 1985; *Wunsch and Roemmich,* 1985], and a potential resolution to this question [*Schmitz et al.*, 1992] has been suggested. In addition, reconciliation of different perspectives of the thermohaline circulation [*Gordon,* 1986; *Gordon et al.*, 1992; *Rintoul,* 1991] is outlined. New versions of the circulation of Antarctic Bottom Water (AABW), North Atlantic Deep Water (NADW), Labrador Sea Water (LSW), and Subpolar Mode Water (SPMW) are also described [*McCartney and Curry,* 1993; *McCartney,* 1993].

Circulation cartoons for various layers in the North Atlantic will be presented, based on a broad spectrum of published results as opposed to a single technique or individual point of view. By cartoon we mean a qualitative or semiquantitative description of general features of the circulation but not rigorously or accurately determined transport streamline contours as established by careful observation and analysis, the latter too ambitious a project in any case. This paper is organized as follows. Recently developed ideas about the flow in the low-latitude North Atlantic will be discussed first, followed by a section on the circulation at mid-latitude and higher latitude. Then there is a discussion of the relation between the North and South Atlantic thermohaline circulations, followed by a section describing the presentation of transport cartoons for various ocean layers. There is a summary section, which includes our resolutions of four major dilemmas defined by W76, and finally a brief discussion of the state of the art with an outline of future prospects.

The specific water mass (type) name abbreviations used in this paper are listed in Table 1. We will use the generic names, thermocline layer (water), intermediate layer (water), deep layer (water), and bottom layer (water) to describe successively deeper layers of water, when we do not refer to a specific temperature–salinity (hereafter *T/S*) interval. The nonspecialist is referred to the glossary for a definition of technical terms. Figures 1*a* and 1*b* are maps that schematically depict general topographic features and place names. The 3000- and 4000-m contours in Figure 1*a* enclose shaded areas except that the 3000-m contour is present for clarity only north of roughly 40°N, and neither contour is shown in the Caribbean or the Gulf of Mexico area, but see Figure 1*b*, where indicated depth contours are in meters. To orient the nonspecialist, we have included also (Figure 1*c*) an adaptation of a two-layer scheme for the Atlantic circulation according to *Stommel* [1957, 1965]. Figure 1*c* shows upper layer flow (approximately main thermocline and above, roughly a 1000-m-thick layer) that includes a subtropical gyre forced primarily by the wind in each ocean basin. Water (NADW, the lower layer flow analogy) is depicted as sinking in the northern North Atlantic and rising in the vicinity of the Antarctic Circumpolar Current south of 50°S as a thermohaline-driven cell, along with some upwelling in the interior of the North Atlantic. Our circulation scheme is similar to Stommel's.

GLOSSARY

Dynamic height: refers to the pressure associated with a column of water. Dynamic height varies horizontally, as a result of horizontal variations in the water's *T/S* characteristics, which determine density and thus pressure through the hydrostatic balance. The geostrophic balance requires that surface currents in the northern hemisphere have larger dynamic height on their right than on their left, relative to their direction of flow. The usage of a chart of dynamic height is analogous to a meteorologist's usage of a pressure chart, with the direction of flow aligned with the contours and the intensity of flow inversely proportional to the contour spacing.

Ekman layer and transport: the Ekman layer is the name generally given to the boundary layer (typically O(100 m) thick) of the upper ocean through which the stresses exerted on the water surface by the wind are transmitted to the interior of the ocean. In the steady open ocean Ekman layer, surface wind stress is balanced solely by the Coriolis force associated with the water currents. Vertical integration of this boundary layer's currents yields the Ekman transport (directed 90° to the right of the wind stress in the northern hemisphere and 90° to the left of the wind stress in the southern hemisphere), which is dependent only on the magnitude of the wind stress and the magnitude of the local vertical component of Earth's rotation.

Eulerian mean circulation: the time-averaged flow field in a fixed coordinate system, which can be markedly different in structure from the synoptic mean circulation (defined below).

Geostrophic flow: the simplest possible large-scale steady state dynamical balance between Coriolis and pressure gradient forces, similar to the situation in the atmosphere. The vertical current shear is proportional to the horizontal density gradient as a good first approximation ($\sim \pm 10\%$) across large-scale low-frequency ocean currents below the mixed layer. The determination of geostrophic currents therefore requires direct determination of the current at some level (the reference level), a routine atmospheric measurement but quite difficult oceanographically, where there are also serious temporal and spatial sampling considerations.

Mesoscale features: currents and eddies having horizontal dimensions, especially width, of approximately 100–300 km. The term "eddy field" indicates a horizontal (geographical) distribution of eddies. The idea that mesoscale eddies were energetic features in the ocean circulation was first highlighted by the results of the Aries Expedition [*Stommel,* 1965]. Sampling procedures have become more sophisticated in the post-Aries Expedition time frame.

Potential temperature: the effective temperature of a parcel of water after removing the heat of the parcel associated solely with compression. Hence, at great depths, potential temperatures are always less than measured temperatures.

Recirculating gyres: western boundary currents, like the Gulf Stream in the upper ocean and in the deep western boundary current in the deep water of the North Atlantic, in many places have adjacent strong opposing flow elements. Their existence reflects a subbasin-scale component to the corresponding gyre flow, which can dominate the basin-interior distribution of transport.

Reference level: see geostrophic flow above.

Retroflection: refers to a geographical looping of a current away from its original direction to a substantially different direction.

Subtropical gyre: in the northern hemisphere a clockwise circulation forced by the wind with western intensification in the form of a western boundary current: the Gulf Stream in the North Atlantic and the Kuroshio in the North Pacific. In both these oceans the subtropical gyres span the oceans' widths and extend from roughly 10°N to 40°N. There are also intermediate-scale flows called recirculation gyres that return water to boundary currents. A closed clockwise recirculating gyre north of the subtropical gyre was called the northern gyre by *Worthington* [1976]. Counterclockwise gyres north of the subtropical gyres are called subpolar gyres and also have western boundary currents: the East Greenland and Labrador currents in the North Atlantic and the Oyashio Current in the Pacific. Analogous subtropical and subpolar gyres occur in the southern hemisphere oceans, where the rotation senses are reversed because of the change of sign of the local vertical component of Earth's rotation. In the southern hemisphere the subpolar gyres are linked by the Antarctic Circumpolar Current.

Sverdrup circulation: refers to a wind-driven flow field associated with purely geostrophic and Ekman layer dynamics. The curl of the wind stress produces convergence/divergence of the Ekman transport (defined above), which imposes pressure gradients on the water below. Below the Ekman layer the flow in response to these pressure gradients is purely geostrophic in the Sverdrup circulation, with convergent Ekman flow forcing the subtropical gyres and divergent Ekman flow forcing the subpolar gyres.

Sverdrup relation/dynamics: the Sverdrup relation refers to a balance between meridional water motion (which is in geostrophic balance at lowest order) and the curl of the wind stress and represents the simplest relation describing the motion of interior oceanic water in response to surface winds. Sverdrup dynamics refers to this balance as well. See also Sverdrup circulation and Sverdrup transport.

Sverdrup transport: the Sverdrup transport is the meridional transport estimated from the wind stress curl. It is comprised of the sum of the Ekman transport in the Ekman layer and the geostrophic transport resulting from the pressure gradients set up by the convergent or divergent Ekman layer flow.

Synoptic mean circulation: the time-averaged flow field obtained in a coordinate system whose axes are parallel and perpendicular to the instantaneous axis of a particular strong current such as the Gulf Stream. Hence the coordinate system changes with time.

Thermocline: the sharp vertical temperature gradient that is the boundary between the ocean's abyss and its surface waters.

Thermohaline circulation: refers to the flow field associated with the sinking of water cooled by contact with cold air or associated with sources and sinks of salt water or fresh water. Water sinking at high latitudes tends to return equatorward in relatively strong, narrow currents called deep western boundary currents.

***T/S* characteristics:** water masses can be identified and tracked by their chemical characteristics. The most common are their temperature (T) and salinity (S). Other valuable characteristics include oxygen, silicates, nitrates, fluorocarbons, and so on.

ON THE LOW-LATITUDE NORTH ATLANTIC CIRCULATION

Replacement for NADW, formed in the northern North Atlantic and flowing south across the equator, was found by SR91 to be consistent with 13 Sv of water of South Atlantic origin flowing into the Caribbean and out through the Straits of Florida at temperatures greater than (or equal to) 7°C, nominally the coldest temperature for the Florida Current.

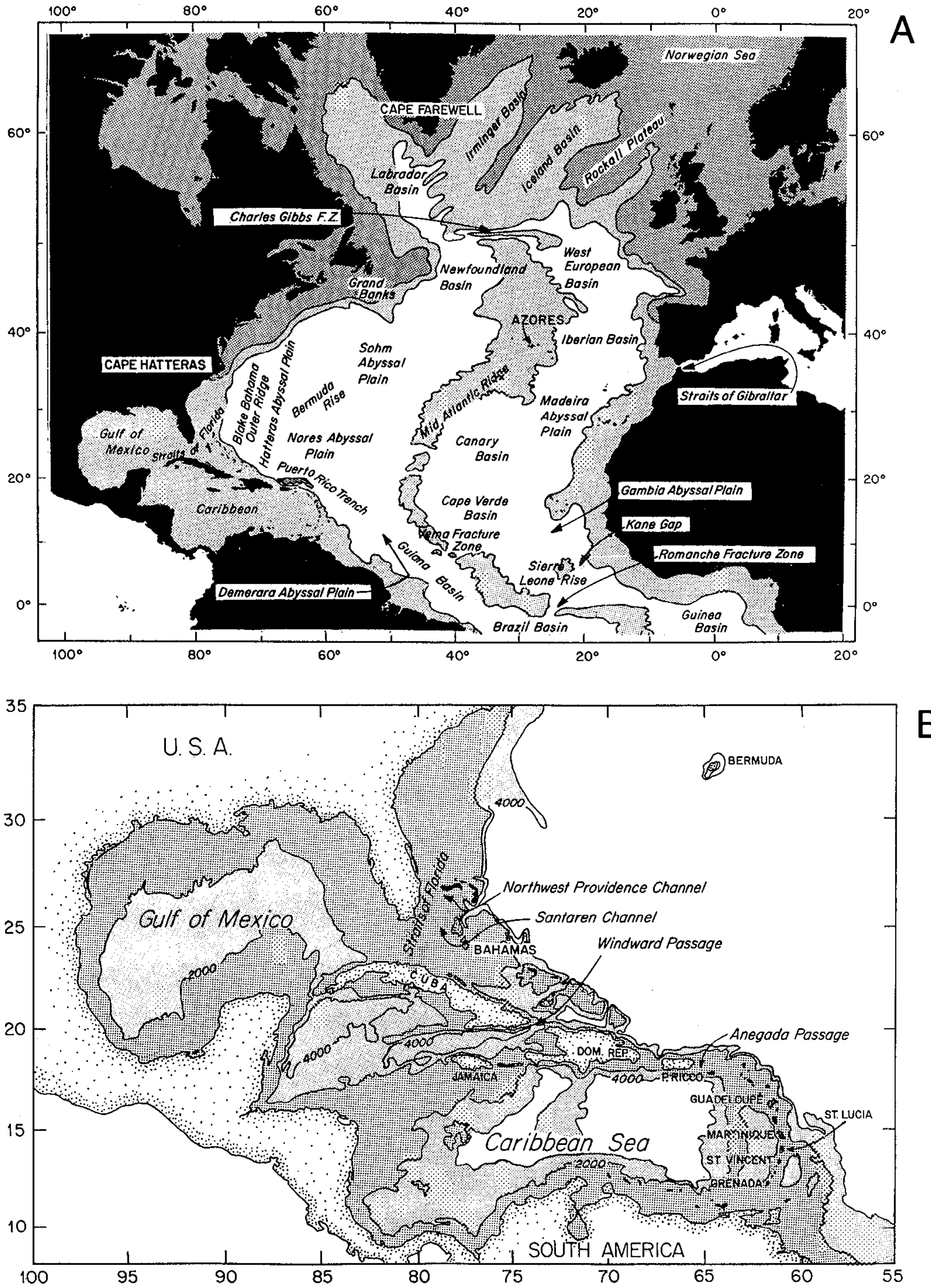
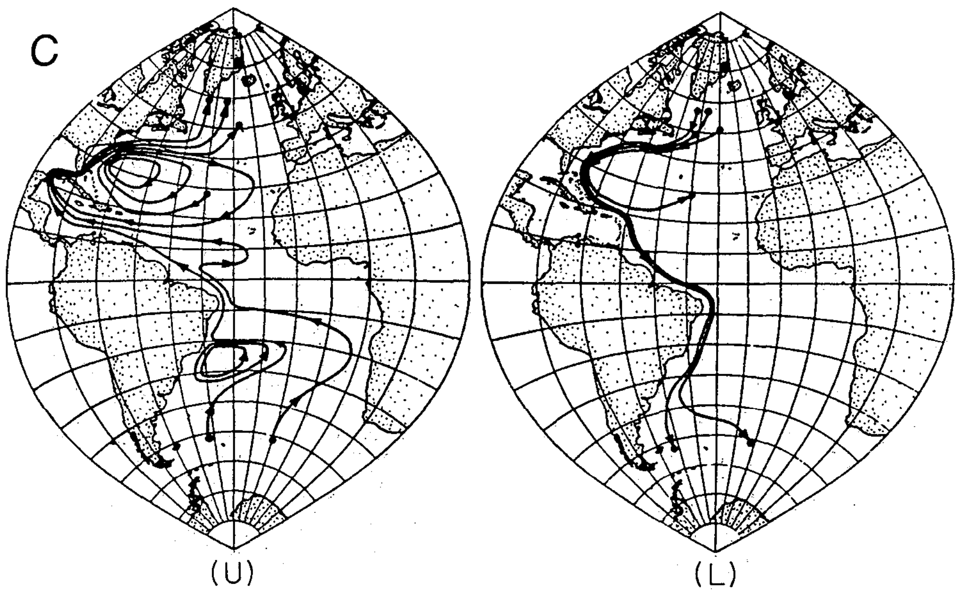


Figure 1. Maps of the North Atlantic: (*a*) and (*b*) summary topographic features and place names used in the text, (*c*) a schematic two-layer transport streamline field adapted from *Stommel* [1957, 1965], (U) denotes upper layer and (L) denotes lower.

All temperatures referred to in this review are potential temperatures. This suggestion, although the first explicit demonstration of large transport of South Atlantic origin through the Straits of Florida, is compatible with most other observational evidence [*Gordon,* 1986; *Hall and Bryden,* 1982; *McCartney and Talley,* 1984; *Rintoul,* 1991; *Roemmich,* 1980, 1981; *Roemmich and Wunsch,* 1985; *Tsuchiya,* 1989; *Wunsch,* 1984] and some dynamically motivated ideas [*Csanady,* 1986; *Stommel,* 1957, 1965]. Also, *McCartney and Talley* [1984] have proposed independently 14 Sv as the rate of deepwater formation by convection in the northern North Atlantic, and *Wunsch* [1984, Figure 6*b*] found 15 Sv of cross-equatorial thermocline layer flow in his inverse calculation with maximum heat flux. *Roemmich* [1980] also found 14 Sv as the net deep flow south across 24°N, and *Rintoul*'s [1991] transport balance across 32°S has 17 Sv of NADW flowing south with 4 Sv AABW flowing north, again a net of 13 Sv of southward deep transport.

The transport assignment by SR91 is not as hypothesized by W76, who noted that the major fraction of thermocline water transported into the North Atlantic from the South Atlantic retroflects to form the Equatorial Undercurrent [*Met-*



calf and Stalcup, 1967]. This is clearly true, with only about 1 Sv (comparatively fresh) in the 12°–24°C range (the undercurrent temperature (T) interval) moving into the Straits of Florida from the South Atlantic. However, about 7 Sv of water in the upper 50–100 m of the water column ($T > 24°C$) above the undercurrent depth and T/S range, and 5 Sv ($7° \leq T \leq 12°C$) below the undercurrent T/S range, can move into the Caribbean from the South Atlantic and out with the Florida Current [SR91; *Schmitz et al.*, 1993]. *Worthington* [1976] closed the Florida Current (30 Sv) within his subtropical gyre, which is confined essentially to the southern recirculation of the Gulf Stream west of the Mid-Atlantic Ridge.

Another low-latitude transport dilemma is associated with the Sverdrup relation [*Böning et al.*, 1991; *Leetmaa et al.*, 1977; *Leetmaa and Bunker,* 1978; *Roemmich and Wunsch,* 1985; *Wunsch and Roemmich,* 1985]. Sverdrup dynamics, relating the Sverdrup transport distribution to the curl of the wind stress, is a good first approximation for the currents in the interior of oceans and is the cornerstone of widely accepted ideas about the wind-driven circulation. The reader interested in pursuing this topic could start with *Stommel* [1957, 1965], *Wunsch and Roemmich* [1985], and *Schmitz et al.* [1992] including references. The question typically posed is whether or not the well-established 30 Sv or so flowing north through the Straits of Florida [*Schmitz and Richardson,* 1968; *Richardson et al.*, 1969] is balanced by a southward Sverdrup transport in the interior North Atlantic, and the answer is controversial. A partial resolution [*Schmitz et al.*, 1992] of this quandary appeals both to SR91 and to the idea that the Sverdrup transport contribution to the Florida Current is coming from east of roughly 55°W along 24°N. *Schmitz et al.* [1992] suggest that the more eddified thermocline layer flow field west of 55°W is associated with a smaller-scale recirculation overlying a strong deep western boundary current (DWBC) system.

The comparison of the geostrophic flow that would result from the Sverdrup relation using known mean winds with the geostrophic flow calculated from observed hydrographic data and a reference level estimated by inverse techniques by *Roemmich and Wunsch* [1985] indicated that at about 55°–60° W along 24°N the theoretical and observed curves begin to diverge. East of this longitude the calculated and observed geostrophic transports agree to within a few sverdrups for a total of 20. West of this line where the observed geostrophic currents are varying on much smaller zonal scales than the calculated transports and may be strongly time dependent, the disagreement may reach 15 Sv east of 55°W the Sverdrup transport is 17 Sv, comprised of a northward Ekman transport of 3 Sv and a southward interior

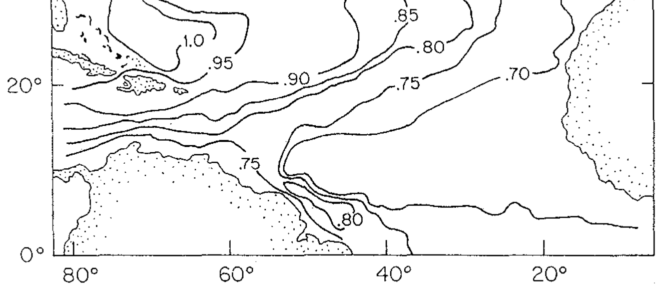


Figure 2. The relative dynamic height [ΔD (100/700 db)] pattern near the Bahamas, taken from the data set used by *Leetmaa et al.* [1977] and *Stommel et al.* [1978], and adapted from *Schmitz et al.* [1992*a*].

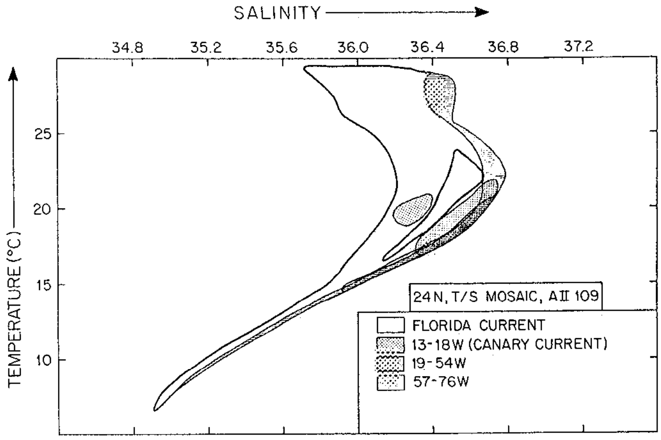


Figure 3. A *T/S* mosaic, adapted from *Schmitz et al.* [1993]. The solid border is the envelope of *T/S* curves for about 20 stations made across the Florida Current in August 1981, and the stippled areas are for stations made along 24°N on the same cruise.

geostrophic transport of 20 Sv. This is much smaller than the observed total Florida Current transport of 30 Sv. Taking, however, the estimate by SR91 of 13-Sv thermohaline contribution to the Florida Current leaves 17 Sv available to compensate for the interior southward Sverdrup transport, and there is no problem with an interior 24°N net Sverdrup transport of 17 Sv [*Schmitz et al.*, 1992].

A more complete calculation of transports associated with the Sverdrup relation for the entire North Atlantic based on an independent and high-quality wind data set was completed by *Leetmaa and Bunker* [1978]. Their 25- and 30-Sv contours impinge on the Bahamas and do not pass through the Straits of Florida. *Böning et al.* [1991] made a similar calculation, getting larger transports, but their 25 Sv and higher contours are also not clearly entering the Caribbean and exiting through the Straits of Florida. They are impinging on the Bahamas with a pattern similar to *Leetmaa and Bunker* [1978] although at higher amplitude. There is no major inconsistency between these studies and a Sverdrup transport compensation of 17 Sv in the Straits of Florida according to SR91 if the Sverdrup transport contours above 20 Sv or so [*Leetmaa and Bunker,* 1978; *Böning et al.*, 1991] contribute to the Gulf Stream and its southern recirculation north of the Bahamas rather than to the Florida Current. The dynamic height anomaly (ΔD) contours immediately east of the Bahamas are shown in Figure 2, which is a newly contoured version at a higher ΔD resolution [*Schmitz et al.*, 1992] of the data used in Figure 2 by *Stommel et al.* [1978; *Reid,* 1978]. Sverdrup transport contours [*Leetmaa and Bunker,* 1978; *Böning et al.*, 1991] have the same scales as the C-shaped pattern of dynamic heights in Figure 2 west of 60°W (nominal), so that the (re-) circulation in this area may be related to a higher-order dynamical response to wind forcing [*Schmitz et al.*, 1992].

It is also possible to demonstrate compatibility between these ideas and water mass properties [*Schmitz et al.*, 1993]. The *T/S* envelopes for hydrographic stations along (nominally) 24°N, 52°W, and in the Caribbean passages are superimposed on the Florida Current *T/S* envelope in Figures 3–5 [see *Schmitz et al.*, 1993]. The *T/S* characteristics along 24°N (Figure 3) overlay only with the salty segment of the Florida Current *T/S* envelope and then only above 9°C. The fresher contributions along 52°W (Figure 4) from the South Atlantic fill in most but not all of the gaps not covered by the 24°N data. One of these gaps may be associated with water mass modification in the Gulf of Mexico [*Wennekens,* 1959]. The partition in the Caribbean passages (Figure 5) shows that the deepest water flowing through the Straits of Florida (7°–9°C approximately) enters only through Anegada and Windward passages (perhaps Mona). The fresh to salty segments of the Florida Current *T/S* envelopes are filled sequentially from flow into the southern to northern Caribbean passages (Figure 5).

ON THE NORTH ATLANTIC CIRCULATION AT MID-LATITUDES AND HIGHER LATITUDES

Figure 6 is the circulation diagram for total transport from W76 (his Figure 42) but does not include all of his thermohaline circulation. This scheme has been criticized for a variety of reasons, especially with regard to his postulates of a closed "northern gyre" in the Newfoundland Basin [*Clarke et al.*, 1980; *Worthington,* 1962] and deviations from geostrophy at leading order in the southern recirculation. There are in addition questions about W76's thermohaline circulation [*Ivers,* 1975; *McCartney and Talley,* 1984] including a lack of exchange with the South Atlantic (SR91). *McCartney and Talley* [1984] identify 8 Sv of Upper North Atlantic Deep Water (UNADW) formation, compared with zero by W76. They also have 6 Sv of Lower North Atlantic Deep Water (LNADW), for a total formation of 14 Sv of NADW, compared with 10 Sv (all LNADW) by W76. The absence in W76 of a subtropical gyre segment in the easternmost North Atlantic (Azores Current) is in conflict at the 10-Sv level with several other authors' examinations of this

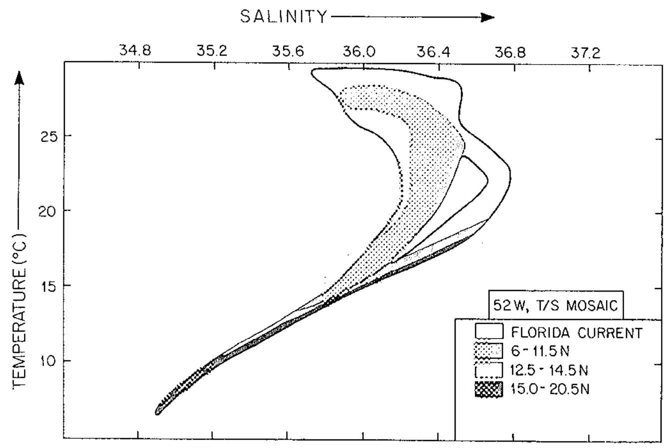


Figure 4. A *T/S* mosaic, adapted from *Schmitz et al.* [1993]. The solid border is the envelope of *T/S* curves for about twenty stations made across the Florida Current in August 1981, and the stippled areas are for stations made along 52°W.

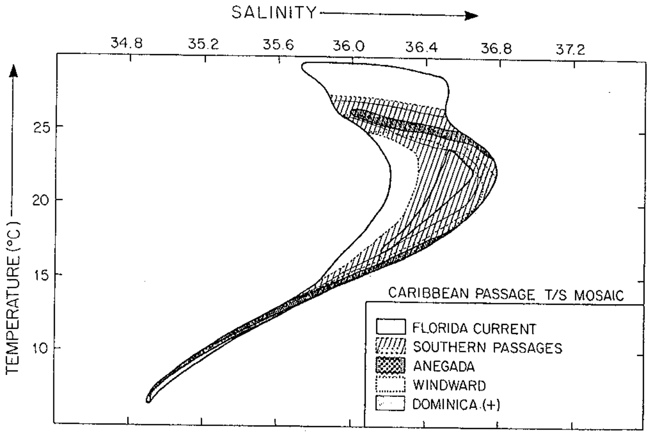


Figure 5. A *T/S* mosaic, adapted from *Schmitz et al.* [1993]. The solid border is the envelope of *T/S* curves for about 20 stations made across the Florida Current in August 1981, and the stippled areas are for stations made near the indicated Caribbean passages.

region, where a consistent picture has emerged in the last decade [*Stramma,* 1984; *Sy,* 1988]. Other mid-latitude areas where there is disagreement with W76 are for the northern recirculation in the slope water (located in the area north of the Gulf Stream and west of the Grand Banks), in the Gulf Stream [*Hogg,* 1992], and in the Gulf Stream southern recirculation near the Bahamas, as sketched in Figure 2.

The "northern gyre" problem is highlighted in Figure 7, where W76's and *Mann*'s [1967] circulation patterns near the Grand Banks are superimposed. *Clarke et al.* [1980] have reviewed this problem in great detail, and *Sy* [1988, Figures 12 and 18] has developed a summary picture of the flow across the Mid-Atlantic Ridge north of 24°N. If 13 Sv of thermocline layer water (that compensates for the high-latitude formation of deep water by convection) is flowing north in the Gulf Stream system as suggested by SR91, then approximately that amount is transported through the NAC system. Our picture is that this is the case for 12 Sv of compensation, with the other 1 Sv entering the Mediterranean from the subtropical gyre. The total transport of the upper level NAC is taken here to be 37 Sv, 25 Sv in addition to the 12 Sv compensating for the formation of deep water. The recirculating 25 Sv (19 to 26 Sv according to *Sy,* [1988]) in our view is contained in a closed gyre north of the subtropical gyre, i.e., a northern gyre. The needed west-northwest flow takes place near the Azores, primarily just to their north and definitely to the north of the Azores Current, along the line from Azores to Newfoundland. Southward transport greater

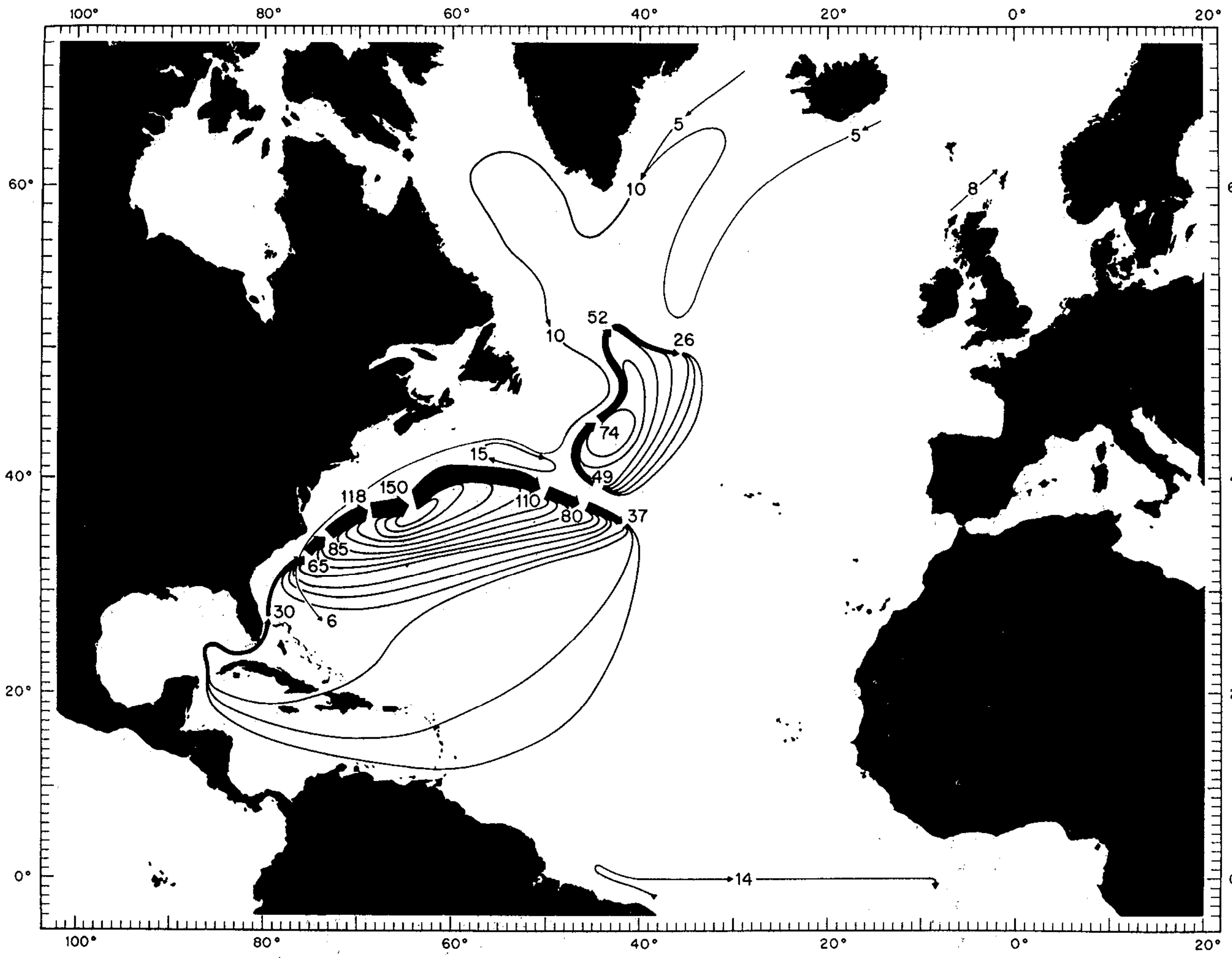


Figure 6. The North Atlantic circulation according to *Worthington* [1976]: total transport, in sverdrups (10^6 m^3 s^{-1}).

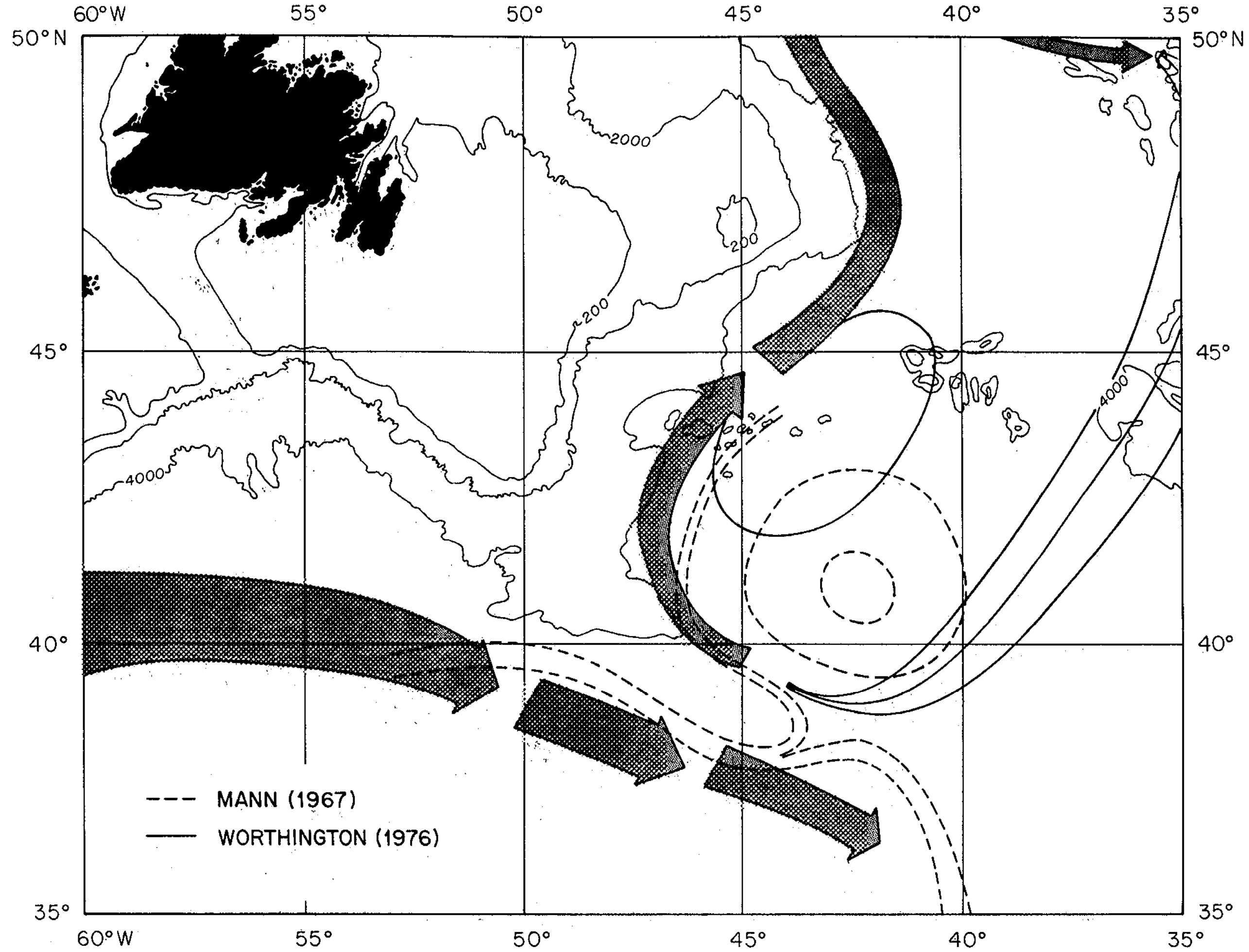


Figure 7. A schematic illustration of flow patterns near the Grand Banks of Newfoundland. Solid lines are adapted from *Worthington* [1976], with the shaded areas denoting the boundary currents, and the dashed lines are from *Mann* [1967].

than roughly 3 Sv (which we take to be SPMW, see below) between the Azores and Portugal is ruled out by *Stramma* [1984] and *Sy* [1988]; see also *Saunders* [1982]. The 12-Sv compensation flowing through the Gulf Stream system does so in the upper layers on the inshore edge. It is therefore highly oxygenated as is the case for the upper level flow in the Newfoundland Basin in general, removing one of W76's objections to flow from the Gulf Stream system into the NAC system.

ON THE THERMOHALINE CIRCULATION IN THE ATLANTIC

Many basic features of the thermohaline circulation in the Atlantic Ocean have been known for decades [*Wüst,* 1935; *Stommel,* 1957, 1965], including the formation of NADW and its penetration into the South Atlantic and the Antarctic Circumpolar Current, with an influence on the Pacific and Indian oceans [*Reid and Lynn,* 1971]. According to *Gordon* [1986], this water is then upwelled at a variety of locations in the world's oceans, being eventually compensated for to a large extent by net thermocline layer flow into the South Atlantic from the Indian Ocean, along with some lesser amount of intermediate water transported through the Drake Passage into the South Atlantic. *Rintoul* [1991] alternatively proposes no net flow of thermocline water (warm path) from the Indian to the South Atlantic Ocean, compensating for all of the net southward deep flow from the North Atlantic with 13 Sv of intermediate water moving through the Drake Passage (cold path) into the South Atlantic. Since NADW is formed by cooling thermocline layer water in the northern North Atlantic [*McCartney and Talley,* 1984], it is necessary in *Rintoul*'s [1991] scheme to convert intermediate water to thermocline water somewhere. According to *Rintoul* [1991, Figure 5], 13 Sv of Antarctic Intermediate Water (AAIW) transported into the South Atlantic through the Drake Passage has been converted by 32°S into 8 Sv of thermocline water, with 5 Sv of AAIW remaining. This is reminiscent of the 13 Sv according to SR91 and *Schmitz et al.* [1993], whose cross-equatorial transport breakdown is 8 Sv upper layer and 5 Sv of "upper" intermediate water, all within the thermocline layer.

It is now possible to suggest a consistent thermohaline circulation for the Atlantic Ocean. The simplest explicit demonstration (Table 2) of the compatibility noted above involves

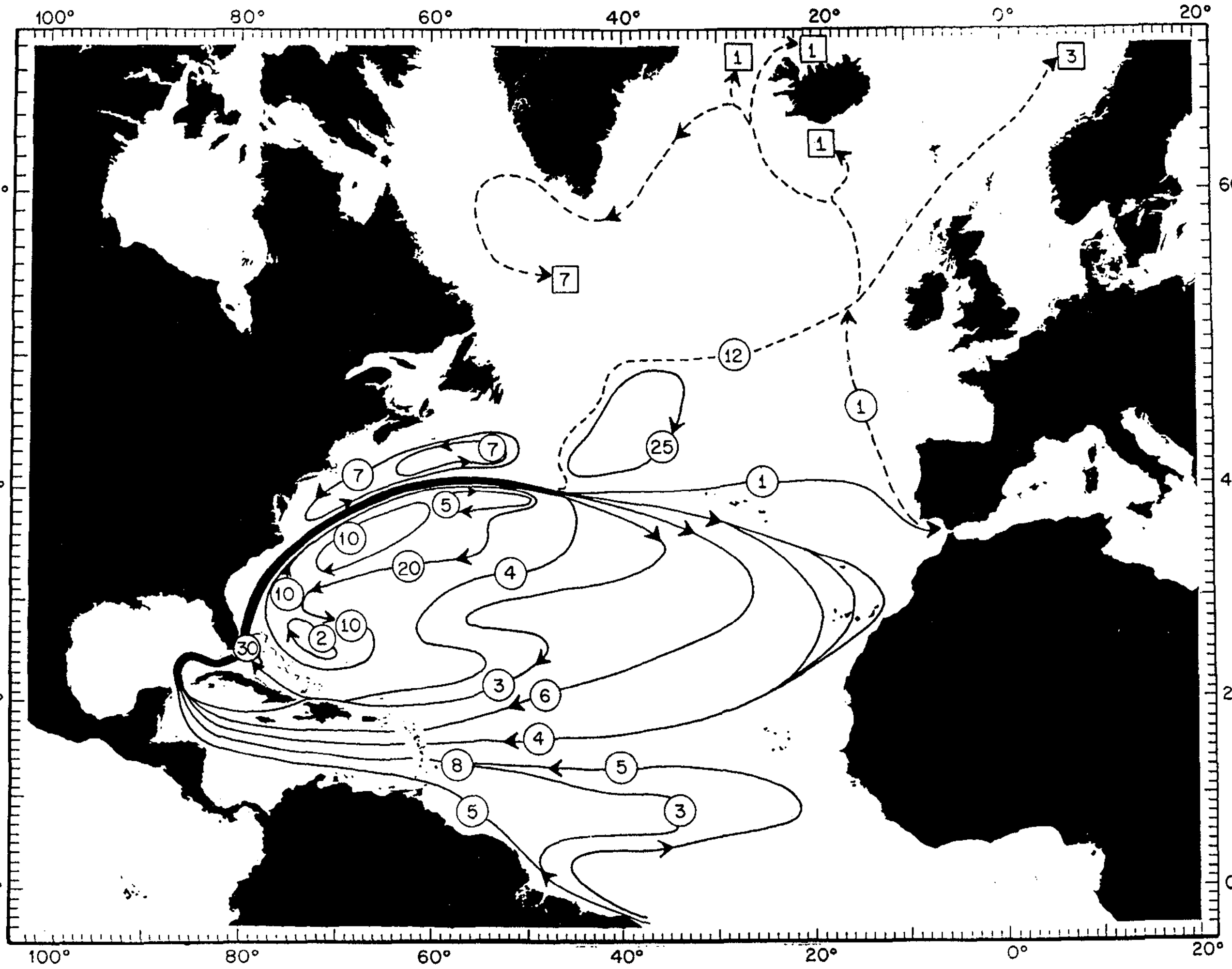


Figure 8. A transport (values are in sverdrups) cartoon for the North Atlantic, at temperatures above 7°C (nominal). Numbers in squares denote sinking.

summary transports from two latitudes only: 32°S from *Rintoul* [1991] and 24°N from SR91 and *Schmitz et al.* [1992]. These 24°N results are also in line with *Roemmich and Wunsch* [1985], *Roemmich* [1980], and *Hall and Bryden* [1982]. *Rintoul* [1991] has a net of 13-Sv intermediate water entering his South Atlantic sector through the Drake Passage (consistent with the mechanism and location of AAIW formation by *McCartney* [1977, 1982]; see also *England* [1992] and *England et al.* [1993]), leaving north across 32°S as 8-Sv thermocline layer water and 5-Sv intermediate water. SR91 and *Schmitz et al.* [1992] find a transport into the Caribbean and out through the Straits of Florida of 7 Sv of surface water (upper 50–100 m, $T > 24°C$, comparatively fresh), presumably somewhat upwelled near the equator, along with 1 Sv of relatively freshwater in the 12°–24°C range and 5 Sv (of "upper" intermediate water) in the 7°–12°C range, again a total of 13 Sv.

Most of Rintoul's 8 Sv of thermocline water transported north across 32°S (Table 2) might be upwelled (perhaps in stages) in the vicinity of the equator to provide the near-surface cross-equatorial flow of 7 Sv suggested by SR91. Also, Rintoul's 5-Sv intermediate water could be upwelled slightly and modified by vertical mixing under salt fingers [*Schmitz et al.*, 1993] to become the 7°–12°C water crossing the equator and flowing through the Caribbean and Florida straits as noted above by SR91. Both *Atkinson* [1983] and *Tsuchiya* [1989] have noted the existence of AAIW influence in the Gulf Stream system, and *Richardson* [1977, Figure 2] identified AAIW-influenced flow in the 7°–10°C range near Cape Hatteras. *Wunsch* [1984, Figure 6*b*] has 5 Sv of deep upwelling in the North Atlantic thermohaline cell, occurring near the equator. Note that *Broecker et al.* [1978] found a total of 16 Sv upwelling in the upper equatorial Atlantic. At 8°–11°N the Ekman transport is roughly 13 Sv northward, the corresponding geostrophic flow about 5 Sv southward for a net Sverdrup transport of about 8 Sv [*Roemmich*, 1983]. The northward 4 Sv of AABW at 32°S per *Rintoul* [1991] (based on results by *Hogg et al.* [1982]) is consistent with the net transequatorial transport of 4 Sv of AABW found by *McCartney and Curry* [1993], which is modified to "deep water" in the North Atlantic. These transports are lined up side by side in Table 2 to demonstrate agreement to within 1 Sv.

The compatibility between *Rintoul* [1991] and SR91 plus

TABLE 2. Thermohaline Transport Summary

Water Type	*32°S*	*24°N*
Thermocline water	8	13
Intermediate water	5	
Deep water	−17	−18
Bottom water	4	5

Transport is measured in sverdrups.

Schmitz et al. [1993] suggests that the main path for replacement of the NADW formed in the northern North Atlantic would be with AAIW through the Drake Passage. This does not mean that the warm-water exchange between the South Atlantic and Indian oceans is not important; on the contrary, we see these subtropical gyres as coupled but with no net exchange of mass in the thermocline layer (consistent with the work by *Gordon et al.* [1992]). However, the only known ultimate source to the Southern Ocean for the formation of AABW and AAIW is NADW. Since AAIW is formed in the Subantarctic South Pacific and in the Scotia Sea and AABW is formed in the Weddell Sea, this amount of NADW (or modified NADW, see next sentence) must be upwelled in the vicinity of the Antarctic Circumpolar Current, where the relevant property surfaces do outcrop [*Reid and Lynn,* 1971]. These authors also suggest a conversion of modified LNADW in the northernmost areas of the North Pacific and North Indian oceans to intermediate water that returns to the circumpolar area, where we feel it would then contribute to AAIW formation. It is, however, thermocline water that is cooled to form NADW in the northern North Atlantic, not intermediate water, so a critical question is how and where transformation of AAIW to thermocline water occurs. We suggest that a total of 13 Sv of intermediate water is upwelled into the thermocline layer, 8 Sv in the South Atlantic per *Rintoul* [1991], with 7 Sv of this further upwelled to the surface layer as a result of Ekman divergence near the equator. Five sverdrups of AAIW are also slightly upwelled near the equator and modified to lower thermocline water in the tropical North Atlantic. We also have AAIW and AABW entering the North Atlantic (see below) and being modified to the temperature/salinity ranges associated with deep water, with the estimated net 5 Sv for AABW much better established than for AAIW (2 Sv?).

The warm-water return path for NADW upwelled in the Antarctic Circumpolar Current need not involve significant net exchange across layers (more than a few sverdrups) between the Atlantic and Indian oceans as suggested by *Gordon* [1986; *Broecker,* 1991; *Gordon et al.,* 1992]. Of course, the Benguela Current thermocline layer flow is influenced by the Indian Ocean, but *Gordon et al.* [1992] indicate that this is replaced by SACW flowing to the south of the Agulhas Return Current. Conversion of thermocline layer water from one ocean to the next, which we agree with at the 5–10 Sv level, is not a net exchange between layers but a modification. We also find, relative to *Gordon* [1986], a notably lower (13 Sv versus 20 Sv) rate of "new" NADW formation in the northern North Atlantic. However, 18–20 Sv is the net amount transported by the DWBC in the North Atlantic (see below) because 5–7 Sv is added to the "newly formed" 13 Sv of NADW by the modification of AABW and AAIW. The total transport of the DWBC system may reach 35–40 Sv when recirculation(s) is (are) included.

CIRCULATION CARTOONS

What is desirable as a guide to the general circulation of the North Atlantic is a scheme that is not based only on one author or one observational technique or one method of data analysis but on a synthesis of community-wide observations. In this vein, qualitative or semiquantitative transport cartoons for the North Atlantic are presented. By cartoon we refer to the schematic location and amplitude of major circulation features, not a quantitative delineation of transport streamlines. In these cartoons (Figures 8–14), numbers in circles represent transport in sverdrups (10^6 m^3 s^{-1}), always rounded off to avoid fractional transports, squares represent sinking, and triangles represent upwelling. Flow lines without major water mass modification are solid; dashed lines indicate substantial along-path changes; dotted lines indicate upwelling. We present cartoons for various layers primarily as defined by temperatures associated with conventional water masses (Table 3, approximately but not exactly the layers used by W76), with some repetitive maps where more than one interpretation is possible or where multiple features overlap. There are a total of seven layers in Table 3; the upper three, all water at potential temperatures greater than 7°C, will be referred to as the upper layer, and the lower layer will refer to all water below 7°C. Full basin transport cartoons will be presented explicitly for six of the seven individual layers; UNADW and LNADW will be combined to develop a composite flow map for NADW. We have developed a picture based on results from a variety of authors who have used diverse techniques.

The starting point for the circulation cartoon presented for the upper layer (Figure 8) (temperatures ⩾ 7°C, depths less than 800–1000 m typically) is the specification of sources of the well-established 30 Sv. transported by the Florida Current off Miami [*Schmitz and Richardson,* 1968; *Richardson et al.,* 1969], here partitioned as 13-Sv thermohaline cross-equatorial compensation for deep water formation and 17 Sv compensation for the southward Sverdrup transport

TABLE 3. Layer Definitions

Name	*Potential Temperature Range*
Surface layer	>24°C
Thermocline	12°–24°C
Lower thermocline	7°–12°C
Intermediate layer	4°–7°C
NADW	
UNADW	3°–4°C
LNADW	1.8°–3°C
AABW	less than 1.8°C

across 24°N [SR91, *Schmitz et al.*, 1993]. The latter becomes 7 Sv flowing through the Windward Passage according to *Roemmich* [1981] (the possibility of a few sverdrups branch through the Old Bahama and Santaren channels is also indicated; K. Leaman, personal communication, 1991, 1992), with about 10 Sv transiting the eastern North Atlantic near 20°–30°N according to *Stramma* [1984]. The transport along the South American coast is based partly on *Candela et al.* [1992], along with SR91.

The tropical path showing double retroflection between 0° and 15°N is taken from *Cochrane et al.* [1979], *Bubnov and Egorikhin* [1979], and *Siedler et al.* [1992], as a representation of the North Equatorial Countercurrent and North Equatorial Undercurrent, whose easternmost extent is associated with the Guinea Dome [*Siedler et al.*, 1992]. The C-shaped circulation to the immediate east of the Bahamas in Figure 8 is based on an interpretation by *Schmitz et al.* [1992] of *Reid* [1978] and *Stommel et al.* [1978], a pattern first seen in charts by *Montgomery and Pollak* [1942]. The transport amplitude of the Mediterranean inflow-outflow is based on *Bryden and Kinder* [1991] and a northward path for the outflow is approximately that according to *Reid* [1979]. The flow through Northwest Providence Channel is about 2 Sv [*Finlen*, 1966]; it is not included in Figure 8, for simplicity. Small transports involving 18° water formation and upwelling off Africa are also not in Figure 8 for the same reason. This is also true of SPMW. These transports will be identified in the following on more detailed charts.

The transports near the Gulf Stream in Figure 8 where it flows east as a mid-latitude jet, with recirculations, are adapted from *Hogg* [1992]. In particular, *Hogg*'s [1992] concept [see *Richardson*, 1985] of the differences between the Eulerian mean circulation and the average synoptic circulation has a strong influence on Figure 8 and on all of our diagrams, which are meant to represent the Eulerian Mean Circulation. Synoptic or average synoptic transports, those in the frame of reference of the axis of the Gulf Stream and its recirculations, are larger than or equal to the Eulerian means [*Hogg*, 1992]. Hogg's picture of the Gulf Stream is based on primarily direct measurements, whereas our ideas about the interior circulation are based on primarily hydrographic or occasionally tracer data.

The Gulf Stream Eulerian mean transport above 7°C in Figure 8 off Cape Fear is ~50 Sv (5 Sv below 7°C), consistent with *Richardson et al.* [1969], also ~55 Sv above 7°C (10 Sv below 7°C) near Cape Hatteras, in agreement with *Richardson and Knauss* [1971]. At 73°W, about 67 Sv above 7°C (28 Sv below 7°C) is in line with *Halkin and Rossby* [1985] and *Hogg* [1992]. The transports of the Gulf Stream and its recirculations at 55°W in Figure 8 (69 Sv above 7°C, 21 Sv below) are adapted from *Richardson* [1985] as well as *Hogg* [1992]. South of the Grand Banks (~50°W), the total transport of the Gulf Stream is 70 Sv (55 above 7°C and 15 Sv below), in line with *Clarke et al.* [1980], *Mann* [1967], and *Worthington* [1962, 1976].

We propose that 13 Sv flowing from the South Atlantic through the Straits of Florida also transit the inshore edge of the Gulf Stream system near the surface (consistent with the work by *Lazier* [1993]). A small part, 1 Sv, of this 13 Sv transits the eastern Atlantic ultimately to enter the Mediterranean Sea to be converted there to Mediterranean Outflow Water (MOW). The bulk, 12 Sv, eventually exits northward from the stream, after recirculating and cooling of the warm near-surface component, through the NAC and its recirculation to sink and form NADW after further cooling in the north. This is high-oxygen water, removing one of *Worthington*'s [1962, 1976] objections to exchange between the subtropical gyre and the northern North Atlantic. Actually, *Worthington* [1962, Figure 9] does at one point show a 10-Sv exchange, only slightly less than our estimate, but W76 shows none in Figure 6. This figure does include 8 Sv of warm water entering the Norwegian Sea, without showing an explicit pathway, but with his other figures and text identifying it as comprised of 3 Sv from the NAC and Gulf Stream and 5 Sv from the eastern subtropical gyre—with a MOW contribution flowing northward along the eastern boundary in a manner similar to that described by *Reid* [1979]. We represent the rest of the flow in the Newfoundland Basin in Figure 8 as a recirculating gyre with transports according to W76 and *Clarke et al.* [1980]. The throughput from the Gulf Stream system is limited by the amount of new NADW formed, consistent with a very small transport to the south across the line from the Azores to Portugal [*Stramma*, 1984; *Sy*, 1988]. However, a small (~3 Sv) circulation of SPMW [*McCartney and Talley*, 1982; *Tsuchiya et al.*, 1992] across this line will be discussed when individual layers are examined. We will also describe a recirculation in the northern North Atlantic that is of larger horizontal scale than the Newfoundland Basin Eddy according to W76. Our upper level NAC carries 37 Sv, a recirculation of 25 Sv along with the 12 Sv associated with NADW formation.

The circulation above 7°C (Figure 8) is broken down (Table 3) into three layers (temperatures 7°–12°C, 12°–24°C, >24°C) in Figure 9. In Figure 9*a* a comparatively fresh 7 Sv at temperatures greater than 24°C in the upper 50–100 m are flowing into the Caribbean from the equatorial South Atlantic along two dominant trajectories that vary seasonally. The coastal path is after *Candela et al.* [1992], and retroflection is according to *Siedler et al.* [1992]. In both cases the water eventually flows out of the Caribbean into the Gulf of Mexico, then out through the Straits of Florida and into the Gulf Stream system. North of the Caribbean and Florida straits, this water is cooled by interaction with the atmosphere, so that the flow lines are dashed. Six sverdrups exit the Gulf Stream system through the North Atlantic Current system, possibly recirculating there, and being cooled on the way through both current systems, finally sinking to form NADW. This water has high-oxygen content, being in immediate contact with the atmosphere near the sea surface, removing one of *Worthington*'s [1962, 1976] objections to contact between the subtropical gyre and the northern North Atlantic. One sverdrup recirculates through Northwest Providence Channel in Figure 9*a*, and 2 Sv of 18°C water are formed (*Hall and Fofonoff* [1993] and M. Hall (personal communication, 1992) indicates that their results are consistent with 2 Sv of 18°C water formation). There is 1 Sv

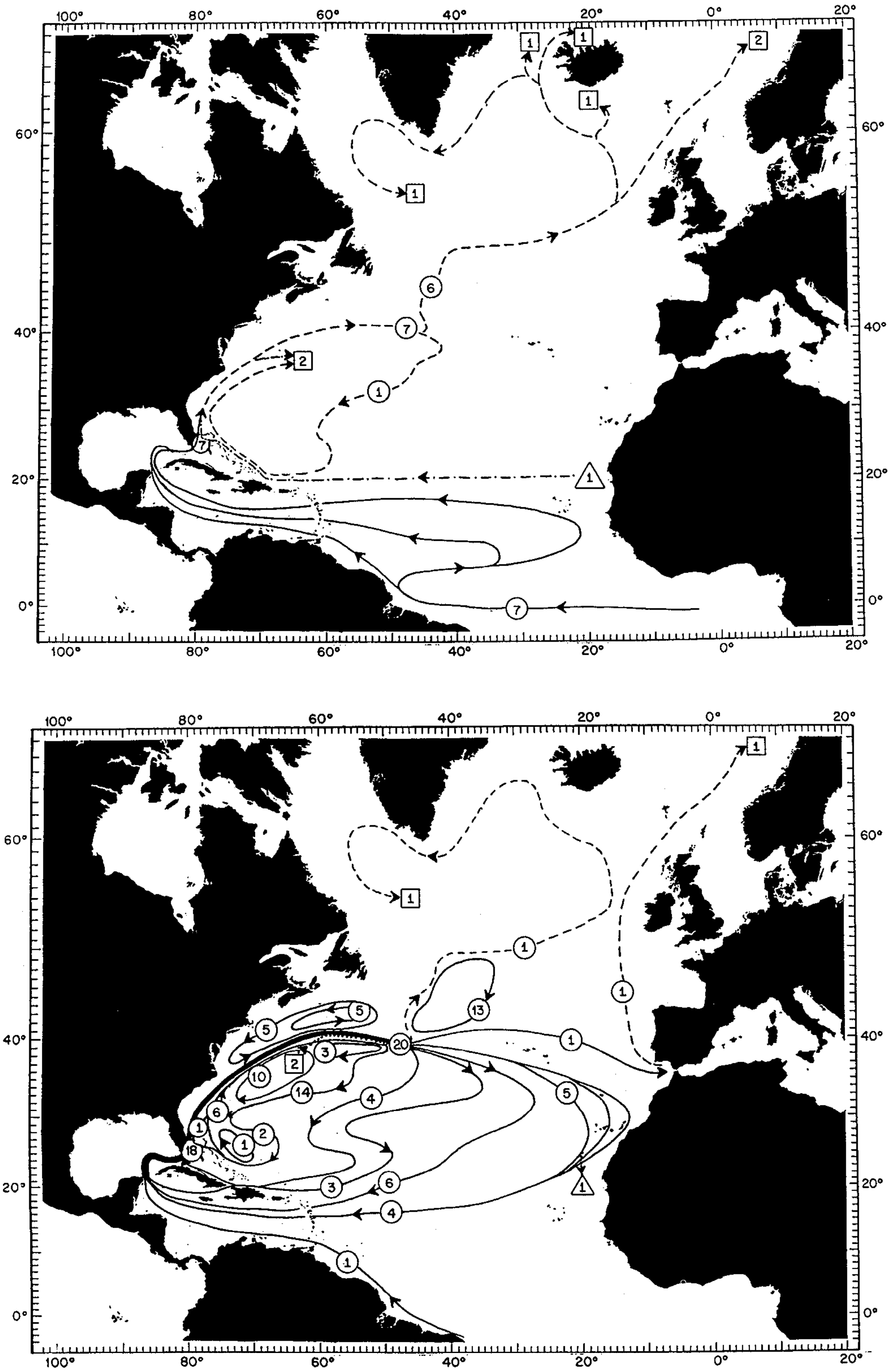
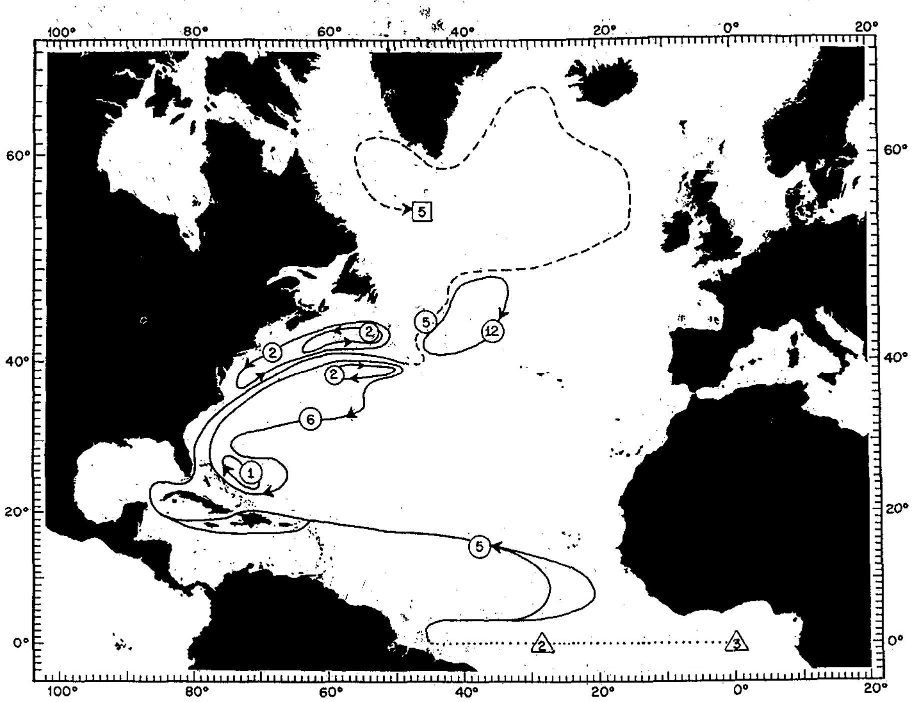
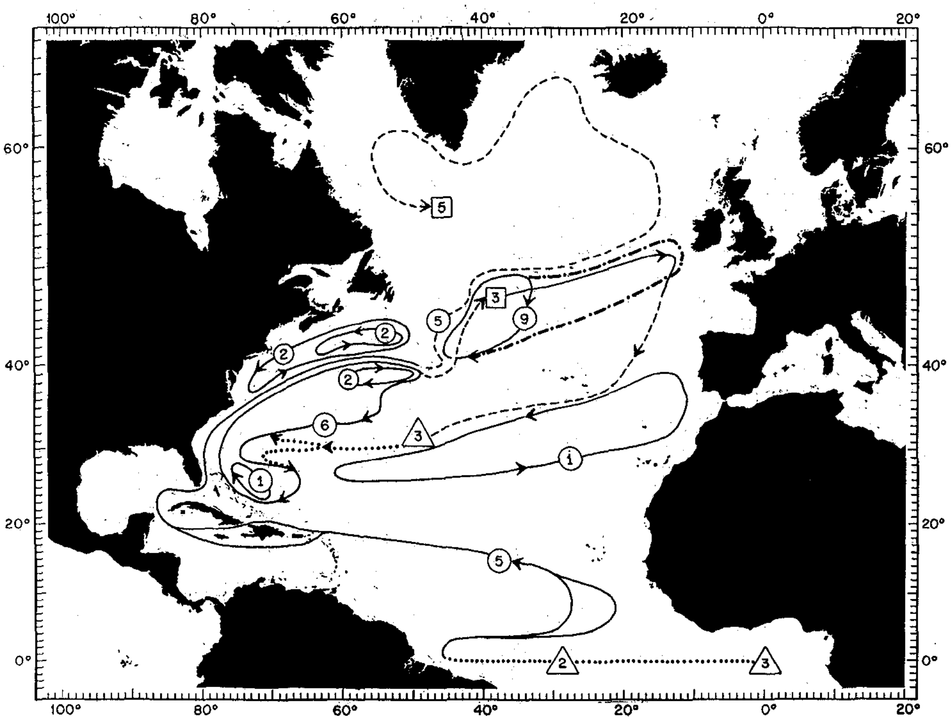


Figure 9. The composite circulation in Figure 8 is split into three layers: (*a*) near surface (>24°C), (*b*) 12°–24°C, (*c*) 7°–12°C, and (*d*) 7°–12°C including the circulation of Mediterranean water and SPMW. Transports are in sverdrups, squares represent sinking and triangles represent upwelling.

upwelled into the surface layer from the 12°–24°C layer off the coast of Africa.

The 12°–24°C range in Figure 9*b* contains the bulk of the thermocline layer flow in the North Atlantic subtropical gyre, with only 1 Sv entering from the South Atlantic. Figure 9*b* does not depict the circulation of all 12°–24°C water, because the surface flow in Figure 9*a* is cooled through this range. One sverdrup flows into the Mediterranean [*Bryden and Kinder,* 1991] in the 12°–24°C layer, and 1 Sv exits the 12°–24°C layer by being upwelled off the coast of Africa. The Mediterranean outflow in Figure 9*b* is shown as a dashed line because after exit from the Strait of Gibraltar it could outcrop in the north [*Reid,* 1979]. On Figure 9*b* there is 1 Sv flowing through Northwest Providence Channel, and the





possibility of flow through Santaren Channel is indicated.

The 7°–12°C range in the tropical Atlantic on Figure 9c shows 5 Sv of water just above the salinity minimum associated with intermediate water, somewhat upwelled from AAIW at the equator, and made slightly saltier by mixing down from salt fingers on its path in the tropical North Atlantic and Caribbean [*Schmitz et al.*, 1993]. *Siedler et al.* [1992] indicate that in the eastern tropical North Atlantic this flow has *T/S* characteristics that are close to SACW in the latitude range 5°–10°N, becoming more like halfway between SACW and NACW in the latitude range 10°–15°N. This flow is referred to as the North Equatorial Undercurrent by *Siedler et al.* [1992] and as a subthermocline countercurrent by *Cochrane et al.* [1979]. Retroflection in this area at ther-

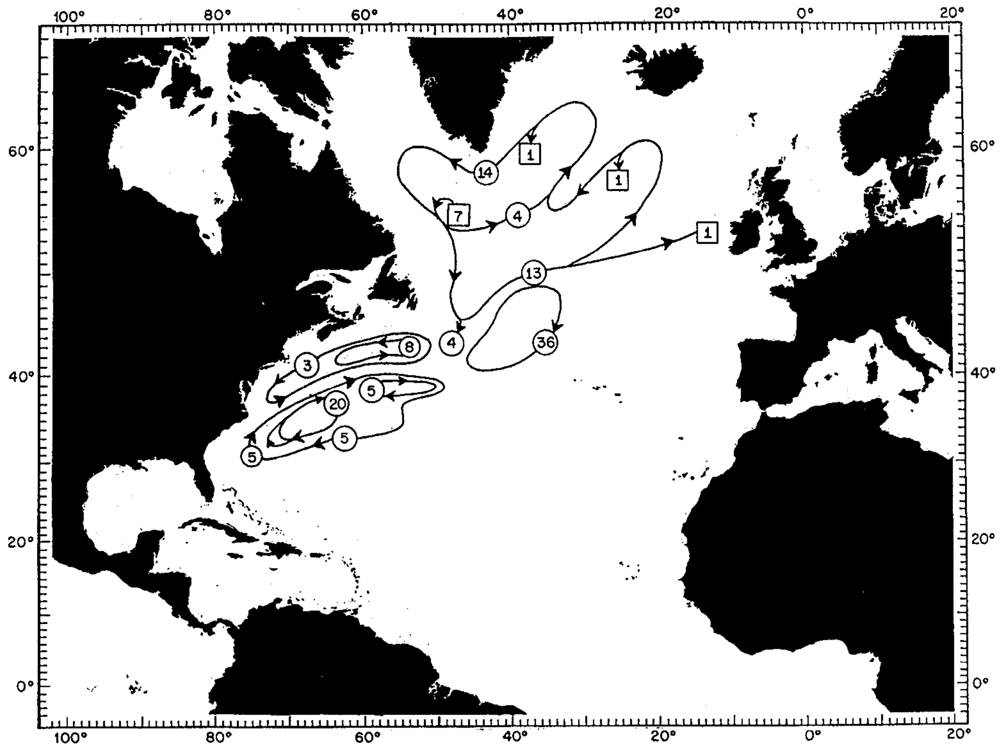


Figure 10. Selected circulation features at temperatures below 7°C (see text for discussion). Transports are in sverdrups, squares represent sinking and triangles represent upwelling.

mocline layer depths is associated with the Guinea Dome [*Siedler et al.*, 1992]. This 5-Sv flows through Anegada and Windward passages into the Straits of Florida (consistent with the works by *Atkinson* [1983] and *Tsuchiya* [1989]) and is found farther north in the Gulf Stream system on its inshore edge [see *Richardson*, 1977, Figure 2]. This flow is modified (dashed line) in the North Atlantic Current system to sink in the Labrador Sea and eventually form UNADW. Other features in Figure 9*c* are the remnants of the southern and northern Gulf Stream recirculations and the NAC recirculation.

We have kept Figure 9*c* as simple as possible, but there are other more complex (and perhaps arbitrary) circulation features in this temperature range. The flow pattern in Figure 9*c* is modified by the addition of three extra features in Figure 9*d*. The first is a recirculating tongue of Mediterranean water, the second is a recirculating gyre with extended longitudinal scale (marked by a combined dotted-dashed line) in the northern North Atlantic that also transports SPMW, consistent with the works by *Sy* [1988], *McCartney and Talley* [1982], and *Tsuchiya et al.* [1992]. Our view is that for layers above 7°–12°C (above SPMW) this recirculation has a southern branch with westward flow along the line from Azores to Newfoundland. Third, an entrainment of SPMW into the southern recirculation of the subtropical gyre is indicated also [*Tsuchiya et al.*, 1992]. We show a transport of 3 Sv of SPMW in the depth range 800–1000 m south across the line from Azores to Europe on the basis of *Stramma* [1984] and *Saunders* [1982].

We now turn to the circulation of the North Atlantic (below 800–1000 m) at temperatures less than 7°C. The composite lower layer circulation is too complex to put on one diagram because there are strong recirculating gyres within basins that mask the net flows linking basins. Figure 10 shows the deepwater (<7°C) expressions of strong recirculations in the Gulf Stream system and east of the NAC. We also have included in Figure 10 the recirculating flow of LSW (amplitude 14 Sv off Cape Farewell, Greenland) in the subpolar gyre, the dominant component of UNADW (3°–4°C; 4 Sv in the DWBC) at these latitudes, following *Talley and McCartney* [1982] and the circulation schematics of *McCartney* [1992]. The LSW flow includes a source from above in the Labrador Sea and sinks in the north and east into the denser levels of NADW, as elaborated upon next. Flows associated with the rest of the thermohaline circulation and with the intermediate layers and the deeper Mediterranean water tongue are shown separately in the following.

We have retained in Figure 10 the deep clockwise gyre in the Newfoundland Basin after *Worthington* [1962, 1976], with transports also compatible with *Clarke et al.* [1980], but wish to emphasize three problems to be addressed in the future. First, the flow direction of the deep Newfoundland Basin gyre in Figure 10 assumes, after W76, a bottom reference level, which associates the bowl-shaped isopycnals in this basin with clockwise flow intensifying upward from the bottom. A middepth reference level would give the reverse below the reference level, counterclockwise flow increasing toward the bottom. *Worthington* [1976] used this middepth reference only in the DWBC, preferring a bottom reference for the North Atlantic Current and the adjacent recirculation. *McCartney* [1992] uses silicate distributions to argue for counterclockwise flow below roughly 3000 m, corresponding to a partial recirculation of the southward DWBC flow along the continental slope of Newfoundland (see below).

Second, separation of the Newfoundland Basin Gyre circulation from the deep circulation to the south is probably not complete. *Worthington* [1976] used a contrast in deep silicate to argue for the separate circulations, and *Stommel et al.* [1978] showed dynamic height contours at deep levels suggesting separation of the two circulations. *McCartney* [1992] shows, however, that there is a contouring ambiguity in the data and that other data sets show evidence of a connection between the two areas in the deep water. The more complete silicate data base now available shows a tongue of high-silicate deep water entering the Newfoundland Basin from the south and penetrating northward on the eastern side of the Basin—the eastern side of the deep isopycnal bowl. This suggests that both the circulation connection between the two regions and the middepth reference level within the Newfoundland Basin yield southward flow of northern source waters in the west and northward flow of southern source waters in the east. We will leave a deep clockwise circulation in the Newfoundland Basin on Figure 10 and present a partial alternative in Figure 11.

Third, the size of the North Atlantic Current recirculation will be dependent on temperature range (see Figure 9*d*), generally of larger horizontal extent than W76 considers.

The meridional overturning system of the North Atlantic transports water with temperatures greater than 4°C to subpolar latitudes and returns colder water to subtropical latitudes. *Worthington*'s [1976] deep water formation and associated thermohaline circulation for the northern North Atlantic have been carefully reviewed and replaced by *Ivers* [1975], *McCartney and Talley* [1984], and *McCartney* [1992], with modified circulation cartoons for the northern North Atlantic from the latter reference presented in Figure 11. In this figure the NADW is split into two layers (UNADW, 3°–4°C, and LNADW, 1.8°–3°C) to focus separately on the LSW circulation and the denser levels.

There are three main sources for cold water in the subpolar gyre: the dense overflows from the subpolar seas, the less dense LSW formed within the subpolar basin, and recirculating deep water flowing northward from mid-latitudes. The subpolar basins (Figure 1*a*) are separated by a system of islands and submarine ridges, south of which a deep northern boundary current (DNBC) is found flowing from east to west, conveying the dense overflows and recirculating deep waters to the Labrador Basin. Joined there by LSW, the DNBC continues as a DWBC carrying the cold waters to low latitude. Recirculation of warm waters and LSW into the DNBC warms it and increases its transport. The amplitude of the DWBC exiting the subpolar gyre is 16 Sv, larger than the 13-Sv amplitude of the thermohaline circulation because of a 3 Sv northward flow of AABW-derived LDW in the interior.

A composite circulation cartoon for deep water (temperatures 1.8°–4°C) is shown in Figure 12*a*, taken primarily from *McCartney and Talley* [1984] and *McCartney* [1992], and excluding the deep gyres shown in Figure 10. The deep circulations in Figure 10 are indicated by hatched areas on Figure 12*b*. The transports indicated by triangles in the Canary, Sohm, and Newfoundland basins, totaling 4 Sv, represent the upwelling of AABW from the south into the NADW layer (see below). This water has a much higher silicate content than the northern source waters, allowing recognition of its influence as it flows into the northern North Atlantic along the pathways indicated by dotted curves. In the eastern basin the northward flow of warmed AABW initiates the DNBC by turning west along the Rockall Plateau before looping through the Iceland Basin where it is joined by the dense overflow from the Norwegian-Greenland Sea [*Tsuchiya et al.*, 1992]. A counterclockwise recirculation over the West European Basin, south and west of the Rockall Plateau and east of the Charlie-Gibbs Fracture Zone, acts to mix water from northern and southern sources. The combined flow through the fracture zone is joined by additional southern source water (dotted curve) that has come northward through the eastern side of the deep Newfoundland Basin Gyre. The DNBC also carries the LSW produced in the Labrador Basin and the Denmark Strait Overflow into the Irminger Basin to give 15 Sv at the southern tip of Greenland. Not included

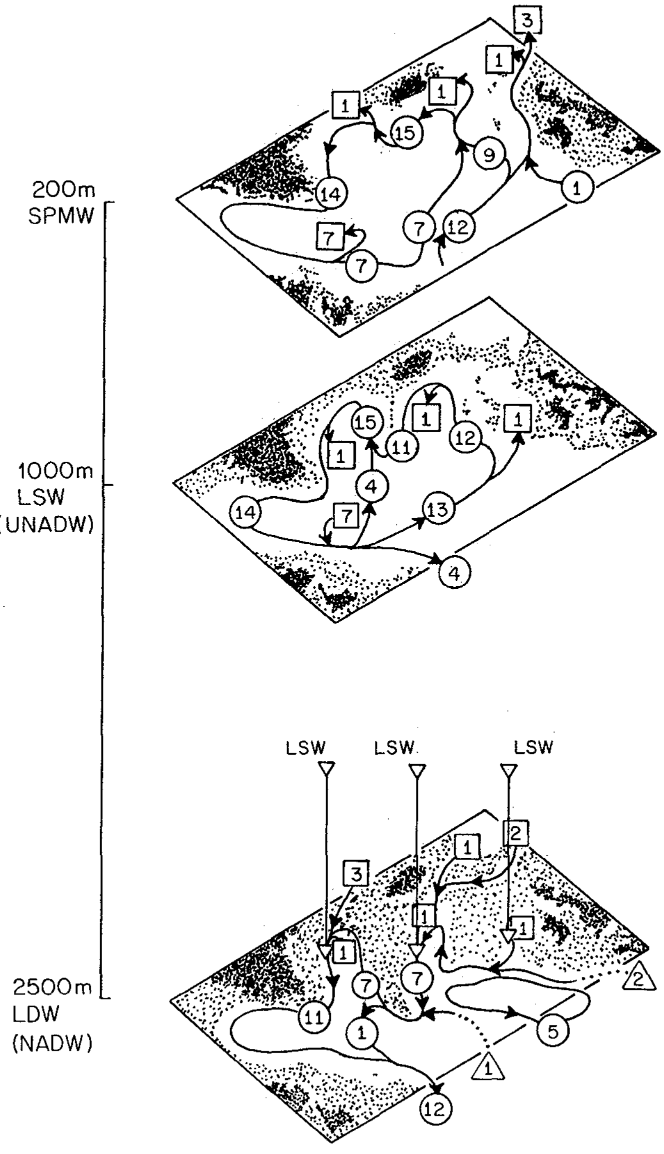


Figure 11. A circulation cartoon for the northern North Atlantic, adapted from Figure 5 by *McCartney* [1992]. Transports are in sverdrups, squares represent sinking and triangles represent upwelling.

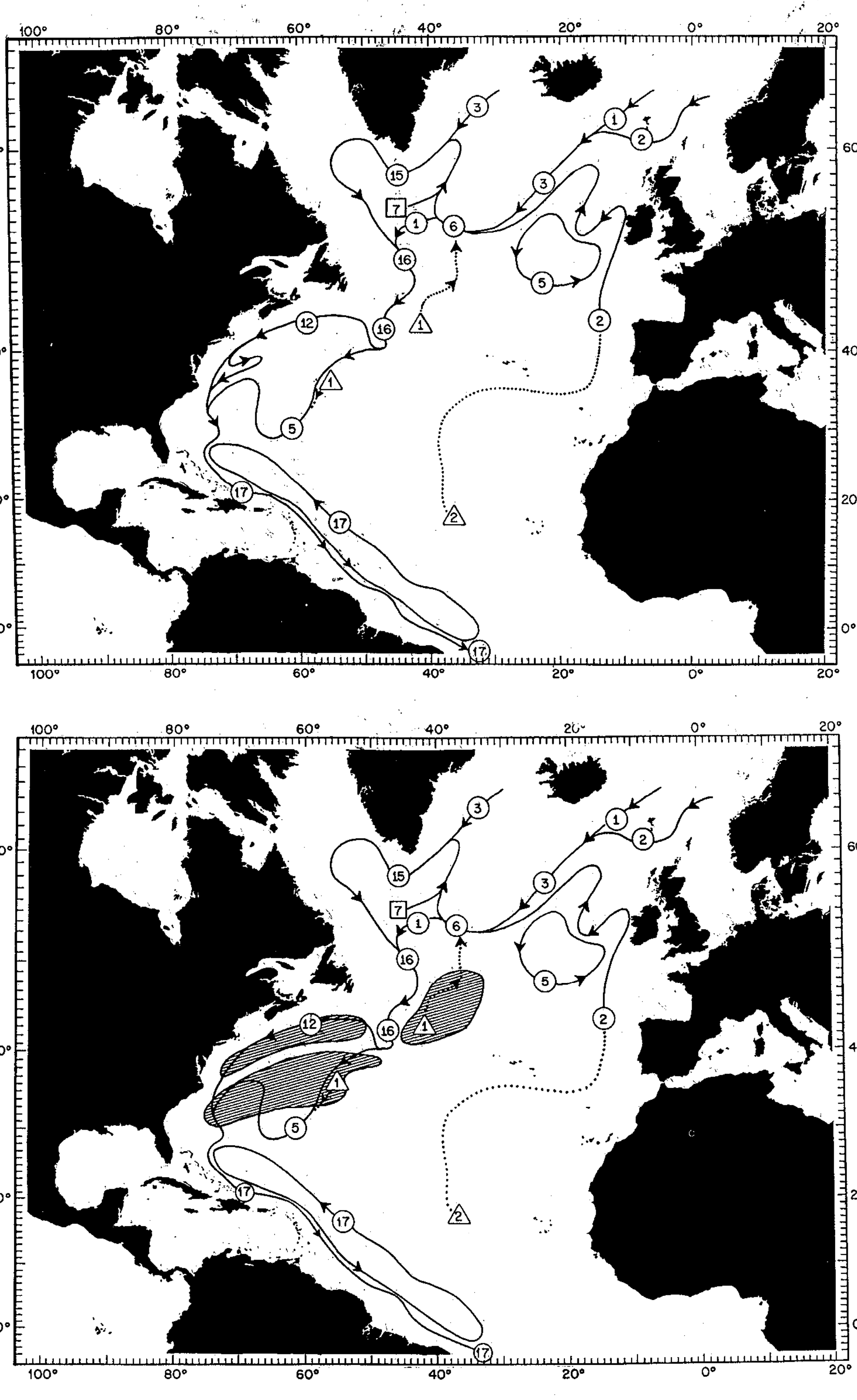


Figure 12. Circulation cartoons for deep water (1.8°–4°C); (*a*) thermohaline-forced flows only, based on *McCartney* [1992], and (*b*) with the deep mid-latitude gyres in Figure 10 added as shaded areas. Transports are in sverdrups, squares represent sinking and triangles represent upwelling.

in this cartoon is the recirculation of LSW within the subpolar gyre shown in Figure 11 as about 13 Sv, which would boost the total transport of deep water at the continental margin of the Labrador Basin from the 15 Sv shown in Figure 12 to 28 Sv (consistent with the work by *Clarke* [1984]).

In the mid-latitude western basin we show (Figure 12) the DWBC splitting as it turns into the slope water region. A direct path along the continental slope carries a DWBC component under the Gulf Stream at Cape Hatteras. We also show (on Figure 12*a*, not Figure 12*b*) a possible retroflection at Hatteras, following *Pickart and Smethie* [1993]. The other branch turns toward the southwest onto the Sohm Abyssal Plain to merge with southern source water to the east of the Bermuda Rise and flows west to the western boundary, looping south of the rise and then north around the Hatteras Abyssal Plain to join the DWBC southeast of the Blake Bahama Outer Ridge. DWBC measurements at a number of locations along the western boundary [*Fine and Molinari*,

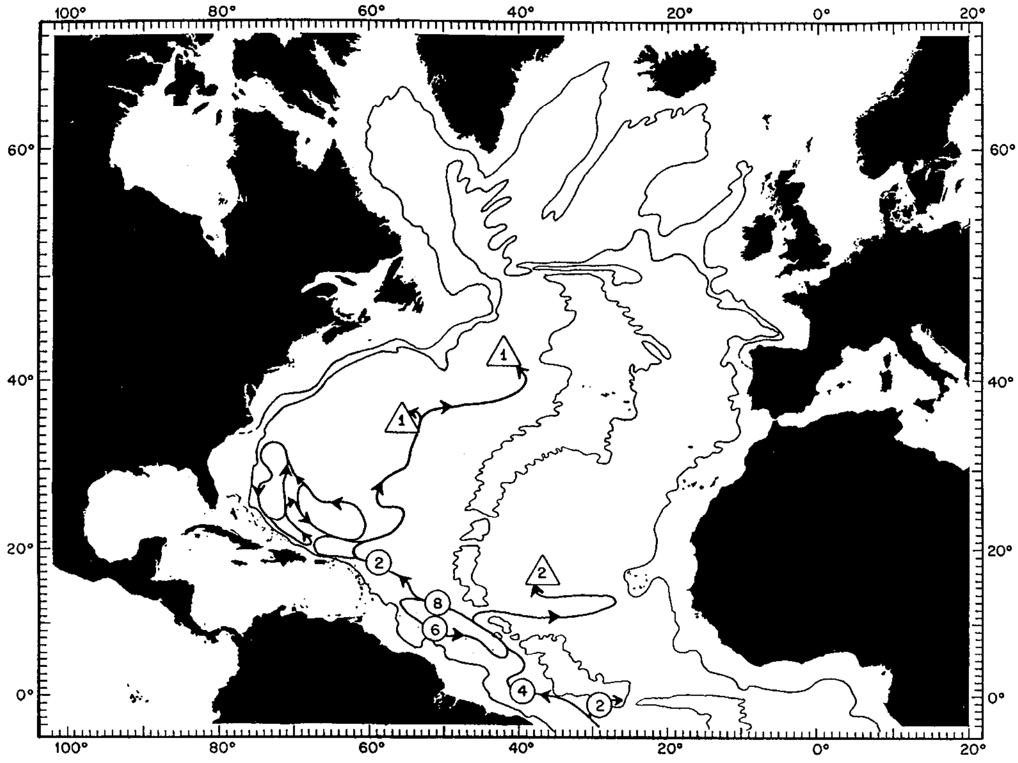


Figure 13. A circulation cartoon for bottom water (1.3°–1.8°C). Transports are in Sverdrups (10^6 m^3 s^{-1}), triangles represent upwelling; 2000- and 4000-m depth contours are added in light lines.

1988; *Johns et al.*, 1993; *Leaman and Harris,* 1990; *Lee et al.*, 1990; *Molinari et al.*, 1992] have revealed transports of NADW much larger than the throughput transport of 13 Sv (below nominally 4°C). We have represented this as a single elongated recirculating gyre in the NADW circulation cartoon (Figure 12). There may be more than one "center" within this gyre, but by and large the variations in DWBC transport along the boundary could be entirely due to sampling differences, different reference level decisions for hydrographic sections, and low-frequency variability, rather than the convergence and divergence of flow into and out of the DWBC recirculation as it flows from Abaco to the equator. *McCartney* [1993] estimates a DWBC transport immediately south of the equator (3°S) of 34 Sv and finds evidence for a northward return flow offshore. It appears that this flow reaches to at least 5°S and may actually penetrate to near 20°S in the Brazil Basin. *Richardson and Schmitz* [1993] have observed a coupling between the southward cross-equatorial flow of UNADW and equatorial upper ocean dynamics, as well as a horizontal displacement between boundary currents transporting UNADW and LNADW. These results suggest that the flow pattern shown for NADW in Figure 12 is simplified dramatically near the equator.

The bottom water flow pattern in Figure 13 is taken primarily from *McCartney and Curry* [1993] and *McCartney et al.* [1991]. The northward spreading of AABW through the Atlantic Ocean occurs predominantly in the western basin, first encountering a passage to the eastern basin at the Romanche Fracture Zone at the equator and subsequently a second at the Vema Fracture Zone at 11°N. Antarctic Bottom Water from the South Atlantic crosses the equator (Figure 13) in the western basin with an estimated transport of 4 Sv [*McCartney and Curry,* 1993]. This is consistent with the estimated 5 Sv northward transport of AABW in the Brazil Basin (from sections at 11°S and 23°S, *McCartney and Curry,* [1993]), provided that 1 Sv diverts to the eastern basin through the equatorial Romanche Fracture Zone.

McCartney et al. [1991] found no evidence for flow in the Kane Gap through the Sierra Leone Rise, which could convey Romanche Waters northward in the eastern basin. So the AABW source for the eastern basin of the North Atlantic is a flow of about 2 Sv through the Vema Fracture Zone at 11°N onto the Gambia Abyssal plain [*McCartney et al.*, 1991]. This flow extends well eastward along the southern edge of the Plain before retroflecting back westward and turning north through a gap at 38°W in the Cape Verde Ridge into the Canary Basin. At this point the AABW has warmed above 1.8°C, and its continued influence to the north is shown on the NADW cartoon (Figure 12). The flow lines in Figure 13 could be dashed throughout, indicating constant modification, but we show AABW within the temperature range 1.3°–1.8° until upwelled; these sites are of course of larger horizontal scale than the precise size of the triangles shown in the figure.

In the western basin of Figure 13 we use an estimate of 4 Sv crossing the equator. An elongated counterclockwise gyre in the Guiana Basin, centered over the Demerara Abyssal Plain, recirculates about twice the amount of AABW that actually continues on north in the western basin. As a result, the DWBC in this area has a sizable southward transport of AABW as cold as 1.3°C. This gyre flow, unlike the overlying NADW's elongated gyre, seems to be broken at the northeastern corner of the Antilles, where the continued northward flow of AABW diverts westward into the Puerto Rico Trench. There are two exits from the trench onto the Nares Abyssal Plain through which AABW as cold as 1.4°C

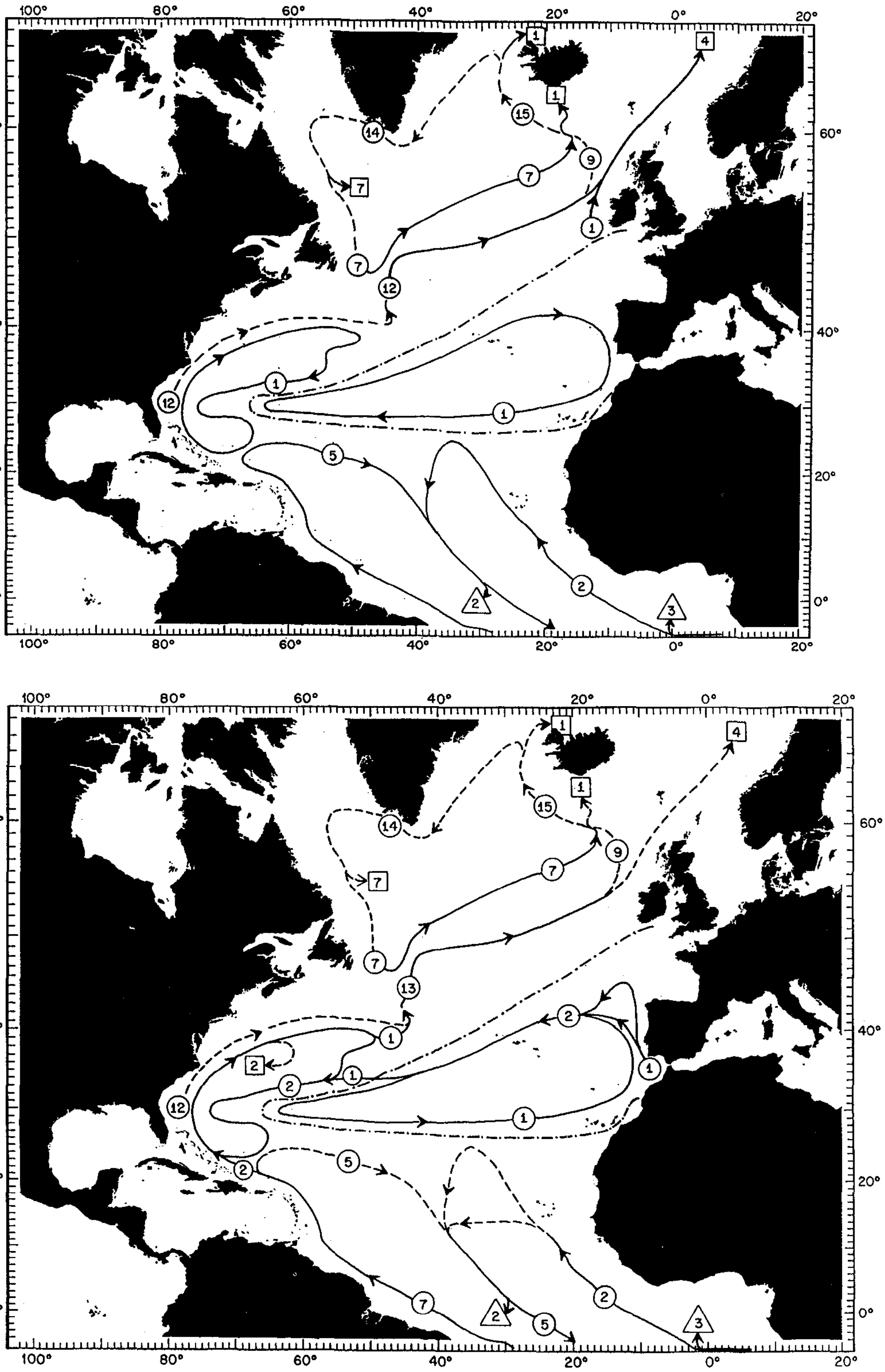


Figure 14. Circulation cartoons for intermediate water (4°–7°C). Transports are in sverdrups (10^6 m^3 s^{-1}): (*a*) the simpler version, (*b*) with additional and modified features. Squares represent sinking and triangles represent upwelling.

passes to mid-latitudes. A recirculation gyre lies over the Nares Abyssal Plain between the trench and the Bermuda Rise, while a second flow path is a loop through the Sohm Abyssal Plain east of the rise, long ago recognized by *Wüst* [1935] as the principal northward flow route in the western basin. It is here that the AABW from the south first contacts the overflow waters from the north, and where we have indicated the AABW rising into the NADW layer to form a weakly stratified water mass at 1.9°C.

Intermediate-water (4°–7°C) circulation is the most arbitrary of any layer we have discussed, and our corresponding cartoons are shown in Figures 14*a* and 14*b*. The circulation at mid-latitudes in Figure 14*a* is adapted partially from *Reid* [1978, 1979] and *Tsuchiya* [1989]. There is a remnant of the C-shaped circulation at mid-latitudes and a 1-Sv clockwise circulation of MOW. The low-latitude intermediate-water circulation is adapted from *Kirwan* [1963] and *Tsuchiya* [1989]. Antarctic Intermediate Water flowing west through Vema

Channel is adapted from *McCartney et al.* [1991]. The northern North Atlantic in Figure 14 (like Figure 11 (top)) contains the circulation of SPMW according to *McCartney* [1992], consistent with *Sy* [1988, Figure 12]. Another, more complex and somewhat different version of Figure 14*a* is shown in Figure 14*b*. Here the circulation of (lower) MOW is counterclockwise rather than clockwise, a feature dependent on choice of a deep (counterclockwise) or shallow reference layer. In Figure 14*b* we also show 2 Sv of intermediate water entering the Gulf Stream system from the south (consistent with the works by *Richardson* [1977], *Tsuchiya* [1989], and *Atkinson* [1983]), being modified and sinking to join UNADW (this is sufficiently tentative that we have not included it on Figure 12).

SUMMARY

We have presented a replacement for W76's picture of the North Atlantic circulation. Our scheme exhibits both differences from and similarities to W76, but we are in any case appreciative of his influence. Significant divergences are with his thermohaline circulation, cross-equatorial transport and Florida Current sources, flow in the eastern Atlantic, circulation in the Newfoundland Basin, slope water currents, and flow pattern near the Bahamas. The circulation patterns that we show are consistent with nearly all other published accounts of various flow components, perhaps amazingly so.

The following is a list of some of our results that we feel resolve most of the dilemmas encountered by W76:

1. The thermohaline flow involves the northward movement of about 13 Sv of warm water from the equator to high latitudes. We describe the pathway for this water, retroflecting in the tropics, flowing into the Caribbean, and through the Florida Current, the Gulf Stream, and the North Atlantic Current, eventually sinking at high latitude. *Worthington* [1976] has a 30-Sv Florida Current totally comprised of recirculating North Atlantic waters. Our interpretation is that it is more nearly equal proportions of recirculating North Atlantic Water and the thermohaline flow from the South Atlantic. In this respect our interpretation supports the earlier hypothesis by *Stommel* [1957] in Figure 1*c*.

2. After *Hogg* [1992] our charts show a pair of counterrotating recirculation gyres to either side of the Gulf Stream causing the augmentation of the Gulf Stream transport. In contrast, Figure 6 (from W76) shows the augmentation entirely from a Sargasso Sea gyre, with a weak clockwise gyre to the north actually diminishing the Gulf Stream transport. We also show an order of 10-Sv return flow in the eastern North Atlantic where W76 has none.

3. The "northern gyre" east of Newfoundland in Figure 6 has been disputed before [e.g., *Clarke et al.*, 1980] with regard to its complete isolation from the Gulf Stream. Our interpretation has a branch from the Gulf Stream initiating the North Atlantic Current southeast of Newfoundland, with the magnitude of the branch essentially that of the thermohaline flow. The North Atlantic Current is augmented by recirculating gyre flow.

4. The main pathway by which the thermohaline flow of cold water returns southward is the deep western boundary current. The measurements of the DWBC transport are generally larger than the 13-Sv amplitude of the newly formed deep water. Two contributions to this augmentation are described and lead to a considerably more complex deep circulation than in the earlier interpretations. First, there are several distinct counterclockwise recirculating gyres with the flow on the west sides of these gyres enhancing the DWBC transport, effectively doubling it at many locations. Second, the thermohaline flow is more nearly a three-layer system than a two-layer system: the North Atlantic exports North Atlantic Deep Water to and imports warm water from the South Atlantic, but it also imports about 4 Sv of Antarctic Bottom Water from the South Atlantic, which is modified and flows equatorward with the DWBC.

The thermohaline circulation amplitudes found by SR91 (partly based on *Hall and Bryden* [1982], and *Roemmich and Wunsch* [1985]), *McCartney and Talley* [1984], and *Rintoul* [1991], three independent investigations that together cover the Atlantic Ocean from 32°S to about 60°N, are amazingly consistent. The idea of a thermohaline conveyor belt *requiring* a worldwide distribution of upwelling locations [*Gordon*, 1986], a large warm-water transport from the Indian to South Atlantic oceans, and a total of 20 Sv of NADW formation is not necessary in our opinion [see also *Rintoul*, 1991]. There is, however, evidence for an exchange of water between these two oceans in the thermocline layer. We hypothesize that the main upwelling of NADW occurs primarily in the Antarctic Circumpolar Current regime, eventually to form 13–15 Sv of AAIW along with 4 Sv of AABW. A 20-Sv net transport for the DWBC (as opposed to 13–14 Sv pure recently formed NADW) in the Atlantic could involve 4 Sv of modified AABW and 2 Sv of modified AAIW. Recirculations could increase this total to 35–40 Sv. We realize that there are other interesting thermohaline circulations in the Pacific and Indian oceans that involve NADW but in comparatively small amounts, probably not playing a crucial role in the NADW cycle.

THE STATE OF THE ART AND FUTURE PROSPECTS

Substantial strides toward describing and rationalizing the structure of the general ocean circulation in the North Atlantic have been made in the last decade. We present a zero-order description of these phenomena. (There are also zero-order ideas and models that have some relevance.) The eddy field has turned out to be easier to describe than either the "mean" circulation or long-term fluctuations in the general circulation that may be related to climate. With regard to climatic scale variability, there is at present a great deal of interest relative to the thermohaline circulation [i.e., *Broecker*, 1991], especially in the North Atlantic.

Observationally, the data base on the general circulation and its climatic fluctuations is sparse to say the least. We would like to see a more systematic observational delineation of the structure of deep western boundary currents and their recirculations (and eddy fields) in the world's oceans, as was originally proposed for the World Ocean Circulation Experiment [*Reid and Bryden,* 1984] but not yet carried out. The circulation of (Antarctic) intermediate water is virtually unexplored, and the tropical circulation including flow through the Caribbean passages needs better definition. We feel that the explicit inclusion of both equatorial physics and upwelling in the circumpolar region into thermohaline models should be pursued actively.

ACKNOWLEDGMENTS. W.J.S. was supported in this investigation by the Office of Naval Research under contract N00014-84-C-0134, NR 083-400 and grant N00014-89-J-1039, as well as by grants OCE85-21082 and OCE91-04656 from the National Science Foundation. M.S.M. was supported by grants from the National Science Foundation, OCE91-05834, and the National Oceanic and Atmospheric Administration, NA16RC0528-01. The authors thank the referees and the editor for their many helpful suggestions. Contribution number 7889 from the Woods Hole Oceanographic Institution. This article is dedicated to Hank Stommel.

D. Luther was the editor responsible for this paper. He thanks L. Talley, R. Molinari, and M. Neugebauer for their assistance in evaluating the paper.

REFERENCES

Atkinson, L. P., Distribution of Antarctic Intermediate Water over the Blake Plateau, *J. Geophys. Res., 88,* 4699–4704, 1983.

Böning, C. W., R. Döscher, and H.-J. Isemer, Monthly mean wind stress and Sverdrup transports in the North Atlantic: A comparison of the Hellerman–Rosenstein and Isemer–Hasse climatologies, *J. Phys. Oceanogr., 21,* 221–235, 1991.

Broecker, W. S., The great ocean conveyor, *Oceanography, 4,* 79–89, 1991.

Broecker, W. S., T.-H. Peng, and M. Stuiver, An estimate of the upwelling rate in the equatorial Atlantic based on the distribution of bomb radiocarbon, *J. Geophys. Res., 83,* 6179–6186, 1978.

Bryden, H. L., and T. H. Kinder, Steady two-layer exchange through the Strait of Gibraltar, *Deep Sea Res., 38,* suppl. 1, S445–S463, 1991.

Bubnov, V. A., and V. D. Egorikhin, Study of water circulation in the tropical Atlantic, *Deep Sea Res., 26,* suppl. II, 125–136, 1979.

Candela, J., R. C. Beardsley, and R. Limeburner, Separation of tidal and subtidal currents in ship-mounted acoustic Doppler current profiler observations, *J. Geophys. Res., 97,* 769–788, 1992.

Clarke, R. A., Transport through the Cape Farewell–Flemish Cap section, *Rapp. P. V. Reun. Cons. Int. Explor. Mer, 185,* 120–130, 1984.

Clarke, R. A., H. W. Hill, R. F. Reiniger, and B. A. Warren, Current system south and east of the Grand Banks of Newfoundland, *J. Phys. Oceanogr., 10,* 25–65, 1980.

Cochrane, J. D., F. J. Kelly, Jr., and C. R. Olling, Subthermocline countercurrents in the western equatorial Atlantic Ocean, *J. Phys. Oceanogr., 9,* 724–738, 1979.

Csanady, G. T., Gross-gyre transports, *J. Phys. Oceanogr., 16,* 1703–1711, 1986.

England, M. H., On the formation of Antarctic Intermediate and Bottom Water in ocean general circulation models, *J. Phys. Oceanogr., 22,* 918–926, 1992.

England, M. H., J. S. Godfrey, A. C. Hirst, and M. Tomczak, The mechanism for Antarctic Intermediate Water renewal in a world ocean model, *J. Phys. Oceanogr.,* in press, 1993.

Fine, R. A., and R. L. Molinari, A continuous deep western boundary current between Abaco (26.5°N) and Barbados (13°N), *Deep Sea Res., 35,* 1441–1450, 1988.

Finlen, J. R., Transport investigations in the Northwest Providence Channel, Master of Science thesis, 110 pp., Univ. of Miami, Coral Gables, Fl., 1966.

Gordon, A. L., Interocean exchange of thermocline water, *J. Geophys. Res., 91,* 5037–5046, 1986.

Gordon, A. L., R. F. Weiss, W. M. Smethie, Jr., and M. J. Warner, Thermocline and intermediate water communication between the South Atlantic and Indian oceans, *J. Geophys. Res., 97,* 7223–7240, 1992.

Halkin, D., and T. Rossby, The structure and transport of the Gulf Stream at 73°W, *J. Phys. Oceanogr., 15,* 1439–1452, 1985.

Hall, M. M., and H. L. Bryden, Direct estimates and mechanisms of ocean heat transport, *Deep Sea Res., 29,* 339–359, 1982.

Hall, M. M., and N. P. Fofonoff, Downstream development of the Gulf Stream from 68° to 55°W, *J. Phys. Oceanogr., 23,* 225–249, 1993.

Hogg, N. G., On the transport of the Gulf Stream between Cape Hatteras and the Grand Banks, *Deep Sea Res., 39,* 1231–1246, 1992.

Hogg, N., P. Biscaye, W. Gardner, and W. J. Schmitz, Jr., On the transport and modification of Antarctic Bottom Water in the Vema Channel, *J. Mar. Res., 40,* 231–263, 1982.

Ivers, W. D., The deep circulation in the northern North Atlantic, with especial reference to the Labrador Sea, Ph.D. thesis, 179 pp., Univ. of Calif. at San Diego, 1975.

Johns, W. E., D. M. Fratantoni, and R. J. Zantopp, Deep western boundary current variability off northeastern Brazil, *J. Phys. Oceanogr.,* in press, 1993.

Kirwan, A. D., Circulation of Antarctic Intermediate Water deduced through isentropic analysis, *Ref. 63-34F,* 34 pp., Texas A & M Univ., College Station, 1963.

Lazier, J. R. N., Renewal of subpolar water in the North Atlantic Ocean, *J. Phys. Oceanogr.,* in press, 1993.

Leaman, D. K., and J. E. Harris, On the average absolute transport of the deep western boundary currents east of Abaco Island, the Bahamas, *J. Phys. Oceanogr., 20,* 467–475, 1990.

Lee, T. N., W. Johns, F. Schott, and R. Zantopp, Western boundary current structure and variability east of Abaco, Bahamas at 26.5°N, *J. Phys. Oceanogr., 20,* 446–466, 1990.

Leetmaa, A., and A. F. Bunker, Updated charts of the mean annual wind stress, convergences in the Ekman layers, and Sverdrup transports in the North Atlantic, *J. Mar. Res., 36,* 311–322, 1978.

Leetmaa, A., P. Niiler, and H. Stommel, Does the Sverdrup relation account for the mid-Atlantic circulation?, *J. Mar. Res., 35,* 1–10, 1977.

Mann, C. R., The termination of the Gulf Stream and the beginning of the North Atlantic current, *Deep Sea Res., 14,* 337–359, 1967.

McCartney, M. S., Subantarctic Mode Water, in A Voyage of Discovery, George Deacon 70th Anniv. Vol., edited by M. V. Angel, *Deep Sea Res.,* suppl., pp. 103–119, 1977.

McCartney, M. S., The subtropical recirculation of Mode Waters, *J. Mar. Res., 40,* suppl., 427–464, 1982.

McCartney, M. S., Recirculating components to the deep boundary current of the northern North Atlantic, *Prog. Oceanogr., 29,* 283–383, 1992.

McCartney, M. S., The crossing of the equator by the Deep Western Boundary Current in the western Atlantic Ocean, *J. Phys. Oceanogr.,* in press, 1993.

McCartney, M. S., and R. A. Curry, Trans-equatorial flow of Antarctic Bottom Water in the western Atlantic Ocean: Abyssal geostrophy at the equator, *J. Phys. Oceanogr.,* in press, 1993.

McCartney, M. S., and L. D. Talley, The Subpolar Mode Water of the North Atlantic Ocean, *J. Phys. Oceanogr., 12,* 1169–1188, 1982.

McCartney, M. S., and L. D. Talley, Warm-to-cold water conversion in the northern North Atlantic Ocean, *J. Phys. Oceanogr., 14,* 922–935, 1984.

McCartney, M. S., S. L. Bennett, and M. E. Woodgate-Jones, Eastward flow through the Mid-Atlantic Ridge at 11°N and its influence on the abyss of the eastern basin, *J. Phys. Oceanogr., 21,* 1089–1121, 1991.

Metcalf, W., and M. Stalcup, Origin of the Atlantic Equatorial Undercurrent, *J. Geophys. Res., 72,* 4959–4975, 1967.

Molinari, R. L., R. A. Fine, and E. Johns, The Deep Western Boundary Current in the tropical North Atlantic Ocean, *Deep Sea Res., 39,* 1967–1984, 1992.

Montgomery, R. B., and M. J. Pollak, Sigma-*t* surfaces in the Atlantic Ocean, *J. Mar. Res., 5,* 20–27, 1942.

Pickart, R. S., and W. M. Smethie, Jr., How does the Deep Western Boundary Current cross the Gulf Stream?, *J. Phys. Oceanogr.,* in press, 1993.

Reid, J. L., On the mid-depth circulation and salinity field in the North Atlantic Ocean, *J. Geophys. Res., 83,* 5063–5067, 1978.

Reid, J. L., On the contribution of the Mediterranean Sea outflow to the Norwegian–Greenland Sea, *Deep Sea Res., 26,* 1199–1223, 1979.

Reid, J. L., and H. L. Bryden, Consideration of mid-depth and abyssal circulation studies during WOCE: A brief meeting report, *Bull. Am. Meteorol. Soc., 65,* 1219–1220, 1984.

Reid, J. L., and R. J. Lynn, On the influence of the Norwegian–Greenland and Weddell seas upon the bottom waters of the Indian and Pacific oceans, *Deep Sea Res., 18,* 1063–1088, 1971.

Richardson, P. L., On the crossover between the Gulf Stream and the Western Boundary Undercurrent, *Deep Sea Res., 24,* 139–159, 1977.

Richardson, P. L., Average velocity and transport of the Gulf Stream near 55°W, *J. Mar. Res., 43,* 83–111, 1985.

Richardson, P. L., and J. A. Knauss, Gulf Stream and Western Boundary Undercurrent observations at Cape Hatteras, *Deep Sea Res., 18,* 1089–1109, 1971.

Richardson, P. L., and W. J. Schmitz, Jr., Deep cross-equatorial flow in the Atlantic measured with SOFAR floats, *J. Geophys. Res.,* in press, 1993.

Richardson, W. S., W. J. Schmitz, Jr., and P. P. Niiler, The velocity structure of the Florida Current from the Straits of Florida to Cape Fear, *Deep Sea Res., 16,* suppl., 225–231, 1969.

Rintoul, S. R., South Atlantic interbasin exchange, *J. Geophys. Res., 96,* 2675–2692, 1991.

Roemmich, D., Estimation of meridional heat flux in the North Atlantic by inverse methods, *J. Phys. Oceanogr., 10,* 1972–1983, 1980.

Roemmich, D., Circulation of the Caribbean Sea: A well-resolved inverse problem, *J. Geophys. Res., 86,* 7993–8005, 1981.

Roemmich, D., The balance of geostrophic and Ekman transports in the tropical Atlantic Ocean, *J. Phys. Oceanogr., 13,* 1534–1539, 1983.

Roemmich, D., and C. Wunsch, Two transatlantic sections: Meridional circulation and heat flux in the subtropical North Atlantic Ocean, *Deep Sea Res., 32,* 619–664, 1985.

Saunders, P. M., Circulation in the eastern North Atlantic, *J. Mar. Res., 40,* suppl., 641–657, 1982.

Schmitz, W. J., Jr., and W. S. Richardson, On the transport of the Florida Current, *Deep Sea Res., 15,* 679–693, 1968.

Schmitz, W. J., Jr., and P. L. Richardson, On the sources of the Florida Current, *Deep Sea Res., 38,* suppl. 1, S389–S409, 1991.

Schmitz, W. J., Jr., J. D. Thompson, and J. R. Luyten, The Sverdrup circulation for the Atlantic along 24°N, *J. Geophys. Res., 97,* 7251–7256, 1992.

Schmitz, W. J., Jr., J. R. Luyten, and R. W. Schmitt, On the Florida Current T/S envelope, *Bull. Mar. Sci. (Scheduled for vol. 53,* July, 1993), in press, 1993.

Siedler, G., N. Zangenberg, R. Onken, and A. Morlière, Seasonal changes in the tropical Atlantic circulation: Observation and simulation of the Guinea Dome, *J. Geophys. Res., 97,* 703–715, 1992.

Stommel, H., A survey of ocean current theory, *Deep Sea Res., 4,* 149–184, 1957.

Stommel, H., *The Gulf Stream, A Physical and Dynamical Description,* 2nd ed., 248 pp., University of California Press, Berkeley, 1965.

Stommel, H., P. Niiler, and D. Anati, Dynamic topography and recirculation of the North Atlantic, *J. Mar. Res., 36,* 449–468, 1978.

Stramma, L., Geostrophic transport in the warm water sphere of the eastern subtropical North Atlantic, *J. Mar. Res., 42,* 537–558, 1984.

Sy, A., Investigation of large-scale circulation patterns in the central North Atlantic: The North Atlantic Current, the Azores Current, and the Mediterranean Water plume in the area of the Mid-Atlantic Ridge, *Deep Sea Res., 35,* 383–413, 1988.

Talley, L. D., and M. S. McCartney, Distribution and circulation of Labrador Sea Water, *J. Phys. Oceanogr., 12,* 1189–1205, 1982.

Tsuchiya, M., Circulation of the Antarctic Intermediate Water in the North Atlantic Ocean, *J. Mar. Res., 47,* 747–755, 1989.

Tsuchiya, M., L. D. Talley, and M. S. McCartney, An eastern Atlantic section from Iceland southward across the equator, *Deep Sea Res., 39,* 1885–1917, 1992.

Wennekens, M. P., Water mass properties of the Straits of Florida and related waters, *Bull. Mar. Sci. Gulf Caribb., 9,* 1–52, 1959.

Worthington, L. V., Evidence for a two-gyre circulation system in the North Atlantic, *Deep Sea Res., 9,* 51–67, 1962.

Worthington, L. V., On the North Atlantic circulation, *The Johns Hopkins Oceanogr. Stud., 6,* 110 pp., 1976.

Wunsch, C., An eclectic Atlantic Ocean circulation model, Part I, The meridional flux of heat, *J. Phys. Oceanogr., 14,* 1712–1733, 1984.

Wunsch, C., and D. Roemmich, Is the North Atlantic in Sverdrup balance?, *J. Phys. Oceanogr., 15,* 1876–1880, 1985.

Wüst, G., Schichtung und Zirkulation des Atlantischen Ozeans, Die Stratosphäre, in: *Wiss. Ergebn. Dtsch. Atl. Exped., 6,* Part 1, 2, 180 pp., 1935. (in English translation: *The Stratosphere of the Atlantic Ocean,* edited by W. J. Emery, 112 pp., Amerind, New Delhi, India, 1978.)

M. S. McCartney and W. J. Schmitz, Jr., Woods Hole Oceanographic Institution, Clark Laboratory 3, Woods Hole, MA 02543.