# THE NORTH ATLANTIC CURRENT AND SURROUNDING WATERS: AT THE CROSSROADS

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**Abstract.** The North Atlantic Current is a well-defined western boundary current that flows north along the east side of the Grand Banks from 40° to 51°N, where it turns sharply to the east and begins its journey across the ocean. The current is unique in transporting warm tropical waters to much higher latitudes than any other western boundary current and thus plays a crucial role in ameliorating the climate of the European subcontinent. The North Atlantic Current originates in the Gulf Stream when the latter curves north around the Southeast Newfoundland Rise, a major submarine ridge that stretches SE from the Grand Banks. A well-defined front delineates the path of the current as long as it flows north as a western boundary current. After the current turns east in the north, it broadens into a widening band of eastward drift without a sharp or permanent front in the sense of the eastward flowing Gulf Stream after it separates from Cape Hatteras. The North Atlantic Current transports more than 40 Sv (1 Sv = $10^6$ $m^3$ $s^{-1}$) in the south and about 20 Sv by the time it flows east across the Mid-Atlantic Ridge. The currents along the northward flowing front are quite swift, with typical maximum average speeds in the upper 300 m near 1 m $s^{-1}$ (= 2 knots). The current meanders almost as wildly as a "snaking" river, but unlike steep meanders in the Gulf Stream these meanders appear to be stable, and with one exception have not been observed to break off to form pools of warm and/or cold waters as frequently occurs in the Gulf Stream. The meanders appear to be induced by major topographic features along the path of the current, namely, the Southeast Newfoundland Rise, the Newfoundland Seamounts, and Flemish Cap. Strong recirculations develop on the concave side of the meanders. One of these, the "Mann eddy" at the first meander crest of the North Atlantic Current, should be regarded as a permanent feature of the North Atlantic circulation. Other meanders also contain recirculations that can persist for months. Under certain conditions these can merge together to form an extended SW flow (recirculation) just east of the North Atlantic Current.

## INTRODUCTION

Southeast of Canada and the Grand Banks, something happens to the Gulf Stream that has puzzled oceanographers for years. Rather abruptly after it passes the 50°W meridian, it undergoes a transformation or breakdown that has posed a formidable challenge to describe and understand. Speculation has ranged from the Gulf Stream's splitting into two or more branches, to the current switching or alternating between different directions of flow, to its dissolution into a turbulent field of eddy motion. While there has been much controversy in the past, we now know that a significant fraction of the Gulf Stream turns north as the North Atlantic Current (NAC). This current is unique in transporting warm waters to much higher latitudes than in any other ocean. The uniqueness of the North Atlantic Current gains in significance owing to its role in moderating the climate over the northern North Atlantic and European subcontinent [*Krauss*, 1986].

The North Atlantic Current, in broad perspective, is a crucial link in a series of connected boundary currents that swiftly ($\ll$1 year) transport warm tropical waters to subpolar latitudes. Thanks to this rapid advection, the temperature of the surface waters of these currents almost always exceeds that of the surrounding waters and overlying atmosphere. Should this rapid poleward transport decrease or turn zonal at midlatitudes as in the other ocean basins, the mean temperatures of the North Atlantic and European landmasses would drop precipitously.

The character of these currents varies strongly with region. The Florida Current, constrained by southern Florida on one side and the Bahamas on the other, shows little path variability. The Gulf Stream, on the other hand, after it separates from the coast at Cape Hatteras, flows east as a free meandering jet. It entrains waters from both sides until it reaches a maximum transport of about 150 Sv [*Hogg*, 1992] near 60°W (1 Sv = $10^6$ $m^3$ $s^{-1}$; see the glossary following the main text). Southeast of the Grand Banks where the Gulf Stream flows along the Southeast Newfoundland Rise, it undergoes a poorly understood transformation or splitting process. In my view, the baroclinic flow in the Gulf Stream breaks up into two parts, a broad, perhaps diffuse return flow to the south and west feeding a recir-

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Reviews of Geophysics, 34, 4 / *November 1996*
pages 463–481
Paper number 96RG02214

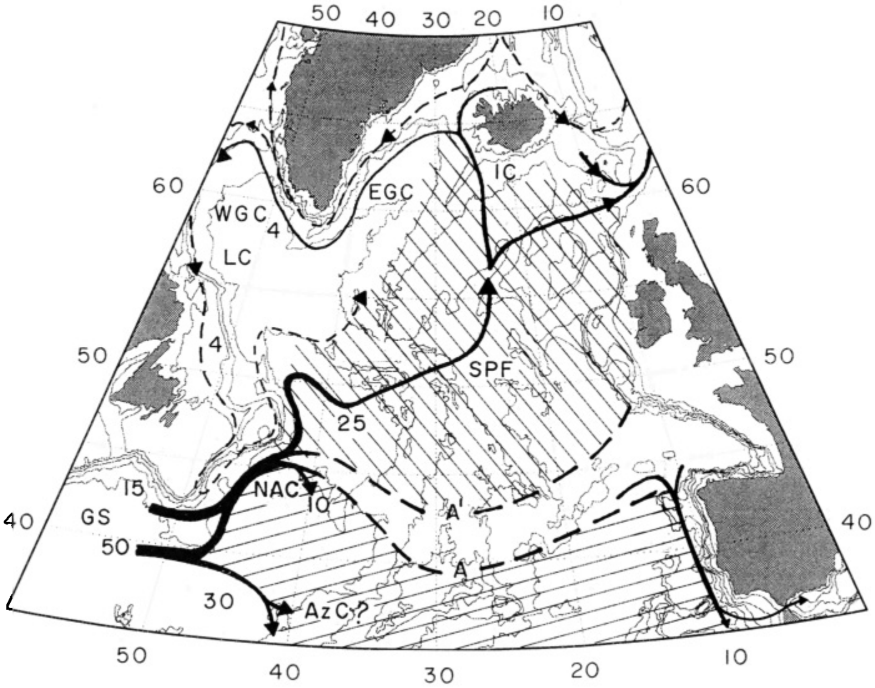

**Figure 1.** The major currents of the northern North Atlantic adapted from *Krauss* [1986]. The left slanted shading indicates the region where the warm waters of the Subpolar Front can be found. The shading in the south represents waters of the subtropical gyre. The numbers indicate the volume transport in sverdrups (1 Sv = $10^6$ $m^3$ $s^{-1}$). Abbreviations are NAC, North Atlantic Current; SPF, Subpolar Front; IC, Irminger Current; LC, Labrador Current; EGC and WGC, the East and West Greenland Currents; and AzC, Azores Current. Isobaths are drawn at 200, 1000, 2000, 3000, and 4000 m. The topographic ridge extending SE from the Grand Banks is the Southeast Newfoundland Rise.

culation back toward the Gulf Stream at and downstream of Cape Hatteras [*Hogg*, 1992], and a northeastward branch, the North Atlantic Current. Additional waters break off, presumably in the form of streamers, pools of water, or eddies, which drift away as part of a large-scale eastward drift. In the eastern Atlantic some of this drift concentrates into a shallow but well-defined baroclinic front known as the Azores Current [*Klein and Siedler*, 1989].

The North Atlantic Current flows northeast along the continental rise past Flemish Cap and continues NW toward what has become known as the Northwest Corner [*Worthington*, 1976], where the current turns east toward the Mid-Atlantic Ridge (MAR). West of the NAC along the continental shelf edge, the Labrador Current flows south toward the Tail of the Grand Banks, where some waters round the corner and continue west while the greater part turn northeast and joins the NAC along its inshore edge. As a result, warm, saline waters of tropical-subtropical origin and very cold, fresh waters from the Labrador Sea come into direct contact along a more than 1000 km front between the start of the North Atlantic Current and the Northwest Corner, where the flow turns east at 50°–52°N. Although many authors refer to continuing flow to the east across the Atlantic as the North Atlantic Current as well, we will find it convenient below to refer to the eastward flow as the Subpolar Front.

The eastward flowing Subpolar Front marks the northernmost extent of the subtropical circulation system. So far as is known, it is not a sharply defined front in the sense of the Gulf Stream after it separates from the coast, but a limited swath or region where the main thermocline shoals to the surface, along which a stronger baroclinic transport is sustained than to either the south or north. From numerous drifter studies the eastward drift waters appear to be generally difluent, with waters peeling off to the southeast and northeast, some gradually or poorly defined, and some in perhaps stronger, transient flows. If there is a single permanent branch, it would be the warm waters continuing NE toward the gap between Scotland and Iceland. Figure 1, published by *Krauss* [1986], provides a schematic overview of the North Atlantic circulation. It is based on a large number of surface drifter observations obtained throughout the early 1980s. The meridionally shaded area indicates the region of predominantly north and eastward flowing waters. In some ways, Figure 1 is a simplification of earlier descriptions [cf. *Sverdrup et al.*, 1942; *Dietrich et al.*, 1975] in which the circulation tended to be depicted in terms of discrete branches of flow. The descriptions of the branching vary significantly, suggesting that these most likely should be interpreted not as permanent currents but as indicators of what may really be an inherently variable or restless region of the ocean. Most recently, *Krauss* [1995] has suggested that much of the waters entering the Nordic Seas may do so by continuing north in the Irminger Current to Iceland and branching to the SE toward the Faroe Islands (62°N, 7°W) rather than east along 60°N as is indicated in Figure 1. Although the North Atlantic Ocean is often said to be the ocean we know best, our knowledge and understanding of its circulation are still very limited.

The purpose of this article is to review recent progress in our understanding of the North Atlantic Current and its relationship to the surrounding waters. First, we survey the major advances that have taken place in our knowledge of the region south and east of the Grand Banks. This is followed by a first review of a major Lagrangian study of the North Atlantic Current and neighboring waters. A number of observations have emerged that we hope will lead to an improved understanding of this major yet elusive current. We begin with a few remarks on observational methods.

Most of our ideas and understanding about large-scale ocean circulation have been interpreted from data collected by the many hydrographic sections and surveys oceanographers have undertaken over the years. From these observations, which consist of vertical profiles of temperature, salinity, and other properties, one can compute for instance the density and hence the pressure field, from which the speed of the current can be estimated. The appeal of this technique, known as the dynamic method, lies in its simplicity of use: from two hydrographic stations separated a few tens of kilometers or more, one can determine the horizontal pressure difference as a function of depth and thus the shape (not the absolute value) of the velocity profile between the two stations. However, pressure variations also arise from slight but hitherto unmeasurable variations in sea level (<1 m). This means that our knowledge of the strength and variability of ocean currents consists only of that part observable in the hydrographic field. In deep waters or in the north, where the waters have lost their heat and the density field becomes horizontally uniform, the dynamic method alone is unable to determine the magnitude and direction of flow. In such situations one often resorts to tracing water properties (such as salinity, oxygen, nitrates, tritium, etc.) to determine how waters spread or might flow. Unfortunately, tracer techniques have their own limitations because the observed distributions result not only from steady flow patterns but also from mixing processes, which we cannot quantify without independent observations of how they operate. The paucity of direct measurements of currents and transports has greatly increased the challenge of putting our knowledge of the ocean circulation and its variability on a quantitative foundation.

## THE NORTH ATLANTIC CURRENT

The debate about the origin of North Atlantic Current has waxed and waned over the years. The first paper to put the location and size of the current into clear focus was published by *Iselin* [1936]. Although he cautioned that the region was so complex that many additional data would be needed, his plot of the depth of the 10°C isotherm [*Iselin*, 1936, Figure 47] (shown here as Figure 2) reveals almost prescient similarity with more recent studies of the region [*Lozier et al.*, 1996]. The turning north of the contours at the Tail of the Grand Banks (the SE tip of the shallow Grand Banks) and rapid shoaling of the isotherm near 50°N indicate the path of the current. The strength of the current increases in rough proportion to the slope of the temperature surface. The 10°C surface represents reasonably well the $\sigma_t = 27.2$ density surface in the main thermocline. Only where that surface shoals to less than a few hundred meters and waters come into contact with cold, fresh waters from the north do the two surfaces deviate significantly: the density surface does not shoal as rapidly.

*Worthington* [1962] published a controversial paper in which he argued that the North Atlantic Current does not originate in the Gulf Stream but forms a link in a separate anticyclonic gyre north of the main subtropical circulation of the North Atlantic. Worthington constructed his "two-gyre" hypothesis to account for the higher oxygen levels in the NAC than in the Gulf Stream that presumably fed it. Specifically, the higher dissolved oxygen ($O_2$) levels suggested recent contact with the atmosphere. He proposed a separate gyre in which the northward flows shoal close to the surface and presumably pick up oxygen, then turn east and south and finally back west toward the NAC. In support of his two-gyre thesis he pointed to observations of a trough extending SE from the Grand Banks with flows in opposite directions to either side. At the time Worthington wrote his paper, oceanographers generally portrayed the ocean circulation in laminar, steady terms. In a sense, they had little choice because the few observations available did not permit characterization of ocean variability. More to the point, however, oceanographers had constructed over the years what appeared to be quite robust descriptions of the mean circulation from widely spaced surveys (see Figure 2), thereby reinforcing confidence in the hydrographic survey technique to meet their needs. Ideas about eddies and their role in lateral mixing had yet to become part of the working vocabulary.

Well aware of Worthington's study, *Mann* [1967] published the results of two hydrographic surveys of the waters SE of the Grand Banks in an attempt to examine the question of where and how the North Atlantic Current takes shape. His surveys showed a bifurcation of the Gulf Stream with a southern branch forming, as he stated it, the NE boundary of the Sargasso Sea and a northern branch that fed into the North Atlantic Current, which also received waters directly from what he

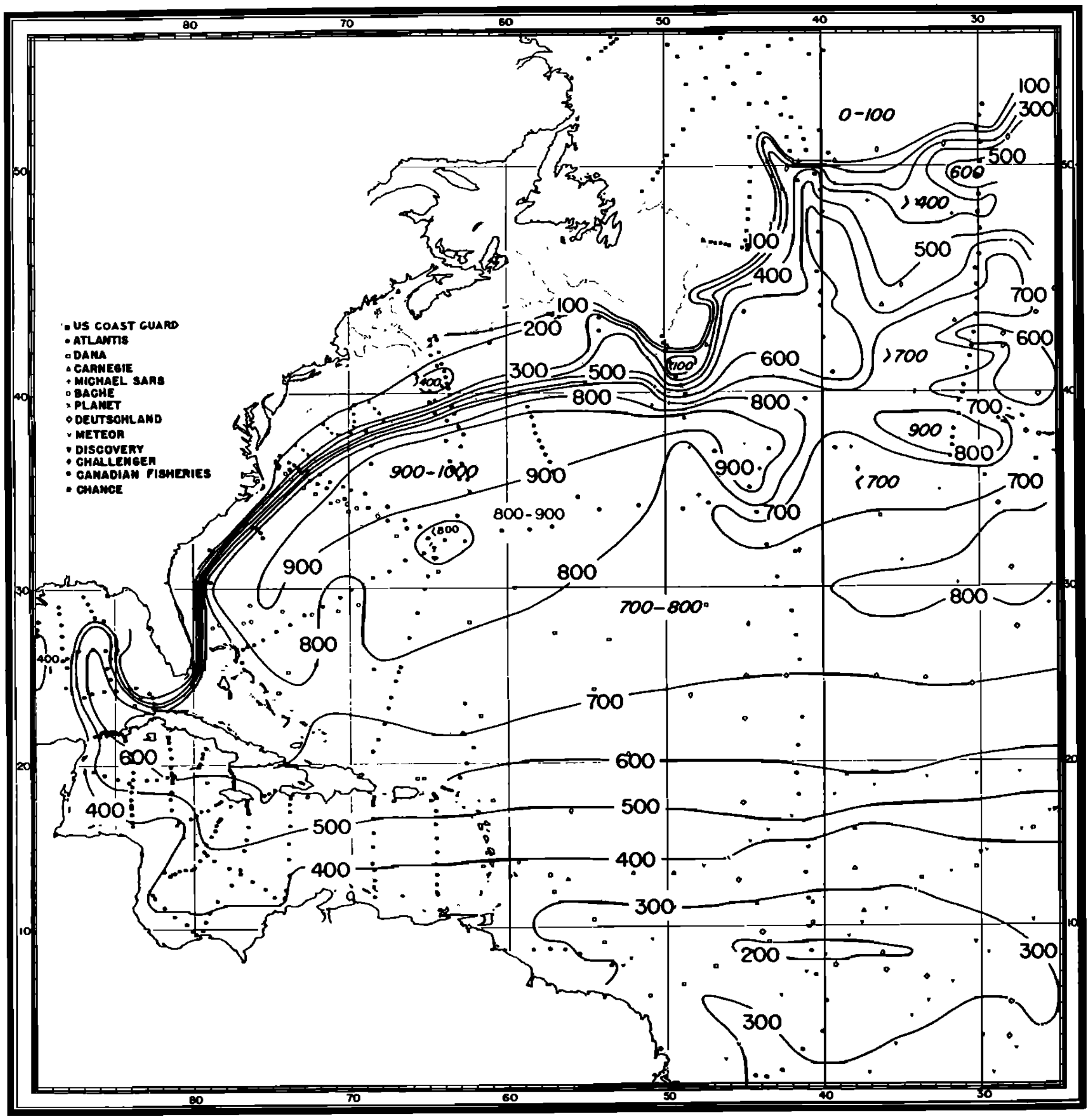

Figure 2. The depth of the 10°C isotherm in the NW Atlantic according to *Iselin* [1936, Figure 47]. The Gulf Stream can be identified by the close spacing of the isopleths (indicating rapid flow) from the Florida Straits to SE of Newfoundland. Where the isopleths turn north marks the beginning of the North Atlantic Current. The sharp turn to the east at 50°N is known as the Northwest Corner.

termed the Slope Water Current, a separate eastward flowing current south of the continental shelf and north of the Gulf Stream. The NAC appeared to be fed by two branches of the Gulf Stream, thereby suggesting a more complex system of bifurcation or splitting than was assumed previously. Mann cited the presence of an anticyclonic eddy in the Newfoundland Basin as a source of oxygen-rich waters (due, he implied, to wintertime convection) that could mix with the North Atlantic Current and thereby increase the $O_2$ levels without changing the temperature-salinity ($T$-$S$) characteristics of the waters. However, Mann's study did not settle the matter.

*Worthington* [1976] described his monograph *On the North Atlantic Circulation* as an update of the *Iselin* [1936] paper. In it he reiterated his earlier belief that the high oxygen levels relative to the $T$-$S$ properties preclude the possibility of the North Atlantic Current's originating in the Gulf Stream. He acknowledged difficulty in constructing a transport field or circulation that maintained consistency with the observed density field. Specifically, he could not find a return flow to match his computed transports in the NAC. However, the high oxygen levels in the NAC impressed him, sufficiently so that he preferred to "violate" the dynamic method and recirculate waters from the NE rather than admit waters from the Gulf Stream in the SW, the diametrically opposite direction. Perhaps he thought or hoped that there might exist in his northern gyre a barotropic component that could not be resolved or detected in the hydrographic observations.

*Clarke et al.* [1980] discussed in detail the results from a major three-ship survey of the region SE of the Grand Banks that took place in spring 1972. They showed conclusively that given a reasonable amount of isopycnal mixing, one could reconcile the observed property distributions with a geostrophic flow pattern of Gulf Stream waters feeding into the North Atlantic Current. They made an important clarifying point by distinguishing between the mean fields of the Sargasso Sea and Newfoundland Basin, which do differ in oxygen and $T$-$S$ on the same isopycnal, and the properties of fluid parcels that enter the Newfoundland Basin with the North Atlantic Current where fluid parcels of Gulf Stream origin are found and noted that the NAC gradually loses its subtropical properties (relatively low oxygen and high salinity) downstream through gradual mixing with the fresher waters inshore. Worthington's difficulty, they argued, consisted in adhering too strictly to the conservation of water mass properties and not appreciating or allowing for the role of lateral mixing processes that are important in water mass modification. For many physical oceanographers the *Clarke et al.* [1980] study persuasively put to rest the hypothesis of two completely distinct Gulf Stream and NAC gyres.

Whereas the aforementioned studies relied almost exclusively upon the hydrographic surveys of water masses and dynamic computations of currents, *Krauss* [1986] assumed a very different approach and used satellite-tracked surface drifters to map out the circulation of the upper ocean of the North Atlantic. These drifters had their drogues attached at 100-m depth to minimize drift due to the action of wind, whether directly or indirectly through the wind-driven Ekman boundary layer. One objective of this major drifter program was to assess or confirm two distinct schemes for the North Atlantic circulation, namely, those of *Dietrich et al.* [1975] and *Worthington* [1976]. In his analysis of 90 drifter tracks, Krauss drew two important conclusions with respect to the North Atlantic Current. First, Krauss could not confirm the elaborate scheme of *Dietrich et al.* [1975] of permanent branch flows peeling off from the Subpolar Front both north and south. This conclusion is significant because it underscores the transient nature of flows at high latitudes and sends a cautionary signal against "overinterpreting" enhanced gradients in hydrographic sections as permanent currents. Second, Krauss found no evidence for waters recirculating back west toward the NAC as required by the Worthington two-gyre hypothesis. His conclusions reinforce those of *Clarke et al.* [1980] and gain in significance because of the study's systematic use of drifters to make direct measurements of fluid motion in the upper ocean.

More recently, *Schmitz and McCartney* [1993] partially revived the two-gyre hypothesis in their review of the North Atlantic Ocean circulation. They gave the hypothesized northern gyre a shape and transport comparable to that of Worthington's 17 years earlier except that they allowed for a northward continuation of the Gulf Stream, specifically, the 12 Sv needed to supply the waters that eventually sink at high latitudes and return south along the deep continental margin as part of the thermohaline overturning of the world ocean. *Schmitz and McCartney* [1993] did not offer any suggestion as to how the northern gyre might be sustained. We can rule out winds as a driving mechanism. The southward mass transport $T$ in a wind-driven gyre can be obtained from the Sverdrup balance, which we approximate here as a mean torque or wind stress curl times the width of the gyre divided by the planetary vorticity gradient, or $T = \langle \nabla \times \tau \rangle L/\beta$ where $\tau$ and $\nabla \times \tau$ represent the wind stress and its curl. Assuming a wind-driven transport of $-25 \times 10^9$ kg s$^{-1}$, an east-west scale $L$ of $10^6$ m, and $\beta = 2 \times 10^{-11}$ m$^{-1}$ s$^{-1}$, the required torque would be $-0.5 \times 10^{-6}$ N m$^{-3}$. *Isemer and Hasse* [1987, Chart 156] show a negative wind stress curl over the conjectured gyre, but the magnitude is much less than that required to sustain the supposed circulation. We will return to this question of recirculations in the discussion.

Much instructive insight into the North Atlantic Current and its origin comes from two synoptic surveys [*Krauss et al.*, 1987, 1990] of the Gulf Stream branching region and north to Flemish Cap. Both studies include, in addition to hydrography, direct measurements of currents using surface drifters drogued at 100 m. The drifters add significantly to the surveys by mapping the spatial structure of the currents. *Krauss et al.* [1987] analyzed a set of 13 sections spanning the North Atlantic Current both south and north/east of Flemish Cap. The dynamic topography at 100 relative to 1500 (100/1500) dbar revealed an unusually extended high-pressure ridge (with superimposed peaks near 42°N, 45°W, and 46°N, 38°W) extending NE along the current. The decrease in dynamic height east of the ridge implied a substantial southwestward transport of water. Four transects across the NAC SW of Flemish Cap showed about 35–40 Sv moving north and 15–30 Sv returning SW [*Krauss et al.*, 1987, Figure 8]. The drifters added considerable value to the study by tracing the structure of the eddy field during and after the conclusion of the survey. The drifter trajectories indicated that (1) the branching at Flemish Cap must have a transient character, (2) significant volumes of water recirculate to the SW, and (3) the eddy field SE of the NAC has a lifetime of several months. In the second study, *Krauss et al.* [1990] took three long hydrographic sections to enclose a triangular region between the Tail of the Grand Banks, Bermuda, and the Azores. They estimated a Gulf Stream inflow of 46 Sv relative to 2000 m, of which 31 Sv continued NE as the North Atlantic Current, with the remainder feeding the Azores Current and Gulf Stream recirculation. The trajectories of numerous drifters drogued at 100 m confirmed the transition into these two branches.

## THE SUBPOLAR FRONT AND FLOWS ACROSS THE MID-ATLANTIC RIDGE

In the mid-1980s, European oceanographers mounted a major coordinated study of the North Atlantic circulation in the general area of the Mid-Atlantic Ridge. The program, known as TOPOGULF, included arrays of current meters spanning the ridge [*Colin de Verdière et al.*, 1989], long meridional hydrographic sections along each side of the MAR [*Harvey and Arhan*, 1988; *Arhan*, 1990], and surface drifter studies [*Krauss*, 1986]. The western section, from 53° to 24°N, traverses the eastern side of the Newfoundland Basin at about 33°W. The high density of hydrographic stations permits a detailed analysis of the property fields. A major strength of the *Harvey and Arhan* [1988] study was their systematic use of isopycnal analyses of the hydrographic sections. Plotting one property such as density against pressure gives information on the dynamical structure, but other properties such salt, $O_2$, and potential vorticity often become more informative when plotted versus density, since mixing and water mass modification in the interior of the ocean takes place along isopycnals, not lines of constant depth. Harvey and Arhan identified three frontal regions which they labeled the Azores Current (36°N), and two branches of the Subpolar Front at 47° and 52°N, respectively. However, at none of these can one find a corresponding water property front or change in stratification except possibly very close to the surface, which suggests that the fronts have a transient or evanescent character (which may enhance mixing). As *Harvey and Arhan* [1988] point out, a difficulty with any single hydrographic section consists in distinguishing between permanent and transient features. Thus, the evidence for a permanent jet at 47°N remains very sketchy. [*Krauss et al.* [1987] did not find it.] Many studies have documented the Subpolar Front [cf. *Krauss*, 1986] and the Azores Current east of the MAR [*Käse and Siedler*, 1982; *Gould*, 1985]. *Krauss* [1986] viewed the Subpolar Front as the only permanent (zonal) feature with a concentrated transport.

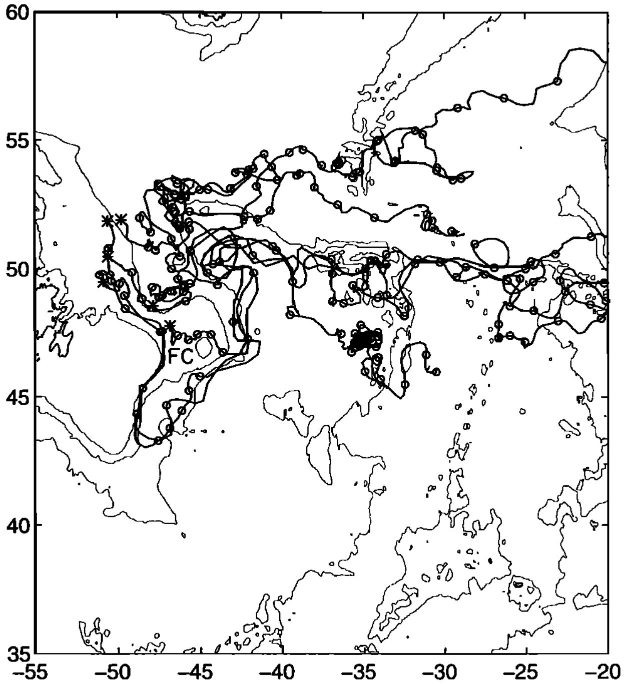

**Figure 3.** Trajectories of five drifters drogued at 50-m depth and deployed in 1989 by the International Ice Patrol (IIP) to study the motion of icebergs drifting south from the Labrador Sea. Each trajectory lasts 310 days. Small circles are plotted every 10 days. The 200-, 2000-, and 4000-m isobaths are shown as thin lines. FC is Flemish Cap. (Courtesy D. Murphy, IIP.)

## VELOCITY FIELD

Direct observations of the velocity field east of the Grand Banks have been collected by several groups. These include the satellite-tracked near-surface drifters by the Institut für Meereskunde (IFM, Kiel, Germany) [*Krauss*, 1986; *Brügge*, 1995], the Woods Hole Oceanographic Institution (WHOI, Woods Hole, Massachusetts) [*Richardson*, 1983], and the International Ice Patrol (IIP, Washington, D. C.) [*Murphy and Hanson*, 1989]. Moored current meter studies include arrays across the MAR [*Colin de Verdière et al.*, 1989] and the Gulf Stream bifurcation area southeast of the Grand Banks [*Fofonoff and Hendry*, 1985]. *Schmitz* [1985] and *Owens* [1991] discuss their work with SOFAR floats in the Newfoundland Basin. The IFM group concentrated on getting a wide area description of surface currents by releasing clusters of drifters in different regions of the North Atlantic. As was mentioned earlier, they drogued their drifters at 100-m depth in order to minimize the impact of the Ekman layer, i.e., the wind-driven surface waters. (As an aside, it should be noted that the surface water drift cannot be avoided altogether. During the winter months, when the mixed layer depth exceeds the depth of the drogue, the drifter motion will reflect the sum of the directly driven surface waters and the underlying geostrophic motion. The impact is not serious in strong currents, but east of the NAC, where the geostrophic flow is weak, the southwesterly winds might set the drifters farther to the ENE owing to the direct action of the wind and Ekman drift than otherwise would be the case.) The clusters released near or in the NAC on the warm water side revealed rapid downstream advection by the current. Significantly, virtually none of the IFM drifters escaped west or north from the NAC into the subpolar gyre. Other clusters, launched within the Newfoundland Basin, show a clear tendency to drift to the east toward the MAR and beyond. Less well known, each Spring since 1979 the IIP has deployed drifters (drogued at 50 m to simulate the center of drag of icebergs) in the Labrador Current to monitor and model the motion of icebergs. As an example, Figure 3 shows 310-day trajectories of five IIP drifters launched in 1989 in the region 49°–52°N, 49°–51°W. All five drift east, either directly or after drifting south along the continental escarpment before turning north on the inshore side of the North Atlantic Current. Significantly, they remain inshore of the NAC all the way to 50°N before turning east around the Northwest Corner. In a study under way, M. E. Carr (personal communication, 1996) has combined all IIP and IFM drifters to examine pathways of motion and cross-NAC exchange. It appears that less than 10% of the IIP drifters cross over to the warm side of the NAC into the Newfoundland Basin. Instead, they follow the NAC past Flemish Cap, north of which some drifters turn east while the majority continue to the Northwest Corner. There is very little exchange of waters across the NAC near the surface.

We have frequently referred to the Northwest Corner as if it were a self-evident feature of the North Atlantic Current. It can be seen already in *Iselin*'s [1936] map (Figure 2). It shows up clearly in the North Atlantic maps of temperature and salinity at 200 m published by *Fuglister* [1954] and in the *Lozier et al.* [1996] climatology of the North Atlantic. It does not appear in the *Levitus* [1982] climatology owing to the heavy smoothing employed. The sharply curved flow around the Northwest Corner emerges clearly in surface drifter trajectories [*Krauss*, 1986]. A recent paper by *Lazier* [1994] on direct measurements of currents in the Northwest Comer clearly defines its NW limit. Using a SE-NW array of four equally spaced (57 km) current meter moorings (between 51.8°N, 45.7°W, and 50.7°N, 44°W) and drifters (drogued at 100 m), Lazier showed that strong baroclinic currents pass through the two SE moorings on at least three occasions for monthlong periods whereas the two NW moorings remain in cold quieter waters during the entire $8\frac{1}{2}$-month observation period. These observations limit the NW penetration of the Northwest Corner to the SE of the third mooring at 51°30′N, 45°W. Lazier estimated the volume transport across the entire section to be 50 ± 23 Sv. The large variance may result from lateral shifting (and thus how much of it passes through the array) and variations in the strength of the current, whereas the large mean may indicate significant recirculation of waters within the Northwest Corner as indicated by the near-circular trajectories of several drifters.

The eddy kinetic energy (EKE) in the region west of the MAR exhibits strong spatial gradients. At the surface, EKE averages 600 $cm^2\ s^{-2}$ in the NAC and decreases to about <100 $cm^2\ s^{-2}$ to the south and east according to *Krauss and Käse* [1984], while at 700 m the EKE rarely exceeds 50 $cm^2\ s^{-2}$ from the SOFAR data in the NAC [*Owens*, 1991]. Figure 4, shows the EKE from 217 IFM and IIP drifters deployed between 1979 and 1993. A band of very high EKE follows the path of the NAC from the Southeast Newfoundland Rise in the south to the Northwest Corner near 51°N. All along this envelope the EKE drops very rapidly and uniformly to the east. Even the baroclinic Subpolar Front, the continuation of the NAC, shows only slightly elevated EKE.

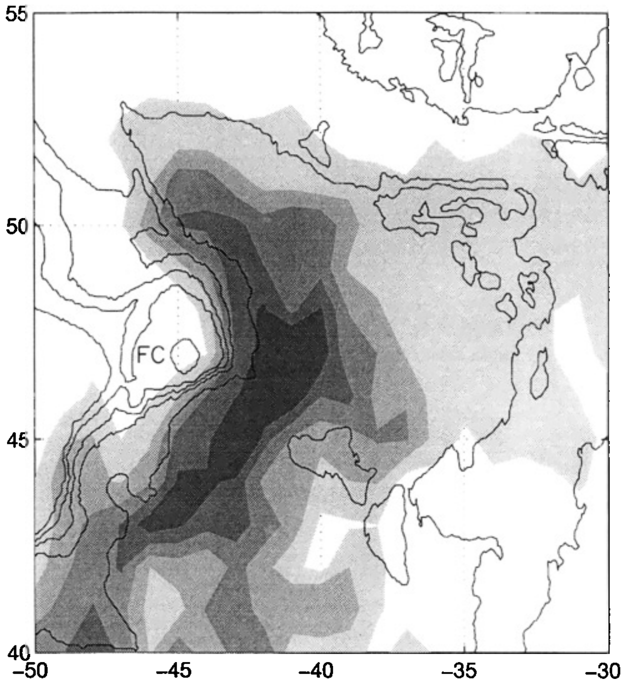

**Figure 4.** Eddy kinetic energy (EKE) at 50- to 100-m depth, shaded in increments of 250 $cm^2\ s^{-2}$, constructed from 217 drifters deployed between 1979 and 1992 by the International Ice Patrol and the Institut für Meereskunde (IFM) in Kiel, Germany. The data have been grouped into 1° × 1° bins. The data were very kindly made available to us by W. Krauss at the IFM and D. Murphy at the IIP. The 200-, 1000-, 2000-, and 4000-m isobaths are shown. This figure was prepared by M. E. Carr.

In general, Figure 4 mimics rather well the surface EKE distributions computed from the Geosat mission [*Le-Traon et al.*, 1990], but the drifter estimates have not been smoothed, and thus Figure 4 reveals more local structure along the path of the NAC. The EKE levels exceed those reported by *Krauss and Käse* [1984]. We attribute this to the significantly larger data set. Specifically, the IIP drifters that drift south and turn north just inshore of the NAC may accelerate to very high speeds compared with those launched on the warm water side.

As part of the French-German TOPOGULF project in 1983–1984, four clusters of current meters spanned the MAR along 48°N for 1 year to study cross-ridge mean flows and eddy variability. The westernmost cluster at 35°W exhibited very high EKE levels: at 350-m depth the average EKE, 349 $cm^2\ s^{-2}$, is almost a factor of 2 larger than the EKE at 50- to 100-m depth in Figure 4. *Colin de Verdière et al.* [1989] found evidence of an upgradient (i.e., toward warmer water) eddy heat flux west of the MAR and conversely east of the ridge. This flux, reminiscient of the upgradient fluxes south of Cape Hatteras noted by *Webster* [1961], could be accounted for by a downstream decrease in amplitude of the meandering of a baroclinic jet [*Rossby*, 1987]. In the TOPOGULF case, increasing topographic control by

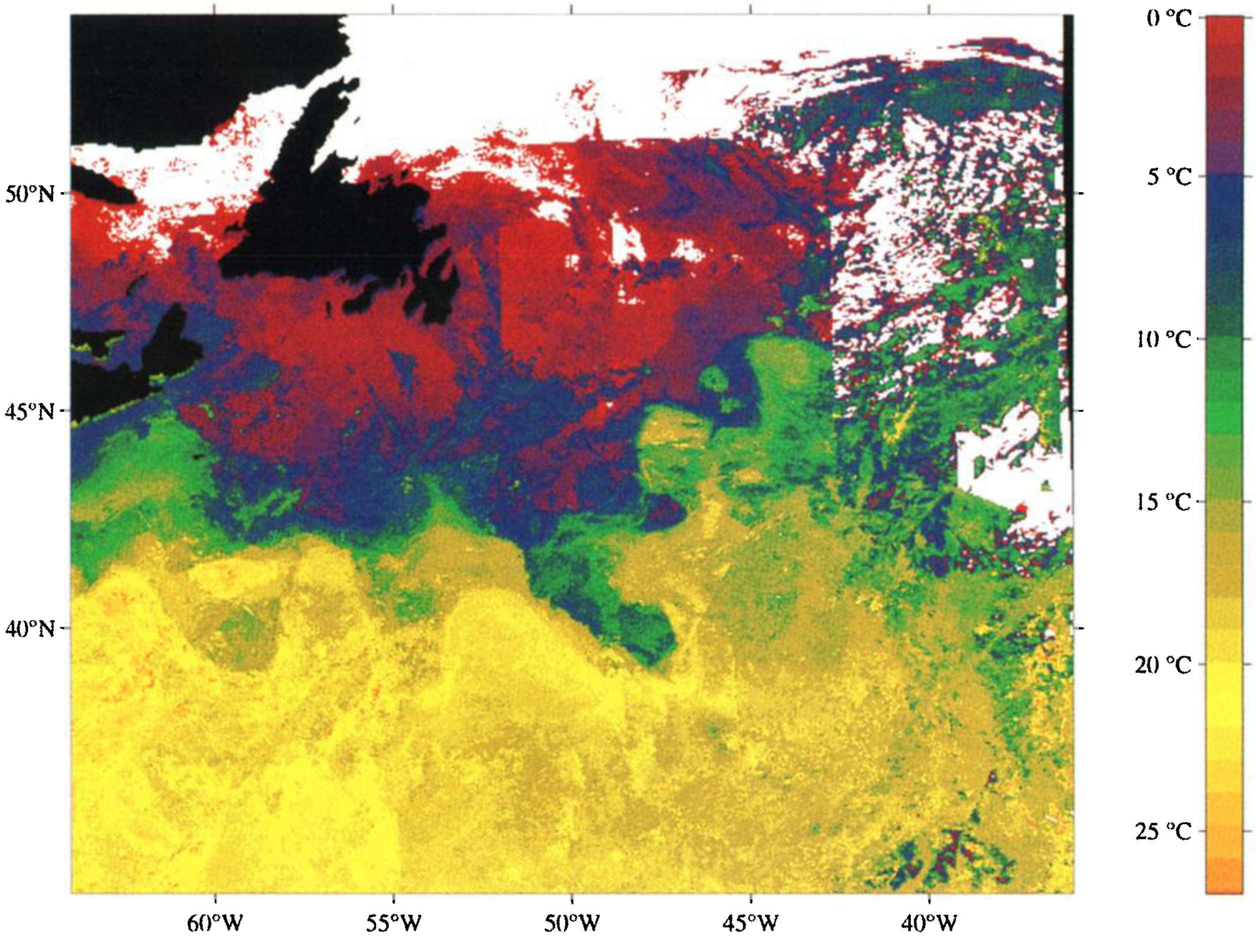

**Plate 1.** A composite view (spanning 2 weeks) of sea surface temperature from early May 1994 using advanced very high resolution radiometer (AVHRR) images from NOAA polar-orbiting satellites. Note the wavy thermal front extending NE from the trough at 42°N, 50°W (compare Figure 2). This figure was prepared by S. Schollaert.

the MAR might cause a decrease in meandering of the eastward flow as it crosses the ridge.

IR imagery of sea surface temperature (SST) east of the Grand Banks has provided less information than we have become used to elsewhere because of >80% cloud coverage most of the year [*Peixoto and Oort*, 1992]. Spotwise, the images can provide useful SST, but only rarely do they offer spatial information. Thus they have contributed very little to our knowledge about the mesoscale field and its temporal evolution in the Newfoundland Basin and southern Labrador Sea. In the Gulf Stream this limitation is circumvented by superimposing several images from a limited period of time, including only the warmest observed temperature for each location. Using the same approach and compositing IR images over a couple of weeks or even a month [e.g., *Krauss et al.*, 1990], one can find sequences that permit a reasonably clear view of the North Atlantic Current off the Grand Banks. Plate 1 shows a 16-day composite IR image (from early May 1994) of SST of the region around the Grand Banks. Note the strong meandering of the Gulf Stream south and the NAC east of the Grand Banks. A tongue of cold water extends SE from the Tail of the Grand Banks along the Southeast Newfoundland Rise. This trough may correspond to the cold tongue extending to the SE [*Worthington*, 1962; *Clarke et al.*, 1980; *La Violette*, 1982], and around which the northern branch of the Gulf Stream curves to the NW and the beginning of the NAC. Warm waters can be seen extending to the north with sharply defined meander crests near 44°–45° and 46°N along the NAC.

## RECENT OBSERVATIONS OF THE NAC

Over the last decade, our group here at the University of Rhode Island (URI, Kingston) has gained considerable experience in the use of Lagrangian techniques to study ocean currents. These subsurface drifters or floats can be adapted to a variety of applications. We have used them in the Gulf Stream, a rapid, highly baroclinic or surface-intensified flow, as well as in the deep, slow waters of the South Pacific. In baroclinic flows such as the Gulf Stream it had not been clear to what extent water parcels advecting downstream move up and down along the steeply inclined isopycnals and to what extent such inclined motions might be stochastic, perhaps due to small-scale lateral stirring processes (a turbulent jet), or systematic, reflecting the dynamics of the meandering current. To address these issues, we developed the isopycnal RAFOS float, which can mimic or follow the vertical motion of fluid parcels of a particular density [*Rossby et al.*, 1985; *Goodman and Levine*, 1990]. From two studies, one conducted in 1984–1985 and the other in 1987–1989, it became evident the lateral and vertical motions could be quite large and that these depend very closely upon the curvature of the current such that between troughs and crests with path curvature turning from positive to negative, floats will always upwell, and vice versa between crests and troughs [*Bower and Rossby*, 1989; *Song et al.*, 1995].

We thought the float technology might offer an effective means to study the NAC and its interactions with the surrounding waters. It is clear from the preceding review that many questions remain about the NAC. Could it be regarded as a simply connected front as we had come to view the Gulf Stream, i.e., would a parcel or float in the center of the current remain in it as it drifted downstream through several meander wavelengths, or should the current and surrounding waters be viewed as a turbulent transition region between the subtropical waters in the Newfoundland Basin and subpolar gyre farther north? In other words, to what extent does the NAC act to separate the two water masses (the barrier concept), and to what extent might an energetic eddy field promote exchange of waters instead (the blender concept)? Do waters leave the NAC preferentially in zonal jets as has been conjectured (the Subpolar Front at 52°N; a jet at 47°N east of Flemish Cap; the Azores Current), or is the loss more gradual or stochastic? To address these and related issues, since July 1993 we have been tracking a total of 100 isopycnal RAFOS floats that have been deployed in the current in several locations as well as in both gyres to either side. We have had the good fortune to work with R. A. Clarke of the Bedford Institute of Oceanography, who has a program of repeat hydrography of the NAC between the Tail of the Grand Banks and Flemish Cap. Thanks to his program, we have been able to deploy floats in the region on three separate occasions while also having a detailed hydrographic description of the state of the NAC and surrounding waters at the time. In addition, Clarke and R. Watts of the University of Rhode Island have recently recovered an array of moored current meters that was deployed across the NAC for a 2-year period. We provide here early salient results from the float program that may aid in understanding the character of the NAC.

We summarize briefly here the characteristics of the RAFOS float (see *Rossby et al.* [1986] for a more complete system description). The float tracks reasonably accurately an isopycnal surface (1) by matching its compressibility to that of seawater to within $-0.5 \pm 2\%$, and (2) by using a borosilicate (Pyrex) glass housing that has a very small coefficient of thermal expansion (<10% of water). The first requirement ensures that no buoyancy or ballast results from a change in pressure that would cause the float to rise or sink relative to the water, and the second requirement ensures that the float remains on the same density surface regardless of any temperature or salinity change that might occur as a result of small-scale mixing. This follows from the fact that neither salinity nor temperature variations can alter the volume of the float. In practical terms, a float that downwells across the NAC 500 dbar with a compressibility mismatch of 1% should follow the isopycnal to within 15 m for a typical density stratification of 0.1 $\sigma_T$ units/75 m or 0.2°C assuming 10°C/$\sigma_T$ unit. (One $\sigma_T$ unit is equal to 1 kg $m^{-3}$, where the density of seawater is $\sim 10^3$ kg $m^{-3}$.) Cross-frontal and cross-gyre variations in temperature greatly exceed this uncertainty, as we shall see. The floats "track" themselves by listening for and storing in their microprocessor memories the arrival times of acoustic signals transmitted from four moored sound sources twice per day. The sources consist of a resonant pipe projector developed by Sparton of Canada and an electronics–power pack driver developed by Webb Research Corporation [*Rossby et al.*, 1993]. The mooring deployments and first release of floats took place in July–August 1993. This acoustic navigation system covered most of the North Atlantic Ocean between 30° and 60°N. The field program ended in summer 1995, when all four sound source moorings were retrieved.

Perhaps nowhere in the world ocean do waters of such contrasting properties as the Gulf Stream and Labrador Sea water come into direct contact with each other. To illustrate this, Figure 5 shows a section across the NAC at 43°N in four panels: density versus pressure and temperature, salt, and oxygen, the latter three plotted against density. The choice of $\sigma_t$ as the ordinate highlights the property contrasts across the current in light of the fact that mixing, where it occurs, does so preferentially along isopycnal surfaces. The deepening isopycnals in Figure 5a reflect the strong baroclinicity of the current. The strongest slope of the $\sigma_t$ surfaces at 275 km indicates the approximate location of the axis of the current. The temperature field in Figure 5b brings out two important features. First, the principal thermal contrast, i.e., the property front, is quite sharp and in this section is about 150 km inshore of the baroclinic (or dynamic) front for $\sigma_t < 27.2$ and about 100 km farther west on the deeper density surfaces. Second, below $\sigma_t = 27.2$ there is more variability along most of the section, suggesting greater exchange on deeper than shallower isopycnals. In principle, the salinity distribution in Figure 5c adds no information beyond that of temperature, since salt and temperature together determine density. Nonetheless, because temperature plays the major role in setting a fluid parcel's density (hence the horizontal

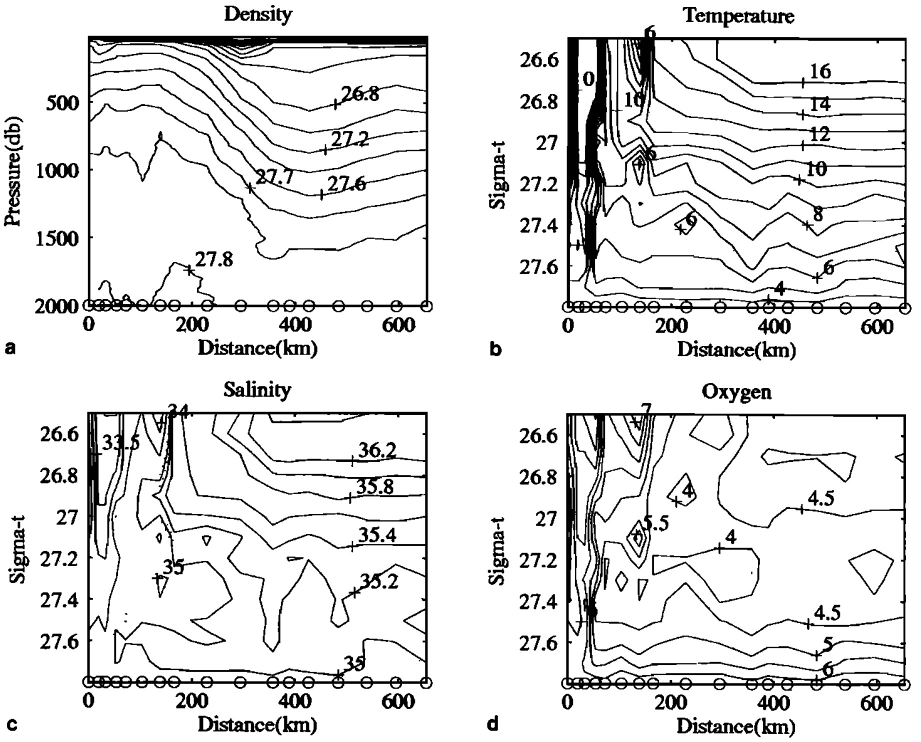

**Figure 5.** Hydrographic section across the NAC at 43°N: (a) density ($\sigma_t$) versus pressure, (b) temperature (degrees Celsius) versus $\sigma_t$, (c) salinity (practical salinity units, PSU) versus $\sigma_t$, and (d) oxygen (milliliters per liter) versus $\sigma_t$. The thin circles indicate the station locations.

layering of the temperature fields), salt tends to act more like a tracer. As a result, the salinity fields bring out more clearly the exchange of fresh and salty waters between the Labrador Current side and the Newfoundland Basin. Note also that the salinity field reveals a weak property front coincident with the dynamical front on shallow isopycnals. The $O_2$ distribution in Figure 5d highlights the strong contrast between the low-oxygen waters originating from the south and the cold, more recently aerated waters from the Labrador Sea.

## THE LAGRANGIAN VIEW

Figure 6 shows the 10-month tracks of floats 254 and 265, along with the corresponding temperature and pressure time series of float 265. The floats were deployed as a pair to examine how long they might continue together before separating. This pair is the most extreme of all, staying close together for almost 3 months. (Other pairs typically part ways after 3 weeks.) Immediately after launch in the NAC (near 250 km in Figure 5) the floats upwell toward the cold water side, but after 15 days they start accelerating to the east and cross the NAC as indicated by the 500-dbar downwelling to >950 dbar. Sixty days after the start at 48°N, they reverse direction and head south. About 15 days later they part ways, with 254 making N-S excursions between 46° and 49°N while 265 continues south to 39°N (15% decrease in planetary vorticity) before turning north again. The single loop during the long southward transit during which float 265 shoals 200 dbar (day 130) reveals a cyclonic structure that also appears in the trajectory of float 256 (not shown) at the same site about a month earlier. (As an aside, the tiny saw-toothed wiggles in the trajectory just north of the loop indicate inertial motion. The apparent period of ~2 days with anticlockwise rotation results from aliasing the ~17-hour inertial period (= 12 hours/sin (latitude)) by the 12-hour position sampling rate. Because of the well-known spectral gap between these energetic high-frequency motions and the geostrophically balanced motions on longer timescales [see *Webster*, 1968], the inertial oscillations stand out clearly.)

One of the most impressive trajectories must be that of float 260 (Figure 7). During its 10-month drift on the $\sigma_t = 27.2^+$ surface, it ceaselessly loops anticyclonically within a 300-km box centered at 42°N, 44°W. At various times during the 10-month period the float shoals during its western excursions into the NAC. This float confirms the persistence if not permanence of the anticyclonic circulation in this region [cf. *Mann*, 1967; *Clarke et al.*, 1980]. Very high resolution analysis of all hydrographic data in this region shows unequivocally a deepening of the thermocline centered at 42°N, 44°W [*Carr et al.*, 1995; *Kearns*, 1996].

Immediately to the north a cyclonic circulation dom-

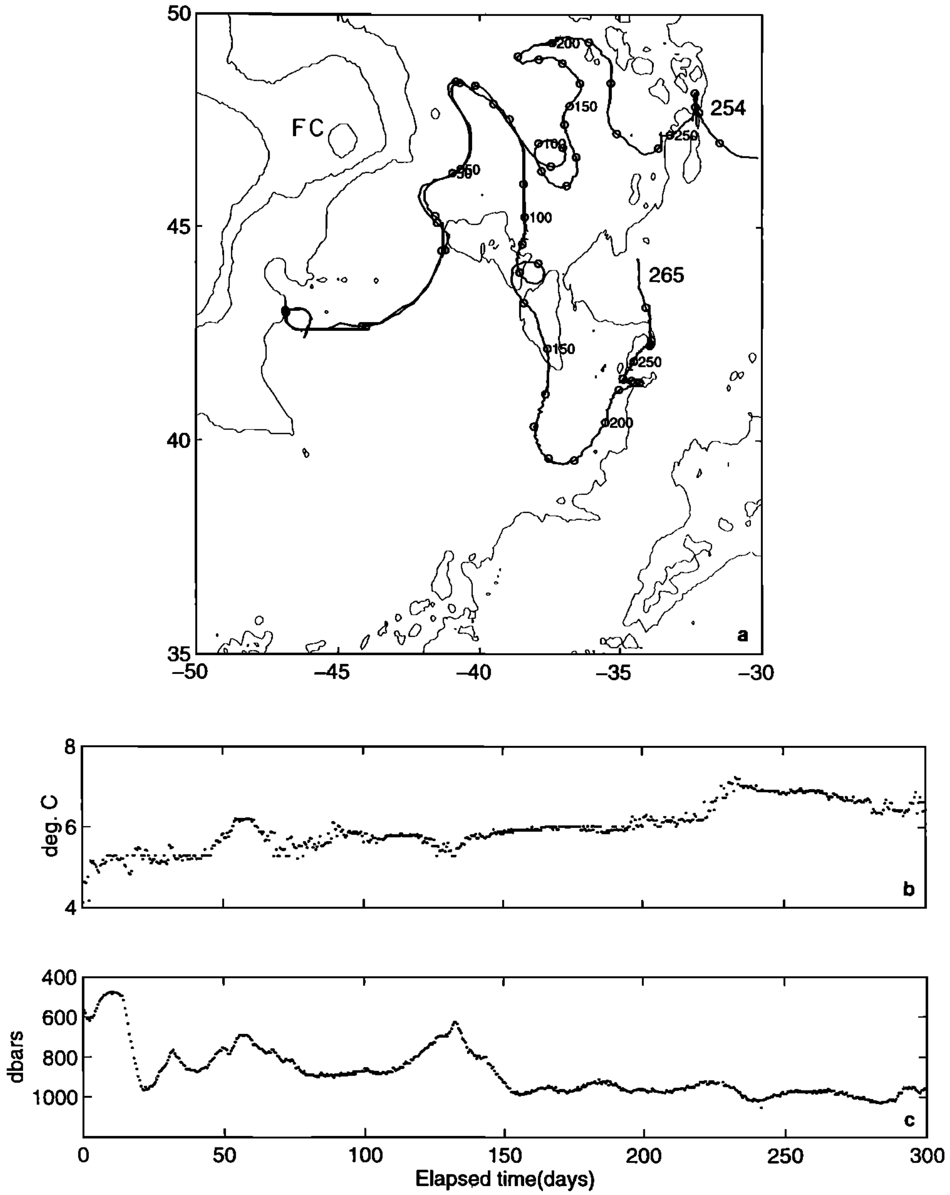

**Figure 6.** (a) Trajectories of floats 254 and 265 on the $\sigma_t$ = 27.5 surface, and (b) temperature and (c) pressure as a function of time for float 265. The thin lines in Figure 6a indicate the 200-, 2000-, and 4000-m isobaths; FC is Flemish Cap.

inates the flow field. Float 272 on the $\sigma_t = 27.5^+$ surface typifies this quite well (Figure 8). Launched at the same site as 260, float 272 at first drifts south with 260 but continues quite a bit farther south before getting entrained back to the north over the SE Newfoundland Rise. The transition toward the cold side occurs around day 70 when the float rises about 300 m. After it loops through the trough at 41.5°N, it winds up in a cyclonic region starting around day 110. Only 20 days before the end of its 300-day mission does the float break off to the north. Another float, 285 (not shown), indicates that this cyclonic region persists for at least another 5 months. The temperature record from float 272 (not shown) shows significant drops around days 70, 90, and 140, always in conjunction with upwelling motion toward the cold, fresh waters from the Labrador Sea between the NAC and the continental shelf. After day 150 the temperature shows little further change. The near-permanence of this cyclonic region or trough in the NAC has the effect that no float in the NAC or on the warm side can get north of 44°N without getting caught in it unless it moves offshore to at least 42°W (as in Figure 6). Floats on the cold side can drift north inshore of the trough.

Between the trough and Flemish Cap to the north, floats often upwell through a tight anticyclonic crest before continuing east past Flemish Cap, as is evidenced by the sharp clockwise turn of floats 254 and 265 SE of Flemish Cap in Figure 6. The downstream increase in

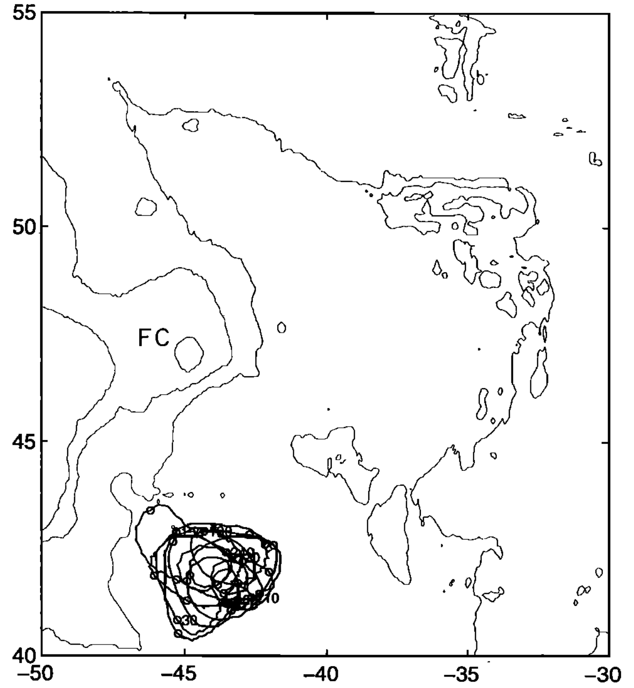

**Figure 7.** Trajectory of float 260 on the $\sigma_t$ = 27.2 surface. The orbital period when the float is near the center is ~14 days. The thin lines indicate the 200-, 2000-, and 4000-m isobaths; FC is Flemish Cap.

depth east of Flemish Cap appears to induce strong cyclonic curvature to the current. The current turns north and west toward Flemish Cap at 47°–48°N, where it again turns offshore. Float 307 (Figure 9) illustrates this well. Launched inshore of the NAC on the $\sigma_t = 27.5^-$ surface, this float traces out the cyclonic and anticyclonic patterns discussed above (including a "figure 8"). It then loops offshore of Flemish Cap, turns west, and weaves its way northward in an onshore-offshore pattern. This float has the unusual distinction of maintaining a high speed (>50 km $d^{-1}$) much of the time after day 30, when it enters the cyclonic loop at 44°N, and day ~130, when it leaves the Northwest Corner at 52°N and heads east.

North of ~47°N, the thermocline starts shoaling more rapidly towards the north, (Figure 2). The Subpolar Front coincides with the northernmost extent and outcropping of the subtropical thermocline. Geostrophically speaking, this requires an eastward mean flow in the upper layers. However, there is significant eddy motion throughout this region such that the float trajectories (compare Figs. 3, 6, and 9) will exhibit more complex motion than just a uniform eastward drift.

At the risk of some exaggeration, it is instructive to summarize what we have observed from the above and many other float trajectories in the form of a cartoon of

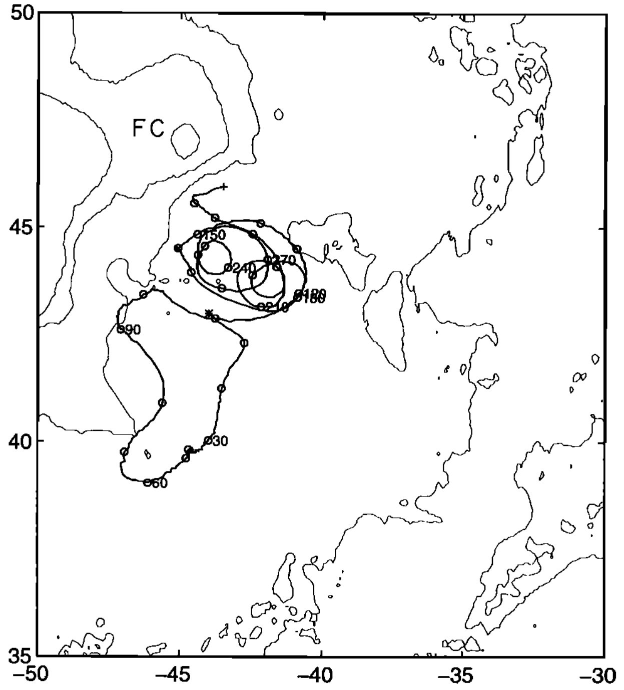

**Figure 8.** Trajectory of float 272 on the $\sigma_t$ = 27.5 surface. The cyclonic motions at 44°–45°N continue for over 6 months. The thin lines indicate the 200-, 2000-, and 4000-m isobaths; FC is Flemish Cap.

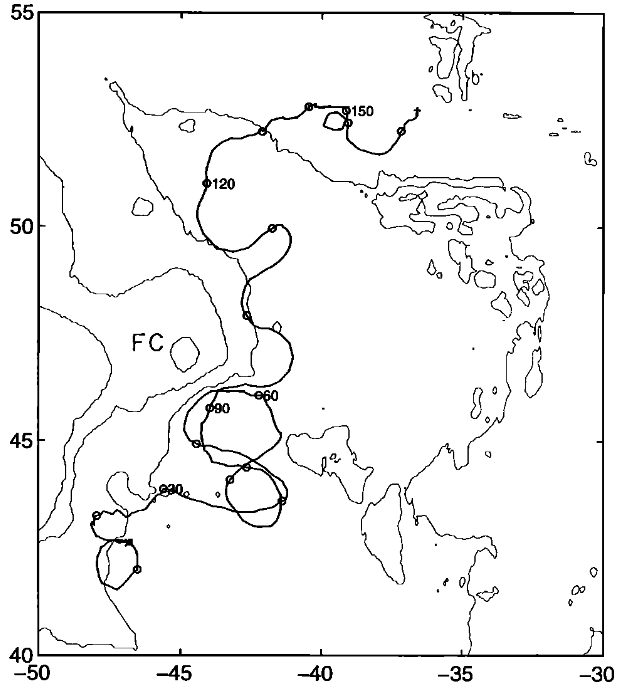

**Figure 9.** Trajectory of float 307 on the $\sigma_t$ = 27.5 surface. The thin lines indicate the 200-, 2000-, and 4000-m isobaths; FC is Flemish Cap.

the mean path of the NAC. Likely pathways of fluid loss from the NAC, as well as locations where fluid tends to recirculate, are also indicated. The heavy line in Figure 10 indicates the mean path of the current and its offshore-onshore meandering. Perhaps the single most striking aspect of the NAC to emerge from this study consists in the stability of the meander path: the meanders do not propagate. They grow and recede, and disappear entirely, but it appears that the location of the crests and troughs depends upon the bathymetry around the Grand Banks and Flemish Cap. Unlike the Gulf Stream, which flows east as an unbounded free jet, the NAC flows north as a western boundary current, with the details of its path most likely governed by the interaction between the current and the local bathymetry [*Warren*, 1969; *Shi and Chao*, 1994]. Strong recirculating flows develop on the concave side of the meanders, presumably as a consequence of the stationary meanders. Further, from a number of float tracks (Figures 7 and 8) it has become apparent that the recirculating flows in the meanders of the NAC last much longer than anything ever observed in the Gulf Stream [*Bower and Rossby*, 1989; *Song et al.*, 1995]. Where the floats indicate sustained or coherent recirculations, Figure 10 shows a closed loop at the corresponding concave location of the meander. Where the NAC approaches a meander extremum, the flow on the convex or outer side of the current becomes increasingly diffluent, meaning that the velocity vectors diverge. Waters close to the center of the current may continue through the meander, whereas waters close to the outer edge may recirculate back upstream, and waters in between may drift away from the current toward the interior (indicated by the arrows pointing away from the NAC).

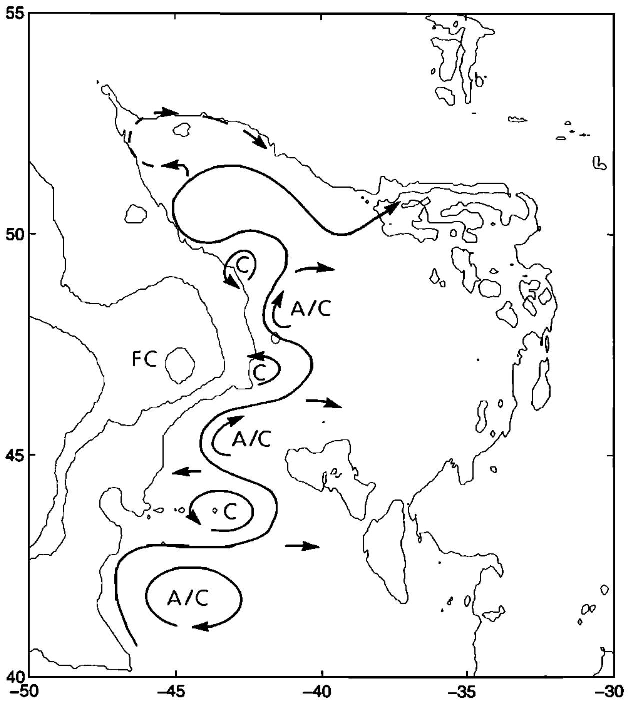

Figure 10. Path of the NAC and adjacent recirculation cells. The arrows indicate probable pathways and directions of loss from the NAC to the surrounding waters. The dashed line in the north indicates an additional meander (or partially attached eddy) that appears in some of the deeper float trajectories. The thin lines indicate the 200-, 2000-, and 4000-m isobaths; FC is Flemish Cap.

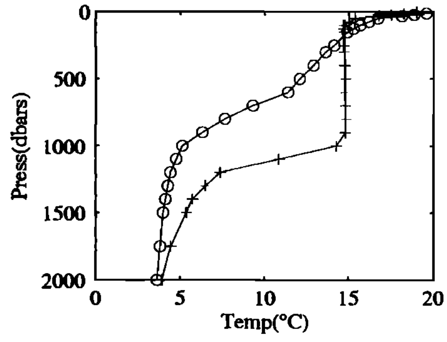

**Figure 11.** Two temperature profiles from the Mann eddy [*Mann*, 1967] centered at 41°N, 43°W. One (station 58, pluses) is from the center, and the other (station 60, circles) is from outside the eddy, 50 km to the east.

We now see how exchange can take place between the current and surrounding waters. Regardless of the dynamical reasons, if a stationary meander decays or pulls back, a fluid parcel entering the point of maximum curvature will have a velocity component that takes it away from the current toward the slack waters outside. Trajectories and streamlines can coincide only in steady flows, as illustrated by the simple yet elegant kinematical ideas originating with *Flierl* [1981] and adapted by *Bower* [1991] for a meandering jet. The Bower model provides a powerful analytical tool for interpreting particle motions in a meandering jet. Because these kinematical studies work with simple yet rather realistic models of a meandering current, one can, by tuning the model from observations, reproduce many observed patterns quite well [e.g., *Dutkiewicz and Paldor*, 1994].

The extraordinary persistence of the trapped anticyclonic motion as evidenced by float 260 (Figure 7) betrays a remarkable, possibly permanent circulation feature. *Mann* [1967] first observed this extraordinary intense anticyclonic eddy (but see also *Baranov* [1984] for a summary of other observations), and for this reason we call it the Mann eddy. Figure 11 shows two temperature profiles, one from station 58 in the eddy and one from station 59, 50 km to the east. In the center of the eddy the upper layer of uniform temperature (14.7°C) reaches down to 1000-m depth, below which the temperature drops off quite rapidly, but even at greater depths the isotherms are deeper than elsewhere. Quite possibly, nowhere in the world ocean has such light water ($S$ = 36.15 PSU (practical salinity units); $\sigma_t$ = 26.9) been observed at such great depths. *Mann* [1967] assumed that wintertime cooling caused the deepening of the mixed layer, but this does not explain the 50-km scale of the eddy (roughly the radius of deformation), which is smaller by an order of magnitude than that of the typical cold and dry continental air masses responsible for the heat losses. Further, as a mixed layer deepens, its temperature will decrease such that it constantly matches that of the waters immediately underneath without significantly deepening them. Insofar as the convective cooling goes, the deep density surfaces should remain level, contrary to the remarkable deepening of the deep temperature surfaces observed at station 58. In short, the warm, very deep mixed layer and thermocline reflect a substantial gain rather than loss of heat: something other than atmospheric processes is driving the Mann eddy.

Without doubt, cooling and mixing did take place in the eddy. At a salinity of 36.15 PSU, the temperature should be about 1°C higher to match that of Gulf Stream waters. Nonetheless, the warm, saline waters of the eddy point to the Gulf Stream as its source. The extraordinarily deep thermocline at station 58, indicates some form of pumping mechanism or spin-up process. Whether continuously or in bursts, it would appear that the eddy picks up warm water with negative relative vorticity from the NAC. This would happen when packets of water in the NAC have so much negative shear and curvature vorticity that when they enter the cyclonic trough immediately to the north with its strong positive curvature vorticity, the parcels cannot adjust (whether by increasing the negative shear and kinetic energy even further, or through increased stretching and potential energy) and thus leave the current to join or loop around the eddy. Depending on the relative vorticity of the enveloping waters in the NAC, these will strengthen or weaken the eddy over time through lateral exchange. *Evans* [1989] has described numerical experiments of the formation of long-lived anticyclonic vortices at meander troughs. Whatever the process that sustains it, the Mann eddy clearly stands out as a most remarkable and probably permanent feature of the North Atlantic.

If one accepts the cartoon of a NAC with its stationary meanders in Figure 10 then it follows that the Mann eddy has a number of "cousins" farther downstream. These may not have the same degree of permanence, but the same causative factors for their existence should apply: a sharply curved flow continually recirculates a semitrapped volume of water. Another, very striking anticyclonic feature dominates the NAC in the far north at the Northwest Corner. Already *Iselin* [1936] noted the warm waters in this region (see Figure 2). *Lozier et al.* [1996] show that even after averaging all hydrographic data spanning a 50-year period, the Northwest Corner remains in sharp focus. That a highly baroclinic current flowing north and then off to the east (actually southeast at first) should stand out after observations from many decades of time are averaged together implies substantial spatial stability. As was mentioned earlier, *Lazier* [1994] took a very different approach by deploying a linear array of four current meter moorings across the Northwest Corner to examine the stability and NW extent of the flow. We can add to Lazier's observations by noting that several floats (not shown) became trapped in that region for varying periods of time.

## DISCUSSION

The cartoon of the NAC (Figure 10) with its large but nonpropagating meanders is distilled from the major features of float trajectories in the area. It accounts for all recirculations inside meander extrema that have been observed, although not all meanders have had trapped recirculating floats. As was stated earlier, the crest at 42°N should be considered a permanent feature of the NAC. Similarly, the extended trough at 44°N appears in many of the float tracks. The meander was quite extended in 1993–1994, whereas by 1995 it had diminished considerably in amplitude. The eastward flow between the Mann eddy and this trough is highly difluent, and the radius of curvature of the trough at times so sharp that perhaps this portion of the NAC is very "lossy," i.e., the probability of escape is high. The meanders wobble about and vary considerably in amplitude. The "figure 8" trajectory of float 307 in Figure 9 (between days 60 and 70) suggests that the trough became semidetached to open a pathway back south. Indeed, the float tracks inside the trough reveal a tendency for several cyclonic recirculations to develop inside it, suggesting a competition between a larger-scale process driving the trough and a local trend or preference toward axisymmetric recirculation, i.e., coherent eddies. This wobbling of the meanders notwithstanding, the meandering NAC differs substantially from the Gulf Stream, where we saw little if any tendency toward sustained recirculations on the concave side of meanders [*Bower and Rossby*, 1989; *Song et al.*, 1995]. The reason, we believe, is that Gulf Stream meanders propagate whereas in the stationary NAC meanders the waters can be "spun up" in place.

The wavelength of the meanders is most likely determined by the shape of the topography along the Grand Banks. Specifically, the meanders reflect the bathymetry along the way: the Southeast Newfoundland Rise (trough), the Newfoundland Seamounts near 44°N (trough), and finally the trough east of Flemish Cap. *La Violette* [1982] has emphasized the importance of the Newfoundland Seamounts to the path of the NAC.

Exchange of waters between the NAC and surrounding waters can still take place, even though the meanders are nonpropagating, either from their wobbling motions or through growth and decay of the meanders. *Song et al.* [1995] noted how this can happen in the Gulf Stream. In the NAC a growing meander would pick up parcels in previously quiescent waters and sweep them downstream. Conversely, in a decaying meander, parcels would be displaced toward the edge and left behind.

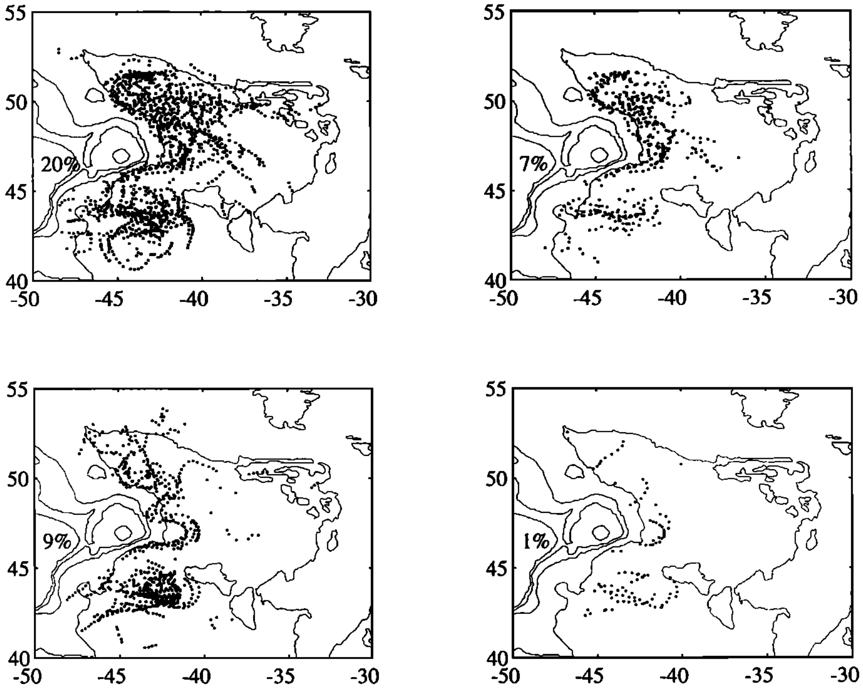

**Figure 12.** Dot distribution of float speeds in excess of (left) 40 and (right) 60 cm $s^{-1}$ for floats on the (top) 27.2 and (bottom) 27.5 $\sigma_t$ surfaces. The thin lines indicate the 200, 1000, 2000, and 4000 m isobaths. The percentages in each panel indicate the fraction of all observations exceeding the threshold.

From the few events observed thus far, the majority of transits across the entire NAC have taken place from the cold to warm side between the crest at 42°N and the trough at 44°N. With one possible exception, not a single float has evinced cross-frontal transfer of water through ring formation, whereas several such events were observed in the course of our Gulf Stream work [*Bower and Rossby*, 1989; *Song et al.*, 1995].

The fact that floats do not cross the entire NAC can be seen as compelling evidence for a simply connected front between the Southeast Newfoundland Rise, Flemish Cap, and the Northwest Corner. A number of floats maintain sustained speeds over substantial distances between these points (the trough at 44°N notwithstanding). High speeds mean strong lateral gradients, i.e., a baroclinic front along which the parcels travel. Further, all along the NAC it consistently serves as a water mass boundary between the cold Labrador Sea waters and the warm subtropical waters from the south. Floats consistently show high temperatures in the NAC and offshore, and consistently cold temperatures on the inshore side for the same isopycnal. The high speeds in the NAC can be illustrated by indicating all those points where a velocity exceeds some threshold value. In Figure 12 we show all observations where the speeds exceed 40 and 60 cm $s^{-1}$ for floats on the $\sigma_t = 27.2$ (top panels) and $\sigma_t = 27.5$ (bottom panels) density layers, respectively. The concentration of high speeds to the west indicates the high speeds along the mean path of the NAC. A nice feature of these figures is how they can emphasize patterns in the eddy field. With higher thresholds the meandering pattern emerges with preferentially high speeds around the meander extrema, such as the troughs near 44° and 47°N. The percentages in each panel indicate the fraction of all observations exceeding the threshold.

The loss of fluid along the NAC upstream and at meander extrema can help explain why the eddy kinetic energy levels drop so rapidly to the east of the NAC. The flow is so diffluent that fluid parcels rapidly decelerate upon leaving the current. Further, this diffluence or dispersal may help explain the lack of a clear indication of semipermanent eastward flows or jets, such as a jet at 47°N as has been hypothesized or even a well-defined jet at the Subpolar Front. The EKE pattern in Figure 4 shows only little enhanced EKE along the Subpolar Front, suggesting a broadening and weakening of the zonal flow. High EKE in zonal flows appear to be associated with the meandering of well-defined fronts [cf. *Rossby*, 1987; *Johns et al.*, 1995].

The proposed pathway for the NAC and resulting standing eddies in Figure 10 makes it easier to understand the *Krauss et al.* [1987] report of an extended recirculation between the Mann eddy at 42°N and Flemish Cap. At those times when the trough at 44°N is not extended and the course of the NAC is more linear, it appears that the anticyclonic cells at 42°N (the Mann eddy) and 45°N can join to form an extended recirculation cell. In addition, detailed hydrographic analysis [*Kearns*, 1996] reveals that there is also, on average, an anticyclonic cell east of Flemish Cap. These three latitudes coincide exactly with those reported by *Krauss et al.* [1987]. These cells, individually and when joined into an extended one, must be driven by the expulsion of negative relative vorticity (and/or large layer thickness) from the NAC. In its extended state this resulting recirculation will assume the scale of a small westward-intensified gyre with a N-S extent of ~600 km. It was shown earlier that the available wind stress curl was insufficient to drive such a gyre, but expulsion of anticyclonic vorticity by the meandering current may provide an alternative driving source. The properties of planetary wave radiation might explain why the recirculation, when it occurs, is limited to a narrow band east of the NAC itself rather than filling the entire Newfoundland Basin as was suggested schematically by *Worthington* [1976]. The float data suggest that the individual cells are connected into an extended cell only infrequently. The extended cell does not appear in high-resolution hydrographic climatologies [*Lozier et al.*, 1996; *Kearns*, 1996].

A major question about the Gulf Stream–North Atlantic Current transition that should be addressed is why the Gulf Stream turns north and the NAC flows so far north as a western boundary current. The high-resolution climatology of *Kearns* [1996] shows the NAC transporting 40 Sv (relative to 2000 dbar) into the Newfoundland Basin. No other western boundary current transports such volumes of warm waters so far poleward. This issue may be connected to the coupled wind-driven–thermohaline system, for it is here off the Grand Banks that the two meet and cross each other, both in the horizontal and in the vertical; hence the subtitle "at the crossroads." In the horizontal the NE flowing NAC and the cold waters from the Labrador Sea attached to it on the inshore side define the boundary between the wind-driven subtropical and subpolar gyres. In the vertical the NAC transports the warm, salty waters of the upper limb to the north, while the lower limb flows south along the continental rise immediately underneath. What is it that sets this system or region apart from the Kuroshio in the western Pacific, which certainly shows no such tendency to flow north? A number of possible causative factors can be mentioned.

**Demands of the thermohaline circulation?** The convective overturning of warm saline waters in the Labrador, Greenland, and Norwegian Seas demands a northward transport of about 12 Sv [*Schmitz and McCartney*, 1993] (*Broecker* [1991], on the other hand, prefers more like 20 Sv). These waters subsequently flow south along the deep western boundary and sink to replenish the deep waters of the world ocean. The transport of warm, salty waters by the NAC to the high latitudes where deep convection can take place is generally accepted as the upper limb of the thermohaline overturning [*Broecker*, 1991], but this does not explain why the waters flow north as a western boundary current as far as 51°N before turning east.

**Bathymetric control?** As the Gulf Stream flows east and makes bottom contact with the Southeast Newfoundland Rise, conservation of potential vorticity forces at least part (the inshore part) of the current to turn north along the bathymetry [*Warren*, 1969; *Shi and Chao*, 1994]. Our observation that the NAC meanders so tightly along the topography suggests that bathymetry plays a major role in governing the Gulf Stream–NAC transition. Indeed, the flow of the NAC NE past Flemish Cap with its retroflection to the NW (and with some waters that return SW) seems to mimic what we have observed of the Gulf Stream at the Southeast Newfoundland Rise. The point is that bathymetry seems to exert a very strong influence on the course of the current. What, then, might result from shifting the Gulf Stream a bit farther south so that it no longer makes contact with the Southeast Newfoundland Rise? Would the Gulf Stream continue east as does the Kuroshio Extension in the Pacific? Reconstructions of sea surface temperatures from the last glacial maximum suggest that the Gulf Stream did just this [*McIntyre et al.*, 1976].

**Winds?** We have previously argued that winds can not be responsible for the hypothetical northern gyre. But this does not preclude the possibility that the NAC as part of the larger subtropical gyre cannot extend the Gulf Stream as the western boundary current farther to the north. Theoretical arguments [*Sverdrup*, 1947; *Gill*, 1982] indicate that zero wind stress curl lines separate wind-driven gyres from each other such that in subtropical systems the wind stress curl induces an equatorward transport, and vice versa in subpolar gyres. Broadly speaking, the NAC–Subpolar Front system does coincide with the zero wind stress curl line. However, the mean wind stress curl is relatively weak compared with its annual and interannual variability [*Isemer and Hasse*, 1987], so that it seems unlikely that the NAC's sharp turn to the north and penetration to 52°N results directly from such variable forcing. Perhaps the ocean leads the atmosphere in this region?

## SUMMARY

Although *Iselin* [1936] perhaps did not realize it at the time, his depiction of the path of the North Atlantic Current and the waters in the Newfoundland Basin was remarkably accurate. The reason for this is simple: The path of the NAC is quite stable, extending the Gulf Stream northeastward along the continental slope east of the Grand Banks. Even sparse, infrequent sampling will resolve a pattern that does not evolve. The International Ice Patrol has maintained a strong interest in the position and currents of the NAC in order to provide accurate information on iceberg movements. Thanks to their activities there is a very substantial hydrographic and drifter database of the region east of the Grand Banks that otherwise would not exist. Oceanographers, on the other hand, have tended to focus on the fate of the Gulf Stream along the Southeast Newfoundland Rise, stimulated perhaps in part by the two-gyre controversy. But the structure of the current in this region is rich in detail, posing a formidable challenge to the hydrographic sampling techniques available to chart ocean currents. This may, in the end, be the reason for the controversy: we have not had the measurement or sampling techniques appropriate for the task. Besides, ships are slow.

Drogued surface drifters have proved to be very helpful in charting the spatial and temporal structures of currents, especially when geostrophic and boundary layers are carefully distinguished. By systematically deploying drifters in different regions the Institut für Meereskunde, Kiel, has built a picture of the mean near-surface circulation and obtained valuable information on the nature of the eddy field. With respect to the NAC, the drifter data indicate that the Subpolar Front cannot be described as a baroclinic jet (à la Gulf Stream) with various branch flows peeling off, but rather as a broad eastward and northward drift with a widening envelope to the east. We suspect that the shallow stratification at high latitudes is unable to provide enough density contrast to maintain permanent baroclinic fronts. Any baroclinic front would be too weak to withstand the disruptive effects of the background barotropic eddy field. The *Krauss* [1986] paper is a very important one, both for what it has taught us about the upper ocean circulation of the North Atlantic Ocean and for its systematic use of direct measurements of currents.

The work in progress by the RAFOS float group at the University of Rhode Island is similar to that of the IFM group with our use of Lagrangian techniques. We are focusing on the NAC as a western boundary current and on how it functions as a boundary between the subtropical and subpolar waters. The isopycnal float trajectory data indicate that the NAC acts effectively as a boundary between the two gyres on shallow density surfaces in the sense that only a very few floats have crossed the current entirely from one side to the other, and then only along specific pathways. The NAC is highly convoluted (has steep meanders), but with the exception of the trough at 44°N, which can shed cold core eddies, warm- and cold-core ring formation, which is commonplace in the Gulf Stream, has not been observed. The mean path of the meandering NAC follows the bathymetry closely, suggesting conservation of potential vorticity by vortex stretching and positive curvature vorticity in deeper waters causing the current to turn back inshore, and vice versa in shallower waters. The meanders do not propagate downstream or upstream. Almost certainly this is due to their generation by prominent topographic features: the Southeast Newfoundland Rise and Flemish Cap. Waters are lost from the NAC in strongly difluent and thus decelerating flows. There appears to be no mechanism for focusing expelled waters into zonal jets, which may explain their absence in the trajectory data. This accords with the *Krauss* [1986] study.

## GLOSSARY

**Anticyclonic motion:** Flow patterns in which the direction of flow turns to the right (i.e., clockwise) in the northern hemisphere and to the left (anticlockwise) in the southern hemisphere.

**Baroclinic flow:** Horizontal motion with vertical shear that is dynamically related to transverse horizontal gradients of the density field.

**Barotropic flow:** There are many definitions for this. Here we mean the flow where the density field is nearly uniform, such as below the main thermocline or in Subpolar waters.

**Crest and trough:** Those parts of a meandering current where the curvature is at an extremum: anticyclonic (clockwise) and cyclonic (anticlockwise), respectively.

**Cyclonic motion:** Flow patterns in which the direction of flow turns to the left (i.e., anticlockwise) in the northern hemisphere and to the right (clockwise) in the southern hemisphere.

**Eddy kinetic energy:** Defined as $(\langle u'^2\rangle + \langle v'^2\rangle)/2$, where $u'$ and $v'$ represent the eddy velocity component, i.e., the observed velocity minus the mean for the region in question.

**Ekman transport:** The 10- to 100-m-thick boundary layer at the surface of the ocean where fluid motion is directly influenced by the action of the winds. In the northern hemisphere the transport in the Ekman layer is directed to the right (up to 90°) of the applied wind stress.

**Eulerian flow:** Description of fluid motion in a fixed coordinate system, i.e., $\mathbf{U}(x, y, z, \text{time})$. All hydrographic descriptions of the ocean use the Eulerian coordinate system.

**Geostrophic flow:** All large-scale horizontal flow, whether in the ocean or the atmosphere is very nearly in geostrophic balance. This means that the pressure gradient and the Coriolis force are equal and opposite to each other and normal to the direction of flow. The latter force results from the rotation of the Earth.

**Inertial motion:** Circular motion with a period of 12 hours/sin (latitude). These motions are ubiquitous in the ocean and are usually induced by sudden changes in wind stress at the surface.

**Isopycnal surface:** A surface along which fluid parcels move without change in density.

**Lagrangian flow:** Fluid motion defined in terms of the time history of labeled fluid parcels, i.e., $\mathbf{X}(x_0, y_0, z_0, \text{time})$ where $x_0$, $y_0$, $z_0$ represent the parcel's starting point. The isopycnal RAFOS floats naturally use the Lagrangian coordinate system.

**Potential vorticity:** Conservation of potential vorticity is an important constraint to fluid motion in the ocean. It states that in the absence of friction, the absolute angular momentum of a fluid parcel must be conserved.

**Sigma-$t$ ($\sigma_t$):** A commonly used definition for density of water (1 $\sigma_t$ unit is equal to 1 kg $m^{-3}$).

**Streamline and trajectory:** A streamline represents lines along which the fluid moves at a particular instant, whereas a trajectory traces out the path of a parcel. The two are the same only if the flow is steady.

**Sverdrup (Sv):** A widely used unit for volume transport in the ocean (1 Sv = $10^6$ $m^3$ $s^{-1}$).

**ACKNOWLEDGMENTS.** I would particularly like to acknowledge my colleagues M. E. Carr and M. Prater for many helpful discussions. It is a great pleasure to acknowledge many stimulating conversations and exchange of ideas with R. A. Clarke, B. Cushman-Roisin, S. Dutkiewicz, E. Kearns, W. Krauss, L. Rothstein, C. Rowley, and R. Watts. What has been discussed here is in large measure the result of these. I would also like to express my sincere appreciation to R. A. Clarke at the Bedford Institute of Oceanography for wonderful collaboration and assistance with the field program on the CSS *Hudson*. The success of a major field program like this is possible only through tremendous teamwork: J. Fontaine is responsible for the development and preparation of the RAFOS floats and has done a truly superb job. S. Andersson-Fontana has been responsible for the excellent data processing and preparation of the float trajectory plots. The installation of the sound source moorings has been expertly handled by J. Kemp at WHOI and T. Orvosh at the Graduate School of Oceanography, URI. We also thank Captain M. Palmieri and the crew of the R/V *Oceanus* for their tremendous support. I particularly wish to acknowledge Joyce Reusch for her cheerful assistance with all things administrative here at URI. Several reviewers and the editor, D. Luther, made much appreciated suggestions for improving the text. Our group is most grateful to the Office of Naval Research and the National Science Foundation for their support of this program.

D. Luther was the editor responsible for this paper. He thanks T. Vallier and four anonymous reviewers for their assistance in evaluating this paper.

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