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Pathways of cross-frontal exchange in the North Atlantic Current

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Abstract. The North Atlantic Current (NAC) forms part of the boundary between the subtropical and subpolar gyres in the North Atlantic Ocean. The current has topographically controlled stationary meanders that appear to grow and decay. A region east of the current in the Newfoundland Basin contains water of mixed subpolar/subtropical properties, suggesting that there is exchange across the NAC. This study considers data from isopycnal RAFOS floats launched in the NAC region from 1993 to 1995. We use the RAFOS data to define the "frontal zone" as a pressure range where the jet is most likely to be found. This definition requires a latitudinal dependence as the NAC shoals to the north. Floats shallower and deeper than this range are defined to be on the subpolar and subtropical side, respectively. These definitions are used to estimate mixing that occurs between the current and its surroundings and to estimate the relative quantity of exchange of water parcels between the two gyres. Only small quantities of mass exchange from one gyre to the other are found, but there is a distinct asymmetry leading to a mean flux from the subpolar to subtropical sides. We also find that floats spend significant time in the frontal region and are frequently exchanged between fast and slow moving waters, particularly at the meander extrema. Diffusion, while in the jet, leads to eddy cross-frontal exchange which is important for the exchange of properties across the NAC.

1. Introduction

Recent studies have explored the mechanisms and frequency of exchange between strong oceanic jets and surrounding slower moving waters and the exchange of water parcels and water properties between two different physical or chemical regions. One of the most intensely studied dynamic fronts is that associated with the Gulf Stream. This ocean current separates the warm, salty Sargasso Sea from the fresher, colder slope water. These waters also have different concentrations of tracers, such as oxygen and biological species. Clearly then, the Gulf Stream acts as a boundary between the two water masses, and yet observations of oxygen concentrations [*Bower et al.*, 1985] and Lagrangian subsurface drifters [*Song et al.*, 1995] have shown that exchange does occur within the Gulf Stream system. These studies have spurred several analytical and modeling investigations of the nature of mixing and stirring within a meandering, propagating jet [*Bower*, 1991; *Samelson*, 1992; *Dutkiewicz et al.*, 1993; *Lozier and Bercovici*, 1992; *Lozier et al.*, 1997].

In this study we consider Lagrangian observations of exchange in the continuation of the Gulf Stream, the North Atlantic Current (NAC). The NAC brings warm water of subtropical origin into the Newfoundland Basin (topographic features of the basin are given in Figure 1). This current can be viewed as an extension of the subtropical gyre, and we will refer to this water as "subtropical." Colder, fresher water from the Labrador Basin enters the Newfoundland Basin from the north. This water is of subpolar origin, and we will refer to it as "subpolar." The Newfoundland Basin is therefore a meeting point of the subtropical and subpolar gyres, and the two very different water masses flow together, creating a strong thermal front. There appears to be a slow eastward moving body of water of inhomogeneous character to the east of the NAC [*Harvey and Arhan*, 1988; *Kearns*, 1996], suggesting a mixing of subtropical and subpolar properties. Exchange across the jet is fundamentally an interaction between the subtropical gyre and the subpolar gyre systems and therefore has important consequences for the gyre-scale dynamics of, for instance, the potential vorticity budget [*Lozier and Riser*, 1990; *Dutkiewicz*, 1997] and the transport of heat from low to high latitudes and in the distribution of chemical tracers and biological species.

A strong meander pathway seen in previous studies of the NAC region [*Kearns*, 1996; *Lozier et al.*, 1996] was also identified in a RAFOS float study conducted during 1993–1995 [*Anderson-Fontana et al.*, 1996; *Rossby*, 1996]. The data collected by these floats are discussed in section 2. We differentiate between two processes: the loss of water parcels from the fast moving jet to slower moving surrounding waters and the exchange of mass and properties between the two gyres to either side of the NAC. In section 3 we define specific regimes, such as the "jet" and the "frontal zone," to aid in the investigation of these processes. In section 4 we determine statistics from the float data that provide a measure of the mixing. In section 5 we discuss and summarize these results.

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2. RAFOS Float Experiment

From June 1993 to June 1995, approximately 100 RAFOS floats were deployed in the Newfoundland Basin. The details

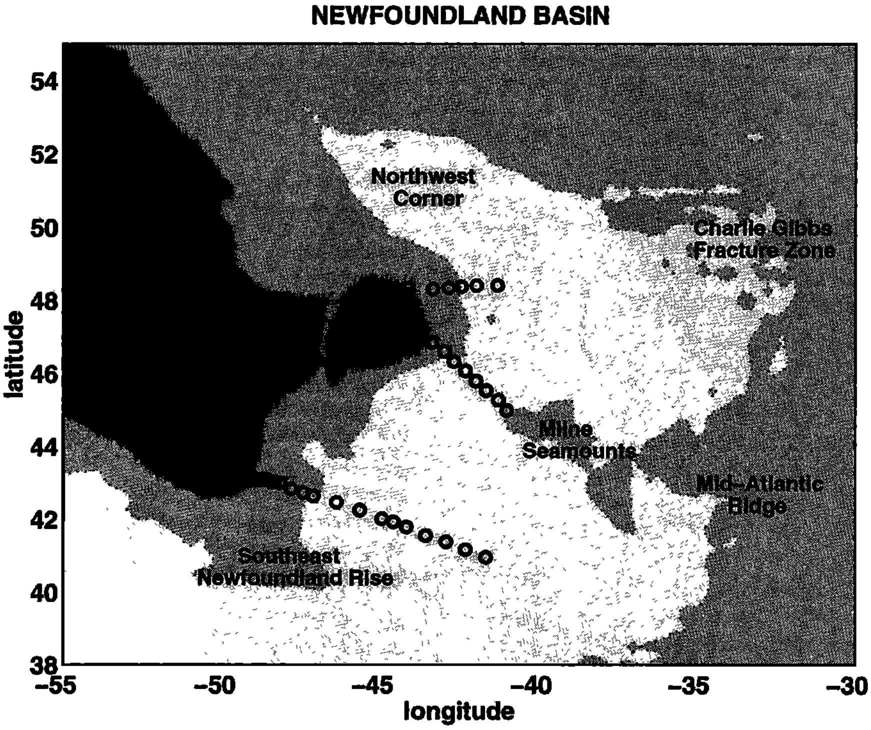

Figure 1. Topographic features of the Newfoundland Basin. The 200-, 1000-, and 4000-m isobaths are shown. Circles indicate conductivity-temperature-depth probe sites for three sections taken during the summer 1993 by the RV *Oceanus*.

of the experiment and the data recovered are discussed by *Anderson-Fontana et al.* [1996]. For the purposes of this paper a few key points will be noted. The RAFOS floats are designed to track water parcels along constant density surfaces and to record temperature and pressure every half day. The temperature measurements are accurate to within 0.1°C, and the pressure measurements are accurate to within 10 dbar. Every half day the floats listen for signals from four sound sources moored in the region. The travel time from two or more of these sources provides the float's location. The floats were also designed to periodically profile up and down $0.1\sigma_t$ unit from their surface, measuring temperature and pressure at the top, middle, and bottom. The floats were deployed on three cruises and had average mission lengths of 10 months, providing coverage in the Newfoundland Basin for 2 years.

The floats have the same compressibility as seawater, so by definition they will follow a specific volume anomaly surface. They were ballasted for one or the other of two specific volume anomalies which, for convenience, are referenced in this paper by the isopycnal surfaces they approximate, $27.2\sigma_t$ and $27.5\sigma_t$ [*Carr et al.*, 1997]. The lower surface ($27.5\sigma_t$) does not outcrop in this region and was, in general, not affected by seasonal forcing. The upper surface ($27.2\sigma_t$) does outcrop in the northern part of the Newfoundland Basin and will certainly be affected by seasonal forcing. To preserve the floats against the damage encountered when on the surface, the floats were programmed to operate in isobaric mode once they reached 200 dbar or less. By using conductivity-temperature-depth (CTD) casts conducted at the time of deployment, *Carr et al.* [1997] estimated the actual density that the floats tracked. The temperature and pressure measurements were then corrected back to the target density surface using the profile information. The corrections were on the order of 0.3°C and 60 dbar. Since this study is interested in the velocity measurements, floats farther than $0.1\sigma_t$ from their target density were not used. A set of 39 floats on the $27.2\sigma_t$ surface and a set of 25 floats on the $27.5\sigma_t$ surface provide data for this study. The trajectories of these floats are shown in Figure 2.

The NAC pathway and variability derived from the float data are discussed in the remainder of this section. The float data have been compiled into 0.5° × 0.5° means and standard deviations. The bins were required to contain data from at least two floats, and no single float was permitted to contribute more than five measurements in any bin: Where there were more measurements in a bin, the chosen data were evenly spaced throughout the record, and no bin with <10 measurements was considered. The above requirements provide a view of the Newfoundland Basin mean velocity, eddy kinetic energy, mean pressure, and mean temperature structure along the two density surfaces (Figures 3 and 4). The fields were smoothed using a simple weighted average method where each bin was weighted one and the eight adjacent bins were weighted one eighth. In Figures 3c, 3d, 4c, and 4d the contours indicate the mean values, and the shading indicates the standard deviation. In all of the figures the thin solid lines indicate the 200-, 1000-, and 4000-m isobaths.

As the waters of the Gulf Stream reach the Southeast Newfoundland Rise (locations of topographic features are shown in Figure 1), several branches separate from the main current system [*Mann*, 1967; *Arhan*, 1990]. *Hogg* [1992] suggested that a branch of water moves south and west, forming part of the Gulf Stream recirculation. A second branch appears to separate south of the Grand Banks, forming the eastward moving Azores Current [*Klein and Siedler*, 1989]. However, a greater part of the Gulf Stream water continues northward along the east flank of the Grand Banks. The mean velocities (Figures 3a

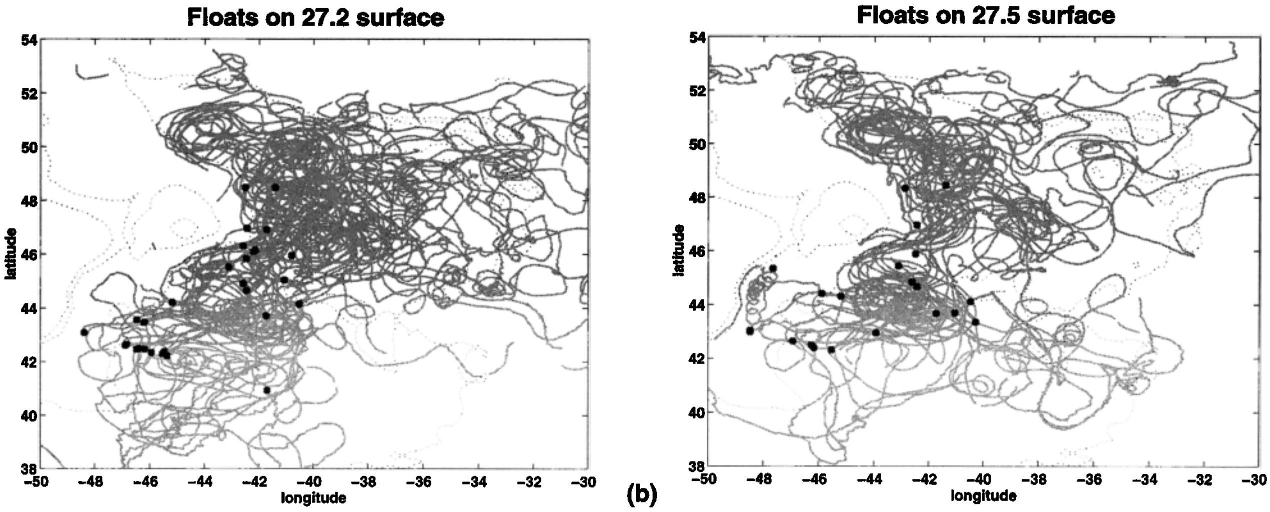

Figure 2. RAFOS float trajectories on the (a) $27.2\sigma_t$ surface and (b) $27.5\sigma_t$ surface. Launch positions are shown as thick crosses. Dotted lines indicate the 200-, 1000-, and 4000-m isobaths.

and 4a) show a strong current there, with a semistationary meander pattern and associated recirculations. Background eddy kinetic energy values are ~200 $cm^2\ s^{-2}$ and ~100 $cm^2\ s^{-2}$ for the upper and lower layers, respectively (Figures 3b and 4b). Higher eddy kinetic energy is associated with the NAC: Maximum values are over 1000 $cm^2\ s^{-2}$ for the upper layer and over 600 $cm^2\ s^{-2}$ for the lower layer. Maximum values around 1250 $cm^2\ s^{-2}$ were found for the 50- to 100-m layer from the International Ice Patrol and the Institut für Meereskunde drifter data sets for this region [*Rossby*, 1996], and a similar

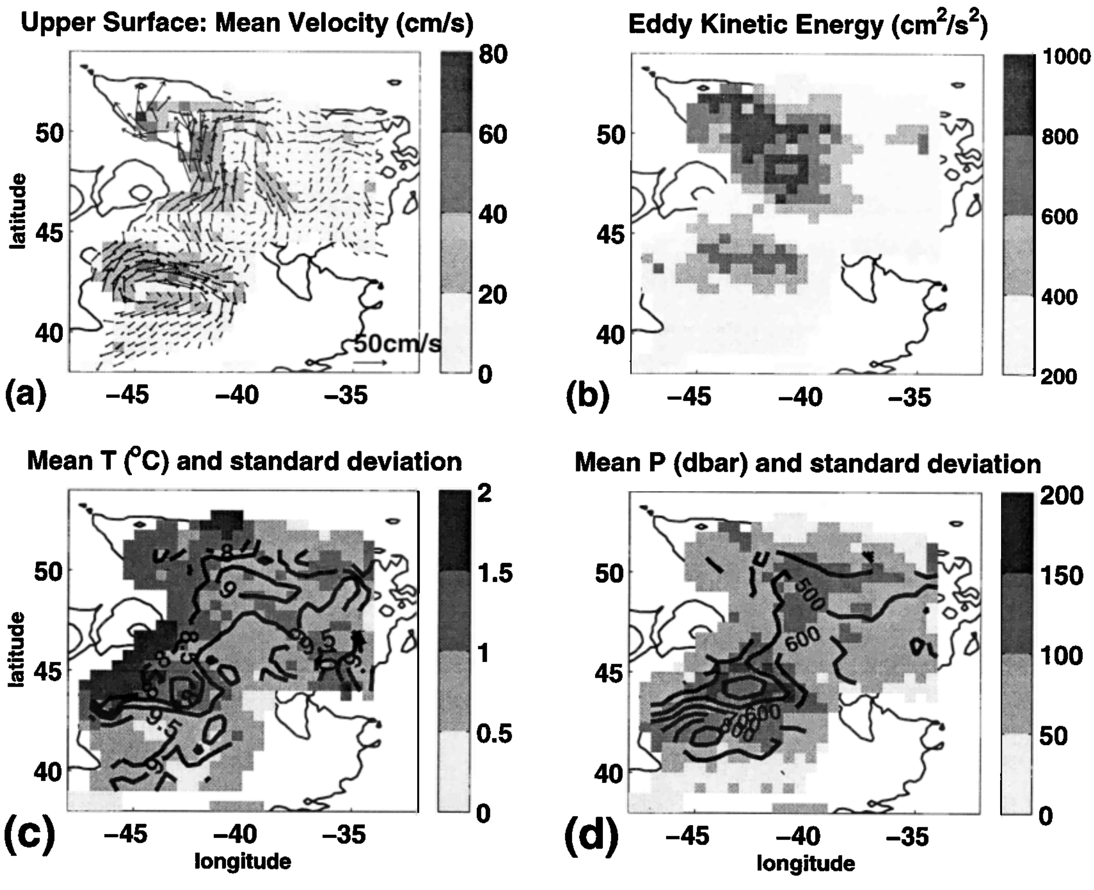

Figure 3. Climatology derived from 2 years of RAFOS float data along the $27.2\sigma_t$ surface: (a) mean velocity (arrows) and speed (shading) (cm s^{-1}), (b) eddy kinetic energy ($cm^2\ s^{-2}$), (c) mean temperature (contour with 0.5°C interval) and standard deviation (shading), and (d) mean pressure (contour with 100-dbar interval) and standard deviation (shading). Lines indicate the 200-, 1000-, and 4000-m isobaths.

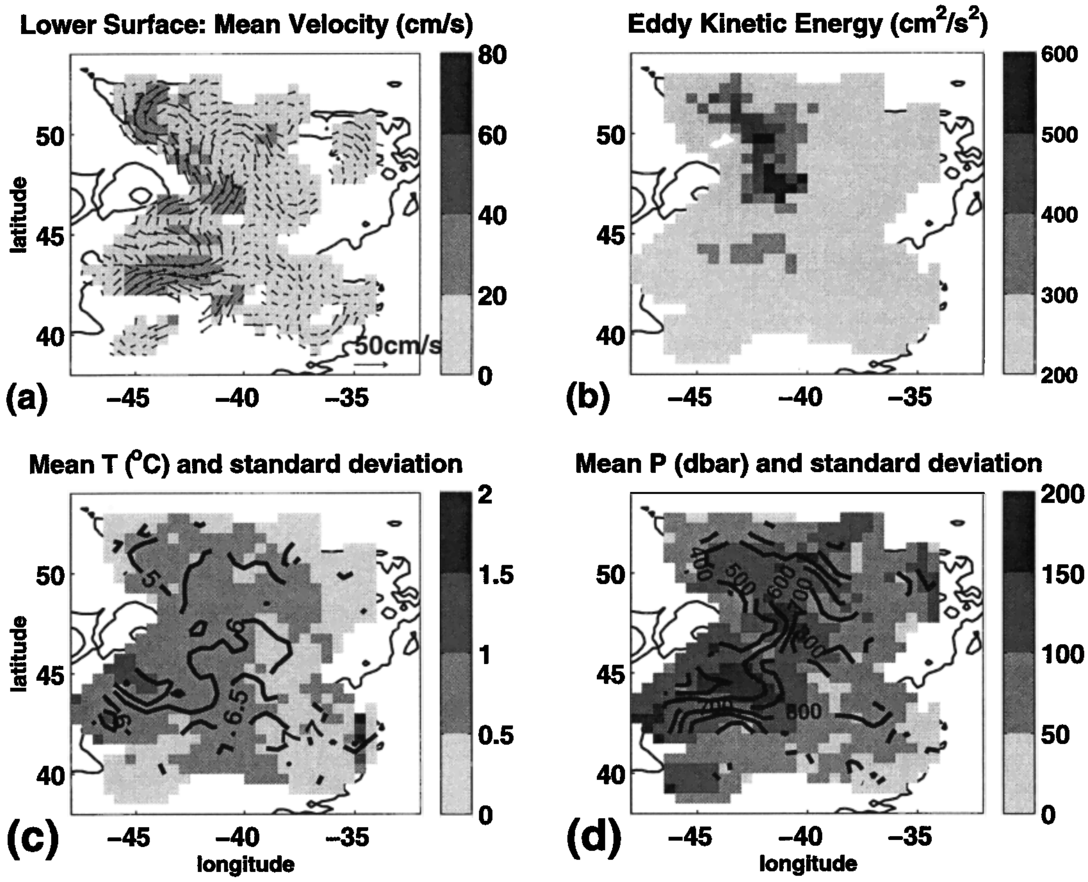

Figure 4. Climatology derived from 2 years of RAFOS float data along the $27.5\sigma_t$ surface: (a) mean velocity (arrows) and speed (shading) (cm s^{-1}), (b) eddy kinetic energy (cm^2 s^{-2}), (c) mean temperature (contour with 0.5°C interval) and standard deviation (shading), and (d) mean pressure (contour with 100-dbar interval) and standard deviation (shading). Lines indicate the 200-, 1000-, and 4000-m isobaths.

maximum was found from ERS-1 altimeter data [*Heywood et al.*, 1994]. The mean pressure (Figures 3c and 4c) and the mean temperature (Figures 3d and 4d) show west-east gradients associated with the NAC. There is also a north-south gradient associated with the shoaling of the isopycnals.

The strong anticyclone at 42°N appears as a permanent feature that has also been encountered by various hydrographic studies and was first documented as an eddy by *Mann* [1967]. It has therefore often been referred to as the Mann Eddy. The current path follows the northern edge of the Mann Eddy and forms a steep trough, at 44°N, whose amplitude appears to grow and decay over time. However, the trough is found to be a more persistent feature during the 2-year float experiment than it is in longer climatologies [*Carr et al.*, 1997]. The area between 42°N and 44°N also shows a localized higher eddy kinetic energy (Figures 3b and 4b), which is an indication of high variability in the location of strong fronts [*Rossby*, 1996; *Johns et al.*, 1995]. There is also higher pressure and temperature variability associated with the trough. Float trajectories additionally indicate a recirculation within the trough (Figure 2). Between 43°N and 44°N, there is colder water flowing from the southwest, which is probably the Labrador Current joining the path of the NAC. After the 44°N trough the current forms a crest against the Grand Bank, south of Flemish Cap. The eddy kinetic energy associated with the crest is lower than the trough, which suggests that the crest does not have as strong a tendency to grow and decay. A second trough that forms just east of Flemish Cap has even higher eddy kinetic energy than the 44°N trough. This feature also coincides with the location of one of the eastward "branches" that has been suggested by various authors [e.g., *Arhan*, 1990]. The current either continues north and retroflects in the Northwest Corner or will join the Subpolar Front to the northeast, leaving an isolated eddy in the Northwest Corner [*Carr and Rossby*, 1995; *Lazier*, 1994]. *Lazier* [1994] found that an eddy of ~100 km would frequently form and persist in the Northwest Corner for 1 to 2 months. After the Northwest Corner the current turns eastward and exhibits large meandering and temporally different pathways and crosses the Mid-Atlantic Ridge in the region of the Charlie-Gibbs Fracture Zone. This eastward moving current appears more diffuse than the current along the Grand Banks [*Rossby*, 1996; *Kearns*, 1996; *Rowley*, 1996] and is termed the Subpolar Front. Further discussions of the NAC transport and the Lagrangian statistics are provided by *Carr and Rossby* [2001] and *Zhang et al.* [2001].

This study focuses on the current between the Southeast Newfoundland Rise and the Northwest Corner. In this region the current appears as a coherent feature, and the float data provide good coverage. A modeling study [*Dutkiewicz*, 1997] demonstrates that much of the cross-frontal exchange occurs in the region where the front and associated instabilities are strong, and less exchange occurs when the front becomes more

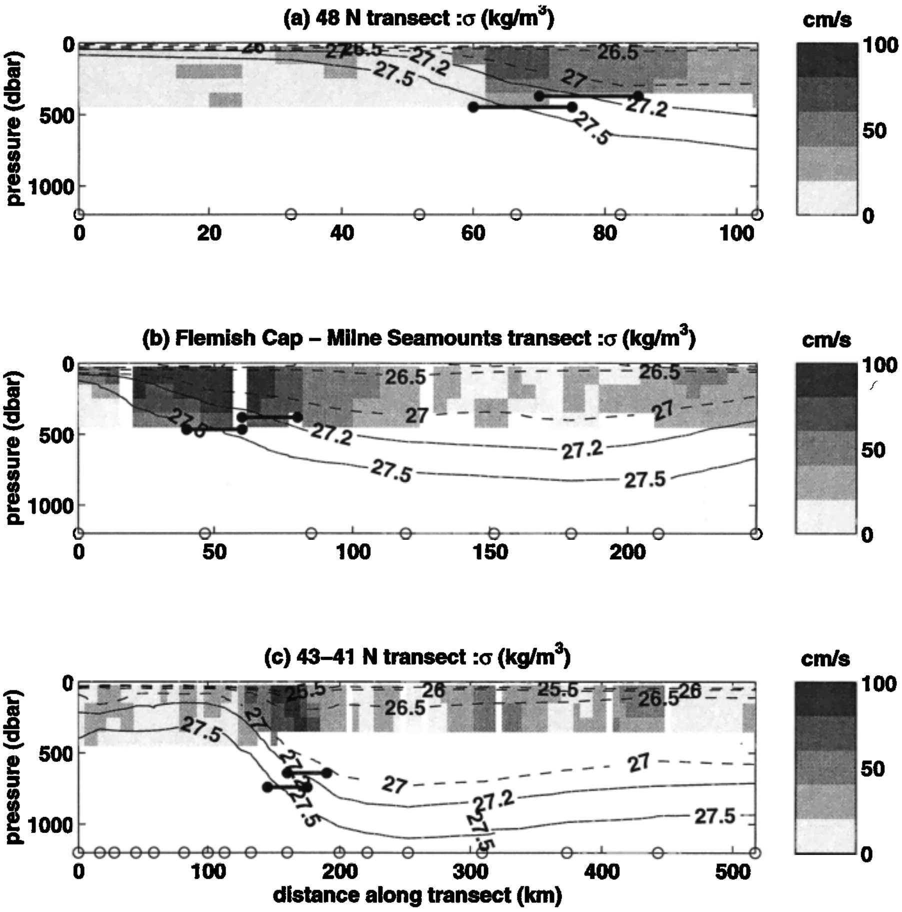

Figure 5. CTD sections (locations shown in Figure 1) from (a) 1000-m isobath at 48°N tending east for ~100 km, (b) Flemish Cap to Milne Seamounts (~250 km), and (c) 1000-m isobath at 43°N tending east-southeast to 41°N (~500 km). Circles indicate position of each CTD station. Contours indicate density (σ_t, kg m^{-3}); shading shows horizontal velocity (cm s^{-1}) from acoustic Doppler current profiler down to ~400 m. Thick horizontal lines indicate third-order polynomial fit $P_f(\theta)$ for the $27.2\sigma_t$ (upper) and $27.5\sigma_t$ (lower) surfaces.

diffuse. Therefore the NAC is a potentially important region for the exchange of subpolar and subtropical properties, possibly more important than the Subpolar Front.

3. Definitions: Jet and Dynamical Front

Studies of exchange in the Gulf Stream have been aided by the constant downstream profile of that current [*Halkin and Rossby*, 1985]. For instance, the definition of the center of the Gulf Stream was taken as the halfway position between the 12°C isotherm crossing 400 m and 600 m [*Halkin and Rossby*, 1985]. However, such a definition with no downstream dependence is not possible for the NAC where, for example, the pressure along the isopycnal surfaces (Figures 3d and 4d) clearly indicates not only an east-west gradient of pressure associated with the jet but also a shoaling toward the north. This shoaling is also evident in CTD sections (Figure 5). Similarly, the temperature is colder both to the west and to the north (Figures 3c and 4c). The isopycnals associated with the jet shoal sharply between 42.5°N and 46.5°N, remain at a more constant depth near 48°N, and shoal again farther north. For the purpose of examining exchange across the current, we therefore require a definition of the current that takes this latitudinal dependence into account. We accomplish this by estimating the range of pressures that encompasses the central part of the NAC at each latitude, θ, using the RAFOS float data. We will refer to this "center" of the jet as the "dynamical front."

From the climatologies shown in Figures 3 and 4 it is possible to define the most likely corridor of the jet's path. The corridor is divided into 1.5° latitude bins (Figure 6), which gives a good coverage of the current, with reasonable numbers of float observations within each bin. We plot the horizontal speed, pressure, and temperature of the float data in each bin (Figures 7 and 8). We have allowed each float to provide only 10 data points per bin, thus minimizing the bias that can occur because of a single slow or fast moving float. In Figures 7 and 8 the fastest 25% of the data are denoted with darker symbols, revealing a subset of fast moving float data that are then used to estimate the pressure of the fast moving core of the NAC. The mean pressure values for this subset in each bin (diamonds) and for one standard deviation on either side (bars) are shown in Figures 7b and 8b for the two isopycnal surfaces. We fit a third-order polynomial to the mean, $P_f(\theta)$, (solid lines) and to one standard deviation on either side, $P_f(\theta) \pm s_f(\theta)$, (thick dashed lines) for each of the isopycnal surfaces as a function of latitude. These polynomials $P_f(\theta)$ show a similar trend to that seen along CTD transects and in the float-derived climatologies. We plot the values of $P_f(\theta)$ for the $27.5\sigma_t$ and

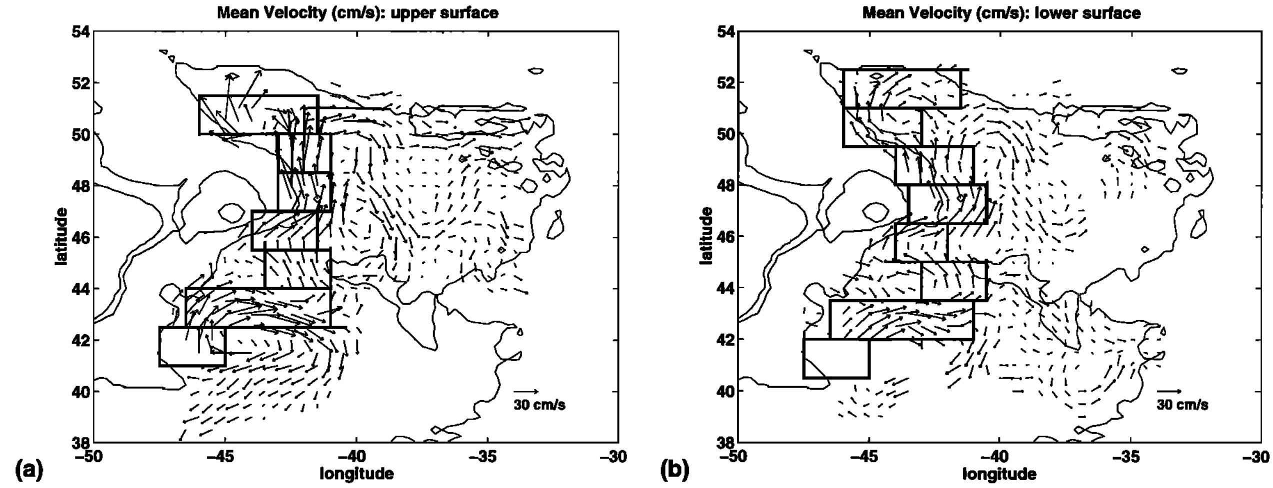

Figure 6. Latitude bins of the most likely path of the North Atlantic Current superimposed on mean velocity fields found from RAFOS data for the (a) $27.2\sigma_t$ surface and (b) $27.5\sigma_t$ surface. Lines indicate the 200-, 1000-, and 4000-m isobaths.

$27.2\sigma_t$ surfaces for the appropriate latitudes with thick horizontal lines in Figure 5. Note that the center of the jet appears to be farther onshore for the lower surface and farther offshore for the upper surface.

The frontal zone is therefore defined as being centered at $P_f(\theta)$ and having a range of $\pm s_f(\theta)$. Thus a float is on the "subpolar side" of the current if

$$P_{\text{float}} < P_f(\theta) - s_f(\theta)$$

and on the "subtropical side" if

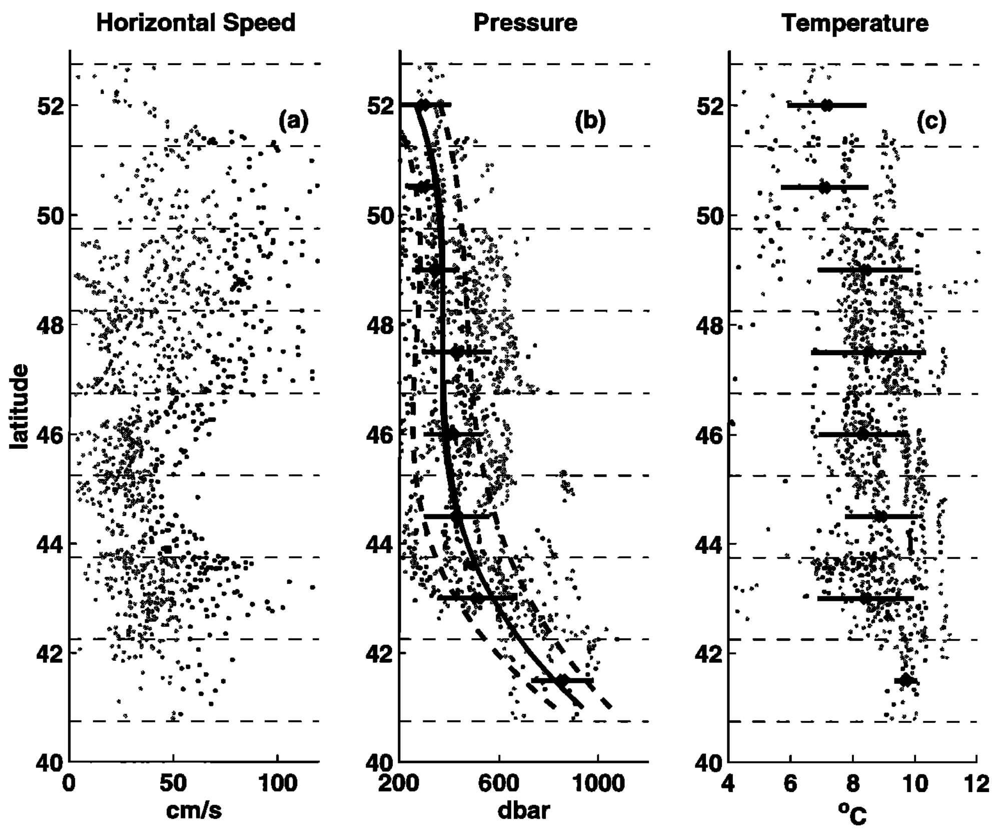

Figure 7. Float data (dots) from bins in Figure 6 for the $27.2\sigma_t$ surface: (a) horizontal speed (cm s^{-1}), (b) pressure (dbar), and (c) temperature (°C). Darker dots indicate fastest 25% of data in each bin. Thin dashed lines mark latitude of each box and diamonds show mean pressure or temperature in each bin, with one standard deviation (bar) shown on either side. Third-order polynomial fit $P_f(\theta)$ is applied to bin mean pressure (solid line) and to one standard deviation $s_f(\theta)$ on either side (thick dashed lines).

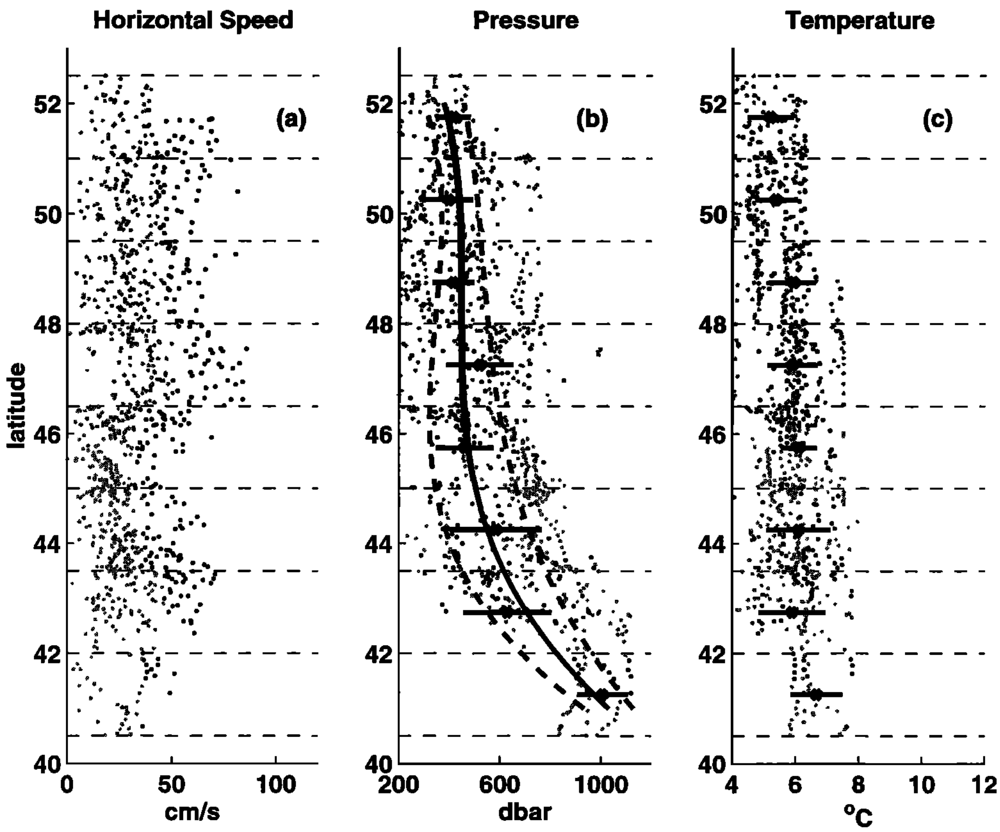

Figure 8. Float data (dots) from bins in Figure 6 for the $27.5\sigma_t$ surface: (a) horizontal speed (cm s^{-1}), (b) pressure (dbar), and (c) temperature (°C). Darker dots indicate fastest 25% of data in each bin. Thin dashed lines mark latitude of each box and diamonds show mean pressure or temperature in each bin, with one standard deviation (bar) shown on either side. Third-order polynomial fit $P_f(\theta)$ is applied to bin mean pressure (solid line) and to one standard deviation $s_f(\theta)$ on either side (thick dashed lines).

$$P_{\mathrm{float}} > P_f(\theta) + s_f(\theta).$$

We find that much of the data discussed in section 4 indicate that floats are not always traveling quickly when in this region; a float can be in the right pressure range for the front and yet be moving relatively slowly. This suggests a breakdown of the tight frontal structures, a phenomenon that was observed in the Gulf Stream [*Halkin and Rossby*, 1985]. We therefore also use a threshold velocity to define the jet: A float is "in the jet" if $|\mathbf{v}_{\mathrm{float}}| > v_{\mathrm{threshold}}$. Three threshold velocities are considered; these speeds ($v_1 = 30$ cm s^{-1}, $v_2 = 45$ cm s^{-1}, and $v_3 = 60$ cm s^{-1}) are taken as fractions of the fastest speeds found in Figures 7a and 8a.

A tight frontal structure as found in the Gulf Stream studies [e.g., *Halkin and Rossby*, 1985; *Bower et al.*, 1985] would be necessary to calculate cross-frontal eddy property exchange. In this study we instead estimate the position of the floats relative to the NAC and investigate how frequently these positions change. We have two ways of defining a float's position: Its pressure indicates where it is in relation to the front, and its horizontal speed indicates if it is in the fast moving current or in the slower moving surrounding waters.

4. Float Statistics

The region of study is the NAC between 40.5°N and the Northwest Corner, 52.5°N; however, we wish to exclude the recirculating portion of the Mann Eddy and the Subpolar Front, for both of which the definitions above are not accurate. The study region therefore covers from 50°W to 36°W, except for regions to the southeast and northeast. The boxes denote the study area in Figures 9, 10, 11, 13, and 14.

As an initial example, we consider float 269 on the $27.5\sigma_t$ surface. Figure 9a shows the trajectory of the float within the Newfoundland Basin superimposed on the mean velocity field found from all the floats on the $27.5\sigma_t$ surface. Float data outside of the study region in both Figures 9a and 9b are indicated by thin lines. Float 269 is launched near 42°N and, after a loop south around the Mann Eddy, moves northward to the Subpolar Front. Figure 9b shows the corresponding Lagrangian time series of pressure (dbar), temperature (°C), and horizontal speed (cm s^{-1}) for this float. The thin line in the pressure record denotes $P_f(\theta)$, where the latitude θ is taken from the float track, and the dashed lines indicate $P_f(\theta) \pm s_f(\theta)$. These frontal zone lines are only plotted while the float

Table 1. Number of Data for RAFOS Floats Referenced to Pressure Data

Number of Data	$27.2\sigma_t$ Surface	$27.5\sigma_t$ Surface
Study domain	6940	7864
Frontal zone	2658 (38%)	1863 (24%)
Subtropical side	3531 (51%)	5378 (68%)
Subpolar side	751 (11%)	623 (8%)

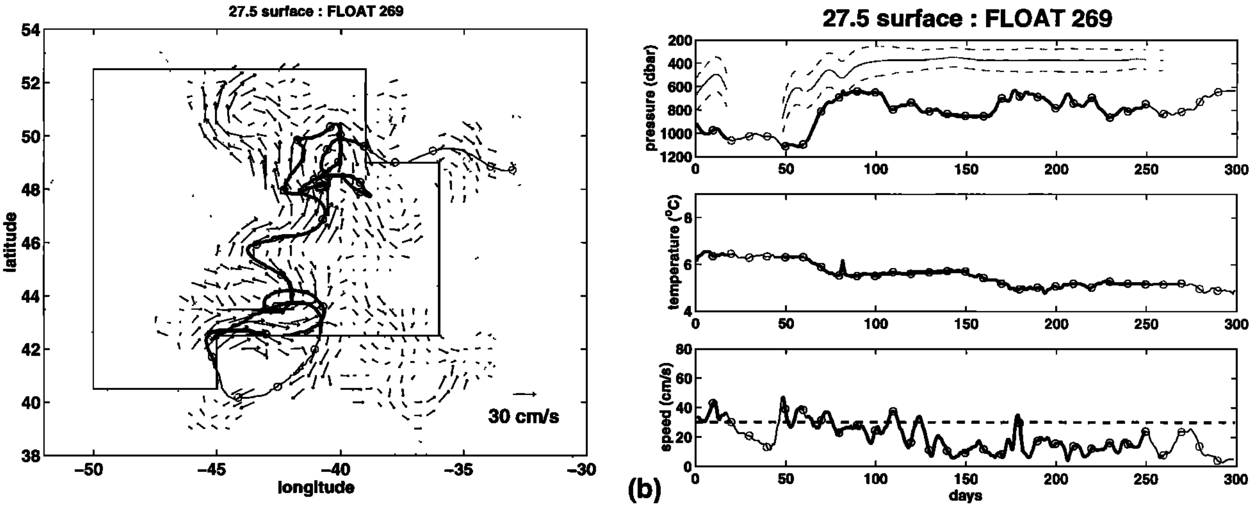

Figure 9. Float 269 (a) trajectory superimposed on mean velocity field, and (b) values of pressure (dbar), temperature (°C), and horizontal speed (cm s^{-1}). Circles are every 10 days. For the pressure record, $P(\theta)$ and $P(\theta) \pm s_f(\theta)$ (thin solid and thin dashed lines, respectively) are shown while the float is in the study region. For the speed record the threshold speed (v_1 = 30 cm s^{-1}) is indicated (dashed line). Float data are denoted by a thick line (within the study region) or a thin line (out of the study region). Dotted lines in Figure 9a indicate the 200-, 1000-, and 4000-m isobaths.

is within the study region. The dashed line on the speed record denotes the threshold speed (v_1 = 30 cm s^{-1}) for the 27.5σ_t surface; any speed greater than this denotes that the float is in the jet. The float is launched on the subtropical side, $P_{\text{float}} > P_f(\theta) + s_f(\theta)$. From days 60 to 80 the float's pressure decreases, and there is a corresponding temperature change. We could, mistakenly, assume that the float crossed the dynamical front. However, the pressure of the front, $P_f(\theta)$, also decreased as the float moved northward, and the float was found to stay on the subtropical side for its entire mission.

A second example is float 295, which is also on the 27.5σ_t surface (Figure 10). The float is launched in cold water on the subpolar side of the front, moves into the NAC, and is caught in the 44°N recirculation. It is expelled to the east around day 90 after crossing the dynamical front, and its temperature increases by 0.8°C. However, it had already crossed a stronger temperature front as it moved off the Grand Banks before encountering the dynamic front. A strong temperature front inshore of the dynamic front in this region was found in CTD sections of this region [e.g., *Rossby*, 1996] and suggests the presence of Labrador Current water which, after retroflecting and turning northward, flows off the Grand Banks and joins the NAC pathway. However, *Krauss and Käse* [1984] suggest that there are two Gulf Stream fronts at 50°W, separated meridionally by a couple hundred kilometers, and they suggest that the southern front is composed of Gulf Stream water, while water in the northern front contains a mixture of Gulf Stream and slope water from the continental shelf.

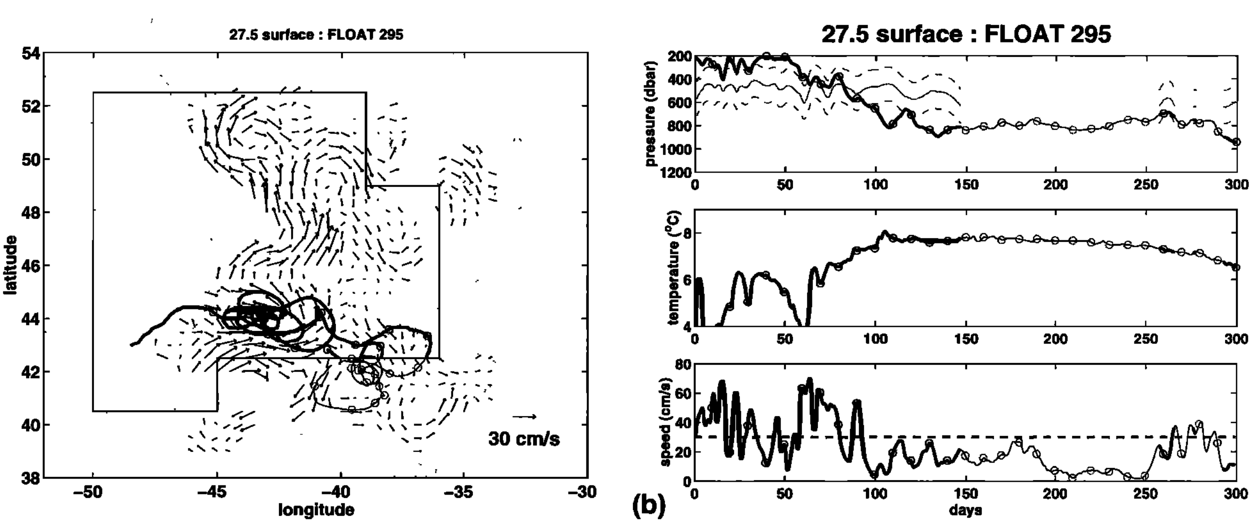

Figure 10. Float 295 (a) trajectory superimposed on mean velocity field, and (b) values of pressure (dbar), temperature (°C), and horizontal speed (cm s^{-1}). Circles are every 10 days. For the pressure record, $P(\theta)$ and $P(\theta) \pm s_f(\theta)$ are shown while the float is in the study region. For the speed record the threshold speed (v_1 = 30 cm s^{-1}) is indicated. Float data are denoted by a thick line (within the study region) or a thin line (out of the study region). Dotted lines in Figure 10a indicate the 200-, 1000-, and 4000-m isobaths.

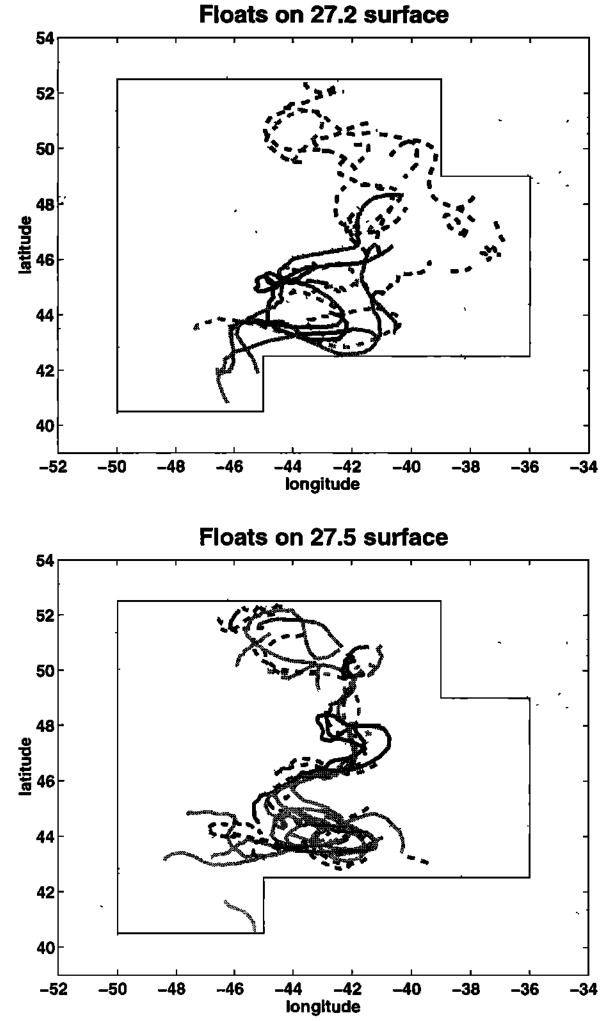

Figure 11. Trajectories of floats with pressures in the frontal zone as defined in section 3, for the (a) $27.2\sigma_t$ surface and (b) $27.5\sigma_t$ surface. Light shaded trajectories indicate floats that enter the frontal zone from the subpolar side; solid trajectories indicate floats that enter from the subtropical side. Dashed lines indicate that the float left the frontal zone to the side of the front that it entered from; dark shaded lines indicate that the float crossed from one side to the other. Dotted lines indicate the 200-, 1000-, and 4000-m isobaths.

We now examine the float data with regard to our two sets of definitions based on (1) float pressure related to the analyzed range of pressures which describe the dynamical front associated with the NAC and (2) float horizontal speed referenced to various (arbitrary) threshold speeds. The observations are composed of floats that remain for 2 days in a specific speed or pressure region. This requires that at least five data points show similar values, thereby reducing the problem of noise and/or small-scale turbulence.

4.1. Referenced to Pressure

For the floats in the study domain we have 6940 pressure data points for the $27.2\sigma_t$ surface and 7864 points for the $27.5\sigma_t$ surface (Table 1). The largest portion of these, 51% for the upper surface and 68% for the lower surface, are pressure values on the subtropical side, $P_{\text{float}} > P_f(\theta) + s_f(\theta)$. Only a small amount of the float data, 11% for the upper surface and 8% for the lower surface, are clearly on the subpolar side of the front; the remaining data fall in the frontal zone.

Table 2. Statistics for RAFOS Floats Defined as in Frontal Zone

	$27.2\sigma_t$ Surface	$27.5\sigma_t$ Surface
Number of portions of trajectories that enter and leave the frontal zone	38	39
Time in frontal zone, days		
Mean	9	15
Median	5	9
Number of floats that enter from subpolar side		
Leave on subtropical	6	12
Leave on subpolar	11	6
Number of floats that enter from subtropical side		
Leave on subpolar	1	5
Leave on subtropical	20	16

For the purpose of considering the likely fate of floats that enter this frontal zone, we consider only those portions of float trajectories that entered and exited the frontal zone while in the domain of study. The trajectories (38 for $27.2\sigma_t$ and 39 for $27.5\sigma_t$), and some statistics for these cases, are shown in Figure 11 and Table 2. The histogram in Figure 12 shows the length of time (>2 days) that floats remain with pressures between $P_f(\theta) - s_f(\theta)$ and $P_f(\theta) + s_f(\theta)$. Floats on the lower surface appear to spend longer in the dynamical front (mean of 15 days and median of 9 days) than floats on the upper surface (mean of 9 days and median of 5 days). However, this may be biased, since floats on the upper surface move faster and may leave the domain more frequently before exiting the frontal zone.

On the $27.2\sigma_t$ surface, 17 of these trajectory portions started on the subpolar side of the front and 21 started on the subtropical side (light and dark lines, respectively, in Figure 11a). Of those entering from the subpolar side, ~35% cross the dynamical front and leave the frontal zone on the subtropical

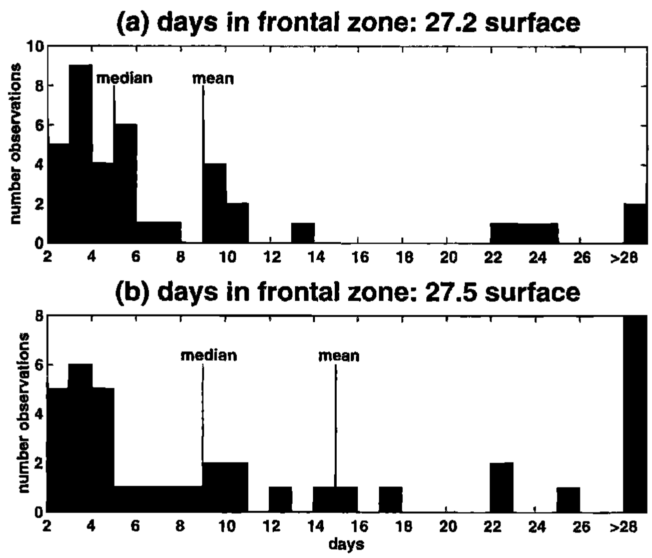

Figure 12. Histogram of length of time floats stay in the frontal zone, as defined in section 3, for the (a) $27.2\sigma_t$ surface and (b) $27.5\sigma_t$ surface. Mean and median number of days in the frontal zone are indicated.

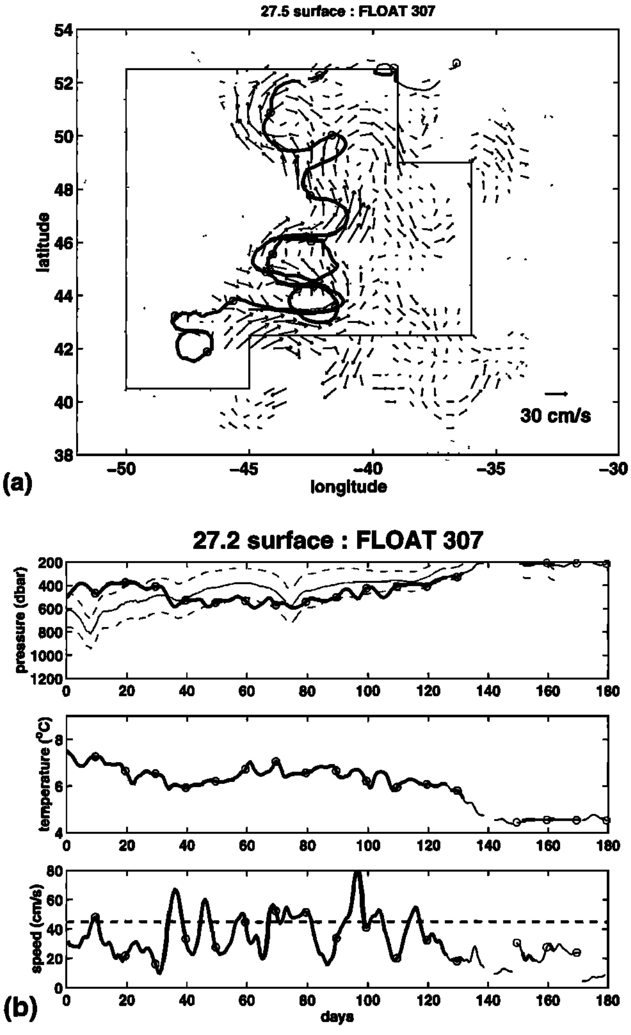

Figure 13. Float 307 (a) trajectory superimposed on mean velocity field and (b) values of pressure (dbar), temperature (°C), and horizontal speed (cm s^{-1}). Circles are every 10 days. For the pressure record, $P(\theta)$ and $P(\theta) \pm s_f(\theta)$ (dashed and dotted lines, respectively) are shown while the float is in the study region. For the speed record the threshold speed (v_1 = 30 cm s^{-1}) is indicated. Float data are denoted by a thick line (within the study region) and a thin line (out of the study region). Dotted lines in Figure 13b indicate the 200-, 1000-, and 4000-m isobaths.

side (solid lines in Figure 11), denoting the exchange of mass from one gyre to the other. The remaining floats entering from the subpolar side return to the subpolar side after some time spent in the dynamical front (dashed lines in Figure 11). Of those that start on the subtropical side, only 1 (5%) crosses to the subpolar side; the remainder are expelled again to the subtropical region. There is therefore an asymmetry in the exchange of mass between the two gyres. This is also true of the $27.5\sigma_t$ surface (Figure 11b), where 66% of the floats cross from the subpolar to the subtropical gyre after entering the dynamical front and only 23% cross from the subtropical to the subpolar side.

On both surfaces, exchange occurring within the 44°N trough appears to be predominantly mass exchange (solid lines in Figure 11), which suggests a mean mass flux from the subpolar to subtropical gyre. Floats that are involved in mass

Table 3. Statistics for RAFOS Floats With Reference to Three Threshold Speeds ($v_{\text{threshold}}$)

	$27.2\sigma_t$ Surface	$27.5\sigma_t$ Surface
Number of data in study domain	7101	7944
Number of Float Data Greater Than $v_{threshold}$		
$v > v_1$	3448 (49%)	2000 (25%)
$v > v_2$	1674 (23%)	593 (7%)
$v > v_3$	685 (10%)	123 (2%)
Number of Days in Jet		
Average time $> v_1$	7	7
Average time $> v_2$	6	4
Average time $> v_3$	4	4
Median time $> v_1$	6	6
Median time $> v_2$	5	4
Median time $> v_3$	3	3

exchange tend to spend longer in the frontal zone and lose/gain more heat along their trajectory than those that cross into the frontal zone and exit again on the same side. Floats on the lower surface gain or lose 0.5°C as they cross between gyres. Farther north, and especially on the $27.2\sigma_t$ surface, floats that enter the frontal zone tend to exit again to their original gyre. However, these floats still lose/gain heat during their exposure in the frontal zone: ~0.3°C for subpolar floats and about −0.05°C for subtropical floats. Such behavior, discussed further in section 4.2, will lead to property exchange along the jet.

4.2. Referenced to Speed

We found that many floats spend significant time with a pressure indicative of the frontal zone. For instance, float 307 (Figure 13), launched in subpolar water at 43°N, passes into the frontal zone at day 20 and remains within it for most of the time it is in the region of study. While the float is within the frontal zone, several excursions in pressure are associated with temperature changes. For instance, the float has a pressure decrease of ~50 dbar at day 100 with a corresponding temperature increase. At the same time, the float shows several excursions between faster and slower moving water (Figure 13b, bottom). Such particles in the frontal zone will tend to mix properties as they travel back and forth across the front, with subsequent losses from the jet on either side transporting these properties into different regions. In a numerical model study [*Dutkiewicz*, 1997] this mechanism was also found to be important in the mixing of tracer between two gyres, provided that a corresponding property front was present. We note that this type of exchange is the same process as the "dissipative meandering" discussed by *Lozier and Riser* [1990] in the context of a quasi-geostrophic midlatitude jet.

To estimate the amount of such an eddy exchange of properties that occurs due to meandering within the frontal zone, we now examine the position of the floats with respect to fast and slow moving regions. We consider three arbitrary threshold speeds and show the results in Table 3. We find that 49%, 23%, and 10% of the float data on the $27.2\sigma_t$ surface are above the three threshold speeds (30, 45, and 60 cm s^{-1}). The lower layer has slower moving water with 25%, 7%, and 2% of the data being above these three speeds. Floats remain in the fast moving regions for only a few days on average (see Table 3).

In Figure 14 the trajectories of these excursions into fast

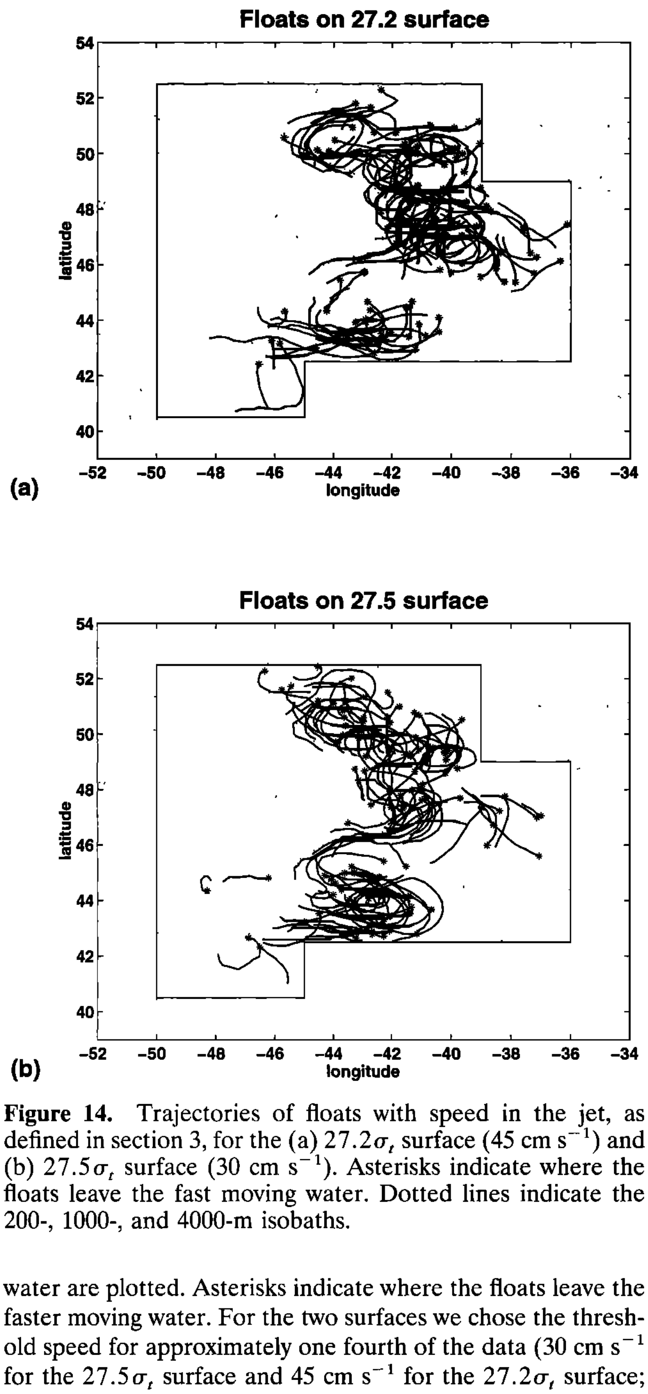

Figure 14. Trajectories of floats with speed in the jet, as defined in section 3, for the (a) $27.2\sigma_t$ surface (45 cm s^{-1}) and (b) $27.5\sigma_t$ surface (30 cm s^{-1}). Asterisks indicate where the floats leave the fast moving water. Dotted lines indicate the 200-, 1000-, and 4000-m isobaths.

water are plotted. Asterisks indicate where the floats leave the faster moving water. For the two surfaces we chose the threshold speed for approximately one fourth of the data (30 cm s^{-1} for the $27.5\sigma_t$ surface and 45 cm s^{-1} for the $27.2\sigma_t$ surface; see Table 3). Expulsion of floats from the jet generally occurs to the east when approaching troughs and to the west when approaching crests; however, losses appear mostly to the offshore side of the current; that is, into the subtropical gyre. The losses to the east at the 44°N and 47°N troughs correspond with the branching of the NAC suggested by *Arhan* [1990]. Those floats lost onshore of the current are frequently caught in the recirculations associated with the troughs (e.g., 44°N and 47°N) and later become reentrained in the jet. The Northwest Corner is also a region of considerable expulsions from and entrainments into the jet.

5. Discussion and Summary

Parcels of water that cross the entire frontal zone not only exchange properties but move mass from one side of the front to the other. The float observations suggest that in the Newfoundland Basin, there is movement of subpolar water mass into the subtropical region but very little mass flux in the opposite direction. The preferred site for floats to cross the dynamic front is the 44°N trough and, to a lesser extent, the 47°N trough and the Northwest Corner. Floats on the $27.5\sigma_t$ surface lose or gain ~0.5°C as they cross between gyres. Floats on the upper surface also appear to lose/gain heat during the crossing, although with significantly smaller amplitudes. The lack of a tight structure to the NAC makes it difficult (i.e., beyond the scope of this paper) to calculate more definite cross-frontal property exchange values.

Additional observations show that floats often enter the frontal region and after some time return to their original gyre. Such behavior is more likely to occur north of the 44°N trough and especially in the Northwest Corner. Since these floats diffuse their properties in the frontal zone and are frequently lost to slower moving surrounding water, properties will be exchanged between the two sides of the jet. Floats within the jet, and thus possibly involved in this "property exchange" within the frontal zone, are lost from the fast moving jet into the recirculation regions associated with the meander extrema to the east from the 44°N and 47°N troughs and to the west from the retroflection in the Northwest Corner. This mechanism of exchanging properties is mechanistically the same as the dissipative meandering discussed by *Lozier and Riser* [1990] as the main mechanism for the exchange of potential vorticity between gyres in a quasi-geostrophic model. *Dutkiewicz* [1997] demonstrated that when the property and dynamic fronts are in close proximity, this type of exchange has a significant impact on the flux of tracer. In the NAC this diffusive mechanism is important for the flux of subtropical properties into the subpolar regions, especially in the northern part of the study domain where the temperature and dynamical fronts appear closer together (see Figures 3 and 4). "Mass exchange" in the 44°N trough may, however, dominate the flux of subpolar properties into the subtropical water.

Subpolar properties lost to the subtropical zone through both mass and property exchange are diffused into the waters of the Newfoundland Basin by the slow eastward moving region of water found to the east of the NAC. This accounts for the mixed properties of the water as found by various authors [e.g., *Arhan*, 1990; *Kearns*, 1996]. In contrast, properties lost to the subpolar side will not mix over as wide an area. We found that many of the floats lost to the jet on the subpolar side would be reentrained into the jet. An exception is the water lost from the Northwest Corner that moves away from the region to the north and west within eddies. Therefore along much of the length of the NAC the subtropical side of the jet has more diffuse properties, and the subpolar side maintains high property gradients.

This study has considered the cross-frontal exchange that occurs along the length of the NAC. Although the amount of "mass" exchange is small compared to the transport of the NAC, there is a net mean flux from the subpolar gyre to the subtropical gyre. This appears to be caused by the more temporarily changing nature of the meanders on the east side of the jet (as can be noted in the eddy kinetic energy, Figures 3c and 4c). Hopefully, future studies of the current systems in the far North Atlantic and Labrador Sea will be able to address the open question of where and when this asymmetric flux is compensated by a net flux in the opposite direction. The most common cause of intergyre exchange of properties, however, appears to be eddy cross-frontal exchange in the form of water parcels moving into and out of the NAC.

The NAC is a unique current system in that it brings waters of such different properties into contact with one another. Exchange of these properties across the front will have an effect on the properties of the surrounding waters, especially to the east of the current, and therefore will potentially have an impact on the gyre-scale dynamics [*Lozier and Riser*, 1990; *Dutkiewicz*, 1997]. With such strong differences in temperature and salinity this mixing will potentially be responsible for inducing density changes through cabbeling processes. The cross-frontal exchange of properties will also cause the property gradients along the NAC to become weaker, especially on the subtropical side, when the current turns eastward as the Subpolar Front and crosses the Mid-Atlantic Ridge.

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