Spreading Pathways of Labrador Sea Water from the Subpolar North Atlantic: A Lagrangian Perspective

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1. Introduction

Profiling float studies in the 1990s showed virtually no evidence of Labrador Sea Water (LSW) being exported from the subpolar North Atlantic by the Deep Western Boundary Current (DWBC). To determine if these results were biased by the periodic surfacing of the floats, a new Lagrangian experiment was conducted using acoustically tracked RAFOS floats. During 2003-2006, RAFOS floats were sequentially released in groups of six every three months in the DWBC at 50°N and tracked for two years (Fig. 1). The floats were released at several positions across the continental slope at 700 and 1500 m, spanning the width of the tracer- and velocity-based indicators of the DWBC at this latitude (Fig. 2).

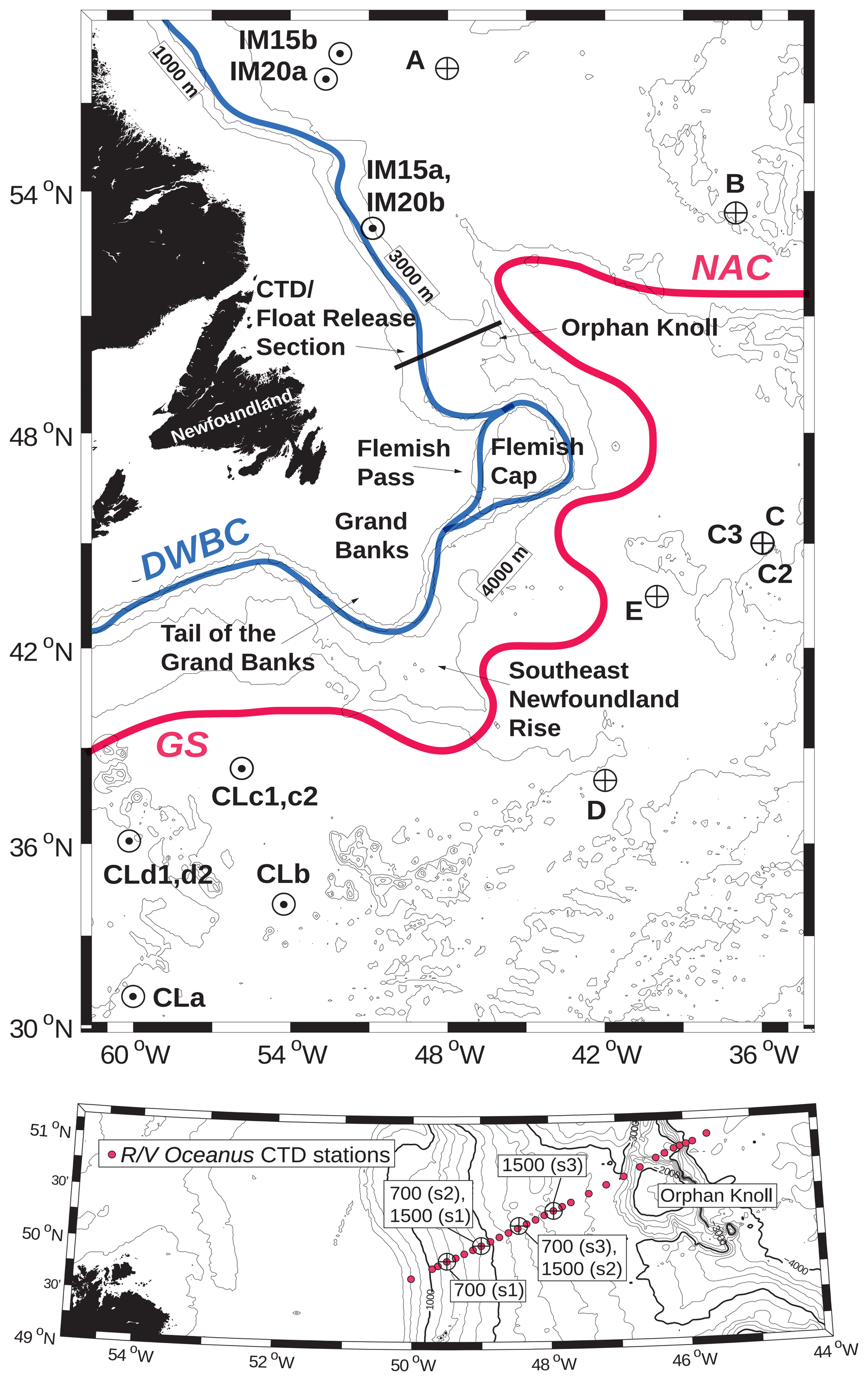

Figure 1.
RAFOS float release site at 50°N and major currents around the Grand Banks.

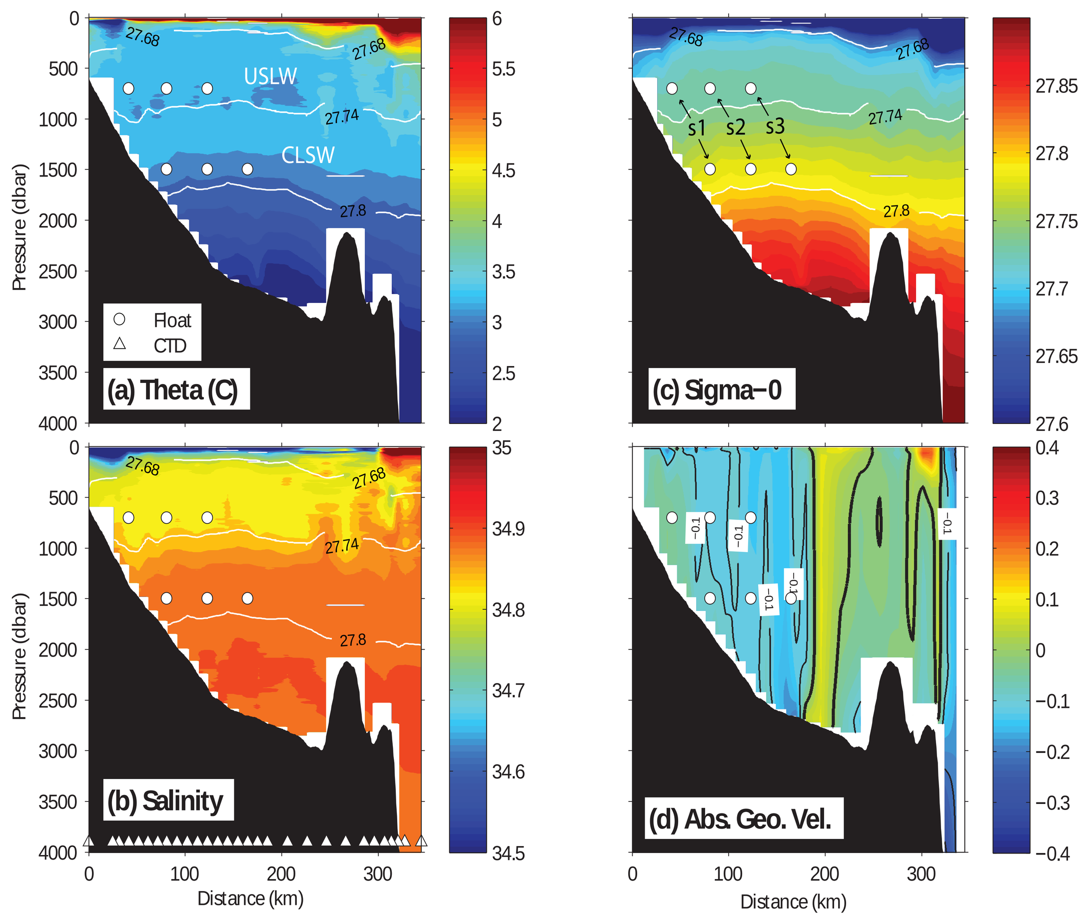

Figure 2.
Cross-sections of temperature, salinity, density and along-isobath speed at the RAFOS float release site in July 2003. Selected isopycnals show layer boundaries of Upper and Classical LSW. Open circles are float release positions.

2. LSW Export Pathways: RAFOS and FLAME

Most (~70%) of the RAFOS floats left the slope and drifted eastward east of the Grand Banks, the same pathway taken by nearly all the profiling floats (Fig. 3a-b). The relatively cold temperatures measured by these floats indicate that they were mainly recirculating within the subpolar gyre (Fig. 3a). Unlike the profiling floats, a few RAFOS (<10%) followed the DWBC continuously around the Grand Banks. A larger percentage (~17%) followed an interior pathway from the southern tip of the Grand Banks into the subtropical interior (Fig. 3b), as reported by Bower et al. (2009) based on a subset of the RAFOS float data set. This suggests that the interior pathway may be at least as, if not more, important than the DWBC pathway for the export of LSW to the subtropical region. The RAFOS export statistics are summarized in Fig. 4a).

The RAFOS float trajectories were compared to 100 ensembles of simulated floats computed using the high-resolution general circulation model FLAME (Family of Linked Atlantic Modeling Experiments). Each ensemble had the same number of floats as the RAFOS group and the same distribution in depth and release site. The trajectories and displacement vectors (Fig. 3c, d) are qualitatively similar in most respects. The export statistics for all 100 ensembles (with standard deviations; Fig. 4b) show slightly less export to the subtropics via any pathway (22±5% for FLAME versus 29% for RAFOS) and substantially less exported to the subtropical interior (7±3% for FLAME versus 17% for RAFOS). The FLAME numbers do not change much between "isobaric" (2D) and "isopycnal" (3D) simulated trajectories. Rather the differences may result from the eddy kinetic energy distribution in the model (not shown).

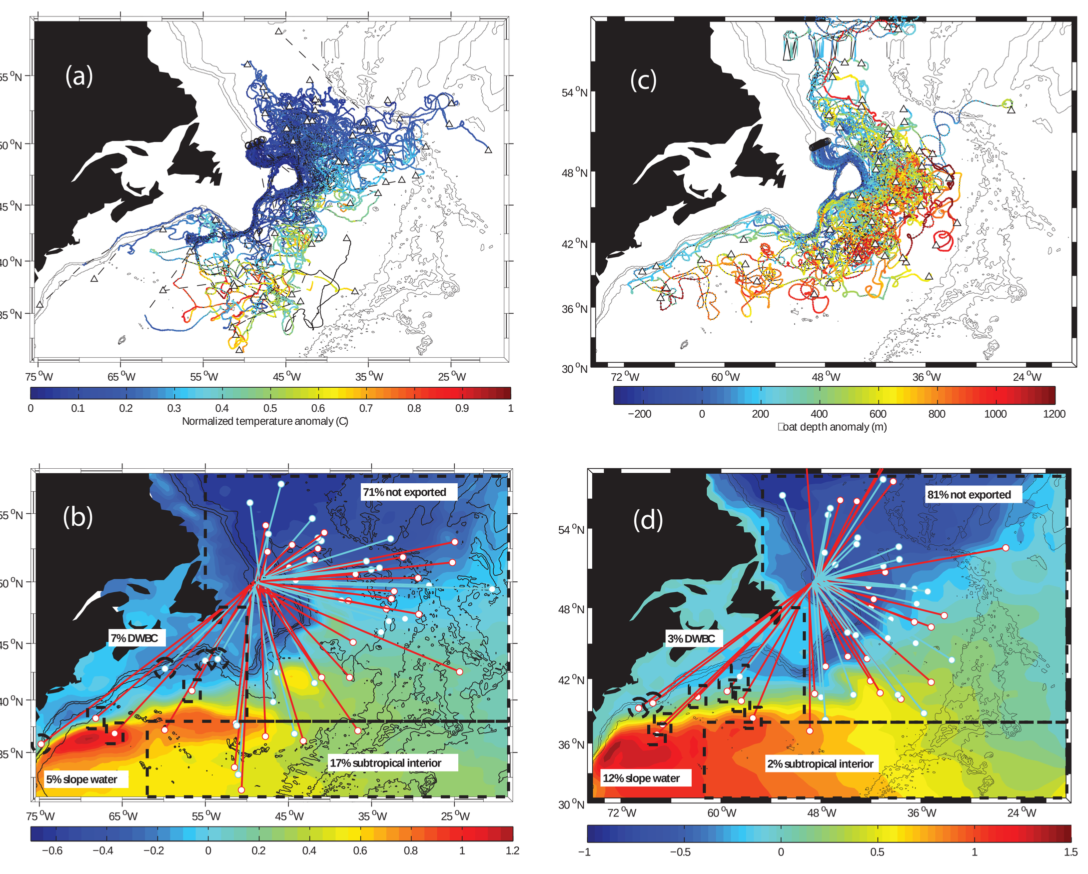

Figure 3.
(a) Trajectories and two-year displacement vectors (superimposed on mean dynamic topography MDT09 from AVISO) for all RAFOS floats. Colored dots indicate normalized temperature anomaly (blue = cold, red = warm). (b) Color vectors indicate float depth (cyan = 1500 m, red = 700 m). Dashed black lines mark regions where floats were found after two years: 'not exported', 'boundary current', 'slope water' and 'subtropical interior'. (c) Same as for RAFOS but for one ensemble of randomly selected simulated "e-floats" from FLAME. Colored dots indicate float depth (blue = shallow, red = deep) and (d) colored vectors indicate initial float depth (cyan = 1500 m, red = 700 m) where floats were found after two years: 'not exported', 'boundary current', 'slope water' and 'subtropical interior'.

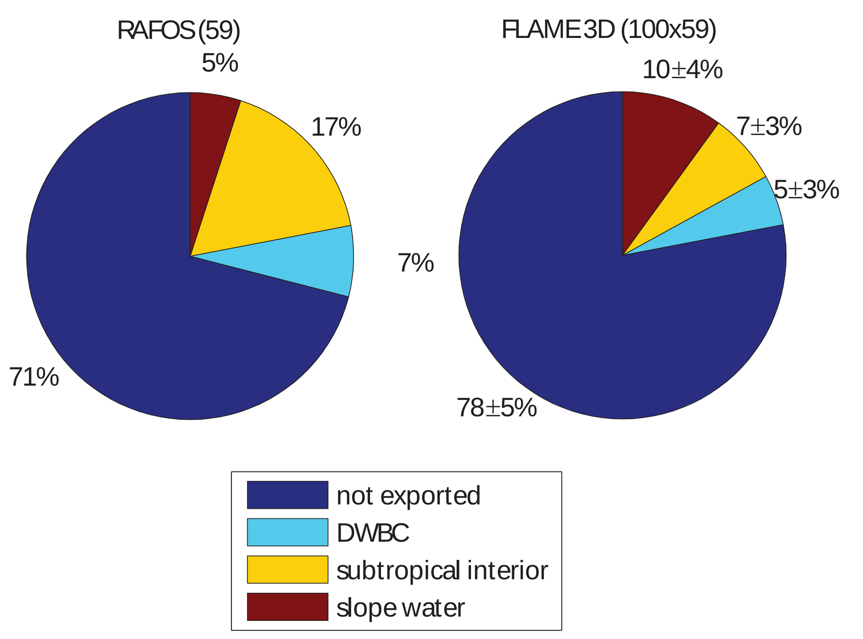

Figure 4.
Summary export statistics for 59 RAFOS floats (left panel) and 100 ensembles of 59 e-floats from FLAME (right panel). In both cases, a large majority of floats (>70%) were recirculated within the subpolar region (not exported) and a small percentage (<10%) followed the DWBC path continuously around the Grand Banks. The model appears to underestimate the pathway to the subtropical interior (yellow) observed with the RAFOS floats.

Reference:
Bower, A. S., M. S. Lozier, S. F. Gary, and C. W. Boening, 2009. Interior Pathways of the North Atlantic meridional overturning circulation. Nature, 459(14), doi:10.1038/nature07979.
Getzlaff, K., Boening, C. W. & Dengg, J., 2006. Lagrangian perspectives of deep water export from the subpolar North Atlantic. Geophys. Res. Lett. 33, L21S08, doi:10.1029/2006GL026470.
Shaw, P.-T., and H. T. Rossby, 1984. Toward a Lagrangian Description of the Gulf Stream. Journal of Physical Oceanography, 14(3):528-540.

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3. Does it Matter that the RAFOS Floats were Isobaric: FLAME

A previous modeling study (Getzlaff et al., 2006) suggested that isobaric floats were less likely to remain trapped in the DWBC around the southern tip of the Grand Banks compared to isopycnal floats. This study used a mean velocity field from one model year of FLAME. A similar analysis conducted using the *time-dependent* model velocity fields (Fig. 5 and Table 1) shows much less LSW exported around the Grand Banks, emphasizing the importance of the eddy field in LSW spreading pathways. There is also little difference between 3D and 2D (Table 1). This is likely because LSW spreads into the interior mainly by eddies that affect most of the intermediate water column, in which case isobaric and isopycnal floats will behave similarly (see next panel).

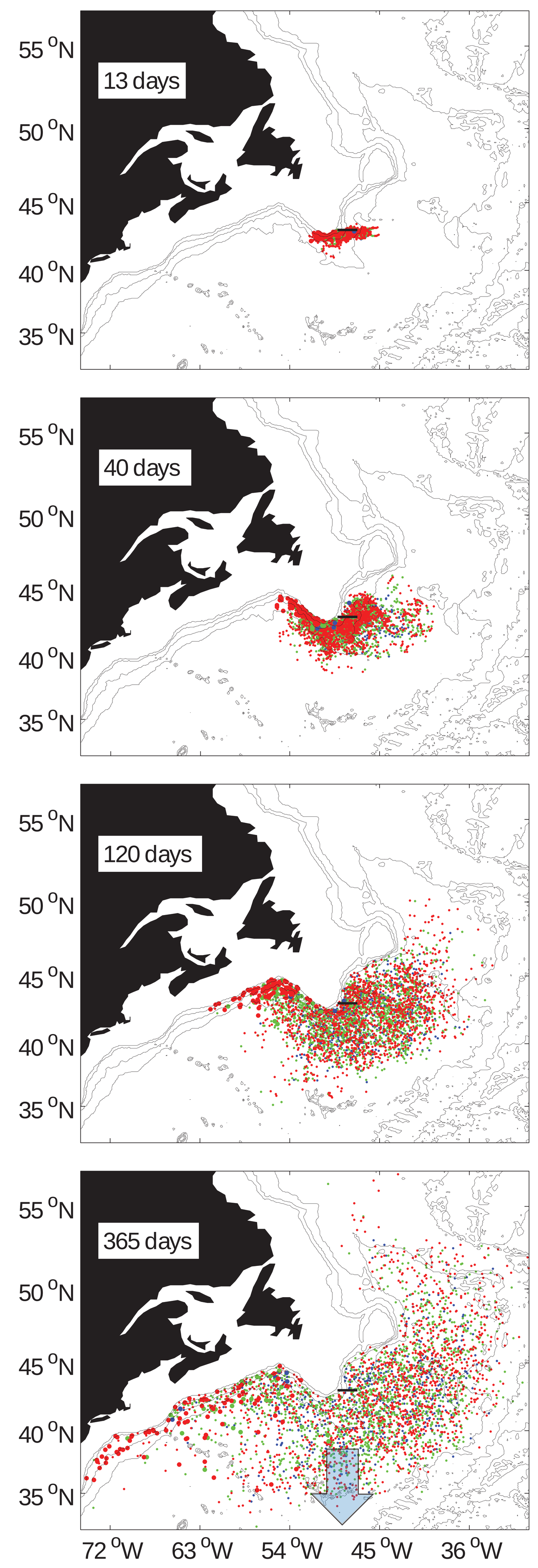

Figure 5.
Time sequence of positions of ~3000 e-float released in the DWBC at 43N in the depth range 700-2000 m, computed using the 3D time-dependent FLAME model velocity fields from 1994-1998. Colors indicate initial e-float depth (red = 700-1000 m; green = 1000-1500 m; blue = 1500-2000 m) and large dots indicate floats which reach 55W by following the DWBC continuously around the TGB. Results are almost identical for 2D case (see Table 1) so not shown here.

Model velocity field used	3D	2D
Time-mean (Getzlaff et al. 2006)	58%	41%
Time-dependent	3%	5%

Table 1.
Percentages of simulated floats which follow the DWBC continuously around the southern tip of the Grand Banks when the time-mean versus time-dependent model velocity fields are used.

4. Does it Matter that the RAFOS were Isobaric: RAFOS

Comparison of the RAFOS float trajectories with maps of absolute dynamic topography from AVISO (Fig. 6) illustrates the potential importance of eddy processes near the southern tip of the Grand Banks in the export of LSW into the interior. Float #582 and two others were entrained into a coherent anticyclonic eddy that appeared to form at the TGB. The eddy had a rotation period of 4-5 days and the floats looped at a radius of about 25 km. The eddy drifted westward in the Slope Water for three months before it was absorbed into the Gulf Stream. Float #582 eventually crossed the Stream and ended up in the subtropical interior. Importantly, the float's temperature (Fig. 7) remained nearly constant during the eddy formation and propagation, indicating little vertical motion (Shaw and Rossby, 1984) and that isopycnal and isobaric drifters would have behaved similarly.

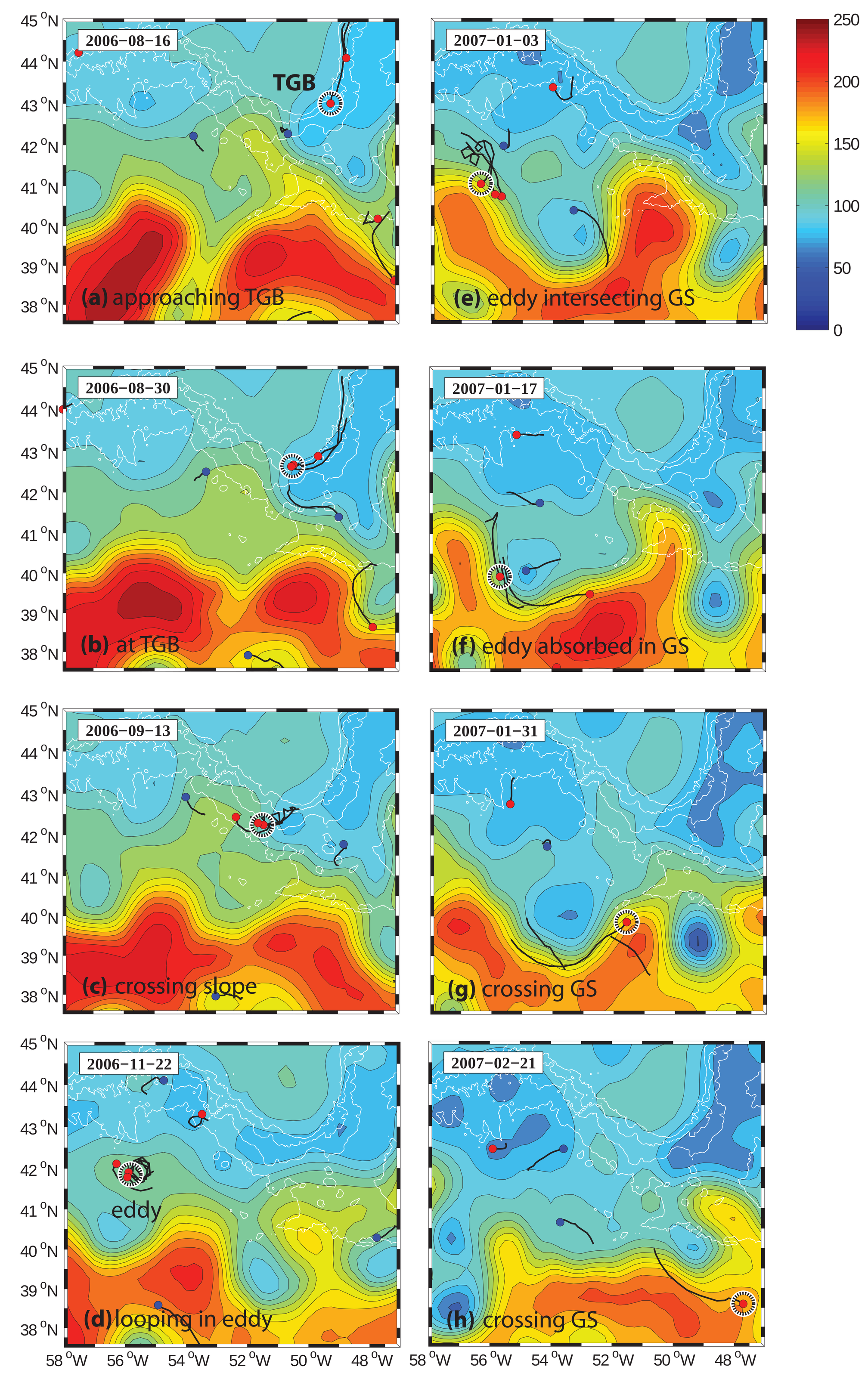

Figure 6.
Sequence of float trajectories and absolute dynamic topography showing the formation of an anticyclonic eddy of LSW forming at the TGB. Note that time interval between images is not constant. Float #582 is highlighted. The eddy is accompanied by a local high in dynamic topography, although the high is not always closed.

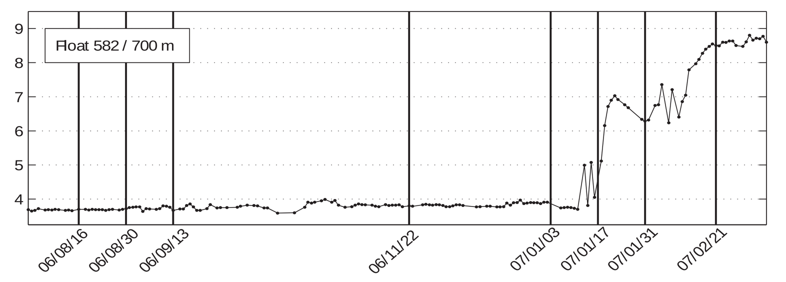

Figure 7.
Temperature for Float #582 showing nearly constant temperature during the eddy formation and westward drift. Vertical lines indicate times corresponding to the panels in Fig. 6.

Conclusions:

- Only 30% of the LSW in the DWBC at 50°N is exported to the subtropical region in two years, and <10% follows the DWBC continuously around the Grand Banks.
- More LSW reaches the subtropical region in two years via an interior pathway from the southern tip of the Grand Banks.
- Comparison with the Lagrangian behavior in FLAME shows similar trends, although the model underestimates the export to the subtropical interior, possibly due to an underestimate of eddy kinetic energy south of the Grand Banks.
- The interior pathway does not appear to be an artifact of the isobaric nature of the RAFOS floats, but rather a real phenomenon related to the high eddy kinetic energy near the southern tip of the Grand Banks.