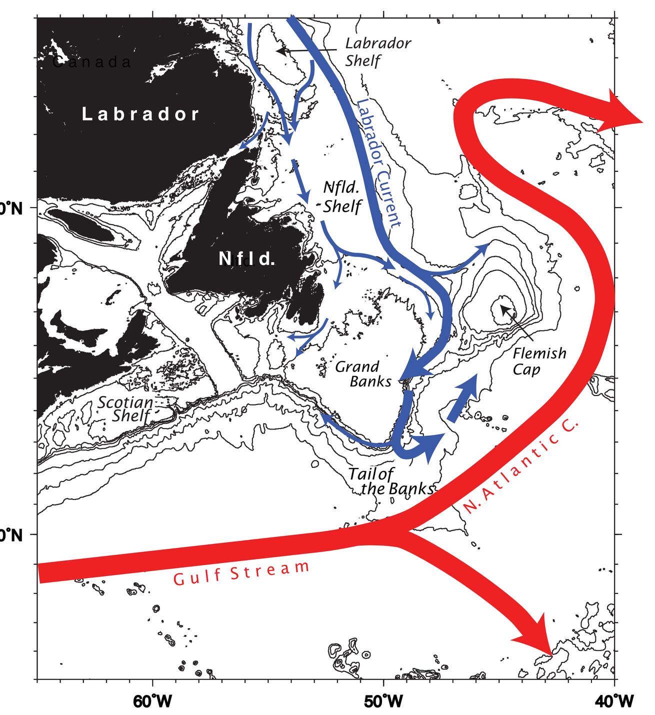
# Freshwater Export from the Labrador Current to the North Atlantic Current at the Tail of the Grand Banks of Newfoundland

Paula Fratantoni and Michael McCartney

Woods Hole Oceanographic Institution, Woods Hole, MA 02540 (pfratantoni@whoi.edu)

## Introduction

The Labrador Current transports subpolar and Arctic-origin water equatorward along the boundary of the western North Atlantic. It is a component of a larger coastal current system that extends over thousands of kilometers, transporting high-latitude climate-driven variability equatorward. Because the current is associated with a strong thermohaline front, it is not clear exactly how and where these signals are communicated to the interior of the Atlantic where they might have an impact on the larger climate system. Recent studies suggest that there are select geographical regions along the path of the current where mass and freshwater are lost. The Grand Banks of Newfoundland appears to be one such location. Here, a portion of the current retroflects offshore, transporting a significant fraction of the coldest, freshest arctic-origin water into the interior. Understanding the behavior and dynamics of this current will enhance our ability to predict the impact of climate-driven variability far from the source. In this study, 100 years of historical hydrographic data have been used to describe the seasonal variations in the freshwater pathways along and across the shelf/slope boundary, paying particular attention to the current branching that occurs at the Tail of the Grand Banks of Newfoundland.

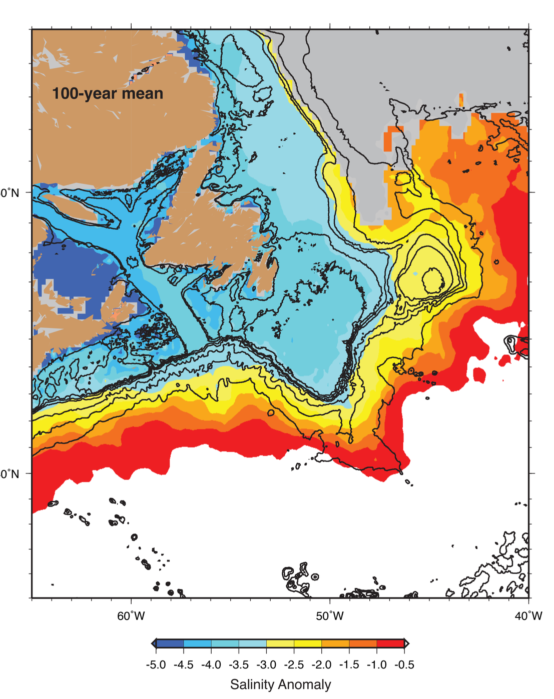



## A Seasonal Climatology

The climatological fields presented here were constructed using the quality-controlled station data and isopycnal averaging techniques from Hydrobase2 (Curry, 1996). The historical data includes CTD and bottle data from the World Ocean Database 2005, and profiling float data from ARGO.

### Approach

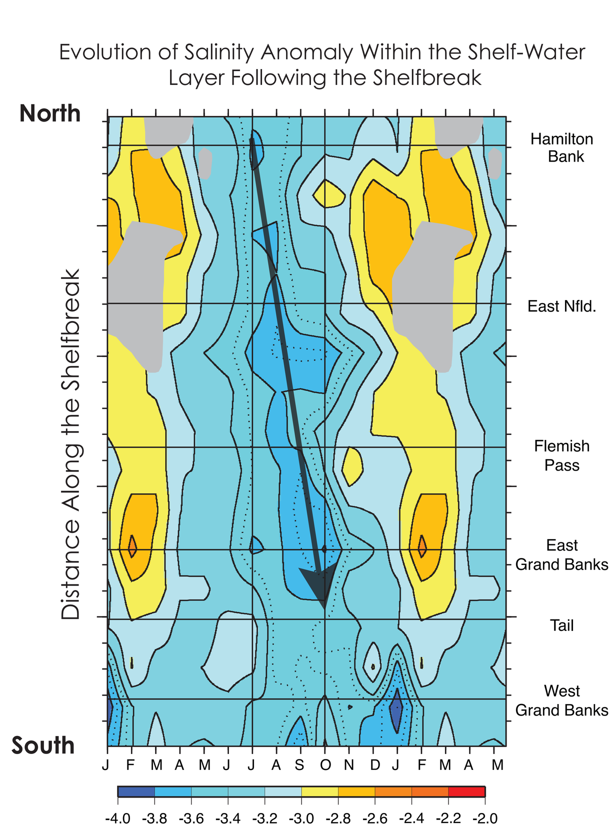
- Monthly data is spatially binned, isopycnally averaged and interpolated onto a standard grid with 20 km spacing.
- A salinity anomaly is calculated as a function of density at each grid point relative to a time-independent standard T-S curve constructed from observations in the Sargasso Sea (Armi & Bray, 1982). This allows us to distinguish the fresh shelf water mass from others in the region.
- The salinity anomaly is vertically averaged between the surface and the 26.80 isopycnal surface. The layer so-defined encompasses the shelf water volume that is found both up and downstream of the Tail of the Banks.




*left: Salinity anomaly within the shelf-water layer calculated from the 100-year mean salinity distribution in our climatology. The gray masking shows where the layer is outcropped.*

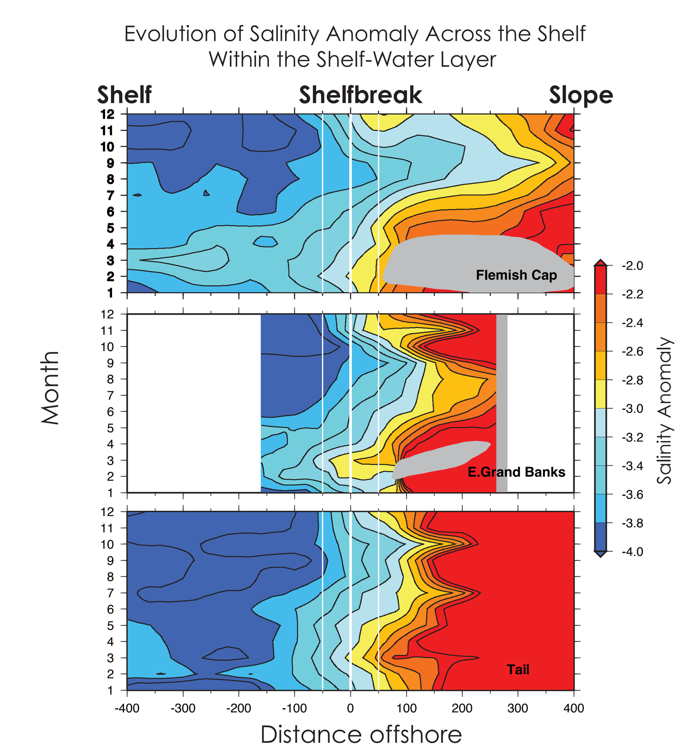
## Seasonal Variations in Freshwater

If the shelf/slope region is dominated by advection, we should be able to track the propagation of the seasonal freshwater pulse southward along the boundary in the monthly climatology. Following the shelfbreak from the Labrador Coast to the southwest side of the Grand Banks, the seasonal progression of the salinity anomaly in the shelf-water layer shows:




- An annual cycle is evident at all locations north of the Tail, with least fresh anomaly in late winter and most fresh in summer/fall.
- There is a 3-month lag between when the freshest water is observed along the Labrador Shelf and when it is observed east of the Grand Banks. This is consistent with an advection speed of 23 cm/s along the 1800 km distance. To first order, the signal is advective and not just a phased response to air-sea forcing.
- The water is fresher and persists for a longer period than at other locations on the Newfoundland Shelf north of Flemish Pass (Aug.-Oct.), and along the eastern flank of the Grand Banks south of Flemish Pass (Sep.-Nov.). It is most likely that a portion of this water has been advected by the inner-shelf branch of the Labrador Current.
- The temporal persistence of the minimum north of Flemish Pass is not observed downstream, suggesting that not all of the freshwater arriving at the shelfbreak to the north of Flemish Pass is advected south through the Pass. Instead, some of the freshwater leaves the boundary within a bifurcated path north of Flemish Cap. Due to persistent outcropping in the north, this is the first offshore pathway available to the current.
- Downstream of the Tail, the temporal pattern is not as smooth and the anomaly is not as fresh as it was east of the Banks.

*above: Monthly mean salinity anomaly averaged over the shelf-water layer within a 100 km swath following the shelfbreak from the Labrador Coast to the southwest side of the Grand Banks. The gray masking shows where the layer is outcropped.*

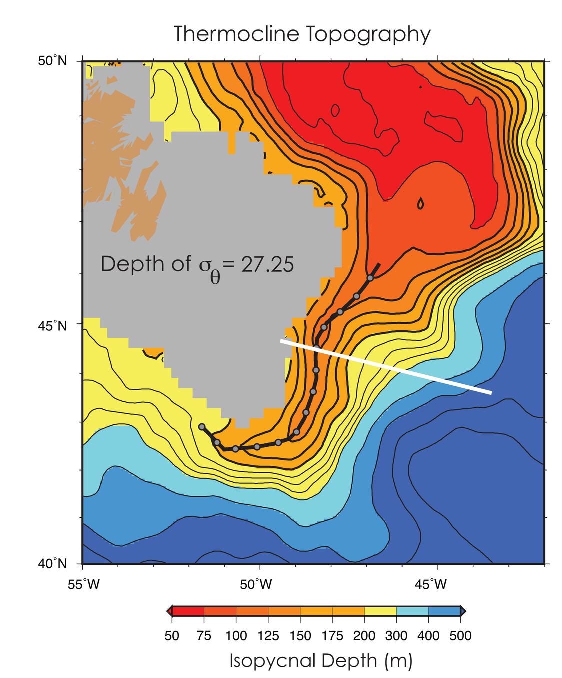



The clean propagation of the seasonal freshwater pulse along the shelfbreak appears to break down at the Tail of the Grand Banks. Is this because a majority of this freshwater has been advected offshore by the retroflecting Labrador Current?

- The freshwater following the bifurcation north of Flemish Pass penetrates well-offshore, encompassing the region around Flemish Cap when the layer is not outcropped.
- The fresh water penetrates onto the slope on a seasonal timescale in the region south of Flemish Pass where we expect that the retroflected pulse would influence offshore salinities.
- While there is a single seasonal salinity minimum at the shelfbreak, multiple minima appear in the offshore region downstream of Flemish Pass, suggesting that more is going on than simple advection of the freshwater pulse along the retroflection pathway.
- The offshore freshening happens in phase from north to south. The freshest water arrives on the boundary and is very shortly observed offshore at both locations south of Flemish Pass.
- Low salinity water persists offshore for roughly the same period everywhere south of Flemish Pass (June–October).

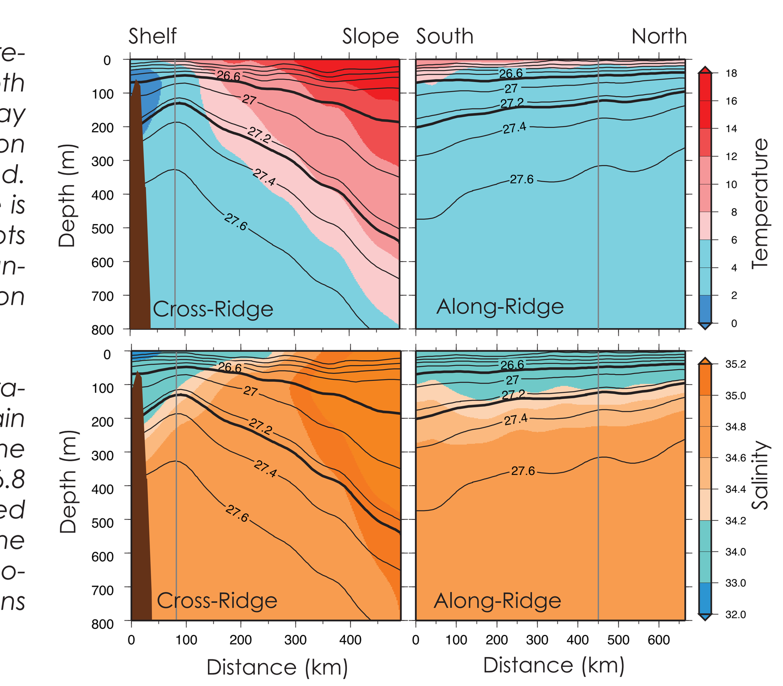
*above: Monthly mean salinity anomaly averaged over the shelf-water layer across the shelf and slope at Flemish Cap (top), across the eastern flank of the Grand Banks (middle), and at the Tail of the Grand Banks (bottom). The gray masking shows where the layer is outcropped.*

## The Retroflection Geometry

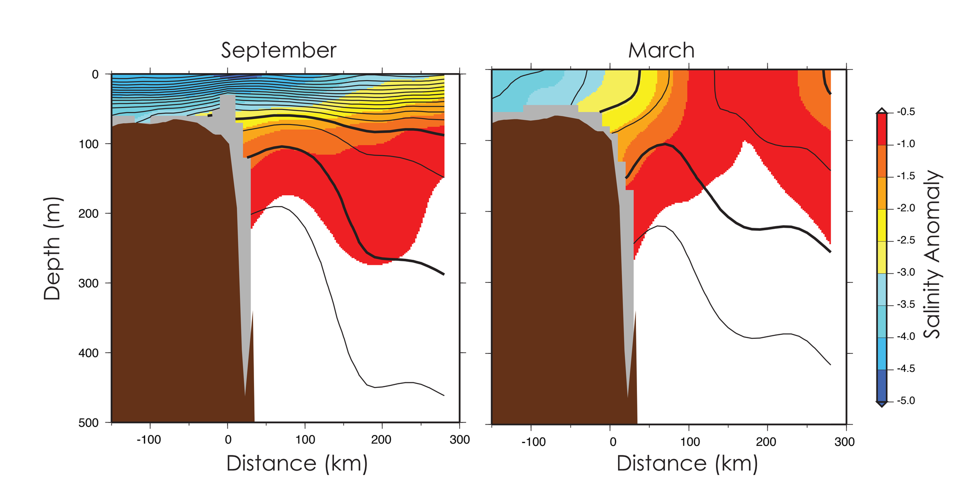



*left: Thermocline topography represented by the 100-year mean depth of the 27.25 isopycnal. The gray masked region represents the region where this isopycnal is grounded. The crest of the thermocline ridge is traced by the black line with dots placed every 50 km along the transect, and a cross ridge crest section is traced by the white line.*

*right: Vertical sections of temperature and salinity with density overlain across (left) and along (right) the thermocline ridge crest. The 26.8 and 27.25 isopycnals are depicted by the heavy contours showing the shelf-water layer and the thermocline marker used left. The sections intersect at the vertical gray line.*



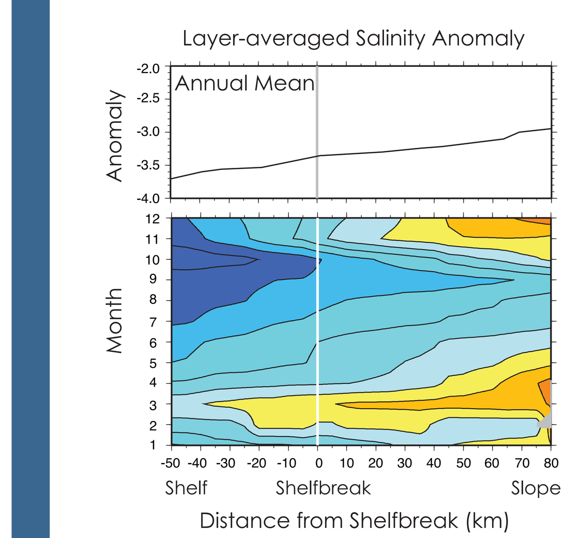

The thermocline forms a ridge that roughly parallels the shelf between Flemish Cap and the Tail of the Grand Banks. Because this pattern is representative of the density structure in the water column above this depth, the configuration suggests southward flow along the boundary, retroflecting offshore at the Tail of the Grand Banks and returning within the northward flow regime. This is consistent with the ***traditional retroflection pathway*** that is typically depicted in circulation cartoons of this region. However, there is also a north-south tilt to the thermocline ridge structure, with the surface shoaling toward the north indicative of offshore geostrophic shear. This suggests that a second geostrophic export pathway exists whereby the flow is directed offshore across the full length of the thermocline ridge crest between Flemish Cap and the Tail of the Grand Banks (***cross-ridge retroflection pathway***). The distribution of temperature and salinity across the ridge shows the dramatic property front that exists between the cold, fresh polar-origin water flowing south and the warm, salty subtropical water flowing north. The mean salinity distribution in both sections shows that fresh water is located over the ridge crest suggesting that freshwater is being advected from the southward to the northward flow regime.




*top: Mean vertical sections of salinity anomaly with density overlain across the thermocline ridge crest for September and March. The 26.8 and 27.25 isopycnals are depicted by the heavy contours showing the shelf-water layer and the thermocline marker used above.*

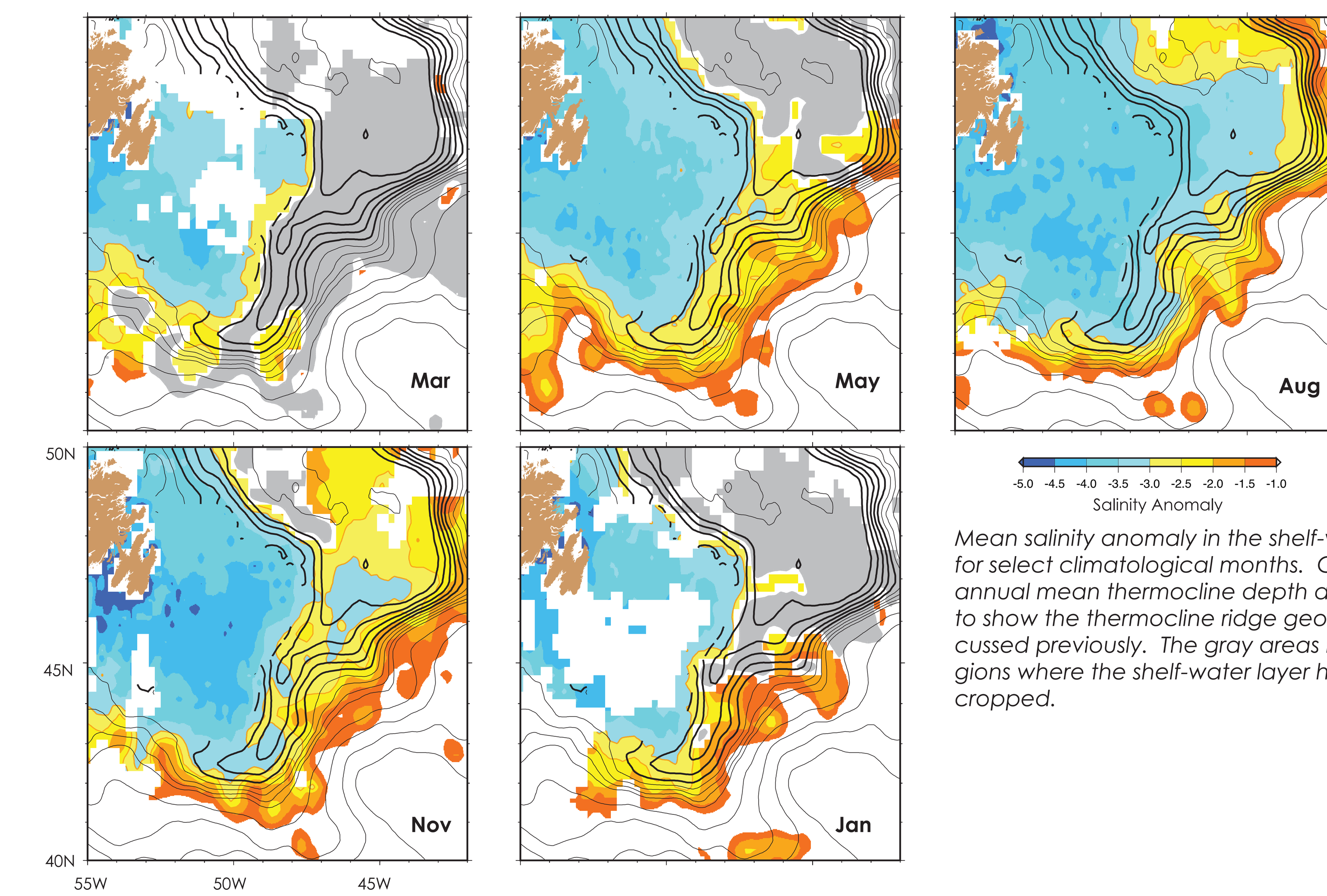
Seasonally the structure of the thermocline ridge is robust. However, seasonal cooling dramatically alters the density distribution in the shelf-water layer, setting the properties of the water available for export along geostrophic pathways. Winter cooling and convection during fall removes buoyancy from the shelf-water layer and the stratification begins to break down. The lightest isopycnals outcrop first, cutting off the cross-ridge advection pathways for the freshest near-surface water along these surfaces. Within a few months, the entire shelf water layer is completely outcropped over the thermocline ridge crest and the freshwater in the boundary current is trapped at the shelfbreak. The convection process is most effective over the thermocline ridge where there is a much weaker buoyancy cap, resulting in a totally outcropped layer.

## Freshwater Export




The freshness of water geostrophically exported from the Labrador Current is primarily controlled by the flushing of the seasonal freshwater pulse, derived from run-off and ice melt, through the boundary current system. The freshwater pulse is advected quickly southward by the current and this is evident in the abrupt seasonal transitions in the salinity across the boundary current. The freshness is further modulated by seasonal surface buoyancy forcing over the region. During late fall, winter cooling begins and ice formation and evaporation act to quickly remove buoyancy from the shelf and contribute to the salinification of the water column. The effects on the salt content of the shelf-water layer are enhanced because the cooling takes place at a time when the seasonal freshwater run-off is reduced, leaving the boundary current with a saltier source.

*left: (top) annual mean salinity anomaly averaged over the shelf-water layer within the Labrador Current immediately south of Flemish Pass (note the zoomed distance axis). (bottom) monthly mean salinity anomaly averaged over the shelf-water layer within the Labrador Current immediately south of Flemish Pass.*




*Mean salinity anomaly in the shelf-water layer for select climatological months. Contours of annual mean thermocline depth are overlain to show the thermocline ridge geometry discussed previously. The gray areas mask regions where the shelf-water layer has outcropped.*

Selected maps of monthly mean salinity anomaly illustrate the seasonal evolution of freshwater relative to the retroflection geometry south of Flemish Cap. In **March**, the freshwater boundary is retracted well inshore of the southward flow regime and the shelf-water layer is outcropped along the full length of the thermocline ridge. In the following months the outcropping region retracts northward along the thermocline ridge and the freshwater boundary begins to move offshore into the southward shear at the shelfbreak. By **May**, we see evidence for freshwater advection across the thermocline ridge as plumes of freshwater (yellow) extend across the ridge in three locations. Very fresh water (blue) now encompasses the region of southward shear along the northern thermocline ridge. By **August**, plumes of this very fresh water now extend across the ridge into the region of northward shear. In **November**, winter cooling begins to erode the stratification in the shelf-water layer, particularly in the north, and the cross-ridge pathway is blocked for all but the densest (saltiest) portion of the layer. Because this process begins in the north, the time-lagged arrival of the seasonal freshwater pulse at the Tail of the Grand Banks survives and is visible as a fresh tongue following the traditional retroflection pathway. By **January**, the outcropping region has begun to creep southward along the axis of the thermocline ridge, cutting off all of the cross-ridge advection pathways within the shelf-water layer.

## Summary

Our 100-year climatology suggests that, while cold/fresh northern-source waters are advected offshore within the retroflecting Labrador Current at the Tail of the Grand Banks, this is not the only (and perhaps not even the dominant) export pathway for these waters to reach the interior North Atlantic. Thermocline topography suggests that freshwater is advected offshore along the full length of the boundary between Flemish Cap and the Tail of the Banks. This dynamical evidence is supported by salinity anomaly maps that show the time-lagged arrival of fresh shelf water at the boundary, followed by its appearance offshore along the multiple retroflection pathways. Several factors combine to produce the patterns of freshwater distribution that we have observed across the retroflection region south of Flemish Cap: (1) the arrival and flushing-rate of the seasonal freshwater pulse, originating as run-off and ice-melt, sets the boundary condition for freshwater export, and (2) seasonal buoyancy forcing at the surface alters the vertical stratification, modulates the freshness of the water in the boundary current, and seasonally restricts certain export pathways. Although we have not shown it here, there is direct evidence in synoptic bottle data that the fresh retroflected Labrador Current water returns north as an identifiable component of the western North Atlantic Current.

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