Submesoscale streamers exchange water on the north wall of the Gulf Stream

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Key Points.

Lateral detrainment clearly observed from North Wall at depth. Salt flux similar to bulk estimates. Detrained water is from a defined partially mixed water class.

The Gulf Stream is a major conduit of warm surface water from the tropics to the subpolar North Atlantic. Large mesoscale ($> \mathbf{20}$ km) "rings" often pinch off, but like the Gulf Stream they are resistant to lateral mixing and retain their properties for a long time. Here we observe and simulate a sub-mesoscale ($< \mathbf{20}$ km) mechanism by which the Gulf Stream exchanges water with the cold subpolar water to the north. The front exhibits a strong temperature-salinity contrast, with a distinct front composed of "mixed" water between the two water masses that is between 2 and 4 km wide. This mixed water is not seen to increase downstream despite there being substantial energy available for mixing. A series of "streamers" detrain some of this water from the Gulf Stream at crest of meanders. Subpolar water is entrained replacing the mixed water, and helping to resharpen the front. The water mass exchange can account for a northwards flux of salt of $0.8{-}5$ psu m^{2}s^{-1}, which can be cast as an effective local diffusivity of $O(100\ \mathrm{m^2s^{-1}})$. This is similar to bulk-scale flux estimates of 1.2 psu m^{2}s^{-1} and supplies fresh water to the Gulf Stream required for the production of 18-degree subtropical mode water.

1. Introduction

The Gulf Stream (GS) is the western boundary current of the North Atlantic subtropical wind-driven circulation. It separates from Cape Hatteras where it flows eastward into the North Atlantic. As it flows, it loses heat to the atmosphere and by mixing with the cold water in the subpolar gyre to the north. It also becomes fresher, an observation that can only be explained by entrainment of fresh water from the north [*Joyce et al.*, 2013]. As it entrains water, the GS increases its eastward transport by approximately $4 - 8 \times 10^6 \mathrm{m^3 s^{-1}}/100$ km (*Johns et al.* [1995]).

The GS has a sharp density front, but it also has a sharp temperature and salinity front, as has been demonstrated at the surface from shipboard surveys [*Ford et al.*, 1952] and satellite images [*Churchill et al.*, 1989]. The sharpness of the front beneath the surface has been less-clear, and requires high-resolution lateral sampling to resolve. The front has a sharp potential vorticity gradient [*Rajamony et al.*, 2001], and such gradients act as a barrier to lateral mixing [*Marshall et al.*, 2006; *Naveira Garabato et al.*, 2011]. Despite this barrier, property budgets indicate that there is significant exchange across the north wall [*Joyce et al.*, 2013], and that entrainment of fresh water is necessary to create the dynamically important "18-degree water" that fills much of the upper Sargasso Sea.

The mechanisms controlling this lateral mixing have not been identified. There are large eddies that periodically pinch off the GS and carry warm water to the north. However, some of these are re-entrained into the GS and do not result in a net exchange. Instead, tracer budgets across the front appear to be dominated by small, submesoscale processes [*Bower et al.*, 1985]. To date some of the best direct evidence for cross-front exchange consists of the trajectories of density-following floats placed at the north wall [*Bower and Rossby*, 1989; *Bower and Lozier*, 1994]. These floats were observed to regularly detrain from the GS, such that of 95 floats, 26 stayed in the GS, 7 were detrained in rings, and 62 were detrained by mechanisms other than rings [*Bower and Lozier*, 1994]. Kinematic theories have been examined to explain the detrainment of the floats [*Flierl et al.*, 1987; *Stern*, 1985; *Pratt et al.*, 1995], and the similarity to satellite images of "streamers" of warm water detraining from the Gulf Stream has been noted. However, direct observations of the processes as it occurs at depth have been lacking.

Here we present indirect evidence that there is small-scale mixing (<0.5 km) on the northern cyclonic side of the GS, and that the mixed water periodically peels off the GS in thin (5-10 km wide) "streamers". We describe our experiment, and the observations that it yielded before briefly discussing the implications.

2. Methods

In March 2012 we made high-resolution measurements of the north wall of the GS from 66 W to 60 W (figure 1), about 850 km east of where the GS separates from the North American continental slope. A Lagrangian float [*D'Asaro*, 2003] was placed in the Gulf Stream front based on a brief cross-stream survey, and programmed to match the density of the surface mixed layer (upper 30 m). The float moved downstream at a mean speed of 1.4 $\mathrm{m\,s^{-1}}$. The *R/V Knorr* tracked the float and deployed a Chelsea Instruments TriAxus that collected temperature, salinity, and pressure (CTD) on a 200-m deep sawtooth with approximately 1-km lateral spacing in a 10-km box-shaped pattern relative to the float (figure 1, magenta). *R/V Atlantis* performed larger cross sections approximately 30 km across the front, trying to intercept the float on each front crossing. *R/V Atlantis* was deploying a Rolls Royce Marine Moving Vessel Profiler equipped with a CTD that profiled to 200 m approximately every 1 km. Both ships had a 300 kHz RDI Acoustic Doppler Current Profiler (ADCP) collecting currents on 2-m vertical scale averaged every 5 minutes (approximately 1 km lateral scale), collected and processed using UHDAS and CODAS (http://currents.soest.hawaii.edu *Firing et al.* [2012]). Velocities are put into a float-following frame as a proxy for along- and across-front, with u being defined as along the floats path, and v as perpendicular to the path and to the north. Velocity data at 2-m vertical resolution reached about 130 m, and was supplemented at deeper depths with data from 75 kHz RDI ADCPs, with 8-m vertical resolution.

At select times during the float evolutions, fluorescein dye releases (100 kg per release) were conducted at depth as close as possible to the float. Dye was pumped down a hose to a tow package deployed off the side of the ship, consisting of a CTD and a dye diffuser. Prior to injection, the dye was mixed with alcohol and ambient sea water to bring it to within 0.001 kgm^{-}3 of the float's target density. Initial dimensions of the dye streak were $\approx$1 km along-stream, $\approx$100 m cross-stream (after wake adjustment), and ranging from 1 - 5 m in the vertical. The TriAxus system on the *R/V Knorr* tracked the fluorescein from its CTD package.

Numerical simulations of the GS were performed with the Regional Oceanic Modeling System [ROMS *Shchepetkin and McWilliams*, 2005]. The simulation has a horizontal resolution of 500m and 50 vertical levels. The model domain spans 1,000 km by 800 km and covers a region of the GS downstream from its separation from the U.S. continental slope. Boundary conditions are supplied by a sequence of two lower-resolution simulations that span the entire GS region and the Atlantic basin, respectively. The simulation is forced by daily winds and diurnally modulated surface fluxes. The modelling approach is described in detail in *Gula et al.* [2015].

Neutrally buoyant Lagrangian (flow-following) particles were seeded into the model at a time $t0$ and advected both backwards and forwards from this time by the model velocity fields without additional dispersion from the model's mixing processes [*Gula et al.*, 2014]. A 4th-order Runge-Kutta method with a time step $dt = 1$ s is used to compute particle advection. Velocity and tracer fields are interpolated at the positions of the particles using cubic spline interpolation in both the horizontal and vertical directions. We use hourly outputs from the simulation to get sufficiently frequent and temporally-smooth velocity sampling for accurate parcel advection.

3. Observations

During these observations, the GS had a shallow meander crest at 65 W (figure 1b) followed by a long concave region (63 W) and then another large crest (61 W). Satellite measurements show the sharp temperature changes across the front, superimposed with thin intermediate-temperature (15-18^{o}C) streamers detraining to the north at approximately 65 W, 64 W, and at the crest of the large meander at 61 W. An older streamer that has rolled up can also be seen at 62 W. The ships passed through the three newer streamers providing a detailed observation of their underwater structure.

The front consists of density surfaces that slope up towards the north (figure 2a-d). The water along density surfaces is saltier (and warmer) in the GS, and fresher (and colder) to the north. The transition between the two water masses is remarkably abrupt, occurring over less than 5-km. This sharpness persisted from the western-most section during the cruise (71.5 W) to the eastern-most (60.5 W). Some cross sections show lateral interleaving of salinity north of the front (figure 2a) with approximately 5-km wide salinity anomalies ($S \approx 36.15$ psu). These anomalies move slower than the front (figure 2e), and have high potential vorticity that is normally associated with the front (figure 2i).

The temperature-salinity (T/S) relationship of this data shows the contrast between the GS and the subpolar water as two distinct modes (figure 3a, labeled "North" and "Gulf Stream"), except near the surface where the water masses are strongly affected by the atmosphere. For the deeper water, there is a third distinct population between the two larger modes in T/S space that represents the water in the salinity anomalies, and we have labelled as "streamers". The distinctness in T/S space of the streamers indicates that after the GS and subpolar waters mixed, the partially mixed water continued to mix, condensing it in T/S space so that it forms an almost-separate water mass.

Looking at the GS in plan view along the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ isopycnal (figure 3b) we see the mixed water that that makes up the streamers is connected along the length of our observations. The first streamer (64.5 W) is horizontally connected over 100 km, and is about 5 km wide, and at least 150 m deep. Where the streamer is the most detached (figure 2a) the main front is the sharpest of the 4 cross sections. Downstream of this streamer, the mixed water thins before the eastern meander (60.5 W) where there is a second streamer. Further downstream, the mixed water almost disappears by the last cross-section (59 W).

We can estimate the rate of detrainment from the first streamer (64.5 W). It starts on the fast side of the front with water flowing approximately 0.25 $\mathrm{m\,s^{-1}}$ faster than the float (figure 2h). Upstream, where it is detached (figure 2e), it is flowing almost 0.5 $\mathrm{m\,s^{-1}}$ slower than the float. A 5-km wide and 150-m deep streamer, with a relative velocity of 0.75 $\mathrm{m\,s^{-1}}$ represents a rate of detrainment of over $0.5 \times 10^6\,\mathrm{m^3\,s^{-1}}$.

The streamers move up through the water column along isopycnals and the water parcels are stretched vertically. The streamer in figure 2a has risen along isopycnals from 140 m deep (figure 2d) to less than 40 m deep, and titled somewhat as it has done so. The velocity anomaly is about 0.75 $\mathrm{m\,s^{-1}}$ over 100 km so we estimate that the streamer is approximately 1.5 days old, implying vertical velocities of order 50 m/day, similar to rates inferred from large-scale omega-equation calculations *Thomas and Joyce* [2010].

Concurrently, there is a bolus of fresh water from the north that is enfolded between the streamers and the GS that we will call an "intrusion". This entrained water is part of the strong shear on the North Wall, so the amount of entrainment is harder to quantify than the detrainment from these observations.

A different survey (14 Mar) included a dye release in water that was subsequently entrained between the wall and a streamer (figure 4a-c). The dye was injected near the surface at the North Wall, centered at approximately 50 m depth on the 26.0 $\mathrm{kg\,m^{-3}}$ isopycnal in the fresh water. A subsequent pass 43 km downstream shows that the dye has been enfolded in a streamer (figure 4b). In T/S space, this water is in the "surface" water class (figure 4c). The streamer did become deeper, down to 100 m, and deterained further from the front than shown here.

4. Simulations

High-resolution numerical simulations ($dx \approx 500m$, see methods) resolve these features and also confirm the entrainment of the fresh intrusion (figure 4d-i). Seeding the simulation with Lagrangian particles (see methods) allows us to track the evolution of the streamers and the intrusion as the flow moves downstream. Before the streamer is formed, the water in the intrusion (magenta contours) is near the surface and the streamer water (green contours) is well within the front (figure 4d,g). Downstream (figure 4e,h) the fresh water has been subducted to 150 m depth, and the streamer has been pushed north of the front. Both water masses accelerate with the GS (figure 4f), but the fresh intrusion accelerates more, such that the intrusion is entrained and the streamer slows and is detrained. As in the observations, the streamer occupies an intermediate region in T-S space (figure 4i, green contour), and originates in the high-vorticity region of the front. The acceleration of the fresh intrusion relative to the streamer is an important finding of the model, as the fresh water now forms a new sharp T-S front with the warm salty GS, and the mixed streamer water is carried away from the front. The model further shows that the streamers are more prominent on the leading edges of meanders, also clearly seen in satellite images (figure 1).

There are differences with the observations, however. The data show very distinct T-S signatures associated with the streamers, whereas the model streamer T/S "mode" is less isolated (figure 4i). The two interleaving water masses are confined to a narrow isopycnal band in the model, with the intrusion being slightly lighter than the streamer, whereas in the observations the temperature-salinity front cuts across more isopycnals (compare figure 2b to figure 4h). There is also clear evidence of strong subduction of the intrusion in the model, reminiscent of intrathermocline eddies *Thomas and Joyce* [2010].

5. Discussion

The distinct T/S mode on the density-compensated front of the Gulf Stream is a new finding to our knowledge, and enabled by our very high density of sampling. The implication of this water class is that mixing at the Gulf Stream front is relatively "complete" in that water trapped in an instability is trapped there for long enough that it is homogenized. Symmetric instability is believed to be quite "explosive" and this fluid may be indirect evidence for its role at the North Wall[*D'Asaro et al.*, 2011].

The streamers that detrain from the north wall have been seen in satellites and inferred from floats, however this is the first time they have been shown to penetrate so deep and to be composed primarily of the mixed class of water. The detrainment helps explain why the front at the north wall of the GS remains so sharp. That only the mixed water is carried away, and not high-salinity GS water (figure 3b) is a mystery. This implies a dynamical link that we have not seen explored. Streamers have been observed in surface temperature satellite images and indirectly by subsurface floats [*Bower and Rossby*, 1989; *Flierl et al.*, 1987; *Lozier et al.*, 1997; *Song et al.*, 1995], and this has led to kinematic models in which particles are displaced from streamlines going around propagating meanders [*Bower*, 1991; *Pratt et al.*, 1995; *Lozier et al.*, 1997]. The observations here add to these models by showing that it is only mixed water that leaves the GS. This co-incidence indicates to us a role for small-scale mixing in producing the destabilizing forces that cause this water to detrain from the north wall.

The streamers are a mechanism that can balance large-scale budgets that require significant exchange across the GS [*Joyce et al.*, 2013; *Bower et al.*, 1985]. Such budgets suggest that this region of the GS loses salinity to the north at a rate of 1.2 psu m^2s^{-1} [*Joyce et al.*, 2013]. Each streamer transports $0.2 - 0.5 \times 10^6$ m^3s^{-1} of water that is $0.8 - 1$ psu saltier than the water that is entrained. Streamers appear approximately every 100-300 km, associated with meanders, so an estimate of their average transport is $0.8 - 5$ psu m^2s^{-1}, bracketing the large-scale estimates. Working against a gradient of 1 psu/10 km over 200 m depth, the equivalent lateral diffusivity is $40 - 250$ m^2s^{-1}. Whether the streamers are the rate-limiting mechanism, as opposed to the small-scale turbulence at the wall, is unknown.

Here we have observed a submesoscale lateral stirring process along the north wall of the GS. The T/S front remains persistently sharp, despite small-scale mixing evident from the T/S diagrams, and due to a number of possible processes [*Thomas and Shakespeare*; *Whitt and Thomas*, 2013]. The mixed water mass does not accumulate, or it would weaken the sharpness of the front. Here we show that the streamers detrain mixed water, and entrain cold and fresh water toward the north wall, resharpening the temperature-salinity front. Further analysis of the data and models will shed light on the exact mechanism triggering the ejection of water from the front via the streamers.

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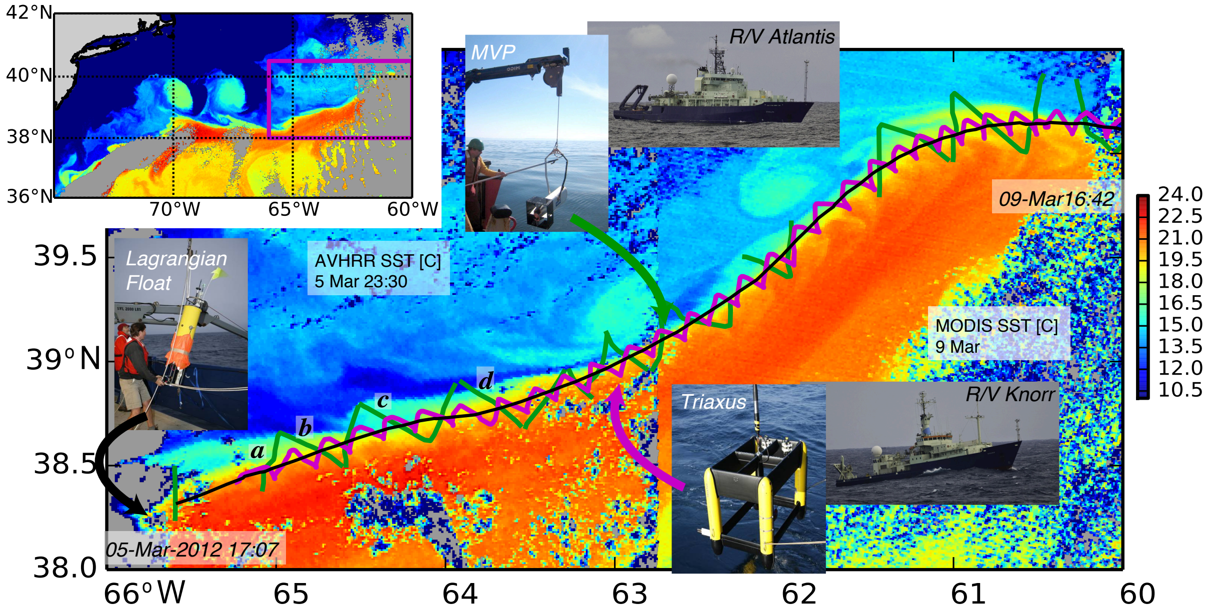

Figure 1: The experimental design Inset: The experiment site on the north wall of the Gulf Stream, between 66 and 60 W, as shown in an AVHRR satellite image of sea surface temperature (SST). Main: Detailed SST image composed from two satellite images. The GS is warm and delineated by a sharp front. The small sub-mesoscale structures north of the front are the focus of this paper. The satellite images are a composite from early in the observation period (AVHRR 6 Mar), and late (MODIS, 9 Mar). A Lagrangian float was deployed in the front (black curve), and the ship tracks bracketed the float's position (green: *R/V Atlantis*, magenta: *R/V Knorr*). *R/V Atlantis* cross-sections labeled a-d are shown in figure 2a-d.

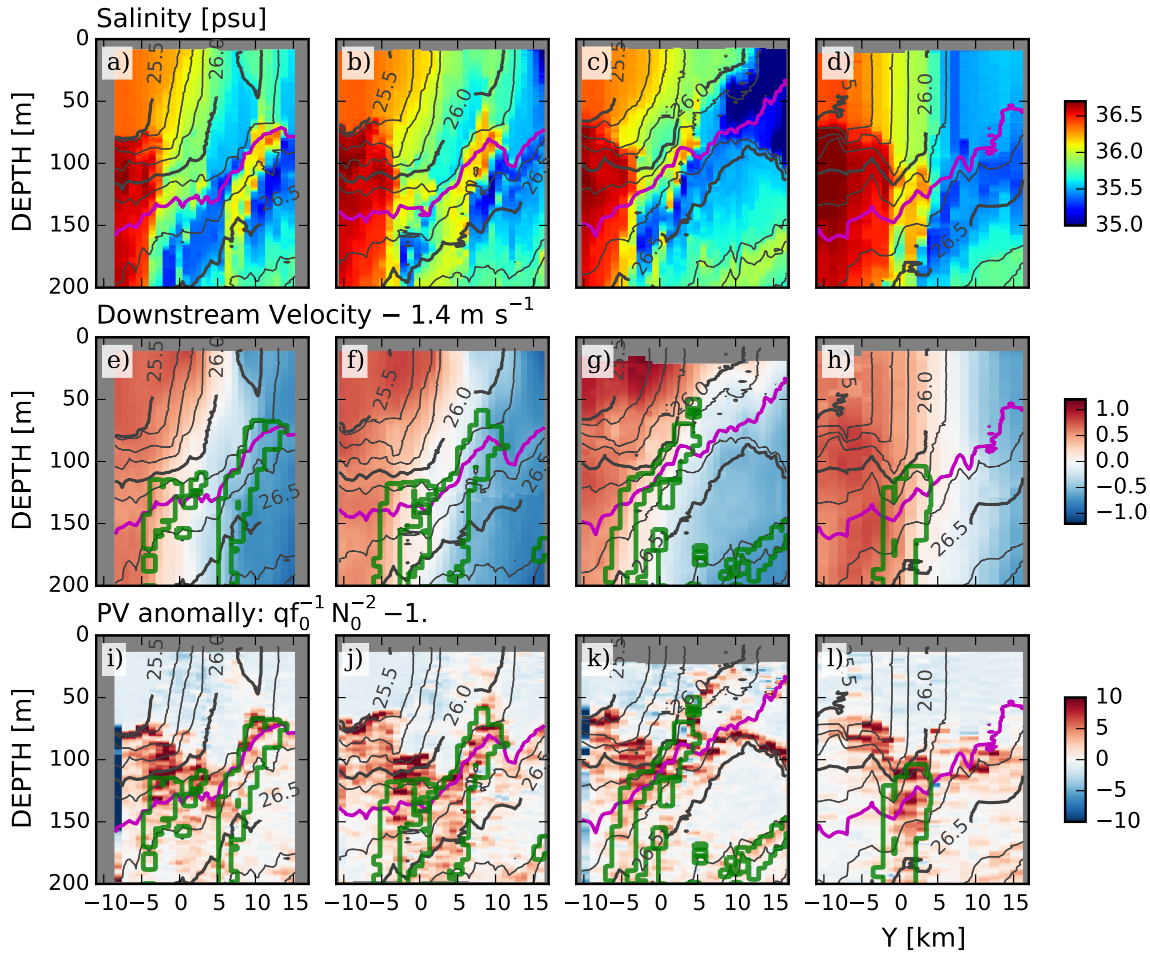

Figure 2: Cross sections of data collected across the Gulf Stream Y is the cross-stream distance perpendicular to the path of the float, positive being northwards. The four columns correspond to the four sections labeled a-d in figure 1. Potential density is contoured in black and $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ is magenta. Along a constant density surface salty water is warmer than fresher water, so the GS on the left is warm and salty. Section a) is the furthest upstream section (65W) and d) is the furthest downstream (63.75 W) (figure 3b). e)–h) downstream velocity calculated relative to the float's trajectory by removing the float's mean speed of $u_{float} = 1.4\ \mathrm{m\,s^{-1}}$ for the observation period. Green contours are regions in temperature-salinity space labeled "streamers" in figure 3a. i)–l) Potential vorticity (see methods);

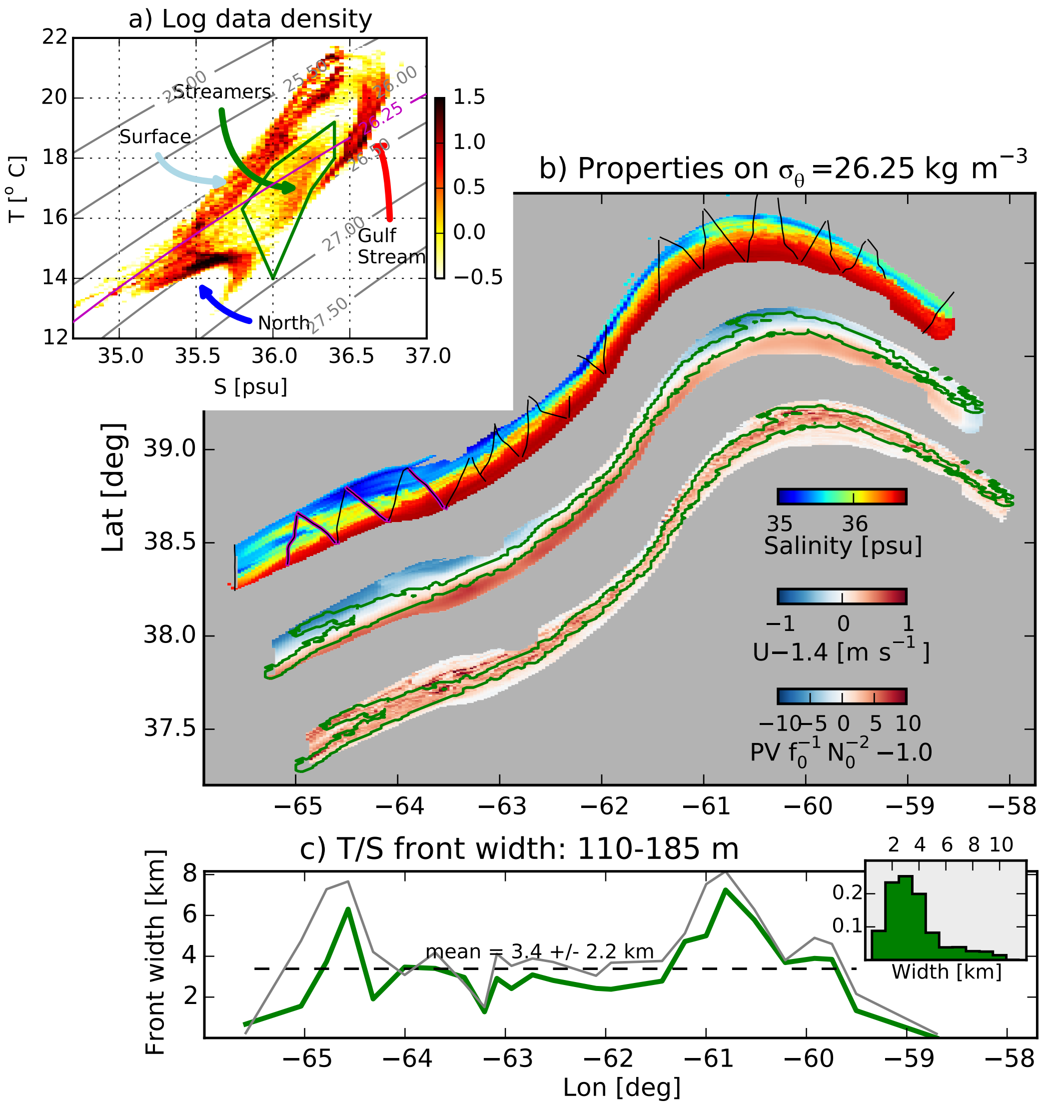

Figure 3: Streamer properties and distribution in space: a) Logarithmically scaled histogram in temperature-salinity space (colours). The warm-salty GS water is distinct from the water to the north, which is cold and fresh. The water near the surface is heavily modified by the atmosphere. Deeper, there is a class of water distinct from the GS water and the water to the north, that we label "streamers". This water is contoured in green in figure 2e-l. b) Interpolation of salinity, velocity, and potential vorticity onto the $\sigma_\theta = 26.25$ kg m^{-3} isopycnal, plotted geographically (with a small exaggeration of scale in the north-south direction, and the latter two fields offset slightly to the south-east). This used data from both ships. The ship track for the *Atlantis* is plotted in black, and the four cross-sections in figure 2 are plotted in magenta. The streamer water is contoured in green. c) The width of the T/S front attached to the north wall, averaged between 110 and 185 m (green line). The grey line is the width of all the water in the "streamer" T/S class. A water parcel is considered "attached" if there there is no more than one kilometer of water from the fresher water class to the north. This is meant to exclude the clearly detached streamers.

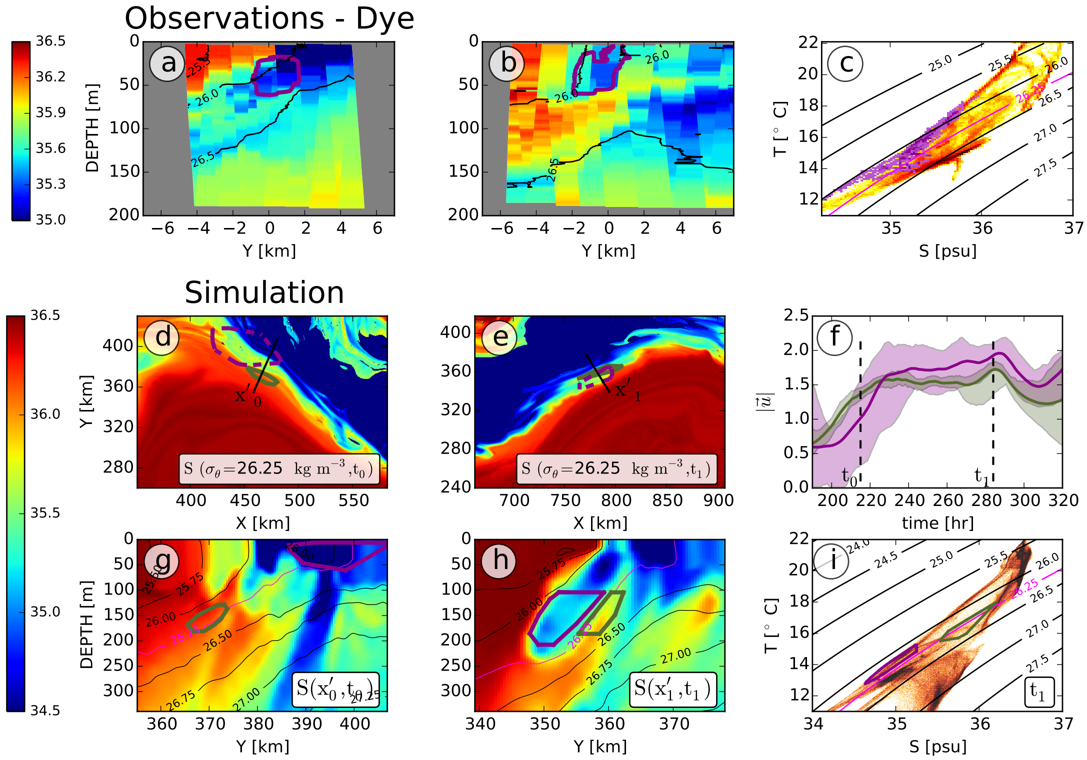

Figure 4: Evidence for entrainment of intrusions from a dye release and numerical simulation. a) Salinity section from an occupation of the GS 14 March. The location of a dye is contoured in magenta. b) Salinity section from downstream. A streamer has enfolded the dye in cold-fresh water between itself and the GS. c) Temperature-salinity diagram for this occupation. The temperature-salinity for the dye is coloured in dark magenta. d) Salinity in the GS on the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ isopycnal from a high-resolution numerical simulation at t_0. The green contours delineate the location of particles seeded downstream in the streamer at time $t_1 = t_0 + 70$h (see panels e and h) and advected *backwards* in time to t_0 showing where the streamer water originated. The dark magenta contour is the location of particles seeded in the fresh intrusion. The straight line shows the location of the salinity cross-section in panel g. e) as panel d, except at $t_1 = t_0 + 70$ h; this is the time and locations where the two clouds of particles were seeded. g) and h) salinity cross sections for times t_0 and t_1. The location of the particles is shown in green and dark magenta contours. The the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ isopycnal is contoured in light magenta. These panels show that the origin of the streamer water was in the GS front, and that the fresh-cold water (magenta contour) enfolded against the front came from north of the front. f) shows the speeds of the particle clouds in time, and shows that the intrusion water (magenta) accelerates relative to the streamer water (green). i) The temperature-salinity of all the data at t_1, with the clouds of seeded particles indicated in T/S space. Note that the green streamer water occupies a mixed mode between the warm GS waters and the cold and fresh water to the north.