Submesoscale streamers exchange water on the ~~North Wall~~ north wall of the Gulf Stream

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The Gulf Stream is a major conduit of warm surface water from the tropics to the subpolar North Atlantic. Its north side has a strong temperature and salinity front that is maintained for hundreds of kilometers ~~,~~ despite considerable energy available for mixing. Large mesoscale ($>$ 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 ($<$ 20 km) mechanism by which the Gulf Stream exchanges water with the cold subpolar water to the north. A series of "streamers" detrain partially mixed wa-

ter from the Gulf Stream at the crest of meanders. Subpolar water is entrained replacing the partially mixed water, and helping to resharpen the front. The water mass ~~exchanges~~ exchange can account for ~~lateral diffusivities if 125-250 $\mathrm{m^2\,s^{-1}}$,~~ a northwards flux of salt of $0.8-5\ \mathrm{psu\,m^2s^{-1}}$, 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 $1.2\ \mathrm{psu\,m^2s^{-1}}$ and is enough to supply ~~the fresh water~~ fresh water to the Gulf Stream as required for the production of 18-degree subtropical mode water~~, as inferred from bulk-scale budgets~~.

The Gulf Stream (GS) is the western boundary current of the North Atlantic subtropical wind-driven circulation. It separates from Cape Hatteras and extends into the interior North Atlantic, traveling east. As it does so, it loses heat not only to the atmosphere, but also ~~the to waters~~ 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 [1]. As it entrains water, the GS increases its eastward transport by approximately $4-8\times10^6\mathrm{m^3s^{-1}}/100\ \mathrm{km}$ ~~[2].~~(Johns et. al.

citejohnsetal95). A sharp density front creates thermal wind shear that confines the current to the upper ocean.

The north wall of the GS has a ~~strong density front, but even along isopycnals there is a sharp temperature-salinity front along the north wall of the SG~~very sharp temperature-salinity front, even along constant-density surfaces. Salinity decreases by almost 1.5 psu ~~moving north across the front, compensated in density by~~ looking north along isopycnals, corresponding to a drop in temperature of 5°C. The sharpness of this front persists for 100s of kilometers~~. The front happens along constant density surfaces, which usually are not a barrier to mixing~~ , despite the fact that mixing along isopycnals is much easier than across them. However, the GS water has a very high potential vorticity gradient (angular momentum; see methods) that is believed to act as a barrier to mixing on large scales [3,4].

Despite this barrier and the presence of the sharp ~~stable~~ front, budgets of properties of the ~~Gulf Stream~~ GS indicate that there is significant exchange across the ~~North Wall[1] . Fresh water is entrained, and is~~ north wall[1] . Entrainment of fresh water is necessary to create the dynamically important "~~18 degree~~ 18-degree water" that fills much of the upper Sargasso Sea. 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 ~~Gulf Stream, and~~ GS and do not result in a net exchange. Instead, tracer budgets across the front appear to be dominated by small-scale processes[5]. To date some of the best direct evidence for cross-front exchange consists of the trajectories of density-following floats placed ~~on the North Wall~~ at the north wall [6,7]. These floats were observed to regularly detrain from the ~~Gulf Stream~~GS, such that of 95 floats, 26 stayed in the ~~Gulf Stream~~GS, 7 were detrained in rings, and 62 were detrained by mechanisms other than rings[7]. Some floats that detrained were also observed to move upwards rapidly. Kinematic theories have been examined to explain the detrainment of the floats [8,9], but direct observations of the relevant processes have been lacking.

Here we present evidence ~~of small scale lateral~~ that there is small-scale mixing (<0.5 km) ~~of the GS on its~~ on the northern cyclonic side of the GS, and that the partially mixed water periodically peels off the GS in thin (5-10 km wide) “streamers”. In March 2012 we made high-resolution measurements of the ~~North Wall~~ north wall of the GS from 66 W to 60 W (Fig. 1), about 850 km east of where the ~~stream~~ GS separates from the North American continental slope. Two research vessels ~~followed a Lagrangian~~ tracked a water-following float placed in the GS front and programmed to follow the density of the surface mixed layer. The float was ~~advected downstream with an average (and relatively constant)~~ transported downstream with a relatively constant speed of 1.4 ~~$\mathrm{m\,s^{-1}}$, and progressively moved to denser water~~ $\pm 0.2\,\mathrm{m\,s^{-1}}$, in water that became denser as the surface of the GS cooled~~downstream~~. One vessel maintained tight sampling around the float and deployed an undulating profiler to 200 m, making 10-km cross sections every 10 km downstream. The second vessel had an undulating profiler making larger 30-km scale sections. Both profilers measured temperature, salinity and pressure, and had approximately 1-km along-track resolution; both ships also measured ocean currents. Fluorescent dye was deployed near the floats on some deployments, and measured by the profilers on the ships. By following the float, a focus on the front was maintained as it curved and meandered to the east.

During these observations, the GS had a shallow meander crest ~~(~~at 65 W ~~,~~ (Fig. 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 ~~giving~~ providing the first detailed observations of their underwater structure.

The front consists of density surfaces that slope up towards the north (Fig. 2a-d). ~~Salinity (coloured)~~ The water along the density surfaces is ~~salty (and warm~~saltier (and warmer) in the ~~Gulf Stream~~GS, and fresher (and ~~cold~~colder) to the north. The temperature-salinity (T/S) relationship shows the contrast between the two water masses as two distinct modes (Fig. 3a), except near the surface where the water masses are strongly affected by the atmosphere. There is ~~also a third less-populated but distinct~~ a third population between the two larger modes in T/S space that ~~identify in T/S space~~ we identify as the streamers. ~~These manifest themselves in~~ In the cross-sections~~as~~, these are the intermediate salinity anomalies ($S \approx 36.15$ psu; Fig. 2a–d). Along $\sigma_\theta = 26.25\,\mathrm{kg\,m^{-3}}$, these anomalies are horizontally connected, peel off the north wall of the GS, are 5-10 km wide, and ~~are stretched out~~ stretch for almost 50 km along the wall (Fig. 3b). The streamers have a strong positive potential vorticity signature~~(equivalent to angular momentum; see Methods)~~. Along the ~~$\sigma_\theta = 26.25$~~ $26.25\,\mathrm{kg\,m^{-3}}$ isopycnal, the region of high potential vorticity corresponds ~~in space~~ very well with the partially mixed streamer water (Fig. 2i–l, Fig. 3b).

The streamers remove water from the ~~Gulf Stream frontal region~~main GS flow. The velocity contrast across the front is sharp, with $> 1\,\mathrm{m\,s^{-1}}$ drop in 5 km (Fig. 2e–h, Fig. 3b). The streamers start on the fast side of the front, moving approximately $0.25\,\mathrm{m\,s^{-1}}$ faster than the float (Fig. 2h). Upstream, where they are detached (Fig. 2e), they are moving almost $0.5\,\mathrm{m\,s^{-1}}$ slower than the float. This represents a considerable detrainment from the ~~Gulf Stream. If we assume a~~ GS. A 5-km wide and 150-m deep streamer~~detraining at~~, detraining with a relative velocity of $0.75\,\mathrm{m\,s^{-1}}$ ~~, then each streamer~~ 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 Fig. 2a has risen along isopycnals from 140 m deep (Fig. 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 ~~on the order of~~ of order 50 m/day, similar to rates inferred from large-scale omega-equation calculations[10].

Concurrently, there is an acceleration of fresh water from the north that is enfolded between the streamers and the GS~~. This is harder~~ , which we will call an “intrusion”. The acceleration of the intrusion is hard to quantify in the ~~data, because we do not know what water upstreamwill be entrained in the future. However, high-resolution~~ sections above because it is drawn from a large pool of water upstream. However, a subsequent survey of the north wall (March 14) included a dye release in this reservoir that was then entrained in an intrusion (Fig. 4a-c). The streamer during this occupation was less pronounced than the one described above, but was clear for a number of passes through the north wall. The dye cloud was quite spread out, but the data show clear interleaving of the intrusion water.

High-resolution numerical simulations ($dx \approx 500m$, see Methods) ~~are able to~~ resolve these features and ~~confirm this effect~~ also confirm the entrainment of the fresh intrusion (Fig. 4d-i). Seeding the simulation with ~~tracked~~ Lagrangian particles (see methods) allows us to track the evolution of the streamers and the ~~entrained fresh water~~ intrusion as the flow moves downstream. Before the streamer is formed, the ~~fresh water (blue~~ water in the intrusion (magenta contours) is near the surface and the streamer water (green contours) is well within the front (Fig. 4~~a,b~~d,g). Downstream (Fig. 4~~c,d~~e,h) the fresh water has been subducted ~~dramatically~~ to 150 m depth, and the streamer has been pushed north of the front. Both water masses accelerate with the whole GS between these two snapshots (Fig. 4~~e~~f), but the fresh ~~water~~ intrusion accelerates more, such that the ~~fresh water~~ intrusion is entrained and the streamer slows and is detrained. As in the ~~data~~observations, the streamer occupies an intermediate region in T-S space (Fig. 4~~f~~i, green contour), and originates in the high-vorticity region of the front.

The acceleration of the fresh ~~water~~ intrusion relative to the streamer is an important finding of the model, as the fresh water now ~~represents~~ forms a new sharp T-S front with the warm salty GS, and the partially mixed streamer water is carried away from the front. The model ~~also~~ further shows that the streamers are more prominent on the leading edges of meanders, also clearly seen in satellite images (Fig. 1). There are differences with the ~~data~~observations, however. The data ~~shows~~ show very distinct T-S signatures associated with the streamers, whereas ~~in the model~~ the model streamer T/S "mode" is less isolated (Fig. 4~~f~~i). The two interleaving water masses are ~~also more~~ confined to a narrow isopycnal band in the model, with the ~~fresh water~~ intrusion being slightly lighter than the ~~salty~~streamer, whereas in the ~~data both water masses share and cut across~~ observations the temperature-salinity front cuts across more isopycnals (compare Fig. 2b to Fig. 4~~d~~h). There is also clear evidence of strong subduction of the ~~cold water~~ intrusion in the model, reminiscent of intrathermocline eddies [10]~~but dissimilar to the cross-isopycnal interleaving shown in the data above~~.

Differences between the data and the model aside, there are two major implications ~~to this~~ of the loss of partially mixed water to the north. The first is that it helps explain why the front at the north wall of the ~~Gulf Stream~~ GS remains so sharp. It is not that there is no mixing taking place in both the horizontal and the vertical, but rather that the mixing product is carried away in the ~~“streamers”~~streamers. It is striking that it is only partially mixed water that is carried away, and not high-salinity GS water (Fig. 3~~m~~b), and that this is also high-vorticity water. This implies a dynamical link that we have not seen explored. Streamers have been observed from surface temperature in satellites and floats[6,8,11,12], and this has led to kinematic models in which particles are displaced from streamlines going around propagating meanders [11,13,14]. The observations here add to these models by showing that it is only partially mixed water ~~leaves the Gulf Stream~~that leaves the GS. This co-incidence indicates to us a role for small-scale mixing in producing the ~~partially mixed water and the~~ destabilizing forces that cause this water to detrain from the north wall. The observations and simulation indicate that the meanders of the GS play an important role in the formation of the streamers.

The second implication is that the ~~detrainment works against a salinity gradient and therefore we can calculate a lateral diffusivity. If there is a meander every 200 km, and each meander detrains 0.5 Sv of fluid over 200 m depth, then a rough northward velocity associated with the turbulent structure is $v' = 0.0125\ \mathrm{m\,s^{-1}}$. Acting over a north-south length scale of $Y' \approx 10 - 20\mathrm{km}$, we get a lateral diffusivity of $K_H = 125 - 250\ \mathrm{m^2\,s^{-1}}$. This is similar to diffusivities from volume budgets using oxygen, temperature, and salinity[1,5]. The observations directly observe this diffusivity, rather than inferring it from inverse calculations. This inferred~~ streamers are a mechanism that can balance large-scale ~~diffusivity is the right size and needed to bring fresh water into the Gulf Stream in order for 18 degree water to be formed further downstream. [1]~~ budgets that require significant exchange across the GS[1,5] . Such budgets suggest that this region of the GS loses salinity to the north at a rate of $1.2\ \mathrm{psu\ m^2s^{-1}}$ [1] . Each streamer transports $0.2 - 0.5 \times 10^6\ \mathrm{m^3s^{-1}}$ 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 $0.8 - 5\ \mathrm{psu\ m^2s^{-1}}$, bracketing the large-scale estimates. Working against a gradient of 1 psu/10 km over 200 m depth, the equivalent lateral diffusivity is $40 - 250\ \mathrm{m^2s^{-1}}$. More observations would need to be made to make this transport estimate more robust.

Here we have observed a lateral ~~mixing process on the North Wall of the Gulf Stream. The streamers lose warm salty water to~~ stirring process along the north wall of the GS. Small-scale mixing due to a number of possible processes[?,15] at the north wall temperature-salinity front creates an intermediate mass of water that, if it accumulated, would weaken the sharpness of the front. However, streamers detrain the partially mixed water, and entrain cold and fresh water toward the north wall, resharpening the ~~north and bring cold fresh water into contact with the North Wall, hence resharpening the lateral gradients~~temperature-salinity front. An alternative possibility is that partially mixed water is squeezed by frontogenetic strain, but ~~this squeezing means that water class must~~ such squeezing would require this water to move downstream. Given the length of the GS, either the ~~squeezed water must get very fast~~intermediate water must accelerate, or there ~~would be~~ is an accumulation somewhere downstream. ~~The~~ Given that there is no strong evidence of either large-scale acceleration, nor a place where this water mass accumulates, the streamers are a ~~mechanism that solves this problem. Closer inspection reveals interleaving of high- and low-salinity water along the entire North Wall, indicating a smaller scale lateral mixing process maybe important (see the alternating green and yellow in n). There is also thought to be significant mixing due to other process such as symmetric instability[?], inertial waves[15], perhaps enhanced by cabelling.~~ viable mechanism that removes this the mixing product.

1 Methods

The Lagrangian float 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 ~~density~~ pressure (CTD) on a 200-m deep sawtooth with approximately 1-km ~~horizontal spacing over short~~ lateral spacing in a 10-km ~~long sections that were approximately boxes in the float's frame~~ box-shaped pattern relative to the float (Fig. 1, magenta). *R/V Atlantis* maintained a larger set of 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[16]). This data reached about 130 m, and was supplemented at deeper depths with data from 75 kHz RDI ADCPs, with 8-m vertical resolution.

Data were interpolated onto ~~density~~ depth surfaces by creating a two-dimensional interpolation onto a grid ~~at each depth via linear interpolation of a~~ via Delauney triangulation. No extrapolation was performed. Data on the $26.25\ \mathrm{kg\,m^{-3}}$ isopycnal were assembled at each grid point by finding the first occurrence of that isopycnal in depth.

Potential vorticity is calculated from the three-dimensional grid as ~~the product of velocity curl ($\nabla \times \mathbf{u}$) added to the Coriolis vector ($\mathbf{f}$) and buoyancy gradients ($\frac{g}{\rho_0}\nabla\rho$):~~

$$q = \frac{g}{\rho_0}\left(\nabla \times \mathbf{u} + \mathbf{f}\right) \cdot \nabla\rho,$$

~~there the~~

$$q = -\frac{g}{\rho_0}\left(\nabla \times \mathbf{u} + \mathbf{f}\right) \cdot \nabla\rho, \tag{1}$$

where f is the Coriolis frequency, g the gravitational acceleration. The bracketed term is twice the angular velocity, including the planet's rotation, and the gradient of density represents the stretching or compression of the water column. In the ~~Gulf Stream~~GS, the potential vorticity is dominated by contributions from the vertical ~~terms,~~ density gradient and the cross-stream gradient of the along-stream velocity:

$$q \approx N^2\left(-\frac{\partial u}{\partial y} + f\right). \tag{2}$$

Dye Release. 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 garden 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 $0.001\ \mathrm{kgm}^{-}3$ of the float's target density. Initial dimensions of the dye streak were ≈1 km along-stream, ≈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 simulation. The high-resolution realistic simulation of the ~~Gulf Stream~~ GS is performed with the Regional Oceanic Modeling System (ROMS[17]). This 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 ~~Gulf Stream~~ 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 ~~Gulf Stream~~ 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[18].

Virtual Lagrangian Particles. The neutrally buoyant Lagrangian (flow-following) particles were seeded at time 285 and advected both backwards and forwards from this time by the model velocity fields without ~~any~~ additional dispersion from the model's mixing processes[19]. A 4th-order Runge-Kutta method with a ~~small time step size~~ 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.

~~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 satellites images. The Gulf Stream is warm and delineated by a sharp front. There are small sub-mesoscale structures north of the front, which 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*).~~

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

~~Streamer properties and distribution in space.a) Logarithmically scaled histogram in temperature-salinity space (colours). The warm-salty Gulf Stream water is very 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 Gulf Stream water and the water to the north, that we label "streamers". This water is contoured in green in e-l. b) Interpolation of salinity, velocity, and potential vorticity onto the~~ $\cancel{\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}}$ ~~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 are plotted in magenta. The "streamer" water is contoured in green.~~

~~Streamers and particles in a high-resolution simulation.a) Salinity in Gulf Stream on the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ isopycnal from a high-resolution numerical simulation at $t_0 = 215\mathrm{h}$. The green contours delineates the location of particles seeded downstream in the streamer at time $t_1 = 285h$ (see panels c and d) and advected *backwards* in time to t_0 showing where the streamer water originated. The blue contour is the location of particles seeded in the fresh intrusion. The straight line shows the location of the salinity cross-section in the next panel. b) Salinity cross section with isopycnals in black, the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ isopycnal in magenta, and the location of the particle cloud outlined in blue and green. c) and d) are the same as a) and b) except for $t_1 = 285\mathrm{h}$; the cloud of particles outlined in green has been seeded in the streamer at this time, and the blue cloud has been seeded in the fresh intrusion. e) The absolute speed of the particles (thin lines) and the average speed of the particles (thick lines) for the clouds contoured in a)–d). Note that the green cloud has slowed relative to the blue cloud, indicating that the streamers have decelerated and the fresh intrusion has accelerated. f) 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 partially mixed mode between the warm Gulf Stream waters and the cold and fresh water to the north.~~

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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 Fig. 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) (Fig. 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 Fig. 3a. i)–l) Potential vorticity sections (see text); 22

3 **Streamer properties and distribution in space.** a) Logarithmically scaled histogram in temperature-salinity space (colours). The warm-salty GS water is very 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 Fig. 2e-l. b) Interpolation of salinity, velocity, and potential vorticity onto the $\sigma_\theta = 26.25\,\mathrm{kg\,m^{-3}}$ 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 Fig. 2 are plotted in magenta. The streamer water is contoured in green. 23

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 $t_1 = t_0 + 70\mathrm{h}$ (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 $t_1 = t_0 + 70\ \mathrm{h}$; 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 partially mixed mode between the warm GS waters and the cold and fresh water to the north. 24

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Competing Interests The authors declare that they have no competing financial interests.

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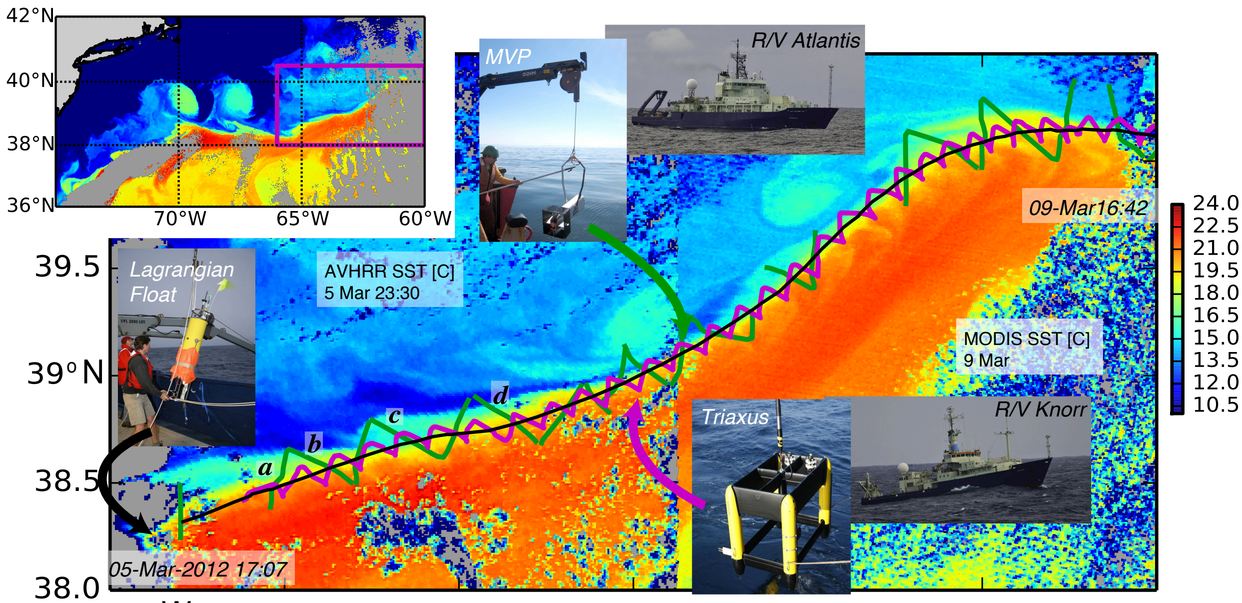


Figure 1: **Experimental design.** Inset: The experiment site on the north wall of the Gulf Stream, between 66 and 60 W, as shown in an AVHRR satellite image of sea surface temperature (SST). Main: Detailed SST image composed from two satellites images. The GS is warm and delineated by a sharp front. There are small sub-mesoscale structures north of the front, which 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 Fig. 2a-d.

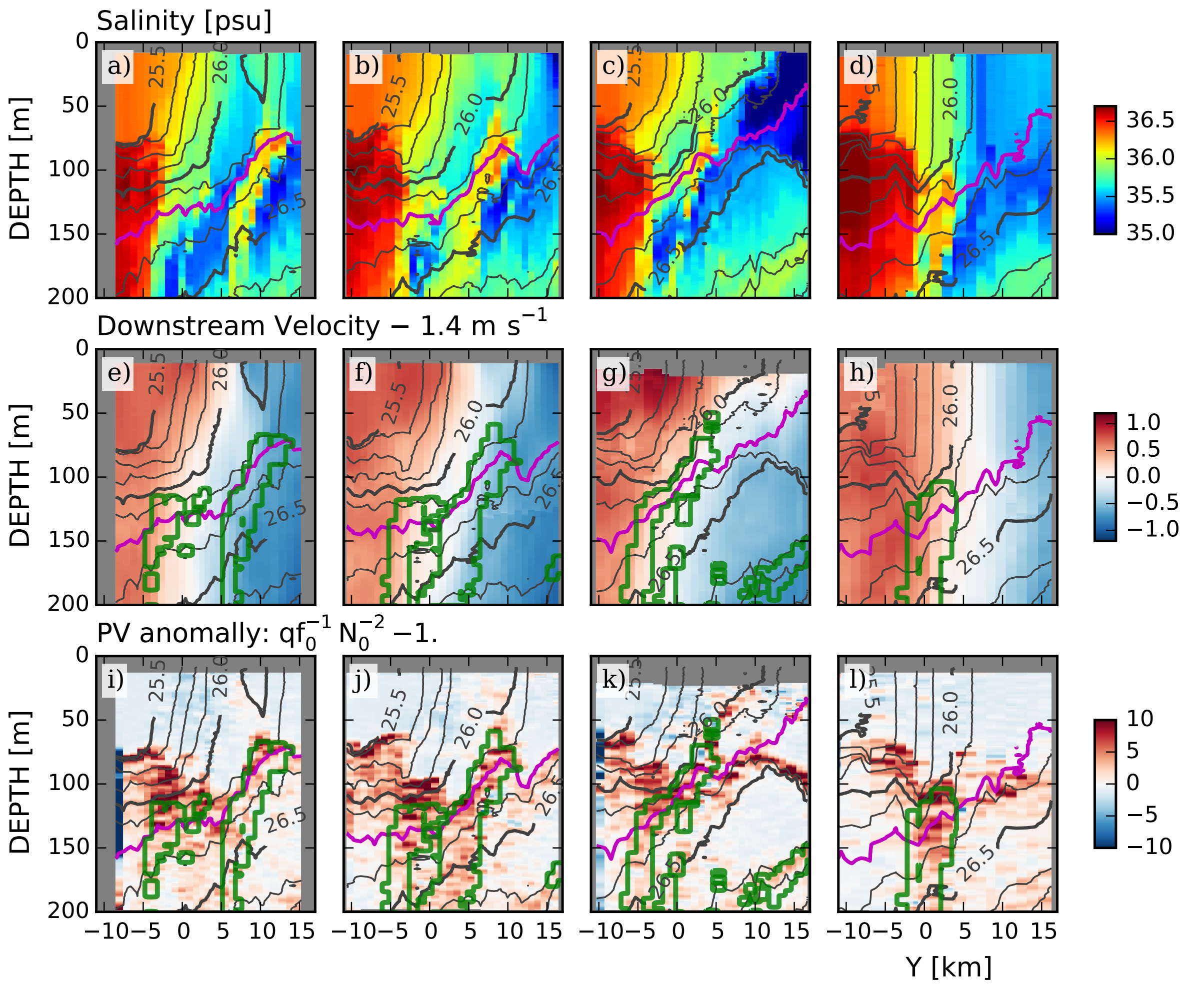
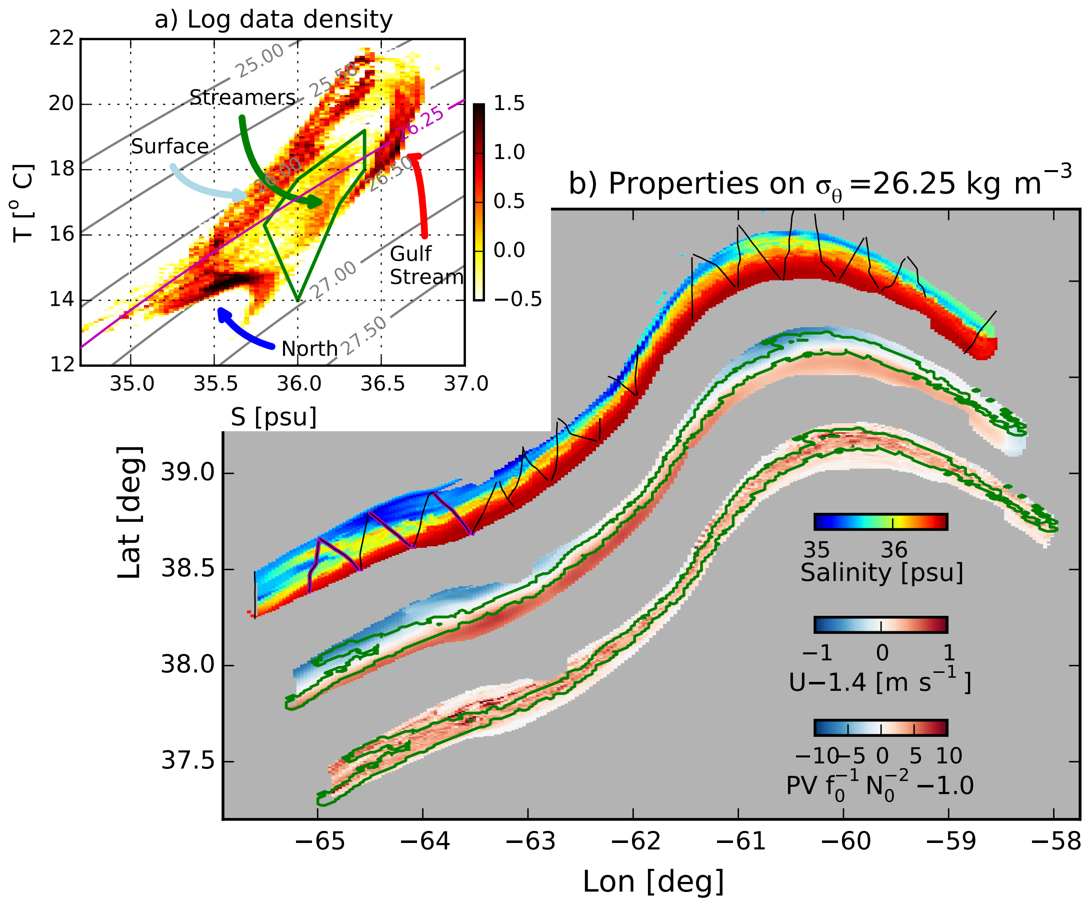


Figure 2: **Cross sections of data collected across the Gulf Stream.** Y is the cross-stream distance perpendicular to the path of the float, positive being northwards. The four columns correspond to the four sections labeled a-d in Fig. 1. Potential density is contoured in black and $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ 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) (Fig. 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 Fig. 3a. i)–l) Potential vorticity sections (see text);



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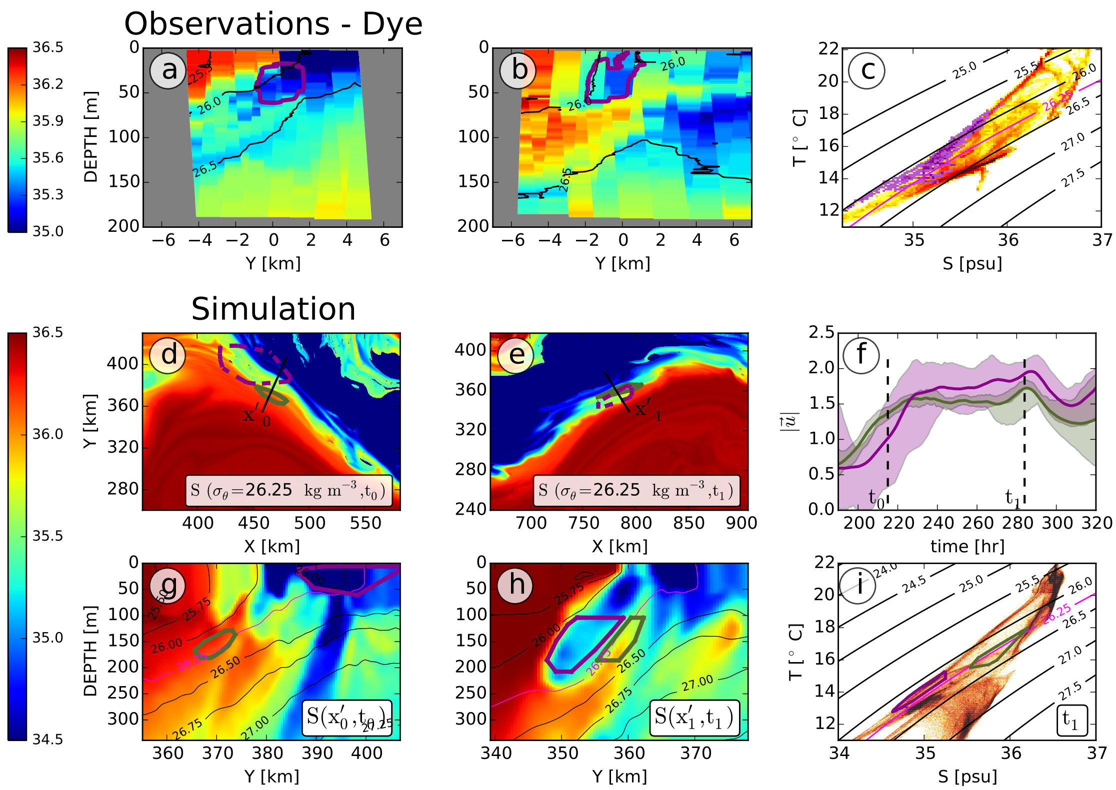

Figure 4: **Evidence for entrainment of intrusions from a dye release and numerical simulation.** a) Salinity section from an occupation of the GS 14 March. The location of a dye is contoured in magenta. b) Salinity section from downstream. A streamer has enfolded the dye in cold-fresh water between 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 $t_1 = t_0 + 70\mathrm{h}$ (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