Submesoscale "streamers" exchange water on the 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 Atlantic. It retains its unique temperature and salinity properties for hundreds of kilometers, as the strongly sheared "North Wall" acts as a dynamical barrier to lateral mixing [1]. 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 demonstrate one sub-mesoscale ($<$ 20 km) mechanism by which the Gulf Stream exchanges water with the cold subpolar water to the north, a series of "streamers" that detrain partially mixed water from the Gulf Stream at the top of meanders. These streamers entrain cold fresh water into the Gulf Stream, an important step in closing the salinity budget for the Stream noted by

previous work [2].

The Gulf Stream is the western boundary current of the North Atlantic wind-driven circulation. It separates from Cape Hatteras and extends into the interior North Atlantic traveling east. As it does so, it loses heat to the north, warming the subpolar gyre. It also entrains water from both the north and south, increasing its eastward transport by approximately XX Sv/100 km. It cools, primarily from atmospheric forcing due to evaporation and sensible heat exchange [2].

Despite being heavily studied, there are a number of things poorly understood about the Gulf Stream. First, there is a very sharp temperature-salinity front on the northern wall. Salinity decreases by almost 1.5 psu moving north across the front, compensated by a drop in temperature of almost 5^{o}C. The sharpness of this front persists for 100s of kilometers, which is remarkably persistent. The front happens along constant density surfaces which usually are not a barrier to mixing, however, the Gulf Stream water has very high potential vorticity (angular momentum), and thus does not tend to mix with the low potential vorticity water, at least on large scales [1].

Regardless of this vorticity barrier and the presence of the sharp stable front, budgets of properties of the Gulf Stream indicate that there must be significant exchange across the North Wall. Joyce et. al. (2013)[2] find that there must be a flux of X Sv of fresh water across the Gulf Stream. This fresh water is necessary to create the dynamically important ”18 degree water” that fills much of the upper Sargasso Sea. This water is also cold and contributes to the cooling of the Gulf Stream, but it is not as important as the atmospheric forcing.

Here we demonstrate that there is indeed small scale mixing at the base of the Gulf Stream, and that this water periodically peels off the Gulf Stream in thin sub mesoscale "streamers". The streamers carry partially mixed warm, salty, and high vorticity water north of the stream. Because they have a cyclonic vorticity anomaly, they also wrap up cold fresh water and entrain it into the Stream. The preferential detrainment of partially mixed water explains the persistent sharpness of the Gulf Stream front despite the presence of mixing processes at the base of the Stream. We also speculate that the preferential detrainment of this water into the streamers is dynamically linked to the partial mixing of vorticity at the base of the Gulf Stream. The entrainment of cold fresh water is quantified to be approximately the right amount to close the salinity budget posed by Joyce et. al. (2013)[2].

In Feb-Mar 2012 we made detailed measurements of the North Wall of the Gulf Stream from 66 W to 60 W (fig:SatOverviewSectD), about 850 km east of where the stream separates from the North American continental slope. Two research vessels followed a Lagrangian float placed in the Gulf Stream front at $\sigma_\theta = XX$

For the deployment discussed here, a shallow convex meander was followed (fig:SatOverviewSectDb), followed by a long shallow concave region before the float passed over a large convex meander. Satellite measurements of sea surface temperature show the sharp temperature changes across the front, but they also show thin intermediate-temperature streamers detraining to the north at approximately 65 W, 64 W, and at the top of the large meander at 61 W. A feature we expect was older can also be seen at 62 W with a clear rolled up signature. The ships passed through the three newer streamers giving the first observation of these streamer's underwater structure.

Four example cross sections and an interpolation of the streamer temperature along the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ potential density surface show that the streamers originate as water that is deeper than 100 m and directly under the sharp T/S front (fig:ThreeDSectionDAnnotateb). Looking upstream, the streamers detach from the base of the Gulf Stream and are advected north, and rise along isopycnals to the surface. The structure at depth is more sharply delineated than the surface structure, which has been modified by atmospheric forcing; distinctive interleaving of high and low salinities is clearly seen between $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ and $\sigma_\theta = 26.5\ \mathrm{kg\,m^{-3}}$. The streamers are order 5 km thick, and are made up of water intermediate to the water in the Gulf Stream and to the north, as clearly seen in T/S space (fig:SatOverviewSectDc).

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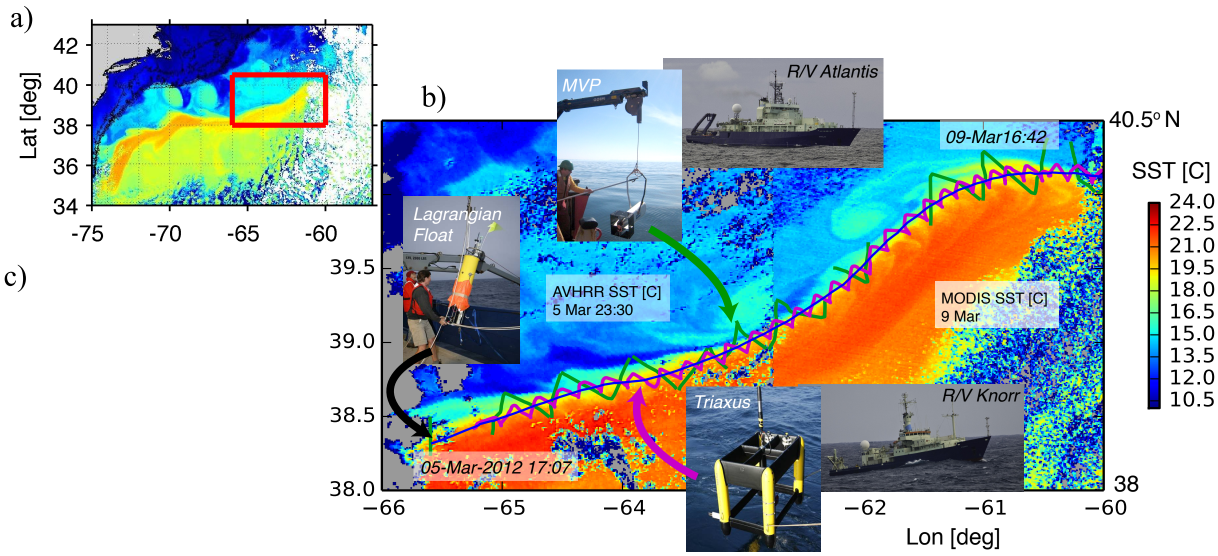

Figure 1: **Experimental design.** a) The experiment site on the north wall of the Gulf Stream, between 66 and 60 W, as shown in this AVHRR satellite image of sea surface temperature (SST) (CITE??). b) Detailed SST image composited from two satellites. The Gulf Stream is warm and delineated by a sharp front. There are small sub-mesoscale structures north of the front, which are the focus of this paper. The front was sampled with two ships (*R/V Knorr* and *R/V Atlantis*) following a Lagrangian float [?,3] which moved downstream in the front at an average speed of $1.4\ \mathrm{m}^{-1}$. The ships each had undulating conductivity, temperature, and depth probes (CTDs), with the *R/V Knorr* tracking the float within 10 km of the front, and the *R/V Atlantis* providing larger-scale surveys of approximately 30 km cross-front distance. Each profiler collected a depth profile to 200 m approximately every 1 km in the horizontal. The float was emplaced at 17:07 5 Mar 2012, and followed for four days along the front. The satellite images are a composite from early in that period (AVHRR 6 Mar), and late in that period (MODIS, 9 Mar) c) The winds were strong ($> 20\ \mathrm{m\,s}^{-1}$), from the northwest for the first two days, before swinging around to coming from the SE. The strong winds and cool temperatures led to a net negative heat flux for most of the observation period.

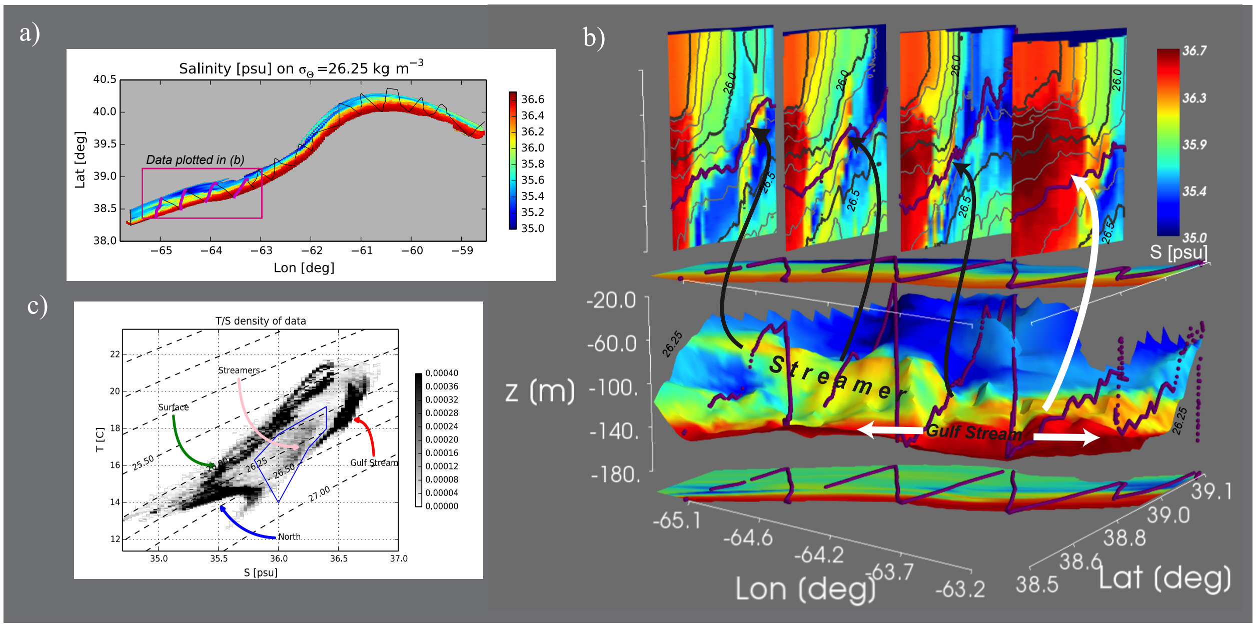

Figure 2: **Streamers on the North Wall of the Gulf Stream.** The upper sections salinity coloured on depth/cross-stream surfaces. Black contours are constant-density surfaces. The dark-purple contour is $\sigma_\theta = 24.25\ \mathrm{kg\,m^{-3}}$, and is the surface shown as a shaded projection in the lower representation of the same data. Here salinity has been coloured at the depth of this constant-density surface. The ship path is indicated on this surfaces, and the flat surface above and below.