Submesoscale "streamers" exchange water on the North Wall of the Gulf Stream

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crest/trough verbiage

vs. top/bottom

vs. convex/concave

pick one & stick w/ it. I like the first

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 directly 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~~ crests of meanders. These streamers are believed to entrain cold fresh water into the Gulf Stream, an important step in closing the salinity budget for the

These streamers are associated with submesocale / 5-10 km scale interleaving of warm/salty GS water and cool/fresh subpolar waters and the water mass exchanges can account for diffusivities of 125-250 m²/s, enough to close...

streamers not a part of Joyce paper

footnotes in abstracts ok?

Stream noted by previous work[1].

subtropical

The Gulf Stream 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 ~~to~~ to the waters in the subpolar gyre to the north. ~~It also~~ The Gulf Stream entrains water from both the north and south, increasing its eastward transport by approximately XX Sv/100 km. It cools, primarily from atmospheric forcing but also due to significant lateral exchanges[1].

30 Sv → Johns et al JGR95

4-8 Sv/100 km

There is a ~~very~~ sharp temperature-salinity front ~~on~~ along the northern wall of the Gulf Stream. Salinity decreases by almost 1.5 psu moving north across the front, compensated overcompensated? in density by a drop in temperature of almost 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. However, the Gulf Stream water has very high potential vorticity (angular momentum), and this acts as a barrier to mixing on large scales[2].

this is confusing the front is not entirely compensated because there is an actual (and large) density gradient too

see methods?

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)[1] find that there must be a significant flux of cold and 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. There are large eddies that periodically pinch off and carry warm water to the north, but they are of such a large scale and temporal persistence that their eventual fate is poorly understood. ~~and~~ Many of ~~them~~ these rings are ~~perhaps~~ thought to be re-entrained into the Gulf Stream as part of a

this is good

this is confusing ~~what~~ who is "their"

strong mean recirculation . Despite their dramatic appearance in satellite images, tracer budgets across the front appear to be dominated by small-scale processes at the front[3]. To date some of the best direct evidence for cross-front exchange consists of the trajectories isopycnal (constant density) floats placed on the North Wall [4,5]. These floats were observed to regularly detrain from the Gulf Stream, and of 95 floats, 26 stayed in the Gulf Stream, 7 were detrained in rings, and 62 were detrained by mechanisms other than rings[5]. Some floats that detrained were also observed to move upwards rapidly in motions that were clearly ageostrophic.

This is good too

Here we ~~demonstrate that there is~~ present evidence of small scale lateral mixing ~~(0.1 km) at the base of~~ of the Gulf Stream on its north cyclonic side, and that this partially mixed water periodically peels off the Gulf Stream in thin (5-10 km wide) "streamers". The streamers carry 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.

for the rest of the paper: pick a consistent term either "stream" or "GS"

In March 2012 we made ~~detailed~~ unprecedented, high-resolution measurements of the North Wall of the Gulf Stream from 66 W to 60 W (Fig. 1), 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 (GS) front at $\sigma_0 = XX\ \mathrm{kg\,m^{-3}}$. The float was advected downstream with an average (and rela-

~~I don't think its / Yeah this is due to the flux / could be still.~~

tively constant) speed of 1.4 m s^{-1}. It progressively moved to denser water as the Stream 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. By following the float, a unique focus on the front was maintained as the front curved and meandered to the east.

good

The GS had a shallow convex meander (65 W, Fig. 1b) followed by a long shallow concave region (63 W) before passing over a large convex meander (61 W). Satellite measurements of sea surface temperature show the sharp temperature changes across the front, but they also show thin intermediate-temperature (15-18 °C) streamers detraining to the north at approximately 65 W, 64 W, and at the top of the large meander at 61 W. An older streamer can also be seen at 62 W with a clear rolled up signature. The ships passed through the three newer streamers giving the first direct observation of these streamer's underwater structure.

The front consists of density surfaces that slope up towards the north (Fig. 2a-d). Salinity (coloured) along the density surfaces is ~~very~~ salty (and warm) in the Gulf Stream, and fresher and colder to the north. The lateral contrast between the two waters is amongst the sharpest in the ocean, with salinity changing almost 1 psu over 5 km. The temperature-salinity relationship has two dominant modes? populations (Fig. 3a) with most of the observations falling on the "North" side of the GS or in the GS. There is a small distinct third population between the two in T/S space that

does that need a reference?

one representing the cooler, fresher and denser "North" side and the other representing the warmer, saltier and lighter GS itself.

we term the "Streamers". These manifest themselves in the cross-sections as intermediate salinity anomalies ($S \approx 36.15$ psu; Fig. 2a–d). Along $\sigma_\theta = 26.25$ kg m^{-3}, these anomalies are horizontally connected, (Fig. 3b) and peel off the north wall of the Gulf Stream, are stretched out for almost 50 km along the wall, and are 5-10 km wide. The streamers have a strong potential vorticity signature (essentially angular momentum; see Methods). We see that along the $\sigma_\theta = \overset{26}{\cancel{24}}.25$ isopycnal, the region of high potential vorticity corresponds in space very well with the partially mixed "streamer" water (Fig. 2i–l, Fig. 3b). ~~The only other region with enhanced potential vorticity is the base of the mixed layer.~~

The streamers remove water from the Gulf Stream frontal region. The velocity contrast across the front is sharp, with over a 1 m s^{-1} drop in 5 km (Fig. 2e–h, Fig. 3b). The streamers where they attach in the downstream section (Fig. 2h) are moving approximately 0.25 m s^{-1} faster than the float, but in the upstream section where they are peeled off (separated from?) the Gulf Stream (Fig. 2e) they are moving almost 0.5 m s^{-1} slower than the floats. This represents a considerable detrainment from the Gulf Stream. If we assume a 5-km wide and 150-m deep streamer detraining at a relative velocity of 0.75 m s^{-1}, then each streamer represents a loss of over 0.5×10^6 m^3 s^{-1} of water. that's amazing!

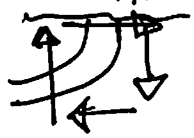
this is pretty sketchy.

The streamers are clearly moving upwards through the water column along isopycnals. As they are stretched out, they also rise in the water column; the streamer in Fig. ??a has risen along isopycnals from 140 m deep (Fig. ??d) to less than 40 m deep, and titled somewhat as it has done so. The velocity anomaly is about 0.75 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 50 m/day, similar to rates

or should we say "of 67 m/day"

Frontogenesis

frontolysis



but WRONG sign in comparison to Thomas paper – this could be attributed to weather the front is strengthening or weakening

inferred from large-scale omega-equation calculations[6].

what's the second?

There are two major implications to this 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 remains so sharp. It is not that there is no mixing of the temperature and salinity taking place, both in the horizontal and the vertical, but rather that the mixing product is carried away in the "streamers". It is striking that it is only partially mixed water that is carried away, and no pure Gulf Stream water (from the high salinity population in Fig. ??m), 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 surface-drogued floats [4,7–9], and this has led to kinematic models in which particles are displaced from streamlines going around propagating meanders [8,10,11]. However, such theories do not explain the observations here, where only partially mixed water leaves the Gulf Stream. 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. This does not rule out the role for the meanders in creating the streamers; the crests are where the the streamers are expelled from the Stream. ~~where perhaps the need to undergo a motion that requires anti-cyclonic vorticity (passing over the fluid crest) cannot remain in geostrophic balance.~~

Samelson 1992 JPO

This is the second. We should say so. This is actually the biggest result.

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 northwards velocity associated with the turbulent structure is $v' = 0.0125\,\mathrm{m\,s^{-1}}$. Acting over a north-south length scale of $Y' \approx 10-20$km, we get a lateral diffusivity and the exchange results in lateral diffusivities that can close salinity budget ...

of $K_H = 125 - 250\ \mathrm{m^2\,s^{-1}}$. This is similar to diffusivities from an inverse calculations using oxygen, temperature, and salinity[1,3]. The results here directly observe this diffusivity, rather than inferring it from inverse calculations.

This needs to be rewritten to emphasize two main results: streamers are mixed water

Here we have ~~resolved~~ observed a specific lateral mixing process that has not been fully resolved on the North Wall of the Gulf Stream before. The streamers lose warm salty water to the north and ~~presumably~~ bring cold fresh water into contact with the North Wall, hence resharpening the lateral gradients. Closer inspection ~~of more sections~~ indicates that there is interleaving of high and low salinity water all the way along the North Wall, indicating a smaller scale lateral mixing process maybe important (see the alternating green and yellow in Fig. ??n). There is also thought to be significant mixing due to other process such as symetric instability [?], inertial waves[12], perhaps enhanced by cabelling.

1 Methods

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

$$q = \frac{g}{\rho_0}(\nabla \times \mathbf{u} + \mathbf{f}) \cdot \nabla\rho \approx \frac{g}{\rho_0}\frac{\partial \rho}{\partial z}\left(\frac{\partial u}{\partial y} + f\right) \quad (1)$$

does there need to be a statement that relates PV to angular momentum

In the Gulf Stream, the appropriate approximation is the vertical gradient in density multiplied by the north-south gradient in the along-stream velocity added to the vertical component of the Coriolis vector. In the North Wall the relative vorticity $\partial y/\partial y >> f$.

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Samelson JPO 1992

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

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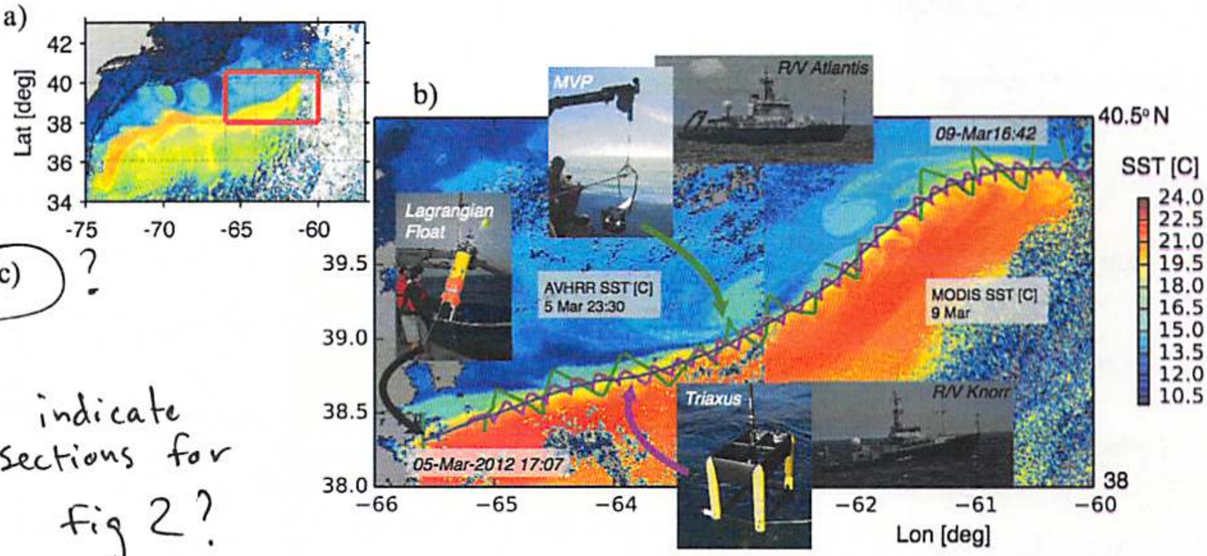
Should we be showing pics of ship etc.?



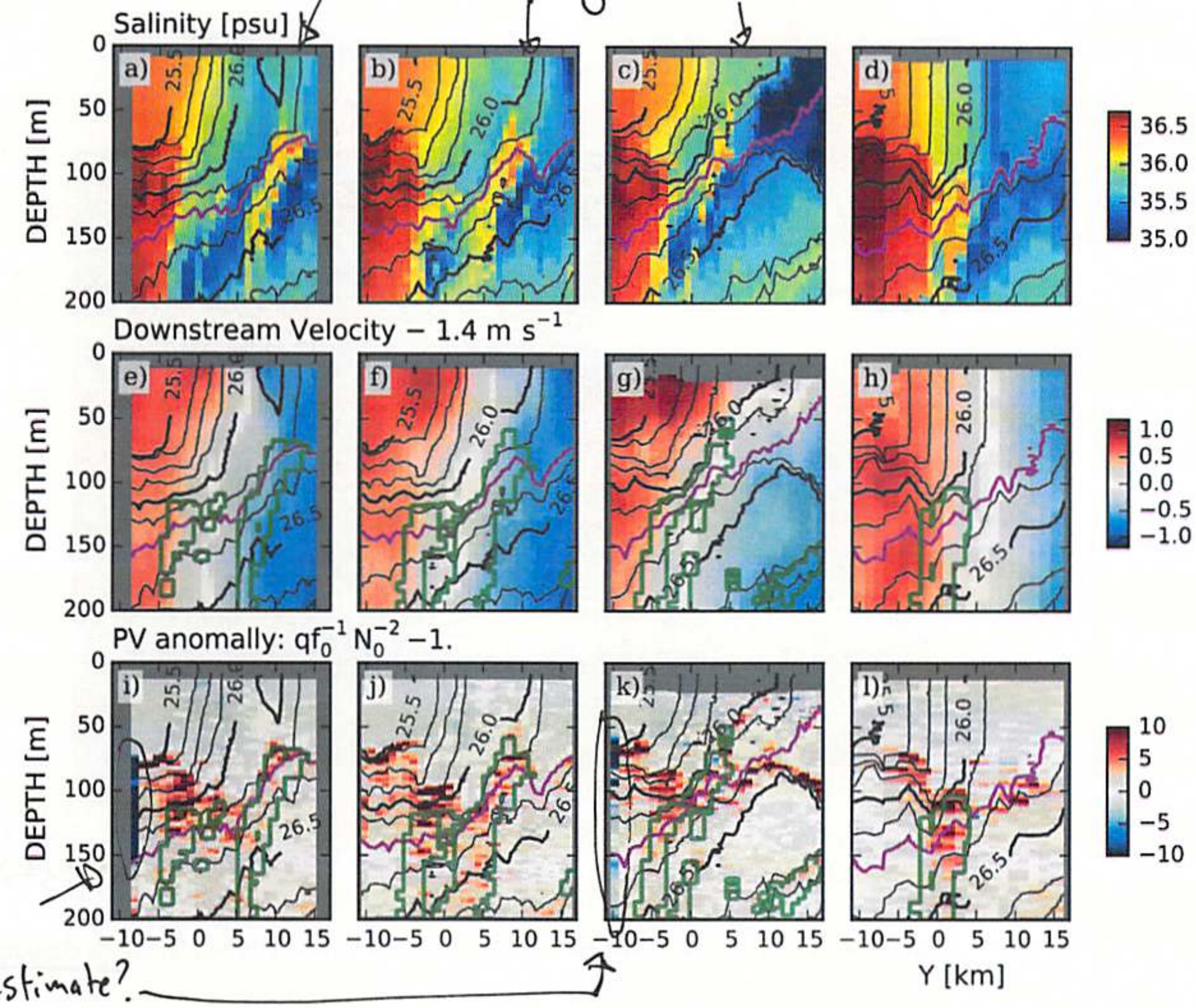
?

indicate sections for Fig 2?

Should the observational details be in the fig caption?

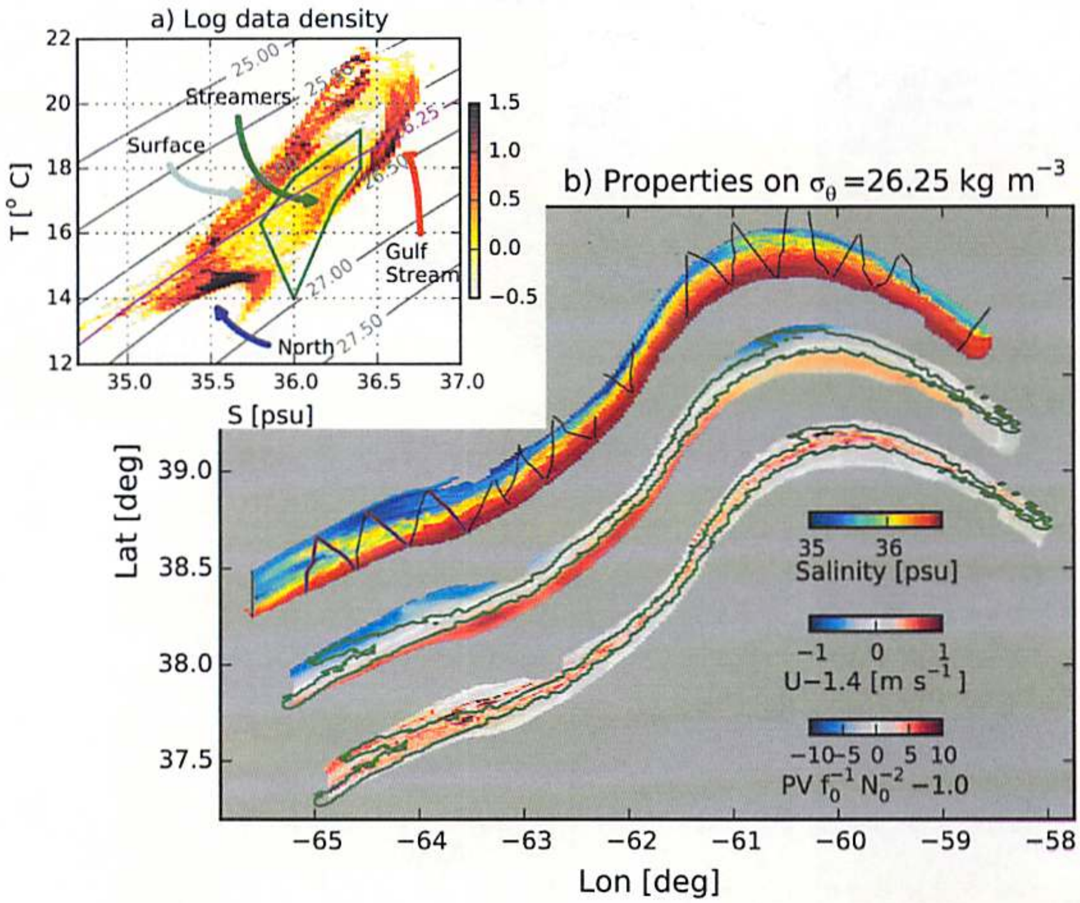
Figure 1: **Experimental design.** a) The experiment site on the north wall of the Gulf Stream, between 66 and 60 W, as shown in this AVHRR satellite image of sea surface temperature (SST) (CITE??). b) Detailed SST image composited from two satellites. The Gulf Stream is warm and delineated by a sharp 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 [13, 14] that moved downstream in the front at an average speed of $1.4\ \mathrm{m\,s^{-1}}$. 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.

it might be confusing not to trace streamer water up to the surface (where it has a sfc exp) since we show the streamers in satellite imagery



bad $\frac{\partial u}{\partial y}$ estimate?

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 (Fig. 1). Potential density is contoured in ~~gray~~ black, the $\sigma_\theta = 26.25\ \mathrm{kg\,m^{-3}}$ density contour is shown in 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, ~~to the west~~ approx. 65W?, and d) is the furthest downstream, to the east (61W) (Fig. 3b). e)–h) downstream velocity calculated relative to the float's trajectory ~~and~~ by removing the float's mean speed for the whole ~~observation of~~ period ($u_{float} = 1.4\ \mathrm{m\,s^{-1}}$). Green contours are regions in temperature-salinity space labeled "streamers" in Fig. 3a. i)–l) Potential vorticity sections (angular momentum - see text);



histogram?

Figure 3: **Streamer properties and distribution in space.** a) Logarithmically scaled data density 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 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 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.

what exaggeration?