On the source of Gulf Stream nutrients

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Along density surfaces, nutrient concentrations in the Gulf Stream are elevated relative to concentrations to either side of the current. We assess the source of these elevated nutrient concentrations in the western boundary current using historical hydrographic data. The analysis is extended to the separated Gulf Stream with four hydrographic sections recently occupied as part of the Climate Variability and Predictability Program (CLIVAR) Mode Water Dynamics Experiment. The results of this analysis suggest that imported, extratropical waters are the primary source of the elevated nutrient concentrations. Because the high nutrient signature is likely imported, diapycnal mixing need not be invoked to explain the Gulf Stream’s high nutrient concentrations, as had been proposed in the past. Moreover, nutrients do not increase along the length of the stream, further suggesting that the stream’s high nutrient signature is imported rather than manufactured by processes within the current. The imported nutrients are likely advected into the North Atlantic within the low-salinity water masses that contribute to the shallow limb of the meridional overturning circulation. Thus the availability of nutrients in the North Atlantic may be linked to upstream processes in the tropics and possibly the Southern Hemisphere as well as to variability in the volume of imported water and its distribution in density space.


1. Introduction

Since the early 1990s, the Gulf Stream has been recognized as a conduit of nutrients in the North Atlantic subtropical gyre [Pelegrí and Csanady, 1991], and the fate of these nutrients is a topic of great interest. It has been proposed that the stream’s nutrient transport ultimately enriches the mixed layers of both the subpolar and subtropical North Atlantic, possibly sustaining primary productivity in both gyres [Jenkins and Doney, 2003; Williams et al., 2006]. Thus variability in the gyres’ productivity may ultimately depend on variability in the upstream conditions that set the nutrient concentrations of the Gulf Stream source waters and the advective pathways and volume fluxes of these source waters. Such a dependence underscores the need to understand the source of the Gulf Stream nutrients as well as their fate.

Because the Gulf Stream’s flow field extends deep into the water column where nutrient concentrations are maximized, its subsurface along-stream nutrient transport is extremely large. Biological utilization depletes nutrients in the surface ocean, so isolines of nutrient transport are closed and resemble a tube of nutrients that has been referred to as a “Nutrient Stream” (Figures 1a and 1b) [Pelegrí and Csanady, 1991]. In addition to the striking tube-like characteristic of the Nutrient Stream, evident in cross-stream sections of nutrient transport (Figure 1b), nutrient concentrations within the stream are elevated on isopycnal surfaces relative to concentrations to either side (Figure 1c). Nitrate concentrations in the Gulf Stream can exceed concentrations to either side by as much as 10 mmol m⁻³ (Figure 1c), with correspondingly high concentrations of the other dissolved nutrients, such as phosphate.

It has been argued that the relatively high nutrient concentrations on surface and upper thermocline isopycnals within the Gulf Stream are caused by the along-isopycnal (epipycnal) advection from the high-nutrient water from the tropical and South Atlantic [Williams et al., 2006] and/or strong diapycnal mixing along the length of the stream [Pelegrí and Csanady, 1991]. The former hypothesis, that epipycnal nutrient fluxes from the tropical and South Atlantic contribute to the elevated nutrient concentrations of the stream, has been suggested by a general circulation model with an idealized nutrient-like tracer [Williams et al., 2006]. The results of this model are consistent with the inference from temperature and salinity data that over 40% of the transport through the Straits of Florida has its origin in the Southern Hemisphere [Schmitz and McCartney, 1993; Schmitz et al., 1993]. As shown by Schmitz and McCartney [1993] and confirmed with our own analysis of a larger database, the T-S signature on several density surfaces in the Straits of Florida resembles more closely the T-S signature found south of the equator than in the subtropical recirculation gyre. The water imported to the North Atlantic is
Figure 1
thought to be balanced by a return flow in the deep limb of the thermohaline circulation. Indeed, estimates of the import flux through the Straits of Florida match closely with the estimated size of the southward, cross-equatorial export of North Atlantic Deep Water [Schmitz and McCartney, 1993, and references therein]. However, the role of these imported waters in setting the Gulf Stream’s nutrient concentrations has not been thoroughly evaluated with the observational record.

The alternative hypothesis, that diapycnal mixing augments the Gulf Stream’s nutrient concentrations on light isopycnals, was based on the spatial coincidence of the Gulf Stream’s enriched nutrients with low-gradient Richardson numbers (Figure 1c) [Pelegri et al., 1996], as well as observations of an increase in nutrient transport on light isopycnals in the western boundary current [Pelegri and Csanady, 1991]. These analyses consequently motivated a conceptual model of gyre-scale nutrient cycling in which diapycnal velocities in the Gulf Stream provide a return path of nutrients to the euphotic zone of the entire subtropical gyre [Jenkins and Doney, 2003]. In this conceptual model, the enriched Gulf Stream waters are advected into the gyre interior, injecting nutrients into the gyre’s seasonally accessible layer. Once in the gyre interior, the nutrients are consumed, exported to deep waters by sinking, and eventually swept back into the Gulf Stream to close the loop. In such a loop, strong diapycnal mixing in the Gulf Stream is required to restore the nutrients on light isopycnals.

Although diapycnal velocities have been shown to mix nutrients in frontal regions and trigger biological responses on submesoscale timescales and space scales [Lee et al., 2006], the overall impact of diapycnal mixing on gyre-scale nutrient distributions remains an open question. The observations that led to the hypothesis of a strong, downstream increase in upper thermocline nutrient transport were primarily from two hydrographic sections occupied 2.5 months apart, without direct velocity measurements. The first section, at 24°N across the Straits of Florida, was occupied in September 1981. The nutrients measured on that cruise were multiplied by velocities measured on a previous mission [Niiler and Richardson, 1973] to yield an approximate nutrient transport. This method implicitly neglects seasonal, mesoscale, and interannual variability of the volume transport through the Straits of Florida, which can be as large as 20% of the mean transport [Leaman et al., 1987]. The nutrient transports for the second section, at 36°N offshore of Cape Hatteras, were calculated as the product of the measured nutrient concentrations and the geostrophic velocities with an assumed level of no motion at 2000 m, though there is a known transport beneath this depth [Bower et al., 1985]. Despite these uncertainties, this analysis has formed the general basis of our understanding of the downstream evolution of nutrient transport in the Gulf Stream.

In this study, we present evidence for an imported source of nutrients to the Gulf Stream in the historical hydrographic data. To also assess the hypothesis that the nutrient signature in the western boundary current is enhanced by diapycnal mixing, we evaluate the along-stream, along-isopycnal evolution of nutrient concentrations and consider the scale of the diapycnal flux of nutrients relative to the other leading terms in the nutrient conservation equation. Finally, the analysis is extended to the separated Gulf Stream with sections from the World Ocean Circulation Experiment (WOCE) and four contemporaneous nutrient sections occupied as part of the CLIVAR Mode Water Dynamics Experiment (CLIMODE) [Marshall et al., 2005].

2. Methods

Throughout this paper, water masses are described as “enriched” or “high in nutrients” when their concentrations exceed the concentrations in neighboring water masses; this does not refer to the status of the nutrient concentrations as compared to concentrations in distant basins or to the kinetics of biological uptake. We refer to the western boundary current (WBC) as that portion of the Gulf Stream between the Straits of Florida and Cape Hatteras, upstream of its separation from the slope. To our knowledge, there are no contemporaneous nutrient sections across the WBC at various along-stream positions. In the absence of such nutrient sections, we assess the along-stream evolution of nutrients in the WBC through a detailed examination of historical hydrographic data. We focus on this region for two primary reasons. First, the WBC is the region where along-stream changes in nutrient concentrations were originally inferred [Pelegri and Csanady, 1991; Pelegri et al., 1996]. Second, it is easiest to identify profiles in the stream where the current’s location is constrained by bathymetry.

Historical hydrographic data used throughout this analysis were downloaded directly from the National Oceanic Data Center (NODC) World Ocean Database 2005 [National Oceanic and Atmospheric Administration (NOAA), 2005] for the years 1950–2003 and the Global Data Analysis Project database [Key et al., 2004], which is composed of data resulting from the World Ocean Circulation Experiment, the Joint Global Ocean Flux Study, and NOAA Ocean Atmosphere Exchange Study. Nutrient measurements in the ocean are far scarcer than temperature (T), salinity (S), or oxygen (O₂) measurements (Figure 2). Because phosphate is the simplest nutrient to measure, there are roughly 4 times as many phosphate observations in the North Atlantic in the NODC repository [NOAA, 2005] as the other nutrients (Figure 2). Therefore phosphate is primarily used to illustrate patterns in the historical nutrient data, though the analyses are valid for the other major nutrients, as phosphate is tightly correlated with both nitrate and silicate. Many of the analyses were repeated for

Figure 1. The North Atlantic Nutrient Stream. (a) A schematic map of the Nutrient Stream from the paper by Pelegri and Csanady [1991] showing the hydrographic sections used in their analysis. (b) Nitrate flux (mmol m⁻² s⁻¹) and density (σ₀) contours for the section at 36°N, taken from the paper by Pelegri et al. [1996]. (c) Nitrate concentration (µM kg⁻¹) in density distance space. The shaded regions depict locales of high vertical density diffusion (2.6 × 10⁻¹⁰–2.6 × 10⁻⁹ kg m⁻³ s⁻¹, estimated as kᵥ(δ²σ/δz²)¹₂, where kᵥ was computed as an inverse function of the gradient Richardson number, σ is the density, and z is the vertical coordinate).
nitrate with the same qualitative results, but for the sake of brevity, only the results for phosphate are presented.

Data from NODC [NOAA, 2005] were subjected to quality control in which all observations outside of 3 standard deviations from the mean were iteratively removed until the mean stabilized. This process was conducted on the data set as a whole and on subsets of the data determined by spatial proximity and density class. A preponderance of phosphate data from the year 1974 was unusually low on dense isopycnals and was far outside the average envelope for the oxygen-phosphate relationship. We suspect the cause of the anomalous data for this year was erroneous reporting. The abundance of data from 1974 caused the standard deviation for phosphate to be sufficiently large that the quality control procedure described above did not recognize these data as outliers, and they were therefore removed by hand. Because the data from a 1978 cruise were the only phosphate data collected in an observation-sparse region of the North Atlantic subtropical gyre, the automated quality control procedure did not remove anomalous data from this cruise, and they were also removed individually. After quality control, maps of properties on isopycnal surfaces were constructed according to the following process. Individual profiles were interpolated onto regularly spaced potential density surfaces. For each density surface, observations were binned into 0.5°C/176 latitude-longitude bins that overlapped by 0.25°C/176. The binned data were averaged with a spatial weighting scheme that assigned a weight of 1 to the center of the bin and decayed by a cosine function to zero at the bin’s edges.

Following quality control, profiles were grouped according to dynamic regime for comparison of properties (Figure 3). The subtropical gyre (STG) was chosen as a box in the interior of the gyre to avoid inclusion of the boundary currents or upwelling regions. Tropical Atlantic profiles were selected as those within a box bounded by 6°S, 10°N, the South American continent, and 10°W. Profiles in the WBC were those found between 24°N and 36°N and less than 100 km offshore of the 100 m isobath. Profiles were only considered to be in the WBC if the temperature of

Figure 2. Locations of NODC profiles [NOAA, 2005] of (a) salinity, (b) oxygen, (c) phosphate, and (d) nitrate. Only observations taken since 1950 that have met our quality control are plotted.
the profile exceeded 15°C at 200 m, a standard reference point for the north wall of the Gulf Stream [Halkin and Rossby, 1985]. On the basis of these criteria, 885 profiles of temperature and salinity and 470 profiles of phosphate in the WBC were used to compare WBC properties to the other oceanographic regions and to analyze the along-stream evolution of nutrient concentrations and temperature. The along-stream distance of these profiles was determined as the distance from 24.7°C, 80.4°C along a smoothed 100 m isobath, as depicted in Figure 4a. The properties of the separated Gulf Stream were examined with WOCE repeat sections A20 and A22, each occupied in 1997 and 2003, and data from the CLIMODE cruise (Figure 4b).

[12] The CLIMODE data were collected aboard the R/V Atlantis between 18 and 31 January 2006 [Marshall et al., 2005]. Velocity data were collected continuously along the ship track using a 75 kHz Teledyne RDI Ocean Surveyor acoustic Doppler current profiler (ADCP) system, which regularly recorded velocities to a depth of 700–800 m. Fifty-two stations were occupied, constituting four full, cross-stream sections (Figure 4b). To our knowledge, these represent the first wintertime nutrient sections across the separated Gulf Stream. Nutrient samples were collected from approximately 20 depths over the top 1000 m of the water column and nominally analyzed within 1 to 2 h after sample collection. All nutrient analyses were performed by Ocean Data Facilities personnel, using a four-channel Technicon AutoAnalyzer II, modified according to the paper by Gordon et al. [1992].

[13] The four sections covered approximately 400 km along the length of the Gulf Stream, with each section extending roughly 100 km in length from the onshore (cyclonic) side of the stream to the offshore (anticyclonic) side of the stream. The first and second sections crossed the upstream and downstream edges of a meander crest, and the third and fourth sections passed through the center and downstream edge of a meander trough (Figure 4b). On the anticyclonic side of the stream, mixed layers of approximately 200 m depth with temperatures of 19°C were actively formed during the cruise.

[14] All data from these sections were rotated into a streamwise coordinate system as follows [Thomas and...
Figure 4
Joyce, 2006]: ADCP velocities along the ship track were binned into 0.05°/C176 latitude bins. The latitude bin in which the binned average velocity is maximized is considered the center of the stream for each section and is assigned the coordinate \((x_o, y_o)\). At this center location, the orientation of the bin-averaged velocity vector is taken as the along-stream coordinate axis (\(x\)), and the cross-stream coordinate (\(y\)) is constructed normal to this velocity vector.

3. Results and Discussion

Atlantic reveal the elevated isopycnal concentrations in the Gulf Stream relative to the neighboring northern recirculation gyre and subtropical gyre (Figures 5a, 5b, and 6). Although oxygen is not considered a nutrient, its concentration generally has an inverse relationship with nutrient concentrations, and oxygen’s greater spatial resolution due to higher data density makes it a convenient proxy for the nutrients. The mean climatological phosphate and oxygen concentrations on selected isopycnals show the Nutrient Stream tracing a path along the southeast coast of the United States (Figures 5a, 5b, and 6). It becomes more difficult to discern the Nutrient Stream within the Gulf Stream after it separates from the western boundary in this mean climatological map view. There are two likely reasons for the attenuated signal in the separated Gulf Stream: (1) Averaging over its large meander envelope smears its signal with that of the surrounding water, and (2) cross-frontal exchange

**Figure 5b.** Phosphate concentration (mmol m$^{-3}$). Isobars have been omitted to emphasize patterns in PO$_4$ concentration. White grid cells denote areas with no data.
may mix Gulf Stream properties with those of the neighboring subtropical and northern recirculation gyres. Such exchange has been observed in the trajectories of isopycnal floats [Bower and Rossby, 1989], most vigorously on density surfaces where lateral gradients are minimized [Bower and Lozier, 1994].

[16] In both the oxygen and phosphate maps, there is a strong visual connection between the WBC and the tropical
Atlantic, including the eastern boundary upwelling region off of Africa. Using historical hydrographic and nutrient data, we investigate this connection in greater detail in section 3.1.

3.1. An Imported Source of Gulf Stream Nutrients

Since the early 1990s, it has been recognized that approximately 13 of the 30 Sv that flow through the Straits of Florida are imported from the tropical and South Atlantic, rather than recirculated from the North Atlantic subtropical gyre [Schmitz and Richardson, 1991; Schmitz and McCartney, 1993; Schmitz et al., 1993]. From hydrographic data, it was deduced that this import flux is not evenly distributed throughout the water column; rather, a majority is advected in density layers both above and below the thermocline. In contrast, the thermocline of the Florida Current is composed primarily of recirculating subtropical water [Schmitz and Richardson, 1991; Schmitz et al., 1993]. Throughout this paper, the tropical Atlantic refers to the extratropical dynamical region that encompasses the cyclonic gyres to the north and south of the equator.

From the T-S relationship on several hydrographic cruises, Schmitz and Richardson [1991] inferred the relative proportions of subtropical and imported water composing the Florida Current. By a similar approach, we use the historical hydrographic data to compare the temperature, salinity, and nutrient concentration of the WBC to surrounding regions. Figure 7 displays the temperature-salinity relationship in the tropical Atlantic, WBC, interior subtropical gyre (STG), and the separated Gulf Stream. Several differences between the WBC and STG are immediately apparent. As expected, the most profound differences are found in the surface (23°C < 26°C) and deep waters (27°C < 27.5°C). These density classes correspond roughly to Schmitz and Richardson's [1991] surface temperature class (>24°C) and deep temperature class (7–12°C), respectively, but in both cases extend to slightly colder, denser waters.

In the densest waters (27°C < 27.5°C), the WBC is considerably fresher than the STG (Figure 7). This T-S signature cannot be traced to the interior of the gyre, but instead appears to be a mixture of tropical and subtropical waters. In this density class, over 5 of a total of 6 Sv of the Florida Current has a South Atlantic origin and is in part composed of Antarctic Intermediate Water (AAIW), which is advected into the North Atlantic via the tropics [Schmitz and McCartney, 1993; Tomczak and Godfrey, 1994; Reid [1994]; Tsuchiya [1989]]. Similarly, the salinity of the WBC's lightest layers appears to be strongly influenced by the fresh waters of the tropical Atlantic (Figure 7). This freshening is consistent with estimates that 7 out of 9 Sv of the Florida Current's surface waters are advected from the tropical and South Atlantic [Schmitz and Richardson, 1991]. On the other hand, the thermocline (26°C < 27°C) of the WBC and STG share a common T-S...
signature, with the WBC being only slightly fresher in these layers. The strong similarity between the T-S signature of the WBC and STG thermocline is consistent with the inference that nearly 12 of 13 Sv of the Florida Current thermocline is fed by recirculations of subtropical water [Schmitz and Richardson, 1991].

[20] The T-S relationship in Figure 7 clearly suggests a strong tropical and South Atlantic influence on the T-S signature of the surface and deep WBC and a strong subtropical control on the thermocline. For each of these regions of the T-S curve, Figure 8 compares the subtropical,
tropical, and WBC distributions of salinity and phosphate observations, as well as the phosphate-salinity relationship. For the lightest layers (23 \( \leq \sigma_\theta < 26 \)), the histogram confirms that the WBC and tropical Atlantic are much fresher than the interior STG. However, there is a cluster of observations in the WBC that matches the mean salinity of the interior gyre, suggestive of an entrainment of sub-tropical waters into the WBC (Figure 8a, top). There is no simple S-PO\(_4\) relationship for this density class (Figure 8a, bottom), and none is expected, as this density bin primarily occupies the top 200 m of the ocean. In this near-surface layer, the euphotic zone frequently extends deeper than the mixed layer in the tropics and subtropical summer. Under these conditions, phosphate is consumed while salinity is essentially conserved. When in the mixed layer, neither salinity nor phosphate is conserved. Despite the lack of a simple relationship between salinity and phosphate, there is a striking difference between the phosphate concentration in the WBC and the STG. The mean phosphate concentration for the WBC is nearly 3 times the concentration in the STG, and both the tropical and WBC phosphate distributions have a long tail of high concentrations. The mean properties of the CLIMODE data in the separated Gulf Stream appear to reflect a mixture of WBC and STG water for these densities (Figure 8a).

[21] The next density class encompasses a large portion of the thermocline (Figure 8b). It is interesting that although the salinity in this density class suggests only a small tropical influence on the WBC, the phosphate signature is considerably greater in the WBC than STG (Figure 8b). Assuming that the WBC is a pure mixture of water from the tropics and subtropics only and that properties are conserved, the temperature and salinity of the WBC thermocline indicates that roughly 5% is imported from outside of the tropics. However, under the same assumptions, the mean phosphate concentration of the WBC thermocline would require approximately 30% imported tropical water. The discrepancy is possibly brought about by the fact that phosphate is not a conservative property; remineralization provides a source of PO\(_4\) and a sink of O\(_2\) both during the transit of waters from the tropical box to the WBC and as the subtropical waters recirculate around the gyre. The thermocline is ventilated to approximately \( \sigma_\theta = 26.5 \) kg m\(^{-3}\) in the northern subtropical gyre in winter, during which time nutrients are depleted because of biological utilization [Palter et al., 2005]. These nutrients are restored through remineralization while the water recirculates in the gyre before being reentrained in the Gulf Stream [Palter et al., 2005]. The quasi-conservative tracer PO\(_4^+\) \((\text{where PO}_4^+ = \text{PO}_4 + \text{O}_2/4.1, \text{for phosphate and oxygen in units of mmol m}^{-3})\) removes the effect of such remineralization by adding the oxygen that is lost from the water column in known proportion to the phosphate created by remineralization [Broeker and Peng, 1982]. Repeating the mixing analysis with PO\(_4^+\) brings a closer agreement with the fractional contributions of gyre water and tropical water as those deduced with T and S. The analysis with PO\(_4^+\) implies that the WBC is composed of 15% imported tropical water with a 95% confidence interval that encompasses the lower estimate from T and S. A possible alternative hypothesis to explain the surplus phosphate in the WBC is that the neighboring northern recirculation gyre provides an along-isopycnal source of nutrients to the WBC. However, this hypothesis is unlikely as the northern recirculation gyre is, in general, lower in phosphate on density surfaces than either the WBC or STG.

[22] Finally, at the base of and just below the thermocline (27 \(\leq \sigma_\theta < 27.5\)), the WBC appears to be a mixture of the tropical Atlantic and subtropical gyre waters both in its salinity and phosphate content (Figure 8c). A major component of the tropical Atlantic on these density surfaces is the AAIW [Tomczak and Godfrey, 1994; Reid [1994]; Tsuchiya [1989]], which has some of the highest nutrient concentrations in the global ocean [Sarmiento et al., 2004]. Phosphate concentrations exceeding 2 mmol m\(^{-3}\) and salinities less than 35, observed with some frequency in the tropical Atlantic and WBC, are conspicuously absent from the entire STG data set (Figure 8c). Again, assuming the WBC is a pure mixture of tropical and subtropical water in this density layer, the T and S data indicate that between 20% and 40% of the WBC is imported from the tropics, much below the 83% deduced by Schnitz and Richardson [1991] for the Florida Current. However, given that the Florida Current composes only 30% of the total WBC volume transport further downstream where recirculating gyre water augments the WBC transport, our lower estimate is consistent with the earlier analysis. The discrepancy between the proportion of imported source water deduced from T and S and that from PO\(_4^+\) again arises in this density level, with PO4 concentrations indicating that tropical waters compose between 45% and 65% of the WBC. Again, employing the quasi-conservative tracer, PO\(_4^+,\) in place of the nonconservative phosphate concentrations brings the proportion to roughly 40%, and well within the error of the estimate from the T and S data.

[23] Deeper than \( \sigma_\theta = 27.5 \) (not shown), phosphate concentrations generally decline for all regions, although there are very few observations denser than 27.5 in the WBC, as defined here. The reduction in nutrients in this densest layer is associated with the North Atlantic Deep Water (T < 5°C, S ~ 34.8) and is indicative of a depleted signature for the deep return flow of the meridional overturning circulation. The presence of this dense, depleted water mass suggests that the high nutrient signature of the densest layers of the WBC cannot be set by a diapycnal flux from below and is very likely imported.

3.2. Downstream Evolution of Nutrients in the WBC

[24] Section 3.1 treated the WBC as single coherent region and showed that its high nutrient concentration can be traced to upstream source waters found in the tropical Atlantic. In this section, we investigate the evolution of the WBC during its transit from the Straits of Florida to Cape Hatteras and, to a limited extent, into the separated Gulf Stream. Our goal is to understand the degree to which the nutrient concentrations change along the length of the WBC in order to test the hypothesis that diapycnal mixing restores nutrients to the Gulf Stream’s light isopycnals.

[25] Figure 9 displays scatterplots of phosphate versus downstream distance for three density bins. These density bins match those examined in section 3.1, with one exception: In order to avoid the euphotic zone and the mixed layer, the lightest density bin excludes observations at densities lighter than \( \sigma_\theta = 25.6 \) and depths less than 150 m. In the
lightest bin (25.6 ≤ σθ < 26) and densest bin (27 ≤ σθ < 27.5), there is a downstream decrease in phosphate, while no such relationship is apparent for the thermocline layer (26 ≤ σθ < 27). However, as there is a strong cross-stream phosphate gradient, any along-stream change in the average cross-stream position of the profiles could influence the downstream trend. Likewise, data distributed unevenly within the density bins could also conceal a possible along-stream nutrient trend. Thus to isolate the impact of the downstream position on the phosphate concentration, we use multiple linear regression analysis (Table 1). This technique allows the examination of the relationship between downstream distance and phosphate concentration, while holding temperature and density constant. Because the

![Figure 9](image-url)
cross-stream position is closely tied to a strong temperature front, removing the temperature dependence should eliminate any bias introduced by the cross-stream position of the profiles. Of course, if the temperature is correlated with downstream distance, this approach could underestimate the impact of the downstream change in phosphate. We addressed this complication by examining separately the downstream evolution of temperature with nearly 1000 profiles (not shown). For $25.6 \leq \sigma_\theta < 26.5$, along-stream distance explains less than 1% of the variance in temperature. The lack of correlation between temperature and along-stream distance justifies our use of the multiple linear regression for these density surfaces. Below this, where there is significant warming with along-stream distance, the influence of cross-stream position should not be explicitly removed, and the change in phosphate with downstream distance is evaluated with a simple linear regression (indicated in Table 1).

The results of the regression analysis are summarized in Table 1. Just above the thermocline ($25.75 \leq \sigma_\theta < 26$), there is a statistically significant reduction in phosphate with along-stream distance, as was inferred from the scatterplot (Figure 9a). One possible explanation for this along-stream nutrient reduction involves the entrainment of additional subtropical waters along the length of the WBC. From the Straits of Florida to Cape Hatteras, the volume transport of the WBC approximately doubles [Pelegrí and Csanady, 1991]. As subtropical gyre waters, which are warmer, saltier, and lower in nutrients than imported waters of the Gulf Stream, join the Gulf Stream and augment its volume transport, the imported signature may be attenuated and reflected in this downstream trend. However, in the upper thermocline ($26 \leq \sigma_\theta < 26.5$), phosphate concentrations remain constant along the length of the stream (to within error). This constancy may reflect the greater proportion of the Florida Current thermocline that is composed of recirculating subtropical water.

Toward the bottom of the thermocline and beneath it ($26.5 \leq \sigma_\theta < 27.5$), the WBC warms and loses phosphate with along-stream distance (Table 1). The decline in phosphate is most dramatic in the very denser layers (Figure 9c), where a mean loss of $2.5 \times 10^{-4} \text{ mmol m}^{-3} \text{ km}^{-1}$ (Table 1) translates to a 50% reduction in nutrients along the length of the WBC (approximately 1200 km). The warming and nutrient loss could ostensibly be caused by a turbulent diapycnal exchange with lighter layers. However, in the absence of a significant cooling (or nutrient enrichment) of the intermediate layers, a more plausible explanation for such loss is along-isopycnal exchange across the WBC. On layers denser than 27.1, cross-stream, mesoscale exchange essentially homogenizes property gradients and erases the water mass boundaries on isopycnal surfaces [Bower et al., 1985]. Such cross-stream, epipycnal mixing would reduce the cross-stream property gradients, supply nutrients to the neighboring gyres, and reduce nutrient concentrations in the Gulf Stream.

The scatterplots of phosphate versus along-stream distance have been extended to the separated Gulf Stream with CLIMODE and WOCE nutrient sections (Figure 9). In the surface and dense isopycnals, the majority of observations in the separated Gulf Stream show phosphate concentrations slightly below the average concentrations in the WBC, perhaps suggesting further dilution with recirculating waters and the erosion of the high nutrient signature of the Gulf Stream after it separates from the coast (Figures 9a and 9c). Along-isopycnal mixing would be expected to erode the high nutrient concentration of the Gulf Stream as it weaves its way between water masses with lower nutrient concentrations to either side. In the thermocline, the phosphate of the separated Gulf Stream resembles more closely the upstream WBC, consistent with these layers being composed of a greater proportion of recirculating subtropical waters such that mixing acts on weaker epipycnal gradients.

This analysis of the historical data does not support the hypothesis of an increase in nutrient concentrations along the length of the WBC, as inferred from the two nutrient sections analyzed by Pelegrí and Csanady [1991]. Without an along-stream enrichment, the WBC cannot provide the upward pitch of the hypothesized “subtropical nutrient spiral,” a mechanism that hinges on an along-stream increase in nutrients on light isopycnals [Jenkins and Doney, 2003]. Therefore the WBC is unlikely to provide an advective return pathway for nutrients lost beneath the seasonal boundary layer of the subtropical gyre in this manner.

3.3. Estimates of Diapycnal and Epipycnal Mixing

To this point, we have examined only the concentrations of nutrients, rather than their fluxes. To consider the size of the turbulent diapycnal flux term, it is useful to put it in the context of the steady state conservation equation for phosphate, neglecting sources and sinks, which can be formulated as

$$\frac{DP}{Dt} = \frac{\partial uP}{\partial x} + \frac{\partial vP}{\partial y} = A_h \left( \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) + A_e \frac{\partial^2 P}{\partial z^2},$$

where $DP/Dt$ is the Lagrangian rate of change in phosphate along the path of the stream, and $\partial uP/\partial x$ and $\partial vP/\partial y$ are the epipycnal, cross-stream and along-stream flux divergence terms, respectively. Because the WBC flows approximately north, the y coordinate axis is set in the along-stream direction. For all terms, the velocity and phosphate quantities are understood to be temporal means. On the right-hand side of equation (1) are the diffusion-like parameterizations of the turbulent exchange terms, which will presently be explored in some detail. In writing

Table 1. Change in Phosphate With Along-Stream Distance in the WBC

<table>
<thead>
<tr>
<th>Density Class</th>
<th>$\Delta_{P\text{mmol}} \pm 2\text{SD, mmol m}^{-3} \text{ km}^{-1}$</th>
<th>Variance Explained (and $p$-Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5–25.75</td>
<td>$-30 \pm 87$</td>
<td>&lt;0.01 (0.48)</td>
</tr>
<tr>
<td>25.75–26</td>
<td>$-126 \pm 64$</td>
<td>0.08 (&lt;0.01)</td>
</tr>
<tr>
<td>26–26.25</td>
<td>$-49 \pm 52$</td>
<td>0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>26.25–26.5</td>
<td>$-8.8 \pm 43$</td>
<td>&lt;0.01 (0.42)</td>
</tr>
<tr>
<td>26.5–26.75</td>
<td>$-79 \pm 54$</td>
<td>0.02 (&lt;0.01)</td>
</tr>
<tr>
<td>26.75–27</td>
<td>$-117 \pm 54$</td>
<td>0.03 (&lt;0.01)</td>
</tr>
<tr>
<td>27–27.25</td>
<td>$-222 \pm 55$</td>
<td>0.10 (&lt;0.01)</td>
</tr>
<tr>
<td>27.25–27.5</td>
<td>$-277 \pm 65$</td>
<td>0.18 (&lt;0.01)</td>
</tr>
</tbody>
</table>

*Simple linear regression (temperature cannot be held constant without removing an along-stream warming trend).
*Significant relationship at $p = 0.05$. 

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The steady state assumption is predicated on the idea that the local time rate of change in phosphate is much slower than the advective flux divergence terms, which are relatively large in the Gulf Stream. The assumption of negligible sources and sinks is justified beneath the euphotic zone, as biological remineralization rates are roughly 0.03–0.1 mmol m$^{-3}$ a$^{-1}$ [Jenkins, 1982; Palter et al., 2005], providing no more than 0.01 mmol m$^{-3}$ of phosphate in the time it takes the WBC to transit from the Straits of Florida to Cape Hatteras (less than 1 month). Biological utilization in the euphotic zone cannot be assumed to be negligible, as phytoplankton can consume phosphate at a rate between 0.1–1 mmol m$^{-2}$ d$^{-1}$ in the presence of sunlight [Wakeham and Lee, 1993]. Therefore in Figures 8 and 9, we have presented only along-stream trends for observations below the euphotic zone (nominally 150 m or $\sigma_\theta = 25.6$, whichever is deeper). Finally, we have neglected the time mean diapycnal flux divergence of phosphate ($\bar{w}P/L$), as this term has been shown to be small relative to epipycnal flux convergence terms, even in strong fronts when diapycnal perturbation velocities become large [Barth et al., 2004].

The entire range of turbulent diffusion coefficients for timescales longer than 2 h yields diapycnal phosphate...
fluxes ranging from $10^{-11}$ to $10^{-9}$ mmol m$^{-3}$ s$^{-1}$ and epipycnal fluxes from $10^{-14}$ to $10^{-7}$ mmol m$^{-3}$ s$^{-1}$ (Table 2). These low estimates for diapycnal mixing mean that even the largest of the diapycnal flux estimates would require 1000 d to increase the Lagrangian phosphate concentration of a parcel in the stream by approximately 10%. Given that an average parcel in the core of the Gulf Stream transits from the Straits of Florida to the easternmost WOCE section in fewer than 100 d [Fratantoni, 2001], this small flux cannot explain the stream’s enhanced phosphate concentration, which can be twice as large as concentrations in the recirculation gyres. In other words, the Peclet number for vertical diffusion is far too large ($O(10^4)$) for a length scale of 1000 km, depth scale of 1000 m, velocity of 1 m s$^{-1}$, and vertical diffusivity of $10^{-4}$ m$^2$ s$^{-1}$ for vertical diffusion to appreciably change the strong signal advected into the WBC.

On the other hand, the largest of the epipycnal turbulent diffusion estimates could lead to considerable down-gradient (out of the Gulf Stream) nutrient flux. During a parcel’s journey in the Gulf Stream, such an eddy flux could account for a loss of phosphate as large as 0.8 mmol m$^{-3}$, assuming a timescale of $10^2$ d and an epipycnal diffusivity of $10^3$ m$^2$ s$^{-1}$, the largest value from the paper by Rajamony et al. [2001]. The slight reduction in phosphate seen along the length of the WBC and between Hatteras and the CLIMODE and WOCE sections in the separated Gulf Stream (Figure 9) may be a result of such epipycnal eddy exchange.

### 3.4. A Snapshot of Nutrients in the Separated Gulf Stream: The CLIMODE Sections

The temperature, salinity, and phosphate CLIMODE data show a separated Gulf Stream with intermediate
properties between the WBC and interior STG (Figures 7 and 8). A closer examination of these CLIMODE sections reveals the degree to which the Gulf Stream’s high nutrient bolus is maintained more than 400 km offshore from Cape Hatteras and how it changes with along-stream distance. The CLIMODE hydrographic section 1 (Figure 10a) displays the steeply sloping isopycnals of the Gulf Stream. By visual inspection, the phosphate isolines appear to coincide with the isopycnal surfaces (Figure 10b). However, when viewed as a function of density and cross-stream distance (Figure 10c), the phosphate contours again display the familiar high nutrient concentrations in the stream. This high-nutrient feature is likely the remnant of the water mass advected from outside the subtropics. The advected feature is much more noticeable for phosphate than for temperature, which shows a sharp water mass boundary at the north edge of the stream (Figure 10d). The elevated phosphate concentrations and transports are found above the $\sigma_\theta = 26.9$, slightly shoreward of the stream’s center, yet still well within the high velocity isotachs of the stream (Figure 10c). These CLIMODE sections demonstrate that the imported, high nutrient signature of the Gulf Stream is maintained far offshore, despite ongoing lateral mixing.

In Figure 11, data from all four CLIMODE sections trace the phosphate concentrations along the center of the stream on various isopycnal surfaces. Above the 26.4 isopycnal, no systematic along-stream evolution of nutrient concentrations is apparent (Figure 11). Below this isopycnal, concentrations increase in the center of the Gulf Stream. The bottle samples on the cruise were collected to a depth of only 1000 m, not deep enough to consistently sample beneath the $\sigma_\theta = 27$ isopycnal and resolve along-stream changes on the dense layers. Between the 26.4 isopycnal and the 27 isopycnal, there is a gain in phosphate concentrations of 0.1 mmol m$^{-3}$. This increase seems incongruent with the along-stream trends in the mean WBC, as illustrated with the historical hydrographic data (Figures 8 and 9), and the cause of such an increase is not clear. Perhaps such increase is an artifact of sampling the stream at slightly different cross-stream positions and/or is brought about by submesoscale variation.

Unfortunately, the CLIMODE sections occupied in January 2006 cannot resolve the degree to which the Gulf Stream nutrients are advected into the subpolar gyre in the North Atlantic Current and/or are mixed with the neighboring subtropical and northern recirculation gyres. The size of these fluxes remains an open question that may be crucial to understanding the supply of nutrients to the North Atlantic. On the recent CLIMODE 4 cruise (February–March 2007), nutrient samples were collected in the eastward extension of the Gulf Stream and should add to the growing body of nutrient data that will help resolve this issue. When the nutrient analyses from these sections are complete, they may also shed light on the flux of nutrients that results from the advection of the nutricline into the winter mixed layer, called an induction flux by Williams et al. [2006].

4. Concluding Remarks

In summary, the Gulf Stream serves as a conduit of nutrients and has aptly been named a “Nutrient Stream” [Pelegrì et al., 1996]. Over much of the water column, the WBC’s temperature and salinity signature cannot be traced to the recirculating subtropical gyre. Instead, a considerable portion of the WBC is imported from the tropical Atlantic, as proposed in the early 1990s. Although this import has long been assumed to balance the cross-equatorial export of North Atlantic Deep Water in the deep limb of the meridional overturning circulation, the possibility that the imported waters act as a conduit of nutrients has only recently been explored, primarily in the modeling domain [Williams et al., 2006]. Here we have shown that the imported waters are associated with nutrient concentrations that are anomalously high relative to the subtropical waters and may provide an important source of inorganic nutrients to the North Atlantic.

Because the high nutrients are likely imported from the tropics, diapycnal mixing need not be invoked to explain the Gulf Stream’s high nutrient concentrations. In
any case, the diapycnal flux term is unlikely to be sufficiently large to appreciably alter the nutrient concentrations during the WBC’s rapid transit from the Straits of Florida to Cape Hatteras. Furthermore, nutrients do not increase along the length of the stream. It is quite the contrary; along the length of the WBC, nutrient concentrations generally decline, especially for the densest isopycnals, as epipycnal exchange diminishes lateral gradients. Such exchange implies that the Gulf Stream may supply a source of nutrients to both the northern recirculation gyre and the northern flanks of the subtropical gyre, while the continued northward advection of the Nutrient Stream in the North Atlantic Current may carry a portion of these nutrients to the subpolar North Atlantic. However, the precise fate of the nutrients is still a largely open question, and a motivation for further research lies in understanding the proportions of the imported nutrients that are mixed with the neighboring gyres and are advected into the subpolar gyre.

[39] The role of advection from the tropical Atlantic in setting Gulf Stream nutrient concentrations illustrates the importance of a fully 3-D view of nutrient cycling in the ocean. The availability of nutrients in the North Atlantic may be inextricably linked to upstream processes in the tropics and possibly the Southern Hemisphere, as well as variability in the volume of imported water and its distribution in density space.

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References


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