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Tracer-based assessment of the origin and biogeochemical transformation of a cyclonic eddy in the Sargasso Sea

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[1] Mechanisms of nutrient supply in oligotrophic ocean systems remain inadequately understood and quantified. In the North Atlantic Subtropical Gyre, for example, the observed rates of new production are apparently not balanced by nutrient supply via vertical mixing. Mesoscale eddies have been hypothesized as a mechanism for vertical nutrient pumping into the euphotic zone, but the full range and magnitude of biogeochemical impacts by eddies remain uncertain. We evaluated a cyclonic eddy located near Bermuda for its effect on water column biogeochemistry. In the density range σ_θ 26.1 to 26.7, an eddy core with anomalous salinity, temperature, and biogeochemical properties was observed, suggesting that the eddy was not formed with local water (i.e., not formed of the waters surrounding the eddy at the time of observations), hence complicating efforts to quantify biogeochemical processes in the eddy. We combined conservative hydrographic tracers (density versus potential temperature and salinity) and quasi-conservative biogeochemical tracers (density versus NO, PO, and total organic carbon) to propose the origin of the eddy core water to have been several hundred kilometers to the southeast of the eddy location at sampling. By comparing the observed eddy core's biogeochemical properties with those near the proposed origin, we estimate the net changes in biogeochemical properties that occurred. A conservative estimate of export was 0.5 ± 0.34 mol N m^{-2} via sinking particles, with export occurring prior to our period of direct observation. Our results suggest that biogeochemical signals induced by mesoscale eddies could survive to be transported over long distances, thus providing a mechanism for lateral fluxes of nutrients and AOU (apparent oxygen utilization). Given that the proposed source area of this eddy is relatively broad, and the eddy-mixing history before our sampling is unknown, uncertainty remains in our assessment of the true biogeochemical impact of mesoscale eddies in the gyre.

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1. Introduction

[2] Much of the midlatitude surface ocean is characterized by low mineral nutrient concentrations. Such low-nutrient regions cover ~30% of the Earth's surface and represent ~10% of global primary production [*Geider*, 1997]. In these systems, photosynthesis by marine phytoplankton is limited by the availability of the major nutrients, such as N, P and Si, and some important trace metals, such as Fe [*Morel and Price*, 2003]. In steady state, export of organic matter from the euphotic zone as sinking biogenic particles or dissolved organic materials should be balanced by upward nutrient fluxes from the subsurface ocean, if other nutrient sources such as atmospheric deposition and nitrogen fixation are ignored. In the oligotrophic North Atlantic subtropical gyre, the estimated new production, the portion of total primary production that is driven by new nutrients introduced from outside of the euphotic zone, cannot be explained by the commonly evaluated nutrient supply mechanisms such as winter convection and diapycnal diffusion [*Jenkins*, 1988; *Siegel et al.*, 1999; *Lipschultz et al.*, 2002; *Jenkins and Doney*, 2003; *Williams and Follows*, 2003]. Mesoscale cyclonic and mode-water eddies (diameter ~10^2 km) have been hypothesized as an additional mechanism for transporting high-nutrient water into the nutrient depleted surface ocean with the uplift of isopycnal surfaces [*McGillicuddy et al.*, 1998], resulting in biological and biogeochemical responses in the euphotic zone [*Falkowski et al.*, 1991; *McGillicuddy et al.*, 1998; *Sweeney et al.*, 2003]. This

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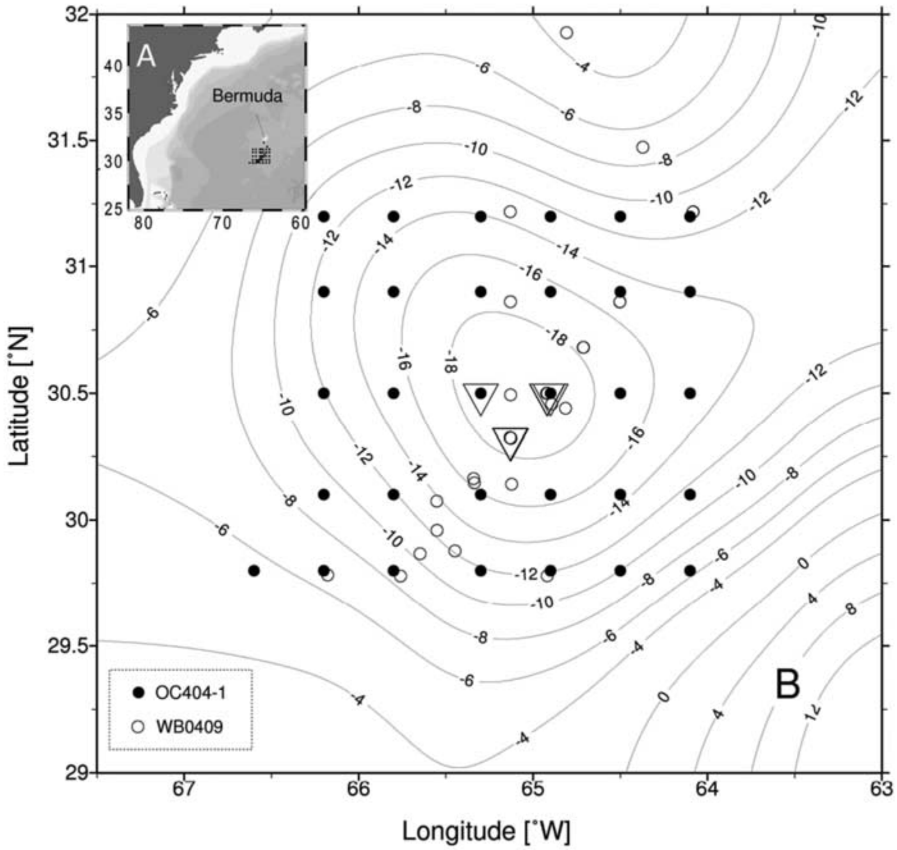

Figure 1. (a) Location of Bermuda in the western North Atlantic. (b) Station map. Contour lines are the sea surface height anomalies (SSHA) (in centimeters), open circles are stations of the R/V *Weatherbird II* cruise, closed circles are stations of the R/V *Oceanus* cruise, and triangles are six eddy core stations (some overlapping in location) as identified by hydrographic anomalies. The comprehensive survey was completed over 10 days, but the SSHA snapshot was from 30 June 2004, which is most representative of the conditions during which the bulk of the hydrographic stations at eddy center were occupied.

hypothesis was supported by several field studies [*Allen et al.*, 1996; *Seki et al.*, 2001; *Vaillancourt et al.*, 2003] but challenged by other investigations [*Oschlies and Garcon*, 1998; *Oschlies*, 2002; *Martin and Pondaven*, 2003].

[3] A number of studies found that mesoscale eddies survive to be transported long distances. Near Station ALOHA, north of Hawaii, *Lukas and Santiago-Manddujano* [2001] reported anomalous water properties in the remnant of a mesoscale eddy that they suggested to have come from the coast of Mexico. Similarly, a warm core ring in the southeast Atlantic Ocean, exhibiting hydrographic and biogeochemical anomalies, was traced back to the Agulhas retroflection using remote sensing data [*McDonagh and Heywood*, 1999]. The discoveries of anomalous water properties in the North Atlantic thermocline [*McDowell and Rossby*, 1978; *McDowell*, 1986; *Prater and Rossby*, 1999] accelerated study of the role of baroclinic eddies in the large-scale mixing. Recently, Lagrangian modes of observation have been used to study physical and biogeochemical evolution of eddies as they propagate [*Harris et al.*, 1997; *Law et al.*, 2001].

[4] In the work described here, a mesoscale cyclonic eddy located in the NW Atlantic Ocean (~30.5°N, 65°W) was comprehensively studied during the Eddy Dynamics, Mixing, Export, and Species composition (EDDIES) project [*McGillicuddy et al.*, 2007]. The eddy was characterized by a core with strong hydrographic and biogeochemical anomalies relative to the waters surrounding the eddy (the latter here termed "local waters"). Using conservative hydrographic tracers (salinity, potential temperature) and quasi-conservative biogeochemical tracers such as NO and PO (the sum of nutrient and oxygen weighted by Redfield ratio N:P:O of 16:1:138; [*Redfield et al.*, 1963; *Broecker*, 1974; *Li and Peng*, 2002]), and total organic carbon (TOC), we seek to identify the region of formation. The biogeochemical impact of the eddy is then assessed on the basis of the change in concentrations of biogeochemical variables between the proposed source waters and the eddy core. We also evaluate uncertainties in this assessment.

2. Methods

2.1. Field Work

[5] In the summer of 2004, two ships, R/V *Oceanus* and R/V *Weatherbird II*, were deployed to investigate a cyclonic eddy near Bermuda, with a suite of supporting measurements of physical and biogeochemical variables. The eddy was occupied over two periods in summer 2004. The first occupation was from 8 June to 3 July and the second from 26 July to 12 August. Figure 1 shows the distribution of

stations in the first occupation. Doming of the main thermocline inside this eddy was observed from sections across the eddy [*Li and Hansell*, 2008]. The eddy feature was identified and tracked during cruises using near-real-time satellite altimetry measurements from Topex/Poseidon, Jason, Geosat Follow-On, and European Remote Sensing platforms, available through the Colorado Center for Astrodynamics Research Northwestern Atlantic Near Real-Time Altimeter Data Viewer (http://ccar.colorado.edu) [*Leben et al.*, 2002] and the U.S. Navy (http://www7300.nrlssc.navy.mil/altimetry).

2.2. Hydrographic Measurements

[6] Hydrographic data were collected using a Seabird CTD (SBE911) that profiled the water column with sensors for pressure, temperature, conductivity, fluorescence, and polarographic oxygen, all of which had been calibrated before and after the cruises. Discrete samples were also collected from nominal depths of 0, 20, 40, 50, 60, 70, 80, 90, 100, 120, 140, 200, 300, 500, and 700 m using 10-L Niskin bottles. Discrete dissolved oxygen measurements were made using the Winkler titration method [*Williams and Jenkinson*, 1982].

2.3. Nutrient Measurements

[7] Nutrient samples were filtered inline with a 0.8 μm pore size Nuclepore filter. Low-level nitrate plus nitrite (DIN) and phosphate (DIP) concentrations were determined immediately after collection by highly sensitive liquid-waveguide techniques [*Li et al.*, 2005, 2008]. Two 200 cm long liquid-waveguide capillary cells (LWCC) were coupled to a flow injection analytical system, which has the advantage of rapid shipboard measurement of large numbers of samples with high precision and sensitivity [*Li and Hansell*, 2008; *Li et al.*, 2008]. The detection limits for DIN and DIP in this system are 2 nmol and 0.5 nmol, respectively. For quality control, each sample was analyzed up to six times. All the DIN and DIP data presented in this paper are means of these six measurements, with coefficients of variation of <5%.

[8] Each step of the nutrient measurements was strictly controlled to avoid contamination. The high-nutrient samples from deeper waters (>300 m) were diluted by surface seawater with a volumetric Teflon flask and determined by the same methods. All the bottles, tubes and flasks were cleaned in HCl baths, and the reagents and chemical standards were analytical grade [*Li et al.*, 2008].

2.4. Total Organic Carbon and Total Nitrogen Measurements

[9] Total organic carbon (TOC) and total nitrogen (TN) samples were collected in ~120 mL opaque, polyethylene bottles, frozen at sea and returned to Miami for analysis using a Shimadzu TOC-V_{csh} high-temperature combustion system. Extensive conditioning and standardization procedures were performed prior to analyzing samples each day. Four point standard curves of potassium hydrogen phthalate were used for the standardization. As daily quality reference waters, large volumes of deep and surface Sargasso Seawater were assessed against consensus reference materials produced by the Dissolved Organic Carbon CRM program (http://www.rsmas.miami.edu/groups/organic-biogeochem/crm.html). To ensure the highest quality control, samples were systematically checked against low-carbon water and deep and surface reference waters every sixth analysis. It should be noted that the TOC reported here includes both dissolved organic carbon and particulate organic carbon, since we did not filter the samples.

[10] TN analyses were performed with a Shimadzu TN detector as part of the Shimadzu TOC-V system, where TN is converted to nitric oxide at high temperature and measured with a chemiluminescence detector. The total organic nitrogen (TON) concentrations were calculated by subtracting the DIN values from the TN values. In oligotrophic gyre waters, where DIN concentrations are very low, TN is essentially equal to TON concentrations. Ammonium concentrations were not determined, so they are part of the TON estimate. Between-day precision in the TOC measurement was 1–2 μM, or a CV of 2–3%, while between-day precision on TON (DIN-free water) was ~0.5 μM, or a CV of 7–8% (depending on the TON concentration).

2.5. Dissolved Inorganic Carbon Measurements

[11] Seawater samples for dissolved inorganic carbon (DIC) were drawn from the Niskin samplers into precleaned ~300 mL borosilicate bottles, poisoned with $HgCl_2$ to halt biological activity, sealed, and returned to the Bermuda Institute for Ocean Sciences (BIOS) for analysis. DIC samples were analyzed using a highly precise (~0.025%; <0.5 μmoles kg^{-1}) gas extraction/coulometric detection system [*Bates et al.*, 1996]. Routine analyses of certified reference materials (provided by A.G. Dickson, Scripps Institution of Oceanography) ensured that the accuracy of the DIC measurements was within 0.05% (~0.5 μmoles kg^{-1}).

3. Results

3.1. Salinity and Temperature

[12] Relative to local waters at the edge of the eddy, elevated salinity and temperature values were observed in the eddy core at σ_θ 26.0 to 26.4 (Figures 2a and 2c). At greater depths (σ_θ 26.4 to 26.7), there was a small decrease in salinity and temperature in the eddy core relative to the local waters.

3.2. Nutrients and Oxygen

[13] Compared to local waters, DIN and DIP were generally higher in concentration in the eddy center at depths from ~140–500 m and lower for oxygen (Figures 2b and 3). A local minimum of oxygen was present at ~300 m depth. Plotted against density (Figure 4), lower oxygen and higher nutrients in the σ_θ range of 26.2 to 26.6 were observed at eddy center. Above and below this layer, the oxygen and nutrient concentrations were similar between the eddy core and the local waters.

3.3. Total Organic Carbon and Nitrogen

[14] TOC profiles plotted against density were generally the same inside and outside the eddy (Figure 5a), except at σ_θ 26.0 to 26.4 where lower TOC concentrations were found in the eddy. At σ_θ 26.2, the difference in TOC was 8.7 ± 2.4 μM (Table 1). Within the error of the measurement,

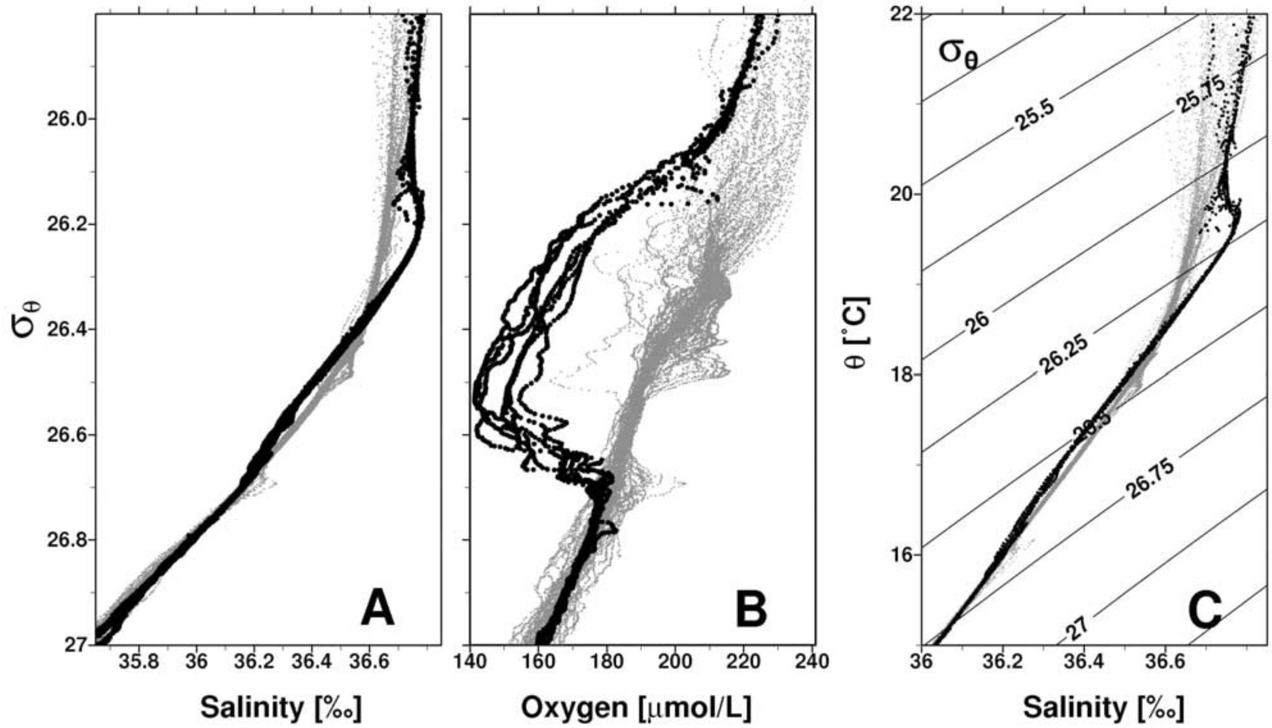

Figure 2. (a) Density-salinity, (b) density-oxygen, and (c) temperature-salinity plots of the investigated eddy (black dots are the eddy core stations, gray dots are all the other stations, θ is potential temperature, and black lines with numbers in Figure 2c are σ_θ).

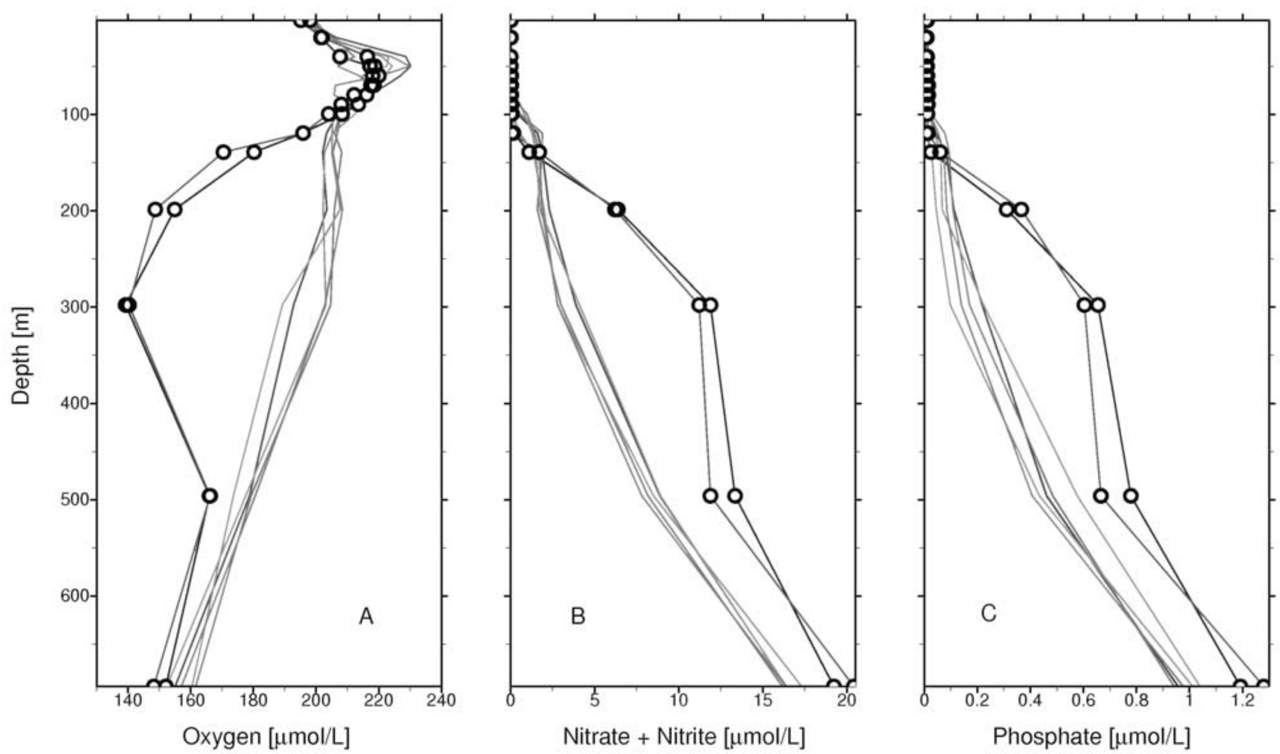

Figure 3. Depth profiles of (a) oxygen, (b) DIN, and (c) DIP in and out of the target eddy (profiles with open circles are stations at the eddy core, and profiles without circles are at the edge of the eddy).

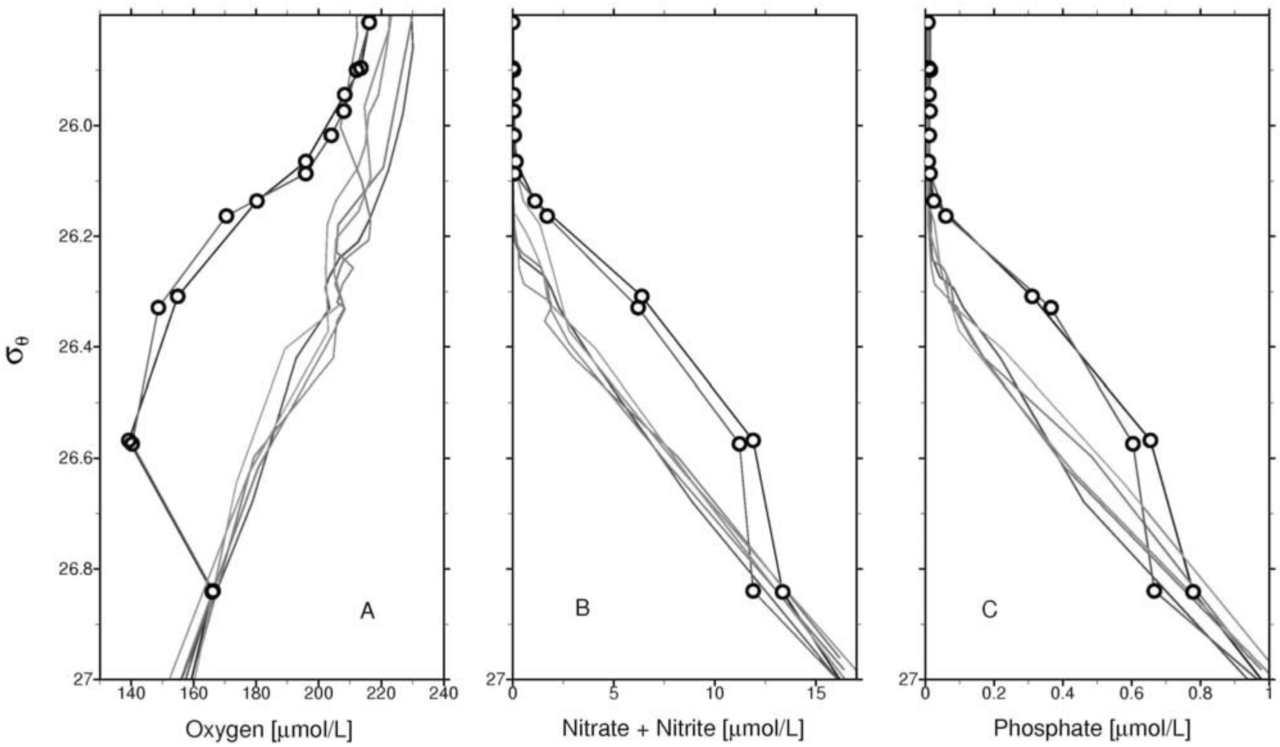

Figure 4. Density profiles of (a) oxygen, (b) DIN, and (c) DIP in and out of the target eddy (lines with open circles are stations at the eddy core, others without are at the edge of the eddy).

TON concentrations were the same in and out of the eddy (Figure 5b).

4. Discussion

[15] In evaluating the impact of an eddy on biogeochemical processes, we first must establish the initial conditions of the waters undergoing change. If the eddy is formed with water that is local to the eddy at the time of sampling, then gauging the biogeochemical impact is straightforward. If the eddy is instead formed with waters of a more distant origin with distinct characteristics, then those waters must first be identified and characterized.

4.1. Can the Eddy Core Be of Local Origin?

[16] We have described the hydrographic and biogeochemical features of an eddy located in the western Sargasso Sea near Bermuda. Several pieces of evidence suggest that the eddy core may not have been locally formed. First, the T/S diagram and density-salinity profile (Figures 2a and 2c) indicate subsurface salinity and temperature anomalies associated with the observed oxygen minimum and nutrient maxima. The adjacent (local) waters both in the vertical and horizontal (on an isopycnal surface) are unlikely source waters at σ_θ 26.0∼26.4, since the adjacent waters are relatively colder and fresher. Second, the quasi-conservative tracers NO and PO [*Broecker*, 1974] indicate that the eddy core has lower NO and PO compared to the surrounding waters (Figures 6a and 6b). The density range of these anomalies is consistent with that of the salinity and temperature anomalies. The local waters outside the eddy generally fall within the typical ranges of values for water observed at Bermuda Atlantic Time series Study (BATS) (Figures 6c and 6d), but those in the anomalous eddy core water fall outside the range. If NO and PO are indeed conservative, these data indicate that the eddy core was not locally formed. Third, we observed low TOC in the eddy core, with differences of up to about 9 μM (Figure 5a), which may again suggest that this water was different from the surrounding waters. Finally, if we simply compare the DIN and DIP profiles in and out of the eddy on density surfaces, we find that there is a significant excess of these nutrients in the subsurface (Figures 4b and 4c). One potential explanation for the elevated DIN signal is remineralization of labile TON. However, TON is similar inside and outside of the eddy (Figure 5b), indicating its relatively conservative nature. The more likely explanation for elevated DIN in the subsurface waters of the eddy core is remineralization of sinking particles. Neither free floating sediment traps nor ^{234}Th-based exported production estimates [*Buesseler et al.*, 2008] demonstrated enhanced particle flux within the eddy core, suggesting that particle flux events took place well before our sampling.

4.2. What Are the Possible Source Regions for the Eddy?

[17] We evaluate the likely source regions for the observed eddy using several physical and biogeochemical tracers. In previously published work, various techniques have been used to address the question of eddy origins. These include tracers, such as salinity and oxygen [*McDowell*, 1986; *Lukas and Santiago-Manddujano*, 2001] or CFCs and

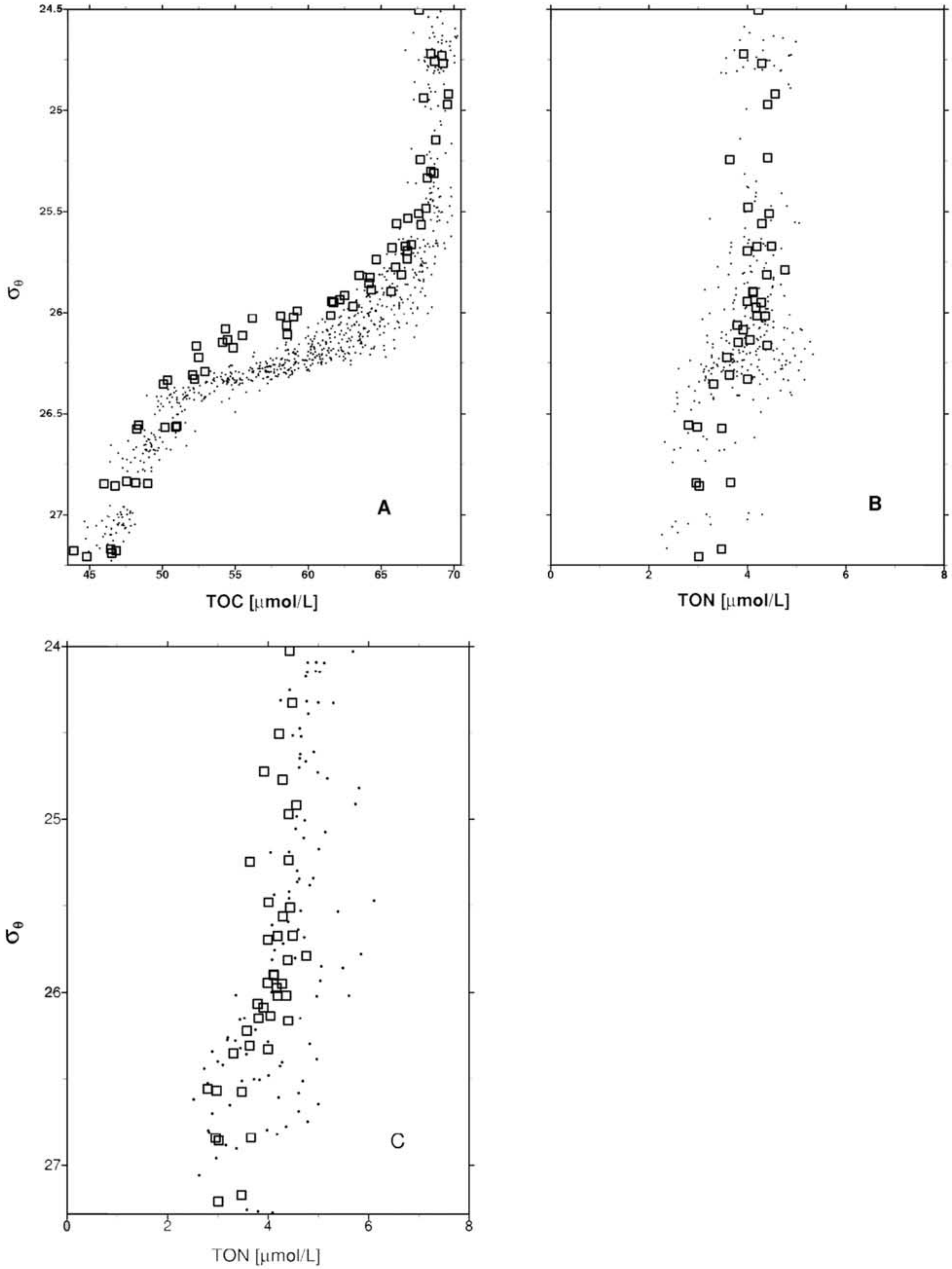

Figure 5. Vertical profiles of the (a) TOC and (b) TON in and out of eddy (open squares are eddy core stations, and small dots are all other stations). (c) TON distribution in the eddy core and in the proposed source waters (open squares are eddy core stations, and small dots are stations from WOCE stations close to the proposed origin).

Table 1a. Mean Nutrients, Oxygen, DIC, and TOC Concentrations in the Proposed Source Region and the Target Eddy (Eddy Core and Ambient Waters) at σ_θ of 26.2, 26.3, 26.5, and 27.0[a]

$\sigma\theta$	DIN	DIP	AOU	O_2	DIC	TOC
Characteristics of the Proposed Source Waters (N = 27 Except for TOC, for Which N = 5)						
26.2	1.56 ± 0.55	0.05 ± 0.03	30.5 ± 5.7	194.4 ± 6.2	2106.7 ± 7.1	53.3 ± 1.0
26.3	2.65 ± 0.99	0.12 ± 0.06	32.1 ± 7.0	195.6 ± 6.9	2109.7 ± 3.5	51.1 ± 1.0
26.5	5.11 ± 1.26	0.25 ± 0.08	38.1 ± 7.2	196.9 ± 7.0	2120.5 ± 6.0	49.5 ± 2.4
27.0	16.6 ± 5.0	0.99 ± 0.33	94.8 ± 24.6	165.1 ± 13.9	2160.5 ± 10.4	45.7 ± 1.5
Core Water Characteristics (N = 6)						
26.2	2.87 ± 0.03	0.13 ± 0.01	55.9 ± 2.3	165.8 ± 1.4	2127.5 ± 3.8	53.3 ± 0.8
26.3	5.68 ± 0.03	0.31 ± 0.02	71.5 ± 2.5	153.8 ± 1.3	2145.8 ± 5.2	51.8 ± 1.0
26.5	10.07 ± 0.35	0.55 ± 0.02	91.2 ± 1.9	143.1 ± 1.9	2153.0 ± 2.0	50.2 ± 1.1
27.0	16.1 ± 0.7	0.97 ± 0.05	102.3 ± 1.5	158.4 ± 1.4	2157.9 ± 2.1	46.8 ± 1.1
Ambient Water Characteristics at Eddy Edge (N = 8)						
26.2	0.29 ± 0.16	0.02 ± 0.02	14.3 ± 3.6	211.0 ± 3.6	2092.2 ± 4.6	62.0 ± 1.6
26.3	1.77 ± 0.48	0.09 ± 0.03	23.8 ± 4.6	203.7 ± 4.6	2095.8 ± 2.7	57.5 ± 1.3
26.5	5.51 ± 0.41	0.30 ± 0.03	44.1 ± 4.8	190.0 ± 4.7	2116.1 ± 3.9	49.7 ± 1.2
27.0	16.9 ± 0.1	1.04 ± 0.02	105.2 ± 2.5	155.1 ± 2.1	2158.0 ± 2.3	47.1 ± 1.2

[a]Units: μmol L^{-1}. Data from WOCE, AR20, Reid-Mantyla, and D. A. Hansell (unpublished data, 2002) were employed for generating regressions to determine concentrations of variables on isopycnal surfaces. Investigated area for the source water: 50–60°W, 20–25°N. *N* is the number of stations used for calculation. DIC, dissolved inorganic compounds; TOC, total organic carbon; DIN, dissolved inorganic nitrogen; DIP, dissolved inorganic phosphorus; AOU, apparent oxygen utilization.

nutrients [*Smythe-Wright et al.*, 1996], as well as remote sensing techniques using satellite altimetry and infrared radiometry [*McDonagh and Heywood*, 1999; *Seki et al.*, 2001; *Sweeney et al.*, 2003]. Biogeochemical diagnostics such as 'PO' and 'NO' [*Broecker*, 1974], and hydrographic characteristics such as salinity and temperature, were measurably different in the eddy core compared to local waters (Figures 2 and 6), so they were employed here as quasi-conservative tracers.

4.2.1. Determination of the Eddy Origin Water in the North Atlantic Basin

[18] The maximum in the salinity anomaly was located at $\sigma_\theta \sim 26.2$ (Figure 2). This density surface is taken to be the core water best preserved since formation, and so the water with the most conserved properties to be traced to its formation site. *Conkright et al.*'s [2002] data provide the climatological distributions of the tracers of interest. Differences in the values of the tracers between the eddy core at σ_θ 26.2 and the *Conkright et al.*'s [2002] data are shown in Figure 7. Deviations in tracer values between the eddy core and the rest of the North Atlantic can be used to identify possible source regions (i.e., where the differences in tracer signal are minimal between eddy core and *Conkright et al.*'s [2002] data). A difference of zero in the variable of interest indicates that water type in that region is essentially the same as in the eddy core, thus suggesting the region as a possible source [Note: if we consider the mixing between core water (with high salinity and low "PO") and background surrounding water in the western North Atlantic subtropical gyre (generally with lower salinity and higher "PO" than core water) during eddy transport, the true source water of this eddy should have somewhat higher salinity (or temperature) and lower "PO" (or "NO") than that found in the eddy core]. Compared to the values observed in the eddy, "PO" and "NO" are similar or lower in an area of 20–25°N and 35–70°W (Figures 7a and 7b). Given inputs of N due to N_2 fixation [*Gruber and Sarmiento*, 1997; *Hansell et al.*, 2004, 2007; *Bates and Hansell*, 2004; *Capone et al.*, 2005] and atmospheric deposition [*Prospero et al.*, 1996; *Hansell et al.*, 2007], NO may not be a fully conserved tracer in the subtropical North Atlantic. Therefore, PO may be the more conservative tracer for the purposes of this study.

[19] The distribution of salinity differences at σ_θ 26.2 are similar to that of potential temperature (Figures 7c and 7d). The elevated salinity and temperature signatures (where ΔT and ΔS are >0 in Figures 7c and 7d) may be associated with Subtropical Underwater, which has higher salinity and temperature because of the subduction of warm and salty central subtropical gyre water beneath fresher water to the south [*Schmitz and Richardson*, 1991].

[20] The most plausible area for formation of the eddy is where the various tracers overlap in their indication of source waters. All four tracers (i.e., NO, PO, salinity and potential temperature) overlap in the vicinity of 50 to 60°W, 20 to 25°N on σ_θ 26.2 (Figure 8). Applying the same technique to deeper isopycnal surfaces (σ_θ = 26.3 and 26.5), the potential source regions include some of the same area indicated by σ_θ 26.2 (Figure 9a). However, consideration of the deeper isopycnals broadens the potential source region considerably. For the case of σ_θ 26.5 the potential source region even includes the area near Bermuda where the eddy was observed. Analysis of other oceanographic data sets, such as Reid-Mantyla (http://odv.awi-bremerhaven.de/data/

Figure 6. Vertical distributions of (a) PO and (b) NO in and out of the eddy (profiles with open squares are eddy core stations, and profiles without symbols are stations at the edge of the eddy). Vertical distributions of (c) PO and (d) NO at the BATS site (small dots) and in the eddy core (squares); BATS data from 1988 to 2003.

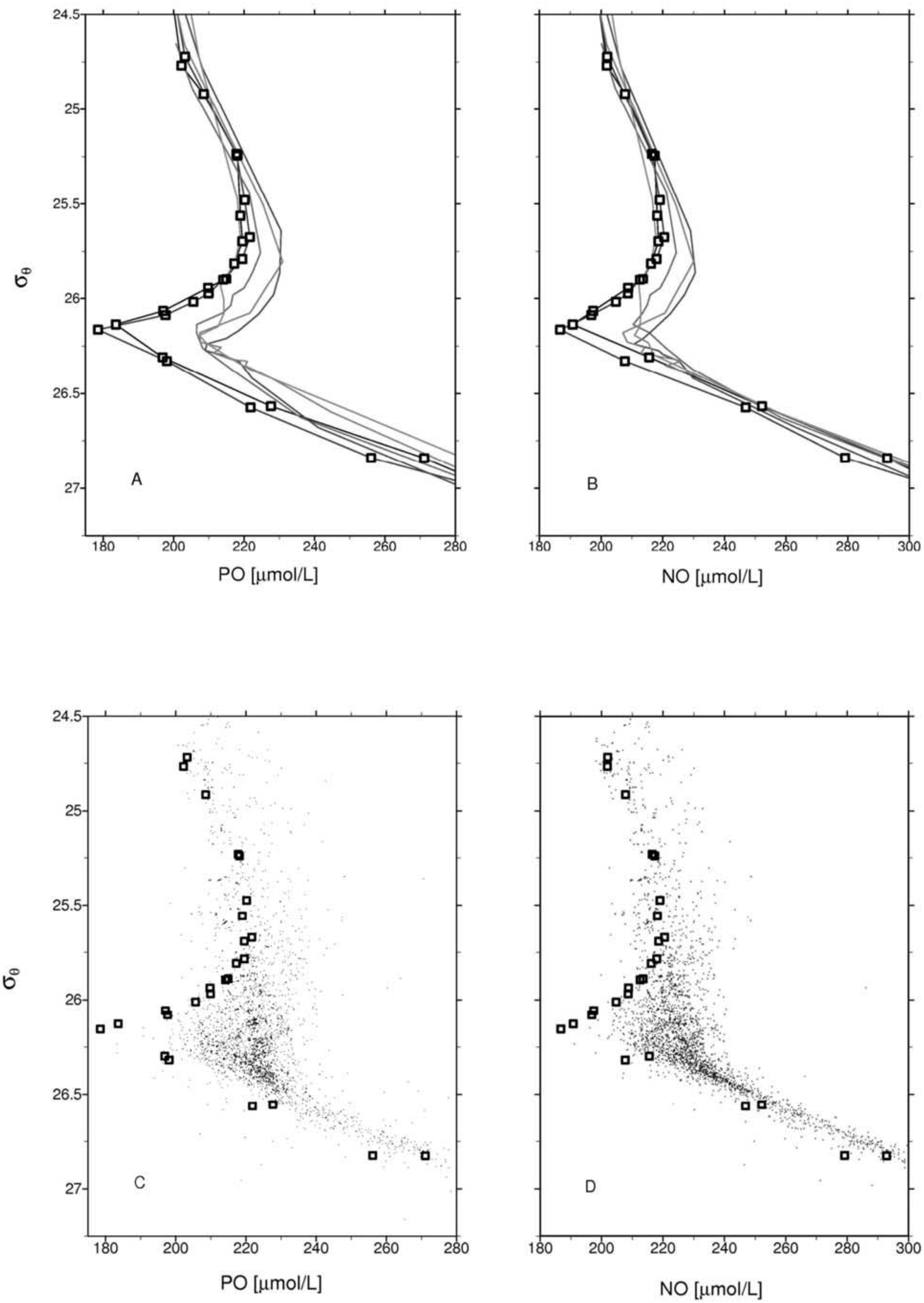

Figure 6

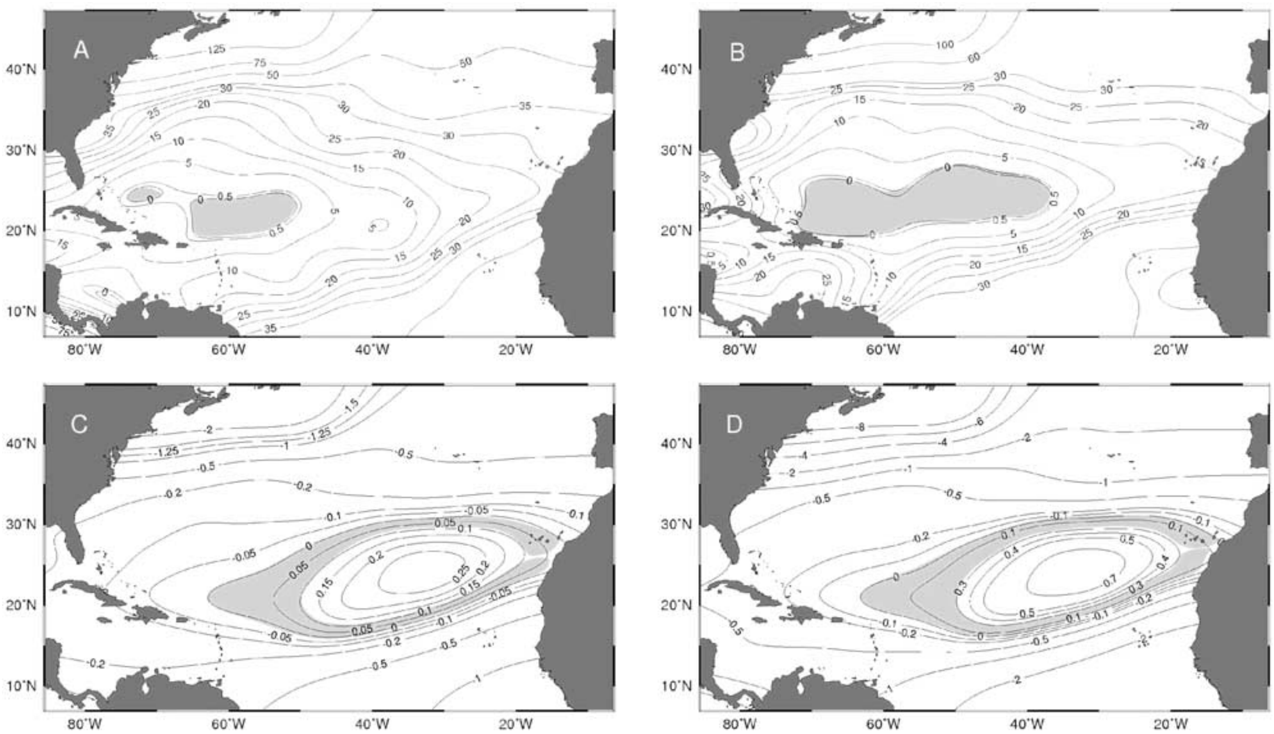

Figure 7. Distribution of (a) ΔPO, (b) ΔNO, (c) ΔSalinity, and (d) ΔT (potential temperature) on isopycnal surface 26.2 in the North Atlantic Ocean ($\Delta X = X_i - X_0$, where X_i is the water properties in North Atlantic and X_0 is the water properties in the eddy core, and shaded area in Figures 7a, 7b, 7c, and 7d is where $\Delta PO \leq 0$ μmol L^{-1}, $\Delta NO \leq 0$ μmol L^{-1}, $0 \leq \Delta$Salinity ≤ 0.1, or $0°C \leq \Delta T \leq 0.3°C$; i.e., the source water cannot have higher PO and NO or lower salinity and temperature than the eddy core; see text). Data are from annual means of *Conkright et al.* [2002].

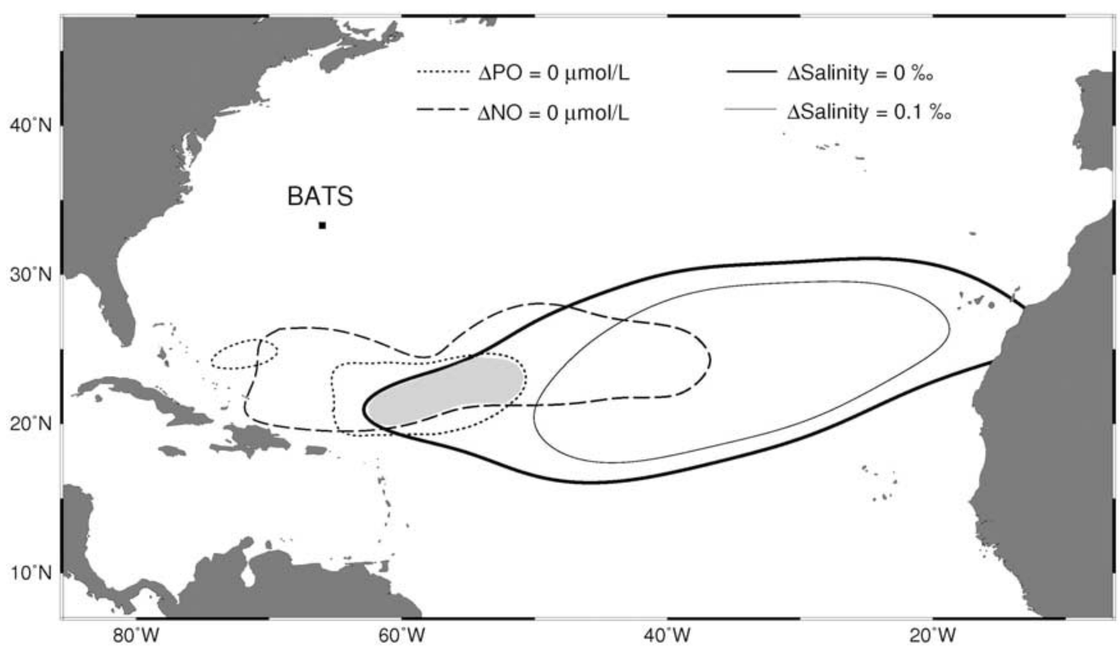

Figure 8. Overlay of the source regions indicated by the tracers in Figure 7 (gray patch indicates the region where PO, NO, salinity, and potential temperature of the seawater are similar to those in the eddy core).

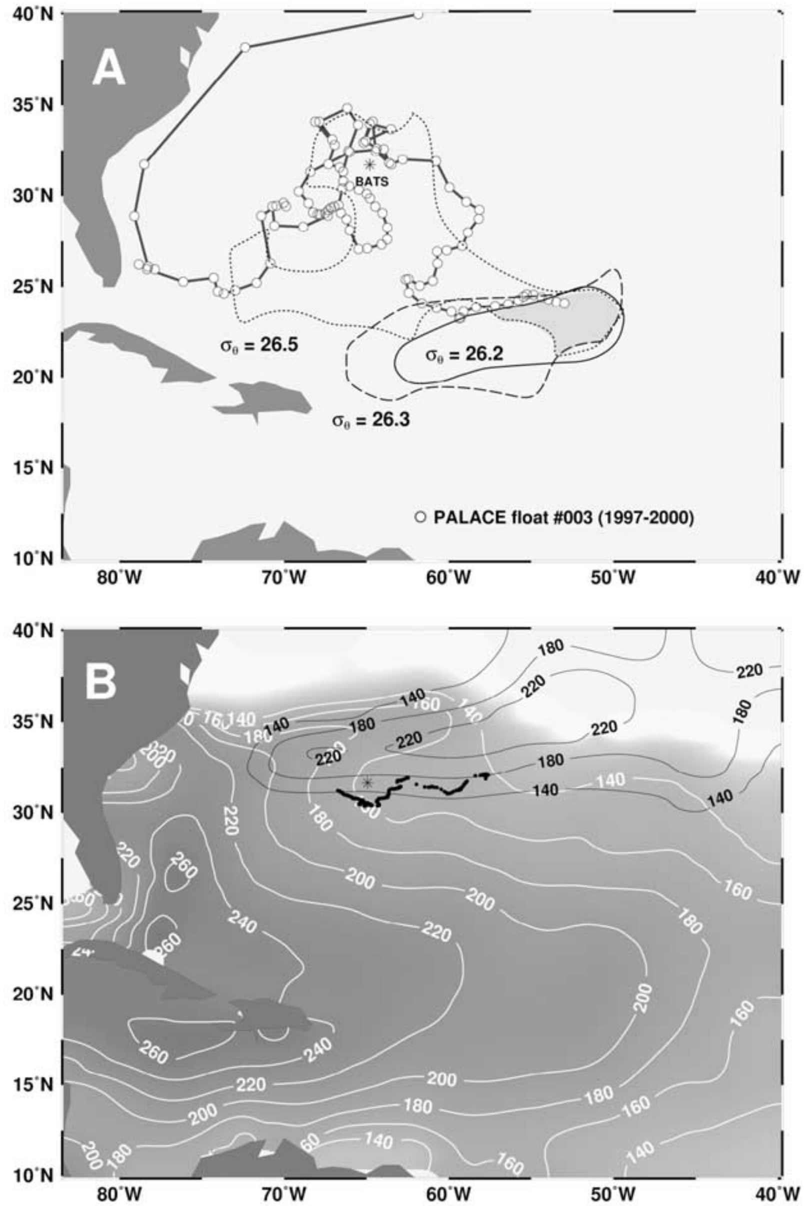

Figure 9. (a) Overlay of potential source waters at three different isopycnal surfaces: 26.2 (black line), 26.3 (broken line), and 26.5 (dashed line). Shading indicates the area of their intersection. The trajectory of a subsurface float from Profiling Autonomous Lagrangian Circulation Explorer (float #003) is shown with open circles and gray lines. (b) The depths of isopycnal 26.2 (white lines) and the climatological mixed layer (black lines) during March in the North Atlantic Ocean (data from *Conkright et al.* [2002]), and the positions of altimeter backtracking (black dots). Star is the position of BATS site. Duration of the altimetry pathway is ~5 months.

ocean/reid-mantyla.html) and WOCE (World Ocean Circulation Experiment) (http://www.ewoce.org/data/index.html), yielded similar results.

[21] We also investigated the sensitivity of our results to the Redfield assumptions used in the analysis. Departures from the canonical Redfield ratio have been noted in this region, both for C:N [*Ono et al.*, 2001; *Koeve*, 2005] and O_2:P [*Takahashi et al.*, 1985]. Using O_2:P ratio of 175 [*Takahashi et al.*, 1985; *Anderson and Sarmiento*, 1994], we recomputed the concentrations of PO in North Atlantic basin as well as those in the eddy. This PO was then used as tracer to locate the possible source region for the eddy. The final result by PO using O_2/P ratio of 175 was not much different from what we have shown in Figure 9a using Redfield ratio of 138 [*Redfield et al.*, 1963; *Li and Peng*, 2002].

[22] It is enigmatic that the source region suggested by the tracer analysis is spatially disconnected from the eddy pathway indicated by satellite altimetry (Figure 9b). Nevertheless, Lagrangian measurements do provide evidence

that a connection between the observed eddy and the proposed source region is kinematically possible. As seen in Figure 9a, float #003 of the Profiling Autonomous Lagrangian Circulation Explorer program moved from the area of 53°W and 24°N (at ~1000 m) to near Bermuda (at ~550 m), with an elapsed time of about 1 year.

[23] It is noteworthy that the winter outcrop of σ_θ 26.2 (i.e, where the depth of the isopycnal is shallower than the depth of winter mixing), north of the Bermuda (Figure 9b), could impact the eddy core on this isopycnal surface as the eddy transited that region, as shown in the altimetrically derived trajectory of the eddy. Clearly, if water mass properties on the target isopycnal were modified by air-sea interaction, that would violate the assumption of conservation or quasi-conservation of tracers used to infer the eddy source region. Unfortunately, we have no way to quantify the degree to which the anomalous layer may have ventilated. Therefore it is not possible to assess the associated uncertainty in the proposed source region.

4.2.2. Comparison of Vertical Profiles Between the Eddy Core and the Proposed Source Water

[24] To further test identification of eddy source waters, it is useful to compare vertical profiles between the possible origin and the eddy core. Figure 10a compares σ_θ-salinity profiles of the eddy core with characteristic profiles from other locations in the subtropical and tropical North Atlantic Ocean. The proposed source water and the eddy core are very similar below the σ_θ 26.2 surface. Differences at lower densities may be explained by mixing of the eddy core with surrounding waters during transit away from the formation area and/or because of net precipitation (lowering the salinity). The vertical profiles for CTD oxygen (Figure 10b) and nutrients (Figures 10c and 10d) at $\sigma_\theta > 26.7$ also indicate that the proposed source water is more comparable with the eddy core than with the other waters examined. The large offset of oxygen and nutrients in the subsurface between the eddy core and the hypothetical source water ($26.1 < \sigma_\theta < 26.7$) can be attributed to remineralization of sinking biogenic materials (further evaluated in the next section). TOC is relatively conservative in the western Sargasso Sea [*Hansell and Carlson*, 2001]. Unfortunately, TOC observations are too few to construct a spatially resolved map in the Sargasso Sea. However, study of the CLIVAR (Climate Variability and Predictability) A20, A22 and AR16N lines (http://cdiac.ornl.gov/oceans/datmet.html) indicate a similarity of TOC concentrations between the eddy core and the proposed source waters, while TOC on the σ_θ 26.2 surface in both those waters was about 9 μM higher at BATS (Figure 5a).

4.3. Biogeochemical Variation of Nutrients During Transit of the Eddy

4.3.1. N:P Remineralization Ratios in the Eddy Core

[25] The eddy sampled near Bermuda displayed a subsurface excess of nutrients (Figures 10c and 10d) along with a commensurate deficiency of oxygen (Figure 10b). These anomalous concentrations (relative to the proposed source water) are attributed to enhanced export of organic particles in the eddy, with subsequent oxygen consumption and release of macronutrients. Mineralization was further evidenced by elevated DIC in the eddy core (Table 1). The concentrations of nutrients, oxygen, DIC and TOC on four isopycnal surfaces in the eddy core, in the water local to the eddy, and in the proposed southern source waters are given in Table 1. Concentrations in the proposed source waters at specific isopycnals were determined by linear regression of the available bottle data (WOCE and Reid-Mantyla data within the area of 50~60°W, 20~25°N) against density. The same technique was applied for the calculation of biogeochemical properties in the eddy core and the local surrounding waters. Descriptions of this technique are given elsewhere [*Hansell et al.*, 2004]. Since WOCE and Reid-Mantyla data set comprises multiple cruises from different times of the year, the seasonal variability of water properties in the proposed region is presumed to be included in the analysis, as inferred from the much larger error bars in the source water than in the eddy core and local waters (Table 1).

[26] The increase in DIN and DIP in the eddy, relative to the proposed source water, occurred near *Redfield et al.* [1963] ratios of ~16 (see ΔN:ΔP; Table 1b). This is to be expected given the Redfield assumptions underlying the use of NO and PO in identifying the potential source region. Relative to the local waters, the nutrients increased at ratios greater than Redfield (ΔN:ΔP = 17.9–23.3). Sinking particles formed by N_2 fixation could cause a deviation from Redfield, but rates of N derived from the process are generally much lower than the apparent accumulation in the eddy. For example, *Hansell et al.* [2004] reported an accumulation rate of N due to diazotrophy on the σ_θ 26.5 surface of 0.09 μM N a^{-1}, but the increase in N in the eddy on that surface was 4.96 μM (Table 1b), which would require 55 years of accumulation. These results indicate that the remineralization of sinking particles is the major mechanism controlling the variability of nutrients in the eddy core.

4.3.2. Estimating Biogeochemical Impact Using Nitrogen Mass Balance in the Eddy Core

[27] Assessment of eddy-induced biogeochemical variability is typically done by comparing water masses and their biogeochemistry inside an eddy to those characteristics outside an eddy [*Law et al.*, 2001; *Vaillancourt et al.*, 2003]. The underlying assumption of this approach is that the target eddy is formed locally and thus both the eddy core water and the surrounding waters are originally identical, with changes occurring subsequent to eddy formation. Except in the case of rings spawned from boundary currents, this assumption is largely valid when an eddy first forms (i.e., the eddy is indeed composed of local water). However, after eddy generation and movement of the eddy away from the site of formation, this assumption fails. For mesoscale eddies carrying water from remote regions [*Richardson*, 1993; *Lukas and Santiago-Manddujano*, 2001], assessments of the eddy's biogeochemical impacts must be made by comparing the eddy core properties with its original properties (i.e., at its source at the time of formation).

[28] Because of their discrete nature, mesoscale eddies can be assessed for mass balance of biogeochemical variables [*Law et al.*, 2001]. In the eddy studied here, a large amount of DIN accumulated in the subsurface eddy core (Figure 10c). To determine the sources of the accumulated nitrogen, an inventory of all forms of nitrogen in this eddy is necessary. There are two forms of nitrogen to be considered: dissolved inorganic nitrogen, most of which is in the form

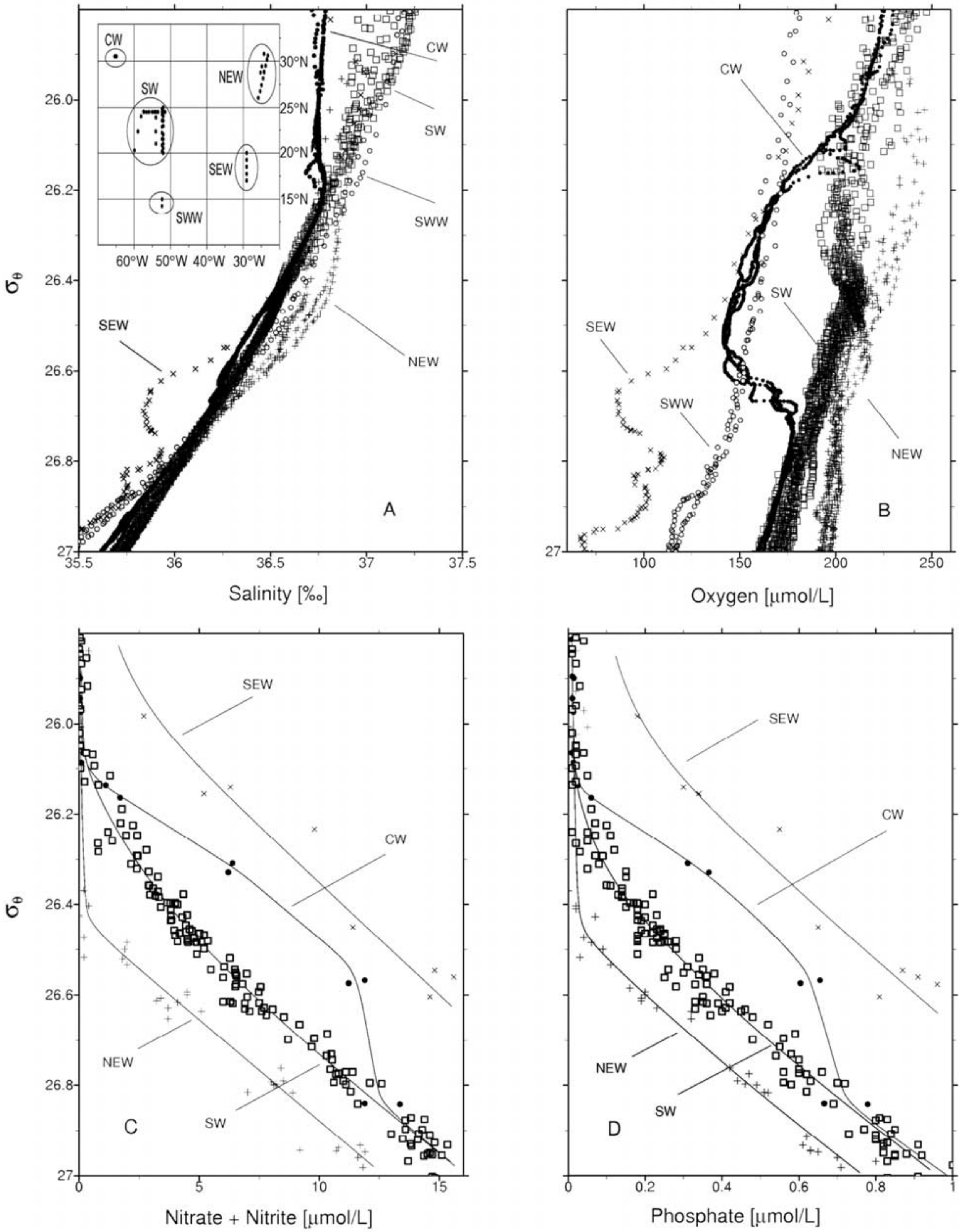

Figure 10. Vertical density profiles of (a) salinity, (b) oxygen, (c) DIN, and (d) DIP in the North Atlantic (black dots are eddy core water (CW), open squares are the proposed source water (SW), crosses are the northeastern water (NEW), Xs are the southeastern water (SEW), open circles are the southwestern water (SWW), and both bottle and CTD data are from WOCE).

Table 1b. Comparisons of Biogeochemical Characteristics Between Different Waters[a]

$\sigma\theta$	ΔN	ΔP	ΔAOU	ΔO_2	ΔDIC	ΔTOC	ΔN/ΔP
			Core Water–Source Water				
26.2	1.31 ± 0.58	0.08 ± 0.04	25.4 ± 8.0	−28.6 ± 7.6	20.8 ± 10.9	0.0 ± 1.8	16.4
26.3	3.03 ± 1.02	0.19 ± 0.08	39.4 ± 9.5	−41.8 ± 8.2	36.1 ± 8.7	0.7 ± 2.0	16.0
26.5	4.96 ± 1.61	0.30 ± 0.10	53.1 ± 9.1	−53.8 ± 8.9	32.5 ± 8.0	0.7 ± 3.5	16.5
27.0	−0.5 ± 5.7	0.0 ± 0.4	7.5 ± 26.1	−6.7 ± 15.3	−2.6 ± 12.5	1.1 ± 2.6	–
			Core Water–Ambient Water				
26.2	2.78 ± 0.19	0.11 ± 0.03	41.6 ± 5.9	−45.2 ± 5.0	35.3 ± 8.4	−8.7 ± 2.4	23.3
26.3	3.91 ± 0.51	0.22 ± 0.05	47.7 ± 7.1	−49.9 ± 6.0	50.0 ± 7.9	−5.7 ± 2.3	17.9
26.5	4.56 ± 0.76	0.25 ± 0.05	47.1 ± 6.7	−46.9 ± 6.6	36.9 ± 5.9	0.5 ± 2.3	18.7
27.0	−0.8 ± 0.8	−0.1 ± 0.1	−2.9 ± 4.0	3.3 ± 3.5	−0.1 ± 4.4	−0.3 ± 2.3	–

[a]Units: μmol L^{-1}.

of nitrate in the subsurface, and organic nitrogen, which includes dissolved organic nitrogen (DON) and particulate organic nitrogen (PON). The TON (DON + PON) concentrations (calculated from TON = TN − DIN) in the eddy core were similar to those found at the edge of the eddy (Figure 5b), but were less than the concentrations in the proposed eddy source waters (Figure 5c) at densities <26.5.

[29] Vertically integrated stocks of TN, DIN and TON in the eddy core and in the source water are given in Table 2. Relative to the proposed source water, DIN accumulation in the eddy core was 0.68 ± 0.19 mol N m^{-2}. This accumulation of DIN has two likely sources: remineralization of labile organic nitrogen present in the source water at eddy formation, and the remineralization of particles sinking from the euphotic zone (Figure 11). TON in the eddy core was 0.87 ± 0.05 mol N m^{-2}, a value less than the TON in the hypothesized origin (1.04 ± 0.10 mol N m^{-2}), which may imply a net remineralization of organic nitrogen of 0.17 ± 0.15 mol N m^{-2} during eddy transport. Therefore, vertical import of 0.51 ± 0.34 mol N m^{-2} is required to balance the nitrogen budget and this nitrogen likely originates from the biogenic particles introduced from above. However, we should keep in mind that a different estimation of export production for this eddy would be inferred if we assumed this eddy feature to be locally generated. Differencing the core waters and the ambient waters over the depth interval of the anomaly yields a value of 1.15 ± 0.28 mol N m^{-2} on the basis of the profiles of total nitrogen (Table 2). Using Redfield stoichiometry and oxygen profiles inside versus outside the eddy, *McGillicuddy et al.* [2007] reported an implied remineralization of ∼1.4 mol N m^{-2}.

4.3.3. Uncertainties in the Interpretation of Biogeochemical Impacts

[30] During the lifetime of the eddy, the entrapped core water is eroded both by horizontal mixing with the surrounding waters and by winter convective overturn from above. Horizontal mixing apparently occurred during our observation period, with profiles of salinity and oxygen demonstrating the introduction of strong interleaving between the first and second cruises (Figure 12). The profiles present during the first cruise (Figures 2, 3, and 4) changed relatively smoothly with depth (little evidence for strong interleaving), so those data alone were used in the mass balance assessment and source water determinations. The spatial scale of the oxygen anomaly was 20–30 km during the time of our sampling, and thus constituted a submesoscale feature within the eddy's inner core. Its volume could have been larger prior to our occupations, but the timing of the inferred export event remains unknown. Since we have only short-term observations (interval of ∼2 months), the eddy's history of mixing between the export event and our visit is not known. Therefore, the amount of mixing of eddy core with surrounding waters, and the impact this has on our assessment of biogeochemical impact, is a major uncertainty.

[31] If the export event occurred in the proposed source region (as opposed to having occurred much closer in time to our sampling), then the oxygen anomaly would have to have been transported relatively intact over a long time period, and only be disrupted by intermittent mixing at the time of our cruises. We cannot rule out the possibility that the export event occurred sometime well after the eddy formation, but at least two months prior to our sampling (given the absence of a strong export signature in the ^{234}Th field [*Buesseler et al.*, 2008]). Given this, our calculation of cumulative export production in this eddy is likely an

Table 2. Integrated Total Nitrogen (ΣTN), Dissolved Inorganic Nitrogen (ΣDIN), and Total Organic Nitrogen (ΣTON) in the Subsurface Eddy Core Water (CW), Ambient Water Locally Surrounding the Eddy (AW), and the Proposed Source Water (SW)[a]

Water Identification	Depth Interval (m)	ΣTN	ΣDIN	ΣTON
		σ_θ = 26.1∼26.7		
CW	262 ± 16	3.02 ± 0.09	2.15 ± 0.04	0.87 ± 0.05
SW	244 ± 29	2.51 ± 0.25	1.47 ± 0.15	1.04 ± 0.10
AW	447 ± 31	4.36 ± 0.17	2.33 ± 0.12	2.03 ± 0.05
CW-SW	18 ± 45	0.51 ± 0.34	0.68 ± 0.19	−0.17 ± 0.15
CW-AW	−185 ± 47	−1.34 ± 0.26	−0.18 ± 0.16	−1.16 ± 0.10
		Z = 140∼400 m		
CW	–	3.10 ± 0.12	2.28 ± 0.08	0.82 ± 0.04
AW	–	1.95 ± 0.14	1.04 ± 0.09	0.91 ± 0.05
CW-AW	–	1.15 ± 0.28	1.24 ± 0.17	−0.09 ± 0.10

[a]Integration was conducted between σ_θ = 26.1 and σ_θ = 26.7, the density range at which the deficiency of CTD oxygen was observed (Figure 9b); the concentrations of TN, DIN, and TON in the eddy core at σ_θ = 26.7 (∼400 m in depth) were assumed to be the same as those of the proposed source water at the same isopycnic surface. For comparison, we also integrate the nitrogen from 140 m to 400 m, the depth range of CTD oxygen deficiency found in the eddy core. Data from CLIVAR (section AR20 occupied in 2003) and D. A. Hansell (unpublished data, 2002) collected aboard R/V *Oceanus* in 2002 in 50∼60°W and 20∼25°N were chosen for ΣTN, ΣDIN, and ΣTON calculations. Units for integrated nitrogen: mol N m^{-2}.

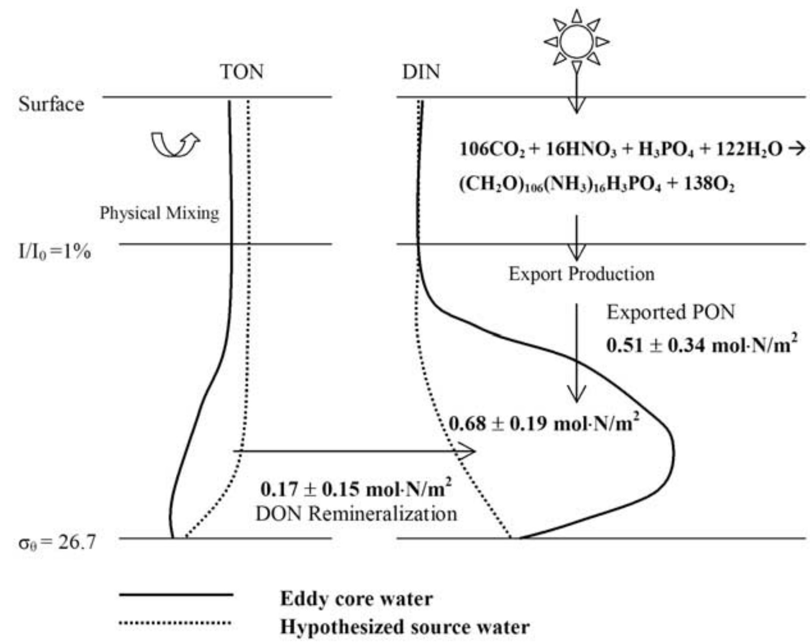

Figure 11. Nitrogen budget in this eddy during its propagation. Dotted line is the distribution of TON and DIN in the source water before the eddy forcing, and black line is the distribution of TON and DIN in the observed eddy core. The values of nitrogen masses presented here are from Table 2, and isopycnal surface 26.7 is the deepest layer where the subsurface excess nitrogen was found.

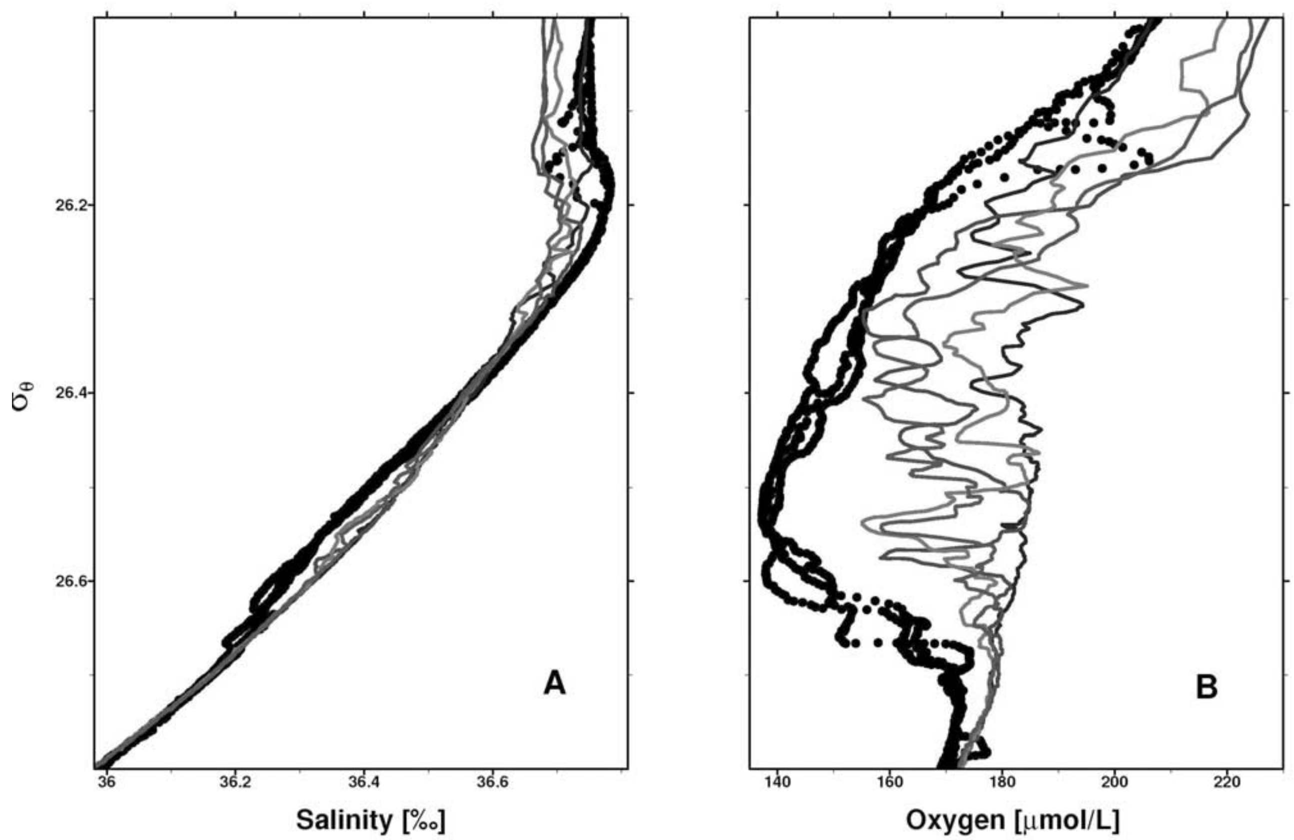

Figure 12. Comparison of (a) salinity and (b) oxygen plots in the eddy center between two different occupations (black dots are the first occupation in June 2004, and gray lines are the second occupation in July-August 2004).

underestimate of the eddy's real biogeochemical activity during transit in the Sargasso Sea.

5. Conclusions

[32] We report hydrographic and biogeochemical anomalies in the core of a mesoscale cyclonic eddy located near Bermuda, and find that the anomalies may not be fully attributable to local physical and biological sources. On the basis of quasi-conservative tracers, our results suggest that the eddy originated in the southern sector of the North Atlantic subtropical gyre. We infer that remineralization of sinking organic particles was the key mechanism for the strong biogeochemical variations observed in the eddy core. Since little enhanced export was observed at the time of eddy occupation in sediment traps or in Thorium-234-based estimates [*Buesseler et al.*, 2008], export is suggested to have occurred at least two months prior to our observations (the timescale for Thorium-234 equilibrium to be achieved). A nitrogen budget indicates minimum new production of 0.5 ± 0.3 mol N m^{-2} is required from the time of eddy-induced event to the time of our sampling.

[33] Our results indicate that the subsurface nutrient remineralization and oxygen utilization estimated near BATS can be impacted by the eddy transport of biogeochemical signatures of export originating at distant sites. Therefore, investigations on the imbalance of new production estimated by geochemical tracers must include both new nutrients supplied via local vertical processes and horizontal advection by mesoscale eddies.

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