



Correction published 7 March 2008

## Decadal analysis of hydrography and in situ nutrient budgets in the western and eastern North Atlantic subtropical gyre

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Received 29 June 2006; revised 30 January 2007; accepted 5 April 2007; published 24 July 2007.

[1] The current debate about the mechanisms and magnitude of new nutrient input to the euphotic zone in subtropical gyres calls for studies which consider large and mesoscale perspectives by combining in situ time series and remote observations. We carried out a first of its kind comparative analysis of hydrography and sea level anomaly (SLA) at the oligotrophic time series stations BATS (Bermuda Atlantic Time Series Study) and ESTOC (European Station for Time Series, Canary Islands) using concomitant 10-yr in situ and satellite altimetry data. The stations are located at about the same latitude in the western and eastern boundaries of the subtropical North Atlantic gyre, respectively, and provide the opportunity to study differences that may exist between both regions. Observed SLA was 0.25 m at BATS, compared with 0.12 m at ESTOC, a consequence of the higher eddy kinetic energy in the western compared with the eastern subtropical gyre. We quantified a detailed in situ nutrient budget for both time series stations; ESTOC received about 75% of the nutrients available for new production at BATS (in average  $0.28 \text{ mol N m}^{-2} \text{ yr}^{-1}$  compared with  $0.38 \text{ mol N m}^{-2} \text{ yr}^{-1}$ , respectively), but the difference was not significant. However, significant differences in input mechanisms existed between both stations; eddy pumping constituted the main new nutrient source BATS, whereas wintertime convection was the main nutrient supply mechanism at ESTOC. In addition, the nutricline was significantly shallower at ESTOC compared with BATS, partly compensating for shallower mixed-layer depths and SLA variability at the western station. We found considerable interannual variability in both eddy pumping and wintertime convection which may be related to NAO-induced changes in the pattern of the subtropical gyre.

**Citation:** Cianca, A., P. Helmke, B. Mouriño, M. J. Rueda, O. Llinás, and S. Neuer (2007), Decadal analysis of hydrography and in situ nutrient budgets in the western and eastern North Atlantic subtropical gyre, *J. Geophys. Res.*, *112*, C07025, doi:10.1029/2006JC003788.

### 1. Introduction

[2] The estimation of nutrient fluxes to the euphotic zone constitutes a major challenge in our efforts to estimate new production in the subtropical gyres. Despite known differences in spatial and temporal variability of new nutrient sources across the subtropical gyres [e.g., *McGillicuddy et al.*, 2003; *Oschlies*, 2002a, 2002b], in situ information for estimating complete nutrient budgets is scarce. Research conducted at BATS (Bermuda Atlantic Time Series Study) in the Sargasso Sea has been invaluable in obtaining insights into the relative importance of different mechanisms trans-

porting nutrients into the euphotic zone [*Siegel et al.*, 1999; *Lipschultz et al.*, 2002]. In general, the physical processes of nutrient transport can be divided into diffusive and advective processes, both including horizontal (isopycnal) and vertical (diapycnal) motions. In addition to diapycnal mixing, eddy-driven nutrient input to the euphotic zone is considered a prominent process in supporting new production in the North Atlantic subtropical gyre (NASTG) [*McGillicuddy and Robinson*, 1997; *McGillicuddy et al.*, 1998; *Siegel et al.*, 1999; *McGillicuddy et al.*, 2003] despite some disagreement as to the relative importance of this process [*Oschlies and Garcon*, 1998; *Oschlies et al.*, 2000; *Oschlies*, 2002a, 2002b].

[3] *McGillicuddy et al.* [1999] referred to three types of eddies according to characteristics such as surface temperature, sea level anomaly (SLA), rotation, and isopycnal displacements. The two most common eddy types at BATS are those that produced elevation or depression of the main thermocline (cyclonic and anticyclonic, respectively). The third type is known as a mode water eddy, which has an intrathermocline lens that consists of a thick (almost 300 m) layer of  $18^\circ$  water [*Worthington*, 1959] or North Atlantic subtropical mode water (NASTMW, *Hanawa and Talley*, 2001).

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[4] Recently, *Williams et al.* [2006] and *Pelegri et al.* [2006] proposed epipycnal advection (nutrient irrigation or induction) as an important nutrient supplier to the euphotic zone in subpolar gyres as well as in the NASTG. Other nutrient sources are horizontal Ekman flow [*Williams and Follows*, 1998], atmospheric deposition [*Prospero et al.*, 1996], and nitrogen fixation [*Capone et al.*, 2005], which vary in importance depending on location. Furthermore, mode water variability [*Palter et al.*, 2005] may cause spatial and temporal variability in the available nutrient pool below the euphotic zone in the western NASTG, and variations in the NAO (North Atlantic Oscillation) were found to affect new nutrient supply at BATS by up to 30% [*Bates*, 2001].

[5] Earlier studies comparing processes across the subtropical gyre have indicated that the strength of the biological carbon pump (the flux of organic carbon from the euphotic zone to deeper layers of the ocean) might differ between the western and eastern parts of the NASTG. *Neuer et al.* [2002a] compared a 3-yr biogeochemical data set for BATS and ESTOC (European Station for Time Series in the Ocean, Canary Islands), and found that export production was considerably lower at ESTOC compared with that at BATS despite similar phytoplankton biomass and productivity. The authors hypothesized that this difference was due to a smaller new nutrient input into the mixed layer in the eastern NASTG, especially due to lower eddy-induced mixing and dinitrogen fixation. Results inferred from eddy-resolving models [*McGillicuddy et al.*, 2003; *Oschlies*, 2002b] and tracer-based observations [*Jenkins*, 1988; *Lewis et al.*, 1986].

[6] The goal of this study was to quantify and compare the new nutrient budgets on either side of the NASTG by analyzing in situ data and satellite derived altimetry at BATS and ESTOC. We analyzed and compared a concomitant 10-yr data set (1994–2003) based on the approach of *Siegel et al.* [1999] (hereinafter referred to as S99), who estimated that nearly 50% of the new nutrients reaching the euphotic zone at BATS site was due to eddy-induced transport. We evaluated the eddy temporal-scale variability to estimate and compare the importance of eddy pumping at both stations. The availability of these extensive data sets provides us with a unique opportunity to study differences between the eastern and western NASTG.

## 2. Data Sources

[7] Our study of hydrographic variability and nutrient budgets is based on the analysis of in situ data sets acquired at BATS and ESTOC, as well as satellite altimetry data provided by AVISO.

[8] BATS is located in 4680 m water depth in the Sargasso Sea near Bermuda [Figure 1; *Michaels and Knap*, 1996], an isolated island with no significant other islands or seamounts nearby. The station is in an area of weak Gulf Stream recirculation with a net flow towards the southwest and mesoscale eddies throughout the region [*Siegel and Deuser*, 1997]. ESTOC is located in the eastern part of the NASTG, north of the Canary Islands [Figure 1; *Llinás et al.*, 1997]. It is bounded to the east by Lanzarote and Fuerteventura islands, to the northeast by the Concepción and Dacia banks, and to the north by the Salvagens and Madeira

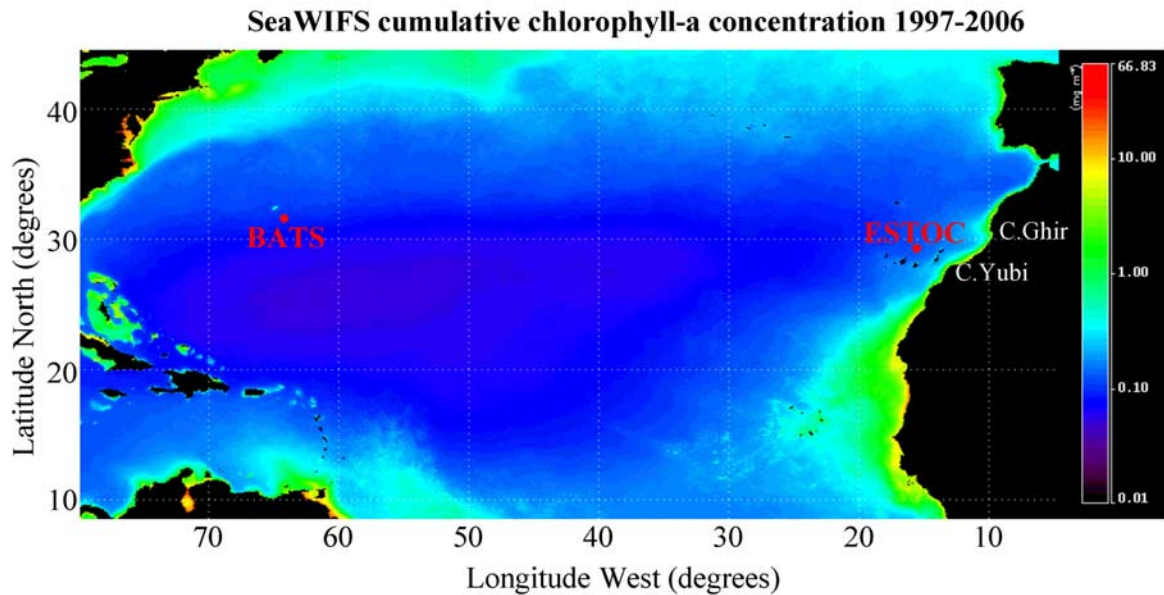
islands. ESTOC (~3615 m water depth) is located about 500 miles west of the NW African coast, far enough removed from the coastal upwelling zone that no upwelling filaments have been found to reach the station [*Davenport et al.*, 2002]. During the main upwelling season in summer and fall, however, surface temperatures were found to be slightly lower than those of a station further to the west [*Neuer et al.*, 2002b]. ESTOC exhibits oligotrophic characteristics [see Figure 1; *Neuer et al.*, 2007] and similar chlorophyll biomass and seasonality compared with BATS [*Neuer et al.*, 2002a]. The circulation is driven by the southward-flowing Canary Current and the NE trade winds.

### 2.1. “In Situ” Data

[9] BATS and ESTOC are sampled monthly except at BATS during the bloom season (February to June) when sampling is twice per month. Data collection at BATS began in October 1988 and at ESTOC in February 1994. The BATS data were obtained from the BATS Web site (<http://bats.bbcr.edu/firstpage.html>). We have selected the bottle and CTD data for the period January 1994 to December 2003 at both stations. No significant gaps were noted in the BATS sampling program and only one at ESTOC (from October 2001 to February 2002). The nutrient data are currently available only from 1994 to 2000 at ESTOC. Rationale, methodologies, and results of station observations have been reported earlier for BATS [e.g., *Lohrenz et al.*, 1992; *Buesseler et al.*, 1994; *Michaels et al.*, 1994; *Michaels*, 1995; *Michaels and Knap*, 1996; *Steinberg et al.*, 2001] and more recently for ESTOC [*Llinás et al.*, 1999; *Santana*, 1999; *Neuer et al.*, 2002a, 2002b; *González-Dávila et al.*, 2003; *Neuer et al.*, 2007].

[10] The original sampling levels were interpolated linearly to similar levels at both stations to facilitate a direct comparison. The mixed layer depth (MLD) determination was first carried out using several threshold criteria based on temperature and density for both stations (see Table 1 in *De Boyer Montégut et al.* [2004]). After the comparison of criteria, we selected a temperature difference of 0.5°C from the level of 10 m depth. This criterion is the most widely used in the literature on the North Atlantic Ocean and is less likely to be conflictive in the comparison of the two sites. For the MLD determination, we used the temperatures recorded in the bottle sampling file because only limited CTD profiles are available at ESTOC from January 1994 to August 1995. The temperature measurements during the in situ samplings, when no CTD instrument was available, were recorded by deep-sea reversing thermometers. Both assessments (from CTD and thermometers) were compared to ensure their coherence.

[11] Similarly, several criteria have been proposed in the literature for determining the nitracline. The criterion normally used is the depth at which the nitrate plus nitrite (hereinafter referred to as nitrate) concentration equals 0.5  $\mu\text{mol kg}^{-1}$  [*Santana*, 1999] or a water column depth associated with rapid changes in nitrate concentration [*Fernandez et al.*, 2005]. For this analysis, we calculated the depth of 0.5  $\mu\text{mol kg}^{-1}$  using a linear interpolation of the nitrate measurements. Other calculations were needed to estimate nutrient transport. For example, in order to identify events due to mode water eddies, we computed mode water thickness as the difference in depth between



**Figure 1.** Cumulative average chlorophyll a concentration from 1997 to 2006. Positions of BATS and ESTOC are indicated.

the 18.5° and 17.5°C isotherms at BATS and the 17.5° and 16.5°C isotherms at ESTOC. Although the range used by *Siedler et al.* [1987] to define mode water in the eastern North Atlantic was 18° to 16°C, we made our selection to avoid artifacts due to winter mixing.

## 2.2. Satellite Altimetry

[12] Satellite-derived sea level anomaly data were obtained from AVISO, CLS/DOS, Ramonville St-Agne, France ([www.aviso.oceanobs.com](http://www.aviso.oceanobs.com)) for the period 1993 through 2003. This data set combines sea surface altimetry from Topex/Poseidon, ERS-1, ERS-2, Jason-1, and ENVISAT, respectively (depending on availability), into a product of merged sea level anomaly. Intensive cross correlation decreases the root mean square error of the final product with respect to the single-sensor input data, especially in regions of high mesoscale variability [*Le Traon and Ogor*, 1998; *Le Traon et al.*, 1996; *SSALTO/DUACS User Handbook*, 2006; *Zhang and Chen*, 2006]. The presented data, produced weekly, have a  $1/3^\circ \times 1/3^\circ$  resolution gridded to a Mercator projection.

[13] To evaluate the mesoscale spatial variation of the SLA signal, we created an SLA data set from which the macroscale background was subtracted. We considered the SLA signal spline smoothed to  $5^\circ$  latitude by  $5^\circ$  longitude as the macroscale fraction; this smoothing area is greater than 15-fold the Rossby radius and larger than the size of SLA features visually detected at BATS and ESTOC. Since the large-scale variation also comprises the seasonal signal of thermal expansion, the original data subtracted by the macroscale background can be considered deseasonalized.

## 3. Data Analysis

[14] In this section, we will compare water column properties and mesoscale variability at both stations during

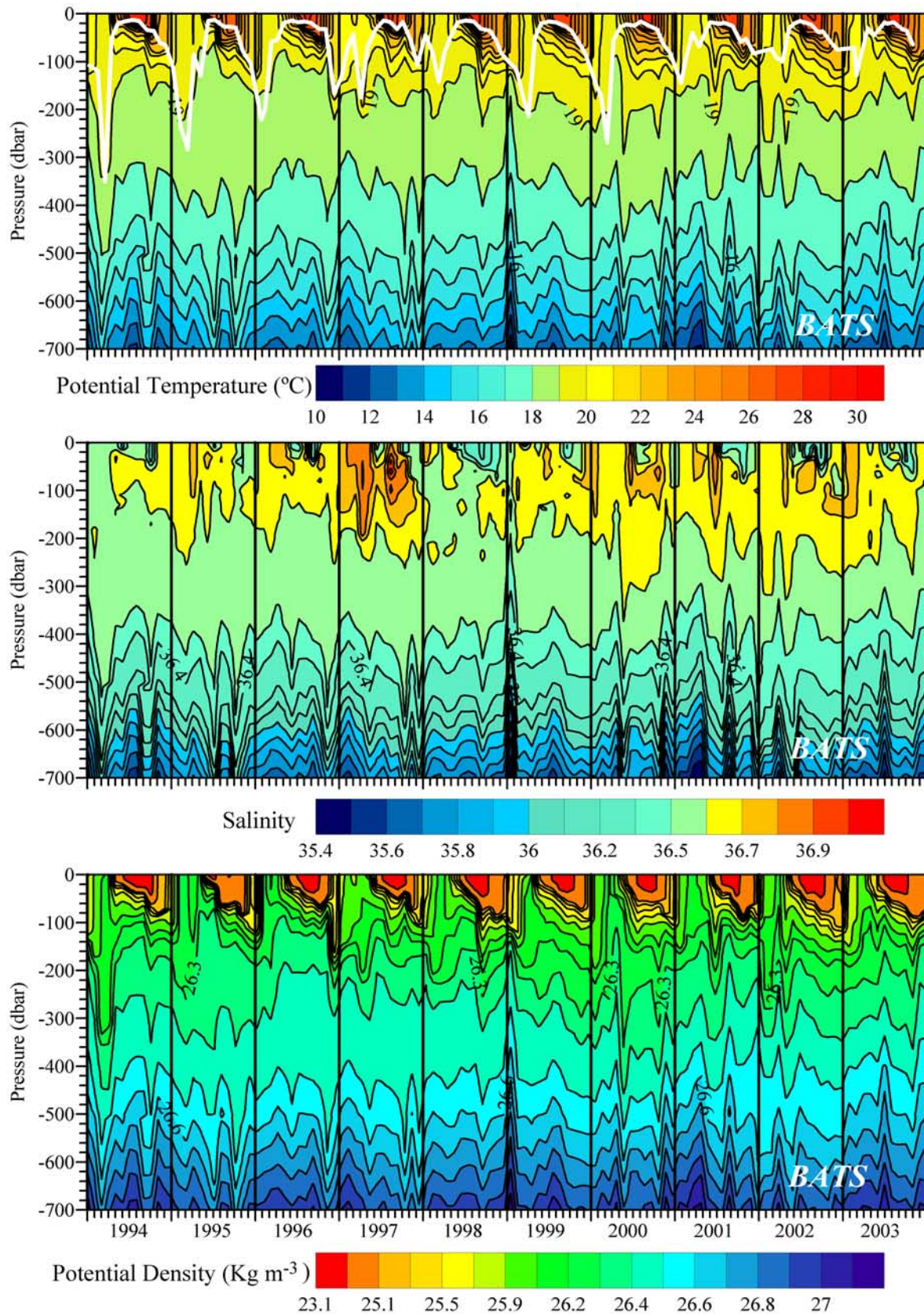
the observational period, as well as the relationship between sea level anomaly and the passage of mesoscale features.

### 3.1. Water Column Properties

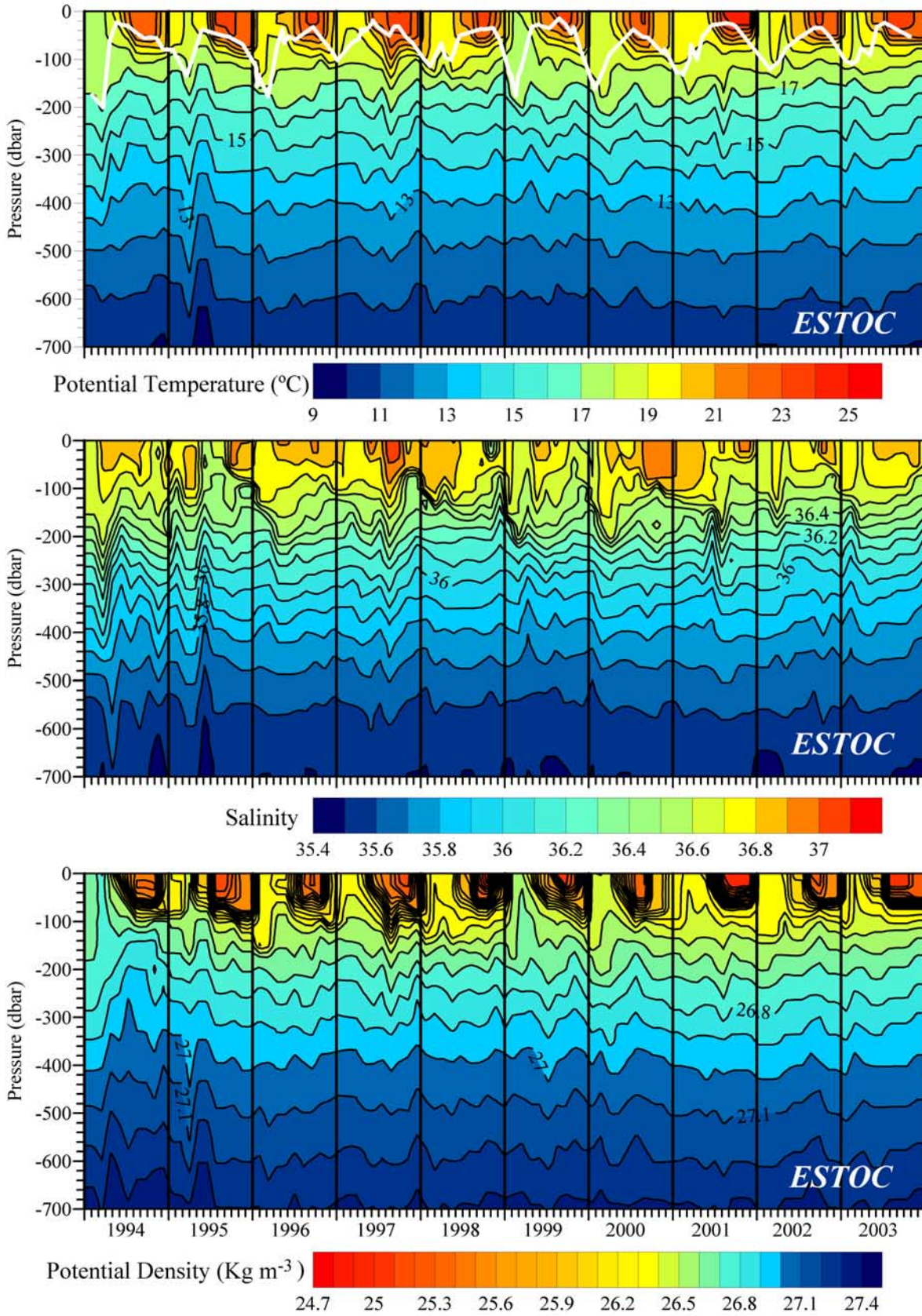
[15] Here we show a decade of concomitant time series data of water column parameters measured at BATS and ESTOC from 1994 to 2003. Similar time series at these stations have been described previously for different time intervals [at BATS: *Michaels et al.*, 1994; *Michaels*, 1995; *Steinberg et al.*, 2001; at ESTOC: *Santana*, 1999; *Neuer et al.*, 2002a; *Cianca*, 2003; *González-Dávila et al.*, 2003; *Santana-Casiano et al.*, 2007; *Neuer et al.*, 2007], and we will focus below on the comparative presentation of the data records.

[16] The main differences in hydrography of the upper layers between BATS and ESTOC resulted from the presence of NASTMW at BATS, which was characterized by a temperature of 18°C, a salinity of 36.5, and a potential density  $26.5 \text{ kg m}^{-3}$ . Below the NASTMW, the main pycnocline was present between 400 m and at least 1000 m. On the surface, minimum salinity was observed every year during the summer (Figure 2) due to local rainfall. Mesoscale variability, which produces displacements in temperature, salinity, and density isolines, is clearly visible. At ESTOC, high variability was observed in the surface salinity mainly due to the trade winds during summer, which obscured a clear seasonal cycle (Figure 3). Also, a large variability in the halocline was due to mesoscale structures known as “Meddies” (eddies of Mediterranean water) or to mixing with intermediate waters (Antarctic intermediate water (AAIW) or Mediterranean outflow water (MOW); *Llinás et al.* [1999]). For example, higher displacements occurred during 1994, 1995, and 1996 at 800 m depth which we associate with meddy passages as documented by *Santana* [1999].

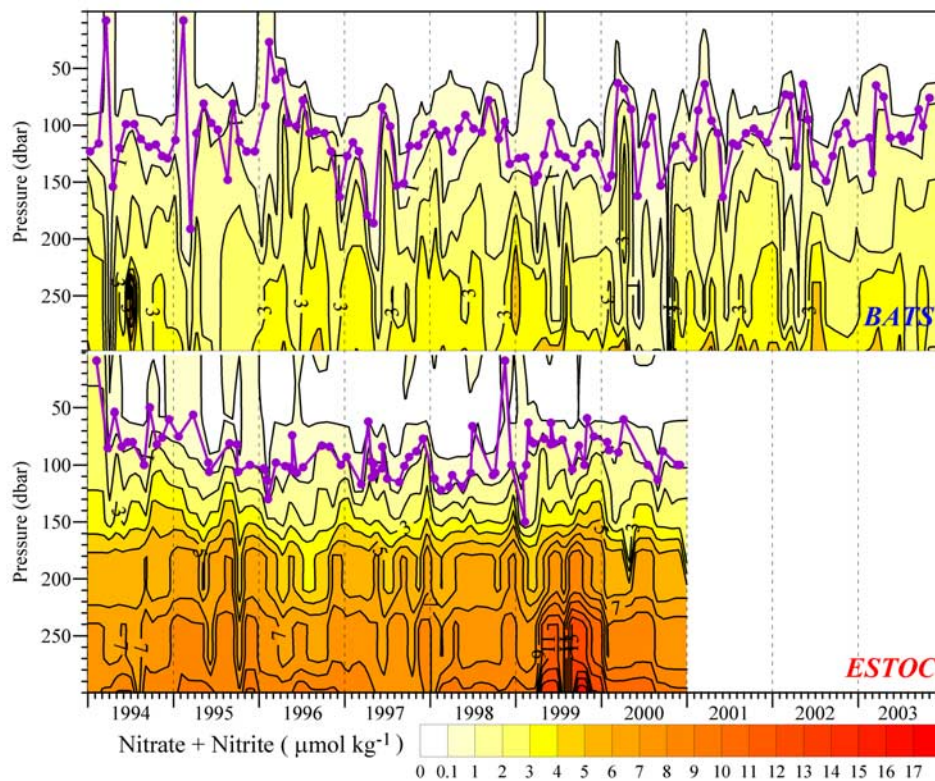
[17] The analogue to NASTMW in the west is the Madeira mode water (MMW) in the east. This water is an



**Figure 2.** Time series of potential temperature, salinity, and potential density at BATS. White lines represent the MLD calculated by the  $0.5^{\circ}\text{C}$  threshold criterion.



**Figure 3.** Time series of potential temperature, salinity, and potential density at ESTOC. White lines represent the MLD calculated by the 0.5°C threshold criterion.



**Figure 4.** Time series of nitrate and nitrite at BATS and ESTOC. Purple lines represent the nitracline depths at each site.

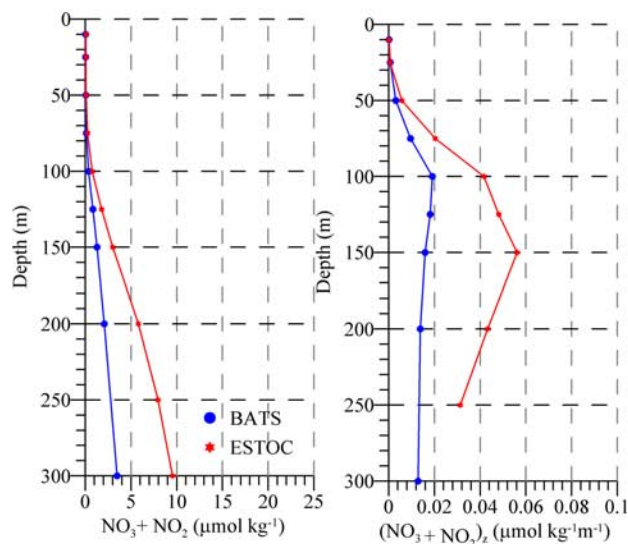
archetype of the low-density subtropical mode waters of the eastern subtropical gyres. *Siedler et al.* [1987] documented the existence of this mode water and found it to be associated with the warm side of the Azores Front and offshore of the coastal upwelling area. Winter mixed layers in its formation region are about 200 m deep [*Käse et al.*, 1985]. MMW is advected southwestward from its formation region and joins the thermocline as part of the North Atlantic central water. In contrast to the permanent presence of NASTMW [*Ebbesmeyer and Lindstrom*, 1986], MMW almost disappears by the end of the summer [*Siedler et al.*, 1987]. The intermittent presence of MMW, which is characterized by temperatures of 16° to 18°C, salinities of 36.5 to 36.8, and potential densities 26.5 to 26.8 kg m<sup>-3</sup> [*Hanawa and Talley*, 2001], could not be easily identified in the hydrography. However, an extension of the isotherm distances and a reduction of the density gradients revealed its presence. This layer was located below the seasonal pycnocline between 100 and 300 m depth and, similar to NASTMW eddies, MMW eddies could have a relevant role in nutrient transport (see section 4.2).

[18] The period of maximum mixed-layer depth (MLD) is February to April, and at both stations, the deepest MLD occurred in 1994, 1995, 1996, 1999, and 2000 (Figures 2 and 3). The deep MLD measured at BATS in 1994 was attributed to an anticyclonic event (other MLDs measured near BATS during this time were shallower; see *Steinberg et al.* [2001] for a review).

[19] The annual cycle of nutrient distribution was linked to physical forcing. Winter vertical mixing brought nutrients

into the euphotic zone and, during summer stratification, these were depleted from the upper layers at both stations. The nitracline (Figure 4, purple line) was located at a mean depth of 113 m (StDev ± 31 m) at BATS, greater than the estimation (84 m) made by S99, while at ESTOC, it was located at a mean depth of 92 m (StDev ± 22 m). The means are significantly different (*t* test, *p* = 0.001). Below this layer, the nutrient concentrations increased more quickly at ESTOC compared with BATS (Figure 5). The nitrate mean concentrations at 300 m depth, for example, were around 9.5 µmol kg<sup>-1</sup> at ESTOC in comparison with only 3.5 µmol kg<sup>-1</sup> at BATS. At ESTOC, concentrations during 1999 reached up to 17 µmol kg<sup>-1</sup>. The maximum nitrate gradient was located near 150 m at ESTOC and below the NASTMW near 500 m at BATS (not shown).

[20] Increases of chlorophyll *a* coincided with deeper mixed layers in the winter of each year both at BATS and at ESTOC. The maximum values were located near the surface during winter blooms and near 100 m for the remaining time (Figure 6). An unusual bloom occurred during July 1995 at BATS with chlorophyll *a* values of more than 1 mg m<sup>-3</sup>. This bloom was due to the passage of a mode water eddy [*Sweeney et al.*, 2003]. There was significant interannual chlorophyll variability in summer at ESTOC, with values occasionally exceeding and penetrating deeper (to about 100 m) than during the winter bloom. This occurred at BATS as well though less frequently. The deepest mixed layer occurred at both stations during the winter of 1994 although we could not find higher chlorophyll *a* values at either site. *Steinberg et al.* [2001] attributed



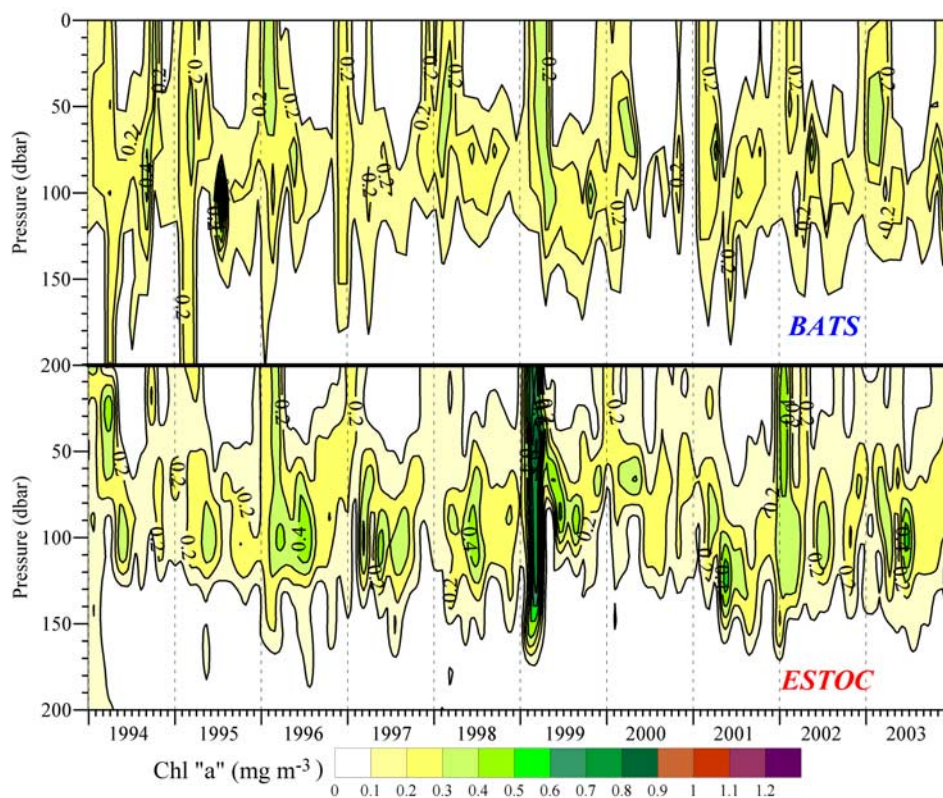
**Figure 5.** Left panel: mean profiles of nitrate and nitrite at BATS and ESTOC. Right panel: the vertical gradients of the mean profiles.

this paradox to the passage of an anticyclonic eddy at BATS, which reduced the concentration of photosynthetic pigments compared to other years. However, a similar explanation does not apply for ESTOC because the lowest surface temperature and the highest surface nutrient concentration measured during the entire sampling period occurred during that event.

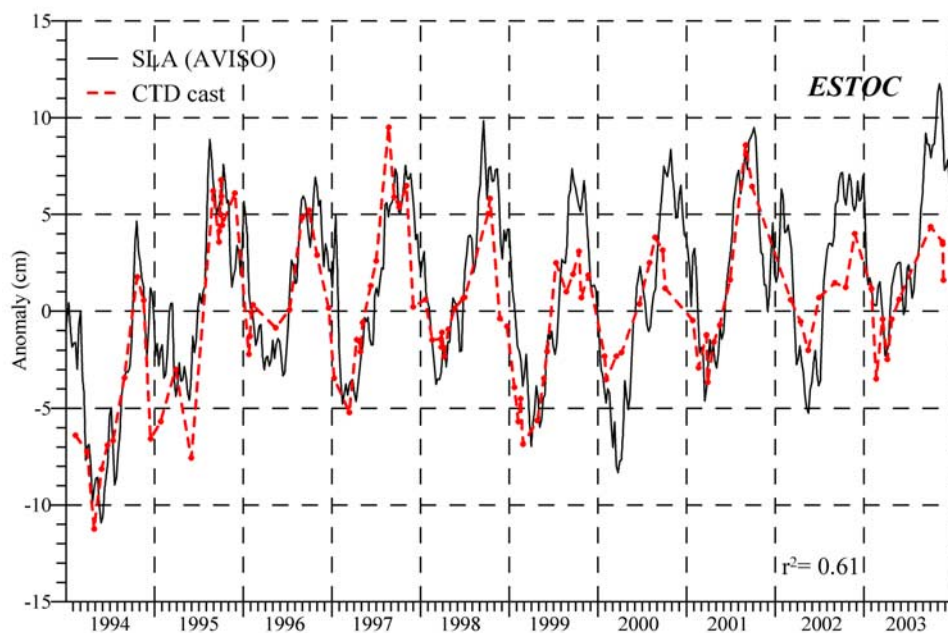
### 3.2. Mesoscale Variability

[21] We analyzed a 11-yr data set from 1993 to 2003 of subtropical North Atlantic merged SLA data to reevaluate the west-east gradient in mesoscale activity (as previously shown by *McGillicuddy et al.* [2003] and *Oschlies* [2002b]). To evaluate the satellite-derived merged SLA for ESTOC, we calculated the squared correlation coefficient between  $SLA_{(satellite)}$  and the dynamic height anomaly,  $\Delta D(0/800 \text{ dbar})$ , from the available ESTOC hydrographic record. We chose 800 dbar as a reference level because many hydrographic profiles at ESTOC were taken only to 1000 m. Furthermore, *Machin et al.* [2006] found little variation in geostrophic velocity estimates when using different reference levels (among them, the isopycnal surface  $27.30 \text{ kg m}^{-3}$  which is the interface between NACW and intermediate waters) in three sections carried out north of Canary archipelago. The correlation coefficient ( $R^2$ ) between  $SLA_{(satellite)}$  and  $\Delta D(0/800 \text{ dbar})$  was 0.61 at ESTOC (Figure 7), which compares well to  $R^2 = 0.65$  found at BATS by S99 [ $\Delta D(0/4000 \text{ dbar})$ , data from 1993 to 1996]. Note that the resolution of  $1/3^\circ \times 1/3^\circ$  in the SLA data could introduce sampling errors for SLA features with a diameter close to this resolution. However, the general feature size at both stations is several times larger than this critical diameter, which makes this effect negligible.

[22] Figure 8a shows that the magnitude of SLA in the BATS region increased strongly towards the north, and around ESTOC, it increased moderately towards the east. While the seasonality of SLA due to thermal effects (Figure 8b, columns I and III) is visible at both stations, it does not explain most of the variance at BATS, where strong



**Figure 6.** Time series of chlorophyll a at BATS and ESTOC.



**Figure 7.** Times series of SLA from AVISO data and dynamic height anomaly,  $\Delta D(0/800 \text{ dbar})$ , from available ESTOC data.

mesoscale variability overlays the seasonal cycle. In contrast, seasonality at ESTOC is responsible for most of the variance. After removing the macroscale background (data smoothed to  $5^\circ$  latitude by  $5^\circ$  longitude), the striking difference in mesoscale activity between BATS (high) and ESTOC (low) emerges (Figure 8b, columns II and IV).

[23] For detection of size, speed, direction, and type of eddy, we created an animation of SLA ([http://www.public.asu.edu/~sneuer/research002\\_05\\_video.html](http://www.public.asu.edu/~sneuer/research002_05_video.html)). The mesoscale activity in the main thermocline on the west side of the subtropical gyre was dominated by Gulf Stream instabilities. Cold-core rings formed by large-amplitude meanders propagate within the Sargasso Sea although their appearance at BATS is unusual. An analysis of the water properties of eddies showed that these structures originated within the Sargasso Sea [McGillicuddy *et al.*, 1999]. Features in the ESTOC region originated from around Cape Ghir, and the smaller capes to the north, and from an elongated 300-km-wide stretch between Cape Ghir and Cape Yubi (Figure 1). In addition, several structures were generated upstream of ESTOC at islands or seamounts. Eddies created by current flow perturbation or trade wind stress have been known for some time to occur in the south of the Canary archipelago [Aristegui *et al.*, 1994, 1997]. The size of the observed mesoscale features was in general 50% larger at BATS than at ESTOC (Figure 8a).

#### 4. Physical Transport of Nutrients Into the Euphotic Layer

[24] In this section, we analyze the new nutrient input into the euphotic zone resulting from physical transport following the approach used by S99. These authors showed that the use of satellite altimetry and hydrographic observations could characterize the mesoscale eddy field and could elucidate the role of mesoscale structures in nutrient transport. We extended the work of S99 using a 10-yr time

series data set for BATS and compared the results with concomitant observations from the eastern side of the subtropical gyre at ESTOC.

##### 4.1. Vertical Nutrient Transport by Eddy Pumping

[25] Our calculation is based on the approach outlined in the work of S99. Briefly, it is assumed that nutrients which are upwelled into the euphotic zone within a cyclonic feature are utilized completely and that the timescale of eddy passage is longer than the remineralization timescale. Nutrient input is then calculated from the displaced nutrient profile and the known relationship between isopycnal displacement and nitrate concentration. The equation used to define the displaced potential density profile is given by:

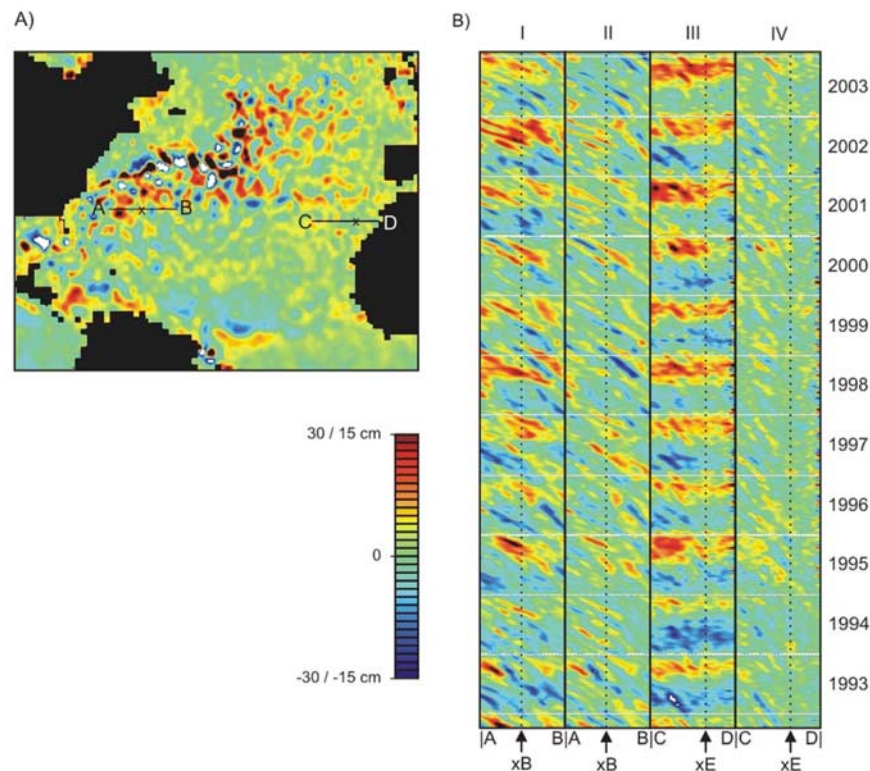
$$\bar{\sigma}\theta(z, t) \cong \langle \sigma\theta(z) \rangle + \eta_\sigma(z, t) \frac{\partial \langle \sigma\theta(z) \rangle}{\partial z} \quad (1)$$

where  $\langle \sigma\theta(z) \rangle$  is the mean potential density,  $\eta_\sigma(z, t)$  is the isopycnal displacement [Siegel *et al.*, 1999], and  $\partial \langle \sigma\theta(z) \rangle / \partial z$  is the gradient of the mean profile of potential density.

[26] After estimating the displaced potential density profile, the displaced nitrate profiles are assessed using the linear fit of nitrate versus potential density (Figure 9).

[27] Uplifting events were identified using the mapped SLA time series by searching the SLA for a pattern of increasing negative values with an end point of where SLA started to increase. An unfiltered SLA time series was used to determine the events at both sites (Figure 10). Within the timescale assumption of the kinematic eddy-pumping approach, we identified 52 individual upwelling events at BATS during the 10 yr, each with a mean duration of 18 days and a mean time between events of 53 days. At ESTOC, there were 49 events with mean duration of 14 days, and the mean duration between events was 58 days (see Table 1 for yearly number of events at both stations).



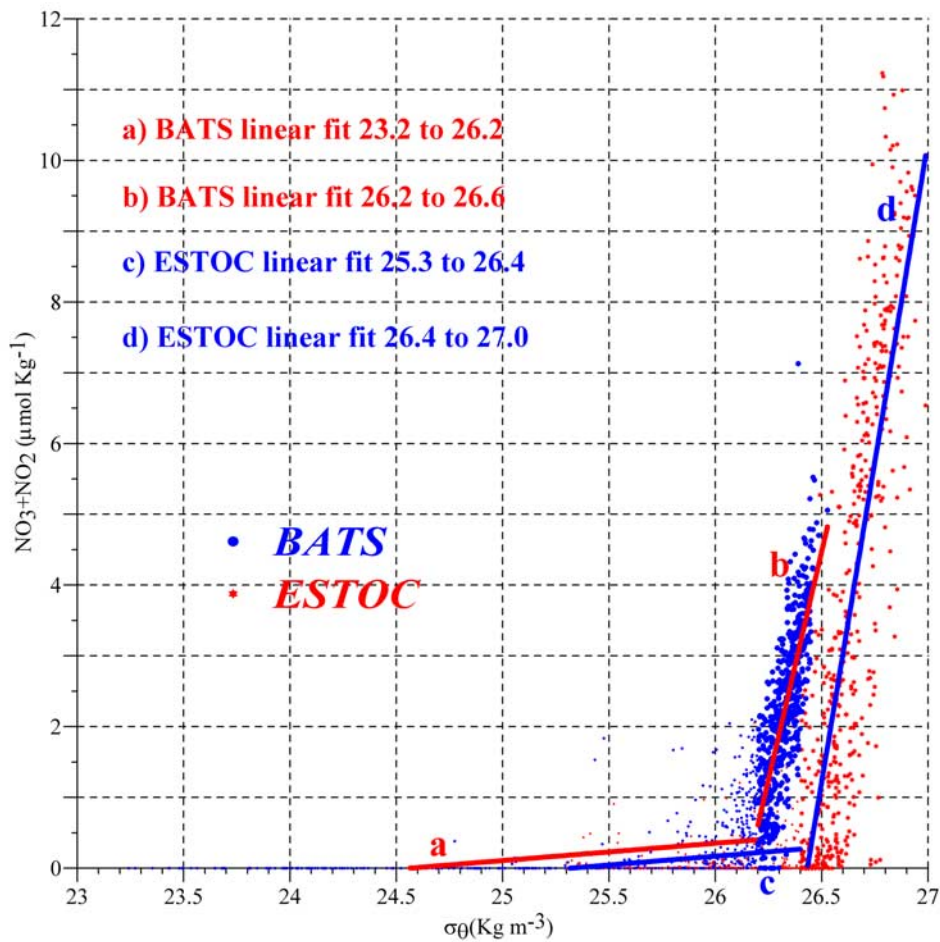


**Figure 8.** (a) Example of North Atlantic merged sea level anomaly from 25 November 1992. Locations for BATS and ESTOC are shown, as well as transect through BATS (AB,  $71^{\circ}$ – $56^{\circ}$ W;  $31.8^{\circ}$ N) and ESTOC (CD,  $25^{\circ}$ – $10^{\circ}$ W;  $29.2^{\circ}$ N) (SLA extraction shown in Figure 8b). Scaled to  $-30$  to  $-30$  cm with the same color scale as in Figure 8b. (b) Hovmoeller representation of AVISO weekly merged sea level anomaly at BATS (columns I and II, transect AB) and at ESTOC (columns III and IV, transect CD). Columns I and III show the total sea level anomaly at both positions; columns II and IV show the mesoscale fraction. BATS and ESTOC are indicated as dotted lines (xB and xE, respectively). Note that the scale for columns I and II is from  $-30$  to  $30$  cm, whereas for columns III and IV, the range is from  $-15$  to  $15$  cm due to the smaller amplitude of mesoscale features at ESTOC.

The uptake for each event was found by integrating that portion of the displaced nutrient profile above the assumed depth of the euphotic layer. We assumed a euphotic zone depth of 95 m at BATS, as in S99, which was based on optical measurements. We chose the same value for ESTOC following the optical estimates by Zielinski *et al.* [2002] obtained during a winter and spring cruise in the area. The mean value of the isopycnal maximum displacements was 23 m at BATS, which resulted in an average nutrient uptake of  $2.5 \cdot 10^{-2} \text{ mol N m}^{-2}$  per event, while at ESTOC, it was only 11 m with an uptake of  $1.5 \cdot 10^{-2} \text{ mol N m}^{-2}$  per event. The estimated yearly eddy-induced nutrient flux for both stations is shown in Table 1. With the exception of 1995, 1997, and 1998, ESTOC received about half the amount of nutrients due to eddy pumping compared with BATS, and in 2003, the difference was almost tenfold. The mean values for the 10-yr period were  $0.13 \pm 0.04 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at BATS and  $0.07 \pm 0.03 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at ESTOC. The means of the eddy induced nutrient transport is significantly different (*t* test,  $p = 0.005$ ). The BATS estimate is very close to that calculated in the paper by S99 ( $0.15 \text{ mol N m}^{-2} \text{ yr}^{-1}$ ). However, S99 considered their result an underestimation because no extreme negative SLA values ( $< -200$  mm) were found at BATS during the observational period (1993–

1995), in contrast to SLA measured in areas around BATS. These authors further noted the importance of a longer time series for calculating robust eddy statistics. The SLA data series that we used for our analysis (10 yr) also did not contain any values lower than  $-200$  mm at BATS. Consequently, we would not expect many extreme negative SLA values at this station.

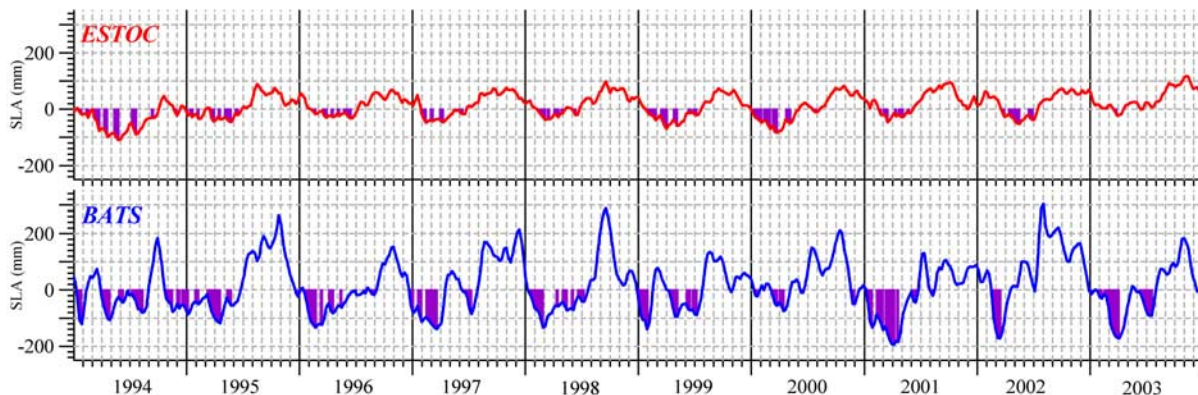
[28] Several uncertainties are associated with the calculation of new nutrient input due to eddy pumping. First, the assumption that every negative SLA event causes an isopycnal displacement; second, the accuracy of the euphotic zone depth; and third, the variability in the linear regression between nitrate and the potential density. Regarding the first assumption, we have shown in Figure 7 that dynamic height variance was well explained by the SLA time series, indicating that the SLA time series is a reliable predictor for isopycnal displacement. Regarding the euphotic zone depth estimate, the estimated eddy pumping flux will increase with a deeper estimate of the euphotic zone as clearly shown in the study of S99. The isopycnal surfaces where nitrate increases significantly are  $26.2 \text{ kg m}^{-3}$  at BATS and  $26.4 \text{ kg m}^{-3}$  at ESTOC (Figure 9). The isopycnal surface  $26.2 \text{ kg m}^{-3}$  is located around 150 m at BATS, whereas  $26.4 \text{ kg m}^{-3}$  is close to 100 m at ESTOC. Thus, at BATS, a



**Figure 9.** Nitrate versus potential density relationships observed at BATS and ESTOC. Linear fits were estimated for two different ranges of density at both stations and represented by lines a and b for BATS and lines c and d for ESTOC.

euphotic depth shallower than 150 m would not imply a striking increase of the flux. At ESTOC, a euphotic zone depth deeper than 100 m would dramatically increase the flux because it would reach into the nitracline. However, we consider a euphotic zone depth deeper than the nitracline unlikely as the nitrate would be utilized by the phytoplank-

ton. Regarding the third assumption, the variances around the mean isopycnal surface displacement are around 40% at BATS and 85% at ESTOC. The value at BATS is close to the uncertainty estimate applied by S99 of around 50%, which included the uncertainty based on euphotic zone determination and the displaced isopycnal surface. In both cases, this



**Figure 10.** SLA time series at BATS and ESTOC. Shaded areas denote upwelling events.

**Table 1.** Comparison of New Nutrient Transport due to Eddy Pumping Using SLA at BATS and ESTOC

		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
BATS	Number of Events	8	4	8	3	6	4	5	6	3	5
ESTOC		9	6	5	5	5	6	4	5	3	1
BATS	Eddy Flux, mol Nm <sup>-2</sup> yr <sup>-1</sup>	0.2	0.1	0.2	0.075	0.15	0.1	0.125	0.15	0.075	0.125
ESTOC		0.135	0.09	0.075	0.075	0.075	0.09	0.06	0.075	0.045	0.015

uncertainty is higher than the one based on the standard deviation of the interannual means (34 and 42%, respectively).

#### 4.2. Vertical Nutrient Transport by Mode Water Eddies

[29] The 18° water studies carried out at BATS showed that mode water eddies corresponded to a positive SLA value, similar to anticyclonic eddies. They differ from the anticyclonic eddies in that they are associated with colder waters near the surface. The direction of the isopycnal displacement in the upper ocean is the same as for a cyclonic eddy and causing upwelling of nutrients into the euphotic zone when they are forming or intensifying [Sweeney *et al.*, 2003].

[30] The two mode waters considered in this study are NASTMW at BATS and MMW at ESTOC. S99 estimated that the input of new nutrients to the euphotic layer was a result of the variability of NASTMW caused by mesoscale eddies. This assessment was drawn from previous studies where it was shown how NASTMW thickness increased due to the presence of mesoscale eddies [Talley and Raymer, 1982; Ebbesmeyer and Lindstrom, 1986; Brundage and Dugan, 1986]. These features have not been studied in Madeira mode water, and we assumed a similar behavior to calculate the nutrient transport to the euphotic zone. Consequently, we assessed NASTMW and MMW thickness using the criteria described in section 2.1. The result obtained for NASTMW was a mean thickness of 188 m ± 54 m, similar to the 196 ± 60 m estimated by S99. The result for MMW was a mean thickness of 50 ± 22 m and a mean depth of the shallower isotherm of 145 ± 23 m.

[31] Finally, to determine the new nutrient transport by the mode water eddies, we assumed that the events should satisfy these following conditions:

[32] The thickness anomalies are around 100 m in NASTMW and 25 m in MMW.

[33] The nutrient concentration at 100 m depth increases.

[34] The shallower isotherm is uplifted.

[35] The SLA is positive.

[36] A total of five events during the 10-yr time series were counted at BATS, while no event could be found at ESTOC satisfying the prior conditions (Figure 11). The events found at BATS occurred during July 1995, October 1995, November 1996, October 1997, and December 1997. In addition, it was assumed that the flux observed for the July 1995 event at BATS, which had been estimated by McNeil *et al.* [1999] with 0.145 mol N m<sup>-2</sup> yr<sup>-1</sup>, was typical. Therefore the vertical nutrient transport by mode water at BATS was estimated to be 0.07 ± 0.03 mol N m<sup>-2</sup> yr<sup>-1</sup>, while it was 0 at ESTOC. In particular, we note that the events at BATS we determined using the above criteria only occurred during 3 of the 10 yr, and their timescale (around 30 days) implies that it is unlikely that any event was missed during the sampling. On the other

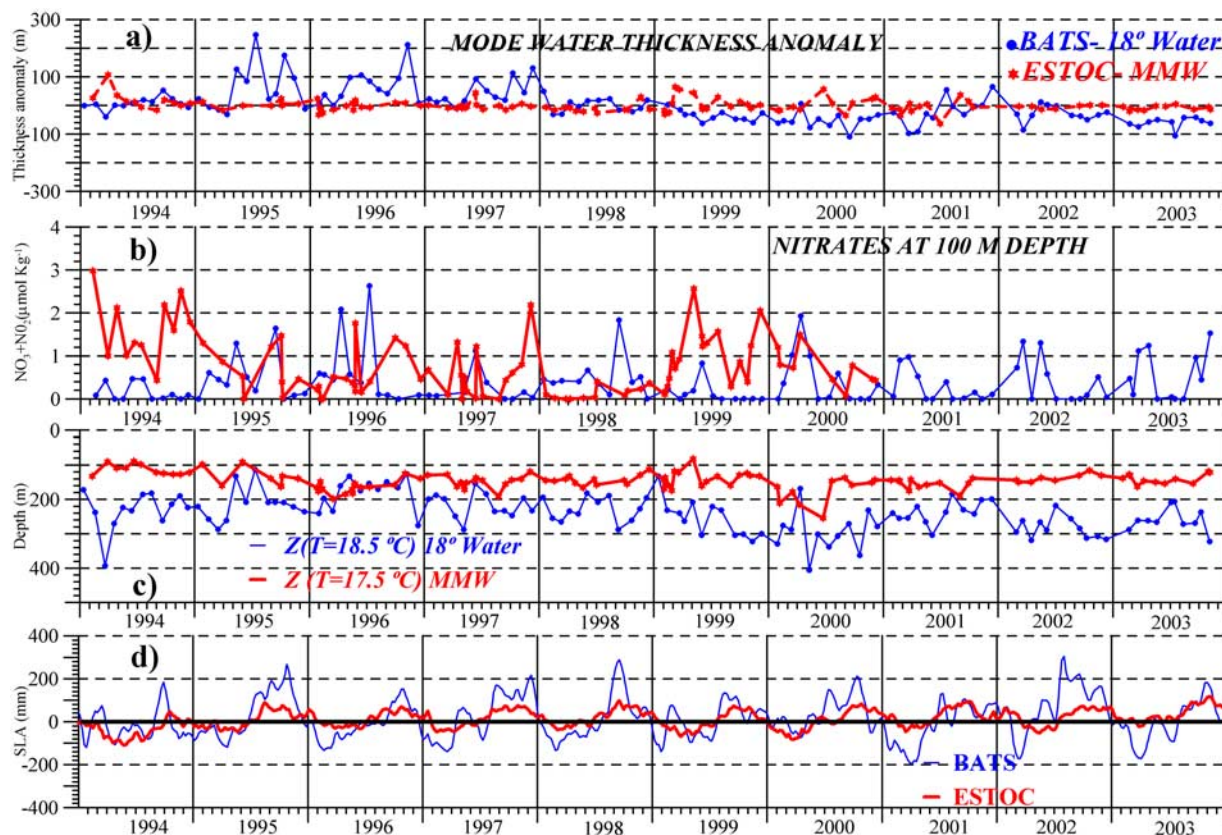
hand, the criteria for the detection of mode water eddies at BATS could be invalid for MMW, and we would need to define new conditions that define the presence of mode water eddies at ESTOC. An uncertainty estimate in mode water input of roughly 50% was suggested by S99. This uncertainty is partly based on possible undersampling of mode water eddies. For example, by using a combined SLA-hydrography approach as in the work of Sweeney *et al.* [2003], Mourinho and McGillicuddy [2006] estimated 7 MW eddies passing near the BATS site during the 1993–2002 period. This possible underestimate in our value should be partly offset by the overestimation caused by assuming that the July 1995 nutrient flux at BATS was typical for mode water eddies, as that eddy crossed BATS in the optimal condition to favor a biogeochemical response.

#### 4.3. Vertical Nutrient Transport by Winter Convection

[37] Wintertime convection is the physical process which dominates the transport of new nutrients to the euphotic zone in areas of the NASTG where the observed MLD is deeper than the euphotic zone. BATS and ESTOC have mean MLDs deeper than 125 m, with the euphotic zone reaching to about 95 m [Siegel *et al.*, 1995; Zielinski *et al.* [2002], respectively]. At BATS, the deepening of the MLD is the consequence of cold and dry winter storms that produce intense air-sea buoyancy exchanges, whereas at ESTOC, surface cooling aided by wind stirring is sufficient to deteriorate the seasonal stratification.

[38] The calculation of winter convective nutrient input was based on the approach of S99 who used the maximum nitrate inventory in the outcropped isopycnal during the 6 months prior to the mixing event and assumed that the water column was homogenized to the depth of the deepest mixing. From our observations, we determined that the maximum inventories always occurred during January to March at both stations except in those years where mesoscale features appeared during November and December. This is the case of mode water eddies observed at BATS during 1996 and 1997. Consequently, these events were not included in our calculation. The vertical nutrient transport by winter convection was calculated by  $\int \text{NO}_{3\text{max}} D_{\text{eu}} / D_{\text{max}}$ , where  $\text{NO}_{3\text{max}}$  is the maximum nitrate concentration found in the layer bounded by the outcropped isopycnal and the sea surface for the 6-month period prior to the deep mixing event,  $D_{\text{eu}}$  is the euphotic zone depth, and  $D_{\text{max}}$  is the maximum MLD.

[39] The yearly values of MLD and convective flux are shown in Table 2. The mean annual transport values at BATS and at ESTOC were 0.13 (±0.06) mol N m<sup>-2</sup> yr<sup>-1</sup>, with a mean MLD of 202 m (±80), and 0.16 (±0.08) mol N m<sup>-2</sup> yr<sup>-1</sup>, with a mean MLD of 142 m (±33), respectively. The MLD is significantly ( $p = 0.01$ ) deeper at BATS, whereas the convective flux is not significantly different between both stations ( $p = 0.05$ ). The BATS value is slightly lower than the value estimated by S99, which is likely due to shallower MLDs occurring after 2000 (S99 used a 7-yr,



**Figure 11.** (a) Time series of mode water (18° water and MMW) thickness anomaly at BATS and ESTOC. (b) Nitrate and nitrite concentrations at 100 m depth. (c) Depths of isotherm characteristics for 18° water and MMW. (d) SLA time series at both stations.

1989–1995, observational period to estimate the convective nutrient transport). The interannual variability in MLD estimates has been related to the North Atlantic Oscillation (NAO) with shallower MLDs associated with a high NAO index and vice versa [Michaels and Knap, 1996; Bates, 2001]. Furthermore, Oeschies [2001] estimated in a model study a NAO-related reduction in nitrate supply of up to 30%.

[40] S99 considered the annual flux due to convective mixing a likely underestimate, as phytoplankton could utilize nutrients below the euphotic zone before the onset of the bloom. Furthermore, convective nutrient input is again influenced by the choice of the euphotic zone depth which determines the depth interval where the nutrients can be

utilized by the phytoplankton. But following our arguments above, we consider the variation in euphotic depth a minor error source in our estimate.

#### 4.4. Vertical Nutrient Transport by Diffusion

[41] There are two additional physical mechanisms that can transport new nutrients into the euphotic zone. One of them is known as diapycnal diffusion because it occurs across isopycnal surfaces. The flux of nutrients transported by diapycnal diffusion is equal to

$$F_{vd} = -K_z \frac{\partial N}{\partial x_z} \cos \theta \cong -K_z \frac{\partial N}{\partial z} \quad (2)$$

**Table 2.** Comparison of New Nutrient Transport due to Wintertime Convection at BATS and ESTOC

Year	BATS			ESTOC		
	MLD, m	$\int \text{NO}_3$ , mol Nm <sup>-2</sup>	Conv. Flux, mol Nm <sup>-2</sup> yr <sup>-1</sup>	MLD, m	$\int \text{NO}_3$ , mol Nm <sup>-2</sup>	Conv. Flux, mol Nm <sup>-2</sup> yr <sup>-1</sup>
1994	349	0.88	0.24	200	0.53	0.25
1995	282	0.47	0.16	134	0.25	0.18
1996	220	0.32	0.14	175	0.44	0.24
1997	174	0.24	0.13	102	0.07	0.07
1998	141	0.15	0.1	114	0.06	0.05
1999	212	0.47	0.16	176	0.34	0.18
2000	268	0.49	0.17	161	0.29	0.17
2001	143	0.1	0.07	132		
2002	99	0.07	0.07	121		
2003	128	0.09	0.07	109		
Mean	202	0.33	0.13	142	0.28	0.16

**Table 3.** Summary of Nutrient Input Into the Euphotic Zone at BATS and ESTOC Calculated for the Years 1994–2003<sup>a</sup>

	Annual Flux, mol Nm <sup>-2</sup> yr <sup>-1</sup>		
	BATS	ESTOC	S99 (at BATS)
Eddy pumping using SLA	0.13 ± 0.04	0.07 ± 0.03	0.18 ± 0.10
Eddy pumping by MW	0.07 ± 0.03	0	0.06 ± 0.03
Winter Convection	0.13 ± 0.06	0.16 ± 0.08	0.17 ± 0.05
Diapycnal Diffusion	0.01 ± 0.01	0.01 ± 0.01	0.015 ± 0.015
Isopycnal Diffusion	0.01 ± 0.01	0.01 ± 0.01	0.03 ± 0.03
Large-Scale Ekman <sup>b</sup>	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
Total	0.38 ± 0.08	0.28 ± 0.09	0.48 ± 0.12

<sup>a</sup> For the calculation of error estimates, see text.

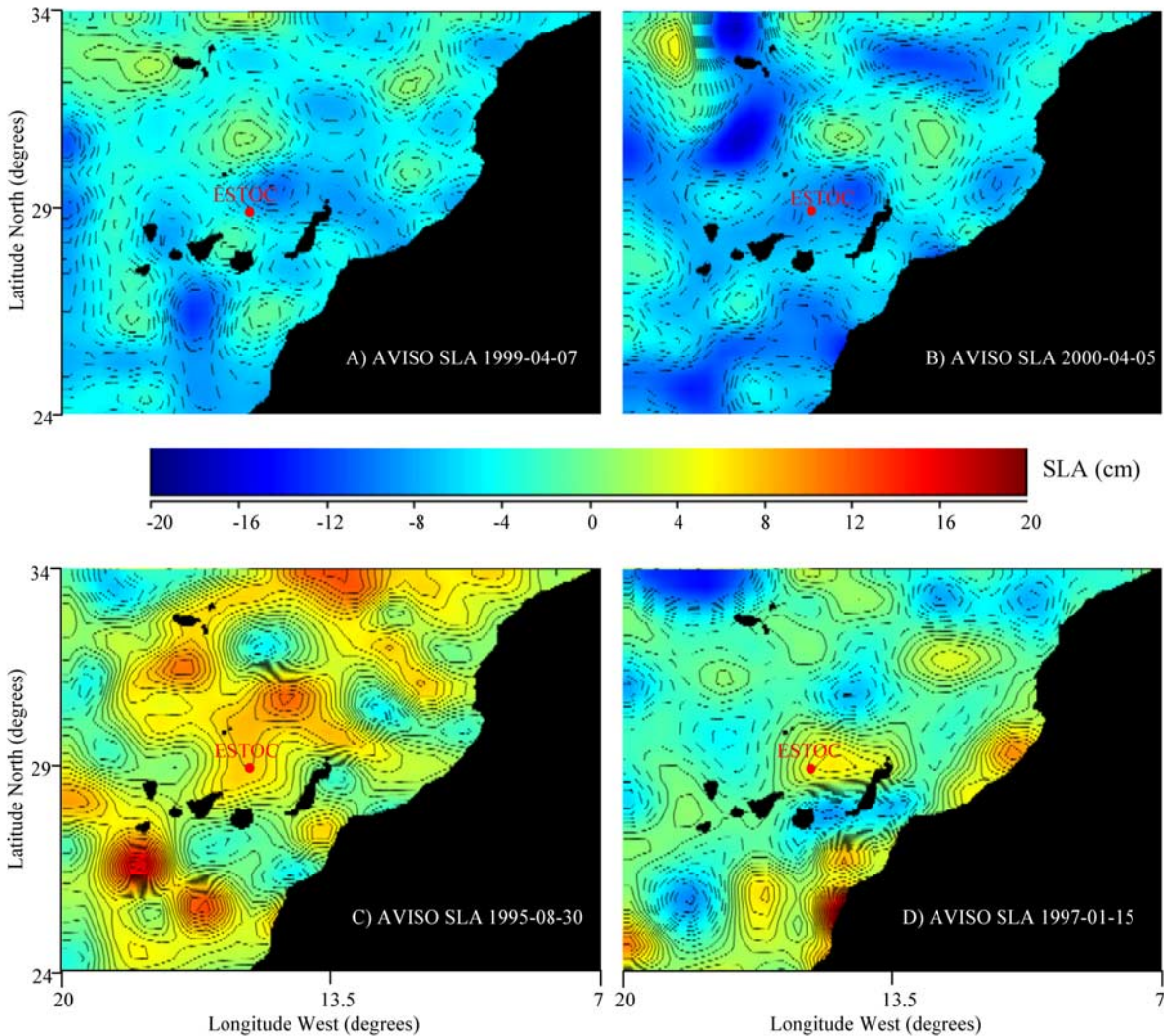
<sup>b</sup> *William and Follows* [1998].

where  $K_z$  is the diapycnal turbulent diffusion coefficient,  $N$  is the nitrate concentration,  $x_z$  is the vertical direction, and  $\theta$  is the angle between the isopycnal and a horizontal surface.

[42] The value of  $\cos\theta = 1$  because the isopycnals are nearly horizontal and the estimation of  $K_z$  was made

assuming that the vertical mixing is mainly due to the effect of internal waves [*Gargett*, 1984]. Thus the turbulent diffusion coefficient is calculated as follows:

$$K_z = \frac{\alpha}{N} \quad (3)$$



**Figure 12.** Averaged merged weekly AVISO sea level anomaly around the Canary archipelago. (a, b) Cyclonic events; (c, d) anticyclonic events, the events are concomitant with a monthly sampling cruise. Dashed line represents negative SLA, and solid lines show positive SLA.

where  $N$  is the Brunt Väisälä frequency, and  $\alpha = 5.4 \cdot 10^{-8} \text{ m}^2 \text{ s}^{-2}$  is a value chosen to approximate similar  $K_z$  estimates as in the study of *Ledwell et al.* [1993] for the region.

[43] The Brunt Väisälä frequency was calculated from the CTD series using the equation

$$N^2 = \left( \frac{g}{\rho_w} \right) \left( \frac{\partial \rho}{\partial z} \right) \quad (4)$$

where  $\partial \rho / \partial z$  is the vertical gradient of the potential density profile.

[44] The estimated mean coefficients of diapycnal diffusion were of the order of  $10^{-5}$  and  $10^{-6} \text{ m}^2 \text{ s}^{-1}$  at both stations, similar to those found in other studies [*Gregg*, 1998; *Ledwell et al.*, 1993; *Mouriño et al.*, 2004]. In addition, *Ledwell et al.* [1998, 2000], using a tracer experiment, confirmed a  $K_z \leq 10^{-5} \text{ m}^2 \text{ s}^{-1}$  in the open ocean, and *Wuest and Lorke* [2003] pointed out that these results could be enhanced over sloping topography. Applying the coefficient  $10^{-5} \text{ m}^2 \text{ s}^{-1}$  to each profile of the time series at 95 m depth, we obtained a mean nutrient transport of  $0.01 \pm 0.01 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at both stations, with the maximum flux reaching  $0.06 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at ESTOC and  $0.04 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at BATS.

[45] The second vertical transport mechanism is caused by eddy diffusive mixing along sloping isopycnals [*Ledwell et al.*, 1993; *Martin et al.*, 2001; *Zhurbas and Oh*, 2004; *Sangrá et al.*, 2005]. The upward vertical component of the isopycnal diffusive transport was represented in the work of S99 as:

$$F_{vi}(\uparrow) = -\frac{1}{2} K_i \frac{\partial N}{\partial x_i} \sin \theta \quad (5)$$

where  $K_i$  is the isopycnal diffusion coefficient,  $x_i$  represents the isopycnal direction, and the factor 1/2 reflects that about half of the time, an isopycnal surface is depressed from its mean position rather than upwelled. We only attempted to derive scale estimates for this vertical transport. Estimate of the slope of an isopycnal was made from prior knowledge of the local geostrophic current. The mean speed of the geostrophic current at the sea surface at BATS is  $0.132 \text{ m s}^{-1}$  which is very similar to that at ESTOC [*John et al.*, 2004]. The horizontal diffusion depends directly on the scale of interest and is very diverse. The values ranged between  $10^3 \text{ m}^2 \text{ s}^{-1}$  in an intense boundary current and  $1 \text{ m}^2 \text{ s}^{-1}$  at the edge of stable mesoscalar structures. We selected a  $K_i$  coefficient of  $1 \text{ m}^2 \text{ s}^{-1}$  because it fitted the characteristics of the regions around BATS and ESTOC. The results we obtained were smaller than  $0.008 \text{ mol N m}^{-2} \text{ yr}^{-1}$ . Thus we assumed a vertical flux of  $0.01 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at both stations with an uncertainty of  $0.01 \text{ mol N m}^{-2} \text{ yr}^{-1}$ . Our value is lower than that of S99, who assumed  $0.03 \text{ mol N m}^{-2} \text{ yr}^{-1}$ , although these authors also considered this value to be overestimated.

#### 4.5. Other New Nutrient Input Terms

[46] In addition to the input mechanisms calculated above, the spatially averaged annual Ekman supply of nitrate to the euphotic zone over the whole North Atlantic (from  $5^\circ$  to  $65^\circ \text{N}$ ) was estimated by *Williams and Follows* [1998] to range from  $0.03$  to  $0.05 \text{ mol N m}^{-2} \text{ yr}^{-1}$ .

Furthermore, atmospheric wet and dry N deposition at BATS was estimated by *Knap et al.* [1986], *Michaels et al.* [1993], and *Prospero et al.* [1996] to amount to around  $0.01 \text{ mol N m}^{-2} \text{ yr}^{-1}$  and to less than  $0.005 \text{ mol N m}^{-2} \text{ yr}^{-1}$  at ESTOC [*Prospero et al.*, 1996; *Baker et al.*, 2003; *Neuer et al.*, 2004].

[47] In addition to physical processes supporting new production, nitrogen fixation is considered an important new nutrient source in some tropical and subtropical regions. Depth-integrated  $\text{N}_2$  fixation by nitrogen fixers such as *Trichodesmium* spp. may equal or exceed the nitrate moved into the euphotic zone by diapycnal transport in the Sargasso Sea [*Gruber and Sarmiento*, 1997]. Nitrogen fixation has been mostly estimated for the western boundary and south-central area of the North Atlantic, and *Capone et al.* [2005] calculated a mean value of pelagic  $\text{N}_2$  fixation in the North Atlantic of  $0.09 \pm 0.01 \text{ mol N m}^{-2} \text{ yr}^{-1}$ . Other studies based on direct measurements of nitrogen fixation at BATS [*Orcutt et al.*, 2001] arrive at only about  $0.015 \text{ mol N m}^{-2} \text{ yr}^{-1}$ , a small fraction of the total new nitrogen budget. There is no report of *Trichodesmium* spp. blooms north of the Canary Islands or at ESTOC, and *Neuer et al.* [2002a], using biogeochemical proxies, postulated that  $\text{N}_2$  fixation was not an important new nitrogen source at ESTOC.

## 5. Discussion

[48] Our results indicate clear differences in nutrient supply mechanisms between the western and the eastern boundaries of the NASTG. Table 3 summarizes the importance of the different physical mechanisms of nutrient supply to the euphotic zone at both stations. At BATS, the main nutrient supply to the euphotic zone was eddy-pumping ( $0.20 \text{ mol N m}^{-2} \text{ yr}^{-1}$ ) representing roughly 50% of the total flux. At ESTOC, the new nutrient transport by winter convection was the highest component ( $0.16 \text{ mol N m}^{-2} \text{ yr}^{-1}$ ), also representing roughly 50% of the total flux. The eddy-pumping transport only amounted to 23% of the available new nutrients at ESTOC, whereas winter convection contributed 32% at BATS. Overall, the new nutrient supply at ESTOC was around 75% of that determined at BATS ( $0.28$  and  $0.38 \text{ mol N m}^{-2} \text{ yr}^{-1}$ , respectively), but the difference of the means was not significant ( $p = 0.1$ ). The above estimates are in good agreement with earlier assessments of new production or nutrient budgets obtained at BATS [*Jenkins and Goldman*, 1985; *Jenkins*, 1988; *Sarmiento et al.*, 1990; *Jenkins and Wallace*, 1992; S99] but lower than those of new tracer-based estimates by *Jenkins and Doney* [2003]. At ESTOC, our results are higher than previous estimates inferred both from modeling studies [*McGillicuddy et al.*, 2003; *Oschlies*, 2002b] and from measured export production [*Neuer et al.*, 2002a]. On the basis of their basin-wide modeling studies, *McGillicuddy et al.* [2003] and *Oschlies* [2002a, 2002b] estimated very low new production rates ( $<0.05 \text{ mol N m}^{-2} \text{ yr}^{-1}$ ) for the eastern subtropical Atlantic around the ESTOC location, whereas our assessments show an overall nutrient input higher than  $0.2 \text{ mol N m}^{-2} \text{ yr}^{-1}$ .

[49] Earlier studies have shown biogeochemical responses to eddy passages observed by satellite altimetry in the subtropical North Atlantic [*McGillicuddy et al.*, 1999; *McNeil*

*et al.*, 1999; *Sweeney et al.*, 2003; *Mouriño et al.*, 2002]. *Sweeney et al.* [2003] analyzed 3 yr (1993 to 1995) of biogeochemical measurements at BATS that included nine eddy passages as recorded by satellite altimetry. The results of their study show variations in productivity, community structure, and carbon export in a significant number of events, reaching rates of productivity similar to spring blooms. One of the more studied eddy events at BATS occurred in July 1995 (*McNeil et al.*, 1999; see Figure 6). It was considered a mode water eddy due to the isopycnal displacements (elevation of shallow isopycnals and depression of deeper isopycnals in the main pycnocline), and the SLA value reached about 13 cm. The biogeochemical response was an increase in nutrient concentration in the euphotic zone and higher productivity, pigment concentration, and export fluxes [Table 3 in the paper of *Sweeney et al.*, 2003]. The measured chlorophyll *a* reached  $1.12 \text{ mg m}^{-3}$  (Figure 6), the highest value observed during the 10-yr data series presented here and twice that of the highest bloom values. Similarly, cyclonic eddies (August 1994 or October 1999) were associated with chlorophyll *a* values higher than  $0.3 \text{ mg m}^{-3}$  (mean value during the entire period was  $0.26 \text{ mg m}^{-3}$ ). In contrast, the eddy that crossed BATS during March 1994 had a positive SLA, was classified as anticyclonic, and was decaying. While that month coincided with the deepest MLD caused by an eddy, it did not produce any production or pigment responses [*Steinberg et al.*, 2001; *Sweeney et al.*, 2003].

[50] Similarly, we have examined some eddies crossing ESTOC to determine if changes in nitrate and chlorophyll *a* could be observed. The eddy events that occurred during April 1999 and 2000 reached SLAs lower than  $-5 \text{ cm}$  and had cyclonic characteristics (Figures 12a and 12b). Both events corresponded to an increase in nutrients and chlorophyll *a* at 100 m depth and an isopycnal uplift of around 50 m. By contrast, during August 1995 and January 1997 SLA values were higher than 4 cm indicated anticyclonic characteristics (Figures 12c and 12d). Nitrate and chlorophyll *a* concentrations at 100 m were lower than average ( $0.75 \pm 0.7 \mu\text{mol N kg}^{-1}$  and  $0.31 \pm 0.11 \text{ mg m}^{-3}$ , respectively). These events show that eddy passages may also cause biogeochemical responses which can be observed on a scale concomitant with the monthly sampling at ESTOC.

[51] It has to be kept in mind that eddy passages do not always lead to a predictable biological response. *Mouriño et al.* [2002] investigated the impact of a cyclonic STORM (Subtropical Oceanic Ring of Magnitude) eddy in the northeast Atlantic subtropical region and found that increases of nitrate concentration, up to thrice in the center of the eddy, were not followed by increases in phytoplankton biomass and primary production rates. More recently, *Mouriño and McGillicuddy* [2006] investigated three eddies in the Sargasso Sea and found biogeochemical responses such as an enhancement in the net community production varying with the type and age of the eddy. Furthermore, *McGillicuddy et al.* [2007] found that diatom blooms are sustained by interactions with the surface wind field in mode water eddies, whereas wind-eddy interactions dampen upwelling in cyclones. Modeling studies have also emphasized the importance of submesoscale processes as a mechanism supplying nutrients to the euphotic zone [*Abraham*, 1998; *Lévy*, 2003; *Lévy et al.*, 2005]. *Mouriño*

and *McGillicuddy* [2006] found that interactions between cyclonic and anticyclonic eddies were potentially affected by submesoscale processes and led to measurable enhancements in net community production. A similar study is lacking at ESTOC.

[52] The interannual variability in the winter mixed-layer depths and the eddy passages observed at BATS result in considerable interannual changes in new nutrient estimates, whereas conditions are more stable at ESTOC (Table 2). *Palter et al.* [2005] linked the variability of the nutrient budget and primary production in the Sargasso Sea to NASTMW stability. They showed a reduction of the nutrient concentration at the base of euphotic layer due to greater presence of mode water which favors lower new production estimates. The analysis consisted of a comparison of two different periods where cold winters and intense convective mixing (negative NAO) produced dense and thick layers of NASTMW, whereas warm winters (positive NAO) decreased NASTMW formation. As the origin of this layer is convective, the nutrient concentration in the mode water is depleted by biological utilization and is exported to the gyre. This represents a wedge of low nutrients within the upper layers of the western NASTG which depresses the nutricline and diminishes the diffusive vertical transport. The situation is different at ESTOC. Madeira mode water has a sporadic presence in the area, and is thinner and shallower than NASTMW; moreover, the trade winds, blowing during summertime, help to mix it with the subsurface water. As a result, the nutricline at ESTOC is shallower than at BATS, and relatively shallow MLDs will result in a similar convective nutrient input compared to BATS where MLDs are significantly deeper.

[53] In addition, we would like to note to the high nutrient concentrations during 1999 at ESTOC in the subsurface water at 300 m of up to  $17 \mu\text{mol kg}^{-1}$ . This supply of nutrients could be due to an increase in the isopycnal or isodepth nutrient transport due to a northward displacement of the Azores current caused by a change in the NAO index. *Siedler et al.* [2005] hypothesized that a change in the sign of the NAO index produces changes both in the baroclinic transport and in the spatial pattern of the NASTG with a delay in the oceanic response by about 3 yr. During 1996, the NAO index displayed a negative value in-between two positive periods (*Hurrell* data available at <http://www.cgd.ucar.edu/jhurrell/nao.stat.winter.html>). The delay of 3 yr could have led to an oceanic response in 1999 resulting in a shallowing of nutrient isopleths and greater nutrient input into the euphotic zone, which could have caused the unusually high phytoplankton biomass during most of that year. Thus a negative NAO index could result in an out-of-phase response at either side of the NASTG. During negative NAO, cooler winters and consequently an increase of the NASTMW formation would lead to a deeper nutricline in the west. However, the winter mixed-layer depth would also be deeper and could favor higher convective nutrient input into the euphotic zone. Therefore higher new production during cold winters could be followed by lower nutrient fluxes in the following years after the mode water is advected into the gyre. Conversely, in the eastern NASTG, the same atmospheric condition enhances the trade wind forcing effect and the baroclinic transport towards the coast. Thus, more nutrients would be available in the sub-

surface waters, which could be eroded into the euphotic zone by winter convection, or be made available through other vertical processes such as mesoscale or submesoscale uplifts.

## 6. Conclusions

[54] Using a 10-yr time series of in situ hydrographic data and satellite altimetry, we compared the hydrography and quantified new nutrient budgets of the two oligotrophic time series stations BATS and ESTOC located at about the same latitude in the western and eastern subtropical North Atlantic gyre, respectively. These two time series stations afforded for the first time the opportunity to investigate the different physical mechanisms responsible for new nutrient input at either station, including differences in the mesoscale variability. The observed sea level anomaly fields were dominated by the occurrence of westward-propagating features at both sites but with SLA signatures as large as 25 cm at BATS compared with 10 cm at ESTOC, a consequence of the higher eddy kinetic energy in the western subtropical Atlantic. The dominant nutrient input mechanism at BATS was due to eddy pumping in accordance with earlier studies, whereas at ESTOC, it was due to winter convection and, to a lesser extent, due to eddy-induced input. The sum of annual nutrient fluxes estimated at BATS was in good agreement with earlier estimates; however, nutrient input at ESTOC was higher than could be inferred from earlier basin-wide modeling studies. Our results suggest that in the eastern subtropical Atlantic, the epipycnal transport supplies a large nutrient reservoir at the base of euphotic zone, which is available during winter convection or during events of increased vertical or diapycnal motions. This basin-wide difference is enhanced by the wedge of low-nutrient mode water present in the western, but not in the eastern NASTG which in part offsets the effect of shallower winter mixing depths and lower SLA found in the eastern boundary of the gyre. In addition, we found evidence that changes in NAO could have produced large interannual variability at both sites, influencing both eddy kinetic energy and winter mixed layers, possibly with a different time lag of oceanic response. The regional differences described here should be noted in future studies of the biogeochemistry of the NASTG.

[55] **Acknowledgments.** We thank the U.S. National Science Foundation, the Instituto Canario de Ciencias Marinas (ICCM), Gobierno de Canarias, and the German Ministry for Research and Education (BMBF) for the financial support of the time series stations. We are especially grateful to the dedicated work of the many scientists and technical staff involved in the data collection and analysis. We are indebted to Dennis McGillicuddy and Ray Najjar for the helpful comments on an earlier version of the manuscript. The altimeter products were produced by SSALTO/DUACS as part of the Environment and Climate European Enact project (EVK2-CT2001-00117) and distributed by AVISO, with support from CNES. We would also like to thank the SeaWiFS Project (Code 970.2) and the Goddard Earth Sciences Data and Information Services Center/Distributed Active Archive Center (Code 902) at the Goddard Space Flight Center, Greenbelt, MD 20771, for the production and distribution of chlorophyll *a* data. This work was supported by a NASA-EOS grant to Susanne Neuer.

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