Shallow remineralization in the Sargasso Sea estimated from seasonal variations in oxygen, dissolved inorganic carbon and nitrate

S. Ono[a,*], A. Ennyu[a], R.G. Najjar[a], N.R. Bates[b]

[a]*Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA*
[b]*Bermuda Biological Station for Research, Inc., 17 Biological Lane, Ferry Reach GE 01, Bermuda*

Abstract

A diagnostic model of the mean annual cycles of oxygen, dissolved inorganic carbon (DIC) and nitrate below the mixed layer at the Bermuda Atlantic Time-Series Study (BATS) site is presented and used to estimate organic matter remineralization in the seasonal thermocline. The model includes lateral and vertical advection as well as vertical diffusion, which are found to be significant components of the seasonal budgets of oxygen, DIC and nitrate. The vertical and seasonal variation of the remineralization rates deduced from the oxygen and DIC distributions are very similar. Both locate the spring–summer community compensation depth at ~ 85 m and the remineralization rate maximum at ~ 120 m; nitrate-based estimates of these depths are about 40 m greater. Remineralization rates based on oxygen, DIC and nitrate all show the seasonal maximum to occur in the late spring, presumably reflecting the decomposition of organic matter formed during the spring bloom. The remineralization rate integrated between 100 and 250 m and between mid-April and mid-December is estimated to be 2.08 ± 0.38 mol O_2 m^{-2}, 1.53 ± 0.35 mol C m^{-2} and 0.080 ± 0.046 mol N m^{-2}. These imply remineralization ratios of $O_2 : C = 1.4 \pm 0.40$ and $C : N = 19 \pm 12$. The former agrees well with the canonical Redfield ratio and the latter is significantly larger. The analysis is consistent with the export and remineralization of nitrogen-poor organic matter from surface waters. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The ocean's "biological pump", characterized by net production of organic matter in surface waters and net remineralization in deeper waters, maintains vertical gradients in a myriad of
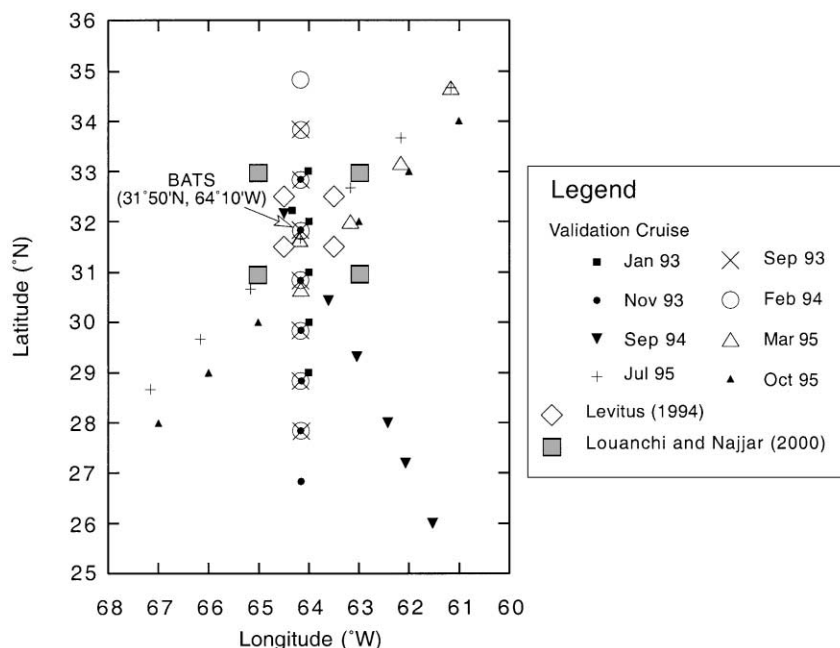
* Corresponding author.

Fig. 1. Map showing location of BATS validation cruises between January 93 and October 95 and the grid points of the climatological data of temperature and salinity (Levitus and Boyer, 1994; Levitus et al., 1994) and nitrate (Louanchi and Najjar, 2000) used in this study.

chemical species in the sea. Much attention has been paid to the production side of the pump, but relatively little is known about remineralization, particularly at shallow depths, where it is suspected that most of the remineralization occurs. Large mesoscale variability and problems with sediment traps have made the task of estimating shallow remineralization a frustrating one. The primary goal of this study is to exploit the measured seasonal variations in oxygen, dissolved inorganic carbon (DIC) and nitrate at the Bermuda Atlantic Time-series Study (BATS) site (Fig. 1) in order to estimate shallow remineralization in the Sargasso Sea. To our knowledge, only two studies have used seasonal variations in oxygen for estimating shallow remineralization rates in the upper ocean (Jenkins and Goldman, 1985; Najjar and Keeling, 2000), one has used seasonal variations in nitrate (Louanchi and Najjar, 2000), and none have used seasonal variations in DIC, mainly due to lack of high-quality and long-term data sets. Our study also differs from these previous efforts in that we account for advection and diffusion of oxygen, DIC and nitrate.

The BATS site, one of the time-series stations of the Joint Global Ocean Flux Study (JGOFS), is located at $31°50'N$, $64°10'W$ in the oligotrophic northwestern Sargasso Sea (Michaels and Knap, 1996). This area of the Sargasso Sea is characterized by weak Gulf Stream recirculation, with a net flow of less than $0.05 \, m \, s^{-1}$ towards the southwest (Michaels and Knap, 1996; Siegel and Deuser, 1997). A remarkable biogeochemical feature of the BATS site is a drawdown of DIC in the surface mixed later during summer and fall in the absence of measurable nitrate and phosphate concentrations (e.g. Bates et al., 1996). Estimation of the carbon budget points to biological community

production as the most important process (e.g. Michaels et al., 1994; Gruber et al., 1998). Horizontal advection of low DIC water also has been invoked to explain the DIC drawdown in the surface water during May–October (Toggweiler, 1994). However, the lateral gradients of DIC are reported to be too small (Bates et al., 1996). Nitrogen fixation is considered to be a source of nitrogen to support new production during summer and fall (e.g. Gruber and Sarmiento, 1997), as is mesoscale eddy pumping (Siegel et al., 1999; McGillicuddy et al., 1999), though the latter is also presumably a source of DIC and so does not help to resolve the strong non-Redfield character of the drawdown. Some have also speculated that nitrogen is preferentially recycled in the euphotic zone, leaving the organic matter exported relatively carbon rich and nitrogen poor. If this were the case, one should expect the subsequent remineralization also to have a high C : N ratio. Thus, a secondary goal of this study is to shed light on the nature of net community production at the BATS site by analyzing the rates of decomposition implied by the seasonal variations in oxygen, DIC and nitrate.

To avoid the difficulties of estimating the impact of mixed layer entrainment on these seasonal variations, we focus our attention on the period from April through December, when the mixed layer is shoaling or only slightly deepening. We do consider, however, vertical mixing in the seasonal thermocline, as well as vertical and lateral advection. The basic approach is to estimate lateral advection from climatological estimates of the geostrophic flow, vertical advection from the Ekman balance, and then to tune the vertical diffusivity to best match the temperature distribution. Remineralization is then determined diagnostically from the oxygen, DIC and nitrate budgets. The approach is conceptually similar to that adopted by Gruber et al. (1998) for the mixed layer budgets of DIC and ^{13}C at the BATS site.

The main data sets we draw on in this study are the temperature, DIC, oxygen and nitrate measurements made at the BATS site, in addition to measurements of these variables (and salinity) from "validation cruises" (Fig. 1). The latter, together with climatological estimates of temperature, salinity, nitrate and oxygen are used to estimate lateral advection of heat, oxygen, DIC and nitrate.

2. Mean annual cycles of oxygen, DIC and nitrate

BATS core data from 1992 to 1998 (http://www.bbsr.edu) were used to construct mean annual cycles of temperature, oxygen, DIC, and nitrate (actually, nitrate + nitrite). BATS core measurements were made monthly except during the spring bloom period (February–April) when biweekly measurements are made. Data were available at 11 standard depths in the top 250 m: 2.5, 10, 20, 40, 60, 80, 100, 140, 160, 200 and 250 m. Mean annual cycles of each property at these depths were constructed by using a weighted moving average. The discrete data for each depth were averaged onto a temporal grid with 15-day intervals using a weighting factor with a normal distribution:

$$\gamma_n(t) = \exp\left[\left(\frac{t_n - t}{\sigma}\right)^2\right], \tag{1}$$

where t is time of year in days (0–365), n is the index of the discrete data point, and σ is a time scale for averaging. In order to obtain smooth mean annual cycles at each depth, we chose $\sigma = 35$ days and an averaging window of 50 days. The seasonal amplitudes of DIC, O_2 and nitrate obtained
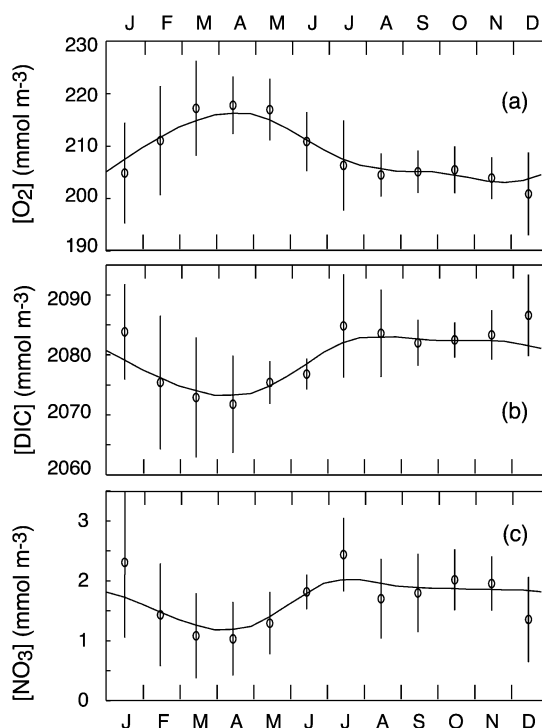
Fig. 2. Mean annual cycles of (a) oxygen, (b) DIC and (c) nitrate concentration at 160 m. Circles: monthly average and standard deviation; solid lines: moving average used in this study.

with these parameters are only $\sim$ 5 % smaller than those obtained by simple monthly averaging, but the cycles are much smoother (Fig. 2).

Fig. 3 shows the computed time rate of change of dissolved oxygen, DIC and nitrate. The dashed lines indicate the depth at which the temperature differs by 1.0°C from the temperature at 2.5 m depth. In surface waters (0–30 m), oxygen and DIC are in phase both increase during fall and winter, and decrease during spring and summer. The short time scale of equilibration ($\sim$ 1 month) with respect to air–sea gas exchange causes oxygen to closely track the saturation concentration, which depends mainly on temperature (Jenkins and Goldman, 1985). For DIC, the gas-exchange equilibration time scale is much longer ($\sim$ 1 year), and other processes, mainly biological production during the spring and summer and vertical mixing during the winter, are dominant (Gruber et al., 1998).

In deeper waters ($>$ 100 m), oxygen is out of phase with DIC and nitrate (see also Fig. 2). Maximum mixed-layer depths reach 180 to $\sim$ 300 m in February from 1992 to 1998 resulting in the mixing of shallow ($<$ 100 m) and deep ($>$ 100 m) water. Since shallow water is generally high in oxygen and low in DIC and nitrate compared to deep water, deepening of the mixed layer in winter causes oxygen to increase and DIC and nitrate to decrease in deep water. For example, from December to April, when this mixing occurs, oxygen at 160 m increases by 12.8 mmol m^{-3} whereas DIC and nitrate decrease by 8.4 and 0.66 mmol m^{-3}, respectively (Fig. 2). Following stratification
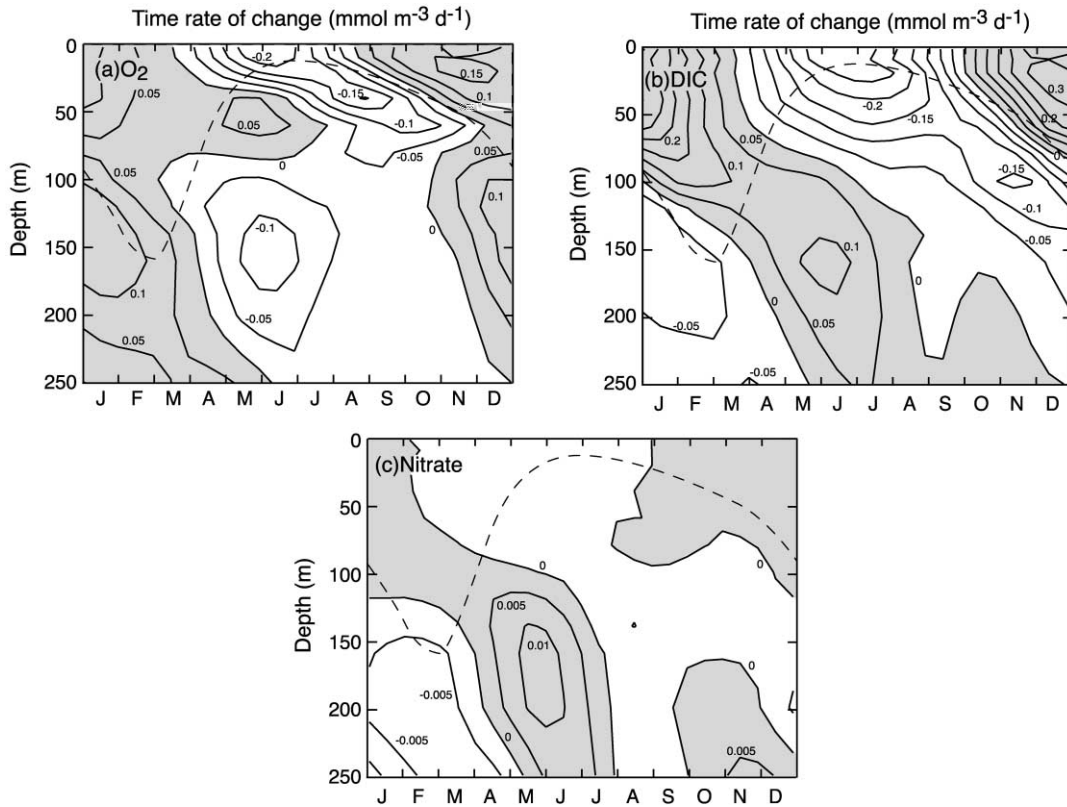
Fig. 3. Mean annual cycles of the time rates of change of (a) oxygen, (b) DIC and (c) nitrate. The dashed line indicates the depth at which temperature differs by 1°C from the 2.5 m value.

in spring, one expects that biological remineralization of organic matter increases DIC (and nitrate) and decreases oxygen. This occurs from April to August, when, for example, oxygen decreases by $-10.5\,\mathrm{mmol\,m^{-3}}$ whereas DIC and nitrate increase by 9.7 and 0.78 mmol m^{-3}, respectively, at 160 m depth. Oxygen, DIC and nitrate are relatively constant from August to December, which one might interpret as a lack of remineralization during this period. We show below, however, that physical transport also contributes to seasonal DIC and O$_2$ variations in this period, which masks the remineralization signal.

3. Model formulation

The general form of tracer conservation used here is

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} - w\frac{\partial C}{\partial z} + \frac{\partial}{\partial z}\left(K\frac{\partial C}{\partial z}\right) + J_C, \tag{2}$$

where C represents temperature, or the concentration of oxygen, DIC or nitrate; u, v and w are the velocity components; K is the vertical diffusivity, and J_C is an internal source term. For temperature, J_C represents the effect of solar radiation that penetrates below the mixed layer. For oxygen, DIC and nitrate, J_C represents the net effects of photosynthesis and respiration.

The surface solar radiation is specified as a simple sinusoidal fit to data of Musgrave et al. (1988). The mean and amplitude are 180 and $80 \, \mathrm{W \, m^{-2}}$, respectively, and the maximum occurs on July 13th. Following Paulson and Simpson (1977), solar radiation is parameterized as a function of depth by a double exponential with coefficients for Jerlov water type I.

Horizontal velocities, u and v, were assumed to be geostrophic and were computed from climatological temperature and salinity data of Levitus and Boyer (1994) and Levitus et al. (1994), and the thermal wind equations. The approach is similar to that of Siegel and Deuser (1997). To obtain the seasonality of lateral advection, we used the "seasonal" (three-month averaged) data. The four grid points surrounding the BATS site were selected (Fig. 1). The density of water was calculated using the formulation of Millero and Poisson (1981), and longitudinal and latitudinal density gradients were computed using averaged density for each x and y component. Velocities were computed for the upper 250 m assuming a level of no motion at 3000 m. The four seasonal values of velocities and T and S gradients were fit with a single harmonic to obtain values every 15 days. The calculated geostrophic flow is from northeast to southwest at the rate of 0.02–$0.03 \, \mathrm{m \, s^{-1}}$ in the upper 200 m, consistent with the calculation of Siegel and Deuser (1997).

The horizontal gradients of oxygen and DIC were estimated from BATS validation cruise data, which were collected from the Sargasso Sea between $\sim 26°\mathrm{N}$ and $\sim 35°\mathrm{N}$ at different times of the year. (Fig. 1). Data are sparse, and only eight transects are available from 1993 to 1995, mainly in north–south and northeast–southwest directions. We assumed a simple linear relationship between the horizontal gradient of oxygen (and DIC) and temperature and salinity. That is,

$$\Delta[\mathrm{O_2}] \text{ (or } \Delta[\mathrm{DIC}]) = \alpha \Delta T + \beta \Delta S, \tag{3}$$

where $\Delta[\mathrm{O_2}]$, $\Delta[\mathrm{DIC}]$, ΔT and ΔS represent the difference between data for a given cast and the cast closest to the BATS site. α and β are coefficients determined by least-squares fit as a function of depth but independent of time. Both $\Delta[\mathrm{O_2}]$ and $\Delta[\mathrm{DIC}]$ correlate well with ΔS and ΔT in surface waters (0–100 m, $r = 0.5$–0.9, $N \approx 30$), reflecting the inverse temporal correlation of surface DIC and oxygen with temperature noted above. Salinity also presumably helps the goodness of the fit, particularly for DIC, which can be significantly affected by evaporation and precipitation (Najjar, 1992). However, the goodness of fit decreases with increasing depth (for 100–250 m, $r = 0.3$–0.9, $N \approx 30$), suggesting that mesoscale eddy or biological processes may predominate. The uncertainty in the lateral advection of oxygen and DIC may therefore be large. We estimate horizontal gradients of $\mathrm{O_2}$ and DIC using the coefficients from Eq. (3). For example, the horizontal gradient of oxygen for the east–west direction is estimated to be

$$\frac{\partial[\mathrm{O_2}]}{\partial x} = \alpha \frac{\partial T}{\partial x} + \beta \frac{\partial S}{\partial x}. \tag{4}$$

The horizontal gradient of nitrate was computed from climatological data of Louanchi and Najjar (2000) interpolated to a regular $2°$ grid. The monthly data were linearly interpolated at 15 days increments with respect to time at the four closest grid points surrounding the BATS site (Fig. 1).

The climatological data of Levitus and Boyer (1994), Levitus et al. (1994) and Louanchi and Najjar (2000) used standard depths of 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, and 250 m. These data were interpolated to BATS vertical grid data (2.5, 10, 20, 40, ... (in m)) by using the monotonic scheme of Steffen (1990).

Ekman downwelling is an important mechanism for vertical transport in the Sargasso Sea (Musgrave et al., 1988). We used the simple harmonic function of Doney et al. (1996) to compute the Ekman downwelling velocity: the amplitude and the annual mean are 34.6 and $60 \, \text{m} \, \text{yr}^{-1}$, respectively, and the maximum value is on January 1st. The Ekman downwelling velocity is set to zero at the surface and increases linearly to the Ekman depth, which is taken to be 30 m (Price et al., 1987), and decreases linearly to zero at 250 m.

The time rate change of temperature was prognostically modeled using Eq. (2) to estimate an appropriate diffusivity. Observed values of temperature at the base of mixed layer (dashed line in Fig. 3) and 250 m were specified as boundary conditions and the model was run to steady state. We explored stratification-dependent formulations of diffusivity, but found that a constant value of diffusivity did just as well at simulating temperature. With the best-fit value of $K = 1 \, \text{cm}^2 \, \text{s}^{-1}$ (determined subjectively), the model does a very good job at simulating the time rate of change of temperature (Fig. 4). This value of diffusivity agrees well with other upper ocean modeling studies in the Sargasso Sea (Musgrave et al., 1988; Doney et al., 1996).

It is difficult to make a rigorous error analysis of the individual terms in Eq. (2). Because of this, we have sought to make our error estimates upper bounds. Starting with the vertical diffusivity, we found, as did Musgrave et al. (1988) in their prognostic modeling of the temperature distribution at the nearby Hydrostation S, that simulations degrade significantly when K is less than $0.75 \, \text{cm}^2 \, \text{s}^{-1}$ or greater than $1.25 \, \text{cm}^2 \, \text{s}^{-1}$. We thus estimate the error in vertical diffusion to 25%. The error in vertical advection is largely related to the error in wind stress at the ocean surface. Hellerman and Rosenstein (1983) estimate errors in the wind stress field of less than $0.01 \, \text{N} \, \text{m}^{-2}$ in the Sargasso Sea, where mean values of the stress are about $0.1 \, \text{N} \, \text{m}^{-2}$ (Doney et al., 1996). This would give an error in downwelling velocity of about 10%. Also uncertain, however, is the shape of the vertical
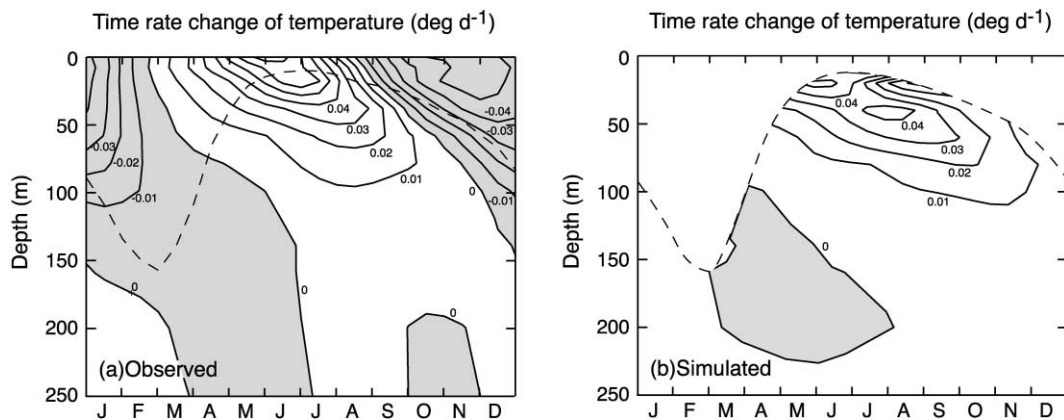

Fig. 4. Observed (a) and simulated (b) time rate of change of temperature in the seasonal thermocline. The dashed line indicates the depth at which temperature differs by 1°C from the 2.5 m value.

velocity profile assumed. We therefore conservatively estimate the error in vertical advection to be 25%. The error in lateral advection is potentially much larger. We assume that the lateral advection error is 100%. Fortunately, as we show below, lateral advection is usually the smallest term in oxygen and DIC budgets of the seasonal thermocline. Our error analysis is applied to the budgets integrated between April 16 and December 12 (a period of 240 days) and 100 and 250 m. The error in the inventory change between April and December is computed from the error in the April and December concentrations. These errors are computed as a weighted standard deviation divided by the number of observations, where the weighting factor from Eq. (1) is used.

4. Results and discussion

4.1. Distribution of remineralization

The biological source terms for oxygen (J_{O_2}), DIC (J_{DIC}) and nitrate (J_{NO_3}), determined diagnostically from Eq. (4) are shown in Fig. 5. J_{O_2} has been multiplied by the canonical $O_2 : C$ Redfield
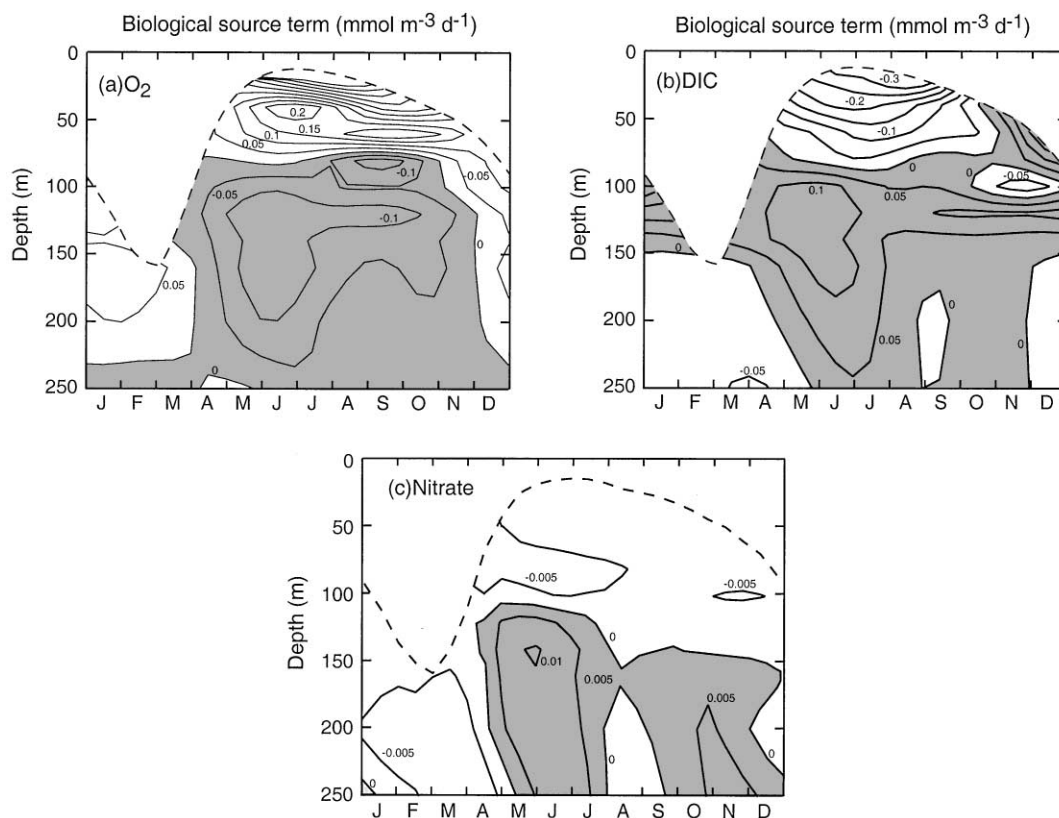

Fig. 5. The biological source minus sink term of inorganic carbon modeled from the (a) oxygen and (b) DIC budgets. (c) The biological source-minus-sink term of inorganic nitrogen calculated from the nitrate budget. An O_2:C ratio of -138:103 was used to convert the O_2-based estimate to carbon units.

ratio ($O_2 : C = -138 : 103$) to highlight the similarities in the respiration and photosynthetic rates computed using oxygen and DIC. We will show below that our best estimate of the $O_2 : C$ ratio during remineralization is in fact very close to the canonical value. J_{NO_3}, on the other hand, has been left in nitrogen units. Both J_{O_2} and J_{DIC} reveal a respiration maximum at 120 m in the spring, with corresponding values of 1.4 and 1.3 mmol C m^{-3} d^{-1}, respectively. The respiration rate decreases with depth below 120 m and throughout the summer and fall. Both J_{O_2} and J_{DIC} also imply that the community compensation depth (defined here by the depth at which $J = 0$) is ~ 80 m in the spring and summer. A clear signal of sub-mixed layer new production, responsible for producing the shallow oxygen maximum (Shulenberger and Reid, 1981; Hayward, 1994), is seen above this depth. The pattern of J_{NO_3} is similar to J_{O_2} and J_{DIC}, though shifted to greater depths: the spring maximum, which has a value of 0.010 mol N m^{-3} d^{-1}, is located at ~ 140 m, and the community compensation depth is ~ 120 m on average in the spring and summer.

A remarkable feature of our analysis is the spring maximum in remineralization, which must be an artifact of the spring bloom in surface waters. It is well known that primary production and particle fluxes are a maximum in spring at the BATS site (Michaels and Knap, 1996). The subsurface drawdown in dissolved organic carbon (DOC), which contributes significantly to the carbon budget at these depths, is greatest during this time as well (Carlson et al., 1994). To our knowledge, the signal of the spring bloom has not been seen before in analyses of oxygen, DIC and nitrate distributions. Previous studies of the oxygen anomaly (the departure from saturation) in the shallow aphotic zone (Jenkins and Goldman, 1985; Najjar and Keeling, 1997) show gradual declines from spring to fall, not the abrupt decrease we see here. It is presumably the higher quality and quantity of the BATS data compared to earlier measurements that has allowed this signal to emerge.

Another important result is our estimate of the community compensation depth, which separates the zone of net photosynthesis from net respiration. As such, the compensation depth is a very important biogeochemical boundary. The more-frequently measured 1% light level is often implicitly used as this boundary, but clearly there is nothing special about 1%, or even why the compensation depth should be directly related to the fraction of surface light reaching a certain depth. Unfortunately, the compensation depth is rarely measured directly. The analysis of the annual cycle of the oxygen anomaly by Jenkins and Goldman (1985) at Hydrostation S suggests a compensation depth of about 80 m, as does a similar analysis of the zonal mean O_2 anomaly at 30°N in the Atlantic Ocean (Najjar and Keeling, 1997). This latter study suggested that the absolute irradiance (not the fraction of surface irradiance) is an important controlling factor of the compensation depth. What is not clear is why the compensation depth based on the nitrate distribution is significantly deeper. One possible explanation is that nitrification, unlike the oxidation of organic carbon, is light inhibited.

4.2. Relative importance of physical transport

To evaluate the relative importance of various terms in the modeled oxygen, DIC and nitrate budgets in the seasonal thermocline, we present in Fig. 6 the vertical distribution of these terms averaged from April 16 to December 12 (a period of 240 days, about 2/3 of the year). It is clear from this figure that physical transport is a significant component of the oxygen, DIC and nitrate budgets. Had we estimated remineralization from the seasonal drawdown of oxygen or
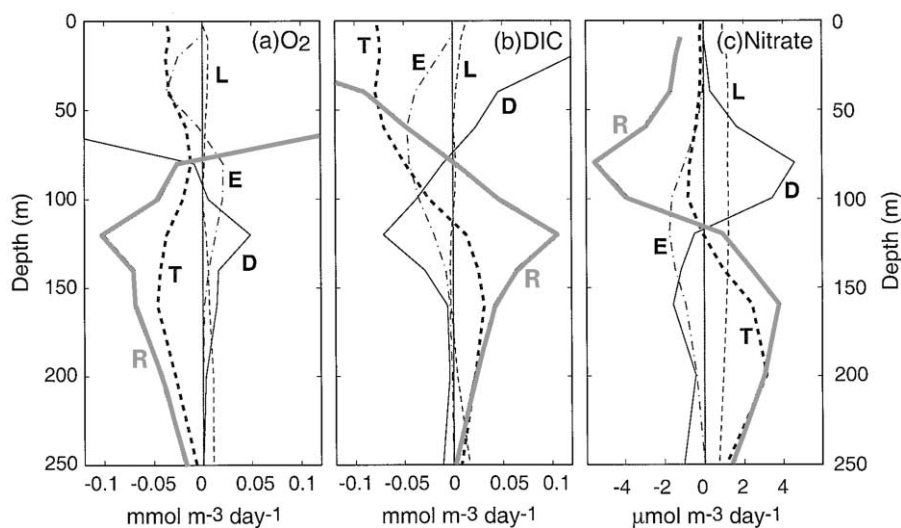
Fig. 6. Modeled budgets for (a) oxygen, (b) DIC, and (c) nitrate as a function of depth, averaged from April 16 to December 12. T: time rate of change; R: remineralization; D: vertical diffusion; E: Ekman transport; L: lateral advection.

accumulation of DIC or nitrate, we would have significantly underestimated the remineralization rate. This is clear from the difference between the time rate of change and the estimated remineralization rate.

Below the compensation depth, diffusion is always a source of oxygen and a sink of DIC and nitrate. Diffusion is a sink of oxygen because the O_2 gradient decreases with depth and therefore the downward diffusive flux decreases with depth, creating a diffusive flux convergence. For DIC and nitrate, the situation is reversed, with the upward flux of these species decreasing with depth. The extrema in the diffusion terms below the compensation depth is located where the change in gradient is largest. This is at about 120 m for DIC and oxygen, but is deeper for nitrate because the nitrate gradients are displaced to greater depths compared to DIC and oxygen gradients at BATS (Michaels and Knap, 1996).

Because oxygen decreases with depth and DIC and nitrate increase with depth, vertical advection (always downward in the model) is always a source of oxygen and a sink of DIC and nitrate below the compensation depth. The extrema in vertical advection are located where both w and the chemical gradients are significant, and, because of the differences noted above, are higher in the water column for oxygen and DIC than for nitrate.

Lateral advection is a relatively weak source for oxygen and DIC throughout the water column. Lateral advection is always a source because the geostrophic flow from the northeast always brings in waters of higher oxygen and DIC nitrate concentrations than it takes away. We also estimated lateral advection of O_2 using climatological data (Najjar and Keeling, 1997) and found the O_2 source to be even weaker. Given that lateral advection is a small term, and that vertical diffusion and advection are sources of oxygen and sinks of DIC below the compensation depth, it is clear why ignoring transport will lead to an underestimation of the remineralization rate at BATS. Lateral advection is also a source for nitrate, since the nitrate concentration is generally higher

towards north throughout the year. The estimate here shows that the lateral advective term for nitrate, not like for oxygen and DIC, may be as large as the vertical diffusion and Ekman transport terms below the compensation depth.

4.3. Integrated budgets

Fig. 7 summarizes the integrated oxygen, DIC and nitrate budgets between 100 and 250 m from April 16 to December 12, including error estimates, which are computed by assuming that the individual errors are uncorrelated. Here we see quantitatively the underestimate of remineraliz-ation if physical transport is omitted: 80% for oxygen, 130% for DIC and 20% for nitrate. For the specified depth and time interval, we find the integrated remineralization rate to be 2.08 ± 0.38 mol O_2 m^{-2}, 1.53 ± 0.35 mol C m^{-2} and 0.80 ± 0.046 mol N m^{-2}. For comparison with previous stud-ies in the Sargasso Sea, refer to Table 1. Sarmiento et al. (1990) summarized remineralization rates in the Sargasso Sea determined from a variety of tracer-based techniques. Between 100 and 250 m,
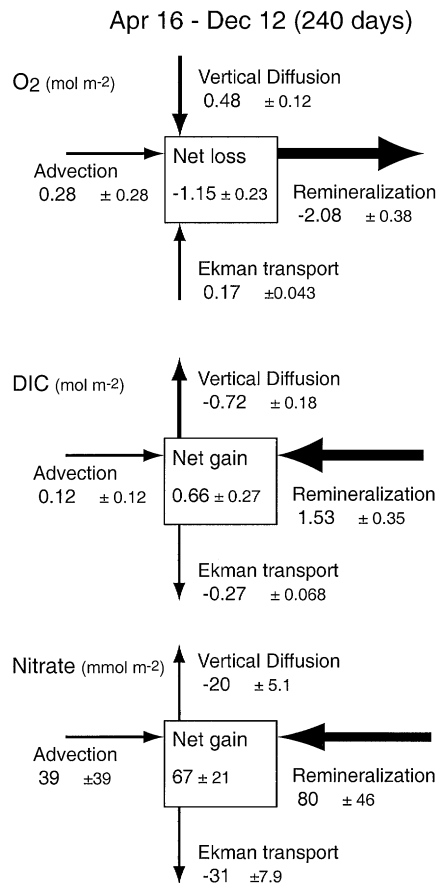

Fig. 7. DIC, nitrate and oxygen budgets integrated from 100 to 250 m, and from April 16 to December 12.

Table 1
Summary of shallow (100–250 m) remineralization estimates in the Sargasso Sea

Source	Technique	Estimate (mol (O_2, C, N) m^{-2})	Period
Sarmiento et al. (1990)	Tracer distributions	0.6–3.3 (O_2)	Annual
Jenkins and Goldman (1985)	AOU seasonal cycle	1.7–3.0 (O_2)	Apr.–Nov.
This study		1.53 $\pm$ 0.35 (C)	Apr.–Dec.
This study		2.08 $\pm$ 0.38 (O_2)	Apr.–Dec.
This study		0.080 $\pm$ 0.046 (N)	Apr.–Dec.
Carlson et al. (1994)	DOC changes	1 (C)	Apr.–Nov.
Lohrenz et al. (1992)	POC fluxes	0.3 (C)	May.–Oct.
This study	POC fluxes	0.38 $\pm$ 0.04 (C)	Apr.–Dec.
This sutdy	PON fluxes	0.058 $\pm$ 0.005 (N)	Apr.–Dec.

these rates vary from about 0.6–3.3 mol O_2 m^{-2} yr^{-1}. Our estimate of 2.08 mol O_2 m^{-2} from mid-April to mid-December falls squarely in the middle of these estimates.

A particularly instructive comparison is with the study of Jenkins and Goldman (1985), who also used seasonal oxygen variations to estimate remineralization for the same time of year in the Sargasso Sea. Based solely on the seasonal drawdown of the oxygen anomaly (the departure from saturation), they found remineralization equal to 1.7 mol O_2 m^{-2} between 100 and 250 m, within the error bars of our estimate. Based on heat and nitrogen budgets however, they estimated a downward diffusive transport of O_2 across 100 m of 1.3 mol O_2 m^{-2}, bringing their remineralization estimate up to 3.0 mol m^{-2}, significantly greater than our estimate. The difference is likely due to the fact that the Jenkins and Goldman analysis was based on observations from the 1960s, when spring mixed-layer depths were much greater than in the 1990s, when the BATS cruises were made (Michaels and Knap, 1996). Productivity and remineralization were presumably much greater as well during the 1960s due to the enhanced nutrient inputs to surface waters. We therefore would expect the Jenkins and Goldman analysis to produce significantly greater remineralization rates than ours.

Another difference we find with the Jenkins and Goldman (1985) study is with regard to the remineralization length scale. A least-squares exponential fit to the O_2-based remineralization rate in Fig. 6a from the depth of the maximum (120 m) to 250 m yields a e-folding length scale of 60 m, much smaller than the 260 m length scale estimated by Jenkins and Goldman (1985). This is at least partially due to the fact that Jenkins and Goldman (1985) did not account for physical transport when estimating remineralization length scale. Support for this is given in Fig. 6a, which shows that the depth scale for the time rate of change of oxygen is greater than the depth scale of remineralization. The difference also may be due to the different time periods over which the data were collected.

Our estimates of the remineralization rate can be compared directly with estimates of the remineralization of particulate organic matter estimated from the divergence of sediment trap fluxes (Table 1). Lohrenz et al. (1992) estimated a loss of particulate organic carbon (POC) of ~ 0.3 mol m^{-2} from May to October between 100 and 250 m. Here we extend their analysis by

including more observations (1989–1998) and the PON flux. These data were also obtained from the BATS web site. Measurements were made at 150, 200 and 300 m. Estimates at 250 m were made by linear interpolation and at 100 m by multiplying the flux at 150 m by 1.5, following the Martin et al. (1987) flux scaling. The decreases in POC and PON fluxes are estimated to be $0.38 \pm 0.04 \, mol \, C \, m^{-2}$ and $0.058 \pm 0.005 \, mol \, N \, m^{-2}$ from April to December, where the error estimates are computed from the standard deviation divided by the square root of the number of observations. These carbon and nitrogen fluxes are 24 and 51% of our remineralization estimates, respectively. These are probably lower bounds, however, since it is believed that sediment traps at BATS underestimate the particle flux by as much as a factor of 2 (Michaels et al., 1994).

Dissolved organic matter also contributes significantly to remineralization in the Sargasso Sea. Carlson et al. (1994) observed a drawdown of about $1 \, mol \, m^{-2}$ of DOC from spring to fall. Observations of dissolved organic nitrogen (DON), are much less conclusive (Carlson, personal communication). These estimates of DOC and DON loss, however, do not account for physical transport. Because the concentration and vertical gradient of dissolved organic matter generally decrease with depth, we would expect that vertical advection and diffusion are sources of DOC and DON in the seasonal thermocline, similar to oxygen. Thus, it seems likely that the estimates of biological DOC and DON losses are lower bounds. In consideration of the potential errors, we conclude that the remineralization rates for carbon and nitrogen estimated here are consistent with the observed loss of particulate and dissolved organic carbon and nitrogen in the shallow aphotic zone at BATS.

It is also useful to compare the remineralization estimates made here to new production estimates. Summaries of new production estimates in the Sargasso Sea have been made by many authors. The most recent summary (Gruber et al., 1998) shows a new production range of $2–4 \, mol \, C \, m^{-2} \, yr^{-1}$. Thus, it appears that about $60 \pm 20\%$ of annual new production is remineralized between 100 and 250 m between April and December.

4.4. Redfield ratios

The Redfield ratios during remineralization in the seasonal thermocline at BATS, taken from the rates in Fig. 7, yield an $O_2 : C$ ratio of 1.4 ± 0.40 and a $C : N$ ratio of 19 ± 12. Here, the errors (assumed to be uncorrelated) are mainly derived from the errors in the net change and lateral advection terms. The $O_2 : C$ ratio is in excellent agreement with the canonical value of the Redfield ratio. The most recent analysis by Anderson (1995) provides an estimate of 1.4 for $O_2 : C$. Had we ignored physical transport in estimating remineralization, we would have found an $O_2 : C$ ratio of 1.7. This highlights the importance of physical transport to our analysis.

The $C : N$ ratio we estimate here is significantly higher than the standard Redfield ratio (6.6), though the low end of our estimate is close to this value and in somewhat better agreement with analyses made on deep isopycnal surfaces (~ 8, Takahashi et al., 1985). The compensation depth with respect to nitrate is deeper than those with respect to oxygen and DIC. Between 100 and 120 m depth, the nitrate budget shows net photosynthesis whereas the O_2 and DIC budgets show net remineralization (Fig. 6). Therefore, integrating between 100 and 250 m contributes to the high $C : N$ ratio for remineralization. Integrating between 120 and 250 m, where the O_2, DIC and nitrate budgets all show net remineralization, yield $O_2 : C$ and $C : N$ remineralization ratios of 1.5 ± 0.5 and 13 ± 6.8, respectively, still leaving us with a $C : N$ ratio higher than the standard value.

The high C : N ratio of remineralization gives additional support to the notion that the summertime DIC drawdown in surface water is of biological origin, and, furthermore, that nitrogen-poor organic matter is exported from surface waters. The sediment trap fluxes we analyzed above yield a C : N ratio in the implied remineralization of 6.6, in good agreement with the standard Redfield ratio. Thus, if these fluxes are correct then the C : N ratio of the respired dissolved organic matter (DOM) is significantly higher than 13 ± 6.8. If the particulate fluxes are actually too low, as suspected by Michaels et al. (1994), then the C : N ratio in the respired DOM is even higher.

What are the implications for the nitrogen budget at BATS? Somehow, nitrogen- poor organic matter is being created and exported to depth, largely in dissolved form. Clearly, the results are consistent with a preferential recycling of nitrogen in surface waters, but nitrogen fixation cannot be ruled out either. Nitrogen-fixing bacteria, such as *Trichodesmium*, which are abundant in the Sargasso Sea, use a carbohydrate ballast to control their buoyancy, and therefore have the potential of creating organic matter with a C : N ratio substantially higher than the Redfield ratio (Michaels et al., 1994).

5. Conclusions

For the first time seasonal variations in oxygen, DIC and nitrate have been exploited simultaneously to estimate remineralization rates and Redfield ratios in the shallow aphotic zone. These are important but elusive quantities for modeling marine biogeochemical cycles. We find that it is extremely important to quantify physical transport in order to make reliable estimates of shallow remineralization. The derived rates for carbon are consistent with direct observations of the loss of POC and DOC in the seasonal thermocline at BATS. The derived $O_2 : C$ remineralization ratio is in good agreement with the standard Redfield value, but the C : N ratio is much higher, suggesting an export of nitrogen-poor organic matter from surface waters. It seems likely that the lion's share of this organic matter is in dissolved form. Any efforts, therefore, at elucidating the strong non-Redfield character of the Sargasso Sea, should focus on the dynamics of dissolved organic matter.

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