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Nutrient Transport and Mixing in the Gulf Stream

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The distribution of nutrient flux (geostrophic velocity times concentration) in five sections across the Gulf Stream–North Atlantic Current (from the Florida Straits to 35°W) is characterized by an intense core, centered at the depth of the 26.8 σ_t isopycnal surface (typically 500 m). This "nutrient stream" carries nutrient transports of the order of 10^3 kmol s^{-1} of nitrate and proportional amounts of other nutrients. Between the Florida Straits and the Mid-Atlantic Bight, water transport doubles, but nutrient transport trebles, because along-isopycnal inflow from the subtropical gyre is concentrated in the layers of the upper thermocline, which are rich in nutrients. Beyond the Mid-Atlantic Bight, both water and nutrient transports decline slowly. Water mass and nutrient balances of nine isopycnal layers reveal significant upward entrainment and mixing of thermocline waters in the sector of the stream between the Florida Straits and the Mid-Atlantic Bight. A two-box model of the nutrient-depleted surface layers ($\sigma_t < 26.8$) and the nutrient-rich thermocline layers ($26.8 < \sigma_t < 27.5$) shows an upward entrainment rate of about 1.6 m^2 s^{-1} per unit length of the stream, or a diapycnal velocity of 2×10^{-5} m s^{-1} over the 80-km width of the stream. In addition, there is two-way diapycnal mass exchange at approximately the same rate. The rate of inflow from the surface layers of the Sargasso Sea is about 12×10^6 m^3 s^{-1}, from the thermocline layers 15×10^6 m^3 s^{-1}.

INTRODUCTION

In a seminal paper, *Rossby* [1936] discussed the continuity of properties on isopycnal surfaces under the Gulf Stream between the Sargasso Sea and the continental margin. He inferred cross-stream advection along these surfaces and attempted to account for it theoretically. The layers involved were primarily those of the upper thermocline, known to be rich in nutrients [*Redfield*, 1936]. Although the important idea of analyzing circulation along isopycnal surfaces was soon taken up and applied to the equatorial North Atlantic by *Montgomery* [1938], western boundary current behavior was not examined again in this manner for a long time.

The concept of a western boundary current originates from ocean circulation models of *Stommel* [1948] and *Munk* [1950], according to which a dynamically active deep surface layer is driven by the wind, causing inflow from a Sverdrup interior into a western boundary current, and equal recirculation. If one includes the upper thermocline in the active layer, inflow into the boundary current, and recirculation, is to be expected also in this layer. A different recent idea [*Luyten et al.*, 1983] is that the thermocline circulation originates from the convergence of Ekman transport at the outcropping of the isopycnal surfaces. From there the subducted water mass makes its way again to the western boundary current. It is not clear how this circulation loop is to be closed. *Riley* [1951] had a conceptual model similar to that of Luyten et al. in mind in examining the behavior of nutrients in the upper thermocline, and he also ended with the nutrients going into the western boundary current. However, a tracer analysis of the North Atlantic thermocline layers by *Sarmiento* [1983] showed gross discrepancies between Ekman convergence at subduction and what actually flows along upper thermocline layers. In the stratum carrying most of the nutrients (between σ_t = 26.7 and 27.3) Sarmiento found westward drift of 11×10^6 m^3 s^{-1}, versus Ekman convergence of $0 \pm 1 \times 10^6$ m^3 s^{-1}.

On account of the importance of nutrient transport to the global biogeochemical cycle, it is clearly desirable to establish from observation just what the mass balance of the nutrient bearing stratum is, and how large a nutrient transport the western boundary current actually carries. *Brewer and Dyrssen* [1987] obtained first-order estimates for the nitrate and phosphate transport across the Florida Straits and suggested that the Gulf Stream is a principal source of nutrients for the North Atlantic. Here we trace this transport further and show that it increases greatly as the stream flows along the continental margin of North America.

In addition to estimating total nutrient transport, we also examine the questions of how the transport of water mass and nutrients is distributed over the different isopycnal layers, what the downstream increase of the transport implies for the circulation of the nutrient-bearing stratum in the ocean interior, and what the changing profile of nutrient transport reveals about processes within the boundary current itself. Specifically, we examine what support there is in the data for the recently proposed concept of "western boundary upwelling" [*Csanady*, 1989].

THE DATA USED

The tracks of the Gulf Stream–North Atlantic Current hydrographic sections used in our study are shown in Figure 1. They will be identified by the latitude or longitude approximately followed during the cruise: 24°N, 36°N, 64°W, 53°W, and 35°W. The dates of the sections were September 5, 1981, June 12–14, 1981, April 23–28, 1985, May 14–17, 1983, and July 28 to August 9, 1983, respectively.

All sections were taken in late spring to summer, and two consecutive section pairs (24°N–36°N and 53°W–35°W) were taken in the same year, with a time lapse of only about two and a half months.

The data were kindly made available to us in processed and verified form by M. McCartney of Woods Hole Ocean-

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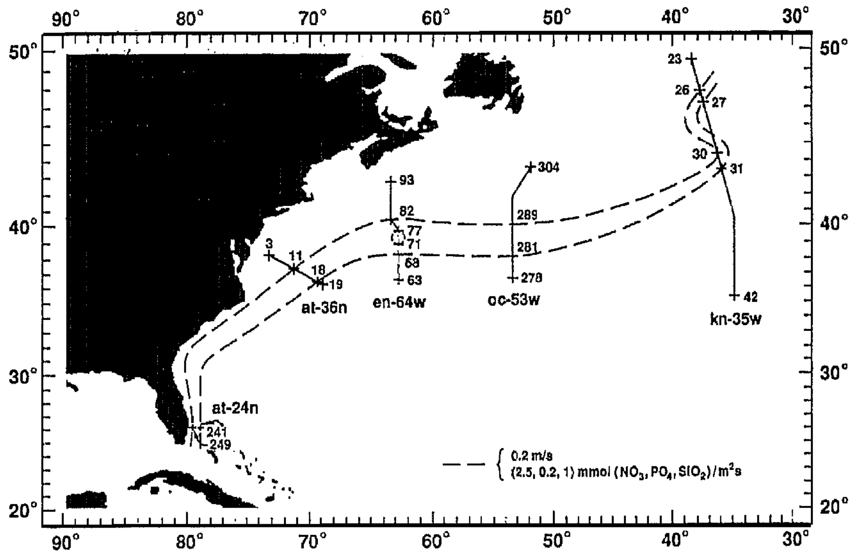

Fig. 1. Hydrographic and nutrient sections employed in this study. The dashed lines indicate the approximate contours for the nutrient stream as defined by the specified nutrient flux density values.

ographic Institute. They included readings of temperature, salinity, nitrate, phosphate, and silicate. From the salinity and temperature data, we have calculated the σ_t field and geostrophic velocities referred to 2000 m, in all sections except 24°N. Below this depth the isopycnals were flat enough to guarantee that the relative error in the velocities and transports in the important isopycnal layers is small. In section 24°N, we used the mean summer velocity field of *Niiler and Richardson* [1973] for a cross section located about half a degree south of section 24°N. This is made necessary by the importance of barotropic flow in the Florida Straits.

Flux density F_n or transport per unit area, defined as the product of concentration c and velocity normal to the section v, was then calculated for the three nutrients named, in all sections. The units are μmol $L^{-1} \equiv$ mmol $m^{-3} \equiv 10^{-6}$ kmol m^{-3} for nutrient concentration, mmol m^{-2} $s^{-1} \equiv 10^{-6}$ kmol m^{-2} s^{-1} for nutrient flux density. Transports given below have units of kmol s^{-1}.

THE NUTRIENT STREAM

Figure 2 shows the σ_t and nitrate concentration distributions in section 36°N, just after the Gulf Stream separates from the continental margin, Figure 3 the calculated velocity and nitrate flux contours. The flux contours define a nutrient stream with a core at about 500-m depth, below and slightly offshore of the high-velocity core of the Gulf Stream. Other nutrients behave similarly to nitrate; see Figure 4 for phosphate and silicate flux contours. Total nutrient transports (flux density integrated over the cross section) are in this section: 863 kmol s^{-1} for NO_3, 55 kmol s^{-1} for PO_4, and 508 kmol s^{-1} for SiO_2.

The continuity of properties along isopycnal surfaces is evident in Figure 2, and in similar sections of other nutrients, not shown. There is one qualification, however, illustrated in Figure 5: nitrate concentration contours in a σ_t-distance map show significant departures from the general horizontal trend at the location of the nutrient stream. Up to σ_t = 26.8, i.e., in the lower and mid-thermocline layers, the nitrate concentration is seen to be almost a function of density alone. In lighter layers the concentration shows a maximum at stations 15 and 16, just seaward of the high-velocity core of the

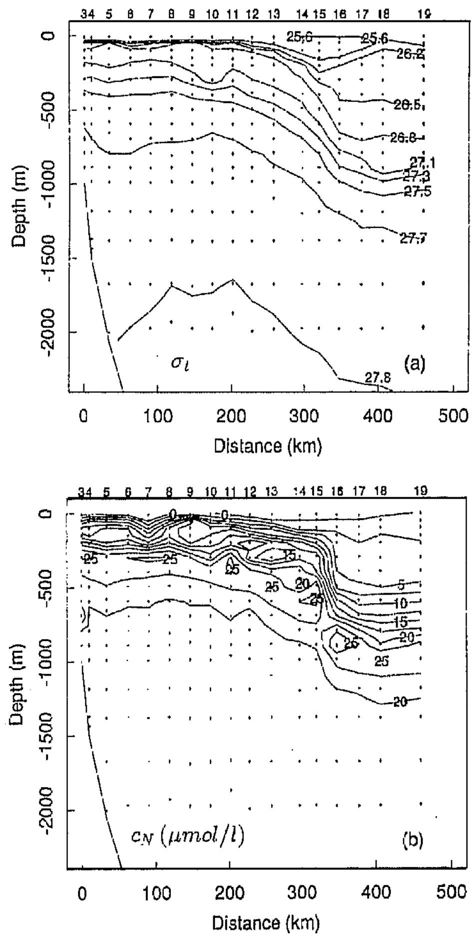

Fig. 2. (*a*) The σ_t and (*b*) nitrate concentration distributions in section 36°N.

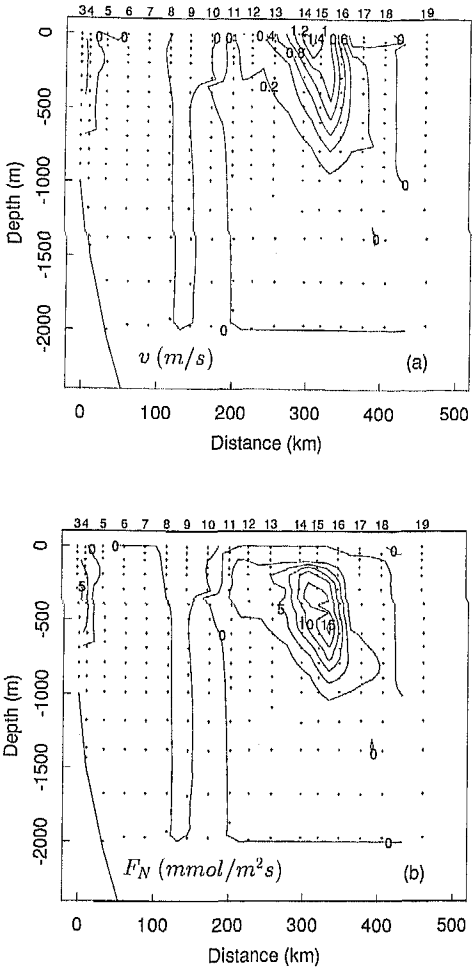

Fig. 3. (*a*) Velocity and (*b*) nitrate flux density distributions in section 36°N.

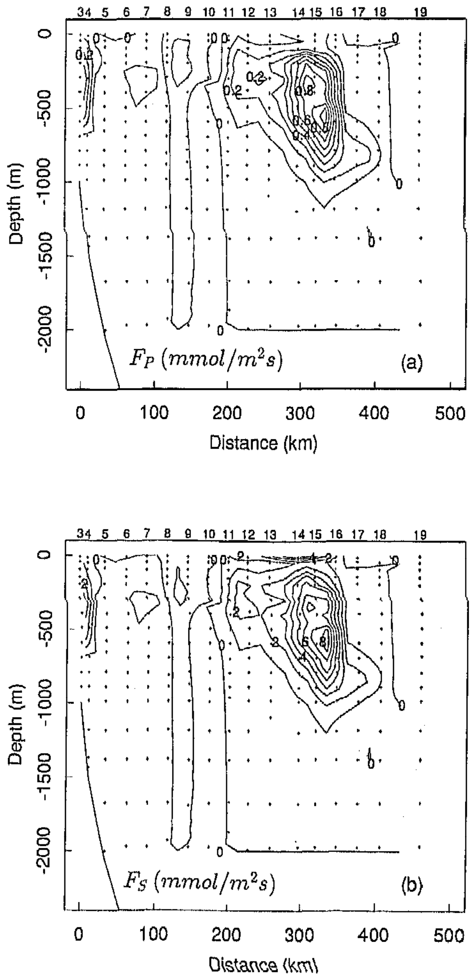

Fig. 4. (*a*) Phosphate and (*b*) silicate flux density distributions in section 36°N.

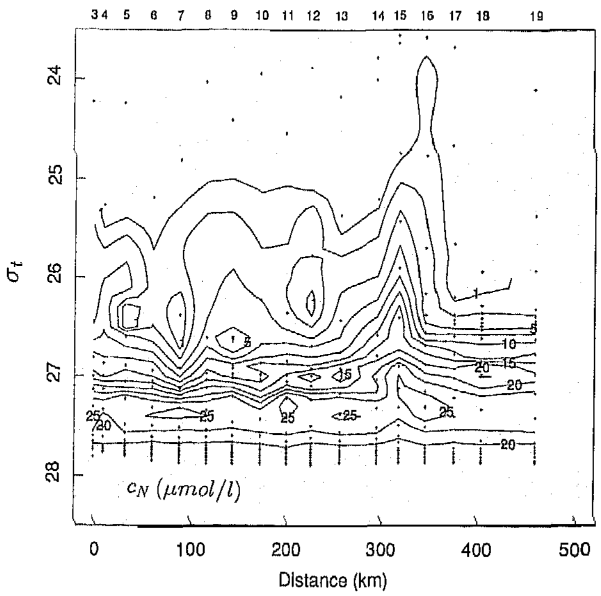

Fig. 5. Nitrate concentration in section 36°N as a function of σ_t and cross-stream distance.

Gulf Stream. This suggests mixing between the upper thermocline and surface waters, a transfer of nutrients from the nutrient-rich thermocline waters into the nutrient-depleted surface layers. It is important to note that a considerable number of data points show the nutrient maximum in the light layers of the Gulf Stream. However, variations shoreward from this maximum (e.g., near $x = 150$ km) are mostly artifacts of the contouring scheme and should be ignored.

The nutrient stream is identifiable in the other four sections (see Figure 6 for the nitrate flux distributions), although downstream of 36°N it has several branches, and at 35°W also reverse transport of significant magnitude. Flux intensity is greatest in the Florida Straits and declines monotonically downstream. The total nutrient transport peaks at the 36°N section (see Figure 7).

The layers of the Sargasso Sea thermocline between the 26.8 and 27.7 σ_t isopycnal surfaces contain a rich lode of nutrients and may legitimately be called the nutrient bearing stratum of the North Atlantic. Various properties of this stratum were discussed by *Riley* [1951]. The nutrient stream, or band of high nutrient flux associated with the Gulf Stream system, flows along the western and northern edge of the nutrient bearing stratum. Figure 1 indicates the position of the nutrient stream, estimated from the five sections used here. The contours of the nutrient stream in the figure correspond to flanking nutrient flux density values of (2.5,

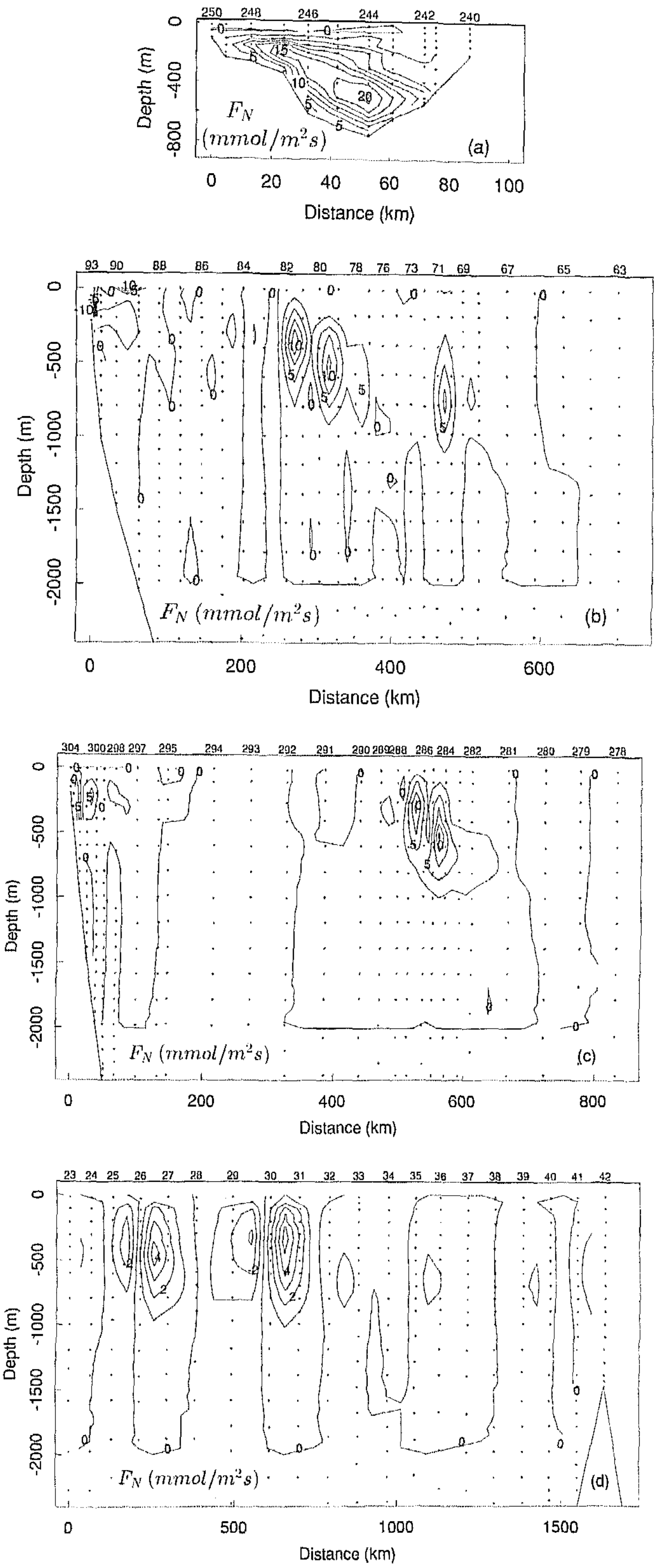

Fig. 6. Nitrate flux density distributions for sections (*a*) 24°N, (*b*) 64°W, (*c*) 53°W, and (*d*) 35°W. Note that the scales in the *x* direction are unequal, in a ratio 4:1:1:0.5. Also note the change in the contour interval for section 35°W.

0.2, 1) mmol of (NO_3, PO_4, SiO_2) m^{-2} s^{-1}, which roughly coincide with velocity contours of 0.2 m s^{-1}. Although it may be conjectured from the nutrient and water mass transport data in Figure 7 that much of the nutrient transport recirculates, a large fraction of it undoubtedly reaches the subpolar gyre.

WATER MASS AND NUTRIENT TRANSPORTS IN ISOPYCNAL LAYERS

In addition to the total transports, from the geostrophic velocities and the nutrient flux densities, we have also calculated the transport of water mass and of nutrients in a succession of overlying layers, between the sea surface and the σ_t = 25.6 isopycnal surface, and then between pairs of the isopycnals, σ_t = 25.6, 26.2, 26.5, 26.8, 27.1, 27.3, 27.5, 27.7, and 27.8. The isopycnal σ_t = 27.8 approximately coincides with the 2000-m assumed level of no motion. The isopycnals chosen divide the cross section of the Gulf Stream into strips of roughly equal depth. The top three strips are in what *Worthington* [1976] called warm water, the next two upper thermocline water, the two below that mid-thermocline water, and the last two lower thermocline water. Down to the mid-thermocline, the layers considered by *Sarmiento et al.* [1982] were nearly the same as ours, although their choice was based on equal surface outcropping areas in winter.

Between an isopycnal layer at depth $z_i(x)$ and another at $z_{i+1}(x)$, the water mass and nutrient transports were determined from

$$V = \int_0^L dx \int_{z_i}^{z_{i+1}} v \, dz$$
$$T_n = \int_0^L dx \int_{z_i}^{z_{i+1}} cv \, dz \qquad (1)$$

where x = 0 and x = L were chosen so as to include all significant baroclinic transport by the Gulf Stream. The concentration in each layer was taken to be the arithmetic average of the observations between the same limits on x and z as V and T_n. This average c_n differed little from T_n/V. Units used are sverdrups (10^6 m^3 s^{-1}) and kmol s^{-1}.

Table 1 contains V and T_n for nitrate, phosphate, and silicate in all the isopycnal layers mentioned, for the two sections 24°N and 36°N. As is well known, the baroclinic water mass transport of the Gulf Stream roughly doubles between these two sections. Nutrient transports, however, are seen to treble. For the discussion here the distribution of the increase over the different isopycnal layers is of prime interest. The increases are generally of the same order as the "upstream" transport at section 24°N, and therefore dwarf any errors in the transport estimates.

Expressed as a fraction of the upstream water transport, the increases in V in the various layers range from zero to 200%, with a pronounced broad maximum between the σ_t = 26.5 and 27.3 isopycnal surfaces (excluding the bottom two layers, which are vestigial upstream). The increases in mass transport will be attributed to along-isopycnal inflow from the Sargasso Sea, with qualifications to be developed later. As may be seen in Figure 8, the layer to layer data scatter a bit but show that most of the mass transport increase occurs in the upper thermocline layers. Because these are the layers constituting the nutrient bearing stratum, the much greater than proportionate increase of nutrient transport is at once

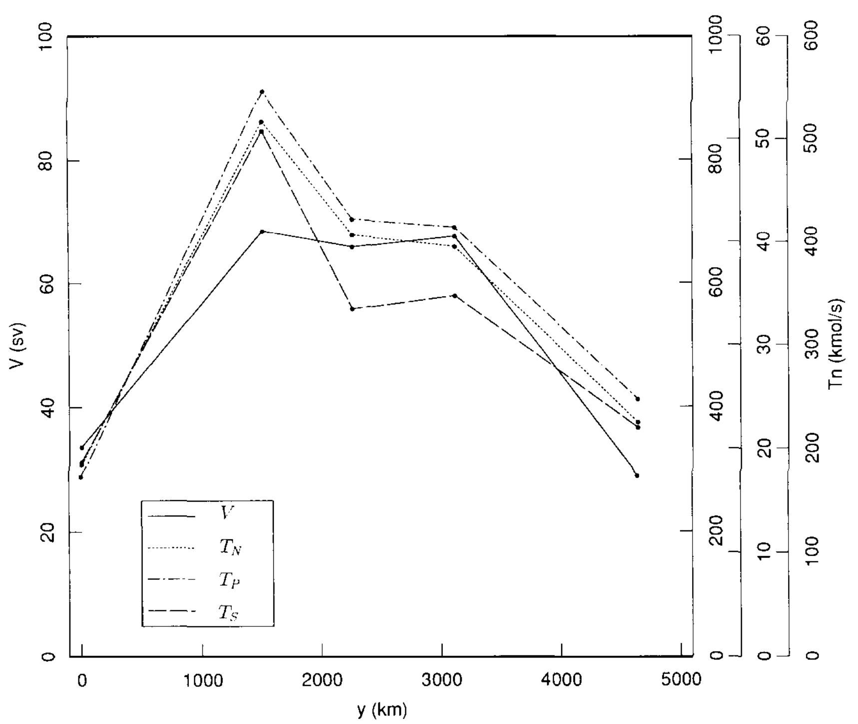

Fig. 7. Variation of total water mass and nutrient transports with along-stream distance. The three scales in the right margin correspond to nitrate, phosphate, and silicate transport, respectively.

explained by the predominance of the inflow from that stratum.

Although this explanation is borne out in a general way by an examination of the nutrient transport changes, there are some important discrepancies. Let an "advective" concentration be defined by

$$c_a = \frac{T_{n2} - T_{n1}}{V_2 - V_1} \tag{2}$$

where the numeric subscripts refer to the upstream and downstream sections. If inflow took place strictly along isopycnals, the advective concentration would equal some weighted mean of the concentrations c_{n1} and c_{n2} (which only differ by about 10%, so that c_{n2} is a reasonable approximation to the concentration in the inflow). As long as the increases in both mass transport and nutrient transport in a given layer are of the order of the upstream transports, any major differences between c_a and c_{n2} are significant and require an explanation. An advective concentration much larger than layer concentration implies excess nutrient supply, the opposite difference a deficiency.

Excluding the uppermost layer and the two bottom layers from consideration (because the $\Delta V/V$ ratio is too small or too large for this argument), significant excess nutrient supply is found in the layers above the $\sigma_t = 26.8$ isopycnal, deficiency below. Combining all the layers above this isopycnal into a single "surface" stratum, and all those down to $\sigma_t = 27.5$ into a "thermocline" stratum, one finds a weighted average c_a about twice c_{n2} *in the surface stratum, a 15% deficiency* in the thermocline stratum. Expressed in terms of total nitrate transports, the increase in the surface stratum is 160 kmol s^{-1}, only half of which is explained by the

TABLE 1. Water Mass (Sverdrups) and Nutrient Transports (kmol s^{-1}) and Concentrations (μmol L^{-1}) in Sections 24°N and 36°N

			NO_3				PO_4				SiO_2			
Layer	V_1	V_2	T_{n1}	T_{n2}	c_a	c_{n2}	T_{n1}	T_{n2}	c_a	c_{n2}	T_{n1}	T_{n2}	c_a	c_{n2}
<25.6	12.14	12.62	12.74	16.62	8.08	1.02	0.79	1.90	2.31	0.14	19.09	27.29	17.08	2.02
25.6–26.2	3.26	6.63	14.33	43.71	8.72	4.32	0.71	2.57	0.55	0.26	6.68	21.03	4.26	2.21
26.2–26.5	6.30	7.96	35.47	59.02	14.19	4.66	1.73	3.18	0.87	0.27	15.88	27.68	7.11	2.13
26.5–26.8	4.08	12.47	52.94	154.58	12.11	10.73	2.77	9.08	0.75	0.62	22.89	73.01	5.97	4.71
26.8–27.1	3.81	11.69	80.10	219.27	17.66	18.18	4.55	13.71	1.16	1.14	42.25	115.57	9.30	9.39
27.1–27.3	1.55	4.99	42.75	112.55	20.29	22.30	2.55	7.20	1.35	1.43	27.79	67.91	11.66	13.35
27.3–27.5	2.26	3.61	64.19	86.66	16.64	24.09	3.94	5.65	1.27	1.57	48.55	56.30	5.74	15.60
27.5–27.7	0.11	4.19	3.38	88.71	20.92	20.96	0.20	5.91	1.40	1.40	2.84	60.11	14.04	14.17
27.7–27.8	0.13	4.34	2.87	81.70	18.16	18.74	0.15	5.48	1.27	1.25	1.39	59.38	13.77	13.99
All	33.65	68.50	308.75	862.81	15.90	16.92	17.39	54.68	1.07	1.11	187.36	508.28	9.21	11.50
<26.8	25.78	39.69	115.47	273.93	11.39	5.83	6.00	16.73	0.77	0.35	64.54	149.01	6.07	3.01
26.8–27.5	7.62	20.28	187.03	418.48	18.28	21.01	11.04	26.56	1.23	1.34	118.59	239.78	9.57	12.26
27.5–27.8	0.25	8.53	6.25	170.41	19.83	19.25	0.35	11.39	1.33	1.29	4.23	119.49	13.92	14.03

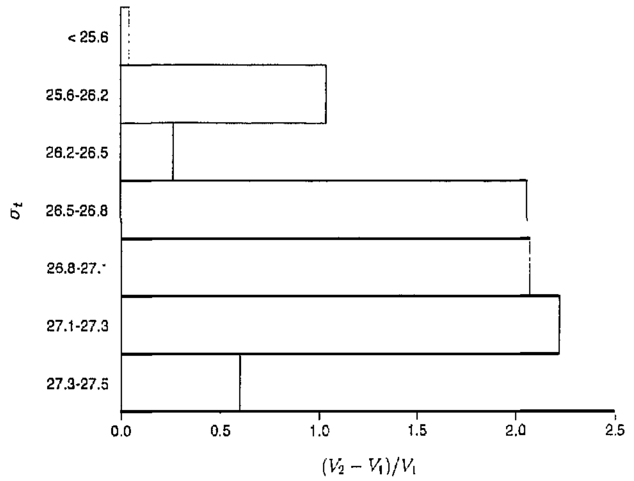

Fig. 8. Relative increase between sections 24°N and 36°N of water mass transport in isopycnal layers.

isopycnal inflow. In the thermocline, the increase is 230 kmol s^{-1}, in place of 265 kmol s^{-1} if the inflow were isopycnal. Similar differences occur with the other nutrients (see Table 1). As may be expected, the exact amount of the smaller discrepancy in the thermocline scatters more, its average over the three nutrients being 17%.

MIXING AND ENTRAINMENT

The "excess" nutrient transport observed in the surface stratum, and the concentration anomalies over the nutrient stream (Figure 5) suggest mixing (two-way exchange) and possibly entrainment (one-way mass transfer) of thermocline waters into the surface stratum. A two-box model of the Gulf Stream between the two sections 24°N and 36°N (Figure 9) can be used to estimate the rates of these diapycnal transfer processes. Given the large nutrient transport increases, nutrient utilization is legitimately ignored in the mass balances (see discussion below). The large water mass transports, and the large increase in these transports, makes it realistic to suppose steady state (ignore "storage" of water between sections) and to neglect any exchange with the continental margin. The water mass and nutrient balances for the surface and thermocline strata are then

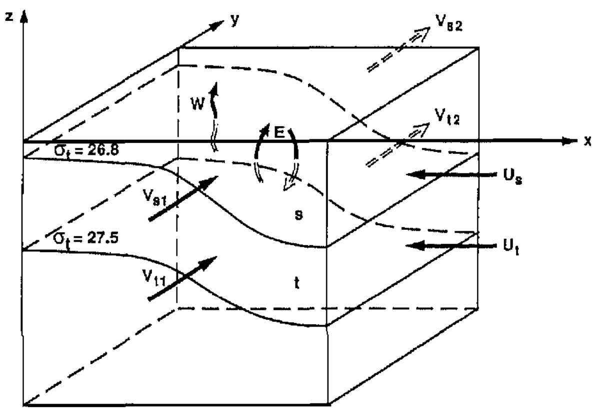

Fig. 9. Schematic representation of the main elements for the two-box model of the Gulf Stream between sections 24°N and 36°N.

$$
\begin{aligned}
\Delta V_s &= U_s + W \\
\Delta T_s &= c_s U_s + W c_t + E(c_t - c_s) \\
\Delta V_t &= U_t - W \\
\Delta T_t &= c_t U_t - W c_t - E(c_t - c_s)
\end{aligned}
\qquad (3)
$$

where the ΔV are increases in water mass transport, the ΔT increases in nutrient transport, U_s and U_t are inflows from the surface and thermocline strata, W is the entrainment rate, and E is the exchange rate. These equations are readily solved for the four unknowns U_s, U_t, W, and E.

The neglect of nutrient utilization is readily justified by empirical data obtained in the South Atlantic Bight. *Yoder et al.* [1983] quote new production rates at the edge of the continental shelf, implying nitrate utilization at the rate of 2.2×10^{-6} kmol m^{-2} d^{-1}, similar to rates used by *Walsh et al.* [1988], 3–5 $\times 10^{-6}$ kmol m^{-2} d^{-1}, in a numerical model of production in the Mid-Atlantic Bight. Supposing a utilization rate of 3×10^{-6} kmol m^{-2} d^{-1} over a 100-km-wide strip between sections 24°N and 36°N (1500 km apart) gives a nitrate transport loss of 5 kmol s^{-1}, or 3% of the calculated increase in transport in the surface layer, which is certainly at the noise level. To utilize hundreds of kmol s^{-1} at the empirical utilization rates would take an area the size of a subtropical gyre. Therefore utilization is important for the balance of nutrients between whole transoceanic sections (as discussed by Brewer and Dyrssen for such a section at 24°N), but not between sections of an intense nutrient stream.

Equations (3) may be applied separately to the nitrate, phosphate, and silicate transports, yielding three sets of estimates for inflow and mixing rates. These are shown in Table 2. While the estimates scatter somewhat (especially for the entrainment rate W), they all show similar inflow rates into the surface and thermocline strata, upward entrainment, and significant two-way exchange. Realistic mean rates, with error bars, are as follows (all in sverdrups):

$$
\begin{aligned}
U_s &= 12 \pm 1.5 \\
U_t &= 15 \pm 1.9 \\
W &= 2.4 \pm 1.9 \\
E &= 2.4 \pm 1.2
\end{aligned}
$$

The along-stream distance between the two sections is about 1500 km, so that the entrainment and exchange rates per unit length of the stream are 1.6 m^2 s^{-1}, with fairly wide error bars. Distributed over the 80-km width of the stream the entrainment and mass transfer coefficients are both about 2×10^{-5} m s^{-1}. An upwelling velocity of similar magnitude characterizes equatorial upwelling [*Wyrtki*, 1981].

TABLE 2. Estimates for Inflow and Mixing Water Mass Transports (Sverdrups) Between Sections 24°N and 36°N Obtained From the Two-Box Model

Nutrient	U_s	U_t	W	E
NO_3	11.53	15.04	2.38	2.17
PO_4	9.62	16.95	4.29	1.19
SiO_2	13.44	13.12	0.47	3.53

TABLE 3. Water Mass Transports (Sverdrups) and Nitrate Transports (kmol s^{-1}) in the Surface s ($\sigma_t < 26.8$), Thermocline t ($26.8 < \sigma_t < 27.5$), and Deep Strata d ($27.5 < \sigma_t < 27.8$) of + Five Sections

	Section				
	24°N	36°N	64°W	53°W	35°W
V_s	25.78	39.69	40.87	43.86	4.48
V_t	7.62	20.28	18.54	17.57	21.05
V_d	0.25	8.53	6.44	6.18	3.49
T_{Ns}	115.5	273.9	187.8	220.8	17.5
T_{Nt}	187.0	418.5	362.3	314.7	292.6
T_{Nd}	6.3	170.4	128.0	123.5	65.4

Water mass and nitrate transports in different strata of all five sections are shown in Table 3 (with $\sigma_t < 25.6$ included in the surface stratum). Transports of other nutrients behave similarly to nitrate. Between sections 36°N–64°W and 64°W–53°W there is little inflow or outflow; from 53°W to 35°W there is large outflow from the surface stratum and inflow into the thermocline. Application of the above box model to these section pairs cannot be justified because the $\Delta V/V$ requirement is not met, and indeed it leads to erratic results.

CONCLUSION

The results here reinforce and flesh out the idea of *Brewer and Dyrssen* [1987] that the Gulf Stream is a major source of nutrients for the North Atlantic. A nutrient stream flows under the Gulf Stream and the North Atlantic Current, with its core at only 500-m depth and carries a very large supply of nutrients northeastward. Only about a third of the supply comes through the Florida Straits, the rest from the Sargasso Sea thermocline, arriving between the straits and the Mid-Atlantic Bight. The water transport from the subtropical gyre into the western boundary current is dominated by inflow from the thermocline. Because the upper thermocline is the principal nutrient-bearing stratum, the inflow from there into the nutrient stream is responsible for the large increase in nutrient transport.

The proximity of the nutrient stream to the surface already suggests the likelihood of nutrients reaching the surface layers. The mass balance of individual isopycnal layers shows clear evidence not only for thermocline-surface mass exchange, but also net diapycnal mass transfer. The intensity of this "western boundary upwelling" is high enough to rival the most intense upwelling observable in the ocean: equatorial upwelling.

The ideas underlying the concept of western boundary upwelling are that energy dissipation in oceanic gyres is concentrated in western boundary currents, and that the first phase of dissipation is the release of potential energy to the "primary" eddies and meanders growing on the current. This first phase involves the upward movement of relatively light fluid along isopycnals, across the direction of the mean current, in accordance with the baroclinic instability mechanism. The eddy energy is eventually transmitted to the environment and dissipated (for example, through the radiation of topographic waves). The dissipation makes the rise of the light fluid permanent.

Our estimate for entrainment plus exchange from the thermocline to the surface layers, 3.2 $m^2\ s^{-1}$, is similar to the estimate of western boundary upwelling, about 4 $m^2\ s^{-1}$, obtained by *Csanady and Hamilton* [1988]. The source for this upward transfer is undoubtedly the along-isopycnal inflow from the upper thermocline, at the rate of some 10 $m^2\ s^{-1}$. Although upward entrainment is not the same as upward advection along isopycnal surfaces, the two are undoubedly connected: upward entrainment takes place where an isopycnal surface approaches the sea surface and is supplied from below by isopycnal advection. Upward entrainment is presumably due to episodic high shear between isopycnal layers, occurring in meanders.

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