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Larry P. Atkinson  
*Old Dominion University*, latkinso@odu.edu  
Leonard J. Pietrafesa  
Eileen E. Hofmann

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An evaluation of nutrient sources to Onslow Bay, North Carolina

by Larry P. Atkinson¹, Leonard J. Pietrafesa² and Eileen E. Hofmann³

ABSTRACT

Hydrographic and current meter data from Onslow Bay, North Carolina, were examined to determine the relative importance of various nutrient sources.

Upwelled Gulf Stream water is the major source of nutrients while rivers represent a minor, if not insignificant, source. In the summer during stratified conditions, the upwelled water penetrates across the shelf, but in the winter the upwelled water is restricted to the outer shelf.

Nitrate flux across the 40 m isobath was calculated from continuous temperature and current records. Flux during the summer of 1976 was 2 µM m⁻² sec⁻¹ which is considerably less than flux estimations for the Georgia shelf or Scotia shelf.

In the climatic scale a cooler climate causing denser shelf water would decrease the nutrient flux into the Bay, while a warmer climate causing less dense shelf water would increase the flux of nutrients into central shelf water.

1. Introduction

Continental shelves have varying geomorphologies which result in fundamentally different nutrient regimes in the overlying water. Deeper continental shelves or semi-enclosed seas such as the Eastern China Sea, North Sea or Gulf of Maine often have a deep nutrient reservoir which may supply the euphotic zone through vertical mixing processes. Other continental shelves are shallower, have little or no deep nutrient reservoir and depend on outside sources, usually rivers or oceans, for nutrients. Nutrient supply to shallower shelves is controlled by continental shelf width, magnitude of diffusion and advective processes and river runoff (Riley, 1967). While in some situations diffusive processes may be important (i.e., the Bering Sea (Iverson et al., 1979; Coachman and Charnell, 1979; Coachman and Walsh, 1981)), there is increasing evidence that vertical and horizontal advection of nutrient-rich deeper ocean water onto the shelf may dominate nutrient flux processes (Smith, 1978; Lee et al., 1981). Studies of North Carolina shelf water by Stefansson et al.

1. Skidaway Institute of Oceanography, P.O. Box 13687, Savannah, Georgia, 31406, U.S.A.
2. Department of Marine Science, North Carolina State University, Raleigh, North Carolina, 27609, U.S.A.
3. Department of Oceanography, Texas A & M University, College Station, Texas, 77843, U.S.A.
(1971) (hereafter referred to as SAB (1971)) concluded that two advective processes, cascading of shelf water and intrusions of Caribbean water contained in the Gulf Stream, probably controlled the nutrient flux into that shelf regime but they had little quantitative evidence. Blanton (1971) elaborated on the Gulf Stream intrusion process proposing a stranding mechanism by which intruding Gulf Stream water (GSW) is isolated in Onslow Bay.

SAB (1971) stated that during the spring and summer, onshore intrusions of deeper GSW formed a lower layer in the Bay, implying that both stratification and wind were causal. They noted that von Arx (1962) postulated that Gulf Stream meanders periodically placed cold water at the shelf break but firmly felt that seasonal dependence of GSW intrusions argued for partial wind control.

The relation of Gulf Stream position, which varies during meanders (Webster, 1961), to an upwelling index has been used by Atkinson (1977) for the Gulf Stream and Nakao (1977) for the Kuroshio Current to demonstrate the coupling of meanders in these analogous western boundary currents to upwelling at the shelf break. A western positioning of the current axis coincides with higher temperatures and strong poleward currents at the shelf break, while an easterly positioning coincides with lower temperatures and weaker shelf break currents. Atkinson (1977) further postulated that the relative density of shelf water vs. upwelled water controls the intrusion mode of this upwelled water into shelf water. Relatively less dense shelf water favors near-bottom intrusions, via ageostrophic gravitational modes, which have been observed in the summer. Relatively higher shelf water densities as would be expected in the winter result in override, a condition of upwelled water lying over resident shelf water. The corollary is that when upwelling water and shelf water have similar densities, no extensive layering occurs and upwelling is limited to the outer shelf. While most of the controlling processes were thus revealed, it was apparent that the absolute flux of nutrients and the seasonality of nutrient influx were unknown. To address these and ancillary questions, a large-scale study of Onslow Bay, North Carolina, was initiated in 1975 (Fig. 1). Many of the results of this study are now published and the concepts developed for Onslow Bay as well as other parts of the southeast continental shelf can be applied to the topic of advective nutrient dynamics in Onslow Bay.

It is the purpose of this paper to examine the relationship of these processes in a more quantitative manner than was previously possible and to summarize the advective nutrient dynamics of Onslow Bay. The processes discussed in this paper are at work on the North Carolina shelf but also may apply to other shelf waters that are adjacent to strong shelf break boundary currents.

2. Methods

Unlike the SAB (1971) study which covered part of Onslow Bay, Raleigh Bay
and the area just north of Cape Hatteras, we chose to limit our observations to Onslow Bay (Fig. 1). This approach was taken because this area was thought to be least affected by alongshore transport, due to the existence of prominent shoals (cf. Fig. 1) and because runoff in this area is relatively low (Bumpus, 1955, 1973). The effects of Gulf Stream-related nutrient sources thus are maximized. Most data were gathered during the summer of 1975 and 1976, since it was thought that the important flux processes occurred in the summer.

Sampling techniques and details of the cruise results are discussed in Atkinson et al. (1976) and Singer et al. (1977). Moored current, temperature and conductivity data were obtained within the Bay from Aanderaa and Endeco current meters and General Oceanics thermographs (Pietrafesa et al., 1977, 1978).

Since there may be a seasonal component to nutrient flux and since nutrients can be related to temperature or salinity, depending on the specific situation, it is possible to examine mean variations in temperature and salinity on a monthly basis and hence infer the mean seasonal nutrient inputs. The mean monthly data we examined were derived from all the hydrographic data available from Onslow Bay, the principal sets being the Stefansson-Atkinson studies in the 1960's (Stefansson and Atkinson, 1967) and our 1975-76 studies (Atkinson et al., 1976; Singer et al., 1977). The Bay was subdivided into inner, middle and outer shelf, based on the following water depths: 0-20 m, 21-40 m, and 41-60 m.
3. Results and discussion

Since nutrient concentrations depend on resident water masses which are usually identified by temperature/salinity characteristics, our discussion of nutrient dynamics will often appear to be more a discussion of physical processes. First we will discuss the temperature/salinity/nutrient relationships in adjacent shelf water and deeper GSW that are known to advect into Onslow Bay. Secondly, we will present new data on the seasonality of temperature, salinity and density variations since intrusion modes are known to be related to density differences. Then we will discuss winter and summer shelf break upwelling and offer concluding remarks.

Temperature/salinity/nutrient relationships

T/S. North Carolina shelf and slope waters are well defined following classical relationships (SAB, 1971; Stefansson and Atkinson, 1971), many of which are shown in Figure 2A. In the T/S plot GSW appears as the well-defined mass of points from 5°C-35‰ to 25°C-36‰ with a salinity maximum at 21°C-36.6‰ that usually lies at 50-200 m depth. In our discussions GSW refers to these offshore waters, which include western North Atlantic Water and subtropical underwater (SAB, 1971). Fresher waters, to the left of GSW on the T/S plot, vary seasonally and represent the variety of coastal waters (SAB, 1971).

Nutrients. Nutrient concentrations are closely related to either temperature or salinity, although temperature is usually chosen as the “independent variable” because it has a larger range and is more depth dependent. In general surface GSW is low in nutrients while deeper water is higher.

The inverse relationship between temperature and nutrients, which was noted by Stefansson and Atkinson (1971), is seen clearly in the GSW envelopes in Figure 2C, D, E. Since we propose to use temperature as a predictor of nutrient concentrations, this relationship must be constant in time (no seasonal variation) and space (water of similar temperature at various depths should have the same nutrient concentration). In this application we are concerned only with GSW warmer than 15°C, thereby avoiding the nonlinear effects which can be seen in the nutrient/temperature plots at high concentrations (Stefansson and Atkinson, 1971, 1972). The fact that the linear portion of the nutrient/temperature relationship is reasonably constant and that these points cover all seasons and a large geographic area confirms our assertion that there is no observable spatial or temporal variation and, therefore, quantifications of such relationships are justified. A nitrate/temperature regression that excludes surface water and the nonlinear portion of GSW yields the following equation:

\[ \text{NO}_3 \mu \text{M} = 38.33 - 1.67 T (\degree \text{C}), \ r = -0.93. \] (1)

Since nitrate and phosphate are related (Fig. 2F), a similar relationship can be made for phosphate.
Figure 2. Temperature/Salinity/Nutrient Plots. The data (Stefansson and Atkinson, 1967) represent all seasons and the area from mid-Onslow Bay to immediately north of Cape Hatteras. These are the same data as discussed in SAB (1971), Stefansson and Atkinson (1971) and Stefansson and Atkinson (1972). The boundary between shelf water (S) and Gulf Stream Water (G) is indicated by the line.

**Alongshore nutrient sources**

Bumpus and Pierce (1955) defined two types of coastal waters in Onslow Bay: local or Carolinian Water and far-field or Virginian Water. More recent work (Singer et al., 1980) suggested that Onslow Bay also was influenced by influx of lower salinity shelf water from the south and west during periods of persistent southerly and southwesterly winds while previous observations (SAB, 1971; Myers,
Figure 3. Mean monthly values for surface and bottom temperature, salinity and density for inner, middle and outer Onslow Bay water. Mean Cape Hatteras air temperature (U.S. Department of Commerce, National Weather Service, Climatological Data) is included in the surface temperature plot. The shaded area in the bottom density plot indicates periods when bottom water densities at the shelf break are less dense or warmer than mid-shelf bottom water.

1967) suggested only occasional invasions of lower salinity, cooler Virginia Water from the north during northerly winds in the winter.

Salinity variations by month in surface water (Fig. 3) indicate the inner shelf was significantly influenced by runoff during the February-May period while the middle and outer shelf is much less affected. Low salinities were no doubt related to the magnitude and persistence of northeasterly to northwesterly winds, which mechanically drive a southerly alongshore flow of relatively fresh Virginian Water south around Cape Hatteras and into inner shelf regions of Raleigh and Onslow Bay (SAB, 1971; Myers, 1967; Norcross and Stanley, 1967; Bumpus, 1955). Near-bottom water displayed a similar pattern with middle and outer shelf bottom waters exhibiting less salinity variation and thus little runoff influence. From both climatic
mean data and the quasi-synoptic studies of SAB (1971) and Singer et al. (1980), we conclude that nutrient flux related to river runoff, which may advect into the Bay from either the north or south, will be maximized in the later winter and spring. An example of the influence of these alongshore flows is presented in Figure 4, which shows the salinity and silica distributions during the winter and summer. In the winter (Fig. 4, left), lower salinity water advects south around Cape Hatteras and Cape Lookout to substantially affect Onslow Bay. Silicates were uniformly low with slightly higher concentrations off Beaufort, N.C. and in outer shelf water. The summer situation (Fig. 4, right), for which we have more data, shows a complex salinity pattern with low salinity plumes invading the Bay from both the south and north, but overall salinity was higher throughout the Bay in the summer relative to the winter. However, in spite of the influx of low salinity water from the north and south, there appears to be little nutrient influx. Surface silica concentrations were uniformly low and not associated with the low salinities either
in the summer or winter. As indicated in the nutrient/temperature plots, high nutrient concentrations were associated only with GSW and thus, although these alongshore flows may advect in freshwater, they were of little direct consequence to nutrient flux into the Bay. Elevated silica concentrations at the shelf break were related to high salinity GSW (Fig. 4). Indirectly, the invasion of low salinity water does affect the nutrient regime because it lowers shelf water densities permitting subsurface intrusions rather than shelf break restricted upwelling.

**Shelf break upwelling**

Temperature distributions (Fig. 3), which indicate the presence of upwelled GSW at the shelf break throughout the year and of advected alongshore water during the winter, demonstrate the moderation of outer shelf surface and bottom waters by the Gulf Stream while inner- and mid-shelf waters follow air temperatures more closely. In the winter, surface water was coldest nearshore (10°C) and warmest offshore (19°C). Bottom water was also coldest inshore in the winter, but during the summer in contrast to surface water, outer shelf bottom water was colder than that farther inshore, again demonstrating Gulf Stream moderation. Bottom water on the outer shelf was always essentially of oceanic origin, except during the cascading phenomenon (SAB, 1971) and thus the nitrate/temperature relationship holds, i.e., nitrate would always be relatively high with the low temperatures. Mid-shelf bottom water salinities were lower in the winter implying coastal water influence and the nitrate/temperature relationship will not hold. During the summer upwelling along the outer shelf counters the surface heating to maintain lower temperatures in contrast to middle- and inner-shelf waters that respond to atmospherically imposed buoyancy flux conditions.

As stated by Atkinson (1977), the density of upwelling water determines the intrusion mode. Between November and April outer shelf bottom water was less dense than middle- and inner-shelf waters (Fig. 3, shaded area). During the other months outer shelf bottom water was less dense than shelf water. Thus, during the winter months, upwelling was restricted to the shelf break and “over-ride” (Atkinson, 1977) could occur, while in the summer months, subsurface intrusions may penetrate into the middle shelf.

**Shelf break upwelling in winter.** Gulf Stream-related upwelling events, which occur at the shelf break, provide enormous amounts of nutrients, which can be advected into the outer Bay, but as we have stated, higher shelf water densities restrict winter shelf break upwelling events from penetrating onto the outer shelf. SAB (1971) made a key observation in March 1967 when they found “relatively high concentrations of nitrates, silicate and apparent oxygen utilization in the surface layers just off the shelf break.” They further stated that “These high nutrient concentrations must be attributed to upward mixing of deeper water, since neither resident surface shelf water nor surface Gulf Stream water contains such high...
Figure 5. Summer and winter cross-shelf section through Onslow Bay. Winter data are from Stefansson and Atkinson (1967) and summer data are from Singer et al. (1977).
concentrations.” They attributed this to possible meander-induced upwelling (von Arx et al., 1955; Webster, 1961) and strong southerly winds. Figure 5 (left) shows a typical cross-shelf section through the center of the Bay in the winter which graphically illustrates this phenomenon. This vertical plane transect shows essentially pure GSW extending inshore to station 37 where it was slightly diluted. At station 38, the GSW was undiluted (compare to T/S plot, Fig. 2A). The shelf water was cold (10-16°C), salty (33-36%) and dense (25.9-26.7 ρT), more dense in fact than GSW at the shelf break. The thermohaline shelf condition, combined with strong wind and surface buoyancy flux-induced mixing (Pietrafesa and Janowitz, 1979), restricted GSW to the outer shelf. The undiluted GSW at the shelf break was less than 22°C and should have contained significant nutrient concentrations (see nutrient/temperature plots, Fig. 2), but as can be seen, water at stations 38 and 39 was nutrient deficient. For example, the 100 m sample at station 39 was 17°C and contained 9.8 μM Si and 8.4 μM NO₃ while undiluted 17°C water at 30 m, station 38 contained only 1.8 μM Si and 0.4 μM NO₃. We propose that all samples at stations 38 and 39 originally contained relatively high nutrient levels but were depleted by biological processes. Unfortunately, no published chlorophyll data exist to confirm this, but, in a similar situation off Georgia and South Carolina, Deibel (1980) observed high chlorophyll in nutrient-depleted upwelled GSW, implying that phytoplankton did alter nutrient concentrations. These upwelled waters could have been cooled GSW but the rapidity with which events occur at the shelf break (Legeckis, 1979) suggests that water is not resident in the area long enough to be thermally altered.

Monthly variations in density (Fig. 3) lead us to conclude that shelf break restricted upwelling will dominate Onslow Bay nutrient dynamics from November through April with little likelihood of significant nutrient influx to the mid- and inner-shelf area.

Shelf break upwelling in summer. The summer situation in Onslow Bay is characterized by resident low density water occupying the mid- to inner-shelf (Fig. 3), which, with upwelling-favorable winds (Janowitz and Pietrafesa, 1980), allows any upwelled GSW to intrude across the shelf. The spatial extent and minimum temperatures of the intrusion are determined by the degree of upwelling and onshore advection, which vary with the intensity and persistence of upwelling-favorable winds (Janowitz and Pietrafesa, 1980; Blanton and Pietrafesa, 1978; Hofmann et al., 1981) or of Gulf Stream frontal events, such as the passage of meanders and filaments (Legeckis, 1979; Brooks and Bane, 1981; Bane et al., 1981).

Atkinson et al. (1980) analyzed the summer intrusions observed in 1975-1976 and found that these events occupied 20% of the Bay volume, may remain in the Bay for up to 60 days and occurred several times during the summer months. The critical points are not only the quantification of the volume and frequency of these...
The summer situation has been intensively sampled, and we will elaborate on it by examining both synoptic cruise data and continuous measurements from current meter moorings.

Typical summer vertical plane cross-sectional distributions of $T$, $S$, $\sigma_t$, Si and NO$_x$ are shown in Figure 5 (right). This particular upwelling event was probably related to the passage of Hurricane Belle prior to the cruises. Three water masses are evident in this cross-section. The first is the upper layer in which temperatures were high (26-29°C) with salinities less than 36.0‰. Surface water inshore of station 16 (Fig. 5) was diluted (see $T/S$ diagram, Fig. 2) with runoff although nitrate and silicate were low. Surface water salinities offshore of station 16 were essentially Gulf Stream salinities. The lower layer, which is 10 to 20 m thick, was composed of two water masses. One was a stranded water mass with minimum temperatures of 24.0°C at station 15. Because of the high temperature no nutrients were present. A second subsurface water mass with temperatures of 17-24°C and high salinities appeared between stations 16 and 118. The low temperatures at stations 17 and 118 imply high nutrient concentrations, which were observed. This water mass was observed at the onset of its intrusion into the Bay (Atkinson et al., 1980).

It is clear from recent comparisons of VHRR imagery, moored current and temperature data and coastal meteorological and sea level data (as discussed variously by Blanton and Pietrafesa, 1978; Janowitz and Pietrafesa, 1980; and Hofmann et al., 1981) that when the Gulf Stream front is seaward of the shelf break and if southeasterly to west-southwesterly winds persist for the order of 2-5 days, upwelling of GSW will occur at the shelf break. Along the Carolina Capes shelf, this summertime upwelling is manifested in the following sequence of events defining a wind-related bottom intrusion: an uplifting of isopycnals across the shelf with preferential uplifting occurring in shallower water; the establishment of a northeasterly, alongshore jet with its maximum at mid-shelf; an onshore bottom flow; a collapse of upwelling in the inner-shelf region and a die-off of the onshore bottom flow; a subsequent propagation of an upward, isopycnal bulge, appearing most dramatically along the seasonal pycnocline, from the inner to the mid-shelf regions; and the persistence of a region of shelf break upwelling. A bottom intrusion thus would enter the Bay along the shelf break, move shoreward and rise up as it approaches mid-shelf waters. It would then turn to the northeast as a mutual consequence of reduced onshore bottom flow in the inner-shelf region and due to the existence and persistence of an alongshore jet flowing with the wind and along the cross-shelf gradient of sea surface. This sequence of events would have the effect of keeping the intruding water mass from entering inner-shelf waters and also of flooding the middle, bottom region of the Bay. If the wind stops, the whole sequence stops, and a water mass would become stranded in the Bay center.
An example of an intruded water mass located in the middle of Onslow Bay is shown in Figure 6. Surface temperatures varied between 27-28°C while bottom water was as cold as 23°C. The high bottom salinities indicated a Gulf Stream origin for these waters but the high minimum temperatures implied low nutrient concentrations. Deeper water at the shelf break was colder and contained significant nutrient concentrations. A vertical section through the Bay (Fig. 7) shows the stranded 23°C water mass was separated from nutrient-rich upwelling water at the shelf break by a band of 25-27°C water. In this case, the intrusion of the nutrient-rich upwelled water at the shelf break would significantly affect the Bay.

It must be stressed that the nutrient regime in Onslow Bay is dominated by horizontal advection of upwelled GSW. Results from a theoretical study (Hofmann et al., 1980) of time-dependent nutrient distributions in Onslow Bay indicate that advection is the dominant physical mechanism in upwelling of nutrient-rich water onto the shelf, while diffusive processes play a minor role, serving only to disperse the nutrients once they are advected onto the shelf. Once onshore advection has occurred, the shoreward penetration of the upwelled nutrients is determined by the rate of nutrient uptake by phytoplankton.

An example of advection of nutrients into Onslow Bay occurred between 23 July and 5-6 August 1976 during a period of wind-induced upwelling (Hofmann et al., 1981). The nitrate distributions associated with this event are shown in Figure 8. The 23 July observations (solid lines), which coincided with the onset of upwelling, show water containing 3 µM NO₃ at the shelf break. Observations made...
Figure 7. Cross-shelf section through Onslow Bay. Hydrogrid 4 (14-16 August 1976).

Figure 8. Cross-shelf nitrate distribution on 23 July (Biogrid II) and 5-6 August 1976 (Biogrid III).
Figure 9. Nitrate time series derived from nitrate-temperature relationship and continuous temperature records. Similar nitrate values were measured in Onslow Bay during this time period, thus verifying this calculation.

approximately two weeks later on 5-6 August (dashed lines), at the same location, show increased nitrate concentrations and movement of the water to mid-shelf. Note the shoreward slant of the nitrate isopleths. Hydrographic and moored current meter data indicated onshore velocities of 7-10 cm sec⁻¹ associated with this event. The high nitrate concentration observed on 5-6 August indicates that the water observed then was newly upwelled and not the same water as observed on 23 July.

Further evidence for the advective dominance and periodicity of upwelling in Onslow Bay is shown clearly in plots of nitrate concentrations (Fig. 9) calculated by use of Eq. 1 and continuous temperature records. The nitrate peaks at mooring locations D and E bottom corresponded to the wind-induced upwelling event discussed above.

The derived nitrate values from mooring F (Fig. 9F) showed the highest concentrations and most variable structure. This is to be expected, since the shelf break region is influenced by Gulf Stream meanders and filaments. The broad nitrate peak at F-Bottom, extending from 20 July to 10 August, corresponds to the period of wind-induced upwelling. The pulse of nitrate observed on 12-22 August, which reached 12 µM NO₃ (Fig. 9), corresponds to the frontal meander observed in the 14-16 August hydrographic data (Figs. 7 and 8). Unlike the nutrients associated
with wind-induced upwelling, these nutrients are not advected into the mid-shelf region (ref. Fig. 10A-D). During the period of upwelling, winds were north-north-easterly, which along the North Carolina coast are downwelling favorable. Hence, nutrients presented at the shelf break, via Gulf Stream upwelling, are unavailable to the mid-shelf region unless the upwelling event coincides with a period of upwelling-favorable winds. This particular nutrient time series is a good illustration of the coupling that occurs between the Gulf Stream and upwelling-(downwelling) favorable winds. Obviously, the degree, duration and causal mechanism of upwelling is variable and leads to a highly variable nutrient regime which in turn exerts a control on the total ecosystem.

**Turbulent nitrate flux**

Since nitrate is related to temperature, under conservative conditions, it is possible to calculate the turbulent flux of nitrate ($u' \overline{NO_3^-}$) into Onslow Bay due to low frequency events at each of the current meter/thermograph locations (see Fig. 1). For this example we limited the calculations to the 22 July-5 August 1976 time period which was discussed in other papers (Atkinson *et al.*, 1980; Hofmann *et al.*, 1981; Janowitz and Pietrafesa, 1980).

In our flux calculations, onshore (negative $u$) transport of nitrate is associated with the onshore transport of cold (negative) water. Therefore, one would expect to see a positive $u' \overline{NO_3^-}$ associated with an upwelling event. The results of the flux calculations are presented in Figure 10. The discrete flux is an estimated flux for
two-day time blocks, while the cumulative flux is the integral of the discrete flux.

Comparison of the discrete fluxes (Fig. 10) from the three moorings (C, D & F) indicates that nitrate entered the southern portion of Onslow Bay around moorings D and F following a period of southwesterly winds. Throughout the entire event there was an onshore nitrate flux at D-Bottom which reached a maximum of 42 µM NO₃⁻ m⁻² sec⁻¹ on 29 July. The discrete fluxes for F-Bottom showed more variability due to intermittent current reversals. Cumulative fluxes for D-Bottom and F-Bottom indicated a net onshore flux of nitrate during the intrusion. This also is seen at D-Top, but to a lesser extent since D-Top was located in the upper extent of the upwelled water. During the period 12-22 August, the discrete fluxes for F-Bottom indicate an onshore flux of nitrate. However, the fluxes calculated at moorings C and D show little or no flux for this period, again illustrating the variability of nutrient input into Onslow Bay.

The discrete and cumulative fluxes for C-Bottom showed no onshore or offshore flux of nitrate during the event period. The negative (offshore) flux at C-Bottom on 3 August was associated with the offshore movement of the cold water intrusion. These flux estimates may be misleading since the intrusion was approximately twelve days old and it is doubtful that nitrate is still conservative. However, this suggests a possible physical mechanism (e.g., a Gulf Stream meander) for removing nitrate from the outer continental shelf. As the meander crest moves by the site, it carries water offshore and alongshore, thus removing nutrient-rich water that may have been upwelled at the shelf break or advected into mid-shelf by a previous meander or wind-induced upwelling event. This process has been described by Brooks and Bane (1981) and Bane et al. (1981).

By assuming that the nitrate is linearly distributed in the water column between the upper and lower meter locations, one can vertically integrate the discrete fluxes. This gives an estimate of the nitrate flux through a 1 m² water column (depth of 40 m) at a given position. This calculation was made for moorings C and D. For the period 22 July-2 August, the vertically integrated nitrate fluxes at moorings C and D were zero and 3.4 µM NO₃⁻ sec⁻¹, respectively. The flux at mooring D was lower than the 22.2 µM NO₃⁻ sec⁻¹ computed for Georgia shelf water (Lee et al., 1981). However, the Onslow Bay value was computed for the mid-shelf area, whereas the Georgia flux was computed for the shelf break region.

The nitrate flux converts to a nitrogen flux of 48 µg N sec⁻¹ for the 40 m × 2.5 cm water column. Assuming this flux is representative for the intrusion, the total amount of nitrogen transported into Onslow Bay by this event can be calculated by the horizontal extent of the intrusion (80 km, Singer et al., 1977) and the event duration (13 days). For this event the result was approximately 1.7 × 10⁸ gN (170 mtons N). This is probably an underestimate since it was based on a mid-shelf flux value, but it indicates that a considerable amount of nitrate was supplied to mid-shelf regions.
Table 1. Low-frequency nitrogen flux into Onslow Bay vs. other regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>µM N m⁻² sec⁻¹</th>
<th>Time period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scotian shelf</td>
<td>12 ± 4</td>
<td>seasonal</td>
<td>Smith (1978)</td>
</tr>
<tr>
<td>Georgia shelf break</td>
<td>8.5</td>
<td>yearly</td>
<td>Lee et al. (1981)</td>
</tr>
<tr>
<td>Onslow Bay (40 m isobath)</td>
<td>2</td>
<td>Summer 1976</td>
<td>this paper</td>
</tr>
</tbody>
</table>

One further calculation can be made using the vertically integrated fluxes from moorings C and D. Integrating these values over the total record time (42 days) and the total length of Onslow Bay (175 km) gave an estimate of the nitrogen flux across the 40 m isobath due to low frequency events. The nitrogen flux estimated in this way was 2 µM N m⁻² sec⁻¹.

Similar nitrogen flux estimates have been made for the Scotian shelf (Smith, 1978) and Georgia shelf waters (Lee et al., 1981). The results of these calculations are shown in Table 1. A direct comparison of these values to that computed for Onslow Bay is difficult since the time intervals, event durations and water column depths differ. The Onslow Bay value appears to be lower, but this value was computed for the 40 m isobath, which was inshore of typical Gulf Stream meanders in this area (Bane et al., 1981), rather than the shelf break and was based on only one intrusion event. Nevertheless, it is obvious from hydrographic and flux observations that most regions of Onslow Bay receive nutrient-rich waters only occasionally.

Criticality of upwelling

Onslow Bay, like much of the southeastern U.S. continental shelf, is at a very crucial point with respect to Gulf Stream-derived nutrient flux. As the nutrient/temperature plots indicate, waters less than about 22°C contain nutrients in increasing amounts. Combining this fact with the observations that waters of those temperatures are what normally appear at the shelf break and may invade the Bay, it is immediately clear that less frequent or less intense occurrences of upwelling will result in lesser amounts of nutrients being advected into the Bay, while more frequent and/or more intense upwelling will pump in significant amounts. The criticality implies that short- and long-term marine atmospheric climatology that alters shelf water density and Gulf Stream frontal location will have a significant influence on nutrient sources to Onslow Bay and biological systems that respond to them. The effect of variable shelf water densities is shown schematically in Figure 11. The heavy line represents typically upwelled GSW that presumably would vary little during climatic changes.

A colder climate, represented by the upper light line, possibly because of a
weakened Azores-Bermuda high, could cause higher shelf water densities lessening
the onshore intrusion of GSW intrusions during the summer, lowering the annual
nutrient input to the Bay. Because winter shelf break upwelling would be unaffected,
biological production within the Bay would probably be reduced over a year’s time.

A warmer climate, represented by the lower light line, would probably result in
lower shelf water densities, more stratification and stronger influence of summertime
intrusions. This should lead to enhanced biological production in the Bay. Any
process that lowers mean Bay densities, such as increased runoff, would have the
same effect.

On a shorter time scale, variations in annual wind patterns may significantly
affect the upwelling process by altering the mean Gulf Stream positions and the
alongshore advection of coastal water.

Onslow Bay and other parts of the southeastern U.S. shelf are unlike other
continental shelf areas such as the Gulf of Maine or North Sea, which are deeper,
are not influenced by strong boundary currents and have a subsurface store of
nutrients built up during the summer to be upwelled during winter mixing. Although
recent work (cf., Bowman and Esaialas, 1978) has shown that this may be over-

Figure 11. Variation of middle shelf near-bottom density for the present and hypothetical
cooler and warmer climates.
simplified, nevertheless, in those cases the nutrient source is always there. In contrast, Onslow Bay and the southeastern U.S. shelf in general possess no reserve nutrient source because of the shallow shelf and persistent Gulf Stream flushing (Atkinson et al., 1978; Blanton and Pietrafesa, 1978; Atkinson and Pietrafesa, 1980). Instead these shelf waters are dependent on the vagaries of Gulf Stream-related upwelling and winds for nutrients, and as we have demonstrated, this is a very sporadic process.

Further research on shelf nutrient dynamics should focus on shelf break upwelling, its cause, frequency, intensity and seasonality, especially in the winter season when little data are available. Since upwelling is dependent on Gulf Stream position relative to the shelf break, it is important to know if that position is controlled by local winds or Gulf Stream meanders.

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