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Gulf of Mexico Science

Volume 23
Number 2 *Number 2*

Article 1

2005

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DOI: 10.18785/goms.2302.01

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Recommended Citation

Belabbassi, L., P. Chapman, W. D. Nowlin Jr., A. E. Jochens and D. C. Biggs. 2005. Summertime Nutrient Supply to Near-Surface Waters of the Northeastern Gulf of Mexico: 1998, 1999, and 2000. Gulf of Mexico Science 23 (2).
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Gulf of Mexico Science, 2005 (2), pp. 137–160

Summertime Nutrient Supply to Near-Surface Waters of the Northeastern Gulf of Mexico: 1998, 1999, and 2000

LEILA BELABBASSI, PIERS CHAPMAN, WORTH D. NOWLIN, JR., ANN E. JOCHENS, AND DOUGLAS C. BIGGS

In the summers of 1998, 1999, and 2000, deep water eddies induced strong anticyclonic currents along the upper slope and outer shelf from the Mississippi River delta to the west Florida shelf. Those currents transported Mississippi River discharge eastward along the outer shelf and slope, reversing the normal offshore increase in salinity, with the exception of a few regions very near the coast that were influenced by the discharges from other rivers or bays. The entrainment of low-salinity river water resulted in anomalously high chlorophyll *a* concentrations in the upper 15 m over the outer shelf and upper slope, in contrast to the concentrations that typically occur over deep water in the subtropics in summer. Nitrate concentrations in this surface water were quite low except near the mouths of rivers, which act as point sources for nutrients; presumably, this was because of the rapid utilization of nitrate by phytoplankton. A significant supply of nutrients to the euphotic zone at regions quite removed from these point sources resulted from eddies intruding onto or formed over the slope. These caused mid-depth water rich in nutrients to be uplifted to within the euphotic zone, the uplift depending on the location and intensity of the eddies. Based on measurements at approximately 100 stations on each cruise, estimates were made of the quantity of nitrate and silicate in the upper 15 m of the water column and in the depth interval from 15 m to 60 m, the nominal depth of the euphotic zone. Study results suggest that the nitrate and silicate in the near-surface interval of 0–15 m largely resulted from riverine discharge and subsequent advection, while the nutrients between 15 and 60 m resulted from uplift of waters by circulation features. The euphotic zone occupied at least the upper 60 m of the water column, but standing stocks of nitrate and silicate in the 15- to 60-m layer were between two and six times those in the upper 15 m on all three cruises and appeared to depend on the strength and relative proximity to the shelf break of local anticyclonic features. The effects of these circulation features were potentially significant in supplying nutrients to the euphotic zone during these summers.

In summer, subtropical regions exhibit generally low productivity because plant growth earlier in the year has reduced nutrient levels and because solar heating stabilizes the water column, preventing nutrients from crossing the pycnocline to reach the surface layers. This general pattern may be altered by physical processes. One well known process is the occurrence of wind events that reduce or break down the stratification leading to a reinjection of nutrients into the euphotic layer with large local or regional impacts on primary productivity (Lalli and Parsons, 1993; Gargett and Marra, 2002). This study, based on data collected during three cruises over the northeastern shelves of the Gulf of Mexico, focuses on the effects of two other physical processes that supply nutrients to the euphotic zone of the northeastern Gulf of Mexico during the summer season. The first is the discharge of nutrient-rich water from rivers (especially the Mississippi River) and the transport of such water along and across the shelf margin by currents. The second is the introduction of nutrient-rich waters into the euphotic zone by uplift of isopycnals, caused by circulation features such as slope eddies.

It is well-known that the Loop Current and its resultant eddies can move coastal water and even Mississippi River water large distances over the shelf and slope region (e.g., Walker et al., 1994; Wiseman and Sturges, 1999; Müller-Karger, 2000; Biggs and Ressler, 2001). Such movements result in major changes to the typical patterns of primary production and chlorophyll *a* concentration in the Gulf of Mexico far from direct influence of rivers. For example, Walker et al. (1994) described conditions during the summer 1993 flood of the Mississippi River. During that time, the Loop Current extended far enough northward to interact with the outer Mississippi-Alabama shelf. As a

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result, Mississippi River water was entrained eastward and southward, eventually exiting the Straits of Florida into the Atlantic Ocean.

Additionally, both cyclonic and anticyclonic eddies are often found over the continental slope in the northeastern Gulf of Mexico and can influence the shelf circulation (Jochens et al., 2002). The density field, and fields of other water mass properties including nutrients, may be uplifted (depressed) at the center of cyclonic (anticyclonic) features relative to their surrounding waters. Vertical perturbation of the density field can also occur in regions of divergence between eddies or between an eddy and the shelf edge. In strong eddies, such as the anticyclones that separate from the Loop Current in the Gulf of Mexico, this deformation of isopycnals extends through the upper 800 m of the water column. Within cyclones, on the other hand, the uplift of isopycnals sometimes extends into the euphotic zone; Zimmerman and Biggs (1999) reported nitrate concentrations of 10 $mmol \cdot m^{-3}$ within cyclones that domed to within 75 m of the surface (i.e., close to the lower limit of, or sometimes extending up into, the euphotic zone). In contrast, the nitracline was deeper than 200 m in an anticyclone they also examined.

Another observed effect of eddies located near the outer shelf in the northeastern Gulf of Mexico is entrainment of low-salinity water from the Mississippi River along the eddies' northern periphery (Müller-Karger et al., 1991). This entrained low-salinity water can be rich in nutrients and contributes to enhanced productivity along the outer shelf, particularly west of the delta. Ortner and Dagg (1995) and Lohrenz et al. (1990, 1999) reported high levels of phytoplankton production, occasionally greater that 8 $g \cdot C \cdot m^{-2} \cdot d^{-1}$ in the river plume, especially after the settling of suspended matter allowed deeper light penetration. High chlorophyll *a* concentrations associated with the Mississippi River plume east of the delta have been reported by Hu et al. (2003).

This study focuses on the effects of the physical processes of (1) river discharge and its subsequent movement by mesoscale eddies and (2) uplift or depression of isopycnals by eddies on inventories of nutrients in the upper water column. The data were obtained during summer cruises over the continental shelf and slope of the northeastern Gulf of Mexico. These cruises were designed principally to describe physical and chemical property distributions. The use of the data collected for the present study is opportunistic and not by design. Therefore, not all of the data we might have wished to have collected for this study were collected.

We first describe the study area and offer background information on processes supplying nutrients to the area. We then present the data sets and methodology used, followed by the results and a discussion. Finally, we present the principal conclusions.

BACKGROUND

Study area.—The study area is the continental margin of the northeastern Gulf of Mexico extending from the Mississippi River Delta to the West Florida Shelf off Tampa Bay and bounded by the 10-m and 1,000-m isobaths (Fig. 1). This area includes a narrow shelf west of Cape San Blas, largely bounded offshore by the DeSoto Canyon, and a wide continental shelf from Cape San Blas to Tampa. We refer to the latter as the West Florida Shelf and the inshore region thereof as the Big Bend. Numerous rivers discharge onto this continental shelf. However, the major river inputs are from the Mississippi River at the western boundary of the study area, the discharge through Mobile Bay into the western region, and from the Apalachicola and Suwannee Rivers onto the West Florida Shelf.

Nutrient sources for the euphotic zone.—River discharge and subsequent transport: River discharge brings waters low in salinity and high in nutrients into the northeastern Gulf of Mexico via a series of point sources, and also influences the circulation through added buoyancy. In summer, the Mississippi River dominates the low-salinity input to the study region (Nowlin et al., 2000; Table 1). This discharge is turbid and rich in nutrients, with annual mean concentrations of inorganic nutrients of about 114 $mmol \cdot m^{-3}$ nitrate, 7.7 $mmol \cdot m^{-3}$ total phosphate, and 108 $mmol \cdot m^{-3}$ silicate (Rabalais et al., 1996). It is speculated that roughly 35–50% of the discharge from the Mississippi River flows south or east (Dinnel and Wiseman, 1986). Dinnel and Bratkovich (1994) showed that nitrate concentrations in the Mississippi River and its tributaries vary seasonally, normally being higher in winter, spring, and early summer, when river flows are higher and lower in late summer and early autumn. However, because of both high discharge rates and relatively high nutrient loading, the Mississippi River remains the dominant source of nutrient input to the northeastern Gulf of Mexico in summer. Normally, nutrient enrichment from rivers east of the study area is restricted to the

DOI: 10.18785/goms.2302.01

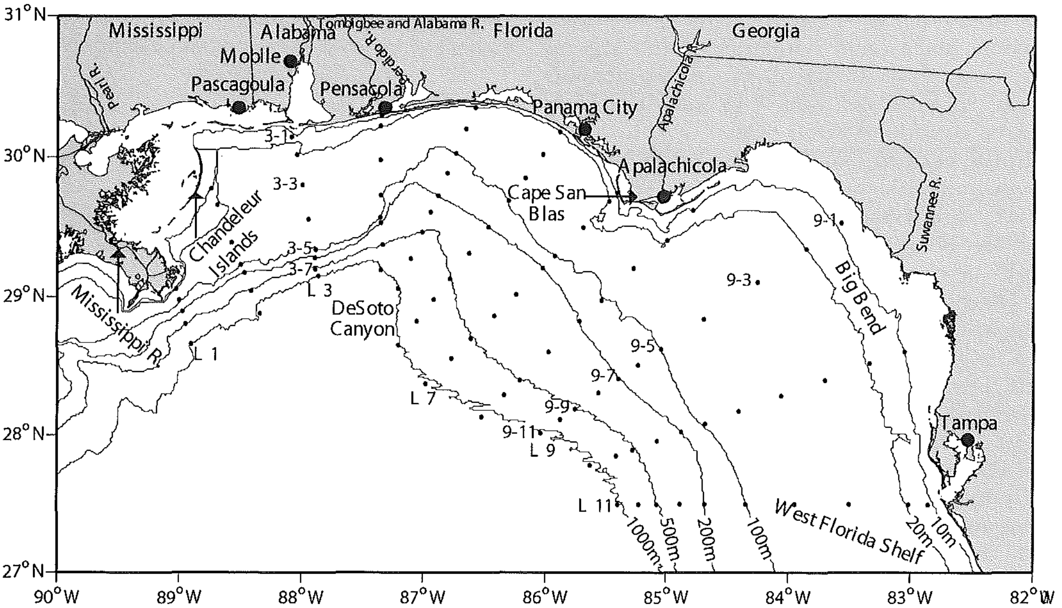

Fig. 1. Map of the study region showing bathymetry, key features, and locations of CTD stations (dots) from which data were examined. Representative station line numbers are shown. Station numbering system is illustrated by stations on Lines 3 and 9.

inner shelf, so these rivers play relatively minor roles in adding nutrients to the outer shelf (Bianchi et al., 1999), except under local flood conditions (Pennock et al., 1999). It should be noted that changes in the local winds field can also affect the shape and direction of the Mississippi River plume; for example, southwest winds (prevalent in summer) will push the plume to the east of the delta.

TABLE 1. Monthly average flow rates ($10^3 \cdot m^3 \cdot s^{-1}$) of the Mississippi River and the sum of lesser rivers discharging into the study area for May, June, July, and August 1998, 1999, and 2000.[a]

	Mississippi River $10^3 \cdot m^3 \cdot s^{-1}$	Sum of other principal rivers $10^3 \cdot m^3 \cdot s^{-1}$
1998		
May	28.23	2.83
June	17.14	1.54
July	19.07	1.54
August	11.08	1.45
1999		
May	23.18	1.63
June	16.12	1.94
July	14.55	2.60
August	8.04	1.05
2000		
May	11.17	0.98
June	11.94	0.65
July	14.08	0.56
August	7.32	0.58

[a] Monthly average flow rates for 15 rivers from the Pearl to the Suwannee were summed.

As stated above, the Loop Current and offshore eddies can entrain and move Mississippi River water eastward over the northeastern Gulf of Mexico slope and outer shelf, particularly during flood conditions (Walker et al., 1994; Ortner et al., 1995). As will be shown, this mechanism can transport substantial amounts of low-salinity water over the outer shelf and slope adjacent to the DeSoto Canyon and along the western edge of the West Florida Shelf. This mechanism for nutrient enhancement of the euphotic zone during summer is one focus of this study.

Uplift by circulation features: Waters with relatively high nutrient concentrations also may be supplied to the euphotic zone as a result of circulation features (McGillicuddy et al., 1999, 2001). Within cyclones, isopycnals and nutrient isopleths are uplifted. Thus, the spin-up of such eddies or their movement into the region may provide nutrient-rich waters to the euphotic zone (McGillicuddy and Robinson, 1997; Siegel et al., 1999). There is a controversy regarding how significant the contribution of this uplifted nutrient is in forming new production. Martin and Pondaven (2003) argued that "current estimates of primary production in the Sargasso Sea fueled by eddy pumping may be considerably too high."

In the eastern Gulf, cyclones occur in close association with the Loop Current (Lee et al., 1994), with Loop Current anticyclones, and with secondary anticyclones (Biggs and Ressler, 2001). According to model results presented by Dietrich and Lin (1994), these cyclones form at the outer edge of an anticyclonic eddy as a result of lateral mixing that changes the local pressure gradient. Mass conservation requires upward motion of water in the central region of the cyclonic eddy, bringing nutrients and cooler water nearer the surface.

Cyclones in the Gulf of Mexico may also be generated from the interaction of anticyclones with the shelf edge. Smith (1986) examined the interaction of isolated Loop Current eddies with the continental slope region using a two-layer model. He found that the topographic dispersion of an anticyclonic eddy can result in the formation of cyclonic features. Additionally, Zimmerman and Biggs (1999) documented that frictional interaction of anticyclonic eddies with shoaling topography along the continental margin may result in the formation of one or more companion cyclonic eddies.

Upwelling of nutrients can be induced in other ways. For example, interaction of an eddy with the slope can result in a bottom Ekman layer, which under the correct circumstances, can give up-slope bottom flow. For example, Nowlin et al. (2000) documented a bottom Ekman layer up-slope transport associated with the presence of an anticyclonic eddy over the upper DeSoto Canyon. The flow in that anticyclone extended to the bottom and was oriented essentially along the isobaths in the canyon. Bottom Ekman layer transport to the left of the flow was induced, leading to movement of bottom water toward shallower depths. Merino (1997) has reported similar bottom upwelling along the eastern slope of the Campeche Bank.

Another mechanism to lift nutrient-rich waters may occur in regions of interaction between cyclone-anticyclone pairs or cyclone-anticyclone-cyclone triads. Vidal et al. (1994) speculated that in these regions, horizontal velocity gradients were greatest, resulting in a maximum horizontal divergence at the ring's periphery. This divergence of surface water resulted in the uplift of water and hydrographic properties. This mechanism has been reported in several studies as resulting in areas of locally high pigment concentrations, followed by high secondary production and locally high fish production (e.g., Biggs and Ressler, 2001).

TABLE 2. Cruise identifiers, dates, and the total number of Conductivity-temperature-depth (CTD)/rosette stations.

ID[a]	Start date	End date	No. stations
N3	Jul. 25, 1998	Aug. 6, 1998	98
N6	Aug. 15, 1999	Aug. 28, 1999	98
N9	Jul. 28, 2000	Aug. 8, 2000	98

[a] Cruise identifier.

CRUISE DATA AND METHODOLOGY

Cruise data.—Nine survey cruises, three each in spring, summer, and fall, were made in the northeastern Gulf of Mexico during 1997–2000 as part of the Northeastern Gulf of Mexico Chemical Oceanography and Hydrography Study (here referred to as NEGOM) sponsored by the Minerals Management Service of the U.S. Department of the Interior. Table 2 gives the dates and number of stations taken on the three summer cruises of interest to this study. Each cruise occupied 11 cross-shelf lines of Conductivity-temperature-depth (CTD) stations perpendicular to the bathymetry (see Fig. 1). The lines are numbered west to east from 1 to 11. It should be noted that station positions were set to meet funding agency requirements and were not necessarily ideally placed to examine either the structure of the Mississippi River plume or the sources of nutrients to the shelf. Note also that although the same stations were occupied during each cruise, station numbers varied from cruise to cruise depending on the order in which the different lines were sampled. Thus, we have renumbered all stations so the numbers indicate the position of each station relative to the inshore end of a line and indicate the line. Thus, Station 3-2 is the second station from the inshore end of Line 3. For clarity, relative station numbers on Lines 3 and 9 are shown in Figure 1.

At all stations a Sea-Bird model SBE-911+ CTD was used to make continuous vertical profiles of conductivity, temperature, and pressure, while a rosette system collected up to 12 discrete water samples at each station. These were analyzed aboard ship, usually within a few hours after sampling, for dissolved oxygen and nutrients. Analyses for dissolved oxygen were obtained using the micro Winkler technique described by Carpenter (1965a, 1965b). Measurement accuracy and resolution for oxygen are ±0.5% and 0.1%, respectively. The nutrient analyses were performed using a six-channel Technicon Autoanalyzer-II, on the basis of the methodology described by Atlas et al. (1971). Measurement accuracy and resolution for both silicate and nitrate are 0.5 $\text{mmol}\cdot\text{m}^{-3}$ and 0.1 $\text{mmol}\cdot\text{m}^{-3}$, respectively.

Near-surface temperature, salinity, and fluorescence were measured aboard ship using a pumped sampling system picking up water at approximately 3.5 m. The water was pumped through a debubbler and mixing chamber of 20-liter volume. Because the pumped flow rate of the sampling stream was 20 $\text{liters}\cdot\text{min}^{-1}$, the water in the mixing chamber had a residence time of about 1 min. This pumped flow was reduced from 20 $\text{liters}\cdot\text{min}^{-1}$ to 1 $\text{liter}\cdot\text{min}^{-1}$ using garden hoses connected by adjustable ball valves to a "Y" splitter valve leading off the debubbler. This 1 $\text{liter}\cdot\text{min}^{-1}$ flow is shunted to the Sea-Bird temperature and conductivity sensors and to a continuous-flow Turner Designs model 10 analog fluorometer, which gives values with accuracy and resolution of 0.1 $\text{mg}\cdot\text{m}^{-3}$ or better over the range 0.1–10.0 $\text{mg}\cdot\text{m}^{-3}$ (Bianchi et al., 1995). Values were logged every 2 min throughout each cruise. One-liter samples were taken several times each day from the flow line concurrently with recorded fluorescence. Those samples were filtered at sea and analyzed to give chlorophyll *a* values. Chlorophyll *a* extraction followed standard methods given by Parsons et al. (1985). For each cruise, chlorophyll *a* was calculated from the flow-through fluorescence by linear regression of fluorescence data with extracted chlorophyll *a* data. Separate algorithms were computed for each cruise, for high and low chlorophyll *a* regimes.

Acoustic Doppler Current Profiler (ADCP) measurements of currents were made along the track lines of all three cruises. (See Figure 2, middle panel, for an example of track lines.) Two types of RD Instruments 150-kHz ADCPs were used: broad band (N3 and N6) and narrow band (N9). The vertical bin size was 4 m. Raw ADCP data were available as ensembles of four 2-sec pings and as 5-min averaged data. Normally, the 5-min averaged data were used in processing, but the ensemble data were used when the data quality of 5-min averaged data warranted more refined processing. The procedure used for processing ADCP data was described by Bender and Kelly (1998). Data segments having low correlation, insufficient beams, or anomalously slow or fast ship speeds were rejected. To reduce errors in ship speed, bottom tracking was usually used for water depths less than 300 m and differential Global Positioning System (GPS) rather than nondifferential GPS was employed whenever possible in deeper water. A common clock was employed in the logging of ADCP and navigation data to minimize timing errors (Jochens and Nowlin, 1998; also see Distribution of Chlorophyll *a*, below). The ADCP data were merged with the navigation data to produce initial estimates of current velocities. The current velocity data were then rotated and stretched using the procedure defined by Joyce (1989). Outliers were identified as being at least two standard deviations away from other data in a moving window with a size of 200 segments, and they were discarded. Then vertical and horizontal plots were examined and data points that represented nonphysical traits, including single point current reversals and unreasonably large currents near the seabed, were removed. When ensemble data were used, similar processing was performed and the processed data were averaged over 5-min intervals. The combined measurement error variance of ADCP water velocity data for these summer cruises is estimated to be near 4 $(\text{cm}\cdot\text{sec}^{-1})^2$. In this study we use ADCP velocities at the closest vertical bin to the surface; namely, the 4-m bin centered at approximately 14 m beneath the sea surface.

Daily river discharge rates for the Mississippi River and rivers to its east were obtained from the U.S. Geological Survey and the U.S. Army Corps of Engineers.

Sea surface height anomaly (SSHA) fields were obtained as a blended product of TOPEX/Poseidon and ERS-2 satellite altimeter data from Dr. Robert Leben, University of Colorado. These SSHA fields were produced by temporal and spatial smoothing using decorrelation scales of 12 days and 100 km (Leben et al., 2002). As a result, features may appear weaker than they actually were, and smaller scale features may not be represented. To estimate the total dynamic topography, the residual mean in the SSHA was removed before adding a model mean to produce the synthetic height estimate. The resulting time series of sea surface height (SSH) fields were interpolated to obtain one SSH field per day.

Estimation of nutrient quantity in the euphotic zone.—To estimate the approximate depth of the euphotic zone, we used data on down-welling irradiance [Ed(PAR)] versus depth (z). (The Ed(PAR) was measured at each station

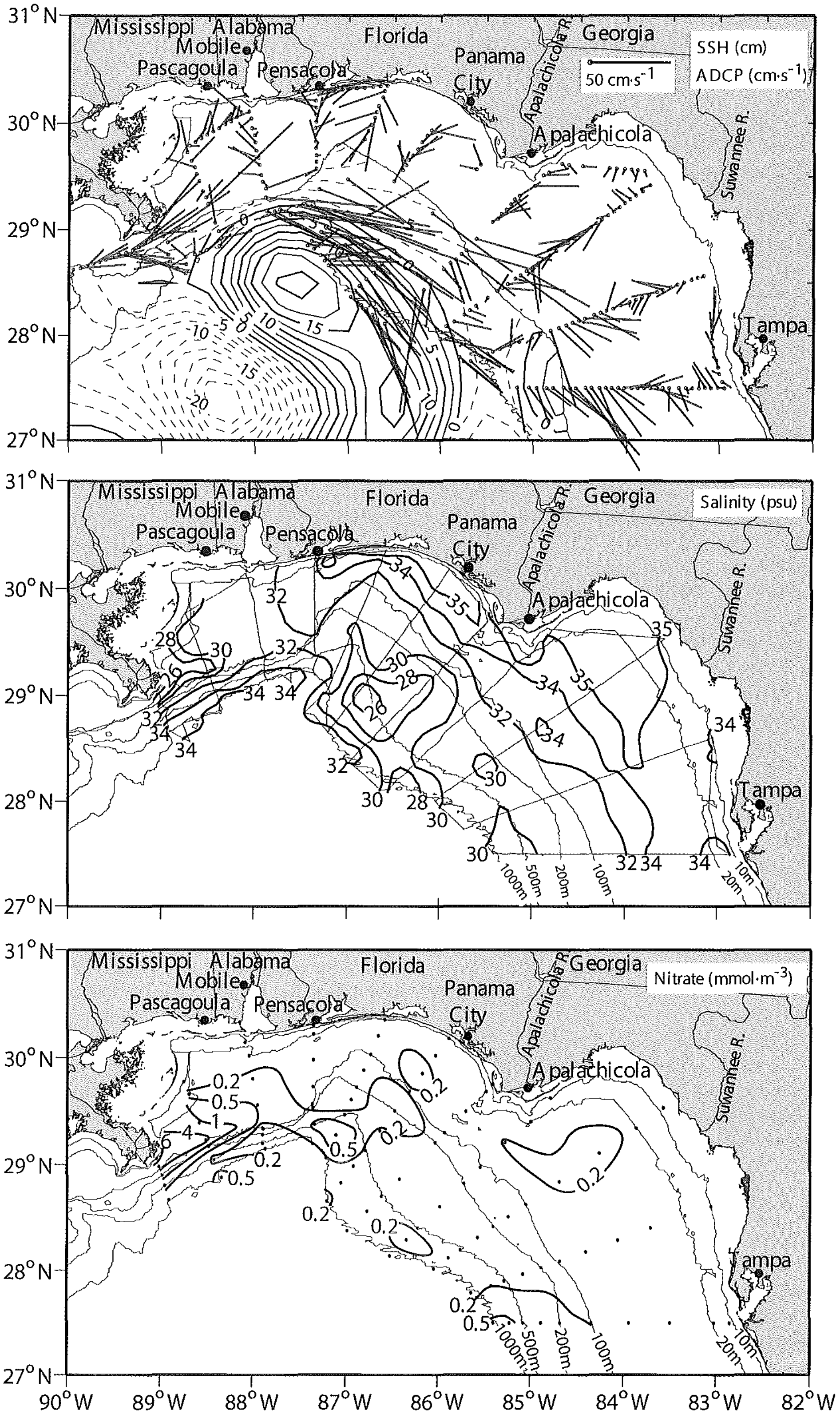

Fig. 2. Sea surface height from satellite altimeter data (1 Aug. 1998) superimposed on gridded ADCP currents at 14-m depth (upper panel), salinity at 3-m depth (middle panel), and nitrate (mmol·m^{-3}) at 4-m depth (lower panel) for Cruise N3. Station locations are shown in lower panel, track lines in other panels.

DOI: 10.18785/goms.2302.01

TABLE 3. Characteristics of depths of 1% irradiance as a function of cruise and depth range based on stations in water depths of at least 50 m and with reliable fits of irradiance vs diffuse attenuation coefficient as a function of depth.[a]

Cruise	Station depth (m)	Min (m)	Max (m)	Mean (m)	SD[b] (m)	No. stations
N3, summer 1998	50–100 m	40	95	58	25	4
	100–200 m	51	89	61	11	10
	200–500 m	47	162	71	33	13
	500–1000 m	58	116	80	16	14
N6, summer 1999	50–100 m	55	97	85	19	7
	100–200 m	47	117	71	26	7
	200–500 m	48	118	72	24	10
	500–1000 m	57	176	95	42	6
N9, summer 2000	50–100 m	40	60	48	9	4
	100–200 m	49	101	71	19	6
	200–500 m	60	85	75	9	11
	500–1000 m	53	167	91	38	8

[a] Minimum, maximum, and mean depth values as well as standard deviation about the mean are given.
[b] Standard deviation.

using a Biospherical Instruments, Inc., PAR sensor, Model QSP-200L). Because data logging did not always begin at the surface (average depth 2.5 m) it was necessary to calculate the depth of 1% irradiance using the diffuse attenuation coefficient (k). So, for each cruise at each station k was computed by fitting data to the following equation:

$$\ln[Ed(PAR)] = k(z) + \text{intercept} \qquad (1)$$

The diffuse attenuation coefficient so determined was used to solve the following equation for the depth of 1% irradiance:

$$Z = [\ln(0.01) - \ln(1.0)]/k \qquad (2)$$

The depth of 1% irradiance was taken to approximate the base of the euphotic depth (Al-Abdulkader, 1996). We did not use stations in water depths less than 50 m because the euphotic depths there essentially depend on water depth, ranging from 80% to 99% of the water depth. For each station deeper than 50 m and having r^2 greater than 0.5 for the fit of irradiance vs diffuse attenuation coefficient, values of euphotic depths were used to construct Table 3. Shown are the number of stations; the minimum, maximum, and mean depth values; and the standard deviation about the means for stations in various ranges of water depth by cruise.

Based on these estimations, we selected 60 m for our nominal depth of the euphotic zone for use in estimating the amount of nutrient mass in that zone. This is likely underestimated for stations past the shelf edge (200 m), but it should be a good proxy for shelf stations.

We sought a method to estimate the relative importance of advection versus uplift in supplying nutrients to the upper 60 m of the water column. River water over the study region was confined to the upper 15 m of that zone (refer to Surface Circulation and Riverine Supply of Nutrients, below). Therefore, we calculated the quantity of nitrate and silicate for the upper 4 m, 15 m, and 60 m to investigate nutrient behavior at different depth levels. For each station, nitrate concentrations were vertically integrated over the upper 4 m, 15 m, and 60 m of the water column. These integrated concentrations were used to create values over 4, 15, and 60 m on a 0.25-degree (approximately 27 km) grid using the Generic Mapping Tools (GMT) software package (Wessel and Smith, 1991). The choice of grid was selected because the contours created by GMT for this size grid seemed reasonable and closely followed hand contours. The objective analysis used in GMT is based on an extension of the minimum curvature method of gridding described by Smith and Wessel (1990). The GMT package does not produce estimates of error fields. Concentration values at the corner of each box were averaged to obtain the value assigned to the box. In each box, the quantities of nitrate and silicate were calculated by multiplying the averaged concentration with the volume. The total standing stock of nitrate and silicate were calculated by summing the concentrations in each box for the three ranges 0–4 m, 0–15 m, and 15–60 m. For locations shallower than 15 or 60 m, the total was the sum of the quantity of nutrient between the surface and the bottom depth at the location.

RESULTS

Surface circulation and riverine supply of nutrients.—The circulation for the three summer cruises and the associated near-surface salinity and nitrate fields are shown in Figures 2, 3, and 4 for 1998, 1999, and 2000, respectively. In all 3 yr, anticyclones were found adjacent or close to the shelf break. In 1998 and 2000, the anticyclone was very close to the shelf break in the western part of the region, being situated near DeSoto Canyon (Figs. 2 and 4, upper panels). This led to enhanced northeastward flow between the western edge of the anticyclone and the Mississippi delta. In both years the flow field associated with the anticyclones followed the bathymetry, with eastward or southeastward flow east of Line 2 between the 100-m and 1,000-m isobaths. In 1998, this longshore flow was concentrated outside the 200-m isobath, while in 2000, it was closer inshore, between 100 and 500 m. Highest velocities observed by the ADCP at a depth of 14 m were about 70 $cm \cdot sec^{-1}$ in 1998, but only about 30 $cm \cdot sec^{-1}$ in 2000, except for the region adjacent to the delta, where they approached 50 $cm \cdot sec^{-1}$. This is consistent with the relative strengths of the anticyclones as indicated by SSH distributions in the figures.

The anticyclone in 1999 was stronger than that observed in the other 2 yr, with an SSH elevation of almost 40 cm (Fig. 3, upper panel), compared to elevations of 20 cm in 1998 and 10 cm in 2000. However, the center of the 1999 anticyclone was considerably farther offshore, in greater water depths. Between the anticyclone and the outer shelf the SSH field for 1999 suggests that the surface flow was strongly cyclonic with two low SSH features of less than −20 cm. One low SSH feature was located just south of the Mississippi River Delta, and the second was located over the apex of the DeSoto Canyon. The two cyclones are observed in the ADCP measurements by eastward (northward) flow on their southern (eastern) limbs. The net result was eastward to southeastward surface flow between the coast and the 50-m isobath as far east as Line 8, together with along-slope flow over the outer shelf and slope (200 m and deeper), from DeSoto Canyon (Line 6) eastward.

Over the inner shelf, currents during all three cruises were weaker and less organized. This was particularly the case over the wide shelf south and east of Apalachicola. However, in all 3 yr a westward coastal current of 15–25 $cm \cdot sec^{-1}$ was observed along the west Florida shelf between Pensacola and Panama City. In 2000, this appeared to originate near Apalachicola.

This general circulation pattern of eastward and southeastward flow over the outer shelf and upper slope, coupled with weak northwestward flow over the inner shelf, led to the observed salinity fields (Figs. 2, 3, and 4, middle panels) with higher salinities inshore and lower salinities offshore. Low-salinity water from the Mississippi Delta region ($S < 32$) was found in a band along the shelf break in all 3 yr. In 1998 and 1999 (Figs. 2 and 3), it covered almost the entire region outside the 100-m isobath from Pensacola to Tampa, but reached only as far as Line 8 in 2000 (Fig. 4) when the anticyclone was weakest. It should be noted that 2000 was also a drought year with very low Mississippi River discharge according to U.S. Army Corps of Engineers data. This low-salinity layer was generally shallow, to depths of 15 to 25 m (Fig. 5 shows typical sections of what we observed over the 200- and 500-m isobaths), and presumably formed a ribbon of low-salinity water along the shelf break. This is seen clearly in Figure 2, in which the salinity increases again offshore over the 1,000-m isobath between Lines 1 and 4. Pockets of lower-salinity water ($S < 26$ in 1998, $S < 28$ in 1999 and 2000) were observed within the low-salinity ribbon.

The nutrient fields tended to correspond well with the salinity fields for near-surface waters less than 15 m on all NEGOM cruises. Because there were few low-salinity data points for each individual cruise, and because it is assumed that the same offshore water mass is involved in mixing during each cruise, data from all nine survey cruises were included in the plot. When nitrate and silicate were plotted against salinity for all cruises (Fig. 6) their inverse relationship with an r^2 of 0.63 showed a conservative relationship. Thus, the highest concentrations of nitrate were found close to the delta in water of low salinity (Figs. 2–4, bottom panels). These concentrations decreased rapidly with distance from the delta, and only small patches of low nitrate concentration were found across the rest of the area. Again, these were generally associated with the low-salinity ribbon over the outer shelf and slope, although isolated stations containing low ($0.2 < x < 0.5$ $mmol \cdot m^{-3}$) concentrations were found over the West Florida Shelf (see Figs. 2 and 3). The cause of these patches is not known. There was no obvious sign of either freshwater or nitrate supply from any of the rivers in the region apart from the Mississippi.

Deep in the water column, between depths

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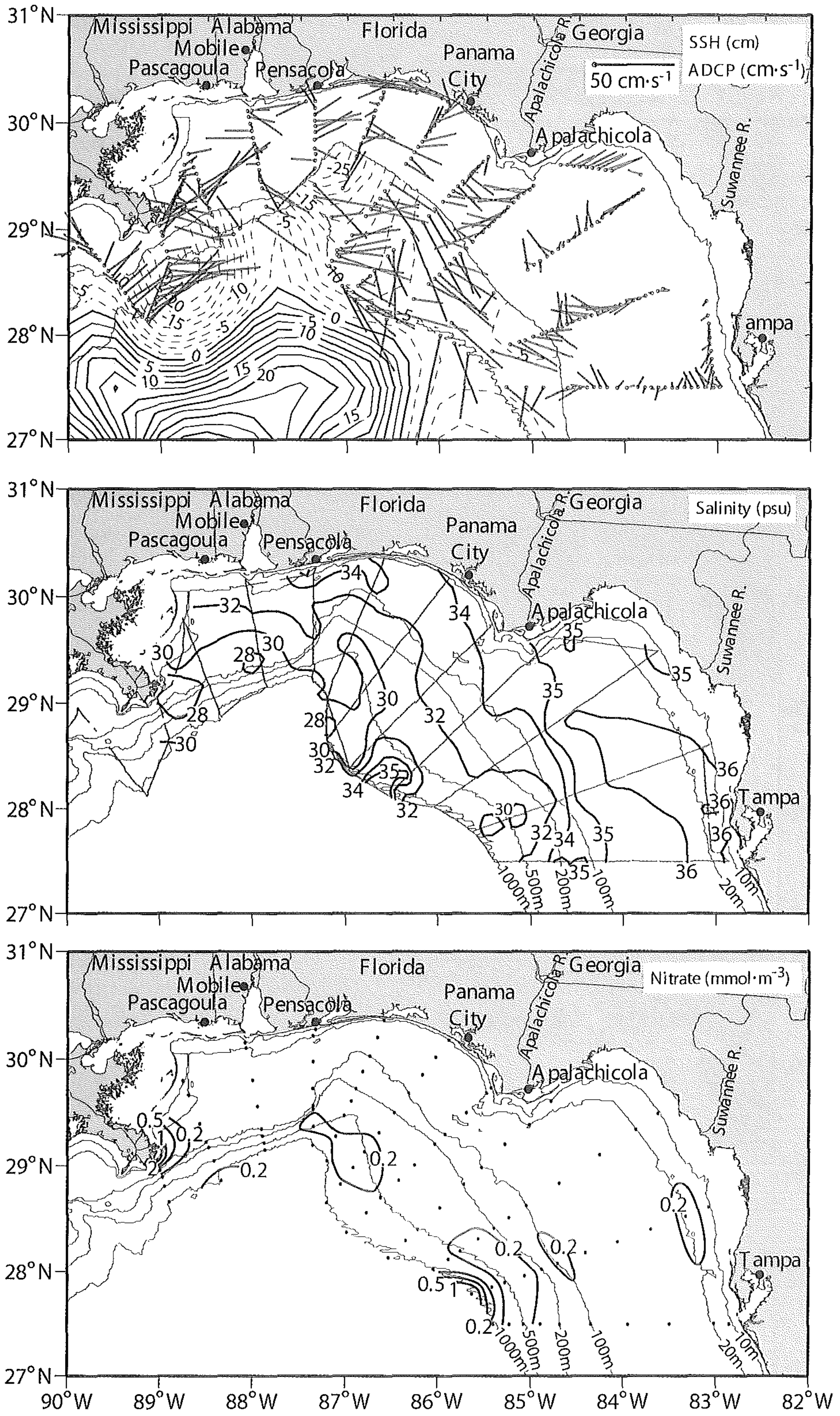


Fig. 3. Sea surface height from satellite altimeter data (21 Aug. 1999) superimposed on gridded ADCP currents at 14-m depth (upper panel), salinity at 3-m depth (middle panel), and nitrate (mmol·m^{-3}) at 4-m depth (lower panel) for Cruise N6. Station locations are shown in lower panel, track lines in other panels.

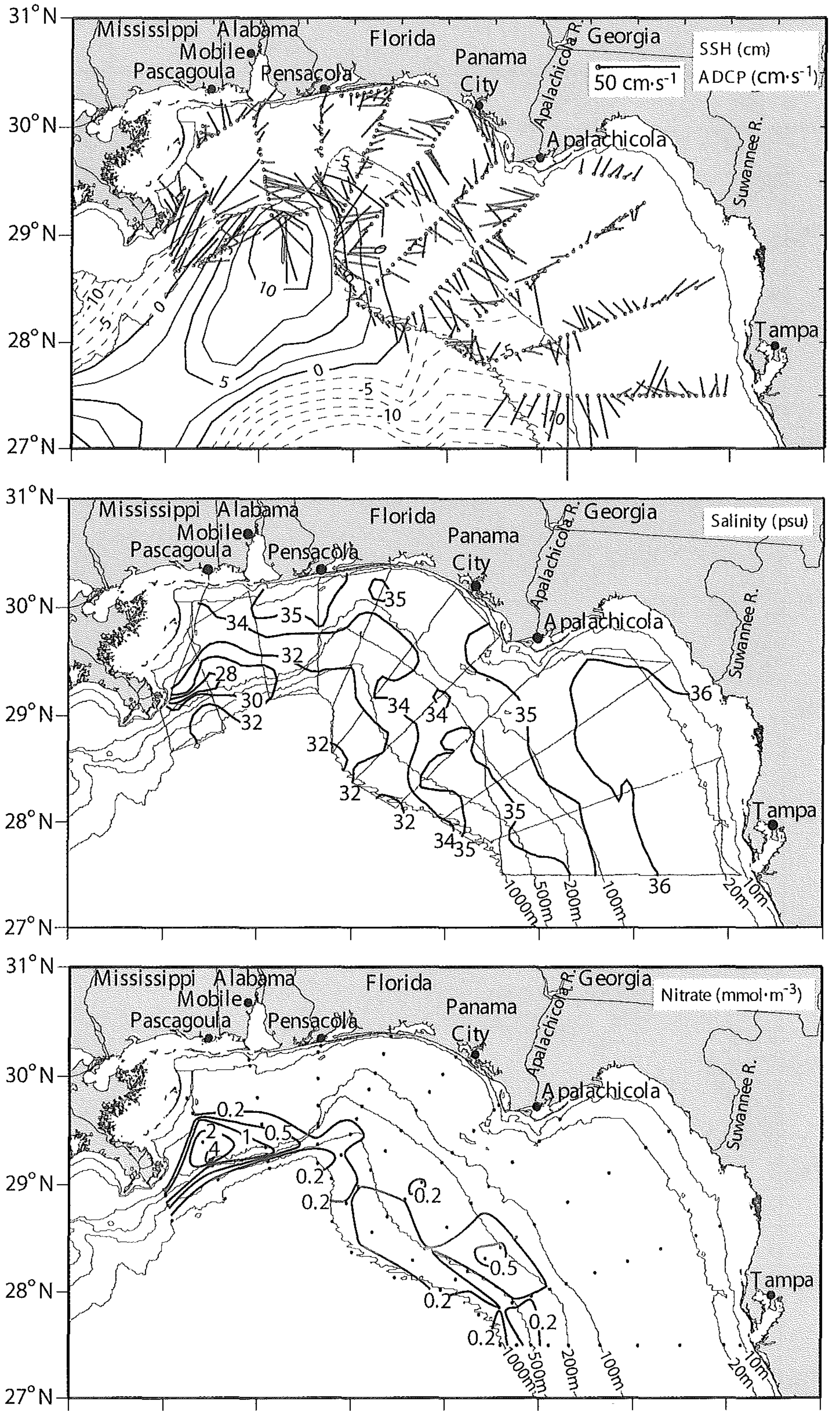
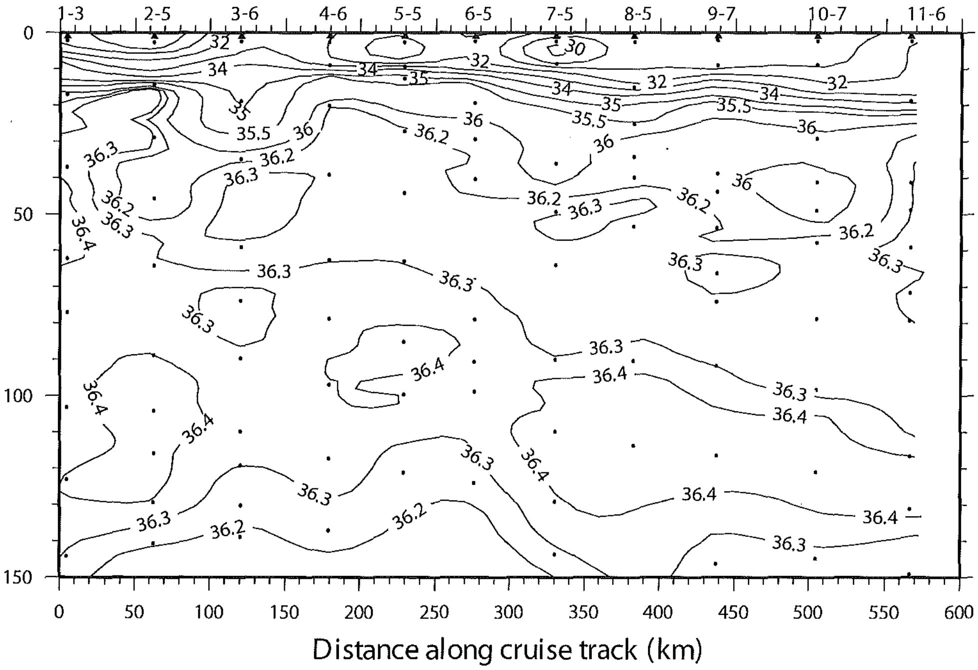


Fig. 4. Sea surface height from satellite altimeter data (2 Aug. 2000) superimposed on gridded ADCP currents at 14-m depth (upper panel), salinity at 3-m depth (middle panel), and nitrate (mmol·m^{-3}) at 4-m depth (lower panel) for Cruise N9. Station locations are shown in lower panel, track lines in other panels.

DOI: 10.18785/goms.2302.01

(a) Salinity (200 m) N3 (summer 1998)



(b) Salinity (500 m) N3 (summer 1998)

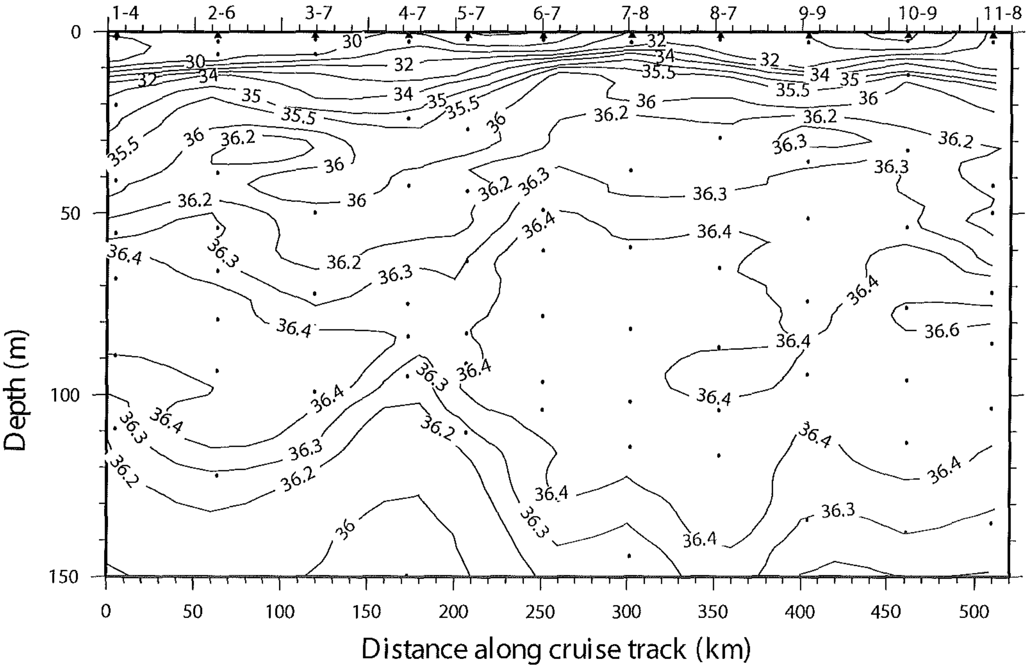


Fig. 5. Salinity on (a) the 200-m isobath for summer Cruise N3, and (b) on the 500-m isobath for summer Cruise N6. Stations are shown on the top axis. Line 1 near the Mississippi Delta is at the left station; Line 11 at the right.

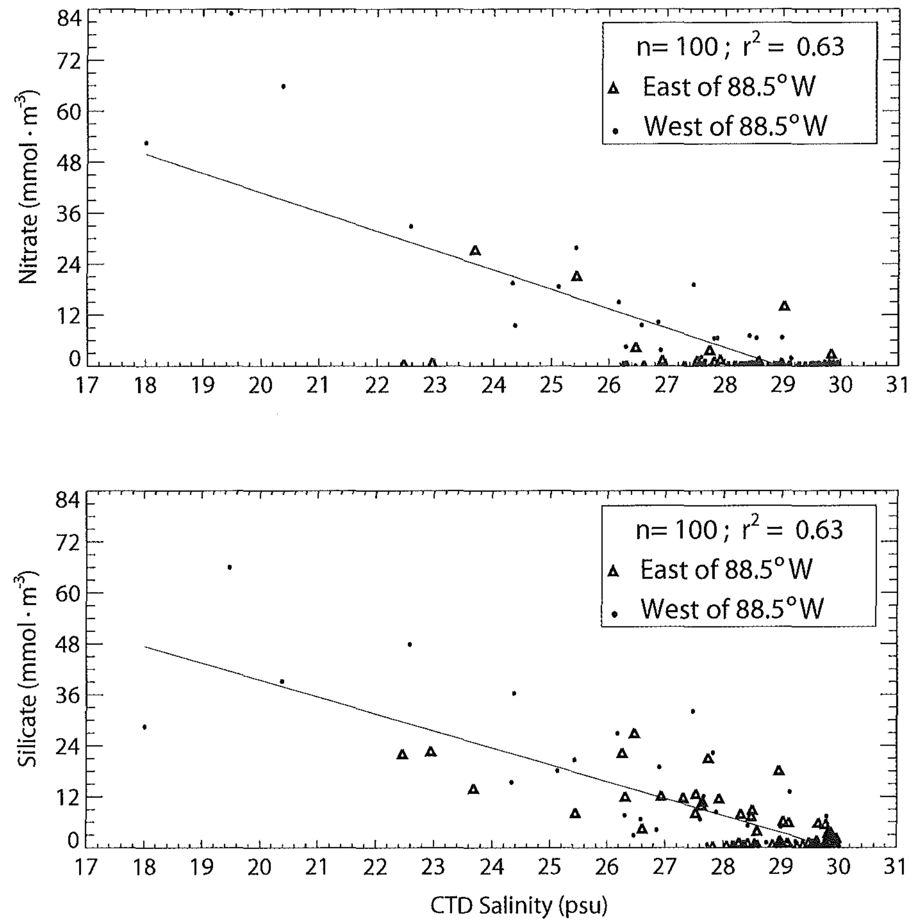


Fig. 6. Nitrate (upper panel) and silicate (lower panel) concentrations versus salinity in the upper 15 m for all nine NEGOM surveys, N1 through N9. The dots and triangles represent locations close to the Mississippi Delta (west of 88.5°W) and far from the delta (east of 88.5°W), respectively.

of 15 and 150 m, nutrients are nonconservative due to biogeochemical activity. Below 150 m, however, plots of nutrients versus salinity show generally conservative nutrient behavior. The inverse relationship showed a high r^2, exceeding 0.85 (Jochens et al., 2002).

How important is the Mississippi River in terms of the nitrate supply to the study region in summer? If we assume that the influence of the river is confined to the upper 20 m of the water column, then a clear riverine influence is found only close to the delta (Fig. 7). In all 3 yr along Line 1 there was a low-salinity, shallow surface layer containing significant, measurable nitrate concentrations. In 1998 (Fig. 7a), surface waters with nitrate concentrations >0.2 mmol·m^{-3} down to 15 m extended past the end of Line 1 (at least 50 km offshore). In 2000 (Fig. 7c), the offshore extent was almost as large (45 km), but the layer was less than 10 m deep, while in 1999, the river-derived layer extended only as far as 20 km offshore (Fig. 7b). Farther east, only isolated pockets of such water were found (e.g., as shown in Figs. 7 and 8). The only other occasions when nitrate was observed at the surface, where it was confined to the upper 6 m of the water column, were along Lines 2, 6, and 11 in 1998, and along Lines 3 and 8 in 2000 (not shown). In 1999, only one other patch was observed, on Line 10 (Fig. 3) in the surface (2-m) sample.

Thus, although the effect of the Mississippi River discharge on supply of nitrate in summer was relatively small when the entire region was considered, one can infer that it is very substantial near the river mouth, where concentrations are large. After the depletion of nitrate in the surface waters during spring, the nitrate introduced in summer by river discharge and subsequent along-shelf flow must be rapidly

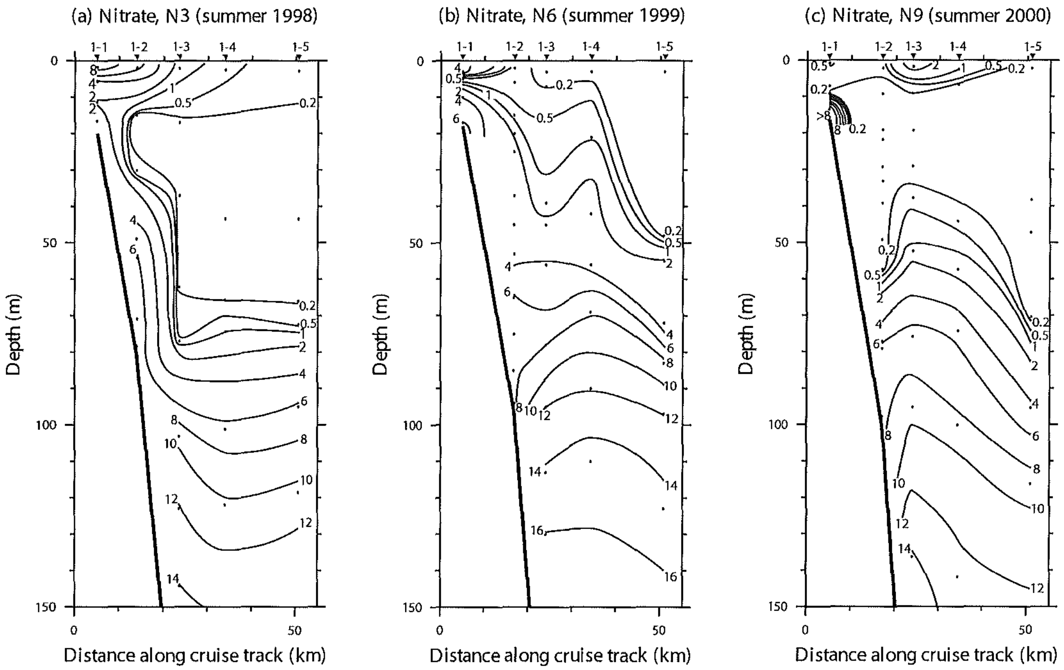

(a) Nitrate, N3 (summer 1998) (b) Nitrate, N6 (summer 1999) (c) Nitrate, N9 (summer 2000)

Fig. 7. Nitrate distributions (mmol·m^{-3}) along cross-shelf Lines 1 on summer Cruises N3, N6, and N9.

utilized by plankton, so little is present in the residual low-salinity surface waters as they flow eastward. The phytoplankton, however, remains visible in the surface layer for several days/weeks as the plume is advected eastward.

Vertical distribution of nutrients: effects of eddies.—Over most of the study area, except near the Mississippi River mouth, surface water nitrate concentrations were <0.2 mmol·m^{-3} down to depths of 20 to 50 m. Contrast conditions on

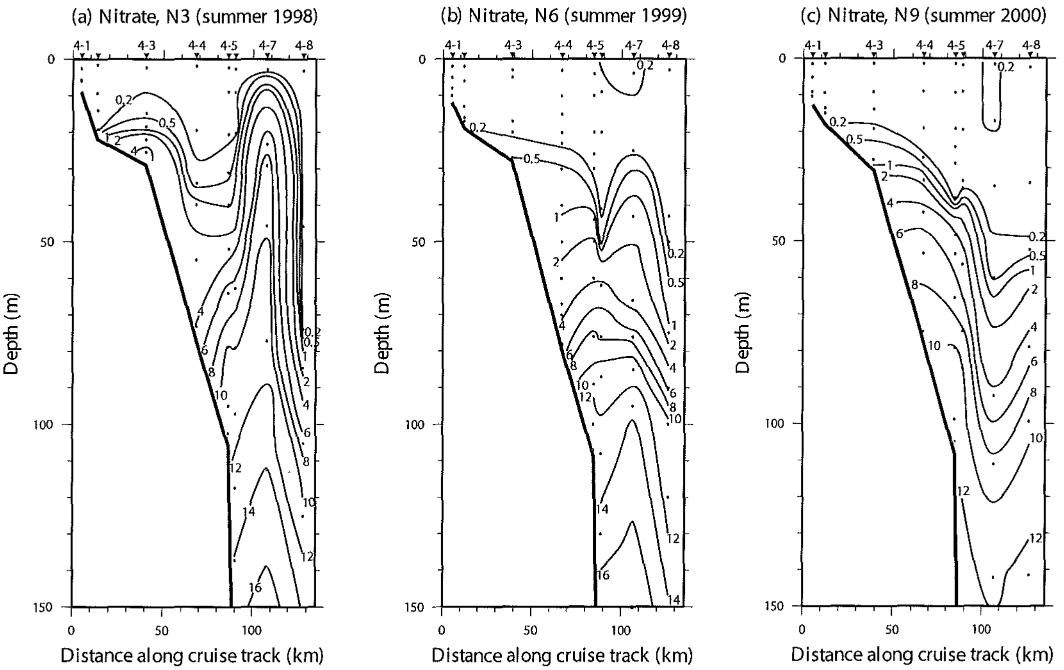

(a) Nitrate, N3 (summer 1998) (b) Nitrate, N6 (summer 1999) (c) Nitrate, N9 (summer 2000)

Fig. 8. Nitrate distributions (mmol·m^{-3}) along cross-shelf Lines 4 on summer Cruises N3, N6, and N9.

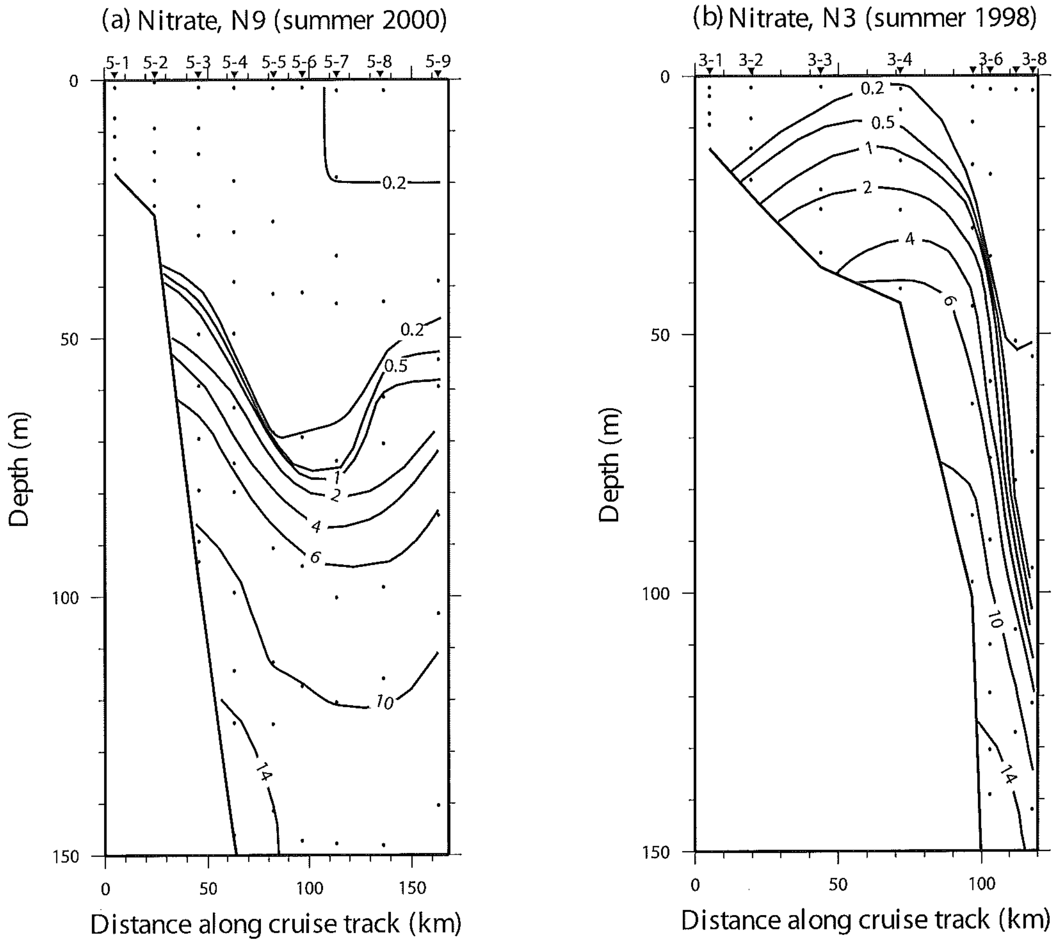


Fig. 9. Nitrate (mmol·m^{-3}) along Line 5 for Cruise N9 (left panel) and along Line 3 for Cruise N3 (right panel).

Line 1 (Fig. 7) with those on Lines 3, 4, or 5 (Figs. 8 and 9). Variations in the shape of the 0.2 mmol·m^{-3} surface were determined by uplift and depression resulting from the eddy field. The effect of uplift over the slope is clear at Stations 1-3 and 1-4 on Line 1 during Cruise N9 (Fig. 7c) and was due to the off-shelf anticyclone (Fig. 4).

While upwelling induced by eastward flowing currents along the relatively steep shelf may have brought nutrient-enriched water into the upper 50–80 m on Line 1 during N3 (Stations 1-2, 1-3; Fig. 7a), lower oxygen concentrations and much higher concentrations of silicate were observed in the nitrate-rich patch than deeper in the water column or farther offshore (figures not shown). These suggest that local regeneration is a more likely explanation for the enrichment as found elsewhere in similar low-oxygen environments (e.g., Bailey and Chapman, 1991). Similar nutrient enrichment/oxygen depletion was observed at shallower depths at the inshore end of Line 1 during Cruises N6 and N9, and in neither case could upwelling account for the observed nutrient concentrations or the decreased oxygen concentrations.

The effects on nutrient distributions of the anticyclones and cyclones found over the slope during each cruise were examined. Within cyclones, in the region of interaction between eddies, and between eddies and the shelf edge, subsurface water rich in nutrients was observed to dome upward toward the surface. During Cruise N3, as the anticyclonic eddy approached the shelf edge, a strong uplift of nutrient isopleths occurred. This was observed centered at Station 4-7 on Line 4 (Fig. 8a), and more strongly on Line 3 (Fig. 9b). ADCP flow fields showed currents of 40–50 cm·sec^{-1} at 100 m during this cruise.

A similar uplift of isopycnals, and consequently of nutrients into the euphotic zone, was also found during summer 1999 (Cruise N6). This can be observed at depths below 50 m along Line 4 between Stations 4-4 to 4-7 (Fig. 8b). In the summer of 2000, the flow along Line 5 was anticyclonic, as seen in the near-surface ADCP current distribution (Fig. 4) and also in the dynamic topography (not shown). This resulted in the depression of nutrient isopleths about Stations 5-3 to 5-7 (Fig. 9a). The effect of this northeastward flow along the shelf edge is also seen in the nitrate distribution at Stations 4-3 to 4-6 on Line 4 (Fig. 8c), where isopleths were uplifted onshelf. It also is possible that the interaction with the bathymetry of the currents along the edge of this anticyclone resulted in a bottom Ekman layer and so enhanced cross-isobath onshelf flow at the bottom. However, we have no hard evidence that this was the case.

We note the different effects of uplift evidenced on the three summer cruises. Apparently, the farther the anticyclone extends up onto the slope, the shallower are the waters, originating from a depth of 50–100 m, that are rich in nutrients. For instance, during Cruise N3, high-nitrate water was lifted almost to the surface at Station 4-7 (Fig. 8a). By comparison, on Cruise N6, when the leading edge of the anticyclone did not extend as far shoreward, cyclones found over the slope forced mid-depth water to be uplifted to no higher than depths of 35 m on Line 4 (Fig. 8b). The strength of an anticyclone appeared to determine the degree of vertical uplift. During Cruise N9, the anticyclone was found adjacent to the slope, but because it was weak, bottom friction did not force nutrient-rich deeper water as high in the water column as was the case for Cruise N3 (Fig. 8c).

The relative importance of riverine input and circulation-induced supply.—We believe we can use the distributions of nitrate and silicate throughout the water column in the region to contrast the relative importance of physical processes such as uplift with river supply. We have compared the distributions of nitrate and silicate in the euphotic zone. A major assumption of this approach is that the snapshot for each cruise can be thought of as representing general summer conditions. For each cruise, the quantities (i.e., concentration × volume) of nitrate and silicate in the upper 4 m, 15 m, and 15–60 m of the water column over ~852 km^2 (0.25-degree squares) were calculated as described in the section, *Estimation of Nutrient Quantity in the Euphotic Zone.* Results are shown in Figures 10 and 12 for quantities of nitrate and silicate in the upper 15 m, and in Figures 11 and 13 for the 15–60 m interval. Distributions of quantities of nitrate and silicate for the upper 4 m are not shown because their patterns are so similar to distributions in the upper 15 m, implying that the upper 15 m of the NEGOM region behaves as a unit.

As expected, because of relatively low levels of river discharge onto the Florida shelf, all three cruises showed very low amounts of nitrate in the upper 15 m of the water column over the eastern study area (Fig. 10). The maximum quantity of nitrate was found close to the mouth of the Mississippi River (Station 1-1 on Line 1) on Cruises N3 (29.6 Mmol) and N6 (13.2 Mmol); it was 19.1 Mmol at Station 2-3 also near the Mississippi River mouth on Cruise N9. Other locations with high quantities of nitrate corresponded to regions where recently discharged Mississippi River water was found; one might refer to the surface salinity distributions in Figures 2–4. During Cruise N6, values greater than 5 Mmol were found also at the seaward end of Line 10, near 85°30′W, corresponding to the presence of low-salinity surface water rich in nutrients: this was an exception to the generally low levels of nutrients over the eastern study area. Thus it seems clear that nitrate added by the river is generally consumed rapidly close to the source.

Deeper in the euphotic zone (15–60 m), higher nitrate levels begin to appear farther to the east (particularly in waters with total depths greater than 100 m) far from the direct influence of the Mississippi River (Fig. 11). For all cruises, regions with higher quantities of nitrate corresponded to regions where water was uplifted by a physical process. For instance, during Cruise N3, a region of high nitrate was observed along the outer shelf edge and upper slope extending eastward from Line 2 to Line 6. This was associated with the uplift of mid-depth waters at these stations, which can be seen on Line 3 in Figure 9b and on Line 4 in Figure 8a. Similar effects were observed in the 1999 and 2000 cruises, but the nutrient isopleths were still dependent on the strength of the anticyclone at the time. Thus, while nitrate >0.2 mmol·m^{-3} was found within the upper 5 m during Cruise N3, uplift occurred only to 25 m during N6 and to 40 m during N9 (Figs. 8, 9).

For all cruises, the quantity of silicate in both the upper 15 m and in the 15- to 60-m depth

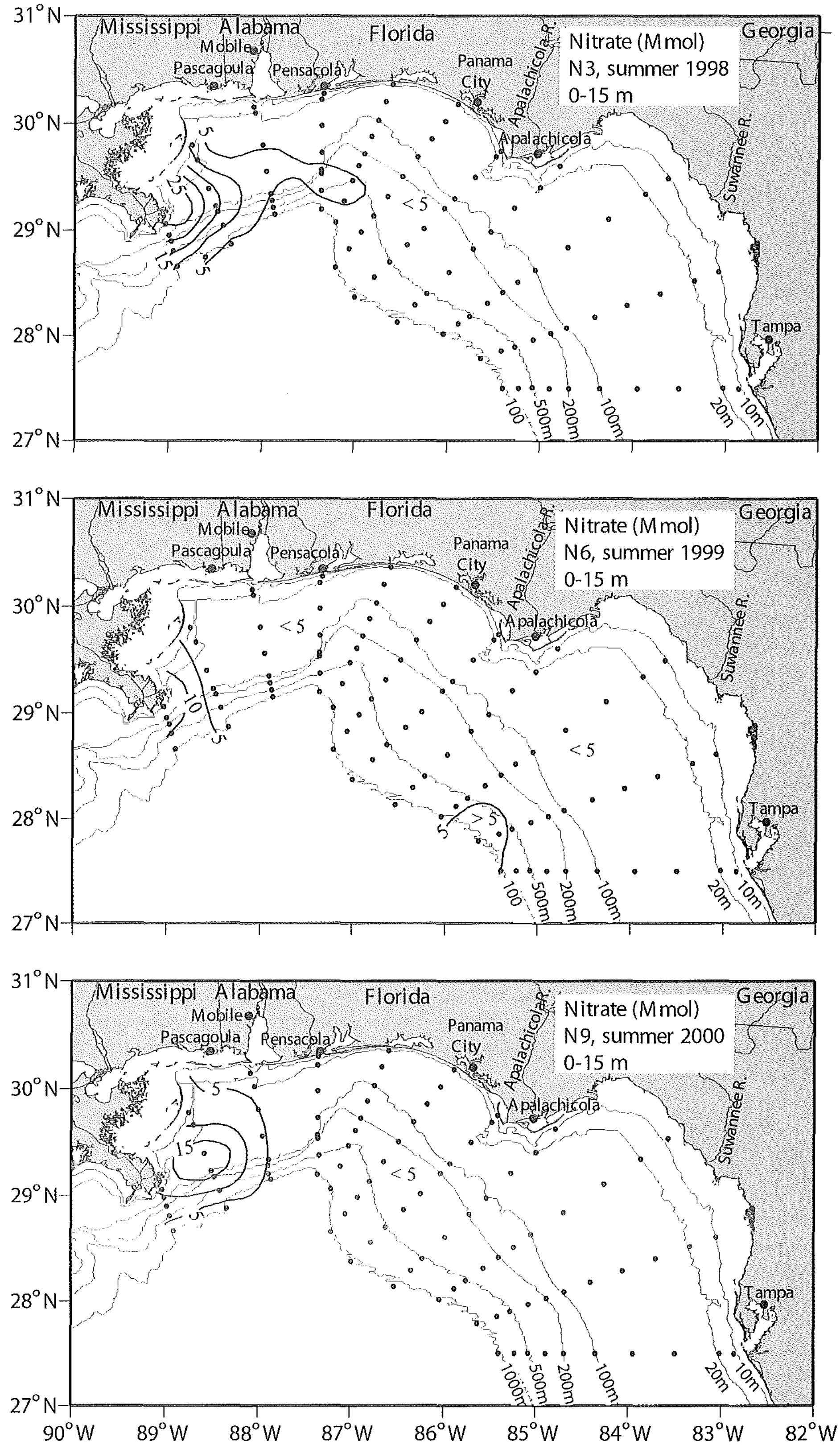


Fig. 10. Nitrate mass (contour interval 5 Mmol nitrate) in the upper 15 m of the water column over 0.25*0.25 degree for Cruises N3, N6, and N9.

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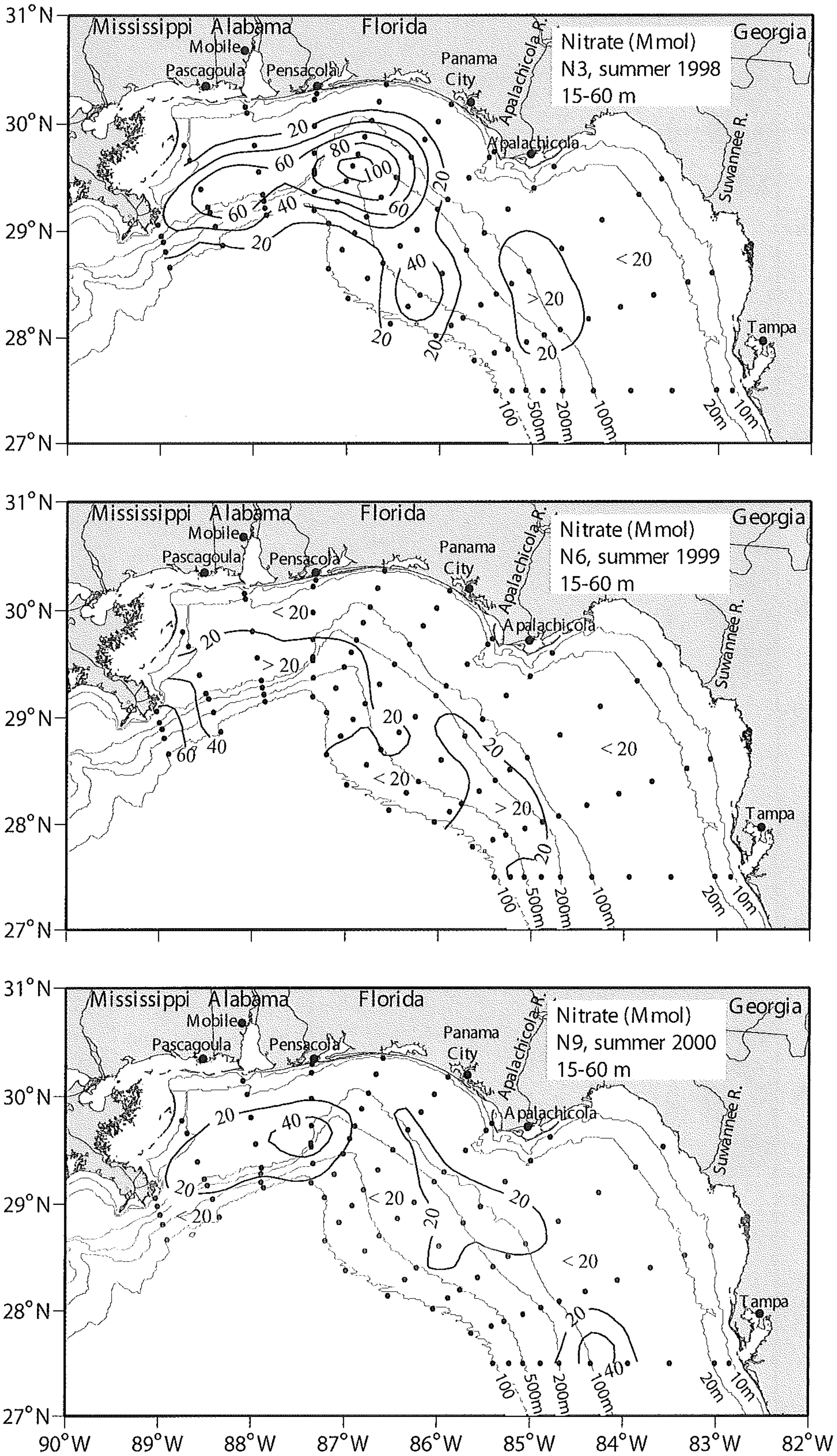

Fig. 11. Nitrate mass (contour interval 20 Mmol nitrate) in the water column interval 15 to 60 m over 0.25*0.25 degree for Cruises N3, N6, and N9.

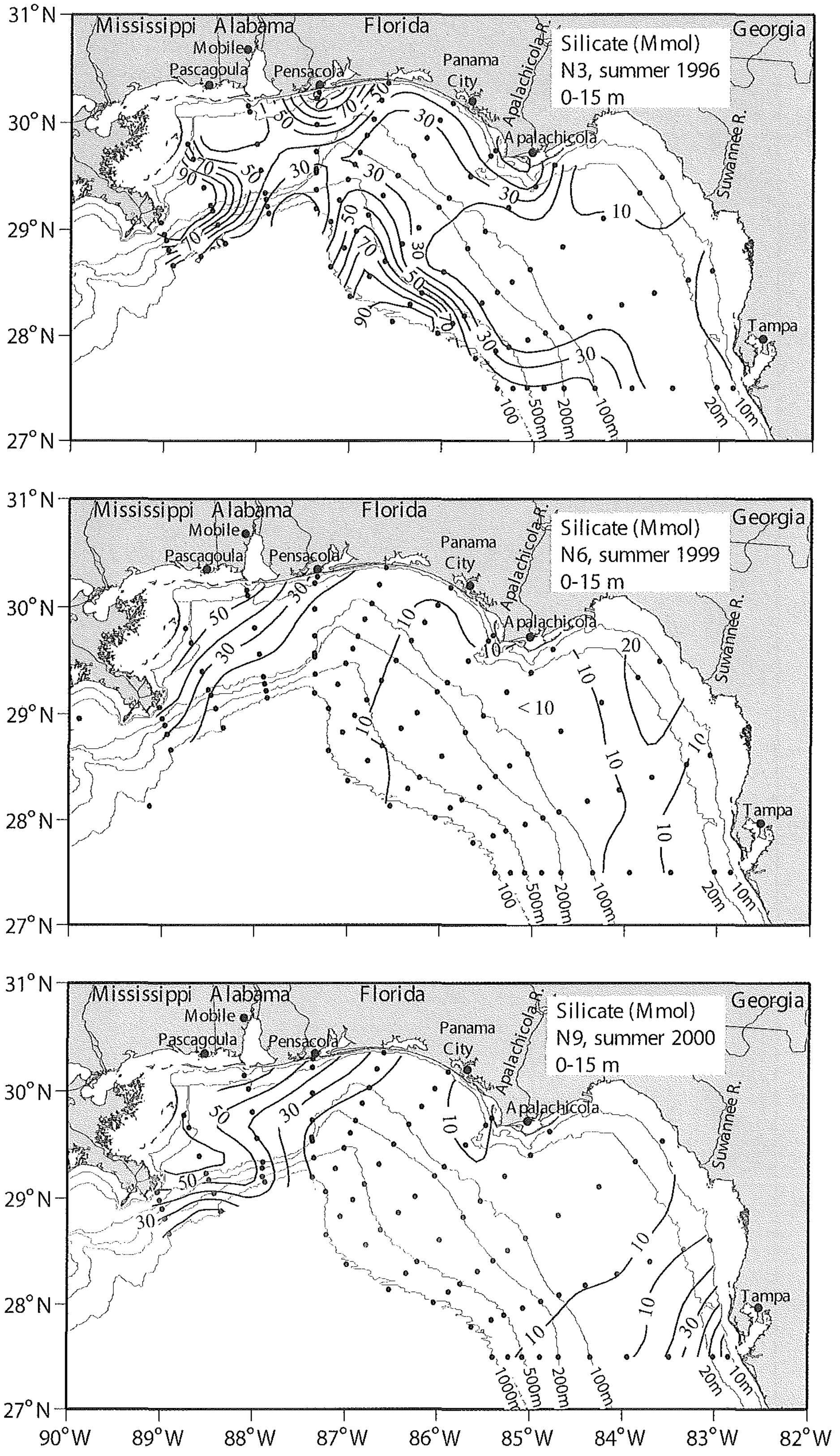

Fig. 12. Silicate mass (contour interval 10 Mmol silicate) in the upper 15 m of the water column over 0.25*0.25 degree for Cruises N3, N6, and N9.

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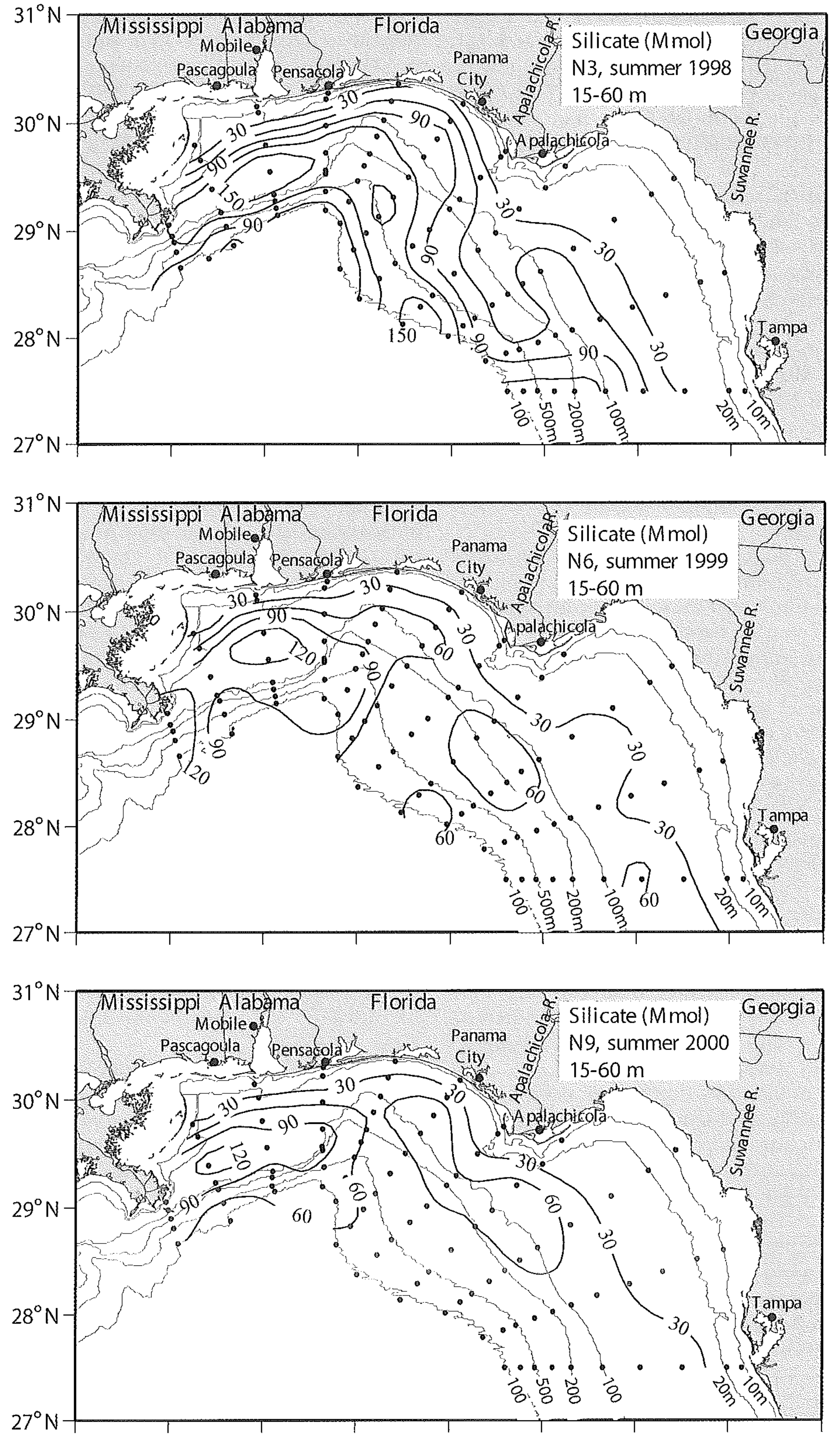

Fig. 13. Silicate mass (contour interval 30 Mmol silicate) in the water column interval 15 to 60 m over 0.25*0.25 degree for Cruises N3, N6, and N9.

interval (Figs. 12 and 13) was much higher than the quantity of nitrate (Figs. 10 and 11). This suggests that either the removal of nitrate by biological or physical processes is faster than that of silicate, or more likely, that silicate is supplied in considerably greater quantities than is required for phytoplankton growth.

The highest amounts of silicate in the upper 15 m (Fig. 12) were associated with the presence of Mississippi River water near the area of discharge, as shown by a comparison with salinity (Figs. 2–4). The maximum quantities of silicate observed were 147.5 Mmol just east of the river mouth on Cruise N3 and 66.2 Mmol and 71.7 Mmol near the Chandeleur Islands on Cruises N6 and N9. Other high inshore silicate concentrations are observed (e.g., off Pensacola and Apalachicola in 1998 or off Tampa Bay in 2000), demonstrating the importance of additional local sources elsewhere along the coast.

Offshore on Cruise N3, high quantities of silicate were found along the outer slope east of DeSoto Canyon. This is in contrast to nitrate quantities, but corresponds relatively well to low-salinity areas, thus marking river waters (Fig. 2, middle panel). Such high-silicate–low-salinity water originating from the Mississippi River outflow was also observed along the edge of the Loop Current–Florida Current system during the 1993 Mississippi River flood (Ortner et al., 1995). Dortch (1994) also reported that Mississippi River discharge was unusually high in silicate during summer 1993.

For the 15- to 60-m interval, high levels of silicate were observed at various locations removed far from the direct influence of Mississippi River water (Fig. 13), generally in water with total depths greater than 100 m. These locations correspond to regions of elevated nitrate levels, and the same physical processes presumably were responsible.

These results show that it is possible to separate a nutrient added by river discharge and subsequent advection from that associated with uplifted waters by examining the amounts in different depth ranges. Low-salinity waters rich in nutrients (nitrate or silicate concentrations greater than 0.5 or 1.0 $\mathrm{mmol \cdot m^{-3}}$, respectively) were restricted to the upper 10 m of the water column. Below 15 m, nutrients were added to the euphotic zone by uplift; so nutrients observed between 15 and 60 m may be considered to be present primarily because of such uplift. For all summer cruises, Table 4 gives the total quantities of nitrate and silicate in the upper 15 m and between 15 and 60 m of the water column.

TABLE 4. Total quantity of nitrate and silicate (Mmol) in water depths 0–15 m and 15–60 m over the NEGOM area for summer cruises N3 (1998), N6 (1999), and N9 (2000).

Nutrient	Cruise	Quantity (0–15 m)	Quantity (15–60 m)
Nitrate	N3, summer 1998	607	2,501
	N6, summer 1999	366	2,358
	N9, summer 2000	485	1,508
Silicate	N3, summer 1998	6,574	11,917
	N6, summer 1999	2,745	8,533
	N9, summer 2000	4,113	8,165

Table 4 shows that on Cruise N3, the quantity of nitrate found in the low-salinity water was 40% greater than the amount of nitrate found on Cruise N6 and 20% greater than the amount found on Cruise N9. For silicate, it was 60% greater than the amount of silicate found on Cruise N6 and 40% greater than the amount found on Cruise N9. This is consistent with the fact that the discharge from the Mississippi River in summer 1998 was higher than in summer 1999 or 2000. Comparing the amount of nitrate found in the uplifted water on the three summer cruises, Cruise N3 had 6% more nitrate than Cruise N6 and 40% more nitrate than Cruise N9. For silicate, Cruise N3 had 28% more silicate than Cruise N6 and 32% more silicate than Cruise N9. This is because on N3 and N6, such uplifted isopleths were common over the outer shelf area, but not so on Cruise N9. Some uplift of waters to shallower depths was found along the bottom in DeSoto Canyon, perhaps attributable to bottom Ekman upwelling. Away from areas where isopleths were uplifted, concentrations of nutrients were low in the lower euphotic zone (15–60 m).

If we consider the euphotic zone of the study region to have two sources of nutrient input (river and mid-depth water) during summer, as based on these three cruise periods, and assume that the observed nutrient patterns can be thought of as being in steady state, nitrate found in low-salinity surface water represented only 15% to 32% of the total amount of nitrate found in the uplifted water. Silicate in low-salinity water represented 32% to 50% of the total amount found in uplifted water. Therefore, during the three summer cruises studied here, uplift, and not the Mississippi River, was the major source of nutrient input to the euphotic zone *in that portion of the study area removed from river mouths.* This latter conclusion could also be drawn when comparing nitrate discharge rates from the Mississippi River with nitrate inventory in the upper 15 m given in Table 4.

Nitrate discharge rates for the Mississippi River were computed by taking nitrate concentrations measured by Kelly et al. (2001) at St. Francisville, LA, and multiplying these by the average daily volume of river discharge in each month of summers 1998–2000. The average nitrate discharge rate over the three summers is about 0.14 Gmol·d^{-1}, but there are two provisos to keep in mind when using these data. First, under easterly wind conditions, only about 35% to 50% of the discharge from the Mississippi River actually ends up in the study area (see the section *River Discharge and Subsequent Transport,* above), so the nitrate discharge rate to the northeastern Gulf of Mexico study region reduces to 0.05 to 0.07 Gmol·d^{-1}. If, as in summer, the winds are westerly or southwesterly, about 75% of the discharge from the Mississippi River ends up in the study area, the nitrate discharge rate to the study region is about 0.11 Gmol·d^{-1}. Thus, considering the two cases, the Mississippi River has the potential to supply some 10% to 23% per day of the inventory of nitrate in water depths 0–15 m (see Table 4). The standing stock of dissolved nitrate is about 0.5 Gmol, hence the residence time for nitrate is about 5–10 d in the upper 15 m over the NEGOM shelf during summer. This is an underestimate because it does not include nitrate used by phytoplankton, nor any input term from other rivers. However, the second proviso is that river nitrate concentrations are reduced 95–99% within just a short distance from the river mouth (i.e., from an average of 120 mmol·m^{-3} at St. Francisville, to <2 mmol·m^{-3} close offshore) by the abundant phytoplankton (high chlorophyll *a* concentrations) already present in the river outflow plume (Bianchi et al., 1999), and by dilution with higher-salinity, low-nutrient surface water. Specifically, near-surface nitrate concentrations were almost always <9 mmol·m^{-3} at Station 1-1 on Line 1 (Fig. 7), even though this station was located <5 km from the shoreline of the Birdsfoot Delta. Clearly, the Mississippi River has but nominal importance as a point source in supplying nitrate for new production (Eppley and Peterson, 1979) to the euphotic zone at locations removed from the river mouth, when compared to the amount of new nitrogen domed to the base of the euphotic zone by the uplift of nitrate-rich midwater.

Distribution of chlorophyll a.—When river water is discharged onto the shelf, the impact of nutrients on biological production is evidenced as "green water" (locally high chlorophyll *a* concentration). In general, chlorophyll *a* concentrations were two to three times greater within the Mississippi River plume than in adjacent shelf waters and there was an obvious color change when entering and leaving the plume, particularly on its outer edge. Specifically, chlorophyll *a* concentrations in water having salinities greater than 35 were only about 0.2 mg·m^{-3} whereas chlorophyll *a* concentrations in water with salinity less than 32 were greater than 0.5 mg·m^{-3}. We believe the locally high near-surface chlorophyll *a* concentrations in low-salinity surface water likely reflect both the transport of coastal "green water" off the shelf break (200 m) as well as in situ new primary production. During all three summer cruises in the northeastern Gulf of Mexico, locally high chlorophyll *a* was characteristic of the low-salinity filament of water derived from the Mississippi River that had been entrained and transported to the shelf edge.

The distribution of chlorophyll *a* at a depth of 3.5 m on Cruise N3 is shown in Figure 14. There is good agreement between higher chlorophyll *a* values and both lower surface salinities and higher surface nitrate concentrations (Fig. 2). High chlorophyll *a* concentrations were observed near the Mississippi River mouth, where recently discharged fresh water was found. In this area, chlorophyll *a* concentrations exceeded 3 mg·m^{-3} for Cruise N3, 4 mg·m^{-3} for Cruise N6, and 1 mg·m^{-3} for Cruise N9, for which distributions are not shown. East of the region of immediate influence by the Mississippi River discharge, chlorophyll *a* concentrations generally varied between 0.2 and 0.4 mg·m^{-3}. Exceptions are observed in regions into which riverine water had been advected as evidenced by relatively fresh water (surface $S < 32$ in Figs. 2–4). At some of those locations, chlorophyll *a* concentrations exceeded 1 mg·m^{-3} (e.g., near 29°N, 86–87°W on Cruise N3).

Does this uplifted water in the lower portion of the euphotic zone actually contribute to phytoplankton production over the NEGOM region? Unfortunately, vertical chlorophyll *a* data were not determined at all depths sampled during the NEGOM cruises. However, vertical distribution of fluorescence (measured by a Chelsea fluorometer) showed no significant increase in biological production in regions of uplift. This may be because uplift was occurring actively during the cruises and the local phytoplankton had not had time to reach equilibrium with the nutrients injected in this way.

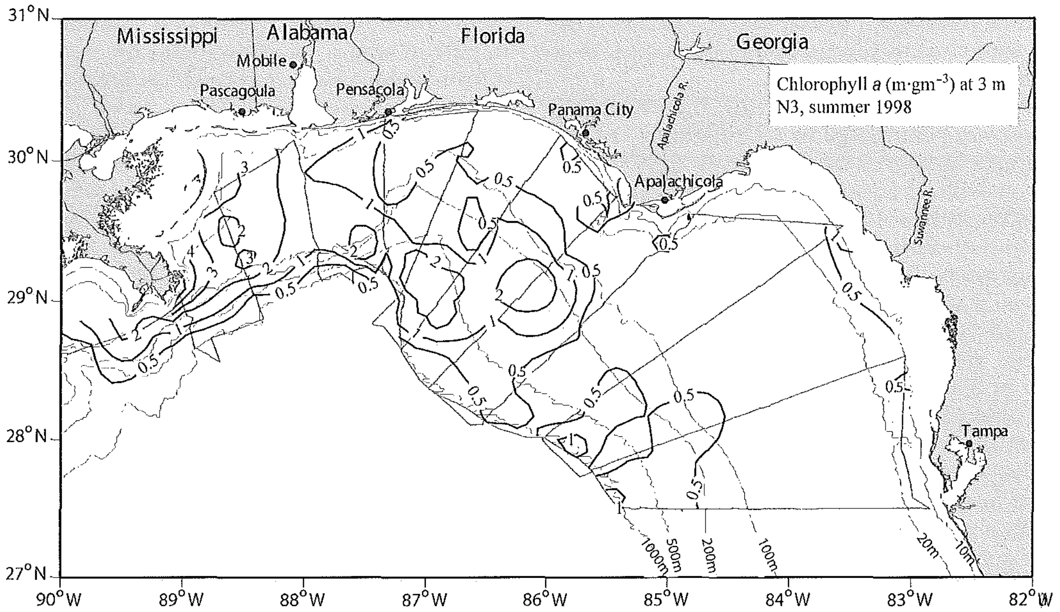

Fig. 14. Chlorophyll *a* (mg·m^{-3}) at approximately 3 m for Cruise N3. Chlorophyll *a* estimated from flow-through fluorometer measurements along track lines shown.

An example of regions where eddy-mediated shoaling of the pycnocline and the nutricline caused subsurface chlorophyll *a* maxima, are the Angulas Bank, south of Africa, and near Bermuda (Carter et al., 1987; McGillicuddy et al., 1999).

Principal Conclusions

This study showed that, contrary to the expectation that nutrient levels in the euphotic zone would be severely depleted by mid summer, measurable nutrient concentrations in near-surface waters were found in many areas over the outer shelf and slope of the northeastern Gulf of Mexico during the summers of 1998, 1999, and 2000. Two major physical processes were responsible for this input. First, Mississippi River discharge contributed nutrients to the upper 15 m of the water column. Eddies adjacent to the shelf played an important role in advecting this water as a shallow ribbon from near the mouth of the river along the outer shelf and slope eastward and southeastward. As a result, for the summers sampled, the expected offshore salinity gradient was reversed, with higher salinities close to the coast and lower salinities offshore. The lower salinity plume also supported elevated phytoplankton populations as compared to the rest of the shelf.

In addition, there was uplift of waters from below the euphotic zone by circulation features such as anticyclones and cyclones, or divergent flow at the peripheries of eddies. This led to shoaling of the pycnocline/nutricline, and resulted in the appearance of nutrient-rich water at shallow depths.

During the three summer cruises studied, uplift rather than riverine input was the major source of nutrients to the euphotic zone in that portion of the study area removed from the Mississippi Delta. However, it is unclear how much effect the uplifted nutrients had on the local primary production. Although there was continuous input from the river, this was far from uniform, and both the quantity of nutrients delivered by the river and the area affected would be expected to vary over relatively short time scales, depending partly on the local wind field. Close to the Mississippi Delta, river-borne nutrients allowed a substantial phytoplankton population to develop, but this production declined rapidly away from the delta. In contrast, uplift caused by circulation features was sporadic, and there may not have been enough seed population downstream of the delta to take advantage of the nutrients uplifted into the euphotic zone in this way.

Acknowledgments

These data were collected with support from the Minerals Management Service of the Department of the Interior (OCS contract 1435-

01-97-CT-30851). This study was supported in part by project R/ES-84 of Institutional Grant NA16RG1078 to Texas A&M University by the National Sea Grant Office, National Oceanic and Atmospheric Administration.

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Texas A&M University, Oceanography Department, Office 609, College Station, TX 77843-3146. Date accepted February 4, 2005.