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Worth D. Nowlin Jr.
*Texas A&M University*

Ann E. Jochens
*Texas A&M University*

Matthew K. Howard
*Texas A&M University*

Steven F. DiMarco
*Texas A&M University*

William W. Schroeder
*Dauphin Island Sea Lab*

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# Hydrographic Properties and Inferred Circulation Over the Northeastern Shelves of the Gulf of Mexico During Spring to Midsummer of 1998

WORTH D. NOWLIN, JR., ANN E. JOCHENS, MATTHEW K. HOWARD, STEVEN F. DIMARCO, AND WILLIAM W. SCHROEDER

**A hydrographic cruise was conducted 5–16 May 1998 over the northeastern shelves of the Gulf of Mexico. Observed distributions of temperature, salinity, oxygen, and nutrients were consonant with prior occurrences of upwelling, particularly near the head of DeSoto Canyon. Shipboard, moored, and satellite observations indicated these upwelling events were related to the presence of an anticyclonic circulation feature over the canyon. In addition, several cool water events occurred during spring in the nearshore region west of Pensacola; these may be attributed to atmospheric effects. High river discharges from rivers west of the Apalachicola during winter and spring likely resulted in the extensive surface distributions of low-salinity water observed from Mississippi Sound to Cape San Blas during the cruise. The combination of cool bottom temperatures and relatively low surface salinities over the inshore shelf west of Cape San Blas, with the usual seasonal warming, resulted in enhanced vertical stability. This stability likely inhibited vertical mixing and contributed to the development of the relatively low concentrations of dissolved oxygen observed in the bottom waters.**

In early May 1998, the onset of a coastal cool water event along the Florida panhandle was noted in advanced very high resolution radiometer satellite imagery (Muller-Karger, 2000). From mid-May into mid-July 1998, numerous instances of unusually cool bottom waters as well as mass mortalities of marine organisms were reported along the Florida panhandle coast west of Cape San Blas (Collard and Lugo-Fernández, 1999; Collard et al., 2000). In early June, the first report of an algal bloom off Panama City was made; by mid-July, such reports largely had ceased (Collard et al., 2000).

During 5–16 May 1998, Texas A&M University conducted a cruise sampling for physical and chemical oceanographic properties of the northeastern shelves of the Gulf of Mexico bounded by 89°W on the west and 27.5°N on the southeast. That cruise, which we refer to as N2, was the second of nine hydrographic surveys conducted during the Northeastern Gulf of Mexico Physical Oceanography Program: Chemical Oceanography and Hydrography Study sponsored by the Minerals Management Service.

Our primary goal is to describe the physical properties observed on cruise N2 in early May 1998. These include conditions of circulation, stratification, and distributions of properties related to the shelf ecosystem, such as salinity, nutrients, dissolved oxygen, and light transmission. As a second objective, we have examined time series of river discharge, wind, temperature, and currents that might provide clues as to how the observed conditions had developed, especially distributions of low-salinity surface waters and low bottom temperatures. Finally, these materials may help provide a framework for the observations of unusual temperatures, oxygen levels, and ecological disruptions that occurred during summer 1998.

Discussed in the next section, Background Observations, are time series of forcing functions for the period March–August 1998: winds, air and sea surface temperatures (SSTs), river discharge, and sea surface height anomaly (SSHA) corresponding to offshelf circulation features. The third section describes the pertinent in situ observations made during cruise N2, with a focus on nearshore and bottom properties. Time series of near-bottom temperature and currents made along the 100-m isobath also are discussed briefly in relation to the property distributions. A short summary concludes the paper.

## BACKGROUND OBSERVATIONS

Figure 1 shows the locations of conductivity-temperature-depth (CTD)/bottle stations occupied during cruise N2. Numbers are in sequence of occupation. Lines are referred to as 1–11 from west to southeast. Lines 4–11 were occupied in reverse order beginning with 11,

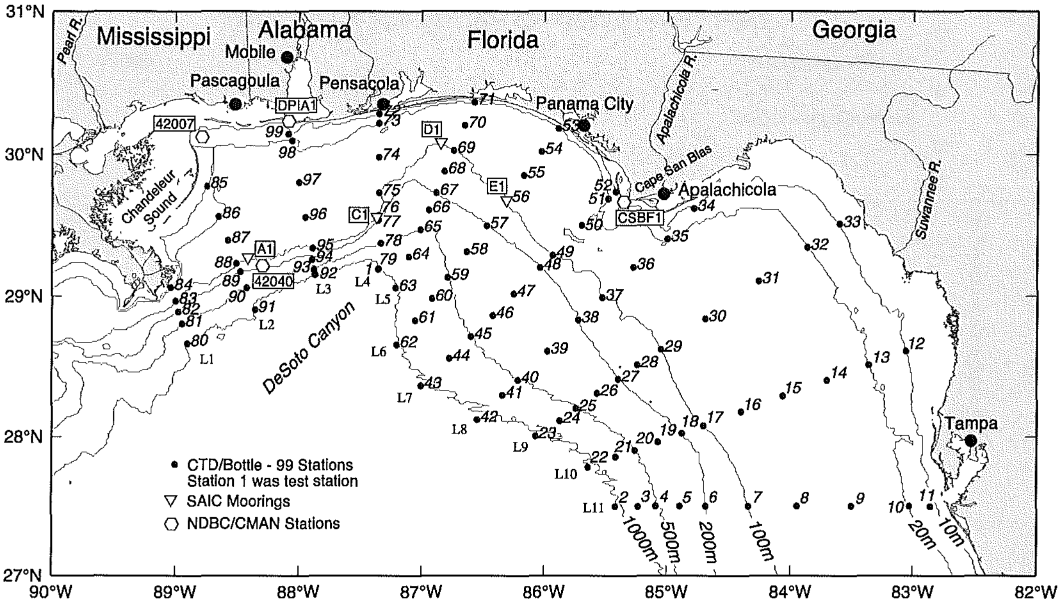

Fig. 1. Station numbers for CTD/bottle stations on cruise N2 conducted during 5–16 May 1998; locations of four Science Applications International Corporation (SAIC) moorings on 100-m isobath along the DeSoto Canyon; locations of two nearshore C-MAN meteorological stations; and the locations of two NDBC meteorological buoys. Station lines are labeled with L and number.

after which, lines 1–3 were occupied in that order.

Surface wind observations from 10 locations including coastal and offshore stations were examined for the period March–August 1998. For the region from about 89°W to Cape San Blas (CSBF1), there was fair to good spatial coherence of the wind field for this period, as demonstrated by Figure 2, which shows the alongshelf components of surface winds from four locations (shown in Fig. 1). There were several intervals of westerly winds, favorable for coastal upwelling and eastward nearshore currents, in this region during the March–May period. However, winds generally were easterly and weak, with average alongshore speeds of 1.2, 0.4, and 0.5 $m \cdot s^{-1}$ toward the west at 42007, DPIA1, and 42040 and 1.2 $m \cdot s^{-1}$ toward the east at CSBF1.

SST records from the National Data Buoy Center (NDBC) meteorological buoy 42007 and the Coastal-Marine Automated Network (C-MAN) meteorological station on Dauphin Island (DPIA1) are shown in Figure 3 (see Fig. 1 for locations). At both locations, there was the expected warming trend during spring. Superimposed on this seasonal trend are several periods of cooling of nearshore surface waters. Such events seem more pronounced off Dauphin Island than those farther westward and offshore at buoy 42007. Nevertheless, there is considerable agreement between variability in these two records, indicative of spatial coherence in temperature changes in the nearshore region. For the period January–August, the cross-correlations of SST between these two records were 0.99 for 40-hr low-passed and 0.45 for unfiltered hourly records; both are significant at the 95% confidence level.

In Figure 4, the alongshelf and cross-shelf components of surface wind and the SST are plotted for March–May 1998 from the meteorological station DPIA1. All records were 40-hr low-passed. To remove the seasonal warming trend, a cubic was fit to the SST record and removed, enabling better examination of wind event scale changes. For the period March into May, before cruise N2, cooling events are seen to be preceded by eastward alongshelf (upwelling favorable) wind events (shaded) and generally correspond with offshore wind components (shaded).

Differences between surface air and sea temperatures recorded on the NDBC/C-MAN stations were examined. For the nearshore locations 42007 and DPIA1 (not station 42040), surface air temperatures were considerably less than (1–3 C) SST at times of temperature dips. Correlations between SST and air temperature were positive and significant at the 95% confidence level with air temperature leading SST very slightly (about 1 hr) for maximum corre-

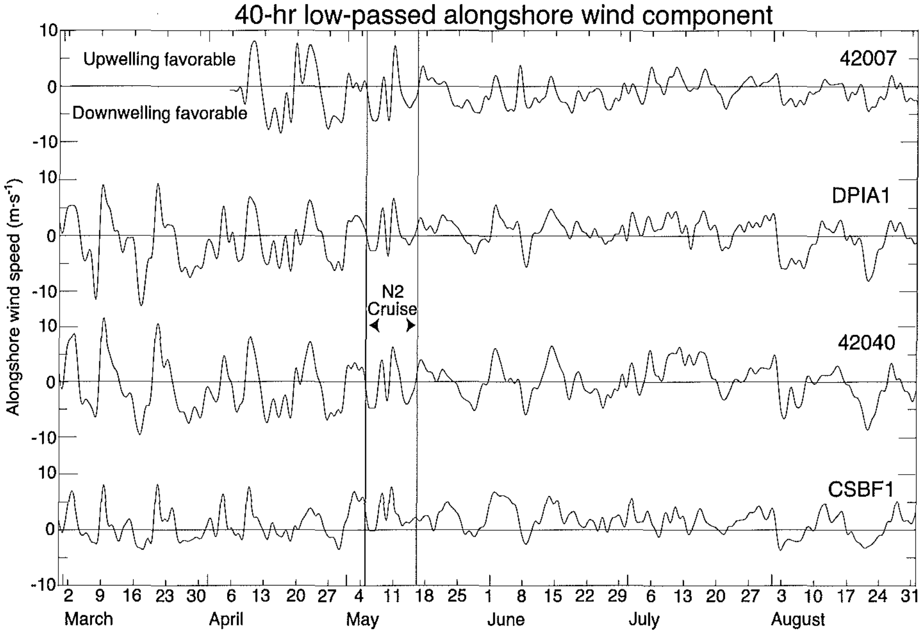

Fig. 2. Alongshelf wind components from four NDBC/C-MAN meteorological stations (see Fig. 1 for locations) during the period March–August 1998. Positive values are associated with generally westerly (eastward) components. The period of cruise N2 is indicated by vertical lines.

lation. We also examined correlations between surface air temperature and cross-shelf wind at the NDBC/C-MAN stations and found significant correlations between offshore wind component and decreasing air temperature. Our conclusion is that the short-term drops in surface air temperature superimposed on the spring warming trend were due to cooler air outflows from over land. They appear associated with eastward alongshelf winds as discussed in regard to Figure 4. Therefore, the cooler nearshore surface events may result from a combination of wind-induced coastal upwelling and sea-air heat exchange.

We obtained historical river discharge rates for the Mississippi River and the larger rivers eastward to the Suwannee River. For each, daily discharge rates were calculated on the basis of long-term records of daily discharge. Then we compared the daily mean discharge rates with the daily discharge rates for 1998. During winter 1998, discharge from all rivers in the region exceeded the long-term mean by significant amounts. In the spring, the Mississippi River continued to discharge at a rate well above its mean, whereas other rivers had flows below their means with the following exception: in late April, rivers from the Pearl to the Apalachicola exhibited a brief pulse of much greater than average discharge—in some cases, significantly exceeding the mean plus 1 standard deviation. This pattern is illustrated in Figure 5, which shows daily discharge rates for the Tombigbee River, which empties into Mobile Bay—long-term mean and standard deviation are based on a 70-yr record. Major rivers examined east of Cape San Blas generally had only one episode during the first half of 1998 (in March) of very high discharge relative to the mean. Greater than average river discharge into the Gulf from Mississippi Delta to Cape San Blas during early 1998 is consistent with the extensive surface expression of low-salinity water observed during cruise N2 in May 1998. However, because we have no reliable estimates of residence time for water over the shelf west of Cape San Blas, we cannot ignore the possibility that the observed lower salinity waters resulted from weaker, but more recent, river discharge than that observed earlier in 1998.

We have observed that cyclonic and anticyclonic eddies in deep water near the shelf have profound influence on the outer shelf circulation in the northeastern Gulf. Therefore, we examined the temporal development of these features through the evolution of SSHA offshore of the 200-m isobath in the northeastern Gulf of Mexico with a product prepared by Robert Leben (University of Colorado) based on a combination of altimeter data from TOPEX/POSEIDON and ERS-2 (Biggs et al.,

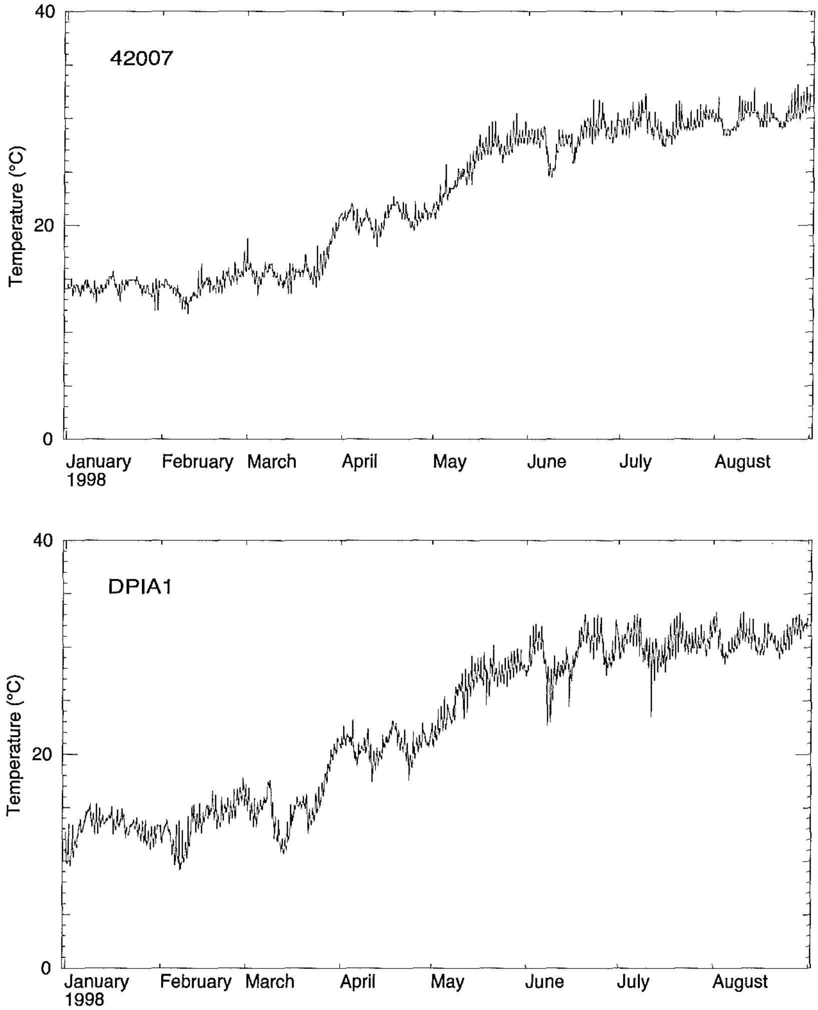

Fig. 3. Time series of sea surface temperature from NDBC meteorological buoy 42007 (top) and C-MAN station (DPIA1) on the east end of Dauphin Island (bottom) (see Fig. 1 for locations).

1996). We looked at one SSHA field per week beginning 1 April 1998 and continuing through August 1998. These SSHA distributions are from data sets that were temporally and spatially smoothed with decorrelation scales of 12 d and 100 km, respectively. Therefore, features may appear weaker than they were, and smaller scale features may have been removed.

On 1 April most of the area with water depths greater than 200 m was under cyclonic flow except for one small anticyclone over DeSoto Canyon. A strong extension of a large anticyclone centered at 25.5°N, 88°W extended toward the shelf break west-southwest of Tampa. By 8 April, the extension off Tampa had reached the 200-m isobath (as seen in Fig. 6 on 15 April), and, after separation of a weak anticyclone near the shelf edge, it subsequently withdrew offshore. Just prior to the beginning of cruise N2 on 5 May 1998, two anticyclonic features were seen impinging on the shelf edge in the region of DeSoto Canyon and southwest of Tampa. Shortly thereafter these two features extended toward one another, coalesced, and strengthened. The situation during cruise N2 on 13 May is shown in Figure 6.

By 1 July, this feature had strengthened to a height anomaly of more than 20 cm and assumed an east-west orientation. Soon after, connections began to form with the larger anticyclonic feature to the south as seen on 15 July in Figure 6. The anticyclone again separated and shrunk, but by late August (Fig. 6), the feature had renewed a connection with an anticyclone to the southwest and was oriented

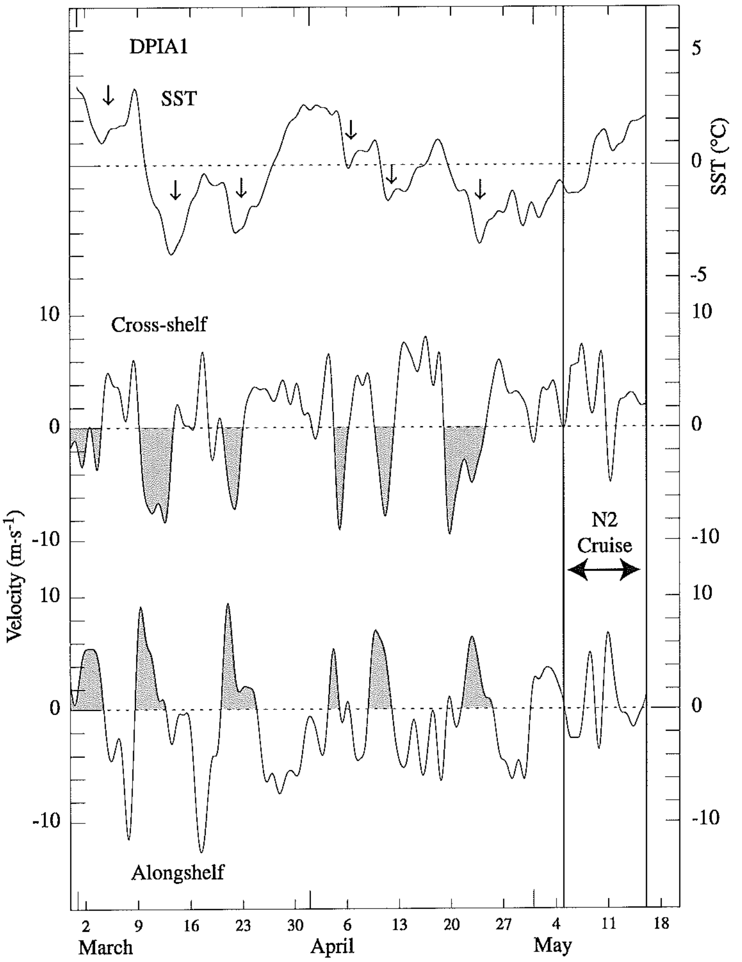

Fig. 4. Sea surface temperature and alongshelf and cross-shelf components of 10-m wind observed at C-MAN station (DPIA1) on the east end of Dauphin Island. All series were 40-hr low passed. A cubic fit was removed from the sea surface temperature record.

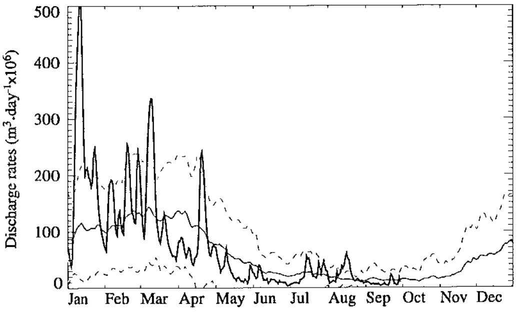

Fig. 5. Daily discharge rates for the Tombigbee River at Demopolis, AL, for 1998 (bold). Also shown are 70-yr mean daily discharge rates with 1 standard deviation (dashed).

over the axis of the DeSoto Canyon with considerable strength.

## OBSERVED PROPERTIES AND INFERRED CIRCULATION DURING EARLY MAY 1998

The distribution of geopotential anomaly for the sea surface (3 m) relative to 800 m is shown in Figure 7. To estimate geopotential anomaly values at stations shallower than 800 m, we first calculated geopotential anomaly relative to 800 db for an offshore station deeper than 800 m. Then, following the method of Montgomery (1941), we used extrapolated specific volume anomaly values along the bottom to obtain contributions of geopotential anomaly to the deepest sample depth of successively shallower stations. The implications of this method were discussed by Csanady (1981).

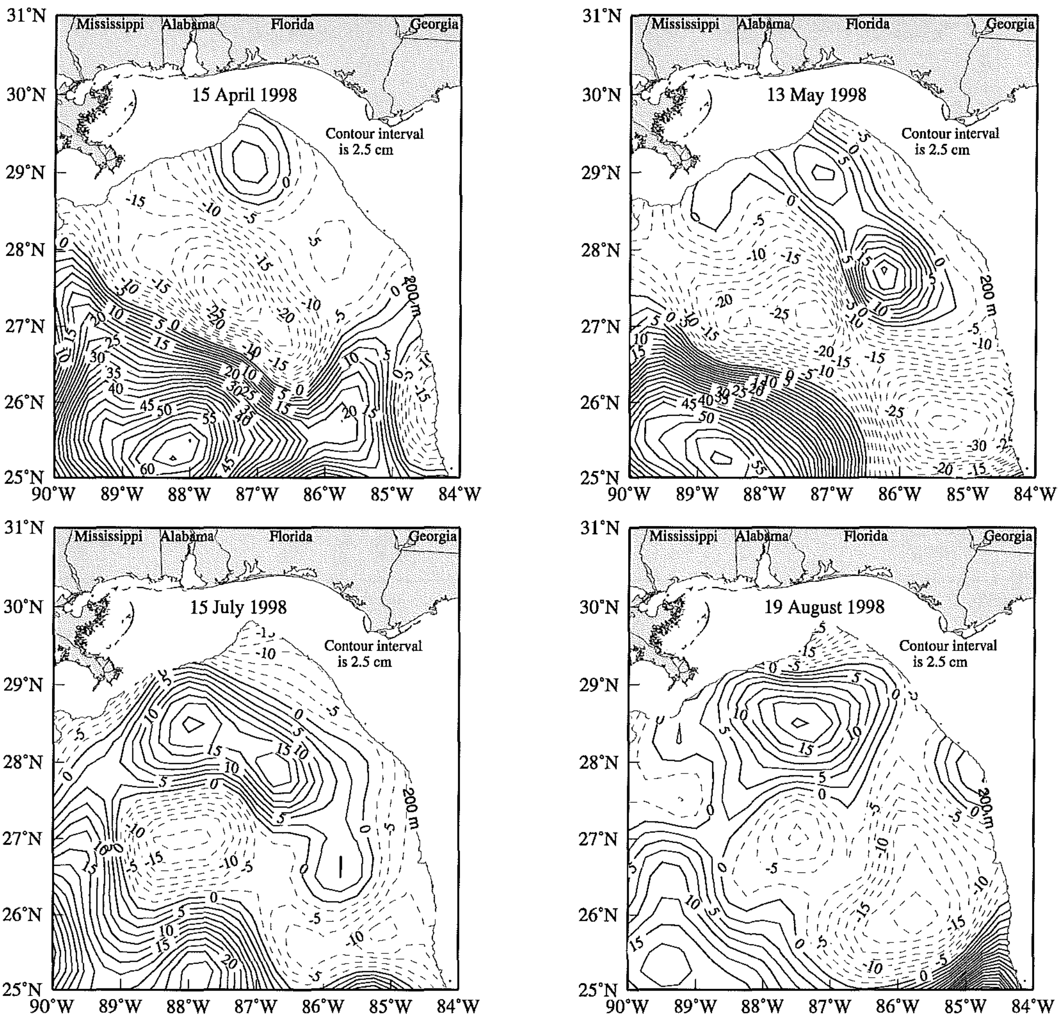

Fig. 6. Sea surface height anomaly fields from satellite altimeter data for 15 April, 13 May, 15 July, and 19 August 1998 (data courtesy of Robert Leben, University of Colorado).

To the extent that the bottom potential density is not uniform along isobaths, the estimation will not be independent of path of integration and caution is advised in interpreting results.

Figure 7 shows an anticyclonic feature over the DeSoto Canyon and a second anticyclone encroaching over the outer shelf edge west of Tampa. The circulation indicated by these features is corroborated by shipboard acoustic Doppler current profiler (ADCP) measurements taken along the cruise track and also shown in Figure 7. The gridded ADCP vector field at 50 m is representative of other levels as well. An anticyclonic feature is seen located over the upper canyon (centered near 29°N, 87°W). There is evidence for along-isobath flow along the northern reaches of the canyon and cross-isobath flow directed inshore on the west side of the anticyclone and near the canyon axis. Such flow will lead to transport in a bottom Ekman layer that is to the left of the flow—leading to more penetration of bottom waters toward shallower depths. Upwelling is indicated by the bottom distribution of temperature (Fig. 8) showing maximum inshore penetration of cool bottom water near the head of DeSoto Canyon (line 5). The spread of cool water onto the shelf is clearly seen by noting the area covered between the 18 C and 19 C isotherms at the bottom. Waters offshore of Alabama are warmer by as much as 2–3 C than those off western Florida.

Vertical sections of hydrographic properties provide clear evidence that onshore near-bottom flow, extending in most cases to the innermost stations (10-m isobath), had occurred

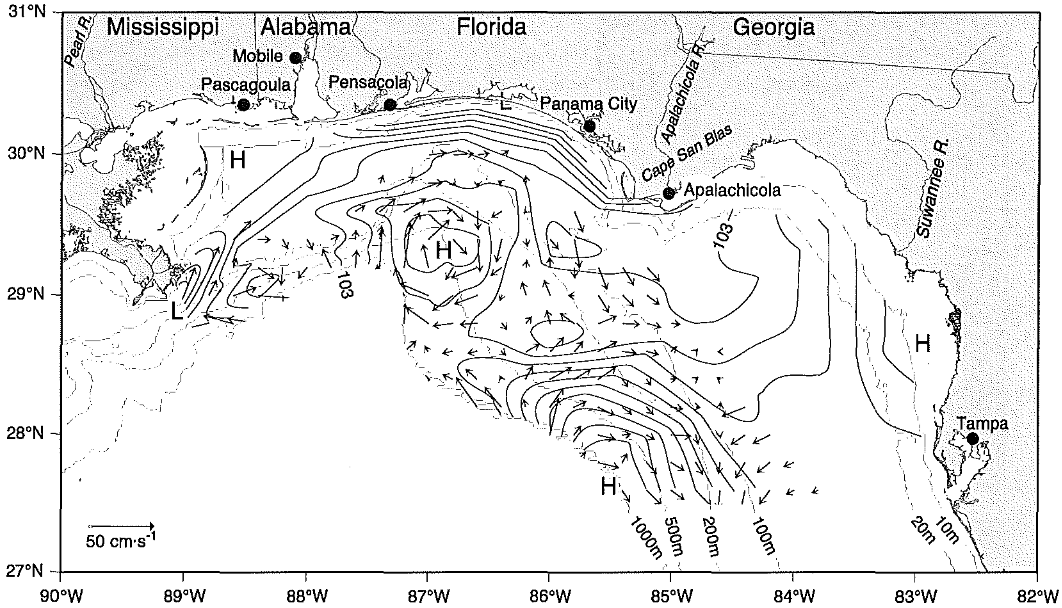

Fig. 7. Gridded shipboard ADCP vectors at 50 m plotted on contours of geopotential anomaly of 3-m surface relative to 800 m. The scale for ADCP speeds is shown. The geopotential anomaly contour interval is 1 dyn cm; the 103 dyn cm contour is indicated. Data from cruise N2, 5–16 May 1998.

prior to cruise N2. Figure 9 (top) shows temperature in vertical section on line 5. This is characteristic of the situation observed on lines 1–7 west of Cape San Blas. Apparently, upwelling had been strong prior to the time of the cruise as evidenced by cooler (18–19 C) water at the bottom at the innermost stations. Southeast of Cape San Blas (lines 8–11), this onshore movement generally did not extend to the shallowest stations, as can be seen from the distribution of bottom temperature (Fig. 8).

In search of upwelling events prior to cruise N2 and during the summer of 1998, we examined time series of temperatures and cur-

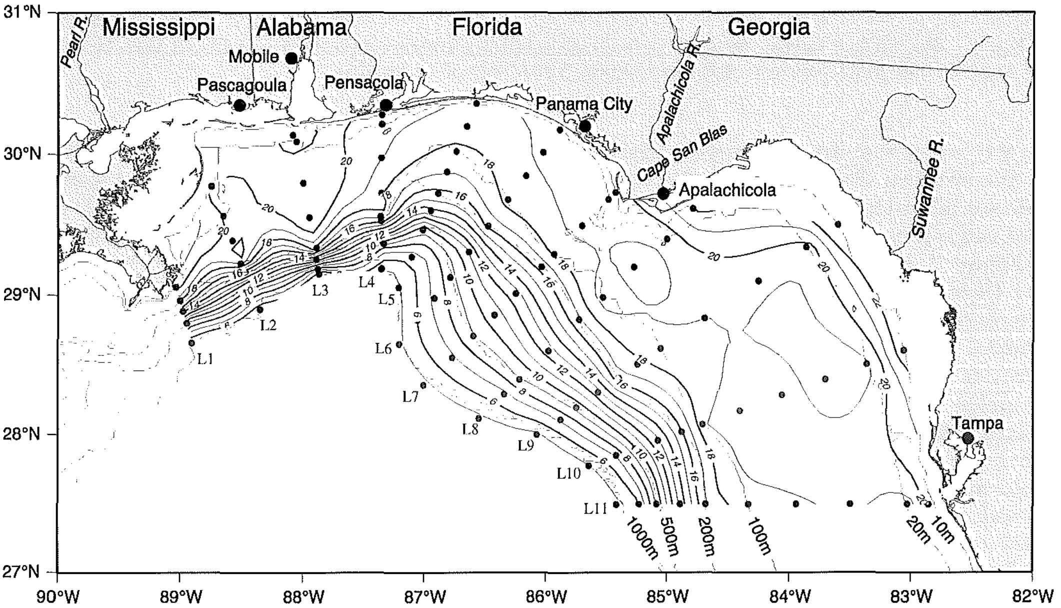

Fig. 8. Potential temperature (C) near the bottom on cruise N2, 5–16 May 1998.

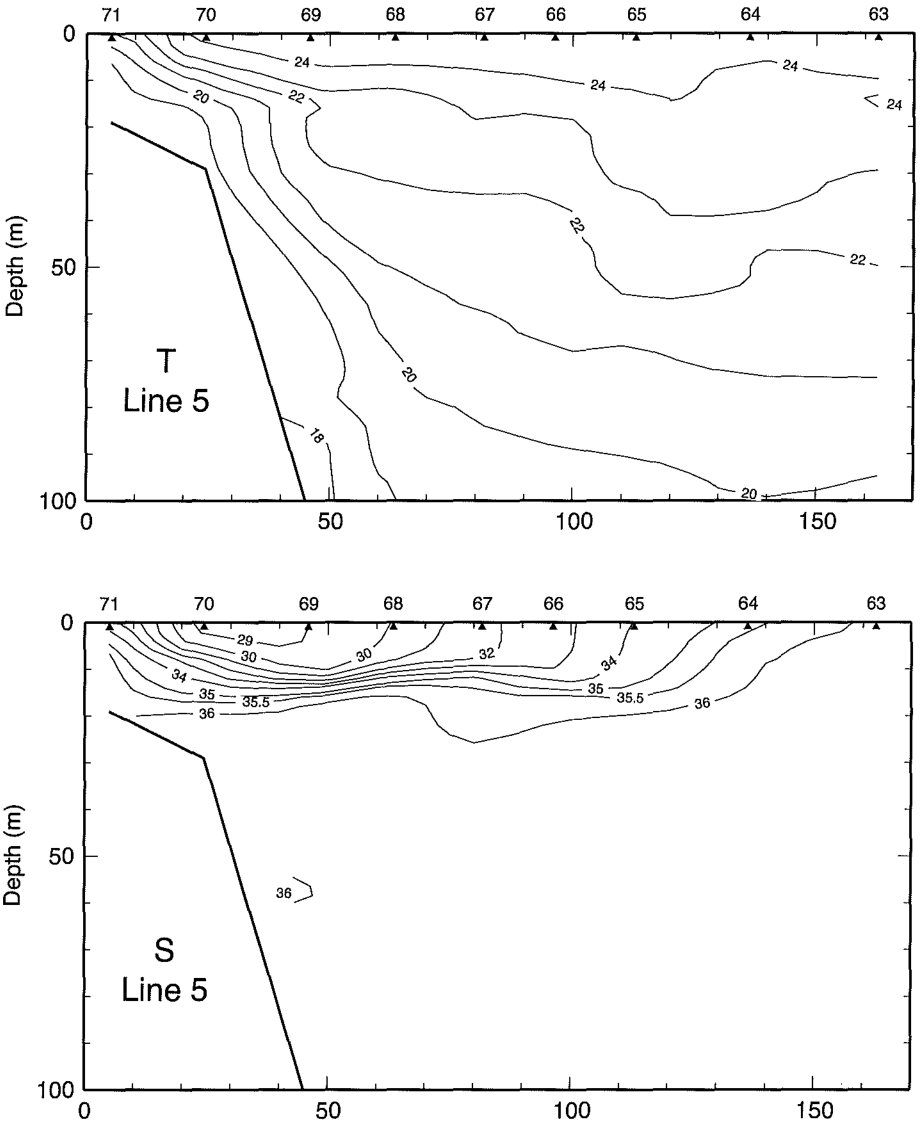

Fig. 9. Potential temperature (C) (top) and salinity (bottom) on line 5 of cruise N2, 5–16 May 1998.

rents from moorings set and recovered by Science Applications International Corporation (1998) in the DeSoto Canyon from early April to early August 1998 (Fig. 10). We focused on near-bottom temperature observations from four moorings located along the 100-m isobath: A1, C1, D1, and E1 (see Fig. 1 for locations). Two pulses with temperatures lower by several degrees than before or afterward were recorded in mid- and late April at C1, D1, and E1. During two periods in April, pulses of cool water occurred at mooring locations C1 and D1 at approximately the same time. These cool water pulses appeared at E1, at the head of DeSoto Canyon, about 10 d later. These intrusions likely set the stage for the cool bottom water observed over the outer west Florida shelf during cruise N2. This cool water penetration near the bottom over the 100-m isobath was not seen at mooring A1. Examination of Figure 10 shows that at the near-bottom instruments on moorings C1, D1, and E1 cool pulses were usually associated with flows directed eastward of north, i.e., toward the head of the canyon and toward shallower depths.

A cooling trend in all four bottom records along the 100-m isobath began in late June and continued until mid-July. Again, the cool-

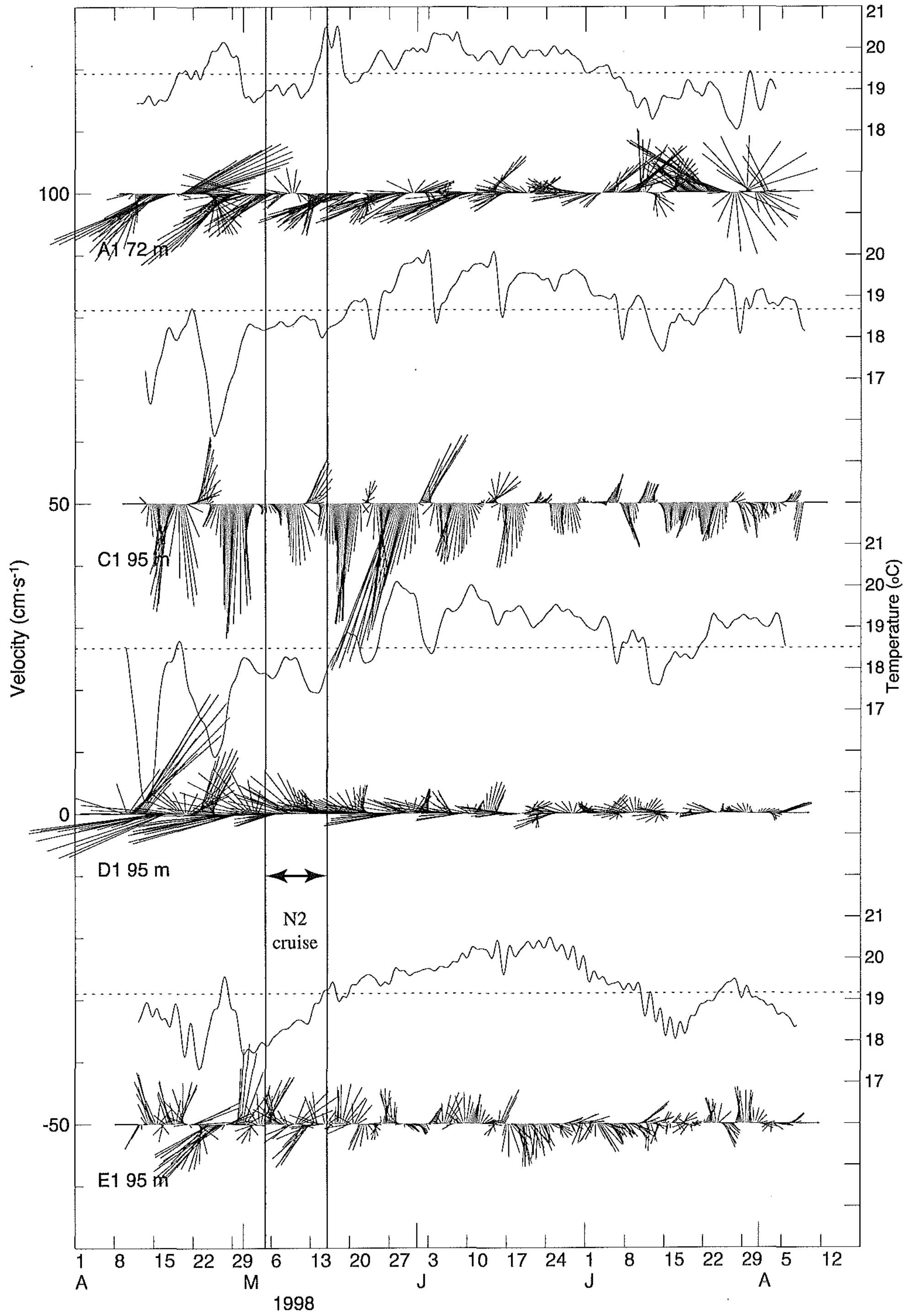

Fig. 10. Time series of 40-hr low-passed temperature and velocity stick plots (north is up) at near-bottom instrument positions (depths shown) on moorings A1, C1, D1, and E1 for April–August 1998. Locations are shown in Figure 1; nominal water depths were 100 m at each mooring location. The dashed lines represents the mean value of each temperature series.

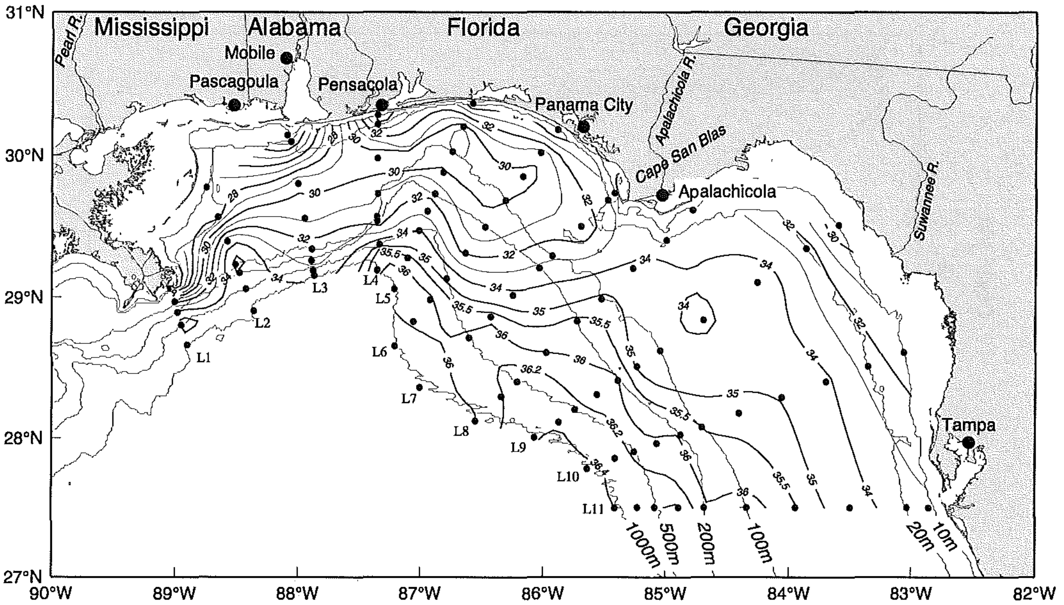

Fig. 11. Salinity at 3.5 m derived from CTD data collected on cruise N2, 5–16 May 1998.

est water seen at each location seemed to occur sequentially in time; its presence was found at D1 about 10 d before E1. Then, after a warming trend until about the end of July, bottom temperatures at moorings C1, D1, and E1 again cooled to the end of the record in early August. The temperature dips superimposed on these trends are not as dramatic as those during the earlier records and are not so generally associated with northeastward current events. The assumption is that these shelf break cooling events may be associated with eddies over the canyon, as was the case during cruise N2.

The high vertical stability associated with the temperature distribution is enhanced west of Cape San Blas by a layer of relatively low salinity surface water. On lines 4–7, the lowest salinity surface waters were found in a longshore lens some 50 km offshore near the 100-m isobath; Figure 9 (bottom) shows the vertical distribution of salinity on line 5. This could have been caused by nearshore upwelling moving surface water offshore, by advection from the west due to the anticyclonic circulation over DeSoto Canyon, or by a combination of both. The extent, core, and possible source of the low-salinity water lens may be deduced from the surface (3.5 m) salinity distribution shown in Figure 11. On lines 1–3, the surface water with lowest values was observed at the inshore stations—evidence of local river sources for this water. Also, east of Cape San Blas, the freshest water was found in the surface layers at the inshore stations.

The combination of cool bottom water, seasonal warming of surface waters, and a lens of lower salinity surface water produced a very strong pycnocline over the inner and mid-shelf regions. West of Cape San Blas, the pycnocline was much stronger than to the east; compare the distribution for line 3 with that for line 9 (Fig. 12). It is likely that this stability would have inhibited vertical mixing, leading to the relatively low oxygen values found at the bottom over much of the survey region (Fig. 13). Such stratification (because of low-salinity surface waters and seasonal heating), lack of mixing, and enhanced primary production is well known to lead to hypoxia or near-hypoxic conditions on the Louisiana shelf (Wiseman et al., 1997; Nowlin et al., 1998). During cruise N2, many bottom dissolved oxygen values were near 3 ml·l$^{-1}$, and values approached 2 ml·l$^{-1}$ near Chandeleur Sound. Dissolved oxygen values at the bottom were not particularly low east of Cape San Blas, which could have resulted because of the difference in stratification in the two regions—stronger pycnoclines were observed west of Cape San Blas. The band of relatively low bottom dissolved oxygen seen centered around the 500-m isobath reflects the intersection of the core of Tropical Atlantic Central Water with the bottom.

Percentage of light transmission at the

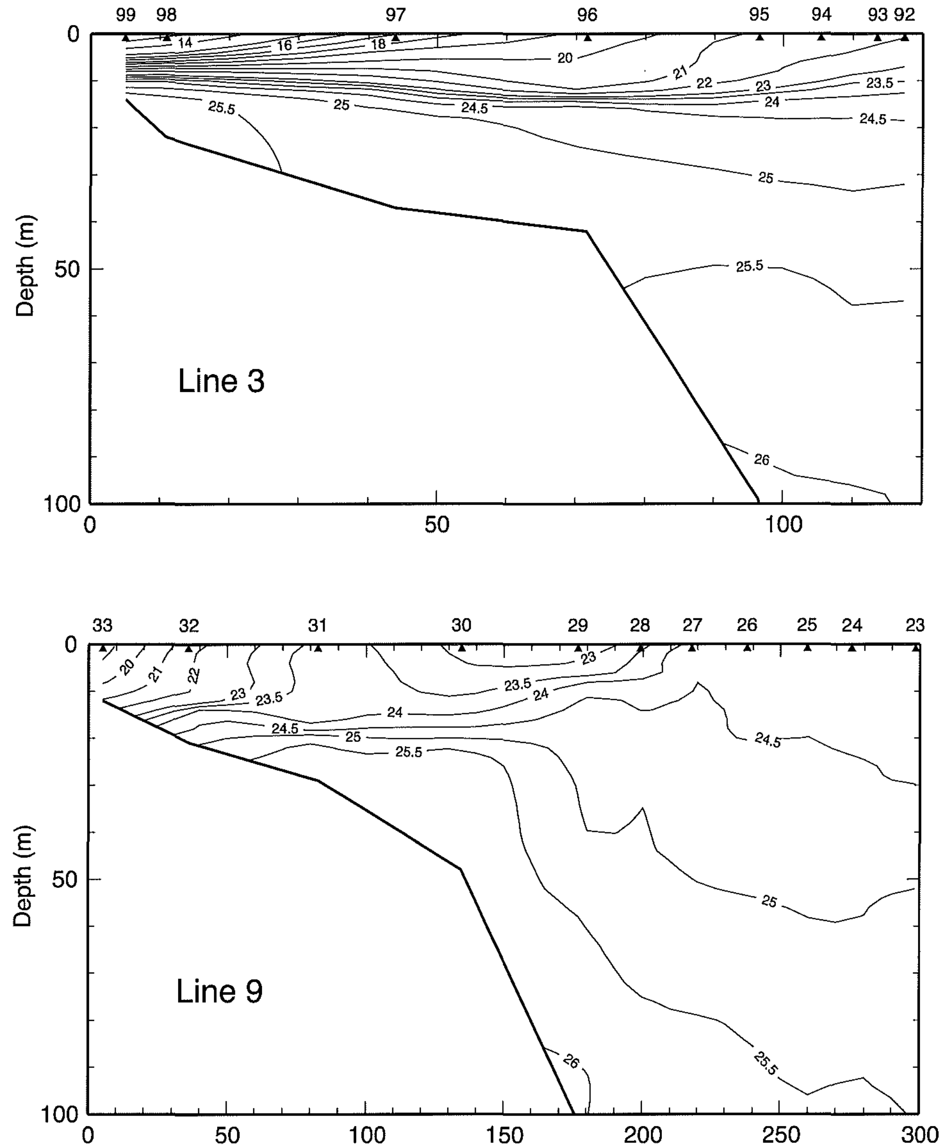

Fig. 12. Density anomaly ($\sigma$ in $kg \cdot m^{-3}$) on lines 3 and 9 on cruise N2, 5–16 May 1998.

660-nm wavelength observed during cruise N2 on lines 4–11 (see Fig. 1 for locations) generally ranged from at least 80% to greater than 90% at all depths, with higher values occurring beneath the surface layer and in water depths greater than 50 m. The exception was on line 8, where values less than 80% were observed at the bottom inside the 30-m isobath. These high transmission values in the cool bottom waters nearshore give further evidence that these are upwelled offshore waters. By contrast, toward Chandeleur Sound on lines 1–3, light transmission decreased inshore and to the west to levels less than 60% on line 3 and to 10% on line 1. This might be expected for waters greatly influenced by river discharge.

The 3.5-m distribution of nitrate (Fig. 14, top) clearly shows the high nutrient loading associated with the relatively fresh surface waters (Fig. 11) associated with river discharge. The distributions of silicate (Fig. 15, top) and phosphate (not shown) at 3.5 m show good correspondence with that for nitrate.

Bottom nutrient distributions observed on

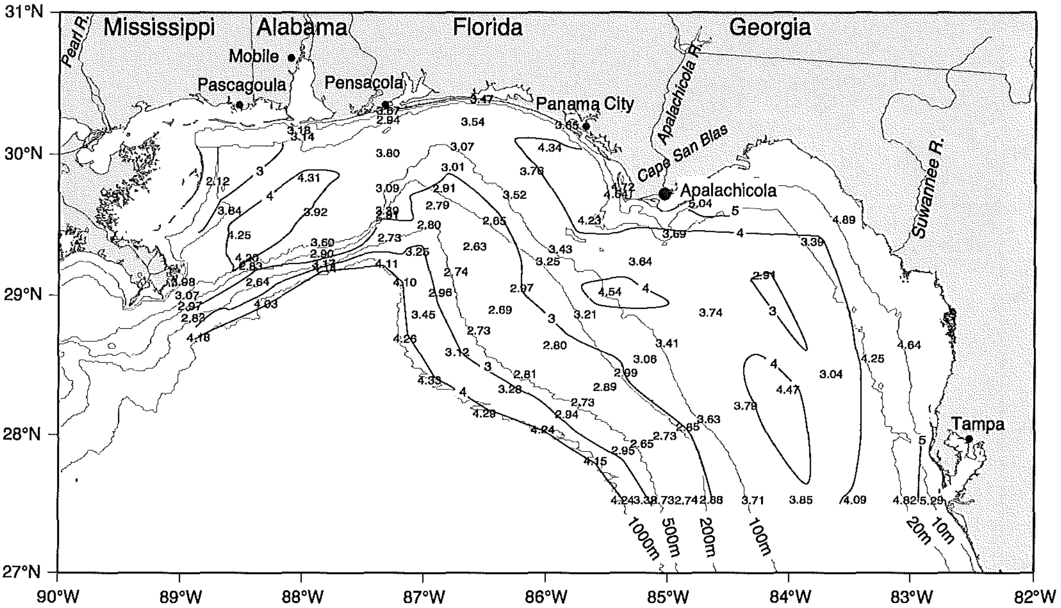

Fig. 13. Dissolved oxygen ($ml \cdot l^{-1}$) near the bottom on cruise N2, 5–16 May 1998.

cruise N2 over the mid- and inner shelf appear elevated at locations corresponding to the cooler upwelled waters. As an example, higher nitrate values at the bottom (Fig. 14, bottom) correspond well with cooler bottom waters (Fig. 8). The bottom distribution shows the effects of onshore movement of nutrient-rich bottom waters and may be compared with bottom oxygen distributions shown in Figure 13; lower values of dissolved oxygen correspond with higher values of nitrate. In general, distributions of phosphate and silicate mirror those of nitrate with the notable exception that quite elevated silicate values were observed at the bottom, as well as near surface, in the inshore, westernmost portion of the region (Fig. 15). Such high values are not unexpected, because quite high dissolved silicon is associated with low-salinity river waters in general and the Mississippi in particular (Liss, 1976), and the inshore waters of the westernmost portion of the study area were characterized by low-salinity river waters during cruise N2.

## CONCLUDING REMARKS

Observed property distributions on cruise N2 in early May 1998 were consonant with prior occurrences of upwelling across the inner shelf; this was most pronounced near the head of DeSoto Canyon from Pensacola to Panama City, FL. We attribute this to the presence of an anticyclonic circulation feature over the canyon as seen in sea surface height anomaly from satellite altimetry, shipboard ADCP measurements, and geopotential anomaly patterns. Several cold events evidenced prior to the cruise in temperature time series near bottom at the 100-m isobath lend support to this supposition.

Sea surface temperatures recorded quite nearshore west of Pensacola show several cooling events superimposed on the seasonal spring warming. There is generally good visual correlation between these cooling events and prior occurrence of eastward alongshelf (upwelling favorable) wind events recorded at the same stations. However, there also is good agreement between cool surface water events, leading to the possibility that the offshore passage of cooler air may have contributed to the cool surface water events. Thus, very nearshore cool events may be attributed to wind effects.

Discharges from all rivers in the region were above long-term means during winter (January–March) 1998. That pattern continued for the Mississippi River during spring. Other river discharges were below long-term means for the spring except that rivers from the Pearl to the Apalachicola had very high discharge rates in late April. These records are consistent with the extensive surface distributions of low-salinity water observed from

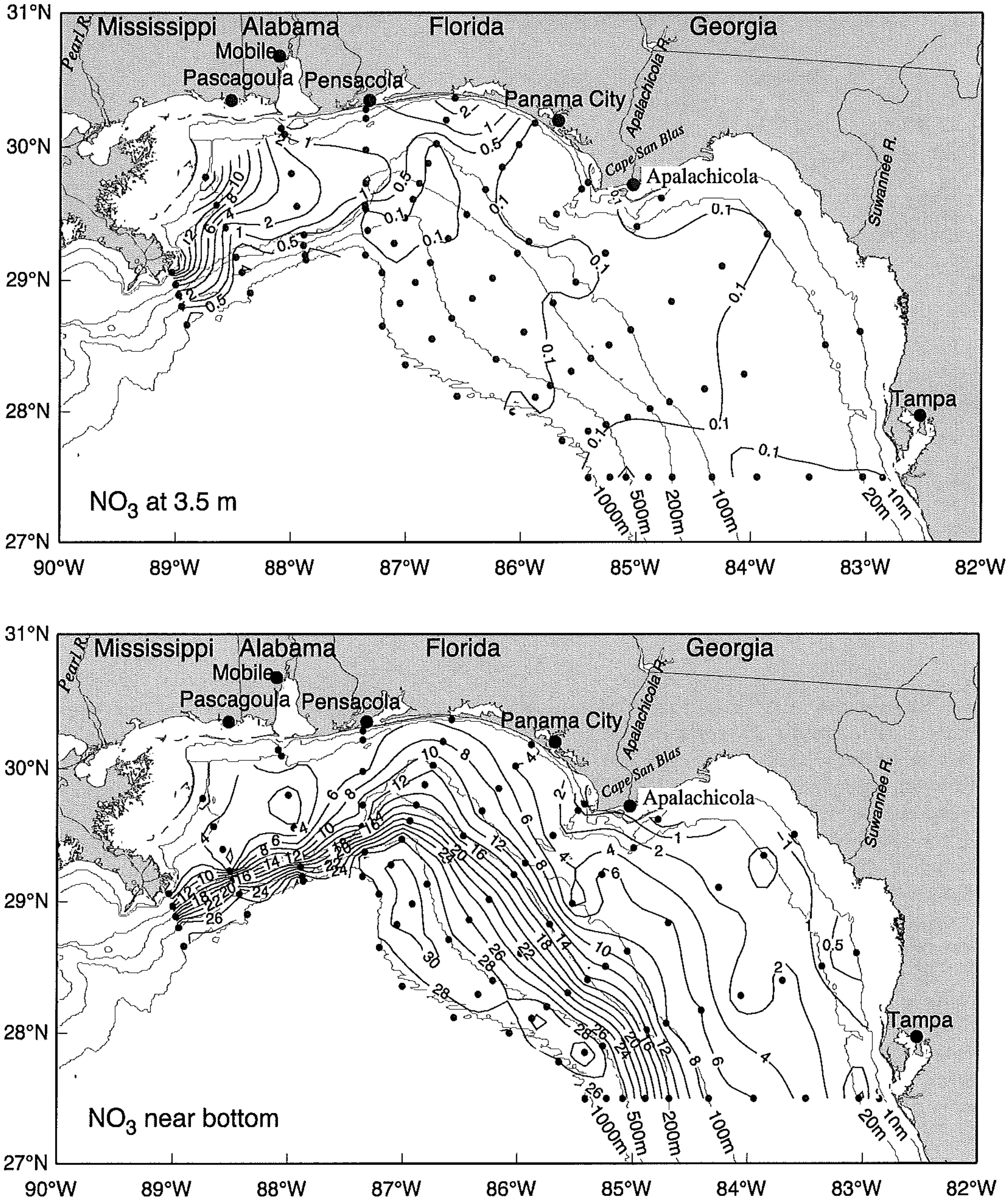

Fig. 14. Nitrate (μM) at 3.5 m (top) and near the bottom (bottom) on cruise N2, 5–16 May 1998.

Mississippi Sound to Cape San Blas during cruise N2 in May 1998.

The combination of cooler bottom temperatures and lower surface salinities over the inshore portions of the shelf west of Cape San Blas along with usual seasonal warming resulted in enhanced vertical stability. At the time of cruise N2, bottom values of dissolved oxygen were relatively low (2–4 ml·liter$^{-1}$) over the inner shelf west of Cape San Blas. This condition could have worsened to produce the biological effects seen (see Collard and Lugo-Fernández, 1999).

## ACKNOWLEDGMENTS

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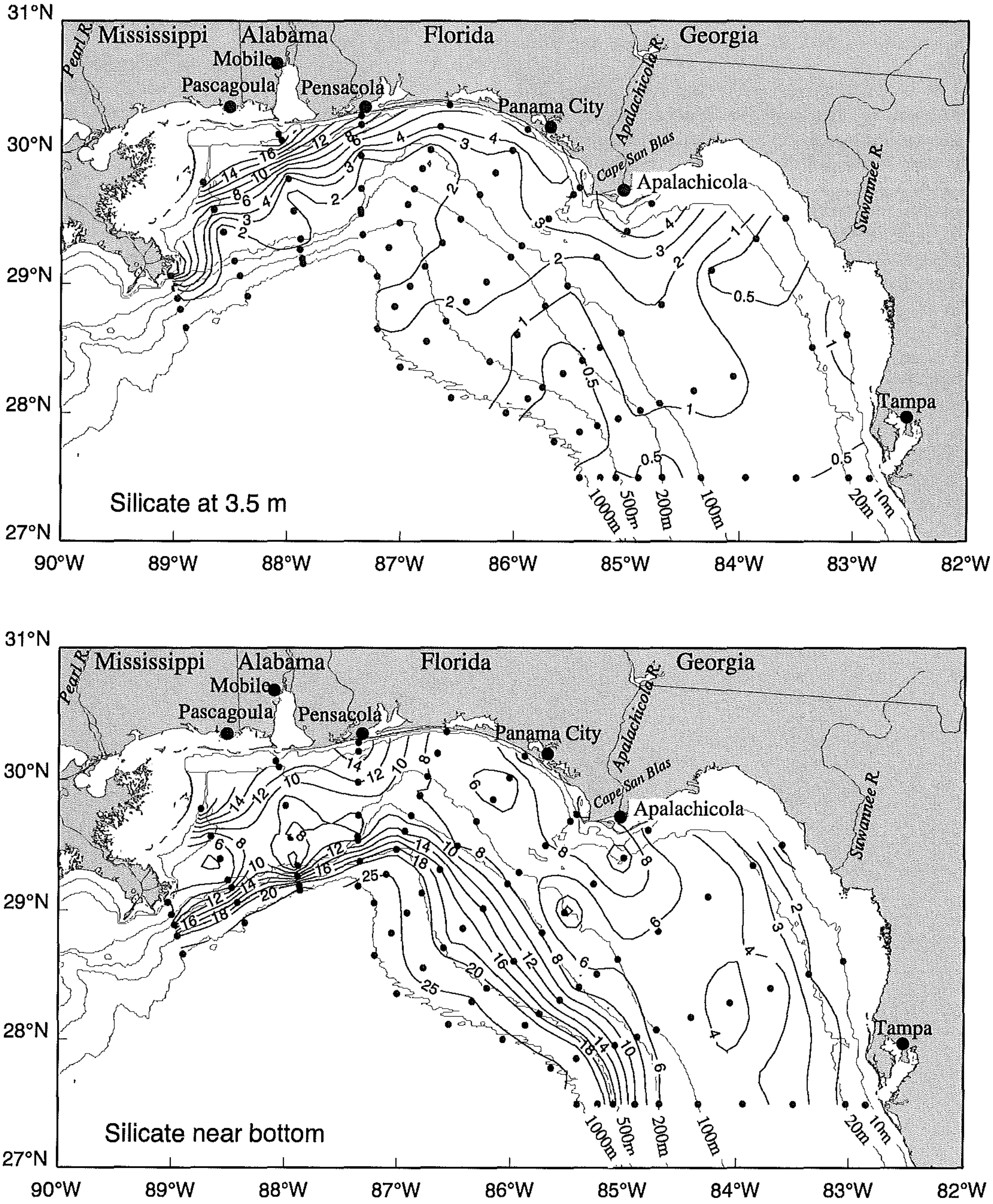

Fig. 15. Silicate (μM) at 3.5 m (top) and near the bottom (bottom) on cruise N2, 5–16 May 1998.

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(WDN, AEJ, MKH, SFD) DEPARTMENT OF OCEANOGRAPHY, TEXAS A&M UNIVERSITY, COLLEGE STATION, TEXAS 77843-3146; AND (WWS) MARINE SCIENCE PROGRAM, THE UNIVERSITY OF ALABAMA, DAUPHIN ISLAND SEA LAB, 101 BIENVILLE BLVD., DAUPHIN ISLAND, ALABAMA 36528. Date accepted: May 12, 2000.