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The Spring 1998 Northeastern Gulf of Mexico (NEGOM) Cold Water Event: Remote Sensing Evidence for Upwelling and for Eastward Advection of Mississippi Water (or: How an Errant Loop Current Anticyclone Took the NEGOM for a Spin)

FRANK E. MULLER-KARGER

Temperatures of coastal waters along the Florida Panhandle in the northeastern Gulf of Mexico were 2–6 C lower in May–July 1998 than is normal for these waters at this time of the year. Surface temperatures were up to 7 C colder than air temperatures measured nearby off Alabama at National Data Buoy Center (NDBC) buoy 42007. Satellite data from the Advanced Very High Resolution Radiometer, Sea-viewing Wide-Field-of-View Sensor, the Ocean Topography Experiment, and European Remote-sensing Satellites altimeter sensors were combined with wind, air temperature, and water temperature data gathered at NDBC buoys to document the anomalous wind, temperature, and river plume dispersal patterns. The difference between the water and air temperatures suggests that upwelling caused the cooling of coastal waters. Eastward, upwelling-favorable winds stronger than $3 \text{ m}\cdot\text{s}^{-1}$ occurred along the Alabama coast up to 32% of the time between May and August 1998 compared with only about 20–26% during the same months in 1996, 1997, and 1999. The altimeter data suggested that a large anticyclonic eddy migrated far into the northeastern Gulf of Mexico, interacting with shelf waters through August 1998. Upwelling was probably enhanced by the presence of baroclinic structure associated with the eddy. The eddy contributed also to convergence near the Mississippi River Delta, eastward flow along the coast, and offshore flow in the region between Fort Walton Beach and Cape San Blas, FL. The region experienced anomalously high river discharge during this period as a result of increased precipitation over northern Florida (a teleconnection to El Niño of 1997–1998), and further, turbid Mississippi River water dispersed eastward along the coast. Decay of local phytoplankton blooms off northern Florida in late June and early July 1998 probably followed after eastward winds relaxed, westward winds increased, and low-salinity waters led to vertical stability in the water column, possibly leading to hypoxia along these shores.

In May 1998, the Remote Sensing Lab of the University of South Florida distributed a series of satellite images to various researchers involved in a Minerals Management Service program designed to study the northeastern Gulf of Mexico (NEGOM), alerting them of a strong upwelling event along the coast of the Florida Panhandle. By June and July 1998, alarming reports appeared in the local press of “strange” water and “unusual” conditions along the northeastern shores of the Gulf of Mexico between Pensacola and Panama City, FL (Fig. 1). Fishermen and the public reported massive fish kills and green or brown water filled with flocculates. News articles cited bottom-dwelling crab, shrimp, and small flounder swimming on top at the surface and massive amounts of shellfish delivering spat. These reports also announced the sudden arrival of cold water at the shore, with one account sug-

gesting a 9 C drop in temperature in about 24 hr. The National Marine Fisheries Service reported low oxygen concentrations in waters at the inlet to St. Andrew Bay by Panama City (Collard et al., 2000), but the media reports led to the conclusion that hypoxia was widespread. These anecdotal accounts linked fish kills to cold, low-oxygen, low-salinity, and discolored water spreading along the coast. Unfortunately, it was not possible to coordinate resources fast enough to conduct detailed scientific ship surveys of the event. To date there are no reports of data that could help assess the extent of this inferred hypoxia. The local press from Louisiana to central Florida covered the event through the end of July 1998, and scientific and government institutions were called upon to explain the mysterious anomaly.

It is hard to decipher what really happened

Fig. 1. Coastal zone of the NEGOM, encompassing the area between 26 and 31.5°N and 82 and 90°W. Squares show the stations from which SST time series were constructed with the AVHRR images (positions shown in Table 1). The filled circles show the location of NDBC meteorological buoys 42040 and 42007, which provided wind, air temperature, and water temperature observations.

in the NEGOM during May, June, and July 1998 with the information available from news reports. The information in the various reports does not seem to add up. For example, how abnormal are cold temperatures along the NEGOM coastline? Why would cold water have low salinity, be discolored, and have low dissolved oxygen? Were the cold water temperatures due to sensible heat loss during a cold air spell or to wind-driven coastal upwelling? Is it possible that both river water and upwelling affected the coast at about the same time? This study sheds some light on these events and helps separate fact from fiction.

During the spring and summer 1998, various oceanographic satellites collected data over the affected area. Here, these data are used to 1) assess the magnitude of the temperature anomaly observed along the NEGOM coast, 2) trace the source of the discolored water, and 3) evaluate the possibility of recurrence of the cold water and low oxygen phenomena.

METHODS

To conduct this study, three primary satellite data sets were used. Sea surface temperature (SST) was derived from infrared (IR) observations collected by the Advanced Very High Resolution Radiometer (AVHRR) sensors flown on the National Oceanic and Atmo-

spheric Administration's (NOAA's) polar orbiting satellite series. A total of 4,077 AVHRR images, collected over the NEGOM between September 1993 and July 1999, were used. Data were collected with the high resolution picture transmission antenna located at the University of South Florida, St. Petersburg, FL (<http://paria.marine.usf.edu>). All passes from all satellites were combined to build the time series (nighttime and daytime passes from the NOAA 11–14 satellites). SST was computed with the multichannel sea surface temperature algorithm developed by McClain et al. (1985). The approximate root mean square (rms) error of the AVHRR SST retrievals, confirmed in this study through comparisons with in situ data, is of the order of 0.5 °C (see also McClain et al., 1983; Strong and McClain, 1984; Walton, 1988; Wick et al., 1992). SST fields were mapped to a cylindrical equidistant projection covering the Gulf of Mexico at a spatial resolution of 11.5 km² per pixel.

Local time series of SST were constructed by averaging all observations within boxes of 3 × 3 pixels (132 km²) for each image. Series were extracted for three boxes, labeled as “stations” 1–3 in Figure 1 and Table 1. The first station was offshore in the central eastern Gulf of Mexico and sampled the oceanic area routinely affected by the Loop Current. Station 2 was located within 15 km of the coast, west of Mo-

TABLE 1. Center latitude and longitude for 3×3 pixel boxes (103 km^2) from which SST was extracted from AVHRR images (stations shown in Fig. 1).

Station	Latitude	Longitude	Area
1	27.1913°N	86.1251°W	NE central Gulf of Mexico
2	30.0859°N	88.3517°W	West of Mobile Bay
3	30.3200°N	86.7500°W	Off Fort Walton Beach

bile Bay, and toward National Data Buoy Center (NDBC) buoy 42007. Station 3 was also within 15 km of the coast but off Fort Walton Beach, FL. This region was identified through visual inspection of the images as where the coldest coastal temperatures occurred in the NEGOM.

Wind speed and direction as well as air and in situ water temperature were obtained from NDBC buoys 42040 (29.18°N, 88.30°W) and 42007 (30.1°N, 88.78°W) (Fig. 1). Winds from buoy 42040 were used in comparison with the AVHRR-derived SST series because this buoy was farther from land than buoy 42007 and presumably was representative of winds in the NEGOM. Air and water temperature data from buoy 42007 were used for comparisons with the AVHRR-derived SST because this buoy was closer to the coast, and one objective of the study was to validate coastal temperatures.

Phytoplankton "chlorophyll-*a* concentration" fields were derived from the Sea-viewing Wide-Field-of-View Sensor (SeaWiFS), also known as Orbview II. This ocean color satellite sensor is flown jointly by the National Aeronautics and Space Administration (NASA) and Orbimage Corporation. The data were processed with the atmospheric correction algorithms described by Gordon and Wang (1994) and the bio-optical algorithm described by O'Reilly et al. (1998). There are unresolved issues that lead to severe errors in estimates of chlorophyll-*a* with the use of SeaWiFS data in coastal zones, particularly in Case II waters (Morel and Prieur, 1977). Here, the SeaWiFS chlorophyll-*a* images are used primarily to infer the dispersal pattern followed by Mississippi River water into the area of concern. These discolored waters are very distinct in these images. The data are not used to determine actual phytoplankton concentrations.

Finally, circulation patterns were inferred from spatial patterns in the IR and ocean color images, and also from satellite altimetry, with the sea surface height (SSH) and geostrophic current approximation products generated by Robert Leben at the Colorado Center for Astrodynamic Research (Univer-

sity of Colorado; <http://www-ccar.colorado.edu/~leben/research.html>). These products incorporate data from the Ocean Topography Experiment (TOPEX) and European Remote-sensing Satellites (ERS) satellites.

RESULTS

AVHRR SST.—Huh et al. (1978) described a cross-shelf gradient in SST in winter 1976–1977 in the NEGOM on the basis of AVHRR satellite data. A multiyear time series of images (1994–1999) shows that the large-scale changes observed by Huh et al. over this area are seasonal. The time series of AVHRR images also shows pronounced anomalies in the form of cold patches within 40 km of the coast of the Florida Panhandle in May, June, and July of 1998. Figure 2 shows examples of the imagery. Figure 3 presents SST extracted at one offshore location (Station 1) and off Fort Walton Beach, FL (Station 3 in Table 1 and Fig. 1). Although the entire coast of the Florida Panhandle (starting immediately east of Mobile Bay through Cape San Blas) was cool between May and June 1998, the area in the immediate vicinity of Station 3 featured slightly cooler temperatures (about 0.5–1°C).

Figure 4 shows air temperatures at NDBC buoy 42007, located to the west of Mobile Bay (Fig. 1). Figure 4 also shows surface water temperatures measured at this buoy (in situ) and near the buoy with the AVHRR (Station 2). AVHRR SST derived for Station 3 were also overlaid on Figure 4. These data have all been smoothed with a five-point running mean filter (the AVHRR series contain up to eight observations per day, and the buoy series consist of hourly observations).

The offshore station taken in the central eastern Gulf of Mexico (Station 1) shows an annual temperature range of about 9–11°C, from ~31°C in June–August to ~20–23°C in February–March (Fig. 3). This region shows winter temperatures that are warmer than all coastal locations in the NEGOM. Warm winter anomalies are observed when the Loop Cur-

Fig. 2. AVHRR-derived SST on (1) 21 May 1995, (2) 17 May 1996, (3) 12 May 1998, (4) 4 June 1998, (5) 7 June 1998, and (6) 17 July 1998. SST (C) has been coded according to the color bar included. Note that extremely high SSTs (>30 C) are shown in blue-grey. Clouds and missing data are shown in black, and land is shown in grey.

rent or one of its warm eddies intrudes north of 27°N , as in January and February 1996 and 1998. In contrast, coastal waters feature cold temperatures (~ 12 C) in January–February. These are, indeed, some of the coldest surface temperatures seen in the Gulf on a seasonal basis. A cold water tongue extends southward along the West Florida Shelf starting usually around November, and persists through May. All waters in the region, including those in the cold plume, show a seasonal temperature increase after March. The structure of this cold plume is shown in panels 2 and 3 of Figure 2. This feature, which may extend from Cape San Blas to the Florida Keys and into the Florida Strait, is also associated with high pigment concentrations (Gilbes et al., 1996).

The AVHRR images frequently show that in May Mississippi River water that enters the ocean is colder than surrounding waters (panels 1, 3, Fig. 2). However, this temperature signal becomes indistinguishable from that of

oceanic waters nearby within a few kilometers of the coast. The May 1996 image (panel 2, Fig. 2) shows a much larger plume of about 23 C that originated in the coastal zone of the Florida Panhandle and extended to the southeast along the shelf break of the West Florida Shelf. Figure 3 shows that SST in the NGOM in May ($19\text{--}25$ C) is always lower relative to SST in the central Gulf of Mexico ($\sim 25\text{--}27$ C). Coastal zones in the NEGOM experience a fast rate of SST increase (up to 0.25 C per day) between early May and mid-June (Fig. 4). By June, temperatures throughout the region are more uniform, with both offshore and coastal waters above $25\text{--}27$ C (Fig. 3).

Of interest here are the pronounced cold water patches seen along the Florida Panhandle east of Mobile Bay. One instance was observed in May 1995, when SST off Mobile Bay reached ~ 23 C, or about $1\text{--}2$ degrees below surrounding waters (panel 1, Fig. 2). There are several examples of narrow (<20 km wide)

Fig. 3. SST time series offshore in the central eastern Gulf of Mexico (Station 1 in Table 1 and Fig. 1; solid line) and immediately off the Florida Panhandle coast (Station 3 in Table 1 and Fig. 1; thin broken line).

bands of cold water along the coast of the Florida Panhandle, and they were observed at any time between May and August in different years. However, of the images examined between 1994 and 1999, those for 1998 showed the most intense springtime cooling and also the coldest coastal water patches (panels 3–6,

Fig. 2). In May, June, and July 1998, waters along the Florida Panhandle west of Cape San Blas were between 2 and 6 C cooler than SST for those months in 1996 and 1999 (data not shown). They were also 3–4 C, and on occasion up to 7 C, cooler than water and air temperatures immediately off the coast of Alabama

Fig. 4. Air and water temperature measured at NDBC buoy 42007 and AVHRR-derived SST at Stations 2 and 3 during the period for which water temperatures off the Florida panhandle were cooler because of coastal upwelling (April–August).

Fig. 5. Wind speed and direction (the direction wind blew from) from 1 May through 30 July 1998 at NDBC buoy 42040 (29.18°N, 88.30°W; Mobile South, 64 nautical miles south of Dauphin Island, AL; see Fig. 1). Vertical lines represent the range of values in wind direction (or speed) experienced in a particular day, with the horizontal line joining consecutive days.

(Fig. 4) at NDBC buoys 42040 and 42007 (see Fig. 1). There were marked cooling events observed along the Florida Panhandle in each of these months (May–July), during which the cold coastal wedge varied in width from undetectable to about 40 km, showing differences of several degrees between occurrences over scales of 2–10 d.

In early May 1998, AVHRR imagery showed a very narrow (<20 km) band of cold temperatures along the coast between Cape San Blas and the entrance to Mobile Bay (panel 3, Fig. 2). SST lower than 18 C was seen in the coldest patch, located between Pensacola and Fort Walton Beach, FL. By May 16, warm temperatures were seen along the Panhandle coast, but the cold wedge returned on May 19. In late May, coastal waters warmed up again (Fig. 4). These cold patches appeared stretched toward offshore and to the east (panel 3, Fig. 2), and ultimately they appeared to disperse to the southeast along the shelf edge of the West Florida Shelf.

Winds.—Figure 5 shows variation in wind speed and direction at NDBC buoy 42040 to the east of the Mississippi Delta between May and August 1998. For 1996–1999, winds were stronger than $3 \text{ m}\cdot\text{s}^{-1}$ greater than 65% of the time between 1 May and 31 August each year. However, winds had an eastward component (wind direction greater than 220 degrees) 32% of the time between May and August only in 1998. This is in contrast to 20% in 1996, 26% in 1997, and 22% in 1999 over the same time period.

The wind at the beginning of May 1998 was about $7 \text{ m}\cdot\text{s}^{-1}$ from the west, but it quickly decreased and reversed to reach about $3 \text{ m}\cdot\text{s}^{-1}$ from the east by 6 May. It then reversed again, and by 10 May, it reached over $9 \text{ m}\cdot\text{s}^{-1}$ blowing from the west. This coincided with a cooling in coastal temperatures as observed in the AVHRR image for 11–13 May (panel 3, Fig. 2). Winds decreased afterward and reached almost $1 \text{ m}\cdot\text{s}^{-1}$ in mid-May. Stronger winds ($>6 \text{ m}\cdot\text{s}^{-1}$) were experienced during 27–29 May

1998, but blowing from the ESE. During this period, coastal waters warmed up rapidly to about 26 C (Fig. 4).

In the first few days of June 1998, winds reversed again (Fig. 5), increasing to nearly $8 \text{ m}\cdot\text{s}^{-1}$ from the WSW. This event was accompanied by marked cooling in air temperatures, from about 27 C in late May to an average of about 24 C on 7 June 1998. Water temperatures in the vicinity of the NDBC buoys closely followed air temperatures. However, cooling off the Florida Panhandle was much more pronounced, and surface temperatures off Fort Walton Beach (Station 3) reached 18–19 C on 4–7 June (panels 4, 5, Fig. 2; Fig. 4). Winds then reversed and decreased in speed, air temperatures increased to over 27 C, and AVHRR images for 10 June showed SST at Station 3 had increased to 26–27 C. Another wind reversal after 10 June led to the strongest winds of the month by 15 June, with winds over $8 \text{ m}\cdot\text{s}^{-1}$ from the west, and AVHRR data showed another drop in SST to about 22 C whereas air temperatures increased above 28 C (Fig. 4). The second half of June was very cloudy, which corresponded with a period of very low winds. A thin wedge of cool waters, however, could be seen again around 29–30 June, after moderate winds with an eastward component on June 28 (Fig. 5).

Winds in early July were moderate ($1\text{--}5 \text{ m}\cdot\text{sec}^{-1}$), but during 10–19 July, winds were very strong ($6\text{--}8 \text{ m}\cdot\text{s}^{-1}$) and from the west (Fig. 5). Air temperatures during this period were as low as 26 C, similar to waters west of Mobile Bay. However, SST off the Florida Panhandle was generally up to 5 C cooler than air temperatures during this period (Fig. 4) and nearly 3 C below those seen during July of other years. Panel 6 of Figure 2 shows the spatial distribution of SST, with nearshore temperatures along the entire coast of Florida west of Cape San Blas 3–6 C lower than water farther offshore.

SeaWiFS.—Figure 6 shows the chlorophyll-*a* product derived from SeaWiFS ocean color imagery for selected dates between April and August 1998. With the use of the sequence of SeaWiFS images shown in panels 2–6 of Figure 6 (1–18 May 1998), the inference was made that a bolus of highly discolored and turbid Mississippi River plume water spread east of 88°W over a period of about 10 d and then continued moving east along the coast. The image for May 3 (panel 3, Fig. 6) suggests the bolus originated in the western sector of the Mississippi Delta (west of 89°W) and that it

rounded the tip of the delta, entering the eastern sector (east of 89°W). This eastward movement was likely driven by the strong ($9 \text{ m}\cdot\text{s}^{-1}$) wind observed blowing from the west-southwest during the first week of May (Fig. 5). The SeaWiFS image for 13 May (panel 5, Fig. 6) also shows an area of over 100 km diameter with low pigment concentrations in the NEGOM centered around 27.75°N, 86.25°W. This is the signature of an anticyclonic feature lodged in the NEGOM.

A portion of the Mississippi water that moved east in May 1998 was entrained in a small ($\sim 50 \text{ km}$ diameter) cyclonic eddy located off the tip of the delta near 28.25°N, 88.75°W (panels 4, 5, Fig. 6). However, most of this turbid water continued to flow to the north and east, past the Chandeleur Islands. Over the period 11–18 May (panels 4–6, Fig. 6), this turbid water spread in a narrow plume east of Mobile Bay along the coast (north of 30°N and between 86 and 89°W). On 18 May (panel 6, Fig. 6), coastal turbidity reached very high levels along the coast west of 86°W, and the SeaWiFS processing software masked coastal pixels as invalid (white mask). Farther to the east, immediately to the east of Fort Walton Beach and before Panama City, the discolored plume turned offshore and to the southeast.

The large amount of discolored water derived from the Mississippi River Delta was trapped in the NEGOM during the second half of June and the early part of July 1998. As winds became westward after 10 June, the Mississippi water seemed to move toward the west. As water from the Mississippi and other rivers was pushed against the Chandeleur Islands and the Mississippi Delta, this discolored plume spread over a large area along the Alabama and Florida Panhandle coasts (panels 7, 8, Fig. 6). This water was dispersed (panel 9, Fig. 6) after winds switched again to the east and gained in strength in mid-July (Fig. 5).

Altimetry.—A large anticyclone shed by the Loop Current in March 1998 moved into the NEGOM, where it remained for about 3–4 mo. Although it was detected in the AVHRR and SeaWiFS images, it was most clearly outlined in the SSH and geostrophic current fields estimated from the TOPEX/Poseidon and ERS altimeters. This anticyclone brought warm water into the otherwise colder NEGOM (see warm peak between February and April 1998 in Station 1, Fig. 3). In April–July 1998, the Loop Current proper remained south of 25°N.

Figure 7 shows SSH fields for the Gulf of Mexico for mid-May and mid-July 1998. The

Fig. 6 The 1988 SeaWiFS imagery for (1) 24 April, (2) 1 May, (3) 3 May, (4) 11 May, (5) 13 May, (6) 18 May, (7) 15 June, (8) 5 July, and (9) 27 August. Purple and blue show clear waters, and green, yellow, and red show increasingly turbid waters. Extremely turbid coastal waters (panels 2, 3, and 6) and some clouds (SW to NE diagonal front in panel 2) are masked white. Other clouds and missing data are masked black.

TOPEX/ERS-1 Analysis May 14 1998

TOPEX/ERS-2 Analysis Jul 15 1998

Fig. 7. Geostrophic velocity and SSH in the Gulf of Mexico inferred from blended TOPEX/Poseidon and ERS altimeter data for mid-May and mid-July 1998 (courtesy of R. Leben, University of Colorado).

strong anticyclone maintained an ellipsoidal shape with its major axis oriented NW to SE throughout the June–August period. SSH values of nearly 20 cm were observed in the central portion of the eddy, located farther offshore. The ellipsoidal eddy formed a SSH ridge that extended into the coastal region between the Mississippi Delta and Cape San Blas. The SSH values near and on the shelf are likely to be less accurate, but the ridge shows lower SSH values than offshore, or values of 5–10 cm. The geostrophic current field inferred from this SSH distribution leads to convergence near the Mississippi River Delta, eastward flow along the coast, and offshore flow in the vicinity of Cape San Blas (Fig. 7).

DISCUSSION

The large, coherent cold water tongue observed between November and May along the West Florida Shelf (panels 2, 3, Fig. 2) is important because it represents recurrent and persistent regional-scale upwelling (Yang and Weisberg, 1999). It is likely to be important for the ecology of the NEGOM because it is associated with elevated phytoplankton concentrations and serves as a mechanism for dispersal of river water along the West Florida Shelf break (Gilbes et al., 1996).

This seasonal cold plume serves as the background on which winds and transient eddies may modulate coastal water temperatures in the NEGOM. Specifically, coastal waters off the Florida Panhandle showed repeated cooling events superimposed on a general warming trend between May and July 1998 (Fig. 4). These waters remained cooler at all times than air temperatures and water temperatures off Alabama and were 3–4 °C cooler than offshore waters (panels 3–6, Fig. 2; Fig. 3). They also occurred exclusively under eastward winds. This strongly suggests that the cooling events seen along the Florida Panhandle coast were the result of wind-driven coastal upwelling as opposed to cooling through heat exchange with the overlying atmosphere. The repeated cooling and warming indicated strengthening and weakening of the upwelling process.

Chuang et al. (1982) and Schroeder et al. (1987) concluded that the nearshore circulation off eastern Louisiana, Mississippi, and Alabama is strongly wind dependent, in spite of the potential for westward geostrophic flow generated by coastal fresh water input (Schroeder et al., 1987). Chuang et al. (1982) also found that winds during summer were relatively mild, with bursts spaced about 10 d apart or

longer, but that wind magnitudes rarely exceeded about $8 \text{ m}\cdot\text{s}^{-1}$. The Hellerman and Rosenstein (1983) climatological winds show that on the average, winds in the NEGOM around 29°N , 89°W have a westward component on a year-round basis, with a southward component between January–March and September–December and a northward component between April and August. The zonal component of these climatological winds shows a minimum in July, and the meridional component shows its minimum in August.

However, if wind data are examined on an annual basis, each year may show a different mean orientation of the wind, as found by Chuang et al. (1982). Indeed, as shown above, the wind records from NDBC buoy 42040 show that winds in the NEGOM can be strong and have variable direction during summers. However, strong eastward winds are infrequent, reaching 32% of the time between May and August only in 1998 and less in 1996, 1997, and 1999. Clearly, inferences made based on Hellerman and Rosenstein (1983) wind climatological products are misleading because they average wind direction as well. Instead, shifting winds may lead to an inconsistent summer circulation pattern on the shelf.

There are specific instances of baroclinic forcing along the shelf break that lead to strong ($>30 \text{ cm}\cdot\text{s}^{-1}$) currents along the shelf in the NEGOM (Paluszkievicz et al., 1983). Chuang et al. (1982), for example, speculated that currents off Alabama in 1976 showed a stronger cross-shelf component because of a northward intrusion of the Loop Current described by Vukovich et al. (1979). The observations of Huh et al. (1981) and Schroeder et al. (1987) also support earlier inferences that the Loop Current plays an important role in exchange of water along the shelf break in the region. Such stronger currents, affected by interaction of large-scale circulation features such as the Loop Current and eddies with shelf waters, are also evident in trajectories of drifting buoys deployed by the Minerals Management (Muller-Karger et al., 1998).

The strong anticyclone shed early in 1998 from the Loop Current drifted into the NEGOM in April and interacted with shelf waters over the narrow shelf and within DeSoto Canyon off the Florida Panhandle. The hydrographic structure of the anticyclone shows an upward tilting of isopleths toward the coast off the Florida Panhandle, particularly in the vicinity of DeSoto Canyon (Nowlin et al., 2000). Also, the eastward wind pulses observed repeatedly between May and July 1998 (Fig. 5)

were favorable to forcing of coastal upwelling along the east-west coast of the Florida Panhandle. Both of these processes acted together to enhance coastal upwelling in the region between May and July 1998. Although upwelling-favorable winds were observed every year between 1994 and 1999, they were less frequent than in 1998, and they probably acted on waters in which the thermocline was deeper.

The anticyclonic eddy also led to warming immediately off the shelf relative to other years. This area typically would experience the effect of the large, regional cold plume early in the year (as in panel 2, Fig. 2), with surface temperatures of 20–22 C, in February. However, in February 1998, surface temperatures reached 26 C as far north as 27°N (Station 1, Fig. 3; see also Müller-Karger et al., 1991). In May–June 1998, waters at 27°N were still 2–3 C warmer than their seasonal average for that time (Fig. 3, curve for Station 1).

The question remains, then: what caused the anomalous fish kills and discolored water in the NEGOM during June and July 1998? The answer to this question may lie in the interaction between the winds, upwelling, and the dispersal pattern of Mississippi and other river water during this period.

Over northern Florida, rainfall and river discharge during winter and spring of El Niño years is higher than normal (Sun and Furbish, 1997). This was also the case for the El Niño episode of 1997–1998 (Schmidt et al., 2000). The increased discharge delivered to the NEGOM in spring 1998 may be expected to lead to higher than normal nutrient availability and blooming of phytoplankton along the coast (Gilbes et al., 1996). The SeaWiFS data also suggest that a large volume of Mississippi plume water moved from the central Louisiana coast, around the tip of the Mississippi Delta, and eastward into the NEGOM in May and June 1998. Such eastward movement of Mississippi water is not unusual (Schroeder et al., 1987; Müller-Karger et al., 1991; Muller-Karger, 1993). However, combined with the large discharge from local rivers, lower than normal salinity should have occurred along the coast in the NEGOM during early 1998. Further, this discolored, fresh water was trapped off the Florida Panhandle from about the second week of June through about 10 July by weak and westward winds (Fig. 5). The discolored

water moved east again after 15 July and eventually cleared the area in late July, after winds became strong and eastward.

To understand the cause for the inferred condition of hypoxia observed off the Florida Panhandle in spring 1998, an analogy may be established with the phenomenon observed annually off the Mississippi Delta west of 89°W. There, the seasonal peak in discharge of the Mississippi and Atchafalaya Rivers leads to substantial phytoplankton blooms. Under conditions of weak winds, vertical mixing is inhibited and these blooms sink and decompose, causing seasonal hypoxia in bottom waters (Turner and Allen, 1982; Walsh, 1988; Turner and Rabalais, 1991; Justic et al., 1993; Atwood et al., 1994; Rabalais et al., 1996). The oxygen depletion begins in late spring, reaches a maximum in midsummer, and disappears in the fall. The area affected has grown and covers approximately 18,000 km² every year but has not yet been reported to extend into the eastern sector of the Mississippi Delta. The problem occurs in the middle of an important commercial and recreational fisheries area and is considered a threat to the economy of this region of the Gulf. A similar but much more modest condition seems to occur within Mobile Bay (W. Schroeder, pers. comm.).

The documentation of the massive eastward transport of Mississippi plume water around the tip of the Delta in May and June 1998 with SeaWiFS and of low salinity with a hydrographic survey (Nowlin et al., 2000) is therefore significant. The discharge of 1998 likely had a stabilizing effect on the water column, which was enhanced during calm periods or periods of weak westward winds.

Figure 8 outlines the spatial patterns expected under the hypothesis of eastward Mississippi plume dispersal with concurrent coastal upwelling. Indeed, the AVHRR image for 12 May 1998 (panel 3, Fig. 2) shows a newly upwelled water patch along the coast. The upwelling of deeper waters would displace low-salinity and discolored water present near the coast farther offshore. The SeaWiFS images for 18 May and 5 July (panels 6, 8, Fig. 6) confirm separation of the discolored plume from the coast eastward of about 86.5°W, with dispersal inferred in a southeastward direction.

As the wind stopped or reversed, blowing from east to west, wind-driven upwelling would

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Fig. 8. Schematic of surface dispersal of low-salinity water from the Mississippi River in the NEGOM during periods of eastward winds (top), westward winds (middle), and calm conditions (bottom).

cease and river water would be moved back toward the coast (Fig. 8). This would be accompanied by inhibition of vertical mixing and of oxygenation, with the concomitant decomposition of organic matter leading to hypoxia.

CONCLUSIONS

Unusual upwelling and river plume dispersal patterns observed in the NEGOM in May–July 1998 were the result of a combination of factors, namely the rare northward migration of an anticyclonic eddy shed by the Loop Current, a significant positive anomaly in rainfall associated with El Niño of 1997–1998, and strong periodic eastward winds. The baroclinic structure of the eddy led to raised isotherms interacting with the continental shelf, and the eastward winds further enhanced upwelling along the coast. Through combined action of strong eastward winds and the motion associated with the anticyclone, Mississippi plume waters moved east of the delta between May and June 1998. Both the enhanced discharge and upwelling led to high chlorophyll concentrations in the northeastern Gulf of Mexico in May 1998 (W. Nowlin, D. Biggs, and F. Muller-Karger, unpubl. in situ observations). As winds relaxed or became westward, the low-salinity water associated with river discharge contributed to vertical stability along the coast in late June and early July, with deposition of organic matter possibly leading to hypoxia in bottom waters near the coast. Hypoxic bottom waters also may have been advected shoreward in subsequent upwelling episodes, leading to the anecdotal reports of coastal anoxia. By late August, most of the Mississippi and other brackish water had been flushed out of the NEGOM and had dispersed toward the Florida Keys and beyond.

There are concerns that the 1998 cold water conditions with possible hypoxia may occur again in the future. It is unclear that we can predict recurrence. However, it appears that we can anticipate substantial meteorological and oceanographic impact from errant anticyclones in the Gulf of Mexico as well as from rainfall patterns associated with El Niño.

Clearly, routine monitoring of the entire Gulf of Mexico with a suite of near-real-time, complementary satellite-based sensors is viable today. Similarly, early warning of El Niño events seems possible today. Together, this information may help determine whether or not processes are underway that can lead to anomalous situations in deep water as well as conti-

mental shelf environments of the Gulf of Mexico.

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LITERATURE CITED

- ATWOOD, D. K., A. BRATKOVICH, M. GALLAGHER, AND G. HITCHCOCK (EDS.) 1994. Papers from NOAA's nutrient enhanced coastal ocean productivity study. Special dedicated issue. *Estuaries* 17(4): 729–911.
- CHUANG, W. S., W. W. SCHROEDER, AND W. J. WISEMAN, JR. 1982. Summer current observations off the Alabama coast. *Contrib. Mar. Sci.* 25:121–131.
- COLLARD, S. B., A. LUGO-FERNANDEZ, G. FITZHUGH, J. BRUSHER, AND R. SHAFFER. 2000. A mass mortality event in coastal waters of the central Florida Panhandle during spring and summer 1998. *Gulf Mex. Sci.* 18:68–71.
- GILBES, F., C. TOMAS, J. J. WALSH, AND F. E. MULLER-KARGER. 1996. An episodic chlorophyll plume on the west Florida shelf. *Continental Shelf Res.* 16(9):1201–1224.
- GORDON, H. R., AND M. WANG. 1994. Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm. *Appl. Optics* 33:443–452.
- HELLERMAN, S., AND M. ROSENSTEIN. 1983. Normal monthly wind over the world ocean with error estimates. *J. Phys. Oceanogr.* 13:1093–1104.
- HUH, O. K., W. J. WISEMAN, AND L. J. ROUSE, JR. 1978. Winter cycle of sea surface thermal patterns, northeastern Gulf of Mexico. *J. Geophys. Res.* 83(C4):4523–4529.
- , ———, AND ———. 1981. Intrusion of Loop Current waters onto the west Florida continental shelf. *J. Geophys. Res.* 86(C5):4186–4192.
- JUSTIC, D., N. N. RABALAIS, R. E. TURNER, AND W. J. WISEMAN, JR. 1993. Seasonal coupling between riverborne nutrients, net productivity and hypoxia. *Mar. Poll. Bull.* 26(4):184–189.

- MCCLAIN, E. P., W. G. PICHEL, AND C. C. WALTON. 1985. Comparative performance of (AVHRR) based multichannel sea surface temperatures, *J. Geophys. Res.* 90:11587–11601.
- , ———, ———, Z. AHMAD, AND J. SUTTON. 1983. Multi-channel improvements to satellite-derived global sea-surface temperatures. *Adv. Space Res.* 2(6):43–47.
- MOREL, A., AND L. PRIEUR. 1977. Analysis of variations in ocean color. *Limnol. Oceanogr.* 22:709–722.
- MULLER-KARGER, F. E. 1993. River discharge variability including satellite-observed plume-dispersal patterns, p. 162–192. *In*: Climate change in the intra-Americas Sea. G. Maul (ed.). United Nations Environmental Programme (Wider Caribbean Region) and Intergovernmental Oceanographic Commissions (Caribbean and Adjacent Regions). Edward Arnold Publishers.
- , F. Vukovich, R. Leben, B. Nababan and D. Myhre. 1998. Northeastern Gulf of Mexico physical oceanography program: eddy monitoring and remote sensing. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region. Technical Report MMS 98-0051.
- , J. J. Walsh, R. H. Evans, and M. B. Meyers. 1991. On the seasonal phytoplankton concentration and sea surface temperature cycles of the Gulf of Mexico as determined by satellites. *J. Geophys. Res.* 96(C7):12645–12665.
- NOWLIN, W. D., JR., A. E. JOCHENS, M. K. HOWARD, S. F. DiMARCO, AND W. W. SCHROEDER. 2000. Hydrographic properties and inferred circulation over the northeastern shelves of the Gulf of Mexico during spring to midsummer 1998. *Gulf Mex. Sci.* 18:40–54.
- O'REILLY, J. E., S. MARITORENA, B. G. MITCHELL, D. A. SIEGEL, K. L. CARDER, S. A. GARVER, M. KAHRU, AND C. McCLAIN. 1998. Ocean color chlorophyll algorithms for SeaWiFS. *J. Geophys. Res.* 103: 24937–24953.
- PALUSZKIEWICZ, T., L. ATKINSON, E. S. PARMENTIER, AND C. R. McCLAIN. 1983. Observations of a Loop Current frontal eddy intrusion onto the west Florida shelf. *J. Geophys. Res.* 88:9639–9651.
- RABALAIS, N. N., R. E. TURNER, D. JUSTIC, Q. DORTCH, W. J. WISEMAN, JR., AND B. K. SEN GUPTA. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries* 19:286–407.
- SCHMIDT, N., E. K. LIPP, J. B. ROSE, AND M. E. LUTHER. 2000. ENSO influences on seasonal rainfall and river discharge in Florida. *Climate*. In press.
- SCHROEDER, W. W., S. P. DINNELL, W. J. WISEMAN, JR., AND W. J. MERRELL. 1987. Circulation patterns inferred from the movement of detached buoys in the eastern Gulf of Mexico. *Continental Shelf Res.* 7(8):883–894.
- STRONG, A. E., AND E. P. McCLAIN. 1984. Improved ocean surface temperatures from space, comparisons with drifting buoys. *Bull. Am. Meteorol. Soc.* 65(2):138–142.
- SUN, H., AND D. J. FURBISH. 1997. Annual precipitation and river discharges in Florida in response to El Niño and La Niña sea surface temperature anomalies. *J. Hydrol.* 199:74–87.
- TURNER, R. E., AND R. L. ALLEN. 1982. Bottom water oxygen concentrations in the Mississippi River Delta Bight. *Contrib. Mar. Sci.* 25:161–172.
- , AND N. N. RABALAIS. 1991. Changes in Mississippi River water quality this century: implications for coastal food webs. *BioScience* 41:140–147.
- VUKOVICH, F. M., B. W. CRISMAN, M. BUSHNELL, AND W. J. KING. 1979. Some aspects of the oceanography of the Gulf of Mexico via satellite and in situ data. *J. Geophys. Res.* 84:7749–7768.
- WALSH, J. J. 1988. On the nature of continental shelves. Academic Press, San Diego.
- WALTON, C. C. 1988. Nonlinear multichannel algorithms for estimating sea surface temperature with AVHRR satellite data. *J. Appl. Meteorol.* 27:115–127.
- WICK, G. A., W. J. EMERY, AND P. SCHLUESSEL. 1992. A comprehensive comparison between satellite-measured skin and multichannel sea surface temperature. *J. Geophys. Res.* 97(C4):5569–5595.
- YANG, H., AND R. H. WEISBERG. 1999. Response of the west Florida Shelf to climatological wind stress forcing. *J. Geophys. Res.* 104(C3):5301–5320.
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