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Mississippi River flood waters that reached the Gulf Stream

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Abstract. Distributions of physical, biological, and chemical parameters in Florida Keys coastal waters seaward of the reef track were surveyed on September 9 to 13, 1993, as part of a coordinated multidisciplinary study of surface transport processes. A band of low-salinity water was observed along the shoreward side of the Florida Current over the downstream extent of the survey from Miami to Key West. Biological and chemical indicators within the band, together with its large volume, satellite imagery, and a surface drifter trajectory suggested the recent Mississippi River flood as the source.

Introduction

While the 1993 flooding itself received considerable popular attention [*Mairson*,1994; *Macilwain*, 1993a, b] much less consideration has been given to its downstream effects. Upper layer salinities in the Florida Straits region are typically 36 or greater [*Wennekens*, 1959; *Schmitz and Richardson*, 1990]. Physical oceanographers have suspected the Mississippi River (MR) as a source of low-salinity water in the Gulf Stream and Florida Straits [*Wennekens*, 1959; *Atkinson and Wallace*, 1975; *Maul*, 1974] but were unable to confirm their suspicions due to a lack of supporting data. As part of an ongoing regional program [*Lee et al.*, 1994], the physics, chemistry, and biology of these waters have been studied for the last 5 years. In this paper we relate physical, biological and chemical measurements in an anomalous low-salinity band to satellite advanced very high resolution radiometer (AVHRR) thermal imagery, Argos tracked surface drifter trajectories, and wind records from the Mississippi delta. Together, these data provide convincing evidence of entrainment of MR flood waters into the Gulf of Mexico Loop Current and subsequent transport through the Florida Straits and along the U.S. east coast on the shoreward side of the Gulf Stream.

Methods and Results

Physical, biological and chemical properties were surveyed continuously for 2 days during which expendable bathythermographs (XBTs) were dropped at regular intervals. Shipboard acoustic Doppler current profilers (ADCPs) profiled currents in the upper 300 m. Biological and physical parameters were measured at approximately 8 m depth by a suite of electronic sensors on a towed V-fin. The data, binned into 1-min averages and displayed in real time aboard ship, included conductivity, temperature, chlorophyll fluorescence, visible (400-700 nm) transmittance, and near-field acoustic backscatter. Temperature, conductivity, hydrogen peroxide, and dissolved organic matter (DOM) fluorescence were also recorded continuously from seawater pumped aboard from an intake at approximately 1 m depth. Subsamples of this water were filtered to calibrate in situ chlorophyll fluorescence.

A hydrographic section with biological and chemical profiling of the upper 200 m was made along a transect offshore of Looe Reef in the lower Keys. The V-fin and a conductivity-temperature-depth (CTD) rosette sampler were used to make a series of vertical casts along the transect. Near-surface bongo net (150-μm mesh) tows were also made to assist in interpreting the acoustic data. Sea surface temperature over the Gulf of Mexico and Florida Current were derived from a 3 day composite of AVHRR satellite thermal imagery. Surface current trajectories were obtained from a satellite tracked Coastal Ocean Dynamics Experiment (CODE) type surface drifter and wind records from the National Buoy Data Center (NBDC). CODE surface drifter 20015 had been deployed on the Texas shelf as part of a Minerals Management Service (MMS; U.S. Department of Interior) study of Gulf of Mexico shelf circulation.

Physical Observations

Continuous, near-surface (1 m) thermosalinograph data revealed a band of low salinity (31 to 35) from Key West to Miami, a distance of 260 km (Figure 1). The band, approximately 20 m deep off Looe Reef, extended offshore 45 km at Key West and 37 km at Miami. The average salinity of the band was approximately 33.5 and its estimated volume in our study region was 20.8×10^{10} m^3. About 1.4×10^{10} m^3 of fresh water would be needed to dilute oceanic water to this

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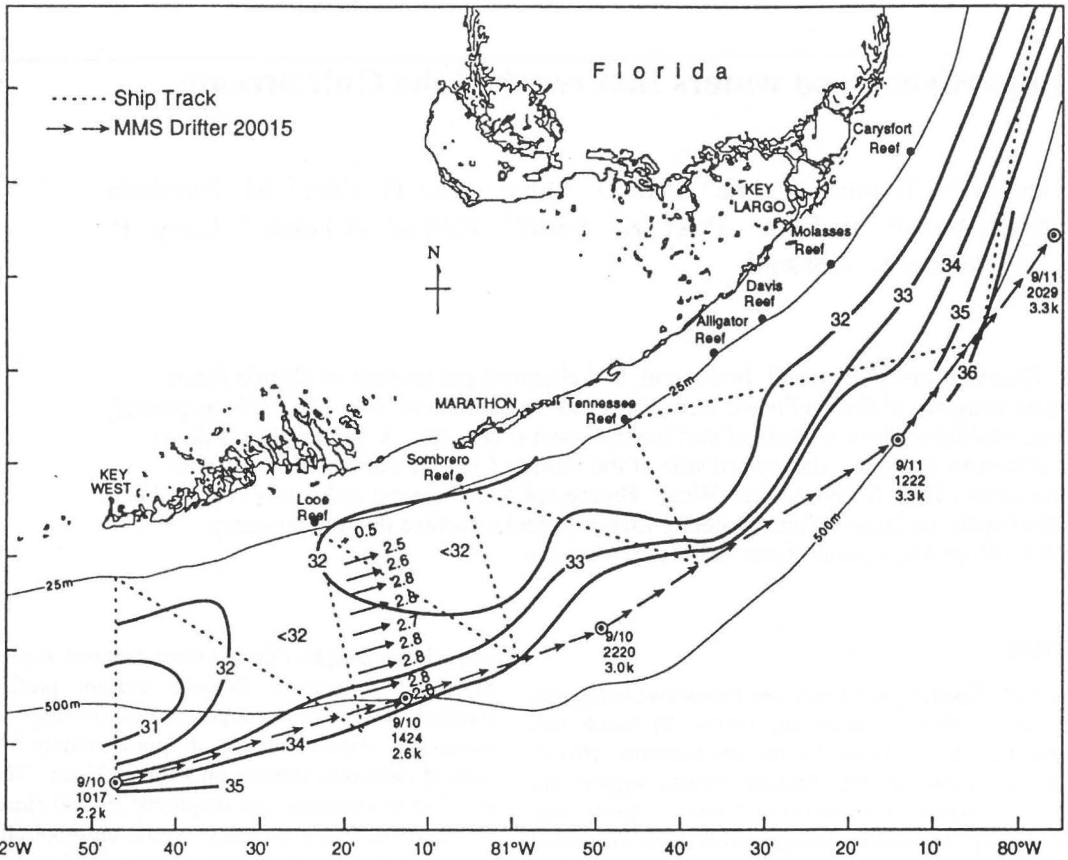

Figure 1. Surface salinity continuously measured by a shipboard thermosalinograph. Near-surface current vectors from shipboard acoustic Doppler current profiler (ADCP) are shown on a section south of Looe Reef, and the trajectory of Minerals Management Service (MMS) satellite-tracked surface drifter 20015 is superimposed, with date, time, and current speed given at drifter locations also shown. The dotted lines are the ship's track.

salinity. The most likely source for such a large volume of fresh water is the MR. Given that the mean peak discharge for the MR during August and September was about 2.5 x 10^4 m^3 s^{-1} [*Boyles and Humphries*, 1994], this additional fresh water is equivalent to approximately 6.5 days of flood discharge. For comparison, the average annual freshwater discharge to the southeast U.S. continental shelf from Cape Canaveral to Cape Hatteras is about 2 x 10^3 m^3 s^{-1}, which would require about 83 days to produce a volume of fresh water equivalent to that found in the low-salinity band. Of course, fresh water discharged to the southeast U.S. shelf is prevented from entering the Straits of Florida by the narrow confines of the strait, which is filled with the strong northward flowing Florida Current [*Leaman et al.*, 1987]. Freshwater inputs from the Florida Everglades through the Florida Bay region are comparatively small at this time of year and would also be highly localized due to restricted flow through the narrow channels between the Florida Keys [*Smith*, 1994].

The Gulf of Mexico Loop Current can connect the MR with the Florida Current. Assuming a reasonable mean velocity of 0.5 m s^{-1} [*Leipper*, 1970], it would take about 3 weeks for MR water to reach the Florida Keys. A composite AVHRR sea surface temperature image shows the northern edge of the Loop Current was located approximately 170 km from the Mississippi Delta in early August (Plate 1, top). The Loop Current is shown by the cooler (green) waters extending northward from the Yucatan Channel. There is also a band of warmer (red) water being entrained east and southeastward around the Loop Current from the region south of the MR delta. This warm band appears to be the same low-salinity MR plume seen in water reflectance images of July 27 and August 10 [*Dowgiallo*, 1994)]. The MR plume normally flows toward the west, against the coast, sometimes observable as far as Mexico [*Wiseman* et al., 1982]. However, an eastward and southeastward movement into the region of the Loop Current front would have been aided by a persistent eastward component in the wind field observed in the region of the delta from July 11 to August 30 (Plate 1, bottom). An eastward wind component over the Texas-Louisiana shelf during August that forced the Mississippi and Atchafalaya River flows to the east was later reported [*Wiesenburg and Sahl*, 1994] .

A connection between the MR and the Florida Keys is also shown by the trajectory of a satellite tracked surface drifter deployed on the Texas shelf in early June that moved through the Florida Straits offshore of the Keys on September 10 and 11 during the time of our survey (Plate 1, top) and continued northward to Cape Lookout, North Carolina, where a similar, but somewhat diluted, low-salinity band was observed on September 22. A more detailed track of the drifter in our study area is shown superimposed on the survey surface salinity data (Figure 1, line of arrows). The drifter trajectory was aligned with the seaward edge of the low-salinity band and the drifter translation velocity was close to that measured by the shipboard ADCP.

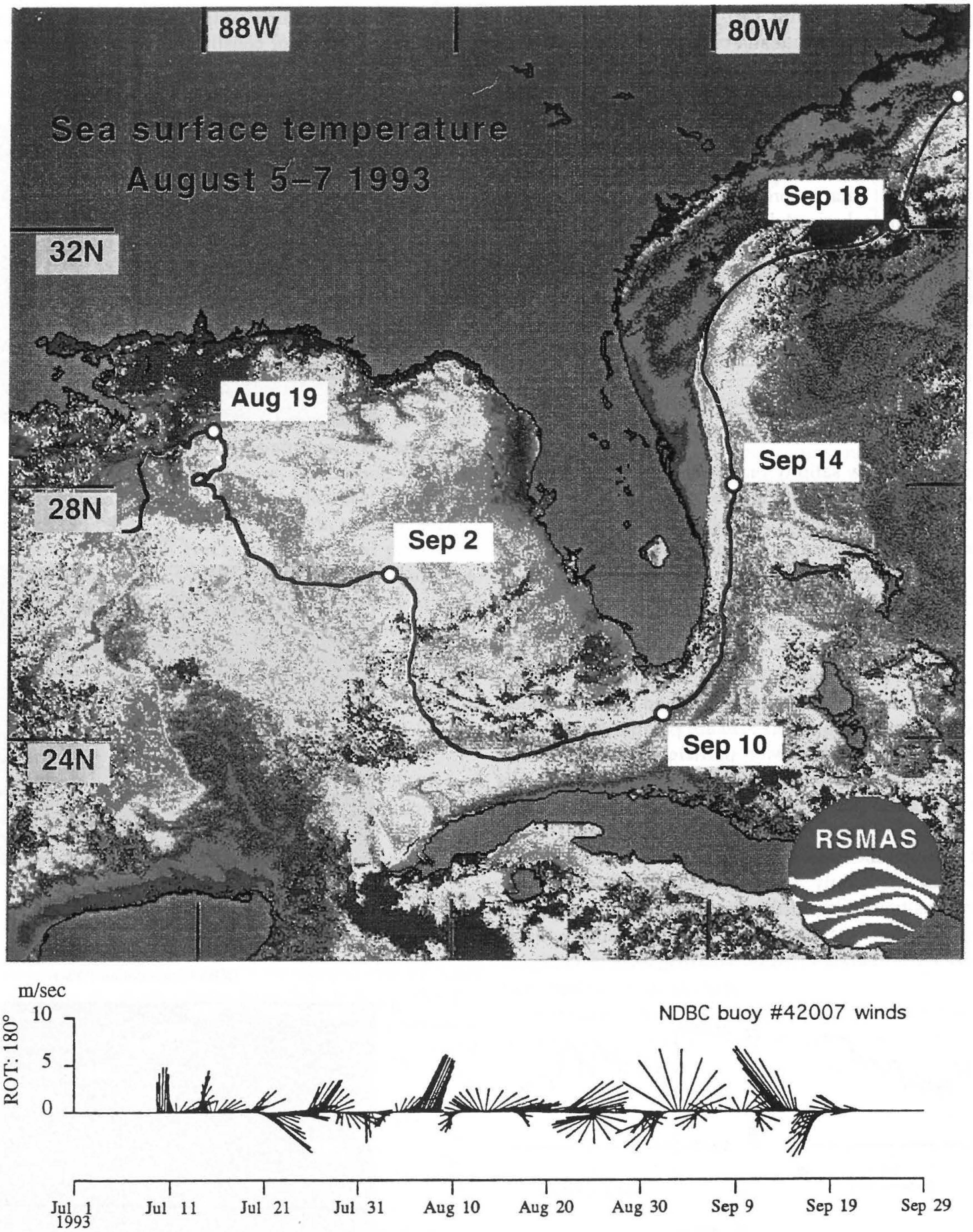

Plate 1. (top) Sea surface temperature patterns derived from a composite of advanced very high resolution radiometer (AVHRR) satellite thermal imagery for the period August 5-7, 1993. Red represents relatively warmer temperatures, green is cooler and blue is colder still. Superimposed on the image is a segment of the trajectory of MMS drifter 20015, originally deployed on the Texas shelf. (bottom) Forty-hour low-pass-filtered wind vectors (meters per second) from National Data Buoy Center (NDBC) buoy 42007 moored in the Gulf of Mexico at 30° N just east of the Mississippi River delta. (Data are from the NDBC via offices of the Texas-Louisiana Shelf Circulation and Transport Process Study.)

A subsequent salinity survey offshore of the Keys showed that 6 weeks later a 30 km-wide, low-salinity band was still present, although salinities were higher (34 to 35). The total volume of fresh water contained within this band was approximately 40% of the earlier estimate.

Freshwater flux through the Looe Reef section can be calculated by multiplying the fresh water required for the observed dilution by the mean alongshore current independently determined by the ADCP and drifter data. The flux obtained by this method is $7.6 \pm 2.4 \times 10^4$ m^3 s^{-1} for September, and $2.9 \pm 2.1 \times 10^4$ m^3 s^{-1} for the October surveys, where the plus/minus represents the flux range based on current variability. The September freshwater flux is about 3 times the peak August MR discharge and the October flux about equal to it, suggesting that fresh water must have accumulated on the shelf south and east of the MR delta or on the west Florida shelf. A large lens of unusually low salinity water was reported in the upper 20 m over the outer part of the west Florida shelf during a cruise of the Florida Marine Research Institute from August 17 to 27 [*Thomas*, 1994]. Our two salinity surveys in the Florida Keys were about 1.5 months apart, but data recorded at the offshore National Oceanic and Atmospheric Administration (NOAA) coastal automated monitoring network (CMAN) towers located at the seaward edge of the Florida reefs show that low-salinity water first arrived in the reef area in mid-August and remained until the end of October; that is the entrainment of MR water into the Florida Current continued for at least 3 months.

Biological and Chemical Observations

Transects of the low salinity feature (Figure 2) suggest that it was not only physically, but also biologically distinct from surrounding waters. Higher chlorophyll concentrations were associated with lowered salinities and elevated temperatures. The feature was itself not uniform but was structured of laminar bands, distinguishably different both biologically and physically. Note the elevated salinities and lower temperatures encountered at approximately 20 km along the transect. Particle distribution (400 µm in diameter) also was not uniform across the lowered salinity band. In subtropical pelagic systems, particles of this size are predominantly small zooplankton. Distinctly lower particle abundances were found within the seaward section of lower-salinity water, not at the lowest salinities encountered nearer shore, while a series of patches of higher abundance were observed at the boundary between the low-salinity band and the normal Gulf Stream waters. Not only zooplankton abundance, but also species composition reflected this structured environment. In the bongo net tows taken within the low-salinity band, cladocerans were abundant, while small cyclopoid copepods dominated more saline waters offshore. Cladocerans were either absent or minor constituents of zooplankton tows taken in this region over the previous 4 sampling years.

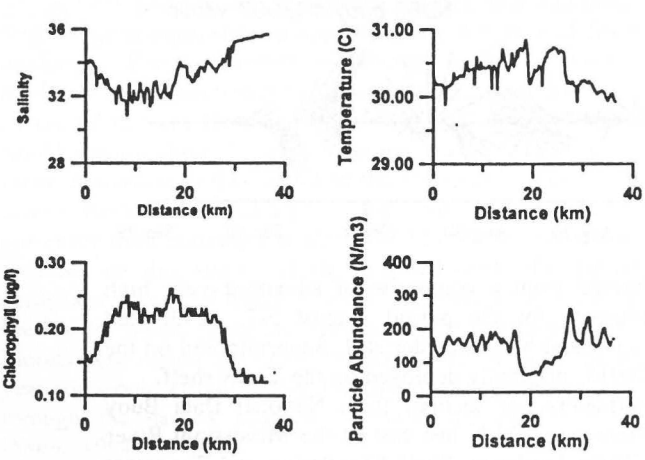

Figure 2. Salinity, temperature, chlorophyll, and particle abundance in the near surface (8 m) along a 36 km transect of the low-salinity anomaly south of Key West. Particle abundance was estimated by solving the inverse problem from measurements of volume scattering strength at 256, 420, 720 kHz, and 1.2, 1.8 and 3.0 MHz as described by Greenlaw [1990].

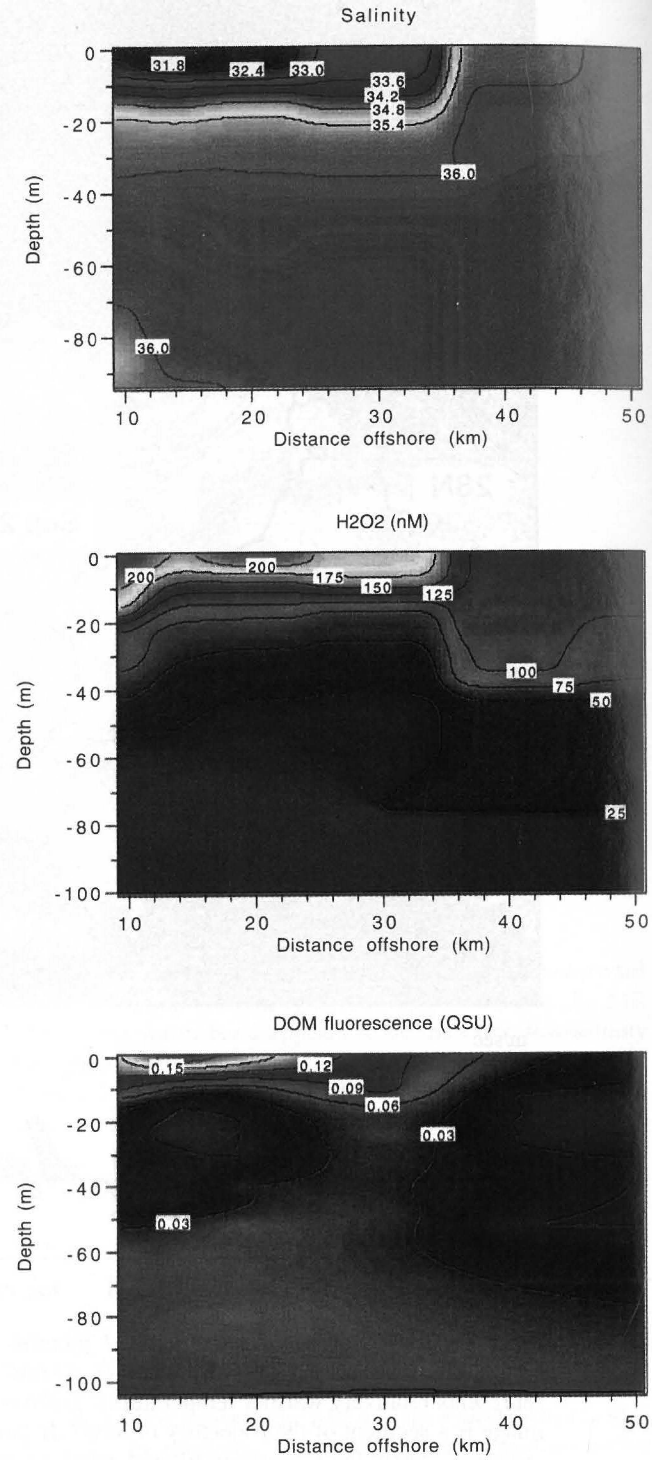

Plate 2. Vertical section plots derived from a series of hydrocasts along a southerly transect off Looe Reef, Florida Keys for the period September 11-12, 1993 for (top) salinity, (middle) hydrogen peroxide (nanomolar, $10^{-9}M$) and (bottom) dissolved organic matter (DOM) fluorescence (expressed in arbitrary units referenced to quinine sulfate). Water samples were taken with Niskin bottles from a conductivity-temperature-depth (CTD) rosette.

Hydrogen peroxide is a useful indicator of the photochemical reactivity of marine surface waters arising as it does from the photochemical oxidation of the dissolved organic matter (DOM) chromophores found in seawater when subject to solar irradiation. A related and more readily observable property of seawater DOM is its characteristic fluorescence. Both the H_2O_2 concentration and the DOM fluorescence of underway and hydrostation samples were monitored throughout the cruise. Peroxide levels in the low-salinity band were 3 times those we have previously measured in these waters. Such high levels of peroxide are strongly indicative of a terrestrially derived source of DOM. Large-scale riverine influxes of DOM have been shown to affect the photochemistry of distant oceanic waters in studies of the Orinoco River plume in the eastern Caribbean [*Zika et al.*, 1993]. Seaward of the low-salinity band, intermediate peroxide (100 n*M*) concentrations were present at depths down to 30 m. (Plate 2). This can be attributed to the greater water clarity and consequent deeper penetration of solar radiation which lead to increased photochemical production [*Sikorski and Zika*, 1993]. Irradiation studies of the surface water samples showed that H_2O_2 photochemical production rates and also dark decay rates measured during the cruise were similar to those expected for open ocean waters at these latitudes and insolation rates. This supports the idea that elevated hydrogen peroxide levels were the result of processes that had occurred upstream of the sampling region. It is likely that the riverine DOM chromophores responsible for peroxide formation had been substantially photobleached before arriving in the Florida Straits.

Dissolved nutrient concentrations (NO_3^-, NO_2^-, NH_4^+, and phosphate) were immeasurable within the euphotic zone throughout the cruise (autoanalyzer detection limits for nitrogen and phosphate species were 0.4 μ*M* for nitrate, 0.1 μ*M* for nitrite, 0.2 μ*M* ammonia and 0.8 μ*M* for inorganic phosphate). In contrast, silicate was notable in the core of the freshwater anomaly (up to 25 μ*M* at 10 m). An estimate of the substantial quantities of nitrate N discharged into the Gulf of Mexico during the three months from July to September (> 0.4 x 10^6 t; compare with 0.17 x 10^6 t for the same period in 1991 or 1992) has been made [*Goolsby*, 1994]. The MR discharge was also unusually high in silicate during the summer of 1993 [*Dortch*, 1994]. The phaeophytin/chlorophyll ratio was comparatively high (>2:1) within high pigment concentration, low-salinity, near-surface waters of the low-salinity band. At depth the presence of phaeophytins has been attributed to zooplankton grazing [*Lorenzen*, 1967].

In situ continuous chlorophyll depth profiles at a station near the core of the freshwater anomaly (Figure 3) had two distinct subsurface maxima. The deeper one was observed at all stations, including those seaward of the low-salinity band. It is to be expected as a consequence of thermal stratification at the end of the summer [*Ortner et al.*, 1980]. However, the secondary near-surface peak was unusual. It corresponded to a more intense transmittance minimum, indicating that not all absorption was associated with viable plant pigments. At the same station, particle concentration maxima were associated with pigment maxima. The vertical profiles of DOM fluorescence and dissolved hydrogen peroxide, together with the chlorophyll and transmittance data (Figure 3) confirm that the freshwater anomaly must have persisted as a discrete entity for some weeks during which photobleaching of

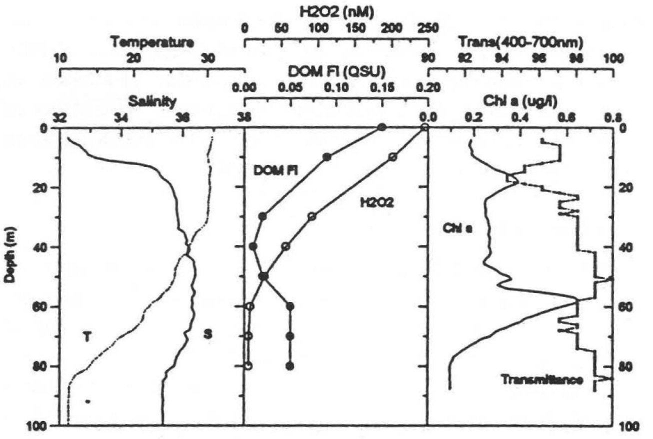

Figure 3. Depth profiles of hydrographic and chemical parameters at one inshore station off Looe Reef, on September 11, 1993. Temperature and salinity were derived from a Sea-Bird CTD, and the accompanying bottle samples were analyzed for dissolved organic matter (DOM) fluorescence and photochemically produced hydrogen peroxide. Light transmittance (from 400-700 nm) and photosynthetic pigment fluorescence calibrated as chlorophyll a (micrograms per liter) plots were measured with an in-situ SeaTech beam transmissometer and SeaTech fluorometer.

riverine DOM chromophores had begun and the secondary maxima had developed. The pigment ratio, DOM fluorescence, and nutrient data further suggest near-field depletion of riverine nutrients (except, perhaps, silicate) with bloom cessation perhaps accentuated by zooplankton grazing. By implication, downstream productivity depended upon recycled rather than riverine nutrients, which is expected in these waters. Nonetheless, downstream animal population distributions were influenced, albeit in a complex manner, either by the presence of these diluted riverine waters and their residual constituents or by the resulting physical structure imposed upon the system.

Additional chemical indications of the ultimate source of the freshwater anomaly were obtained from discrete water samples collected and analyzed after the cruise. Measurements of the stable oxygen isotope $^{18}O/^{16}O$ ratio show an isotopic depletion with decreasing salinity, consistent with a freshwater source of < -2.7. These values were depleted approximately 0.9 below previous measurements in the region [*Leder, 1994*]. The isotopic data were, however, collected over a comparatively small salinity range, resulting in a large uncertainty in the interpolation. At the 95% confidence level this error could indicate a source as light as -6 . Published data on the isotopic composition of MR water generally indicate isotopically light values (-6 to -8). Elevated concentrations (100 ng L^{-1}) of the triazine herbicide atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine), commonly used throughout the MR Basin agricultural region, were also measured in water samples collected in the Florida Straits [*Goolsby*, 1994]. Atrazine is moderately stable and only slowly degraded in the environment [*Richards et al.*, 1987]. Measurements made in the MR during the peak flood period indicated values of approximately 1500 ng L^{-1} (range 2500- 1000 ng L^{-1}) [*Goolsby*, 1994]. Both the oxygen isotope signature and the atrazine levels agreed reasonably well with the 1:9 dilution of freshwater source waters calculated from the observed salinity in the Florida Straits. Triazine herbicides disrupt electron transfer processes in photosynthesis of plants, including microalgae. The effect of these levels of atrazine and other agricultural toxicants upon marine phytoplankton remains conjectural.

Conclusions

The 1993 MR flood discharged sizeable inputs of fresh water into the Gulf of Mexico during normally dry summer months, typically a period of low river flow when the shelf waters are highly stratified. The MR flow was above its 60-year maximum daily record for some 37 days from August 5 through September 10, 1993. The mechanisms required to produce MR entrainment in the Loop Current and transport to the southeast are (1) a northward position of the Gulf Loop Current and (2) high stratification in shelf waters [*Kourafalou*, 1993]. Contributing factors that can increase the volume and duration of entrainment and enhance remote downstream effects are (1) high river discharge rates and (2) persistent eastward winds. While northward penetrations of the Loop Current are not uncommon in the summer [*Maul*, 1977] and seasonal stratification is predictable, east winds are episodic and high discharge rates are infrequent.

Our observations clearly show a strong connectivity between coastal waters in the Gulf of Mexico, Florida Keys (including the Florida Keys National Marine Sanctuary) and southeast United States, and suggest that comprehensive environmental protection of these waters may have to consider natural excursions in physical, biological, and chemical oceanographic conditions as well as distant and upland contaminant sources. The possibility of interaction of MR waters with the Florida Keys and the east Florida shelf cannot be discounted. There is a comparative paucity of long-term oceanographic observations in coastal regions adjacent to any of the world's major river systems. While low salinities had been noticed in preliminary CMAN readings [*Ogden et al.*, 1994], our presence in the region was entirely fortuitous. Far more systematic observations of coastal conditions are required to determine if the phenomenon we observed was truly anomalous in its occurrence, or merely in its extent and persistence.

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