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Mississippi River water in the Florida Straits and in the Gulf Stream off Georgia in summer 2004

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[1] A coherent plume from the Mississippi River was detected in MODIS imagery in July–October 2004 extending from the eastern Gulf of Mexico into the Florida Straits (FS), and reaching the Gulf Stream (GS) off Georgia. The plume was sampled from ships in the FS and the GS. In early August, the plume was about 10–20 km wide in the western FS and about 50 km wide off Georgia. The FS ship survey (16–26 August) documented a 50 km, 10–20 m deep band with anomalies in surface salinity (−0.8), temperature (0.5°C), and surface chlorophyll concentration (2×) relative to FS waters outside the plume. Nutrient concentrations were only slightly higher in the FS plume and there was no apparent increase in colored dissolved organic matter. We estimate that the plume carried some 23% ($\sim 2778 \text{ m}^3 \text{ s}^{-1}$) of the Mississippi River discharge between July and September 2004 into the GS. **Citation:** Hu, C., J. R. Nelson, E. Johns, Z. Chen, R. H. Weisberg, and F. E. Müller-Karger (2005), Mississippi River water in the Florida Straits and in the Gulf Stream off Georgia in summer 2004, *Geophys. Res. Lett.*, 32, L14606, doi:10.1029/2005GL022942.

1. Introduction

[2] The ocean receives about $3.5 \times 10^3 \text{ km}^3$ of freshwater and 2×10^9 tons of solid and dissolved matter from rivers every year [Milliman, 2001]. Nutrient-rich and turbid river waters affect all forms of marine life, from phytoplankton to coral reefs and seagrass, yet little is known about how far coherent plumes of river water may be maintained in the ocean. Draining 41% of the continental United State, the Mississippi River (MR) is the largest river in North America and ranks as the 8th largest worldwide in terms of discharge (mean $1.35 \pm 0.2 \times 10^4 \text{ m}^3 \text{ s}^{-1}$, based on 64 years of USGS data). Although numerous studies have documented the impact of the MR water on regional ocean properties and processes [e.g., Walker, 1996; Del Castillo *et al.*, 2001; Salisbury *et al.*, 2001; Hu *et al.*, 2003], they mainly focused on the northern Gulf of Mexico (GOM) or on the West Florida Shelf.

[3] Some evidence exists that the MR plume can extend into the North Atlantic. Atkinson and Wallace [1975]

speculated that a low salinity water patch observed in the Gulf Stream (GS) off Georgia was of MR origin, but they had no observations to establish the connection to the GOM. Following a period of very high discharge (the 1993 MR flood), surface drifter, satellite infrared imagery and ship sampling data also suggested entrainment of a plume of MR water into the Florida Current and GS [Ortner *et al.*, 1995]. Numerical circulation models show that there are three possible routes by which the MR plume can get to the Florida Keys [Weisberg *et al.*, 2005, and references therein]. However, direct observations of connectivity between the MR in the GOM and the Gulf Stream have not been documented.

[4] Satellite ocean color sensors such as SeaWiFS and MODIS provide a means to assess river plumes over synoptic scales. Here we use MODIS and in situ data to document a long-lasting MR plume in summer 2004 that extended across the eastern GOM, the Florida Straits (FS), to the GS off Georgia in the South Atlantic Bight (SAB).

2. Data and Methods

[5] Satellite ocean color and sea surface temperature (SST) data were obtained from the MODIS sensors. To increase the contrast between water masses with different optical characteristics, three visible channels were combined to generate an “enhanced RGB” (ERGB) product (Figure 1).

[6] Continuous near-surface (~ 2 m depth) salinity, temperature, and chlorophyll and colored dissolved organic matter (CDOM) fluorescence were measured in the GS off the SAB using the R/V *Savannah* on 9–11 August 2004. Hydrographic, chlorophyll concentration, and CDOM absorption coefficient measurements were collected off SW Florida from the R/V *Walton Smith* on 16–26 August 2004. A surface drifter released near the Dry Tortugas (Florida Keys) traced surface currents between 22 August and 8 October 2004.

3. Results

[7] The MR plume is evident in the MODIS ERGB imagery (Figure 1) as a dark, elongated feature extending from the delta toward the southeast. The Loop Current (LC) is also visible and is outlined in satellite altimetry data. The surface drifter (Figure 1) took 25 days to move from the middle Keys (1 September 2004, 24.57°N 80.94°W) to the SAB (25 September 2004, 32.04°N 78.32°W).

[8] Time series of MODIS images distinctly show the MR plume extending from the delta to the southeast into the

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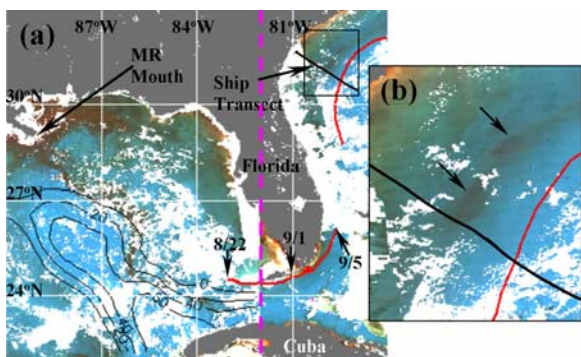


Figure 1. MODIS ERGB image showing the Mississippi River plume extending from the river mouth to the FS (a) and into the SAB (b). The image is a composite of surface reflectance at 551 nm (R), 488 nm (G), and 443 nm (B). West of 82°W (dashed pink line): from 30 July and 1 August 2004. East of 82°W: from 9–10 August 2004. Black line in (b) shows cross-shelf ship survey in the SAB (11–12 August). Plume features in the SAB are marked with arrows. Overlaid on (a) are the surface drifter track from the Dry Tortugas (on 8/22/04) to the SAB (red line) and the sea surface height anomaly (SSHA) contours from 0 to 60 cm for 1 August 2004 (data courtesy of R. Leben, University of Colorado). These features agree with those obtained from a numerical circulation model (Courtesy of Naval Research Lab at Stennis, Mississippi; not shown). White color represents clouds, missing data, or MODIS algorithm failure.

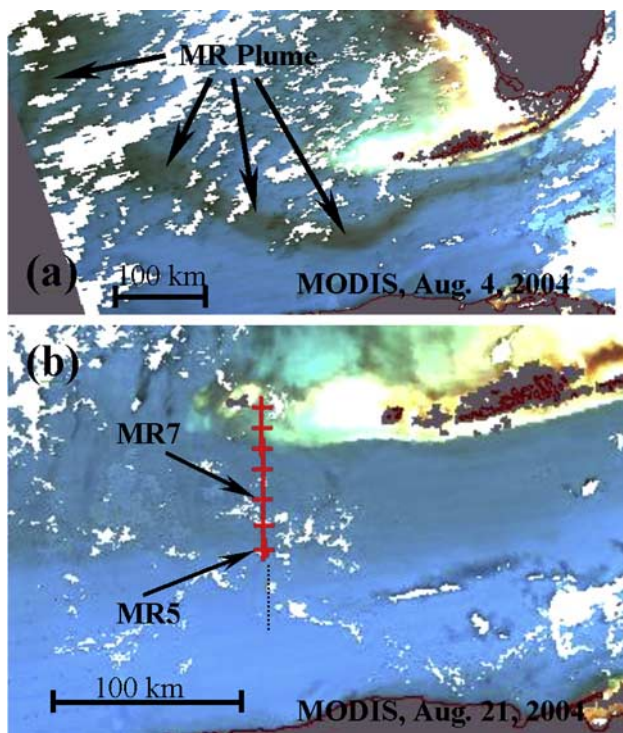


Figure 2. MODIS ERGB images showing the MR plume (dark feature) in the FS. Overlaid on the 21 August image are locations of cruise stations (crosses; 22–23 August). The dotted black line indicates a virtual transect where MODIS reflectance data were studied.

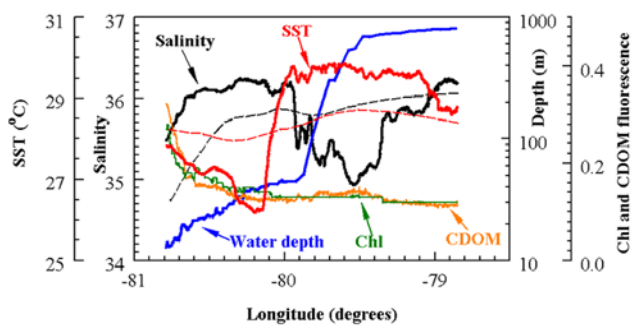


Figure 3. Near-surface water properties along the transect line in the SAB (11–12 August 2004, Figure 1b). Dashed lines indicate climatological means for temperature and salinity for this section of the Georgia shelf and Gulf Stream [Blanton *et al.*, 2003].

GOM in early July 2004. This plume became entrained around the eastern side of an anti-cyclonic eddy in the northern GOM and the LC in mid-July. The plume entered the FS in late July (it was not possible to determine the exact date due to cloud cover). The 4 August image (Figure 2a) showed the plume as a distinct 10–20 km wide dark band in the FS. Subsequently, the plume spread in the N-S direction and reached 50–60 km in width in the FS later in August (Figure 2b). By late October the plume was no longer detected in MODIS imagery.

[9] MODIS ERGB imagery showed that the MR plume reached approximately 34°N 76°W, off the GS off Georgia, on 9 August 2004. The plume seemed to be entrained into a series of GS frontal eddies along the continental margin. A 50-km wide low salinity plume was confirmed by shipboard

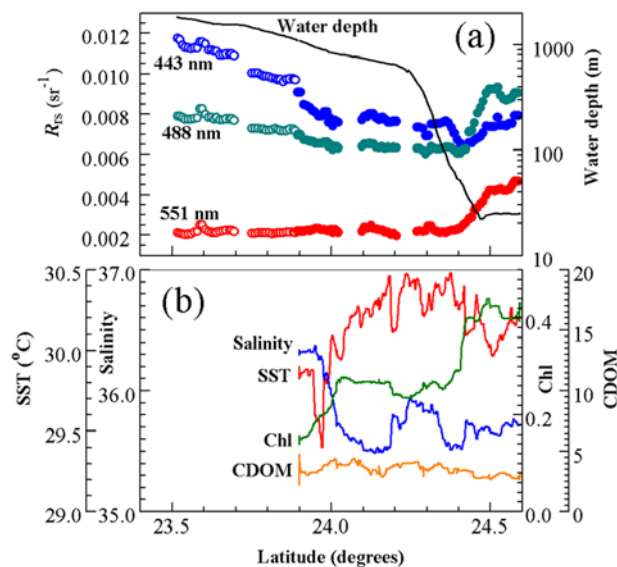


Figure 4. Characteristics of near-surface water in the FS. (a) MODIS remote sensing reflectance (R_{rs}) on 21 August 2004, and (b) in situ data along ship transect of Figure 2b. Open symbols in (a) identify areas where no match-up ship data were available. Chlorophyll (Chl) and CDOM shown as fluorescence (relative units).

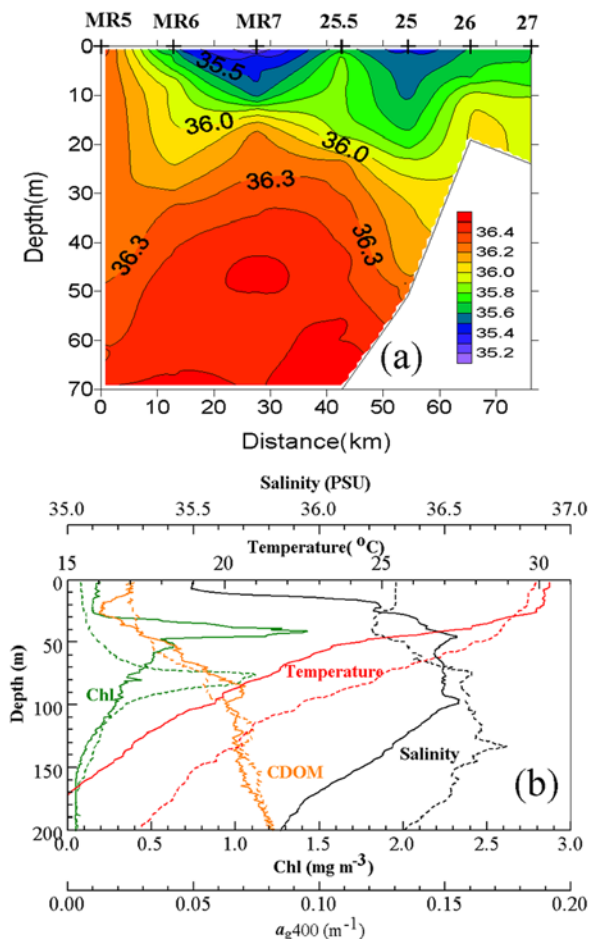


Figure 5. (a) Salinity distribution along the FS transect (Figure 2b). Distance (in km) starts from mid FS (station MR5) and extends north toward the Florida Keys. (b) Vertical profiles of properties at stations MR5 (dotted lines) and MR7 (solid lines). a_{g400} is the CDOM absorption coefficient at 400 nm, measured as CDOM fluorescence but calibrated with discrete water samples.

measurements in the GS off the SAB shelf on 11–12 August (Figure 3). The plume had higher temperature and slightly higher CDOM fluorescence relative to adjacent ocean water, but no detectable increase in near-surface chlorophyll fluorescence. However, a station profile (31.03°N, 79.74°W) showed that chlorophyll fluorescence increased at 10–30 m depth, toward the base of the low salinity surface layer.

[10] MODIS remote sensing reflectance (R_{rs}) data along the FS ship transect (Figure 2b) showed the Mississippi plume and clear Florida Current water to the south (Figure 4a). Low-salinity waters (<36) showed significantly (>30%) lower R_{rs} (443 nm) than clear Florida Current water near 23.5°N. The contrast was less at 488 nm and was minimal at 551 nm.

[11] In the FS, in situ chlorophyll fluorescence and temperature were higher within the low salinity feature. There was no noticeable trend in CDOM fluorescence across the FS. Short-scale variation in properties between 24°N and 24.4°N indicate banding in the low salinity waters in a direction parallel to the coast. This is visible in

variations in the contrast of the plume in Figure 2b, and is consistent with the findings of *Ortner et al.* [1995].

[12] CTD casts performed in the FS (Figure 5) showed differences between the interior of Florida Current (station MR5; 23.90°N 82.76°W; Figure 2b) and the plume (station MR7; 24.15°N 82.76°W). Surface salinity was lower in the plume (35.5 at MR7 versus 36.3 at MR5), surface temperature was higher (30.3 versus 29.8°C), as was the chlorophyll concentration (0.17 versus 0.08 mg m⁻³). The near-surface CDOM absorption coefficient was similar at both stations, but CDOM absorption showed a minimum at about 25 m at MR7. The thermocline and subsurface chlorophyll maximum were shallower by about 50 m in the plume. The low salinity layer (35.5) at MR7 was about 10 m deep and salinity increased to 36.24 at 20 m. Between 50 and 100 m, salinity profiles at MR5 and MR7 were similar.

[13] Nutrient concentrations were only slightly higher in the low salinity feature relative to outside the plume. Surface nitrite plus nitrate concentration was 0.16 μM at MR7 and below the detection limit elsewhere along the N-S transect; total phosphate was only 0.03 μM at MR5 and MR7, and at or below the detection limit elsewhere. Total silicate and ammonia were low at all stations (at MR5 silicate reached 0.38 μM and ammonia was 0.54 μM).

[14] Based on MODIS imagery collected between August and October 2004, in situ hydrographic data, and surface drifter motion, we estimated the freshwater flux through the FS from August to October 2004. Assuming a surface plume salinity of 35.5, a saline marine end member of 36.0, a plume 10 m deep and 50 km wide (Figures 2b and 5a), and an average surface current of 0.4 m s⁻¹ (the drifter speed in the Florida Current was >1 m/s, but this would likely decrease closer to the coast), we estimated that the freshwater flux entrained in the Florida Current was ~2778 m³ s⁻¹ (i.e., $(1 - 35.5/36) \times 10 \text{ m} \times 50 \text{ km} \times 0.4 \text{ m s}^{-1}$). This is about 23% of the mean MR discharge for this period ($1.22 \pm 0.51 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ for July–September 2004, based on USGS river gauge data). Consequently, we estimate that in about three months, $\sim 2 \times 10^{10}$ metric tons of fresh water reached the FS and GS via the plume. This is a conservative estimate, because 36.0 was assumed as the marine end member for salinity. Similarly, assuming a 12:1.7:1 weight ratio for N:P:Chl within phytoplankton (G. Vargo, USF, personal communication) and Chl anomaly of 0.09 mg m⁻³ in the plume, total chlorophyll that reached and FS and GS in the plume between August and October 2004 was estimated to be $93 \times 10^6 \text{ g}$, corresponding to 158 tons of total phosphorus and 1116 tons of total nitrogen. Further, using a Redfield molar ratio of 106:16 for C:N, we estimated the total carbon flux to be 6337 tons.

4. Discussion

[15] While the Mississippi River plume often flows to the west in the northern GOM, a large portion of the discharge flows toward the southeast, particularly during summer months. Satellite ocean color imagery obtained in the late 1970s and early 1980s provided early indications of eastward dispersal of the Mississippi River plume [*Müller-Karger et al.*, 1991]. Between 1998 and 2004, eastward and southward dispersal occurred every

year [e.g., *Hu et al.*, 2003]. The present study confirms that the MR plume can remain a coherent feature over large distances (1000–2000 km) when entrained in the Loop Current–Florida Current–Gulf Stream system, affecting water properties in the Gulf Stream as far as off Georgia.

[16] We were surprised to find no apparent increase in CDOM across the MR plume in the FS (Station MR7, Figure 5b). The CDOM absorption coefficient at 400 nm (a_{g400}) measured in the MR plume during two summer cruises in the northeastern GOM in 1998 and 1999 was about 0.7 m^{-1} at a salinity of 25 [*Hu et al.*, 2003]. If the mixing were conservative, and assuming that a_{g400} was 0.02 m^{-1} for the marine end-member (salinity of 36.3), at MR7 (salinity = 35.5) a_{g400} would be $\sim 0.07 \text{ m}^{-1}$. Figure 5b suggests that CDOM in the MR plume may have been photochemically degraded (bleached) during its transit to the FS (a distance of >1000 km over about a month, assuming an average speed of 0.3 m s^{-1}). The slight increase in CDOM observed in the plume in the SAB (Figure 3) might have resulted from degradation of phytoplankton.

[17] Could the low-salinity water near the SW Florida coast (the dark brownish color in Figure 1a) and/or the excessive rainfall in summer 2004 contribute to the coherent dark plume (associated with low salinity) in the FS and therefore affect our salinity end member estimate? The large, dark patterns observed near and in the FS were disconnected from the dark low-salinity water seen near the SW Florida coast, as revealed by MODIS imagery and by cross-shelf salinity profiles. This was different from fall 2003, when coastal dark water was advected toward the Dry Tortugas by favorable winds [*Hu et al.*, 2004]. Precipitation estimates over the ocean, obtained from the Tropical Rainfall Measuring Mission (TRMM satellite), did not reveal coherent patterns that would result in the offshore plumes seen in the MODIS images. Hence, the freshwater flux estimates appear to be valid.

[18] The underlying dynamics that result in the eastward transport of the MR plume entail complex interactions between the effects of local and deep-ocean forcing on the WFS currents and the deep ocean circulation system of the GOM and the governance of the eddies [*Weisberg et al.*, 2005, and references therein]. Further research is required to understand the exact driving forces for the persistent MR plume in summer-fall 2004.

5. Summary and Conclusion

[19] In July–October 2004, MODIS imagery was used to study the Mississippi River plume in the Florida Straits (FS) and off the South Atlantic Bight (SAB) in the Gulf Stream (GS). The plume was identified as a coherent dark feature in the imagery caused by the absorption of blue-light by elevated concentrations of phytoplankton and/or CDOM in the plume.

[20] The plume was entrained into the eastern Gulf of Mexico in early July 2004, meandered south along the eastern edge of the Loop Current along the 200–500 m isobaths off the West Florida Shelf, and entered the FS in late July. Upon entering the FS, the plume was 10–20 km

wide and expanded to about 50 km subsequently. The plume flowed parallel to the Florida Keys, and persisted for over two months (August–October 2004).

[21] The plume reached about $34^{\circ}\text{N } 76^{\circ}\text{W}$ by 9 August. A survey east of Georgia across the GS (9–11 August) revealed a low-salinity band (anomaly of up to 1) of ~ 50 km wide just seaward of the shelf break. Surface CDOM fluorescence was slightly higher in the plume, possibly due to decay of phytoplankton along the path of the plume. Chlorophyll was not detectable in surface waters off the SAB, but sea surface temperature in the plume was slightly higher ($\sim 0.5^{\circ}\text{C}$) than in adjacent waters.

[22] Ship surveys in the FS in late August confirmed the width of the plume (~ 50 km) and revealed that the depth of the plume was 10–20 m. The color anomaly (>30 % decrease in the blue light reflectance) was associated with a decrease in salinity (-0.8), a slight increase in temperature ($\sim 0.5^{\circ}\text{C}$), and an increase in Chl (2x from 0.08 to 0.17 mg m^{-3}). There was no apparent increase in the CDOM absorption coefficient, possibly due to photobleaching. Slight increases in nutrient concentrations were found in the plume relative to nearby waters. We estimated that at least 23% ($\sim 2778 \text{ m}^3 \text{ s}^{-1}$) of the Mississippi water discharged between July and September reached the FS between August and October 2004, where total excessive chlorophyll (relative to the clear GS) amounted 93 tons, corresponding to roughly 158 ton of total phosphorus, 1116 ton of total nitrogen, and 6337 ton of total organic carbon.

[23] The slightly higher temperature in the plume is likely due to higher light absorption and high stratification of water. Such temperature differences are difficult to detect in satellite SST imagery, because the accuracy is in the order of $\pm 0.5^{\circ}\text{C}$. SST imagery is also limited due to minimal surface contrast during summer in tropical and subtropical waters. However, ocean color imagery, such as those from MODIS, can trace anomalous waters thousands of kilometers away, providing a unique tool to study circulation and changes in biogeochemistry of local waters.

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