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Property fields in an effluent plume of the Mississippi river

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Abstract

Surface property distributions were mapped in the Mississippi River plume during May and August, 1993 while following surface drifters. Prevailing winds were the primary factor controlling the orientation of the plume. In May, under typical southeasterly winds, the plume turned anticyclonically towards the coast, while in August, under anomalous westerly winds, the plume turned east. Remote imagery of sea surface temperature and suspended sediments confirmed the direction of the plume. Optimally interpolated maps of surface salinity, temperature, chlorophyll *a* fluorescence, and transmissivity from underway sampling, and periodic nutrient samples, reveal the plume structure. In May concentrations of nitrate, silicate, and phosphate decreased linearly with increasing salinity. Chlorophyll *a* increased to peak concentrations of 10 μg l^{-1} in the plume, although higher pigment biomass was observed near the coast. In August nitrate and silicate concentrations decreased conservatively near the mouth of SW Pass, except where pigment biomass was enhanced in a convergent surface front. Surface nutrient concentrations in the plume also decreased with increasing salinity. The observations provide the first Lagrangian view of surface property distributions in the Mississippi River plume, and indicate that significant temporal variability exists in physical and biological properties within a day after waters are discharged from the river delta. © 1997 Elsevier Science B.V.

1. Introduction

The Gulf of Mexico receives more than half of its freshwater input from the Mississippi River (Deegan et al., 1986). The Mississippi watershed drains > 40% of the contiguous United States, including the heavily fertilized farmlands of the Midwest, and significant quantities of sediments and dissolved nutrients are delivered to the Gulf by the river. Freshwater from the Mississippi enters the Gulf through Atchafalaya Bay to the west and the birdsfoot (Belize) delta to the east. Seventy per cent of the total river discharge flows from the delta. The freshwater enters the Gulf through three large passes, the largest of which is Southwest Pass (SW Pass), and through several small channels and numerous crevasses.

Nearly twenty years ago Wiseman et al. (1976) described the freshwater plume that originates at SW Pass in a Liège Colloquium. Subsequent field studies have examined the influence of bottom topography,

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the Coriolis force, and prevailing winds on the structure of the plume and the circulation on the Louisiana shelf. The plume of the Mississippi River is similar to the effluent plumes of the Po and Nile rivers, since all three discharge into semi-enclosed seas with minimal tidal range (Wiseman and Garvine, 1995). In comparison to the Chesapeake, St. Lawrence and Columbia rivers, however, the plume at SW Pass has a small Kelvin number, so the Coriolis force has little influence on the direction of the plume at its origin (O'Donnell, 1993).

The orientation of the plume, and consequently the direction of freshwater discharge on the shelf, is regulated by winds and currents. In surface imagery the plume frequently turns northwest towards the coast (Rouse and Coleman, 1976; Walker and Rouse, 1993). Throughout much of the year the prevailing winds in the northern Gulf of Mexico are from the southeast (Cochrane and Kelly, 1986). The diurnal tides about the delta are relatively weak, with amplitudes of 30 cm, and they have less influence on the plume (see Wright and Coleman, 1971). Thus the combined effects of volume discharge, winds, and the Coriolis force are the principal factors that regulate the direction of the freshwater discharge on the Louisiana shelf (Dinnell and Wiseman, 1986).

The freshwater discharge from the Mississippi River delivers a large flux of dissolved nutrients to the shelf (Walsh et al., 1981; Turner and Rabalais, 1991). An estimate of the magnitude of the riverine nitrogen flux delivered to the shelf is on the order of 3000 and 4000 tonnes of nitrate and total dissolved nitrogen per day, respectively (Table 1). Since nitrate contributes, on average, nearly 56% of the total dissolved nitrogen in the river (Dinnel, 1995), the two estimates agree well. The value for nitrate flux is 50% of that estimated by Dagg and Whitledge (1991), who calculated that a nitrogen flux of this magnitude is capable of sustaining rates of "new" primary production at 30 g m^{-2} yr^{-1} of C on the western Louisiana shelf. The impact of riverine nitrogen on shelf productivity is confirmed by rates of production that exceed 1 g m^{-2} day^{-1} of C (Lohrenz et al., 1990; Redalje et al., 1994). In summer, the high productivity rates in the stratified water column of the western Louisiana shelf contribute organic matter which fuels the development of hypoxic conditions in the nearshore waters (Rabalais et al., 1991). Low oxygen concentrations in near-bottom waters alter the distribution of benthic organisms and the commercially fisheries on the western Louisiana shelf.

Table 1
Estimates of the daily nitrogen flux, in metric tonnes (t), delivered to the Louisiana shelf through the Mississippi River delta

1. Nitrate-N daily flux	
Average daily nitrate-N [a]	2.2 mg l^{-1}
Average discharge rate [b]	14.0×10^{3} m^{3} s^{-1}
Conversion factors	10^{5} s d^{-1}
	10^{3} l m^{-3}
Nitrate-N flux	3080 t d^{-1}
2. Total daily nitrogen flux derived from Dinnel (1995)	
Annual total-N flux	115×10^{9} mol yr^{-1}
Molar equivalent	14 g mol^{-1}
Daily equivalent	365 days yr^{-1}
	10^{6} g t^{-1}
Total nitrogen flux	4410 t d^{-1}

The nitrate-nitrogen estimate is derived from long-term, mean concentrations and river discharge rates.
The estimate for total inorganic nitrogen is calculated from total dissolved nitrogen measurements from 1979 to 1992. A mean of 59% of the total nitrogen was found as nitrate nitrogen in Dinnel (1995), equivalent to a nitrate flux of 2602 t d^{-1}, or 84% that derived from Turner et al. (1987) and Walker et al. (1994).
[a] Turner et al. (1987).
[b] Walker et al. (1994).

The Lagrangian-based observations described below were one component of a research program which sought to determine the influence of the Mississippi River on the coastal ecosystem of the western Louisiana shelf. This multi-investigator study, the Nutrient Enhanced Coastal Ocean Productivity (NECOP) program, was sponsored by the National Oceanic and Atmospheric Administration (Atwood et al., 1994). One of the objectives of our component was to determine the rate at which surface properties change as river water enters the shelf. In general, previous studies have described the "plume" in a regional sense by mapping the distribution of surface salinities. Salinity has been frequently employed as a tracer for circulation and as an index to the proportion of river water in the surface layer, although salinity distributions do not indicate time-since-discharge. In our study the time dependent change in surface properties within the plume were observed while following surface drifters.

A series of surface drifter deployments were conducted in the effluent plume of SW Pass in spring and summer, 1993. The main objective of the study was to describe the kinematics of the flow field and document the time course of water parcels as they transit onto the shelf. The second objective, the focus of this paper, was to determine the temporal and spatial variability of surface properties in the plume. As the ship tracked the drifters, the surface salinity, temperature, chlorophyll *a* fluorescence, and transmissivity were continuously mapped. Samples collected at 30 to 60 min intervals for dissolved nutrients and pigments (chlorophyll *a*). Rapid changes were observed in the physical, chemical and biological fields, with the highest gradients observed within a day after water parcels exit SW Pass. Furthermore, the Lagrangian observations revealed that nutrient concentrations within the plume are regulated by conservative mixing.

2. Methods

In May, 1993 a series of drifter deployments were made during the annual maximum in river flow, when discharge from the Mississippi River exceeded 30×10^3 m^3 s^{-1}. This volume discharge was twice that of the 63 year mean for the month of May (14×10^3 m^3 s^{-1}). The May, 1993 discharge rate also exceeds the long-term mean discharge in the spring by almost 50% (Walker et al., 1994). As is typical in the spring, winds were light and predominantly from the southeast. A second series of drifter deployments took place in August, 1993. In June and July strong thunderstorms persisted in the upper Mississippi drainage basin. The high rainfall contributed to a record flow in the Mississippi River and extensive flooding occurred throughout the upper half of the drainage basin (Dowgiallo, 1994). Discharge rates for the Mississippi River in August, 1993 were the highest summer rate in the 64 year history of records, exceeding 20×10^3 m s^{-1}. The river flow was nearly double the long-term, mean discharge for the month of August (Walker et al., 1994). Additionally, the winds along the coast in summer, 1993 had a strong westerly component. Thus the drifters were deployed during a strong spring runoff in May, and during an exceptionally strong summer discharge period in August.

Each drifter deployment was preceded by a survey of the surface properties near the delta. Salinity, temperature, chlorophyll *a* fluorescence and transmissivity were measured on water pumped from 2 m by the Multiple Interface Data Acquisition System (MIDAS) on the R/V *Pelican* (Walser et al., 1993). Observations were recorded at 5 s intervals. After the fresh water plume was mapped, the surface drifters were deployed near SW Pass along a line perpendicular to the axis of the plume. Eight vhf-tracked Coastal Ocean Dynamics Experiment (CODE) drifters (Davis, 1985) were deployed in May and followed for a maximum of 36 h. Drifter positions were determined by moving the ship and triangulating the vhf transmissions. After 24 h the trajectories of the drifters began to diverge as they entered the Louisiana Coastal Current south of Barataria Bay, so only the observations from the first 24 h are discussed here.

The positioning of the surface drifters required that the ship be continually moved to remain ahead of, and within a few km of, the drifters. Thus the property fields derived from the MIDAS system mapped the surface distributions in the plume before the passage of the drifters. The shiptrack and drifter trajectories are superimposed on remote imagery of the suspended sediment field and sea surface temperature (SST) in Fig. 1.

In the August study three modified CODE drifters were deployed with Global Positioning System (GPS) receivers to record positions. The positions and corresponding times were relayed to the ship at 30 min intervals through a vhf signal at 154 MHz. This tracking system permitted the ship to closely follow the drifters and conduct a series of CTD casts in the center of the drifter triad. After the first deployment was completed on August 23, year day (YD) 235, a second deployment was begun on August 24. The drifter trajectories and property distributions in both deployments were very similar, so only observations from the first deployment are presented here.

The seawater from the MIDAS system was sampled for chlorophyll *a* and nutrients at 30 to 60 min intervals. The fluorometer reading on the MIDAS system was recorded as fifty ml samples were collected for chlorophyll *a* analyses. Duplicate aliquots were filtered onto GF/F filters and extracted in 90% acetone (Parsons et al., 1984). Fluorescence was read

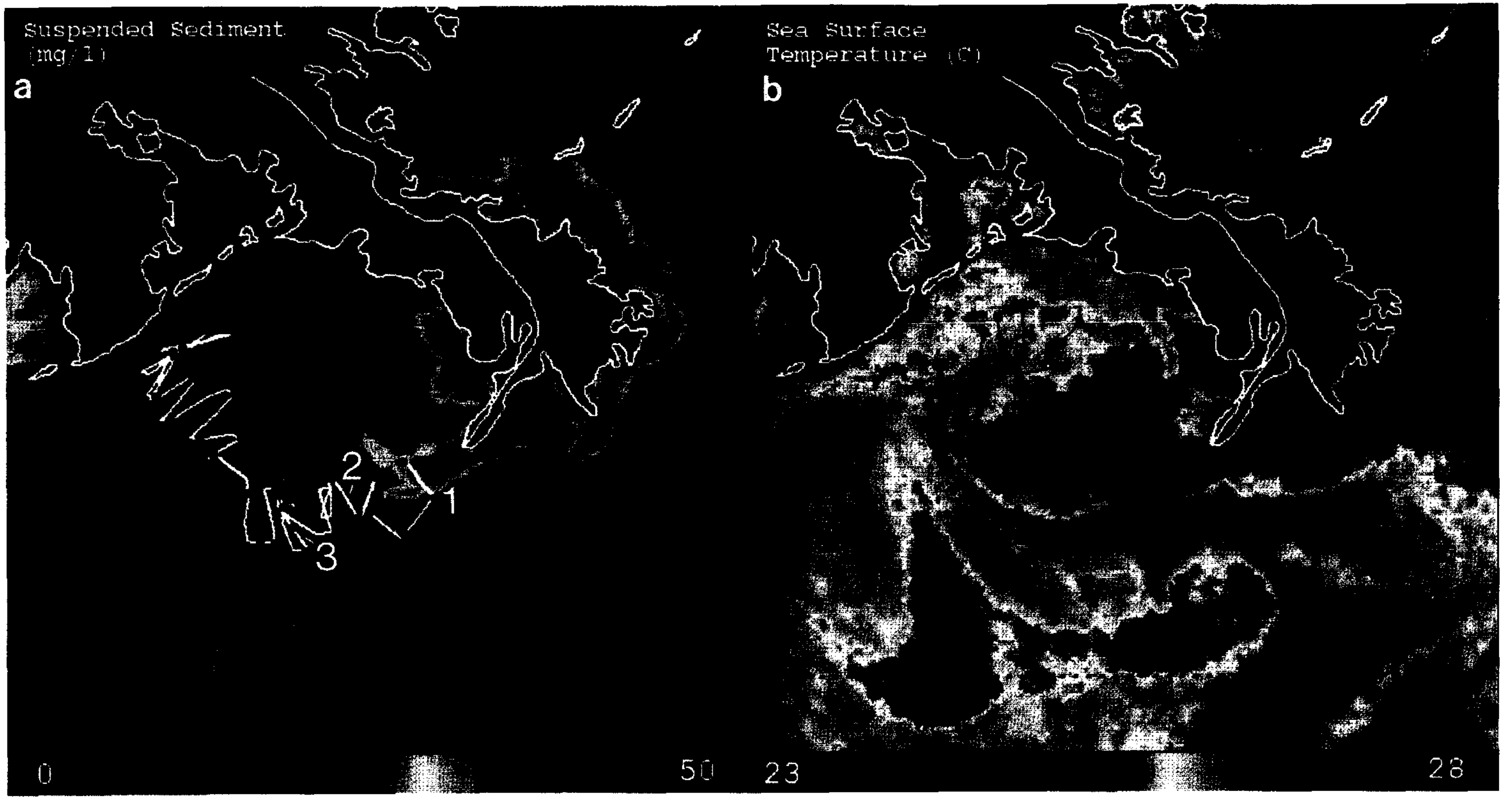

Fig. 1. (a) Image of suspended sediment processed from AVHRR data with methodology as described by Walker and Rouse (1993). Yellow/orange colors correspond to highest sediment concentrations with blue in the clearest waters. The white line indicates the track of R/V *Pelican* during the drifter deployment with transects 1, 2, 3 discussed in the text. The ship position at the time of the image is indicated on Transect 2 by a black dot. Red dots correspond to sampling locations for surface nutrients and chlorophyll *a*. (b) NOAA AVHRR image of SST from May 22, 1993 at 21:25 GMT. Temperatures range from 23°C (blue) to 28°C (red). The eight lines indicate the drifter trajectories with positions at hourly intervals.

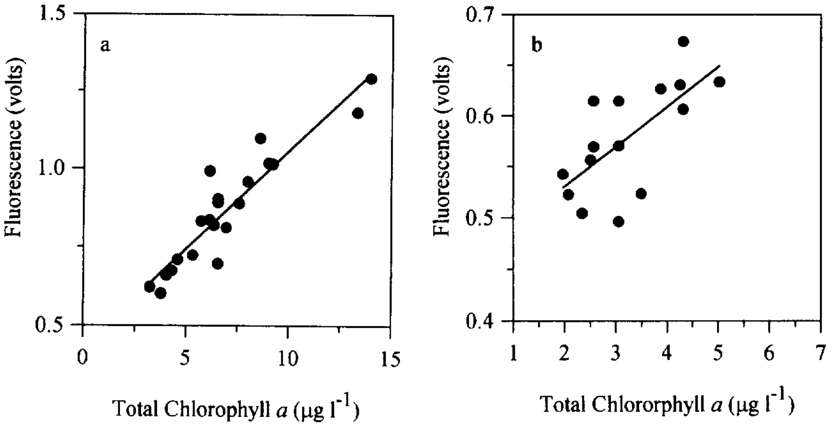

Fig. 2. Fluorescence values (in V) from the MIDAS system as a function of chlorophyll *a* as μg l^{-1} during the drifter deployments in (a) May and (b) August.

before and after acidification on a Turner Designs 10-001 fluorometer to estimate chlorophyll *a* and phaeopigment concentrations. The instrument was calibrated with pure chlorophyll *a* from Sigma Chemical Company. A linear correlation existed between fluorescence and chlorophyll *a* in May, although there was considerably more scatter in August (Fig. 2). Surface maps of fluorescence are in relative units (V), with the chlorophyll *a* and phaeopigment *a* concentrations in various regions of the plume discussed in the text.

In May nutrient samples were stored in acid-cleaned polyethylene bottles in a refrigerator. Nutrient analyses were done onboard the ship on an Alpkem automated nutrient analyzer with analyses for nitrate, silicate and phosphate as described in Whitledge et al. (1988). Although nutrients were analyzed and quality controlled by an experienced technician, the silicate values increased three-fold halfway through the deployment. There was no obvious indication why the apparent "step function" occurred in the silicate analysis, and we have been unable to identify high-silicate (> 80 μmol kg^{-1}), saline (salinity > 25‰) waters in the historical, or contemporary, data from the Louisiana shelf. On the shelf surface waters with salinity = 25‰ originate from a mixture of higher-salinity Gulf waters and fresher Mississippi River water (Wiseman et al., 1982). It was very unlikely that in sequential samples taken only 30 min apart the concentration of one nutrient (Si) would suddenly increase 3-fold in the plume. We therefore conclude that an error occurred in the silicate analyses due to a three-fold dilution in the last half of the analyses. The silicate values for these samples have been corrected by a factor of 0.33. In August the nutrient samples were filtered and stored at −20°C until automated analyses were completed ashore. No inconsistencies were found in the August dataset.

Objectively analyzed maps of surface salinity, temperature, fluorescence, and transmissivity were constructed from the surface MIDAS system data with the parameter matrix technique (Mariano and Brown, 1992). The method decomposes a set of observations into a series at three scales of variability. The largest scale is first estimated by fitting a least-squares, two-dimensional bicubic spline to the data. Residuals about this large-scale trend surface are then smoothed by objective analysis (OA). The final field estimate is the sum of the spline surface and the OA map of the residuals. This method is well-suited for describing time-varying properties in dynamic regions such as the coastal waters of the Louisiana shelf. Maps of surface fields correspond to the mid-point of the drifter deployments.

3. Results

3.1. May, 1993

Remote images of suspended sediment and SST show that during the drifter deployment the plume exhibited an anticyclonic turn towards the coast (Fig. 1). This image was taken on May 22 at 21:25 GMT, 16 h after the drifters were deployed, with the corresponding position of the ship at the time of the image indicated in Fig. 1a. The anticyclonic turn of the plume to the northwest is consistent with the prevailing SE winds (Walker and Rouse, 1993). Surface distributions of particulate matter derived from the visible and near-infrared channels of the AVHRR show highest concentrations near the mouth of SW Pass (Fig. 1a). The suspended sediment distribution suggests that the plume bifurcated west of the delta at 89.6° W. The SST image reveals warmer surface waters along the southern edge of the plume that extended into the Louisiana Bight (Fig. 1b). The filament of warm surface waters appeared to originate near the Loop Current at 28° N, 89° W. The warm surface feature was not present in an SST image from 10:06 GMT, 11 h before Fig. 1b.

Trajectories of the eight CODE drifters are included on the SST image (Fig. 1b). Four drifters were in the cooler surface waters along the shoreward edge of the feature, while the remainder were in the warmer surface waters to the south. All of the drifters remained within the plume, for the salinity distribution across the width of the plume was relatively uniform at any time, and there was no evidence of a horizontal surface front (Fig. 3). None of the drifters stalled in the surface property front at the western edge of the plume until the following day, when all drifters were south of Barataria Bay. The trajectories indicate that the width of the plume rapidly increased, and that there was considerable horizontal shear across the feature (Boicourt et al., in preparation).

The objectively interpolated (OA) maps of surface properties from the MIDAS data confirmed the plume structure seen in the remote imagery. Surface waters along the northern edge of the plume were at 24°C, about 3°C cooler than the surrounding shelf waters at 27°C (Fig. 3a). As in the SST image, the OA map of surface temperature indicated that surface temperatures along the seaward edge of the feature were 26°C. Surface salinity, in contrast, was relatively uniform across the width of the plume at any given time. Near the mouth of SW Pass the surface salinity was $< 10‰$, while surface salinity along the northern edge of the feature was 15‰. There was considerable variability in the surface salinity at scales of km at 89.9° W, near the mid-point of the deployment. South of Barataria Bay the surface waters were warmer ($> 30°C$) and more saline ($> 24‰$) than in the plume.

The spatial distribution of fluorescence in the plume was complex (Fig. 3c). Near the mouth of SW Pass, and in the coastal waters south of Barataria Bay, chlorophyll *a* and phaeopigment *a* concentrations were low, typically $< 2\ \mu g\ l^{-1}$. Corresponding fluorescence values from the OA map (Fig. 3c) are consistent with the chlorophyll–fluorescence relationship (Fig. 2), suggesting that the surface pigment field was as heterogenous as the fluorescence distribution. Chlorophyll *a* biomass increased with time along the axis of the plume, with surface concentrations increasing from 2 to $> 10\ \mu g\ l^{-1}$ in 12 h. The maximum chlorophyll concentrations in the plume coincide with the maximum fluorescence values (red) in the surface OA map. Phaeopigment concentrations, in contrast, remained at $< 2\ \mu g\ l^{-1}$ throughout the deployment. Surveys of surface pigment distributions in the Louisiana Bight before the deployment found chlorophyll *a* concentrations of 25 $\mu g\ l^{-1}$, with phaeopigment *a* concentrations of 5 $\mu g\ l^{-1}$ shoreward of the plume. Thus the low-salinity waters of the plume did not correspond to the region of maximum chlorophyll biomass.

The objectively analyzed map of transmissivity in the plume indicates that riverine particulate material settled rapidly. As indicated in the remote imagery, highest concentrations of suspended material were found near the mouth of SW Pass (Fig. 3d). The western extent of the highly turbid waters in the AVHRR image coincided with the strong gradient in transmissivity at 90° W. Both the remote imagery and MIDAS data reveal that suspended sediments decreased to levels typically found on the western Louisiana shelf within a day after river waters are discharged from SW Pass.

Transects of surface salinity and transmissivity across the plume axis show variability in the plume structure on spatial scales of kilometers. Transect 1 corresponds to the deployment line west of SW Pass (see Fig. 1a). A 1 km wide filament existed at the northern edge of the plume, while within the broad axis of the plume the minimum salinity was 12‰ (Fig. 4a). Narrow, low-salinity filaments were fre-

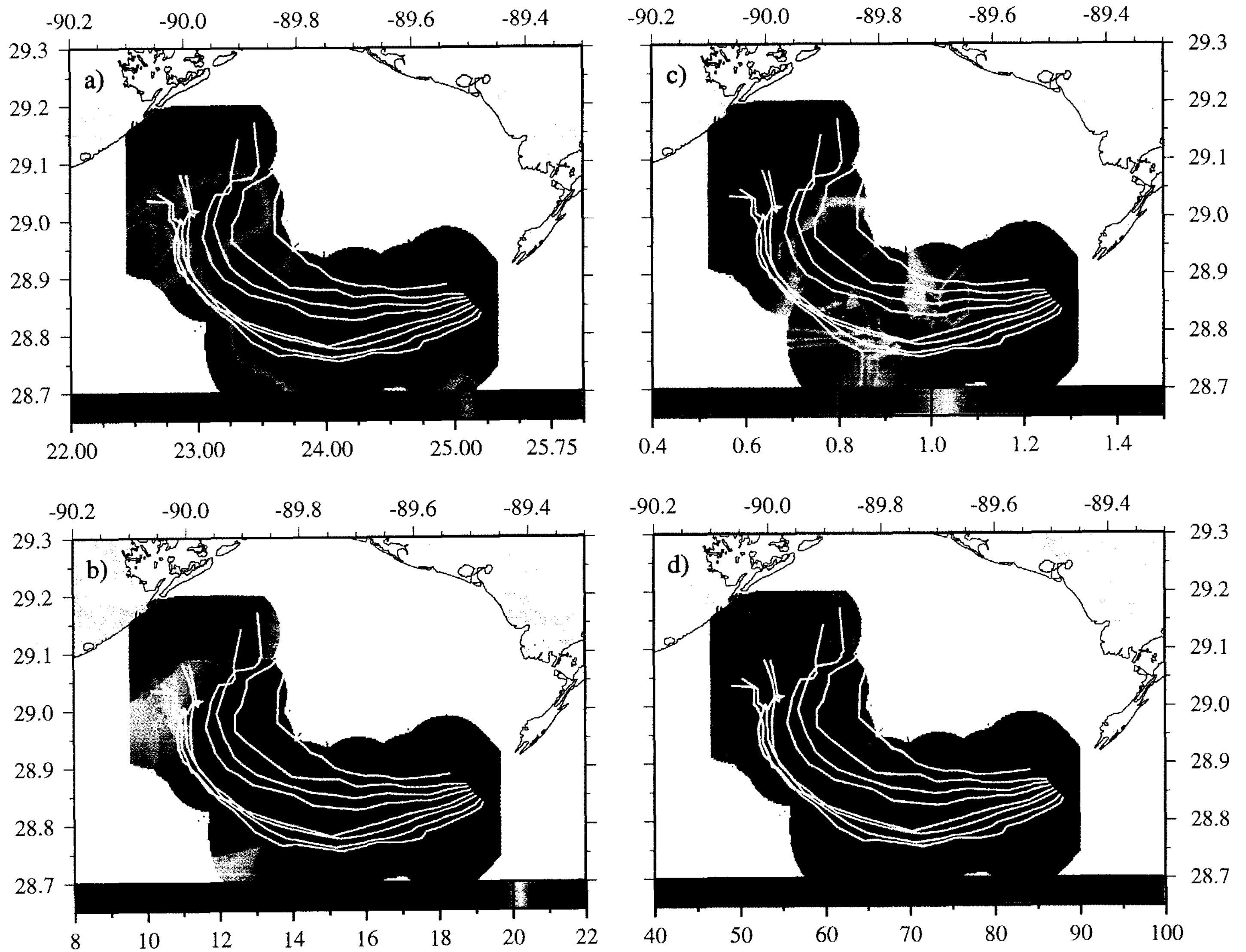

Fig. 3. Objectively analyzed maps of (a) surface temperature in °C, (b) salinity, (c) fluorescence as V, and (d) % transmittance. Surface fields are mapped from the temporal midpoint of the deployment. Color scales correspond to low (purple) to high (red) values for each property with white lines depicting trajectories of the drifters.

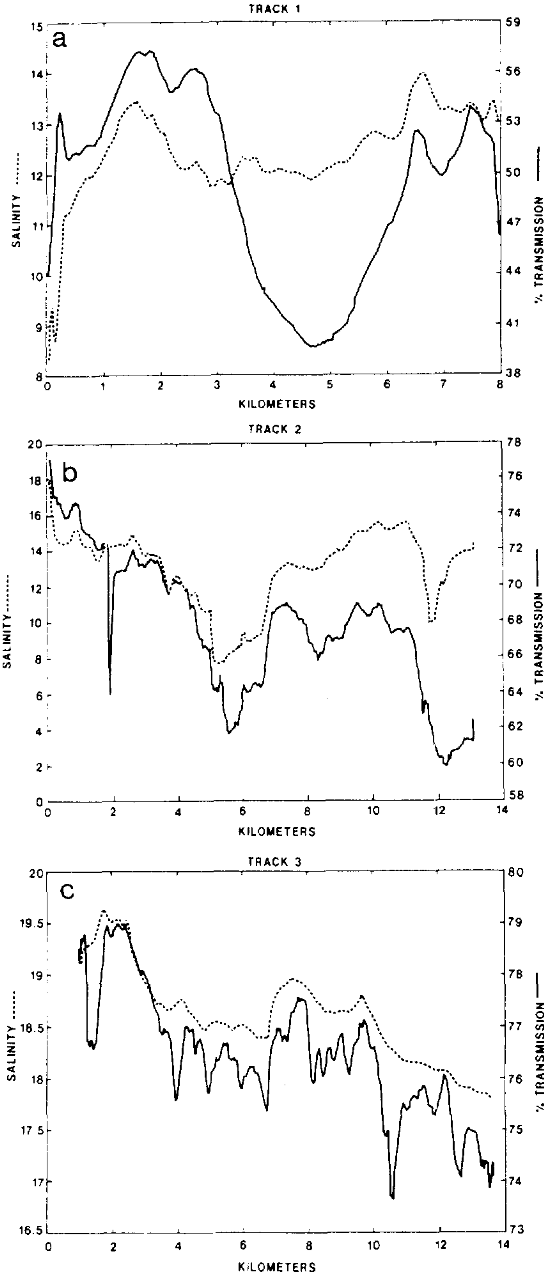

Fig. 4. Salinity and percent transmittance from transects (a) 1, (b) 2 and (c) 3 in Fig. 1a.

quently found along the edge of the plume near SW Pass. Considerable structure was also apparent in the particulate matter distribution as transmissivity decreased from > 50% to < 40% at the plume axis (Fig. 4a). At the time of deployment the surface distributions of salinity and transmissivity suggest the width of the plume was about 6 km. Fluorescence values near the delta were low and quite variable, and displayed no consistent relationship with salinity or transmissivity (data not shown).

A second transect was completed across the plume 2 h later at 89.6° W (Transect 2, Fig. 1a). In the second transect the minimum surface salinity of 8‰ was found at 6 and 12 km (Fig. 4b). The two minima were each about two km wide, and both were bordered by sharp horizontal gradients in salinity and transmissivity. Minimum transmittance in Transect 2 was 60%, so the suspended particulate load had decreased within 2 h. In general, variations in salinity coincided with those in transmissivity, and the low-salinity waters contained the highest sediment loads. The third transect was completed at 89.8° W, about 9.5 h after the drifters were deployed along Transect 1 (Fig. 4c). In contrast to the well-defined salinity minima seen in the first two transects, the surface salinity decreased across the width of the plume from 19.5 to 18‰. Minimum salinities in Transect 3 were at the northern end, where cooler, turbid waters were evident in the remote image. It is likely that the transect did not extend across the entire plume, for there was no evidence of higher-salinity shelf waters at the northern end of the transect. The suspended particulate load in the plume continued to decrease during the deployment, and the minimum transmissivity in Transect 3 was > 70% (Fig. 4c). Turbid "patches" were embedded within the plume, each a few hundred meters wide. In general, as time increased there was less correspondence between salinity and transmissivity, and the surface structure of the plume evolved towards increased variability at smaller spatial scales.

Nitrate, silicate, and phosphate concentrations in the plume surface waters decreased linearly with salinity (Fig. 5). Nutrient–salinity relationships indicate that conservative mixing regulated the nutrient distributions within the plume, with intercepts suggesting source waters of salinity = 25‰ (Fig. 5). Subsurface waters of salinity = 25‰ were observed at the base of the plume, in the pycnocline (see Section 3.2). Biogenic uptake of nutrients was relatively low. The magnitude of phytoplankton nutrient uptake can be estimated from the observed chlorophyll *a* increase of 10 μg l^{-1} (Fig. 5). The biomass maxima occurred within a salinity range of 12 to 17‰, with highest chlorophyll concentrations developing after transmissivity had increased to maximum values (Figs. 4 and 5). Phytoplankton composition in regions where diatoms predominate, such as upwelling zones, is typically 1 mmol N per mg chlorophyll *a* (Dugdale et al., 1989), and the utilization of nitrate: silicate is often 1 : 1 in coastal diatom populations (e.g. Dortch and Whitledge, 1992). Thus an increase of 10 μg l^{-1} chlorophyll *a* could potentially account for nitrate-N and silicate reductions on the order of 10 μmol l^{-1}, assuming that all nitrate-N and silicate-Si was converted to phytoplankton biomass. Within the salinity range of 17 to 20‰ nitrate decreased from 50 to 40 μmol l^{-1}, and silicate declined from 40 to 30 μmol l^{-1}, while phosphate fell from 0.5 to < 0.2 μmol l^{-1} (Fig. 5). The 10 μmol l^{-1} reduction in silicate and nitrate is consistent with an increase in pigment concentrations of 10 μg l^{-1}. However, the major process which regulated nutrient concentrations in the plume was the conservative mixing of plume waters with the low-nutrient, saline waters from the pycnocline.

3.2. August, 1993

In summer the surface winds along the northern Louisiana coast are generally light and from the southeast (Wiseman et al., 1982). During July and August, 1993, in contrast, the surface winds had a strong westerly component (Walker et al., 1994). In late August the Loop Current also made a deep intrusion into the eastern Gulf of Mexico. These two

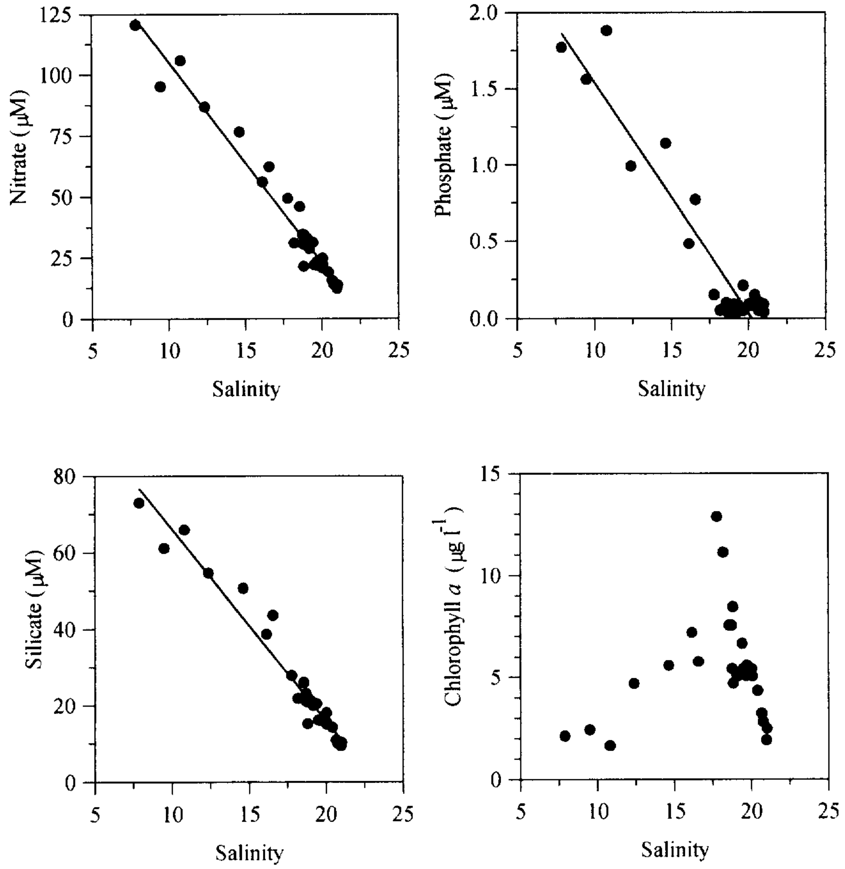

Fig. 5. Concentrations of (a) nitrate, (b) silicate, (c) phosphate, in μmol kg^{-1}, and (d) chlorophyll *a* in μg l^{-1} as a function of salinity. Corresponding station positions from the May deployment are shown in Fig. 1a.

factors contributed to an easterly flow along the Louisiana shelf. The plume orientation is apparent in a surface image of suspended sediments taken about 6 h before a drifter deployment off SW Pass on August 22, 1993 (Fig. 6). The image contains the trajectories of the three GPS-tracked surface drifters all embedded in the eastward flow of turbid, low salinity surface waters.

Surface distributions of salinity and turbidity from transects taken about the mouth of SW Pass describe the turn to the east within 10 km of the river mouth (Fig. 7a). Salinity increased from 6‰ in the channel of SW Pass to > 15‰ in the plume axis with the strongest salinity gradients along the western plume front. Surface salinity decreased from > 20 to < 6‰, and transmissivity decreased from > 90% to

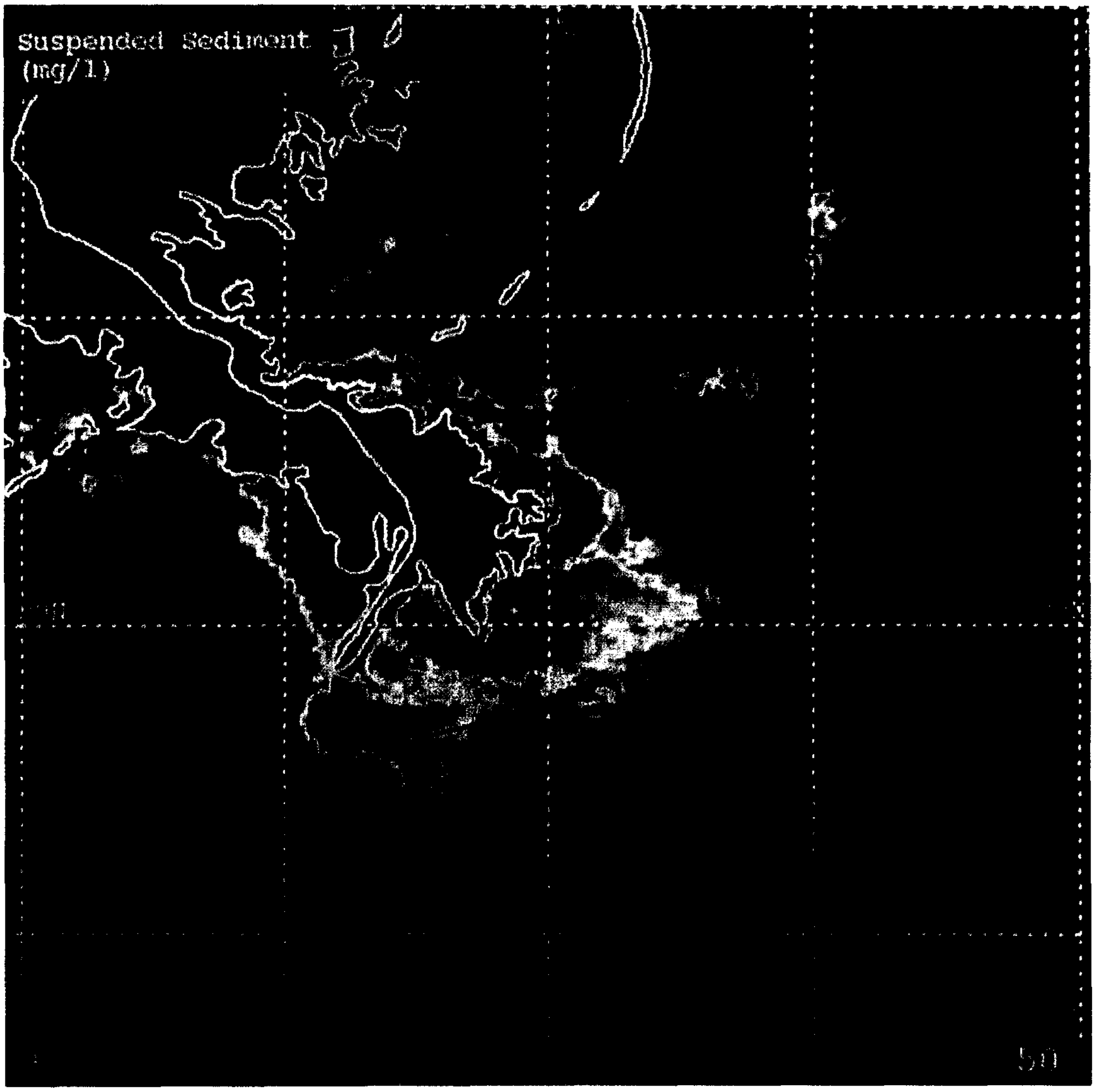

Fig. 6. Surface suspended sediments from NOAA AVHRR satellite data about the Mississippi River delta on August 23, 1993. Drifter trajectories are superimposed for three GPS-tracked surface drifters.

< 30%, within a horizontal distance of 5 km across the plume front. The convergent nature of the front was confirmed by a series of drifter deployments. Drifters released at the mouth of SW Pass converged in the surface front within a few hours of their release. Thus the drifters were deployed in the plume axis downstream of the turn.

Fluorescence patterns about the mouth of SW Pass confirmed that maximum pigment biomass was at the plume front (Fig. 7b). Relatively high fluorescence values in SW Pass were likely attributed to high phaeopigment concentrations, and possibly dissolved organic matter, rather than chlorophyll *a*. Within the channel of SW Pass chlorophyll *a* concentrations were relatively low, < 2 μg l^{-1}, and phaeopigment concentrations exceeded 3 μg l^{-1}, yet fluorescence values were relatively high. Along the western edge of the plume chlorophyll *a* concentrations ranged from 4 to 6 μg l^{-1} (hatched region in Fig. 7b) while phaeopigment concentrations were relatively low at < 2 μg l^{-1}. On August 23 a repeat survey found surface chlorophyll *a* concentrations in the plume front exceeding 40 μg l^{-1}, with phaeopigments concentrations < 10 μg l^{-1} (data not shown). The convergent front along the seaward edge of the plume therefore appears to have contained the maximum surface pigment biomass in August.

Nutrient samples collected during the survey on August 23 suggest that mixing processes and biogenic uptake regulate nutrient distributions near the mouth of SW Pass. In samples collected along the plume axis nitrate and silicate decreased linearly with salinity, indicating conservative mixing within the interior of the plume. In the plume axis maximum chlorophyll *a* concentrations were 2 μg l^{-1} (solid symbols, Fig. 8). Samples collected in the convergent front contained nitrate and silicate concentrations that did not display any consistent relationship with salinity (open symbols, Fig. 8a,b). Chlorophyll *a* concentrations in the front were higher than in the plume, ranging from 3 to 9 μg l^{-1} (Fig. 8d). This pattern suggests that the reduced nutrient concentrations in the front were due to biogenic uptake. Phosphate exhibited less of a consistent relationship with salinity, although concentrations were generally lower in the front than in the plume (Fig. 8c). Thus the entrainment of low-nutrient, saline water appeared to be the major factor regulating nutrient concentrations in the plume interior, while phytoplankton uptake clearly influenced nitrate and silicate distributions at the surface front.

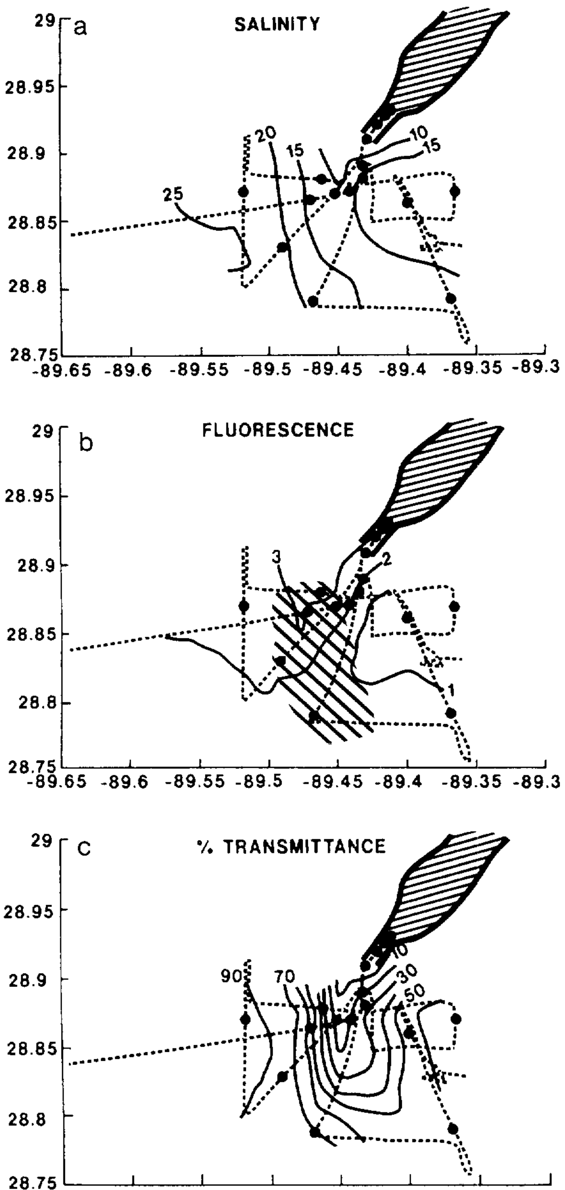

Fig. 7. Surface distributions of (a) salinity, (b) fluorescence in V, and (c) % transmittance near the mouth of SW Pass on August 22, 1993. Maps are contoured from MIDAS transect data. The survey was completed 2 h before the drifter deployment. Cross-hatched area in the fluorescence map covers the region of highest surface chlorophyll *a* concentrations (extracted samples).

Following the survey of SW Pass, three surface drifters were deployed at 28.83° N, 89.38° W, approximately 5 km south of the river mouth. The drifters were launched at 00:00 GMT on August 23 (YD 235) and were retrieved 18 h later at 88.8° W. The eastward velocity of the plume was therefore about 1 m s^{-1}. Surface distributions of temperature, salinity, fluorescence, and transmissivity for the objective analysis included observations from the initial survey at SW Pass, the drifter deployment, a return transect along 28.9°, and a second survey about the river mouth on the next day. Surface temperatures clearly shows that freshwater from the river was cooler (28.5°C) than the surrounding shelf waters of 30°C (Fig. 9a). The temperature of the effluent plume increased to 30°C within a day after exiting the river mouth. The pattern of surface salinities near the mouth of SW Pass was complex. Low-salinity waters from the delta remain on the shoal areas between the passes, where surface temperatures exceed 31°C. As filaments of this warm, fresh water flow seaward from the shoals, they generate large gradients in the surface property fields (Fig. 9a,b).

During a survey on YD 236 the ship crossed one filament of this fresh (salinity < 5‰), warm (> 31°C) surface water at 89.5°W (purple region in Fig. 9b). Similar features were found during the return transect to the river mouth along 28.9°N. The filaments were observed most frequently to the east of SW Pass, near 89.4°W (Fig. 9b). Within the plume

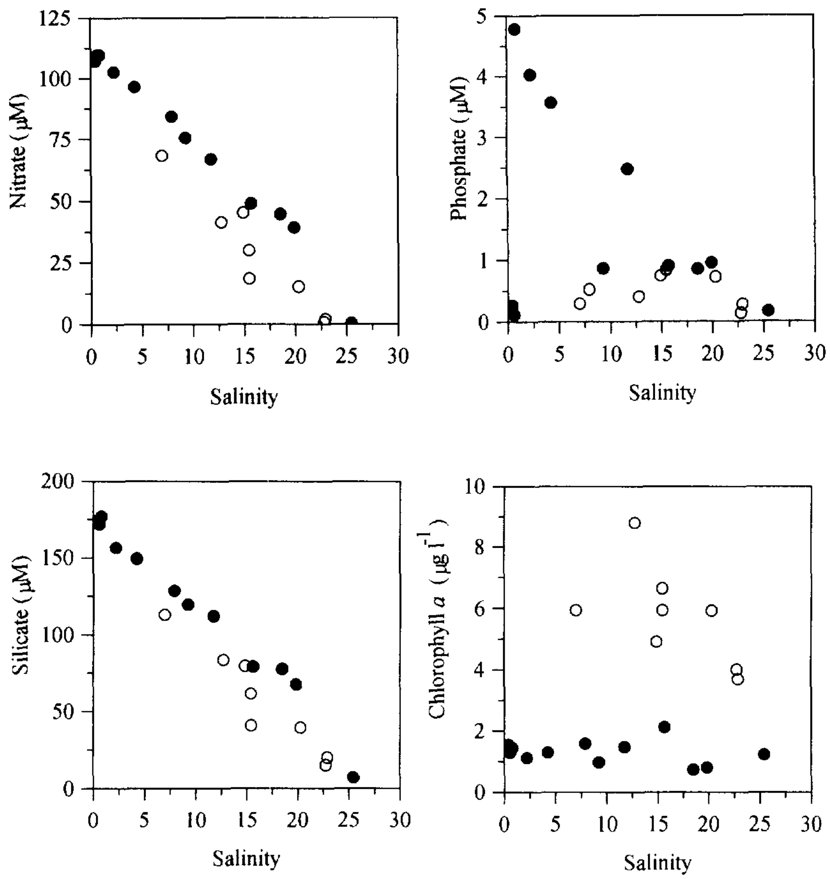

Fig. 8. Concentrations of (a) nitrate, (b) silicate, (c) phosphate and (d) chlorophyll *a* as a function of salinity from surface samples collected about the mouth of SW Pass. Units as in Fig. 5. Open symbols correspond to samples from the convergent front along the western edge of the plume.

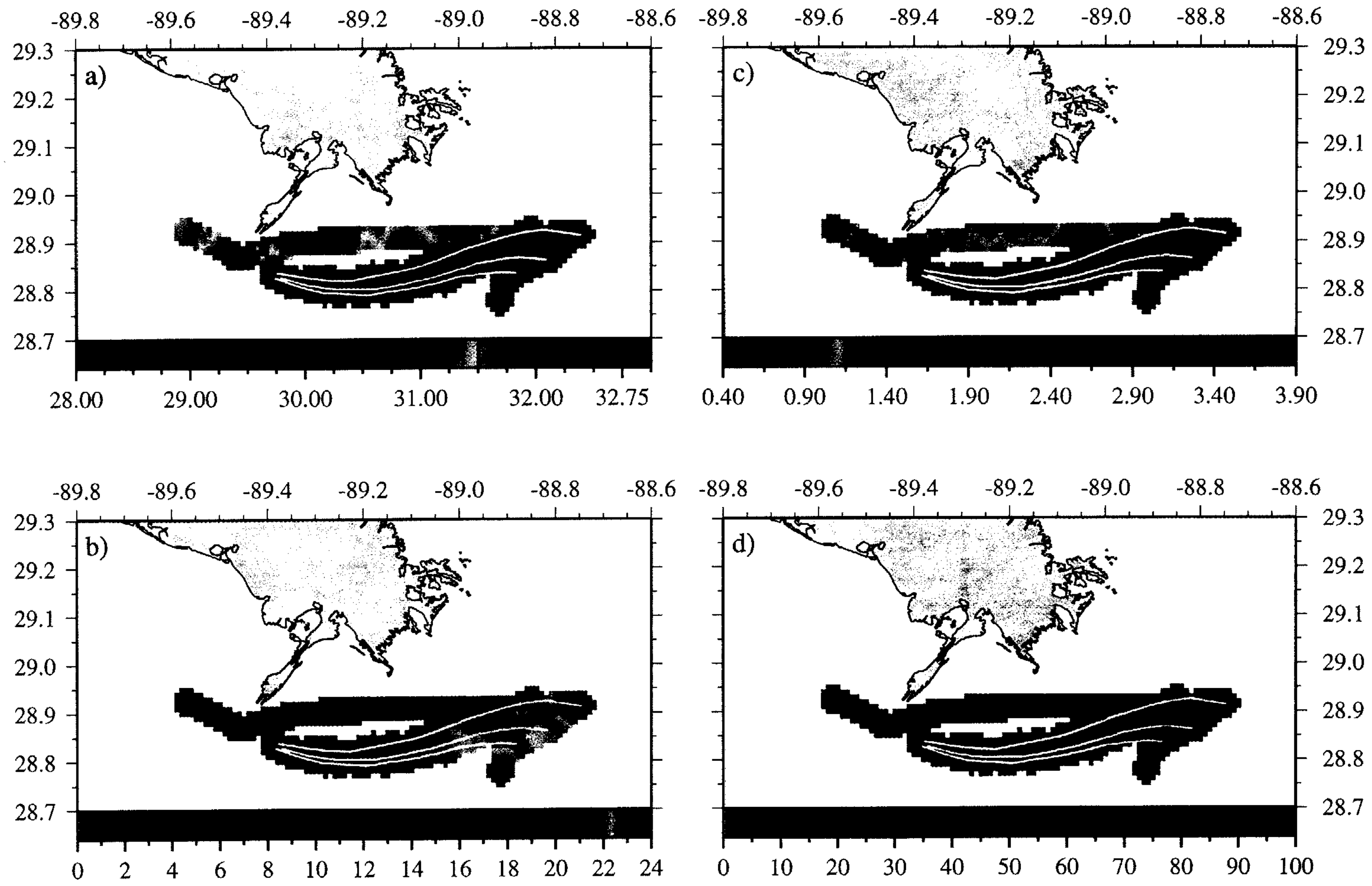

Fig. 9. Objectively analyzed maps of surface (a) temperature, (b) salinity, (c) fluorescence and (d) percent transmissivity during the drifter deployment on August 23, 1993. The data range in color from minimum (purple) to maximum values (red). Individual drifter trajectories are white lines.

the surface salinity field was less patchy. During the drifter deployment salinity values in the plume increased from 15 to 24‰ within 12 h. The surface fluorescence distribution also contained the most heterogenous distributions near SW Pass (Fig. 9c). Maximum fluorescence values, corresponding to chlorophyll *a* concentrations > 10 μg l^{-1}, were observed on the western side of the plume, as in Fig. 8. Pigment concentrations in the warm, low-salinity filament crossed on YD 236 exceeded 20 μg l^{-1} (red area in Fig. 9c). Within the plume, surface chlorophyll *a* concentrations were relatively uniform, with surface chlorophyll *a* concentrations ranging from 2 to 6 μg l^{-1}. The transmissivity data indicated that the highest suspended sediment concentrations were limited to the surface waters near the mouth of SW Pass with little variability in the effluent plume (Fig. 9d). During the 18 h deployment per cent transmittance increased from 70% to > 90%.

Surface nutrients were linearly related to salinity, suggesting that conservative mixing regulated surface nitrate, silicate, and phosphate concentrations in the effluent plume. With the exception of one sample (open symbol in Fig. 10a), nitrate concentrations in the plume decreased from 50 μmol l^{-1} to nearly undetectable concentrations within 18 h. Silicate decreased from nearly 80 to 20 μmol l^{-1} within the same interval (Fig. 10b), while phosphate declined from > 1 μmol l^{-1} to nearly undetectable levels (Fig. 10c). Linear relationships of nitrate, silicate, phosphate and salinity suggest that the source waters of salinity = 24 to 26‰. In contrast to nitrate and phosphate, silicate concentrations at the end of the deployment were still relatively high, at 15 μmol l^{-1}.

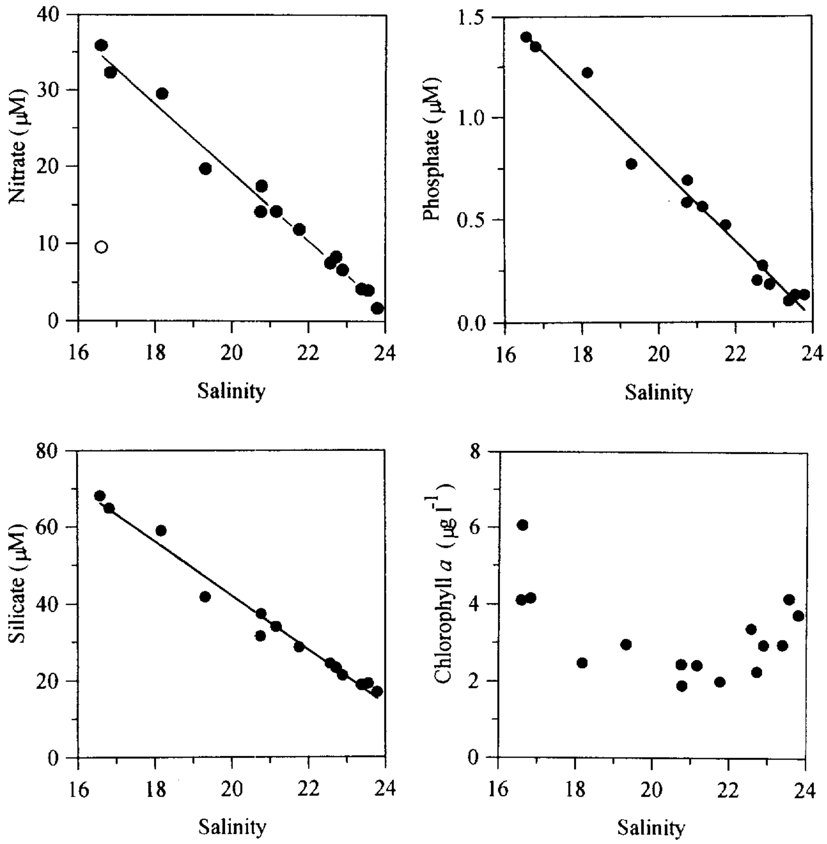

Fig. 10. Concentrations of (a) nitrate, (b) silicate, (c) phosphate and (d) chlorophyll *a* as a function of salinity from samples collected while following surface drifters on August 23, 1993. Units as in Fig. 5.

A series of CTD casts in the plume found salinity of 25‰ in the pycnocline at depths of 2 to 5 m. Nitrate concentrations in the pycnocline were variable, ranging from undetectable to > 5 μmol l^{-1}, with silicate varying from 14 to 17 μmol l^{-1}. Phosphate concentrations within the pycnocline were generally between 0.05 and 0.1 μmol l^{-1}. The pycnocline at the base of the plume corresponds to a large gradient in nutrient concentrations, and is the source of the low-nutrient waters mixed into the surface layer (see Wright and Coleman, 1971).

During the drifter deployment pigment concentrations decreased from initial values of 4 to 6 μg l^{-1} to minimum concentrations of 2 μg l^{-1} within 10 h (Fig. 10d). At the conclusion of the deployment pigment concentrations had nearly doubled to 4 μg l^{-1}. This variability may be a consequence of a diel cycle. The drifters were launched at local sunset, when chlorophyll *a* concentrations were highest. Pigment concentrations decreased throughout the night with minimum chlorophyll *a* biomass at dawn, followed by an increase during the next day. The periodicity may therefore reflect the growth of phytoplankton community during the day, followed by grazing throughout the night.

4. Discussion

The effluent plume originating at the Mississippi delta exerts a strong influence on the surface waters of the Louisiana Shelf. Low-salinity water is present on the western Louisiana shelf throughout the year (Wiseman et al., 1982), and in satellite imagery the effluent plume often turns anticyclonically towards the coast (Walker and Rouse, 1993). Retrospective analyses show that spatial distributions of sediments reflect the productivity of the overlying surface waters. Sediment distributions reveal a west-to-northwest orientation in organic carbon (Nelsen et al., 1995), pigments, and biogenic silica (Turner and Rabalais, 1994) from SW Pass to the coast. Thus the property distributions in sediments reinforce the conclusion that the direction of the effluent plume is most often to the northwest.

Drifter trajectories show that at high discharge rates freshwater parcels transit through the effluent plume within a day. In May the drifters entered the coastal current south of Barataria Bay after 24 h. As the drifter trajectories crossed the 20 m isobath several slowed and stalled in the density front which bordered the western edge of the plume. In August the drifters entered shelf waters with salinities > 24‰ in less than a day. Additional drifter deployments during a period of relatively low discharge in September, 1992 also gave an estimate of transit time through the plume of one-to-two days (Boicourt and Wiseman, unpublished data). Previous estimates of the residence time for water parcels in the effluent plume of the Mississippi River have been calculated from freshwater discharge rates and the plume volume. Lohrenz et al. (1990) calculated a residence time of two days for freshwater to effectively "fill" the effluent plume during the spring runoff in April, 1988 with a river discharge rate of 5.8×10^3 m^3 s^{-1}. The mean plume salinity was estimated at 26.2‰. This discharge rate is $< 50\%$ that in spring or summer, 1993, and corroborates the observations that the average residence time for water parcels in the plume are one-to-two days. The agreement between the two estimates lends support to a hypothesis that water parcels discharged into the plume retain their salinity signature for periods of a few days. Lohrenz et al. (1990) stress that this time is equivalent to the biogenic processes that modify surface properties. The nutrient–salinity relationships suggest that biogenic uptake has little influence on nutrient concentrations within the plume, where conservative mixing dominates the nutrient dynamics. Maximum plankton biomass occurs at the plume front where nutrient–salinity relationships indicate non-conservative processes; here nutrient uptake has a large influence on surface nutrient distributions.

Surveys of nutrients distributions in the surface waters of the western Louisiana shelf typically display considerable scatter at intermediate salinities of 10–25‰. Prior studies have examined the plume as a regional feature, surveying a large area of the Louisiana shelf and relied upon surface salinity as an indicator of the presence of freshwater (Lohrenz et al., 1990; Dagg and Whitledge, 1991; Dortch and Whitledge, 1992; Smith and Hitchcock, 1994). In these four studies nitrate, silicate and phosphate concentrations in spring and summer have consistently shown high concentrations within the riverine source waters, and near-undetectable concentrations in the saline oceanic waters. Non-linear relationships observed between inorganic nutrient concentrations and salinity have been attributed to temporal variability in nutrients within the Mississippi River (Dortch and Whitledge, 1992), as well as mixing and biogenic nutrient uptake. We hypothesize that the nonlinear relationships also arise from sampling the plume front (e.g. Fig. 8).

Evidence of phytoplankton uptake in the nutrient distributions is illustrated by the observation that photoautotrophic biomass, as measured by chlorophyll *a*, is typically at maximum levels at salinities of 15 to 30‰ (i.e. Smith and Hitchcock, 1994). At these intermediate salinities the concentration of suspended particulate matter has declined from high levels typically found in river water (Dortch and Whitledge, 1992). The increased transparency results in a relaxation of light limitation of photosynthesis, and nutrient utilization is enhanced. Nutrient–salinity relationships from the Lagrangian-based observations suggest, however, that nutrient uptake by phytoplankton primarily occurs at the effluent plume front.

Previous surveys of nutrient distributions at the mouth of the Mississippi River have shown that nutrient concentrations are linearly related to salinity (Fanning and Pilson, 1973; Fox et al., 1987). These studies were completed by shipboard surveys, and did not follow Lagrangian tracers. The observations are similar to those seen in August, 1993 (Fig. 8), and confirm that within the Passes of the delta the surface nutrient concentrations are regulated by conservative mixing. In the surface waters of SW Pass biogenic nutrient uptake is reduced since high particulate matter loads contribute to high turbidity. At the mouth of the Passes the plume rapidly expands as saltier water is entrained through the pycnocline (Wright and Coleman, 1971). Thus in the Passes of the delta, and at the mouth of SW Pass, conservative mixing regulates nutrient dynamics in the surface layer as biogenic uptake is constrained by limiting light conditions. Mixing diagrams for nitrate and silicate suggest that seaward of the river mouth, nutrient concentrations within the plume are also regulated by conservative mixing. The pycnocline is the source of the low-nutrient saline waters, generally from depths of 2 to 4 m. Studies of the effluent plume at South Pass show that saline waters of intermediate salinity are entrained by breaking internal waves on the density interface (Wright and Coleman, 1971).

The Lagrangian-based sampling scheme revealed that surface concentrations of nitrate and silicate, and to a lesser extent phosphate, within the plume are consistent with conservative mixing. As water parcels transit the shelf, the drifters provided a mechanism by which the temporal history of surface properties were observed. Conservative mixing within the interior of the Mississippi River plume is consistent with that observed in the river plumes of the Amazon (Edmond et al., 1981), Zaire and Magdalena (Fanning and Maynard, 1978), and Savannah (Fanning and Pilson, 1973) rivers. Discharge rates of large rivers such as the Amazon and Zaire create effluent plumes that expand over many square kilometers, so surveys can easily map the plume interior. In studies of the Magdalena and Savannah rivers the observations were limited to the river mouth. In the effluent plume at SW Pass, where the plume orientation rapidly changes in response to winds, drifters provide a mechanism by which the plume axis can be readily identified. Thus the Lagrangian sampling scheme permits the ship to follow history of properties within the tagged water parcels. A Lagrangian-based sampling program could also prove useful in large estuarine plumes where multiple sources and sinks contribute to temporal and spatial variability in nutrient distributions (e.g. Morris et al., 1995).

Since nutrient concentrations in the plume interior are regulated by conservative mixing, we hypothesize that the highest rates of phytoplankton nutrient utilization occur at the plume front. In support of this hypothesis, Lohrenz et al. (1990) found that the maximum chlorophyll *a* biomass within the low-salinity waters of the Louisiana Bight is less than that predicted from a model of light-limited phytoplankton growth. Reduced phytoplankton biomass in the turbid waters of the plume was attributed to several possible factors, including: (1) limitation of phytoplankton growth by nutrients other than N, Si or P, (2) toxic materials in the river water, such as pesticides, (3) zooplankton grazing and sinking, and (4) the inability of phytoplankton populations to achieve steady-state conditions in the plume.

The short residence time for water parcels in the plume lends support to the hypothesis that phytoplankton populations have insufficient time to achieve steady-state, and therefore establish high growth rates, in response to changing environmental conditions. Water parcels and the resident plankton populations transit through large gradients of turbidity, light, nutrient concentrations, and salinity within a day after exiting from the mouth of SW Pass. Lagrangian-based observations of the time required to alter nutrient uptake rates and photosynthetic processes indicate that time scales for phytoplankton to adapt to rapidly changing conditions are on the order of days in coastal waters (Dugdale et al., 1990). Thus the resident phytoplankton populations in the plume, or those entrained from the underlying pycnocline, may have insufficient time to adapt to the prevailing light and nutrient regime while in the plume interior.

Maximum plankton biomass develops at the plume front. The pigment maxima observed at the plume front in August, 1993 agree with the finescale distributions of chlorophyll *a* observed by Grimes and Finucane (1991) in earlier surveys. Surveys of pigment, macrozooplankton, and ichthyoplankton biomass indicate that maximum concentrations are typically found at the plume front, rather than in the interior of the plume or the contiguous shelf waters (Govoni et al., 1989; Grimes and Finucane, 1991). Fronts are frequently identified as regions of maximum plankton biomass due to enhanced growth and horizontal convergence (Franks, 1992). The structure of the Mississippi River plume front contains intermittent, turbulent features that span distances of 10 to 100 m. These patches form and dissipate on time scales of several hours (Govoni and Grimes, 1992), and are driven by density differences across the interface of plume and shelf waters. We recommend that future studies of nutrient uptake and plankton distributions in the Mississippi River plume concentrate observations in the plume front. Lagrangian tracers may serve as one mechanism by which the plankton populations can be followed in these dynamic regions.

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References

Atwood, D.K., Bratkovich, A., Gallagher, M., Hitchcock, G.L., 1994. Introduction to the dedicated issue. Estuaries 17, 729–731.

Cochrane, J.D., Kelly, F.J. Jr., 1986. Low-frequency circulation on the Texas–Louisiana continental shelf. J. Geophys. Res. 91, 10645–10659.

Dagg, M.J., Whitledge, T.E., 1991. Concentrations of copepod nauplii associated with the nutrient-rich plume of the Mississippi River. Cont. Shelf Res. 11, 1409–1423.

Davis, R., 1985. Drifter observations of coastal surface currents during CODE: the method and descriptive view. J. Geophys. Res. 90, 4741–4772.

Deegan, L.A., Day, J.W., Jr., Gosselink, J.G., Yȁñez Arancibia, A., Soberŏn Chȁvez, G., Saȁnchez-Gil, P., 1986. Relationships among physical characteristics, vegetation distribution and fisheries yield in Gulf of Mexico estuaries. In: Wolfe, D.A. (Ed.), Estuarine Variability. Academic Press, New York, pp. 83–100.

Dinnel, S., 1995. Relative importance of atmospheric deposition to nitrogen flux in the Mississippi River. J. Environ. Qual.

Dinnell, S.P., Wiseman, W.J. Jr., 1986. Freshwater on the Louisiana and Texas shelf. Cont. Shelf Res. 6, 765–784.

Dowgiallo, M.J., 1994. Coastal oceanographic effects of 1993 Mississippi River flooding. Special NOAA Report. NOAA Coastal Ocean/National Weather Service, Silver Spring, MD, 76 pp.

Dortch, Q., Whitledge, T.E., 1992. Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions?. Cont. Shelf Res. 12, 1293–1309.

Dugdale, R.C., Morel, A., Bricaud, A., Wilkerson, F.P., 1989. Modeling new production in upwelling centers: a case study of modeling new production from remotely sensed temperature and color. J. Geophys. Res. 94, 18119–18132.

Dugdale, R.C., Wilkerson, F.P., Morel, A., 1990. Realization of new production in coastal upwelling areas: a means to compare relative importance. Limnol. Oceanogr. 35, 822–829.

Edmond, J.M., Boyle, E.A., Grant, B., Stillard, R.F., 1981. The chemical mass balance in the Amazon plume I: the nutrients. Deep-Sea Res. 28, 1339–1374.

Fanning, K.A., Maynard, V.I., 1978. Dissolved boron and nutrients in the mixing plumes of major tropical rivers. Neth. J. Sea Res. 13, 345–354.

Fanning, K.A., Pilson, M.E.Q., 1973. The lack of inorganic removal of dissolved silica during river–ocean mixing. Geochim. Cosmochim. Acta 37, 2405–2415.

Fox, L.E., Lipschultz, F., Kerkhof, L., Wofsy, S.C., 1987. A chemical survey of the Mississippi estuary. Estuaries 10, 1–12.

Franks, P.J.S., 1992. Sink or swim: accumulation of biomass at fronts. Mar. Ecol. Prog. Ser. 82, 1–12.

Govoni, J.J., Grimes, C.B., 1992. The surface accumulation of larval fishes by hydrodynamic convergence within the Mississippi River plume front. Cont. Shelf Res. 12, 1265–1276.

Govoni, J.J., Hoss, D.E., Colby, D.R., 1989. The spatial distribution of larval fishes about the Mississippi River plume. Limnol. Ocean. 34, 178–187.

Grimes, C.B., Finucane, J.H., 1991. Spatial distribution and abundance of larval juvenile fish, chlorophyll and macrozooplankton around the Mississippi River discharge plume, and the role of the plume in fish recruitment. Mar. Ecol. Prog. Ser. 75, 109–119.

Lohrenz, S.E., Dagg, M.J., Whitledge, T.E., 1990. Enhanced primary production at the plume/oceanic interface of the Mississippi River. Cont. Shelf Res. 10, 639–664.

Mariano, A.J., Brown, O., 1992. Efficient objective analysis of dynamically heterogenous and nonstationary fields via the parameter matrix. Deep-Sea Res. 39, 1255–1271.

Morris, A.W., Allen, J.I., Howland, R.J.M., Wood, R.G., 1995. The estuary plume zone: source or sink for land-derived nutrient discharges?. Est. Coast. Shelf Sci. 40, 387–402.

Nelsen, T., Blackwelder, P., Hood, T., Zarikina, C., Trefry, J.H., Metz, S., Eadie, B., McKee, B., 1995. Retrospective analysis of NECOP area sediments: biogenic, inorganic, and organic indicators of anthropogenic influences since the turn of this century. In: Atwood, D.K., Graham, W.F., Grimes, C.B. (Eds.), Nutrient Enhanced Coastal Ocean Productivity, Proceedings of 1994 Synthesis Workshop. Louisiana Sea Grant College Program, Baton Rouge, LA, pp. 90–101.

O'Donnell, J., 1993. Surface fronts in estuaries: a review. Estuaries 16, 12–39.

Parsons, T.R., Maita, Y., Lalli, C.M., 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon, Oxford, 173 pp.

Rabalais, N.N., Turner, R.E., Wiseman, W.J. Jr., Boesch, D.F., 1991. A brief summary of hypoxia on the northern Gulf of Mexico continental shelf (1985–1988). In: Tyson, R.V., Peason, T.H., (Eds.), Modern and Ancient Continental Shelf Anoxia. Geol. Soc. Spec. Publ. 58, 35–47.

Redalje, D.G., Lohrenz, S.E., Fahnenstiel, G.L., 1994. The relationship between primary production and the vertical export of particulate organic matter in a river-impacted coastal ecosystem. Estuaries 17, 829–838.

Rouse, L.J., Coleman, J.M., 1976. Circulation observations in the Louisiana Bight using Landsat imagery. Remote Sens. Environ. 5, 55–66.

Smith, S.M., Hitchcock, G.L., 1994. Nutrient enrichments and phytoplankton growth in the surface waters of the Louisiana Bight. Estuaries 17, 740–753.

Turner, R.E., Rabalais, N.N., 1991. Changes in Mississippi River water quality this century, implications for coastal food webs. Bioscience 41, 140–147.

Turner, R.E., Rabalais, N.N., 1994. Coastal eutrophication near the Mississippi River delta. Nature 368, 619–621.

Walker, N.D., Rouse, L.J., 1993. Satellite assessment of Mississippi River discharge plume variability. OCS Study MMS 93-0044, U.S. Dept. of Interior, Minerals Management Service, Gulf of Mexico Regional Office, New Orleans, LA, 50 pp.

Walker, N.D., Fargion, G.S., Rouse, L.J., Biggs, D.C., 1994. The great flood of summer 1993: Mississippi River discharge studied. EOS, Trans. Am. Geophys. Union 75, 409–415.

Walser, W.E. Jr., Hughes, R.G., Rabalais, S.C., 1993. Multiple interface data acquisition speeds at-sea research. Sea Tech. 33, 29–34.

Walsh, J.J., Rowe, G.T., Iverson, R.L., McCoy, C.P., 1981. Biological export of shelf carbon is a sink of the global CO_2 cycle. Nature 291, 196–201.

Whitledge, T.E., Bidigare, R.R., Zeeman, S.I., Sambrotto, R.N., Jensen, P.R., Brooks, J.M., Trees, C., Veidt, D.M., 1988. Biological measurements and related chemical features in Soviet and United States regions of the Bering Sea. Cont. Shelf Res. 8, 1299–1319.

Wiseman, W.J. Jr., Garvine, R.W., 1995. Plumes and coastal currents near large river mouths. Estuaries 18, 509–517.

Wiseman, W.J. Jr., Murray, S.P., Bane, J.M., Tubman, M.W., 1982. Temperature and salinity variability within the Louisiana Bight. Contrib. Mar. Sci. 25, 109–120.

Wiseman, W.J. Jr., Bane, J.M., Murray, S.P., Tubman, M.W., 1976. Small-scale temperature and salinity structure over the inner shelf west of the Mississippi River delta. Mém. Soc. R. Sci. Liège 10, 277–285.

Wright, L.D., Coleman, J.M., 1971. Effluent expansion and interfacial mixing in the presence of a salt wedge Mississippi River delta. J. Geophys. Res. 76, 8649–8661.