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An episodic chlorophyll plume on the West Florida Shelf

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Abstract—The episodic formation of an extensive pigment plume on the West Florida Shelf was detected using historical Coastal Zone Color Scanner (CZCS) data collected between 1979 and 1986. The phenomenon is confirmed by *in situ* observations made in March 1992. The plume occurs mainly during spring, when high pigment concentrations persist 1–6 weeks in a pattern which extends >250 km southward along the shelf. In general, the shelf and continental slope had low pigment concentrations during summer and high pigment concentrations during spring. The information currently available is insufficient to determine the cause of the plume with certainty. Plume formation may be associated with one or a combination of the following processes: (1) discharge from small, local rivers along the NW Florida coast; (2) seasonal changes in steric height differences between the shelf and deep Gulf of Mexico waters; (3) circulation of water associated with the Loop Current and upwelling in the DeSoto Canyon; and (4) discharge from the Mississippi and Mobile Rivers. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

The Gulf of Mexico is traditionally classified as an oligotrophic system (El-Sayed *et al.*, 1972; El-Sayed and Turner, 1977; Ortner *et al.*, 1984; Biggs, 1992). However, satellite evidence (Müller-Karger *et al.*, 1991) shows that the Gulf of Mexico undergoes widespread seasonal changes, with large regions showing high production, especially over shelf areas (Riley, 1937; Khromov, 1969; Vargo *et al.*, 1987; Lohrenz *et al.*, 1990).

At the well-studied Louisiana Shelf, high primary production is generated by the discharge of the Mississippi River (Thomas and Simmons, 1960; Sklar and Turner, 1981; Turner and Rabalais, 1991). This river has an average range discharge of $0.81–2.81 \times 10^4$ $m^3\ s^{-1}$ (Müller-Karger, 1993), an average sediment discharge of 2.1×10^8 tons yr^{-1} (Milliman and Meade, 1983), and large nutrient concentrations (Fox *et al.*, 1987; Bratkovich *et al.*, 1994; Smith and Hitchcock, 1994). Primary production at the mouth of the river has been estimated at $0.4–8.17$ $gC\ m^{-2}\ d^{-1}$ (Lohrenz *et al.*, 1990; Redalje *et al.*, 1994).

One of the least studied areas of the Gulf of Mexico is the West Florida Shelf. Episodic

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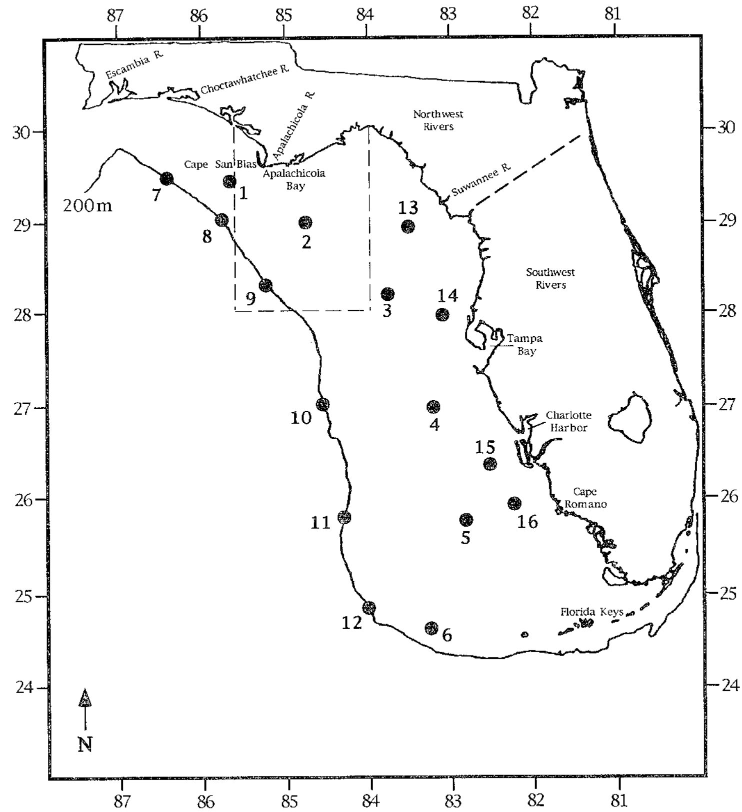

Fig. 1. Study area and stations defined for CZCS time series analysis. Stations 1–6 are on the 40 m isobath, Stas 7–12 are on the 200 m isobath, and Stas 13–16 are on the 20 m isobath. The region enclosed by dashed lines represents the area selected for nitrogen-mass balance calculations.

blooms of toxic dinoflagellates have been reported as potential contributors to the total annual primary production in this area (Vargo *et al.*, 1987). These blooms seem to be more frequent on the south-central shelf during late summer and fall, but occur throughout the year (Steidinger, 1983). During dinoflagellate bloom periods, biomass in surface waters varies from 2 to 30 mg m^{-3} chl *a* and primary production from 0.8 to 3.8 gC m^{-2} d^{-1} (Vargo *et al.*, 1987). During non-bloom periods, these shelf waters have values of <1 mg m^{-3} chl *a* and <0.5 gC m^{-2} d^{-1} for production (Vargo *et al.*, 1987).

As we began to examine the Coastal Zone Color Scanner (CZCS) data to characterize the phytoplankton variability in the Gulf of Mexico, we discovered the periodic formation of a high pigment plume, extending southward from Cape San Blas toward the Florida Keys along the shelf break (Fig. 1). This prompted a search for historical *in situ* data, which confirmed that high (8–10 mg m^{-3}) chlorophyll values within the water column occur in this region (Khromov, 1969). These observations motivated a careful examination of the historical color imagery to determine the extent and frequency of this event, and a series of cruises to examine the composition of the discolored waters. The regular occurrence of this plume supports the idea that energy transfer to higher trophic levels on the northern part of the West Florida Shelf is seasonal (Austin and Jones, 1974). The objectives of our analysis were to determine the frequency of occurrence and duration of this plume, to identify the factors which control the formation of this plume, and to produce time series of pigment concentration on the West Florida Shelf for validation of future ecological models.

METHODS

CZCS image processing

We examined 2781 CZCS images which contained areas of valid data (data without cloud cover) greater than 50 × 50 km in our region of interest. The images were collected from January 1979 to June 1986. We used images at 4 km resolution, which were processed by NASA and archived in the remote sensing laboratory at the University of South Florida, Department of Marine Science. Selected images were further processed at a spatial resolution of 1 km at USF—Marine Science with Digital System Processing (DSP) software, developed at the University of Miami. A sequence of images was used to determine the frequency of occurrence and duration of the high pigment plumes, as well as the plume boundaries, on the West Florida Shelf.

Pigment concentration (chl *a* plus phaeopigments and dissolved organic material) was derived from ratios of the blue (443 nm) or blue-green (520 nm) water-leaving radiances to the green radiance (550 nm), using the atmospheric correction for aerosols, cloud cover, sun glint and bio-optical algorithms of Gordon *et al.* (1983, 1988). We ignored possible colored dissolved organic carbon contamination of the CZCS signal in the application of the algorithms (Hochman *et al.*, 1994). Images of pigment concentration were geographically mapped to a cylindrical equidistant projection and monthly composite images at 4 km spatial resolution were computed based on the arithmetic average of cloud-free pixels.

We examined the series of monthly means from January 1979 to December 1985 to determine the seasonal pattern of pigment concentration over the West Florida Shelf. We selected 16 small areas in the images to extract point time series (Fig. 1). Stations 1–6 were positioned along the 40 m isobath, Stas 7–12 along the 200 m isobath and Stas 13–16 along the 20 m isobath. A box of 3 × 3 pixels (= 144 km^2) was used at each station. We compared these CZCS data with field data obtained during a research cruise on the West Florida Shelf sponsored by the Florida Department of Environmental Protection.

Field data collection

During 16–25 March 1992, continuous vertical profiles of temperature, salinity and chlorophyll fluorescence were measured in the water column at 60 stations on the West Florida Shelf using a Seabird SBE 25 CTD with a fluorometer. Discrete samples for extracted chlorophyll were taken with a rosette sampler equipped with 5 l Niskin bottles in conjunction with the CTD, at depths from 0 to 200 m, usually at 10 m intervals. In this study, we only used chlorophyll and salinity data from the surface (~1 m) and 20 m. Extracted chlorophyll measurements were made using a Turner Designs Fluorometer and the methanol extraction method of Holm-Hansen (1978). The CTD salinity values were verified with occasional duplicate samples run on a Beckman Aquasol induction salinometer calibrated with standard sea-water, while temperature measurements were confirmed by the use of reversing thermometers. Spatial grids of the data were done using Surfer contouring software (Golden Software Corp.).

River discharge and nutrient data

We compiled river discharge data for rivers emptying into the northeast Gulf of Mexico for the period January 1979–December 1985. The data were obtained from the U.S. Geological Survey Water Data Report and grouped into northwest and southwest Florida's rivers. The northwest Florida rivers are the Perdido, Escambia, Blackwater, Yellow, Choctawhatchee, Econfina Creek, Apalachicola, Ochlockonee, Aucilla, Econfina, Fenholloway, Steinhatchee and Suwannee Rivers (Fig. 1). The southwest Florida rivers are the Withlacoochee, Hillsborough, Alafia, Little Manatee, Manatee, Myakka and Peace Rivers (Fig. 1).

We examined the inorganic nitrogen concentration data ($NO_2 + NO_3$) for the Apalachicola, Suwannee, Escambia and Choctawhatchee Rivers. The data were also obtained from the U.S. Geological Survey Water Data Report. We used the sum total for these four rivers to obtain a monthly mean of the total discharge and the total inorganic nitrogen input to the extreme northeastern Gulf of Mexico between January 1979 and September 1981. We selected this period for our calculations because it represented the most complete data set. After September 1981, the measurements were infrequent. We computed the monthly average loading of inorganic nitrogen by multiplying the monthly mean total discharge and the monthly mean nitrogen concentration.

RESULTS

Occurrence and lifetime of the West Florida plume

The CZCS images reveal the annual formation of a plume of elevated pigment concentrations on the northern part of the West Florida Shelf between February and May. In 1979, the West Florida plume occurred during March and it lasted at least two weeks (Fig. 2). The plume was first detected on 9 March, when pigment concentrations were between 0.5 and 1.0 mg m^{-3}. On 15 March, the plume extended southward from Cape San Blas along the shelf (Fig. 2). It had pigment values between 2.0 and 5.5 mg m^{-3} on 15 March and between 1.0 and 2.0 mg m^{-3} on 20 March. Pigment concentrations were <0.5 mg m^{-3} on 1 April (Fig. 2).

In 1980, the plume on the West Florida Shelf had maximum concentrations in May and a duration of approximately one month (Fig. 3). The plume was first detected off Cape San Blas on 24 April, with pigment concentrations >0.5 mg m^{-3} while, further south, the pigment concentration remained low (0.1–0.2 mg m^{-3}). On 16 May, a well-defined plume extended southward with values up to 5.0 mg m^{-3} (Fig. 3). Three days later (19 May), pigment concentrations decreased to <2.0 mg m^{-3} and the plume disappeared on 2 June (values <0.25 mg m^{-3}).

Similar plumes on the West Florida Shelf were detected in CZCS imagery between 1981 and 1986. However, the number of usable images during these years was lower than in previous years, making the analysis of the time sequence of the plumes more difficult. A reduction in CZCS operational time plus cloud cover were the major reasons for decreased coverage. A plume with pigment concentrations >0.5 mg m^{-3} was identified in February

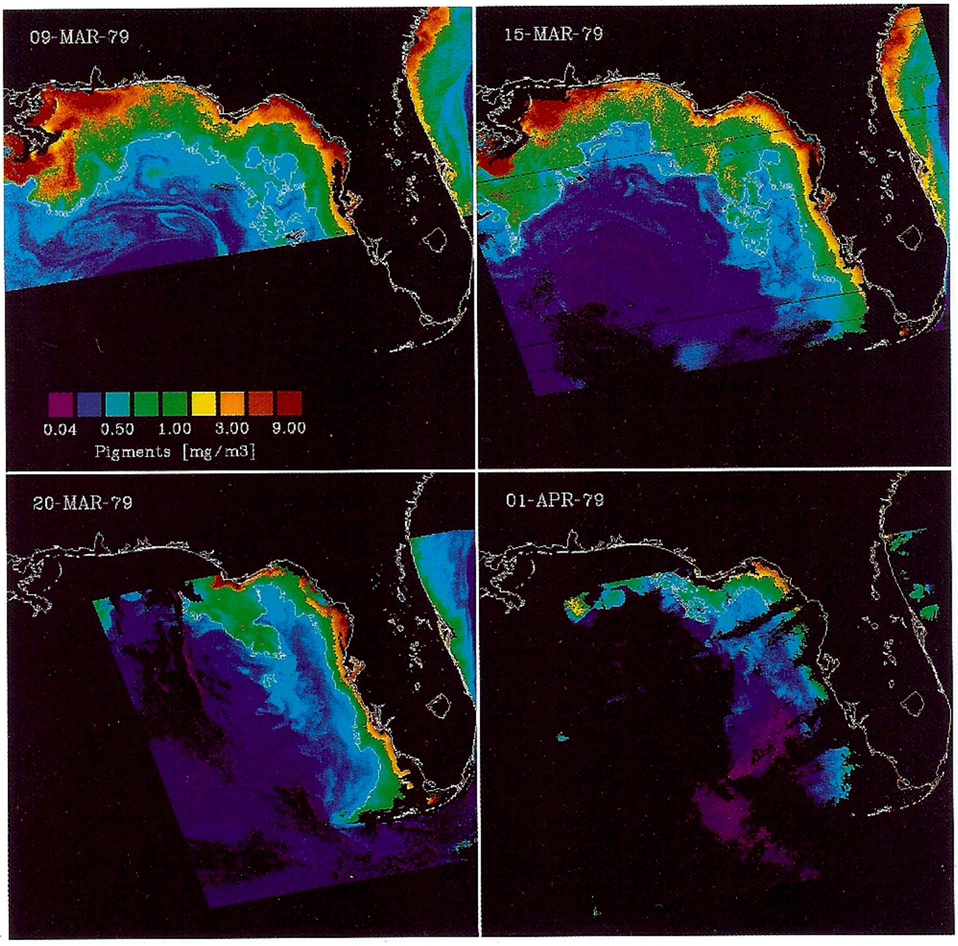

Fig. 2. Daily images of pigment concentration (mg m^{-3}) in the West Florida Shelf obtained with the CZCS during 1979. High concentrations are represented with warm colors (yellow, orange, red). Purple and blue represent low concentrations. The coastline and the isoline of 0.5 mg m^{-3} of pigments are shown in white. Land, clouds and missing data are black.

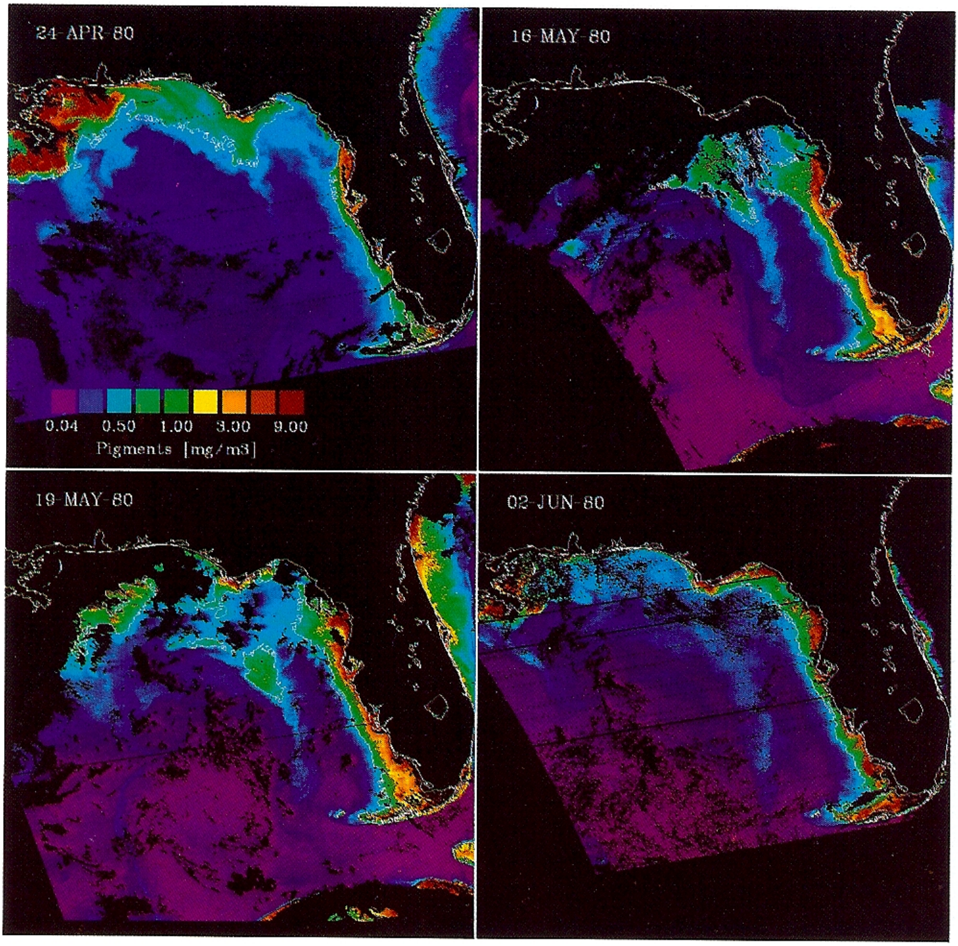

Fig. 3. Daily images of pigment concentration (mg m^{-3}) in the West Florida Shelf obtained with the CZCS during 1980. High concentrations are represented with warm colors (yellow, orange, red). Purple and blue represent low concentrations. The coastline and the isoline of 0.5 mg m^{-3} of pigments are shown in white. Land, clouds and missing data are black.

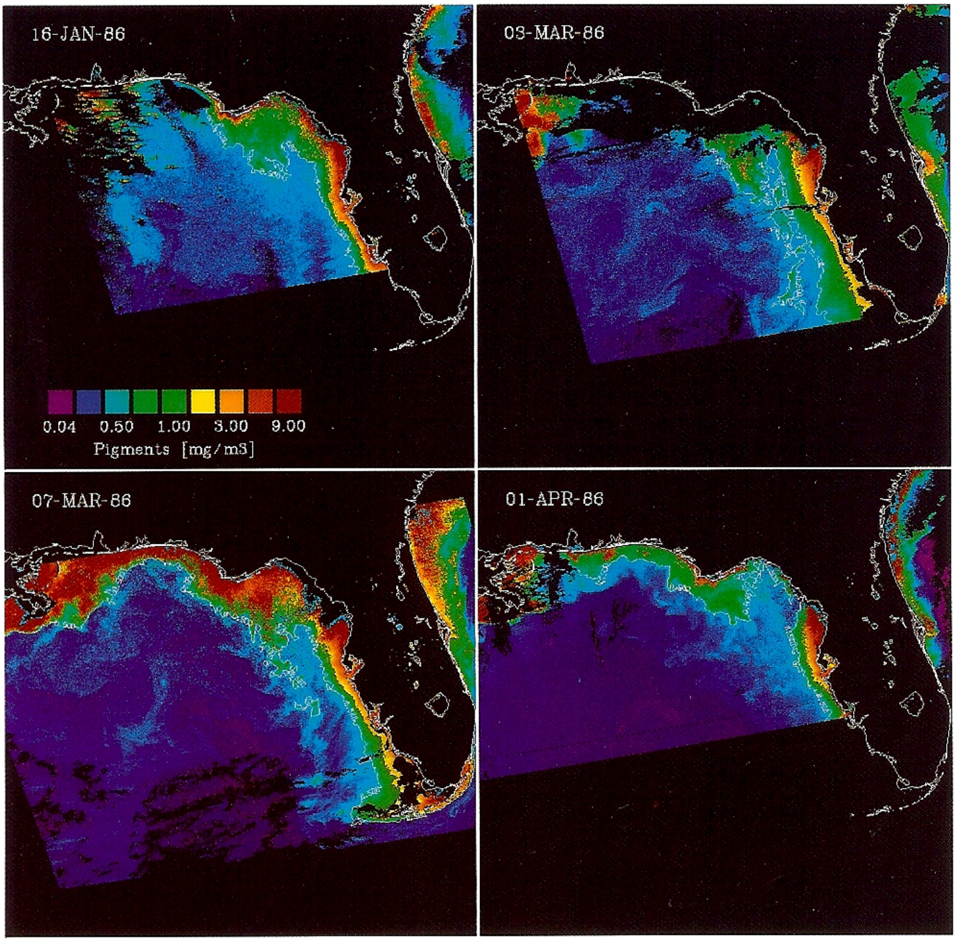

Fig. 4. Daily images of pigment concentration (mg m^{-3}) in the West Florida Shelf obtained with the CZCS during 1986. High concentrations are represented with warm colors (yellow, orange, red). Purple and blue represent low concentrations. The coastline and the isoline of 0.5 mg m^{-3} of pigments are shown in white. Land, clouds and missing data are black.

1981, February 1982, May 1983, April 1984, May 1985 and March 1986. The duration of the plume for those years varied from one week to one month.

In 1986, the maximum concentrations of the West Florida plume was observed in March, lasting for about a month (Fig. 4). In mid-January, coastal waters off Cape San Blas began showing elevated pigment concentrations. On 3 March, a plume occurred along the West Florida Shelf with pigment concentrations >0.5 mg m^{-3}. On 7 March, the plume extended southward and pigment values exceeded 1.0 mg m^{-3}. Pigment concentrations were lower by 1 April (Fig. 4).

Our *in situ* data collected during the March 1992 cruise also show a plume of high chl *a* concentration extending from the surface down to 20 m (Fig. 5). A well-defined plume (>0.5 mg m^{-3}) extended from off Cape San Blas southward. Surface chl *a* values at the center of the plume were greater than 3.0 mg m^{-3} and at one station reached 8.78 mg m^{-3}. Outside the plume, chl *a* values were <0.5 mg m^{-3}.

Surface salinities during March 1992 are shown in Fig. 6. Northern coastal areas had salinities <35 psu. The lowest salinities occurred close to the coast and values between 35 and 36 psu occurred in the area of high chl *a* (Fig. 5). Further south, low salinities were centered over the inner shelf and extended from Apalachicola Bay to Tampa Bay (Fig. 6).

Time series of pigment concentration

The CZCS time series allowed us to quantify the spatial variations of pigment concentration in the West Florida Shelf. The mean pigment concentration at the 40 m isobath (Stas 1–6; Fig. 7) was higher than at the 200 m isobath (Stas 7–12; Fig. 8). The overall mean value (7 yr average) at Sta. 1 was 0.66 mg m^{-3} (S.D. = 0.48; n = 84) and at Sta. 7 it was 0.32 mg m^{-3} (S.D. = 0.18; n = 84). The mean value for Sta. 6 was 0.15 mg m^{-3} (S.D. = 0.08; n = 84) and for Sta. 12 it was 0.13 mg m^{-3} (S.D. = 0.06; n = 84). These stations showed a decrease in mean pigment concentration from north to south. Stations at the 40 m isobath had higher variability than stations at the 200 m isobath. Stations 1, 2 and 3 had the highest mean values and the maximum variability, while Stas 6 and 12 showed the lowest mean values and variability.

Peak values of pigment concentration between November and April were higher at Stas 1, 2 and 3 (>0.5 mg m^{-3}) than at Stas 4, 5 and 6 (Fig. 7). Diatom blooms of 5–7 mg m^{-3} chl *a* and productivity values of 1.7 gC m^{-2} d^{-1} have been reported at this time of year in the adjacent Apalachicola Bay and Alligator Harbor (Marshall, 1956; Curl, 1959a,b; Livingston, 1984). The high CZCS signal at those stations could be produced by these diatom blooms. Peak values were also detected during these months at Stas 7, 8 and 9 (Fig. 8), but the pigment concentrations were lower than at Stas 1, 2 and 3 (Fig. 7).

High pigment concentrations (>1.0 mg m^{-3}) were registered during fall at the inner shelf stations (Stas 13–16; Fig. 9). Fall blooms of the toxic dinoflagellate *Gymnodinium breve* have been reported in this area, yielding surface stocks of as much as 30–60 mg m^{-3} chl *a* (Carder and Steward, 1985). Steidinger and Haddad (1981) showed a bloom of high pigment concentration in the coastal waters of SW Florida using a CZCS image from 14 November 1978. They confirmed a direct correlation between the patches seen in the image and the distribution of high *G. breve* concentrations measured during the same day. The fall peak registered in our CZCS time series (Fig. 9) could indeed reflect the presence of dinoflagellate blooms in west-central Florida. However, in shallow waters (i.e. 20 m), the bloom signal can be contaminated with bottom reflectance (Spitzer and Dirks, 1987).

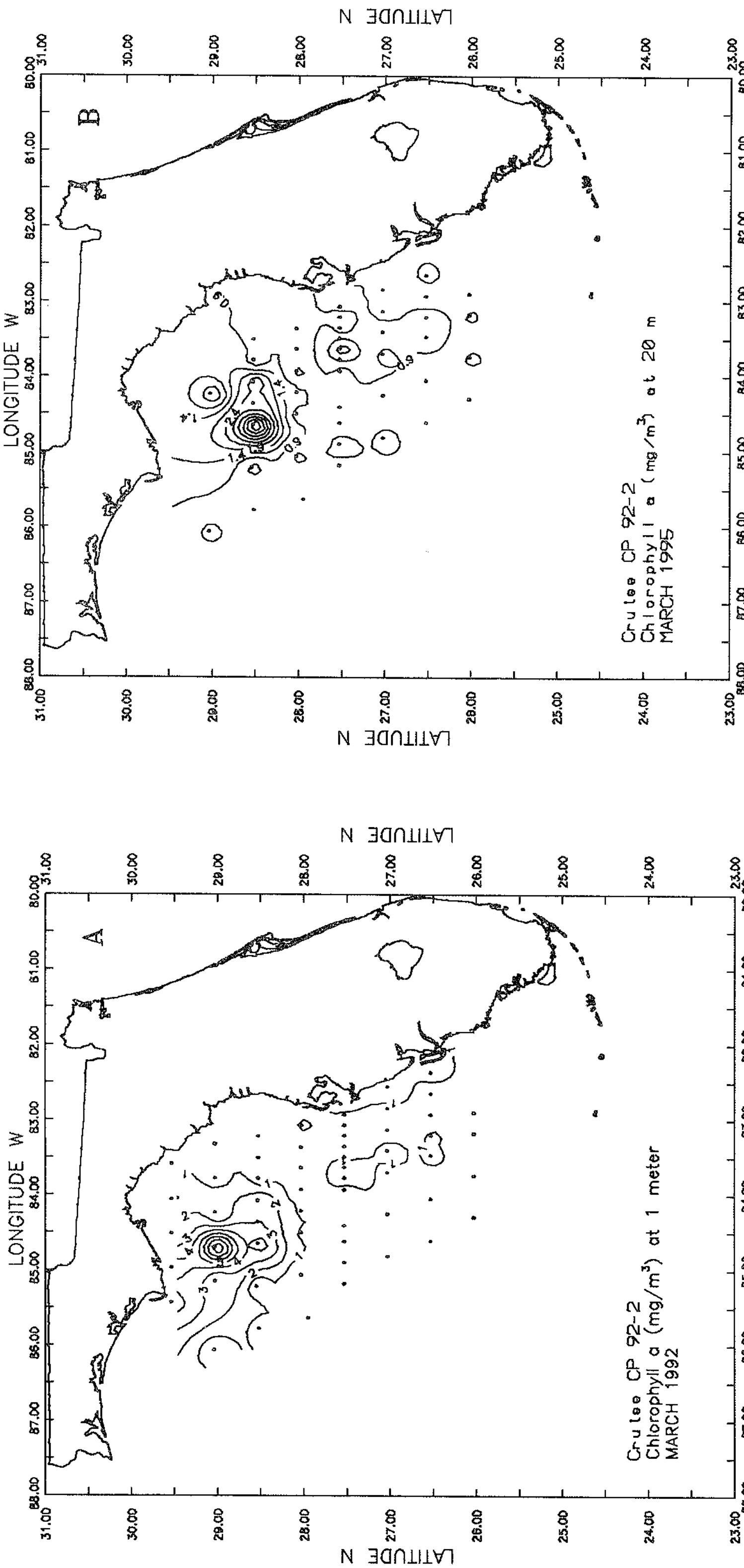

Fig. 5. Chlorophyll *a* concentration (mg m^{-3}) at 1 m (A) and 20 m (B) depths on the West Florida Shelf during March 1992.

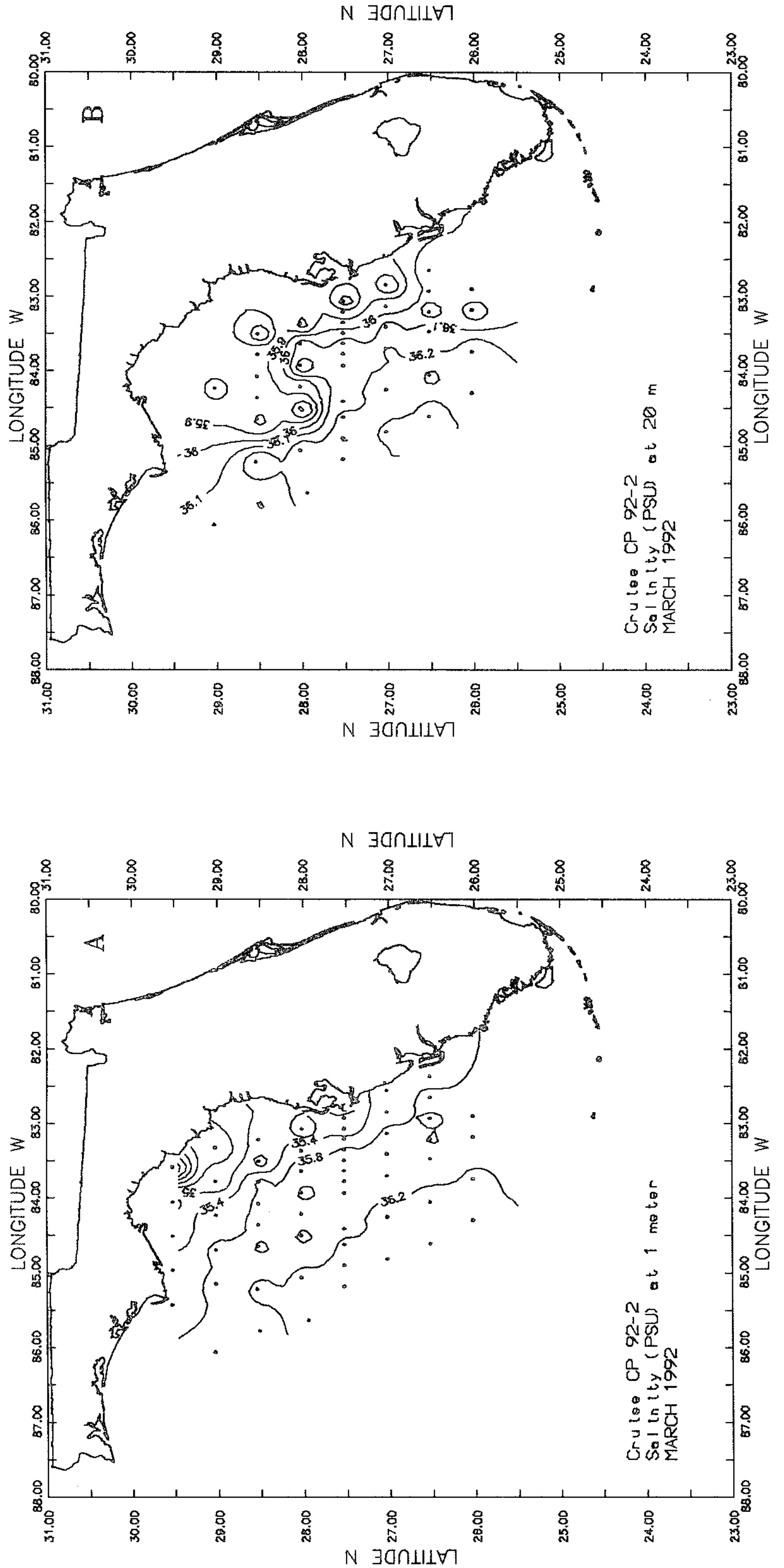

Fig. 6. Salinity (psu) at 1 m (A) and 20 m (B) depths on the West Florida Shelf during March 1992.

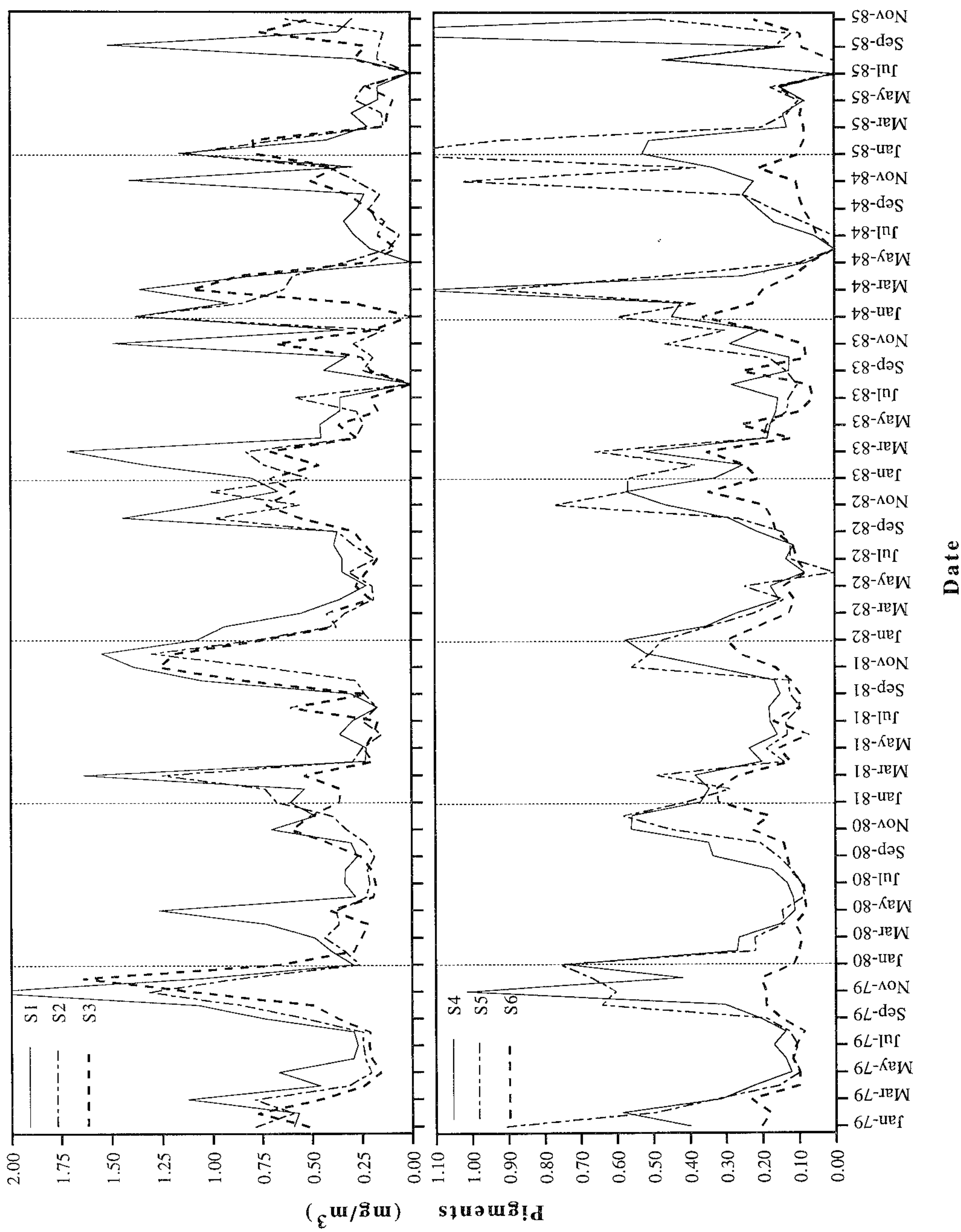

Fig. 7. The CZCS monthly mean pigment concentration along the 40 m isobath on the West Florida Shelf (see Fig. 1 for station locations). Note the different scales on graph ordinates.

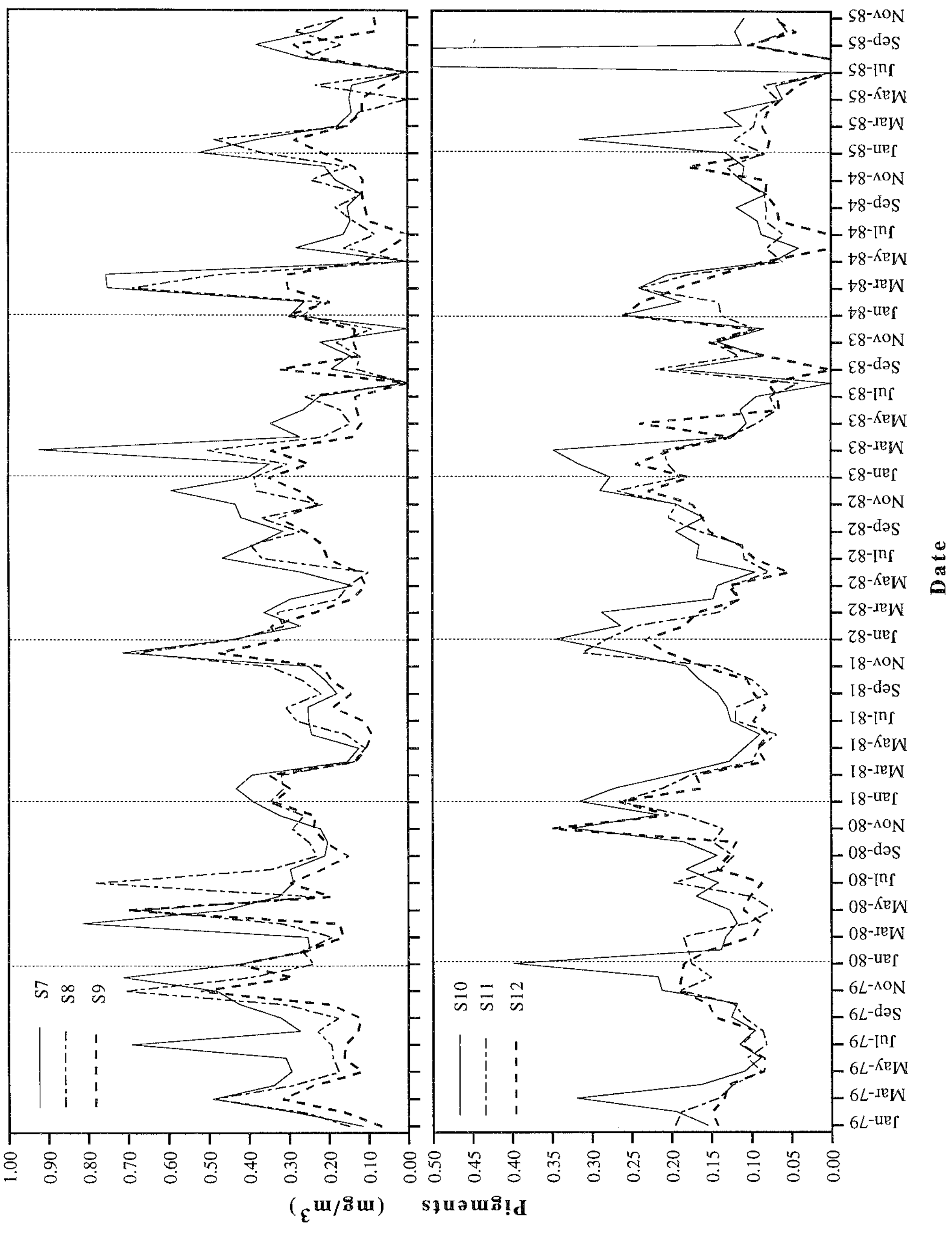

Fig. 8. The CZCS monthly mean pigment concentration along the 200 m isobath of the West Florida Shelf (see Fig. 1 for station locations). Note the different scales on graph ordinates.

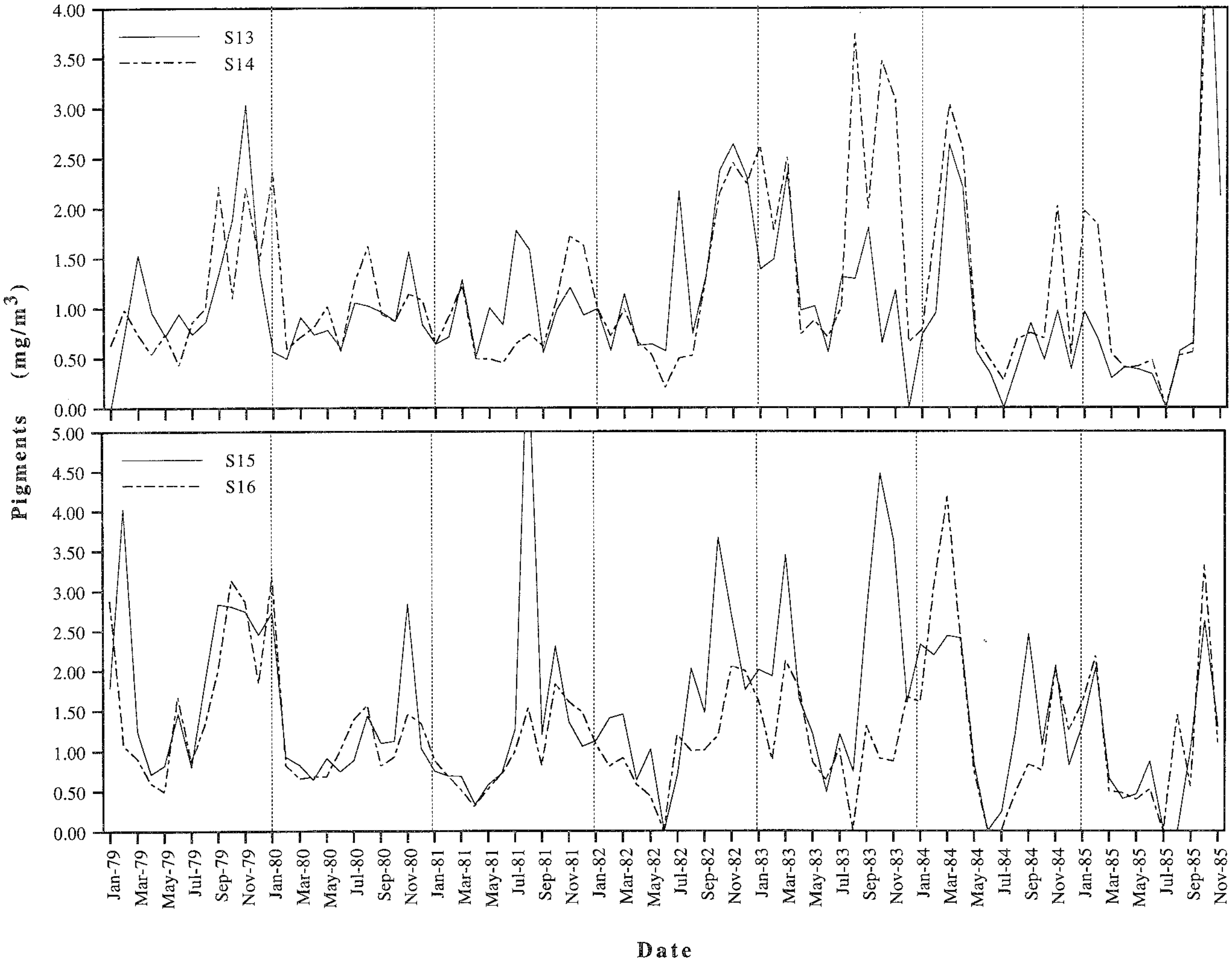

Fig. 9. The CZCS monthly mean pigment concentration along the 20 m isobath of the West Florida Shelf (see Fig. 1 for station locations). Note the different scales on graph ordinates.

More field data are necessary for better discrimination between both signals in future satellite data.

Winter peaks of pigment concentration were detected in several stations. Khromov (1969) and Yoder *et al.* (1987) reported coccolithophorid and cyanophyte blooms in the West Florida Shelf during winter. However, the CZCS spectral signature of coccolithophorid blooms can be confused with other signals like those of whitings (suspended particles of calcium carbonate) or suspended sediments. Brown and Yoder (1994) suggested that the extensive coccolithophores bloom signals identified by them on the West Florida Shelf could mainly be attributed to carbonate sediments resuspended by seasonal stormy weather. However, this hypothesis has not been confirmed and more research is necessary for a better understanding of these signals.

DISCUSSION

The periodic formation of West Florida plumes from 1979 to 1986 is clearly shown with the CZCS data. However, recent studies show that CZCS-derived pigment concentrations suffer a high degree of contamination by colored organic material (COM) within coastal and river discharge areas (Carder *et al.*, 1986, 1989, 1991; Müller-Karger *et al.*, 1989; Hochman *et al.*, 1994). In the northwestern shelf waters of the Gulf of Mexico, the total dissolved organic carbon (DOC) has been reported to be >1.0 mg l^{-1} (Frederiks and Sackett, 1970; El-Sayed *et al.*, 1972), with up to 3.2 mg l^{-1} of DOC found off Cape San Blas (Harvey *et al.*, 1983). It is difficult to separate phytoplankton chl *a* from COM in our CZCS images due to the limited amount of DOC data from the West Florida Shelf and lack of knowledge of the fraction of DOC which is colored. However, the *in situ* data collected by Khromov in 1969 and, more recently, by our 1992 cruise, confirm the extent and persistence of the phytoplankton chl *a* plume on the West Florida Shelf. Furthermore, maximal chl *a* levels occurred in sub-surface waters during our 1992 cruise [Fig. 5(B)] and at concentrations higher than previously predicted from the CZCS images. The CZCS images, as presently processed, may represent an underestimate of the water column concentration of pigments in these coastal waters.

While the periodic occurrence of the chlorophyll plumes is confirmed by our *in situ* and satellite data, the processes responsible for the formation of these plumes remain unclear. In an attempt to determine the cause of formation of these plumes, we examined the available river discharge and nutrient data for this region. We found that such plumes may be related to one or a combination of the following factors: (1) discharge from small, local rivers along the NW Florida coast; (2) seasonal changes in steric height differences between the shelf and deep Gulf of Mexico waters; (3) circulation of water associated with the Loop Current and upwelling in the DeSoto Canyon; and (4) discharge from the Mississippi and Mobile Rivers.

Local rivers

The Gulf coast of Florida receives the discharge of 21 rivers, primarily concentrated in the northern region (Nordlie, 1990). Although it has been demonstrated that the runoff of these rivers affects the chemistry and biology of estuarine zones (Livingston *et al.*, 1975; Myers and Iverson, 1981; Johansson *et al.*, 1985; Livingston, 1990; McPherson and Miller, 1990; McPherson *et al.*, 1990), their impact on shelf waters is unclear.

The NW Florida rivers (Fig. 1) showed maximum and minimum discharge during spring and fall, respectively (Fig. 10). Peak discharge during spring coincided with the appearance of the West Florida plumes in the CZCS images. The SW Florida rivers (Fig. 1) showed more irregularity, but in general the maximum discharge was during summer–fall (Fig. 10).

The high seasonal discharge of the northwestern rivers can represent a source of inorganic nutrients for the formation of the West Florida plume. To explore this hypothesis, we examined the inorganic nitrogen concentration ($NO_2 + NO_3$) for the Apalachicola, Suwannee, Escambia and Choctawhatchee Rivers (Fig. 11; see Fig. 1 for location of rivers). The total average loading for these four rivers was 1.32×10^8 μg-at N s^{-1}. The inorganic nitrogen loading during winter–spring (January–June) was about twice as high as during summer–fall (July–December). We found that changes in pigment concentration from Stas 1, 2 and 3 coincided with our estimates of estuarine nitrogen loading (Fig. 12). High pigment concentrations (>0.5 mg m^{-3}) at Stas 1 and 2 showed a correspondence with high nitrogen loading during March 1979, November 1980 and March 1981. In May 1980, high pigment concentration occurred after a high nitrogen loading in April 1980. During fall of 1979, the pigment concentration was very high but the nitrogen loading was low. At that time high perturbations in shelf areas were detected due to the passage of five tropical cyclones (Halper and Schroeder, 1990) which may have brought nutrients toward the surface via mixing.

The nitrogen loading from the small local rivers may initiate the spring bloom of phytoplankton in shelf waters of NW Florida. We estimated the number of loading days required for such nutrient supplies by selecting a box of 3.45×10^{10} m^2 and 20 m depth (Fig. 1). This box was defined to best characterize the mean region covered by the plumes. The *in situ* mean depth-integrated chl *a* was 45.49 mg m^2 for 13 stations sampled inside the box during March 1992. The total stock of chl *a* was estimated to be 1.6×10^{15} μg for that area. Using a C:N weight ratio of 5.7 (Redfield, 1958) and a C:chl *a* ratio of 50, we calculated that 9.9×10^{14} μg-at of N [= 1.6×10^{15} μg chl *a* * (50 μg C/1 μg chl *a*) * (1 μg N/5.7 μg C) * (1 μg-at N/14 μg N)] are required to produce that amount of chl *a*. We suggest from these simple calculations that this influx of $NO_2 + NO_3$ could be obtained from 67 days of local rivers loading, based on the winter–spring average (1.7×10^8 μg-at N s^{-1}), or 45 days based on the March data only (2.5×10^8 μg-at N s^{-1}).

Water circulation

A recent study suggests that southward circulation on the West Florida Shelf is produced by differential heating and cooling within different regions (Robert Weisberg, personal communication). The Loop Current has a significant year-round effect on maintaining a higher temperature offshore relative to waters on the West Florida Shelf. The latter experiences wider seasonal temperature fluctuations than offshore waters at the same latitude. We calculated the steric height differences (Tabata *et al.*, 1986) that could be experienced between the shelf and offshore locations at 28°N, relative to 200 decibars. Hydrographic conditions during different seasons were determined using data from Nowlin and McLellan (1967), Maul *et al.* (1979) and Marmorino (1983). Offshore and shelf waters have average temperature ranges of 21–24 and 14–19°C, respectively. Our calculations, based on differences in specific volumes (salinity = 36 psu; 200 db; Pond and Pickard, 1983) show that the sea level at a shelf location can be between 27 and 33 cm lower

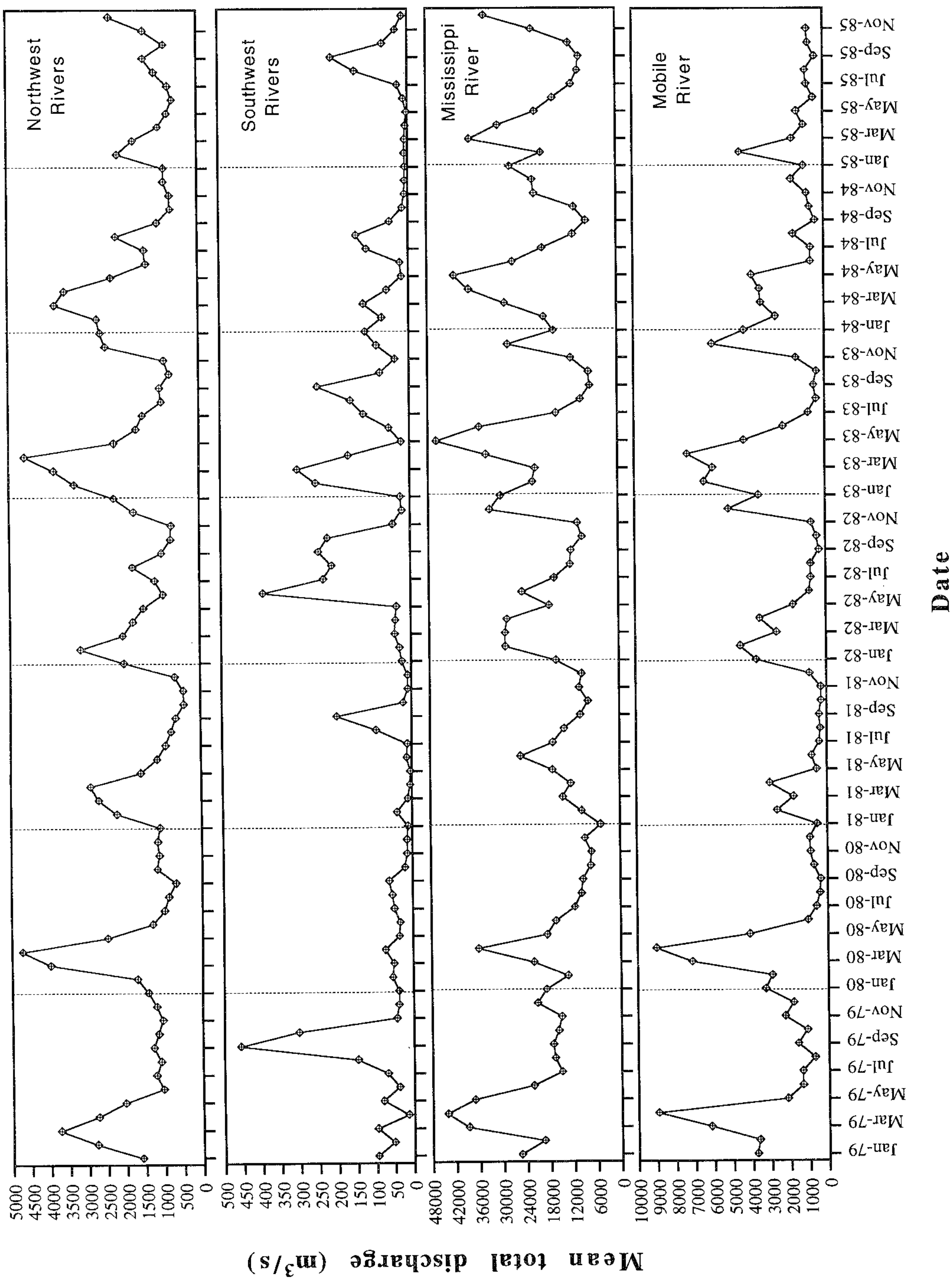

Fig. 10. Total monthly mean river discharge during the study period for northwest and southwest rivers along the West Florida Shelf, the Mississippi River and the Mobile River. Figure 1 shows the division line between northwest and southwest rivers. Note the different scales on graph ordinates.

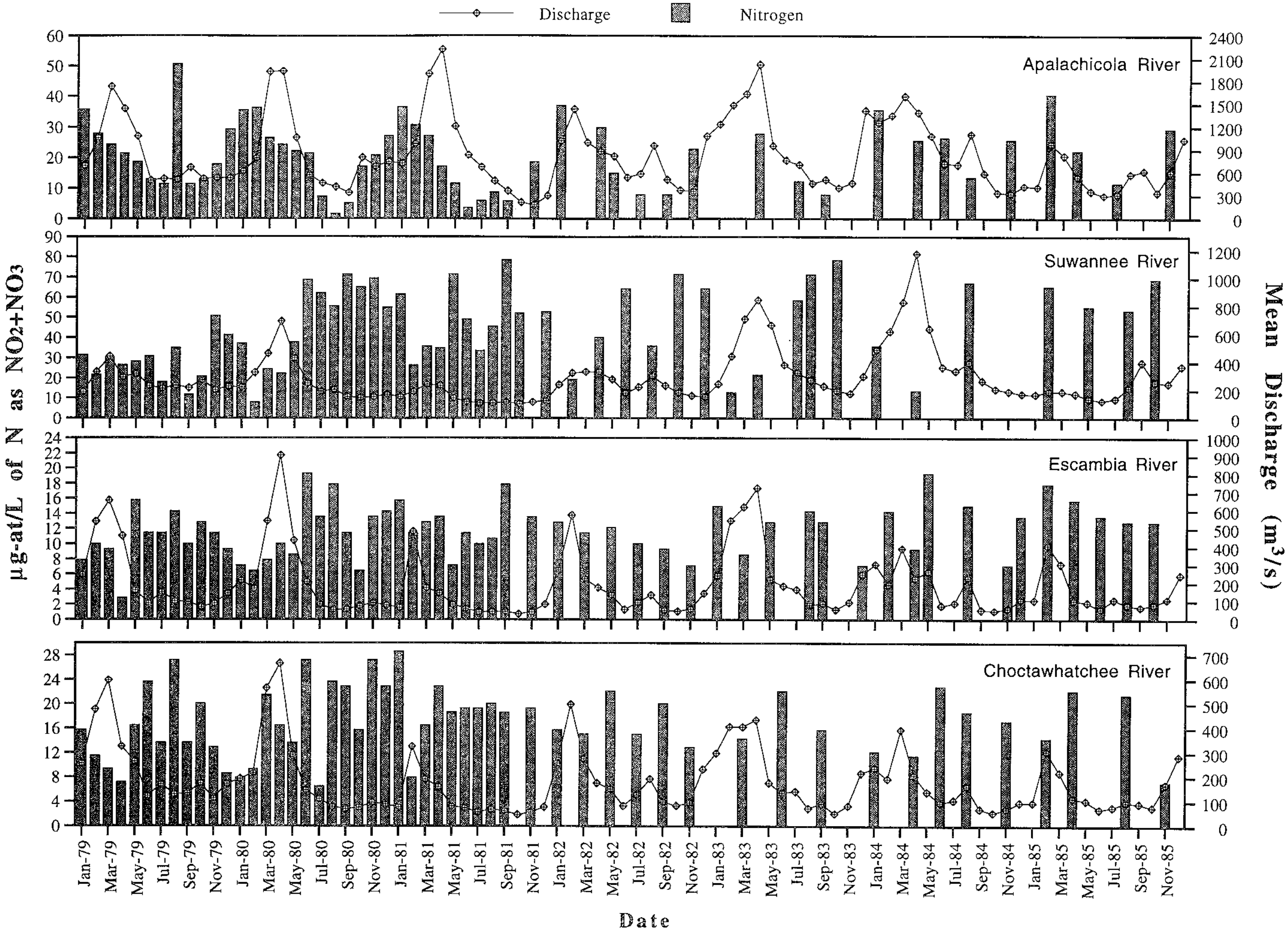

Fig. 11. Inorganic nitrogen concentration and river discharge in Apalachicola, Suwannee, Escambia and Choctawhatchee Rivers during the study period (see Fig. 1 for river locations). Note the different scales on graph ordinates.

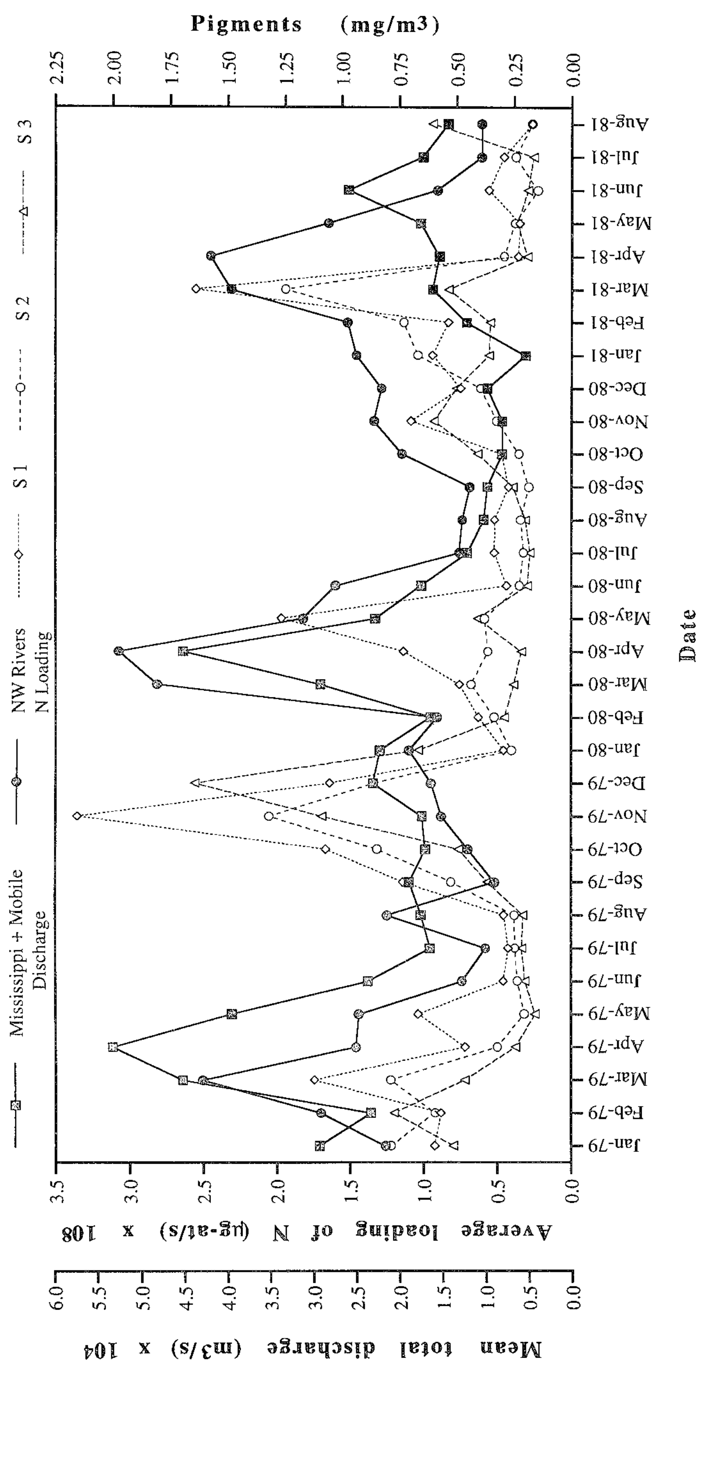

Fig. 12. The CZCS monthly mean pigment concentration of Stas 1, 2 and 3 vs monthly variations of total average loading of inorganic nitrogen as NO_2 + NO_3 for Apalachicola, Suwannee, Escambia and Choctawhatchee Rivers, and vs Mississippi + Mobile Rivers' mean total discharge (see Fig. 1. for stations and river locations).

than an offshore location at the same latitude. These steric height differences generate a pressure gradient toward the shore that will be balanced by Coriolis. Assuming a barotropic condition, the water mass will therefore move southward, with the strength of the flow proportional to the differences in steric height.

Southward movement of shelf waters may transport phytoplankton, nutrients, dissolved organic matter and suspended sediments from northern to central and southern regions. As this effect would have a maximum in the February–April time frame, coinciding with the spring maximum discharge of rivers into the northern Gulf, the seasonal plumes detected along the West Florida Shelf may be caused by this type of circulation.

Loop current intrusions

Nutrient supply associated with upwelling caused by intrusion of the Loop Current to the southwest Florida Shelf is restricted to the outer shelf (Paluszkiewicz *et al.*, 1983). In contrast, on the northwest Florida Shelf, Huh *et al.* (1981) observed during February 1977 that the Loop Current intruded into DeSoto Canyon at 29°10′N, 87°10′W. They observed that the plume formed by this intrusion affects shelf waters to within a few kilometers of the beach. They suggest that "the canyon may have been a conduit for the northward flow of deep gulf waters".

We propose, based on an analogy with the Paluszkiewicz *et al.* (1983) observations, that episodic upwelling through DeSoto Canyon may provide nutrient injections to the inner West Florida Shelf from deep offshore waters. During January and February of 1992, the Loop Current intruded as far as 29°N into the Gulf of Mexico (NOAA, 1992). This intrusion could thus have reached the DeSoto Canyon, supplying nutrients from deep waters. The phytoplankton communities of northwest Florida may have responded to this input during March 1992 (Fig. 5). However, there is insufficient information to quantitatively evaluate the role of the DeSoto Canyon and the Loop Current on episodic nutrient supply; more research is required.

Mississippi and Mobile Rivers' discharge

The discharge of Mississippi and Mobile Rivers represents a possible source of COM on the West Florida Shelf. It is well known that the input of nutrients from the Mississippi River increases the levels of primary production in the northern Gulf of Mexico (Lohrenz *et al.*, 1990; Turner and Rabalais, 1991; Redalje *et al.*, 1994; Smith and Hitchcock, 1994). The Mobile River discharge probably also has a marked effect on the local primary production of the Alabama Shelf. Unfortunately, chemical and biological studies on this second river are limited.

We evaluated the possible impact of nutrient input from the Mississippi and Mobile Rivers to the West Florida Shelf based on estimates of the monthly average discharge (Ho and Barrett, 1977). The Mississippi River ranged from 4932 to 45,960 $m^3\ s^{-1}$ and the Mobile River ranged from 282 to 9018 $m^3\ s^{-1}$ during our study period (Fig. 10). Both rivers showed high and low discharge during spring and summer, respectively. The high discharge in spring coincided with high pigment concentrations at Stas 1, 2 and 3 and the occurrence of the West Florida plume detected by the CZCS. However, the seasonal correspondence between discharge and pigments was not as good as with the NW Florida rivers (Fig. 12).

Several studies show that the Mississippi River outflow can move toward the southeast, and become entrained in the eastern edge of the Loop Current (Maul, 1977; Müller-Karger *et al.*, 1991; Tomas, 1994; this study). The episodic northward intrusions of the Loop Current during winter and spring (Leipper, 1970; Molinari *et al.*, 1977; Behringer *et al.*, 1977; Vukovich *et al.*, 1979; Huh *et al.*, 1981) can transport low-salinity and chl *a*/COM rich waters from the Mississippi and Mobile Rivers to the West Florida Shelf (Maul, 1977). Indeed, low salinity lenses of 33–35 psu have been found off West Florida, from Cape San Blas to Cape Romano; their origin has been attributed, in part, to episodes of the Mississippi River discharge (Chew, 1956; Austin and Jones, 1974; Wallace, 1980). Most recently, Tomas (1994) detected low salinity plumes on the shelf, south of Cape San Blas, with values of 33 and 26 psu in surface waters during August of 1992 and 1993, respectively. Both periods of low salinity coincided with (1) the peak Mississippi River outflow; (2) penetration of the Loop Current into the northern Gulf; and (3) prevailing winds toward the east. In September 1993, a combination of remote sensing sea surface temperature and Argos drifter data combined with ship of opportunity salinity data allowed Mississippi River outflow to be traced as far south as the Florida Keys (Walker *et al.*, 1994; Ortner *et al.*, 1995).

Such low salinity outflows are probably accompanied by high concentrations of COM. It is possible that during the Loop Current intrusion in January and February of 1992, COM from these two rivers was transported to the east. This occasional eastward transport to the West Florida Shelf may be added to the input of local rivers and Loop Current-induced upwelling, all producing good conditions for phytoplankton growth and biomass accumulation.

CONCLUSIONS

The complexity of the West Florida Shelf has been demonstrated with our CZCS time series and the available field data. An initial diatom spring bloom may originate in waters off NW Florida, due mainly to the input of nutrients from local river discharge. Intrusions of the Loop Current may induce both upwelling in the DeSoto Canyon and eastward transport of effluents from the Mississippi and Mobile Rivers. Shelf circulation patterns induced by steric height differences can move the phytoplankton and other suspended organic material southward. Still, these processes are poorly understood. Future studies in the West Florida Shelf must provide more spatial and temporal field data in order to elucidate the relationship between phytoplankton processes, dissolved organic carbon, inherent and apparent optical properties and water circulation.

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