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Variability of Surface Pigment Concentrations in the South Atlantic Bight

CHARLES R. MCCLAIN,¹ JAMES A. YODER,² L. P. ATKINSON,³ J. O. BLANTON,² T. N. LEE,⁴ J. J. SINGER,⁵ AND FRANK MULLER-KARGER⁶

A 1-year time sequence (November 1978 through October 1979) of surface pigment images from the South Atlantic Bight (SAB) was derived from the Nimbus 7 coastal zone color scanner. This data set is augmented with in situ observations of hydrographic parameters, freshwater discharge, sea level, coastal winds, and currents for the purpose of examining the coupling between physical processes and the spatial and temporal variability of the surface pigment fields. The SAB is divided into three regions: the east Florida shelf, the Georgia-South Carolina shelf and the Carolina Capes. Six-month "seasonal" mean pigment fields and time series of mean values within subregions were generated. While the seasonal mean isopleths were closely oriented along isobaths, significant differences between seasons in each region were found to exist. These differences are explained by correlating the pigment time series with physical parameters and processes known to be important in the SAB. Specifically, summertime concentrations between Cape Romain and Cape Canaveral were greater than those in winter, but the opposite was true north of Cape Romain. It is suggested that during the abnormally high freshwater discharge in the winter-spring of 1979, Cape Romain and Cape Fear were the major sites of cross-shelf transport, while the cross-shelf exchange during the fall of 1979 occurred just north of Cape Canaveral. Finally, the alongshore band of high pigment concentrations increased in width throughout the year in the vicinity of Charleston, but near Jacksonville it exhibited a minimum width in the summer and a maximum width in the fall of 1979.

INTRODUCTION

During the past 15 years, the South Atlantic Bight (SAB), shown in Figure 1, has been the site of an extensive multidisciplinary oceanographic research effort (see Blanton *et al.* [1984], Atkinson *et al.* [1985], and papers in the collection "Oceanography of the Southeast U.S. Continental Shelf and Adjacent Gulf Stream (*Journal of Geophysical Research*, volume 88, number C8, 1983)). As a result, it has been found that a wide variety of biological, physical, and chemical processes interplay to form a complex system that had largely been unexamined. Much of the work in the SAB prior to the mid-1970s focused on the vast estuarine system that extends from the Outer Banks of North Carolina to Cape Canaveral, Florida, because it was believed that the estuarine and the nearshore regimes were the primary sites of the biological production [Haines and Dunstan, 1975; Turner *et al.*, 1979; Turner, 1981]. Few observations had been collected beyond the nearshore regime, and sampling strategies for offshore observations were designed after those applied in other areas such as the Mid-Atlantic Bight (MAB) where the spring bloom dominates the annual cycle. As investigations in the SAB intensified during the 1970s, it became clear that the Gulf Stream has a major impact on the oceanography of the SAB and that the SAB was quite different from the MAB and the West Coast systems [Pietrafesa, 1983b]. Because of the episodic nature of Gulf Stream-induced events, traditional sam-

pling methodologies proved inadequate for resolving the space and time scales important on this shelf, and revisions of previous ideas regarding dynamical processes, nutrient sources, and primary production were required [Stefansson *et al.*, 1971; Blanton, 1971; Dunstan and Atkinson, 1976; Atkinson, 1977; Atkinson *et al.*, 1978; Lee and Brooks, 1979; Blanton *et al.*, 1981; Lee *et al.*, 1981; Yoder *et al.*, 1981, 1983; Yoder, 1985]. Thus, subsequent field programs such as Georgia Bight Experiments GABEX-I in 1980 and GABEX-II in 1981, the Spring Exchange Experiment (SPREX) in 1985, and the Fall Exchange Experiment (FLEX) in 1987 were designed using sampling concepts which incorporated multiple ships, mooring arrays, and aircraft.

Concurrent with these developments, satellite infrared observations were proving to be invaluable for observing Gulf Stream filaments [Stumpf and Rao, 1975; Legeckis, 1975; Vukovich and Crissman, 1975] and the deflection of the Gulf Stream by a bathymetric feature called the Charleston Bump and for quantifying the statistical behavior of the Gulf Stream front [Bane and Brooks, 1979; Olson *et al.*, 1983]. The primary limitation of infrared observations of the SAB is that sea surface temperatures are fairly uniform during the summer months, so that frontal boundaries cannot be determined.

In October 1978, the Nimbus 7 coastal zone color scanner (CZCS) was launched offering synoptic year-round estimates of near-surface chlorophyll concentration [Hovis *et al.*, 1980] of reasonable accuracy [Gordon *et al.*, 1980, 1983a; Walters, 1985; Barale *et al.*, 1986]. Color imagery has been combined with field data from the SAB to examine specific events and processes [McClain *et al.*, 1984; McClain and Atkinson, 1985; Yoder *et al.*, 1987]. These studies showed that the pigment retrievals are quite good and that the structures in the surface pigment fields are associated with subsurface structures in other water properties such as temperature, salinity, and nutrient concentrations.

In this paper a 1-year time series of imagery is integrated with a variety of field observations in order to examine the influence of physical processes on the temporal variability and the spatial distribution of surface pigment concentrations

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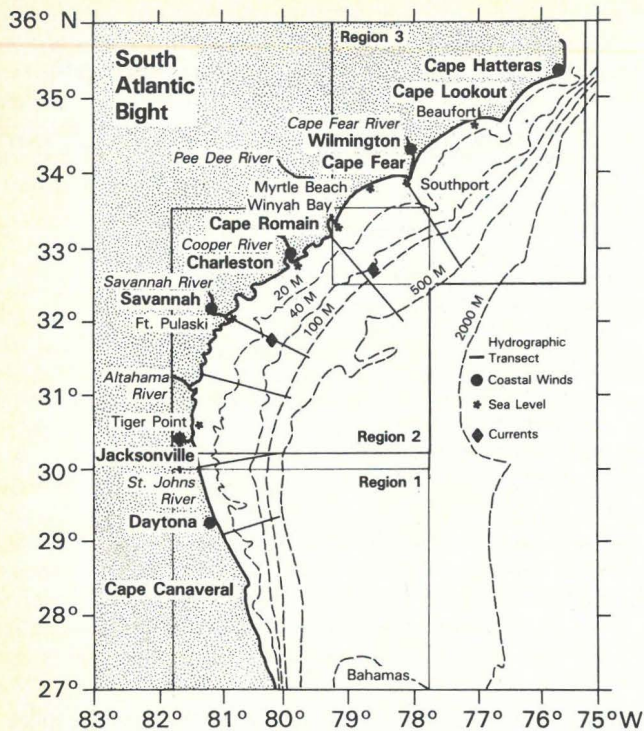


Fig. 1. Map of the South Atlantic Bight with regions 1, 2, and 3 outlined and locations of hydrographic transects, current meters, tide gauges, and meteorological stations identified.

throughout the SAB. The term "surface" is emphasized because the CZCS maps concentrations only in the first optical depth [Clark, 1981] and does not sense subsurface blooms, which can be extensive during highly stratified conditions over the shelf in the SAB [Yoder et al., 1983; Atkinson et al., 1984]. Optical depths can vary from less than 1 m in the turbid nearshore areas to more than 20 m in the Gulf Stream. Particular topics to be addressed include the cross-shelf migration of the nearshore pigment front, the influence of subsurface intrusions on the surface pigment field, the pathways of transport of material across the shelf, and the differences in the seasonal modulation of surface pigment concentrations in the Georgia Bight and the Carolina Capes regions.

ENVIRONMENTAL FACTORS AND FORCING MECHANISMS

Shelf geometry, the Gulf Stream, the winds, river discharge, and stratification act either directly or indirectly to cause episodic and seasonal variability in the cross-shelf and along-shore distributions of surface phytoplankton. These factors are not always independent (e.g., the Gulf Stream and stratification), and while there are a variety of dynamical interactions which couple them, each category is unique in certain ways.

Basin Geometry and Bathymetry

The SAB shelf has a crescent shape which is very narrow near Cape Canaveral and Cape Hatteras and relatively broad off Georgia (maximum width is 200 km). Five capes (Canaveral, Romain, Fear, Lookout, and Hatteras) partition the shelf into four embayments called, from south to north, the Georgia Bight, Long Bay, Onslow Bay, and Raleigh Bay. The Georgia Bight and Long Bay form one continuous shelf, but Onslow Bay and Raleigh Bay are dynamically isolated by the capes and shallow shoals which act to restrict exchange between the bays while enhancing cross-shelf exchange [Blanton,

1971; Blanton and Pietrafesa, 1978; Atkinson et al., 1978; Atkinson and Pietrafesa, 1980; Blanton et al., 1981; Janowitz and Pietrafesa, 1982]. In addition, there exists a sharp protrusion in the continental slope off the coast of Georgia called the Charleston Bump. This feature deflects the Gulf Stream offshore [Brooks and Bane, 1978; Chao and Janowitz, 1979], resulting in enhanced Gulf Stream meandering off the Carolinas [Legeckis, 1979] and a quasi-permanent cyclonic eddy feature called the Charleston Gyre [McClain and Atkinson, 1985].

The shelf break is near the 60-m isobath and is quite abrupt. Between Daytona Beach and Cape Lookout the shelf is gently sloping, so that a distinct middle shelf region separates the freshwater nearshore region and the Gulf Stream-dominated shelf break regime. This separation limits the influence of Gulf Stream-induced intrusions on the nearshore regime and of nearshore processes such as freshwater discharge on the outer shelf regime. The middle shelf regime is not as distinct around Cape Canaveral and in Raleigh Bay. Also, the degree to which the inner, middle, and outer shelf regimes interact varies seasonally with stratification and with the strength of the nearshore front [Blanton, 1981; Blanton and Atkinson, 1983].

Gulf Stream

The Gulf Stream plays a major role in the dynamics and biology of the middle and outer shelf regimes. The mechanisms through which the Gulf Stream influences the transport of nutrients into the euphotic zone on the continental shelf are frontal eddy upwelling [Pietrafesa and Janowitz, 1979; Chew, 1981; Yoder et al., 1981; Bane et al., 1981; Lee and Atkinson, 1983; Pietrafesa, 1983a; McClain et al., 1984], subsurface intrusions of Gulf Stream water [Blanton, 1971; Atkinson, 1977; Hofmann et al., 1981; Leming and Mooers, 1981; Blanton et al., 1981; Janowitz and Pietrafesa, 1982], and frontal and shelf break upwelling during the winter [Oey, 1986; Oey et al., 1987]. The frequency of occurrence of frontal eddy events (also known as filaments and shingles) is of the order of 2 to 10 days and are the major source of new nutrients to the outer shelf. Subsurface nutrient-rich intrusions of Gulf Stream water onto the shelf have been observed in the Georgia Bight and in Onslow Bay but have not been found in Long Bay. Intrusions are the result of Gulf Stream meandering and the current's interaction with the capes and can be reinforced by upwelling favorable winds. That intrusions have not been reported in Long Bay may be due to the lack of observations but could also be due to the fact that the Gulf Stream is usually offshore of the shelf break at that location.

As was mentioned earlier, the Gulf Stream is deflected offshore by the Charleston Bump, resulting in a cyclonic circulation over the outer shelf off Charleston. The upwelling associated with this circulation has been documented by Singer et al. [1983] and McClain and Atkinson [1985]. The intensity of the upwelling is probably modulated by the degree of Gulf Stream deflection and by increased stratification in the summer which inhibits the upwelling of nutrients to the surface.

Stratification

All locations in the SAB experience a seasonal cycle in water column stratification [Atkinson, 1985] which is the result of seasonal variations in wind mixing, solar insolation, subsurface intrusion frequency, and freshwater discharge. In the fall and winter, surface cooling causes convective overturning, and higher wind stress enhances mixing, so that the

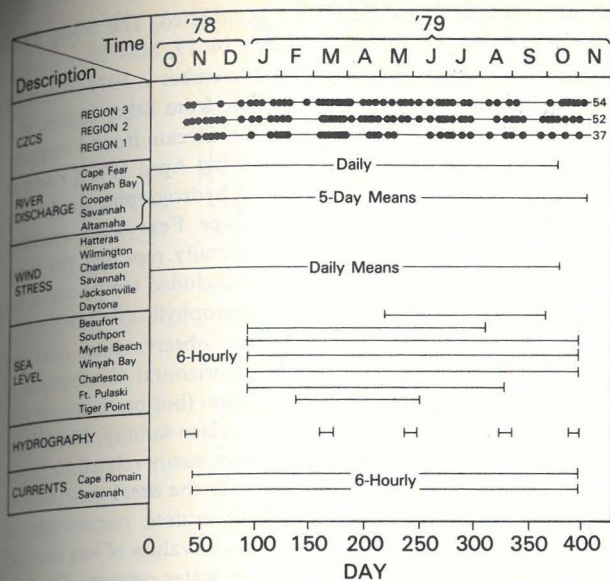


Fig. 2. Data set synopsis.

density field over the inner and middle shelf has relatively little vertical or horizontal structure. The transition to highly stratified conditions, at least in the Georgia Bight, begins in late winter and early spring when freshwater runoff peaks. In the summer, the relaxation of the winds and the increase in solar insolation further the process. The enhanced stratification promotes the subsurface intrusion process by decreasing the surface layer density, making it easier to displace. The range of surface-bottom temperature difference at midshelf is 0°C in winter and can be greater than 10°C in summer. However, in the summer, stratification can be offset by upwelling favorable winds which can cause the subsurface water near the coast to shoal to the surface.

The effect of increased stratification on intrusion processes is dramatic [Atkinson, 1977]. Bottom intrusions of subsurface Gulf Stream water are confined to the outer shelf in the winter but can extend to the coast of northern Florida in the summer. The residence time of stranded intrusions can be a month or longer and bottom chlorophyll concentrations exceeding 7 mg/m³ have been observed in the Georgia Bight [Yoder, 1985; Yoder et al., 1985]. Current-bathymetry interactions can cause onshore bottom flow of Gulf Stream water in the Georgia Bight north of Cape Canaveral where the isobaths diverge and offshore flow off Savannah where the isobaths begin to converge [Blanton et al., 1981; Janowitz and Pietrafesa, 1982]. In Onslow Bay, Blanton and Pietrafesa [1978] also found preferential onshore subsurface flow at the southern end of the bay.

Freshwater Discharge

River discharge in the SAB is concentrated between Cape Fear and Jacksonville. The Altamaha, Pee Dee, and Cape Fear rivers are the major contributors. Normally, the runoff peaks in early spring, with a secondary peak in the fall, causing large but localized cross-shelf and alongshelf density gradients. The transport of this water across the shelf is determined largely by the strength of a nearshore front [Blanton, 1981; Blanton and Atkinson, 1983] which serves as a barrier to lateral mixing. The position of the front is influenced primarily by discharge, stratification, and wind forcing. It tends to be further offshore in the spring and summer when the winds are

predominantly from the south. The front can break down during upwelling favorable wind events, allowing parcels of low-salinity nearshore water to separate from the front and drift offshore, and fingers of high-pigment water stretching across the shelf were often observed in the CZCS imagery.

The Cape Fear River empties on the south side of Cape Fear, and the Pee Dee River empties on the north side of Cape Romain. During high-discharge conditions, large plumes extending eastward from these capes suggest that these locations can be preferential sites of cross-shelf transport.

Winds

The winds play an important role in the circulation, particularly over the inner and middle shelf. Analyses of climatological wind fields by Weber and Blanton [1980] and Blanton et al. [1985] show a seasonal reversal of the general wind patterns, which are northerly in the winter and southerly in the summer. Thus the winds tend to support coastal upwelling in the summer but tend to confine the nearshore front nearer to the coast in the winter. Also, Janowitz and Pietrafesa [1980] found that wind-driven upwelling can occur at locations where changes in bottom slope are abrupt, such as along the north Florida shelf break. Recent observations and theory suggest that upwelling occurs over the shelfbreak and upper slope during strong southward wind events [Oey, 1986; Oey et al., 1987]. Coastal winds are correlated with offshore winds [Schwing and Blanton, 1984; Wesiberg and Pietrafesa [1983] but are lower in magnitude by as much as a factor of 2. This coherence is greatest in the summer.

METHODS AND DATA SETS

The data sets (Figure 2) include CZCS imagery spanning the period from November 2, 1978, to November 4, 1979; coastal winds from six locations; hydrographic and biological data from five cruises which covered the shelf from Cape Canaveral to Cape Fear; biological data from seven other less synoptic cruises in the Georgia Bight (not shown in Figure 2); sea level data from seven coastal locations; river discharge from five sources; and surface currents at two locations.

CZCS

The CZCS data set consists of 143 level-3 (remapped and registered to the coastline) pigment scenes extracted from 71 orbits. The coverage in the SAB was divided into three regions shown in Figure 1: the east Florida shelf, from West Palm Beach to Jacksonville (region 1); the Georgia-South Carolina

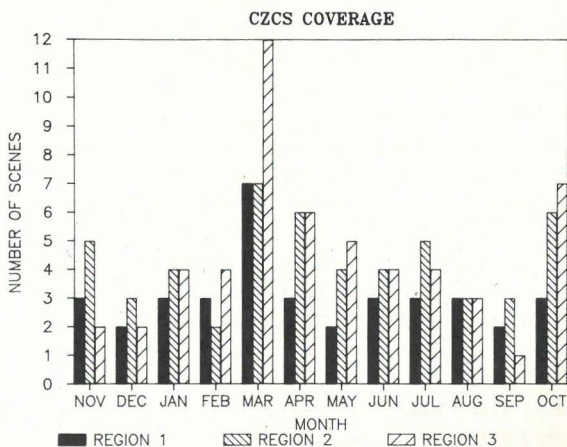


Fig. 3. Number of level-3 scenes per month and region.

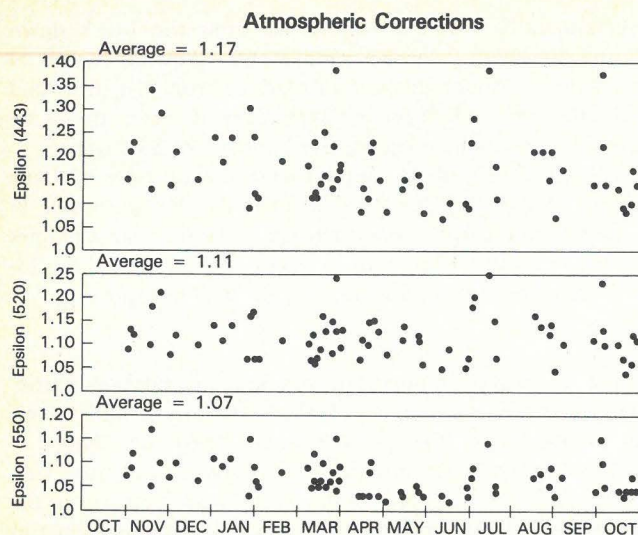


Fig. 4. Time series of ϵ values (ϵ values determine the aerosol correction for the 443-, 520-, and 550-nm bands of the CZCS).

shelf, from Jacksonville to Cape Romain (region 2); and the Carolina Capes, from Cape Romain to Cape Hatteras (region 3). The temporal distribution of coverage by region and month is provided in Figure 3. Few scenes offered cloud-free coverage of an entire region. Any sufficiently large portion of a full resolution pigment scene which coincided with a region was remapped to a universal transverse Mercator projection having the boundaries of that region and registered to the coastline, resulting in three regional time series of coregistered scenes.

A practical reason for selecting three subregions was that the bight is long and narrow, making it impossible to work with full resolution data and still encompass the entire region. Also, these subregions are associated with different physical regimes in that some of the physical forcing mechanisms vary meridionally in relative strength. Region 1 has a very narrow shelf with Cape Canaveral situated in the center. This region receives very little runoff and is dominated by the Gulf Stream. Region 2 is more complex in that all the dynamical mechanisms mentioned previously are important. Most of the freshwater discharge into the SAB flows into region 2. Region 3 is north of the Charleston Bump and, as a result, is influenced by the Charleston Gyre and enhanced Gulf Stream meandering. Also, region 3 is uniquely subdivided into three embayments (Long Bay, Onslow Bay, and Raleigh Bay).

All the CZCS scenes were processed using the *Gordon et al.* [1983a] atmospheric correction and bio-optical algorithms and the *Gordon et al.* [1983b] calibration correction scheme. Since low-pigment water from the open ocean in the Atlantic or Gulf of Mexico was almost always present in the scenes, estimation of the Angstrom exponents required for the aerosol corrections were obtained using the interactive technique discussed by *Barale et al.* [1986]. The ϵ values associated with these Angstrom exponents are plotted in Figure 4; mean values were 1.17 (443 nm), 1.11 (520 nm), and 1.07 (550 nm). These values are somewhat lower than those obtained by *Barale et al.* (1.34, 1.22, and 1.14, respectively) in the Mediterranean Sea from March to September 1979.

Hydrography

During the 13-month period of this study, five synoptic scale hydrographic cruises covering the shelf between Cape

Canaveral and Cape Fear were conducted. The cruise dates were November 9–13, 1978; March 14–19, May 28 to June 6, August 22–27 and October 27 to November 2, 1979 (Figures 1 and 2). Additional data are available from other cruises of a less synoptic nature, including a Gulf Stream frontal mapping experiment in the Georgia Bight during April 1979 [*Yoder et al.*, 1981; *McClain et al.*, 1984]. No hydrographic data south of Cape Canaveral or north of Cape Fear were available during this period. The surveys generally repeated the same transects. The parameters measured included temperature, salinity, nitrate, phosphate, silicate, chlorophyll-*a*, and oxygen.

Of the numerous hydrographic observations obtained during the five synoptic cruises, the horizontal distributions of particular interest are bulk stratification (bottom σ_t minus surface σ_t , [*Atkinson et al.*, 1983]) and surface salinity. These have been chosen because they are the most easily related to physical processes. Figures 5 and 6 provide the areal distributions of these two parameters for the five cruises, respectively. In Figure 5 the shaded area corresponds to values of less than 0.5 which implies a relatively well mixed water column. The bulk stratification index indicates that the water column was nearly homogeneous over most of the shelf in November of both years but was strongly stratified in May and August. The March data show that the shelf had remained well mixed except in the vicinities of capes Romain and Fear. In the salinity plots [Figure 6], the areas having values less than 35‰ are shaded, which clearly shows a seasonal modulation of the fresh nearshore regime with a minimum extent in August 1979 and a maximum expanse in May. Also, fresh water appears to have been confined to the Georgia–South Carolina coast and is evident along the Florida coast only during November 1979.

Biological Observations

Surface pigment data are available from the five synoptic hydrographic cruises, the Gulf Stream frontal mapping cruise (April), and a series of six cruises (July and August) along a single transect across the Georgia shelf. Some intercomparisons of CZCS versus in situ observations have been made by *McClain et al.* [1984], *McClain and Atkinson* (1985), and *Yoder et al.* [1987] and indicate very good agreement. Figure 7 shows all the intercomparisons with discrete surface samples. There is a great deal of scatter, and the analysis indicates that the CZCS estimates may be slightly low for concentrations above 1 mg/m³. Much of the scatter can be attributed to finite time separation (range was +17 to –13 hours relative to CZCS with an average of +3 hours) and to positioning errors in frontal zones. No attempt was made to filter out questionable data points. *Yoder et al.* [1987] note that the CZCS retrievals in the nearshore regime are similar to in situ observations in general.

Freshwater Discharge

Discharge estimates from the Altamaha, Savannah, Cooper, Pee Dee (Winyah Bay), and Cape Fear rivers were obtained from the U.S. Geological Survey. Their combined discharge represents roughly 80% of the runoff in the SAB [*Blanton and Atkinson*, 1983]. Figure 8a is the data from the Cape Fear River which is the major source in region 3, and Figure 8b provides the discharge time series (5-day averages) of the two major sources and the total discharge in the Georgia Bight. In all cases, discharge was lowest in the fall of 1978, peaked in

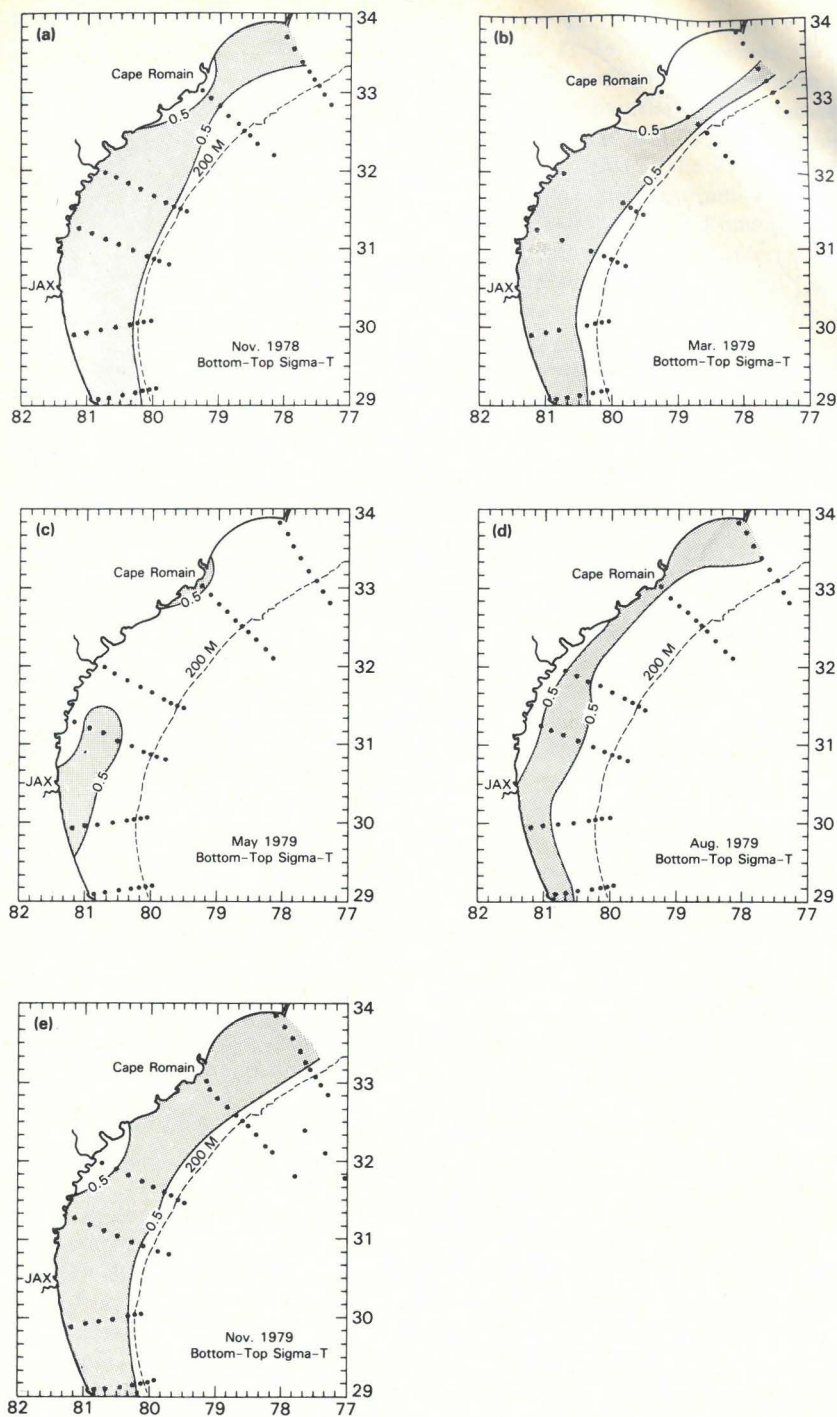


Fig. 5. Bulk stratification maps from each of five synoptic surveys. Bulk stratification is defined as the bottom σ_t value minus the surface σ_t value. The shaded areas correspond to values of ≤ 0.5 . (a) November 1978. (b) March 1979. (c) May 1979. (d) August 1979. (e) November 1979.

early March, and had a secondary peak in late September of 1979.

Winds

Daily mean coastal winds were obtained from stations at Daytona Beach (-28), Jacksonville (-8), Savannah (+36), Charleston (+43), Wilmington (+60), and Cape Hatteras (+60). The values in parentheses are the orientations of the local coastline from north to south in degrees (clockwise) and

are used to define the alongshore and cross-shelf wind components. Note that the curvature of the coastal line produces nearly a 90° rotation of the coordinate system from Daytona Beach to Cape Hatteras. The winds are presented in plots of wind impulse [Blanton and Atkinson, 1983; Blanton et al., 1985] which are shown in Figure 9. The wind impulse is stress integrated over time (computed using a running summation) and is used to show long-term trends in the wind components. A positive (negative) slope implies that the winds were toward the positive (negative) direction, positive being either north or

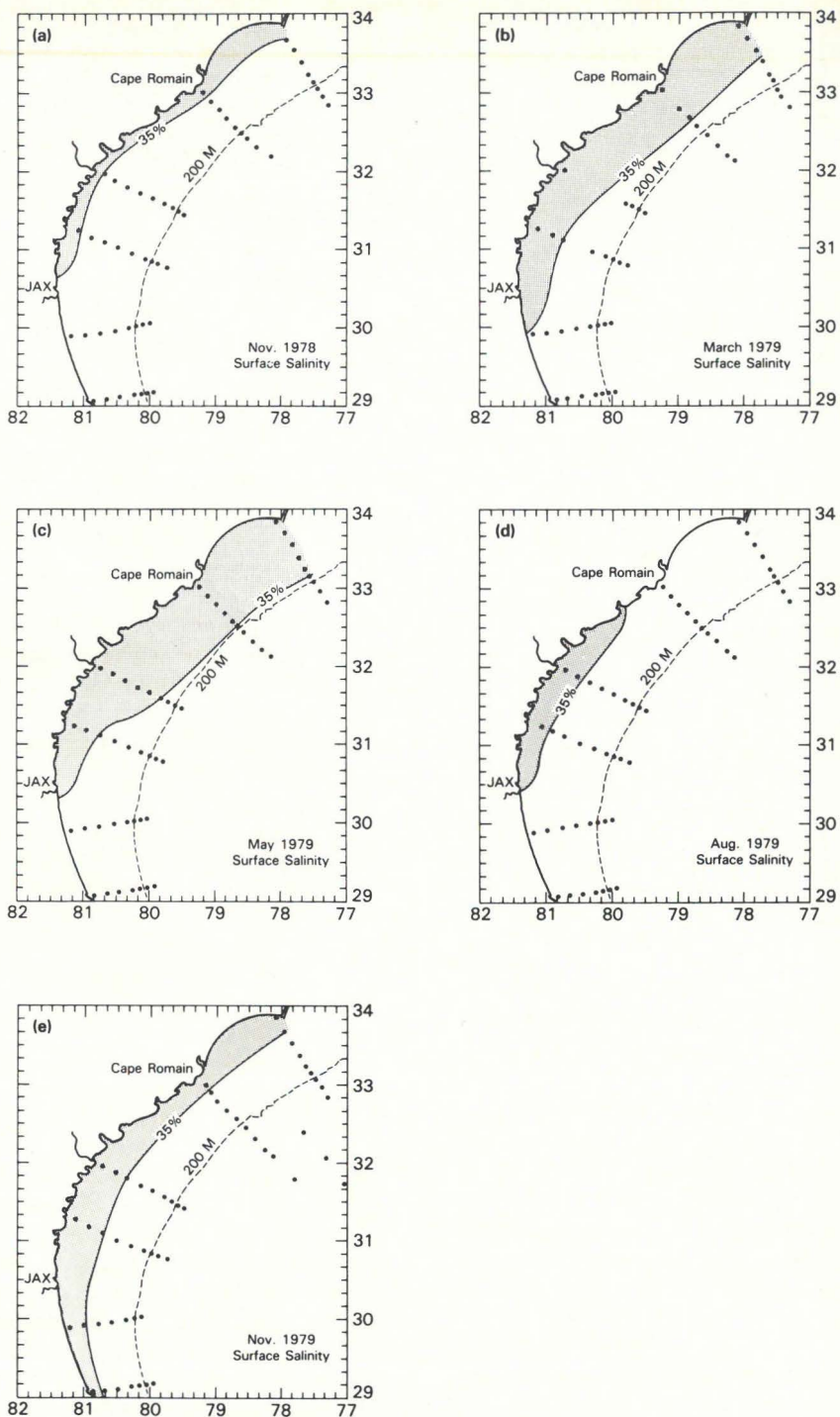


Fig. 6. Surface salinity maps from each of five synoptic surveys. The shaded areas correspond to values of $\leq 35\text{‰}$. (a) November 1978. (b) March 1979. (c) May 1979. (d) August 1979. (e) November 1979.

east. The coastal winds over land were converted to sea surface winds by multiplying the magnitudes by 2 [Schwing and Blanton, 1984] with no correction for wind direction and were then transformed to stress using the standard relationship with C_d equal to 0.002.

The wind impulse plots reveal several significant meridional and seasonal trends in the wind stress components. For instance, at Daytona Beach and Jacksonville the alongshore winds were essentially downwelling favorable until late February. However, further north, the shift to upwelling favorable

winds began around the first of December. Note that the y axis scale of the Hatteras plot is different from the others. After these shifts in direction, the alongshore winds remained decidedly upwelling favorable at all locations until April. From May through August, Daytona Beach, Charleston, and Cape Hatteras winds remained upwelling favorable while Jacksonville, Savannah, and Wilmington winds were mixed. The cross-shelf component exhibited a similar trend through the winter, being onshore at Daytona Beach and offshore at all locations north of Savannah. By May the cross-shelf com-

Satellite-Ship Pigment Intercomparisons

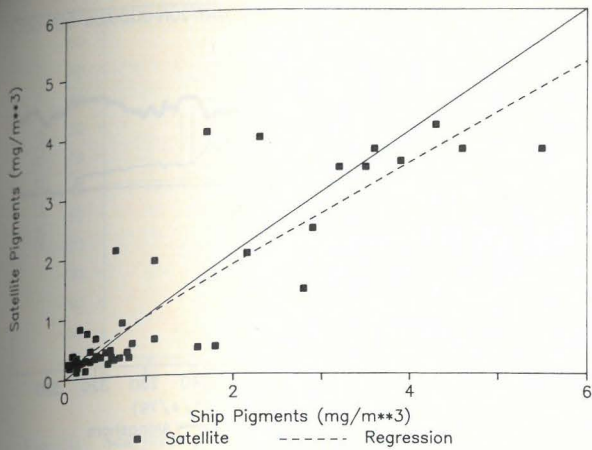


Fig. 7. Intercomparisons of ship and CZCS pigment observations. Intercomparisons are on a same day basis. Some of the scatter is the result of finite time differences and positioning errors in the vicinity of sharp fronts, and no attempt was made to screen the data. The linear regression (dashed line) for the CZCS pigments is $C_{sat} = 0.15 + 0.83 * C_{ship}$, with a coefficient of determination (r^2) equal to 0.77.

ponent was uniformly onshore. Only at Daytona Beach and Jacksonville did the long-term cross-shelf winds reverse twice by going from onshore in the winter to offshore in the spring to onshore in the summer and fall. The other stations were essentially offshore throughout the winter and spring and onshore the remainder of the time. Thus in terms of the local alongshore and cross-shelf components, region 1 experienced a completely different wind regime than did region 3, and region 2 was a transition zone between the two. This meridional variability in the local "oceanographic" winds would exist even if the "meteorological" winds were uniform because of the coastline curvature.

Sea Level

The coastal sea level records did not begin before January and, in some cases, were rather short (Figure 2). The locations used were Tiger Point (near Jacksonville), Fort Pulaski (near Savannah), Charleston, Winyah Bay (near Cape Romain), Myrtle Beach, Southport, and Beaufort (near Morehead City, North Carolina). The records were adjusted for atmospheric pressure and were 40-hour low-pass filtered. Since the records were highly coherent, only the Winyah Bay record is reproduced in Figure 10 (24-hour averages) with a 30-day running mean record overlaid on it. Unfortunately, the stations having relatively long records are clustered in the center of the SAB, precluding comparisons with stations at the southern and northern extremes of the bight. With the exception of Beaufort (short record), all stations indicated a trend of elevating sea level during the transition from winter to summer. This sea level rise was the due to steric effects resulting from increased solar heating and freshwater influx.

Currents

The current meter data are from two moorings in the Georgia Bight. Each mooring incorporated observations at three depths, but only the surface data will be discussed. The moorings were located offshore of Savannah (+30) and Cape

Romain (+50) at the 30-m and 45-m isobaths, respectively (see Figure 1). As with the winds, the coordinate system has been rotated clockwise by the value in parentheses to conform to the local bathymetry. The alongshore and cross-shelf components (24-hour and 30-day running mean averages) are shown in Figure 11. The data have been 40-hour low-pass filtered. Note that the currents at the two locations are scaled differently, those off Cape Romain being much more energetic. Also, currents during the winter and spring tended to have larger amplitudes. The large peak on Day 150 in the Cape Romain data was simultaneous with an extreme northwestward excursion of the Gulf Stream front that was identified in the CZCS imagery during that time. The most striking result from the two time series is that the surface currents off Savannah were predominantly alongshore while those off Cape Romain were cross-shelf. Also, the flow off Cape Romain was essentially to the east during winter and spring and to the west during summer and fall. The flow off Savannah was to the northeast during winter and spring and showed no significant trends over the remainder of the year.

CZCS DATA ANALYSIS

The techniques applied to the imagery are (1) "seasonal" compositing to obtain mean pigment fields over 6-month periods, (2) time series of mean concentrations within subregions of special interest, and (3) estimation of the width of the

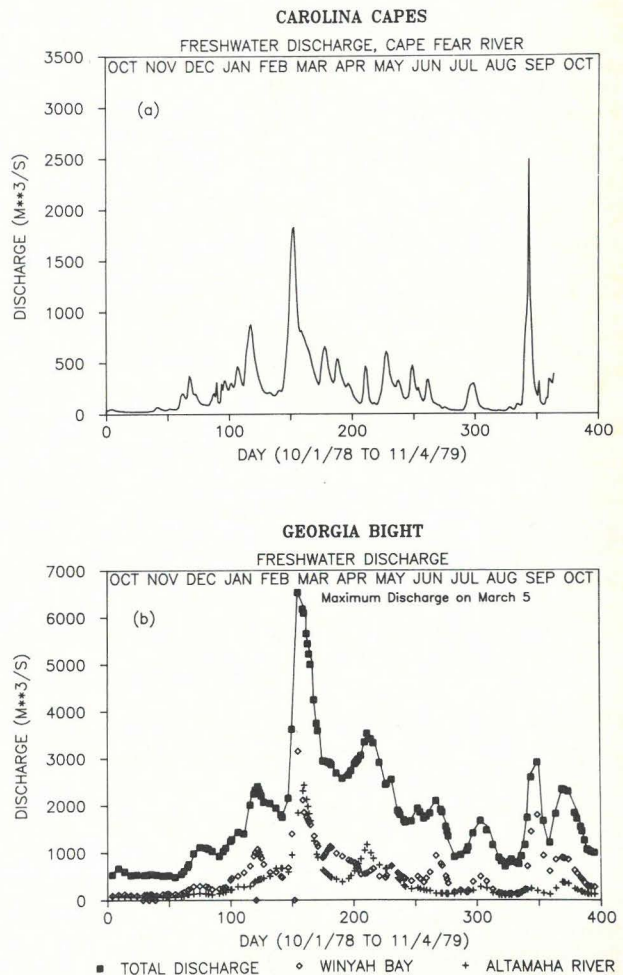


Fig. 8. Freshwater discharge time series for (a) Cape Fear River (daily average) and (b) Georgia Bight (5-day average).

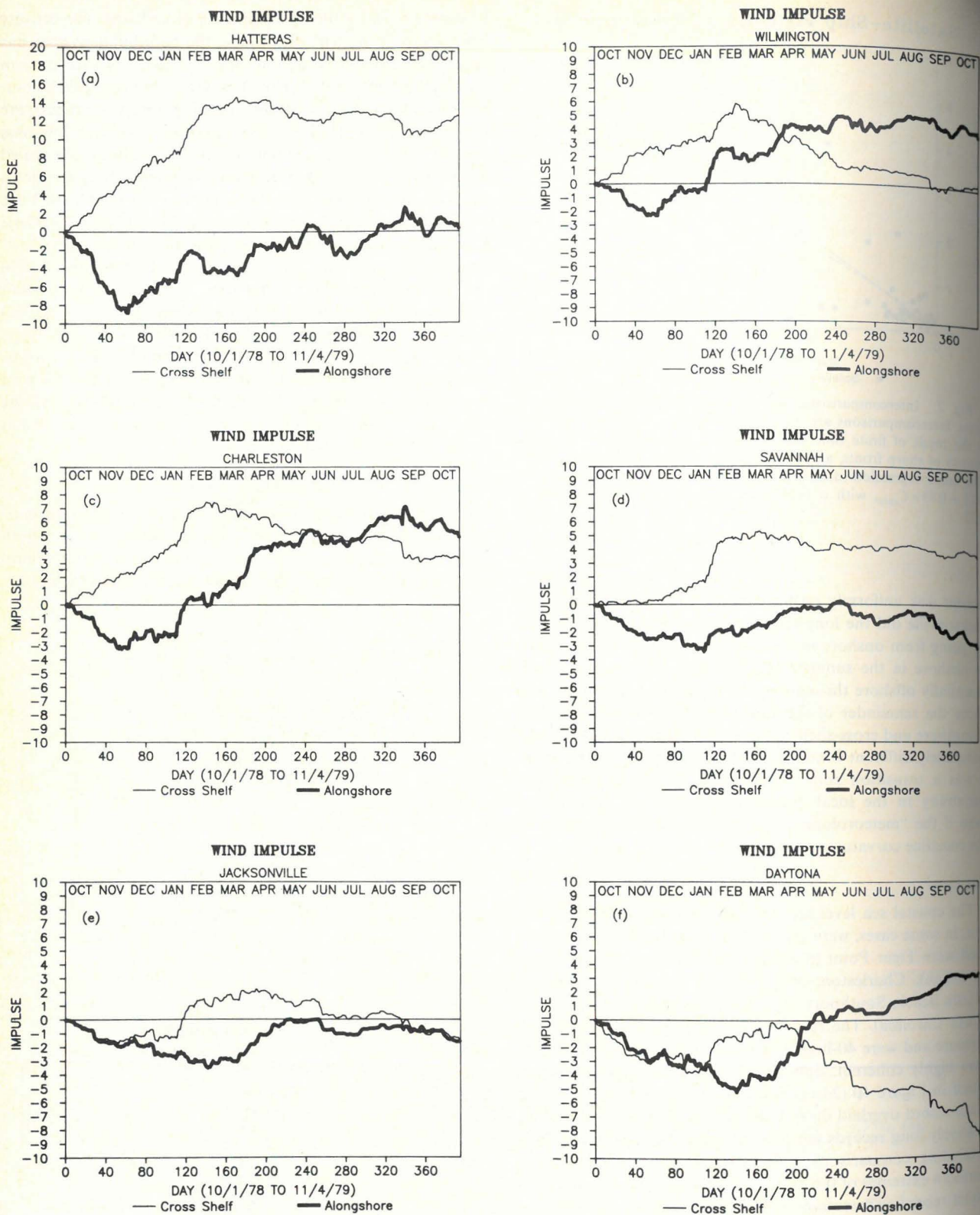


Fig. 9. Wind impulse plots ($N/m^2/d$) at all locations: (a) Cape Hatteras, (b) Wilmington, (c) Charleston, (d) Savannah, (e) Jacksonville, and (f) Daytona Beach. Note that the Hatteras plot is scaled differently.

nearshore zone of high surface pigment concentration. The seasonal mean composites were generated from the level-3 pigment scenes from each region. Values exceeding $20 \text{ mg}/\text{m}^3$ were ignored because very near the coast (within 10 km) the pigment algorithms often saturated, yielding invalid results

during high river runoff periods. The term "seasonal" is used to refer to hydrographic seasons defined as winter (November through April) and summer (May through October) which roughly correspond to well-mixed and highly stratified conditions, respectively. The composites were derived by averaging

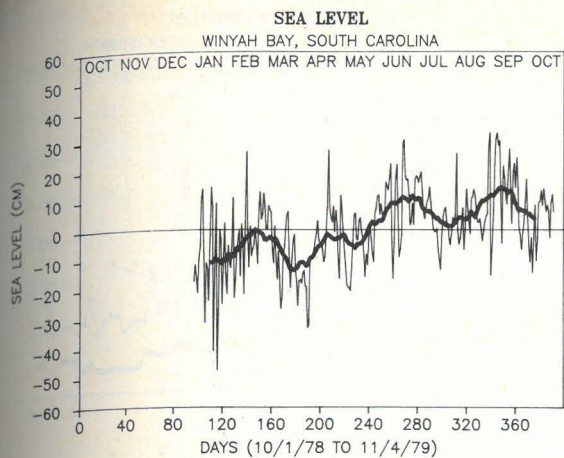


Fig. 10. Sea level plots (daily and 30-day running mean values) from the Winyah Bay tide gauge. The data have been corrected for barometric effects and 40-hour low-pass filtered.

ing the remapped images and were not computed by sorting the unremapped data into spatial bins, which would be the most rigorous technique. However, for the purposes of this paper, these products are adequate.

In order to identify trends at particular locations such as along the shelf break or around Cape Romain, subregions (Figure 12) were defined, and mean values and higher statistical moments were determined for each image and plotted as a function of time. The entries to these series were screened using both 50% and 25% valid pixel thresholds. Scenes that did not contain numbers of valid pixels above these percentages for a given subregion were not included in the series.

The nearshore region is characterized by relatively high pigment concentrations compared with the middle shelf and is usually delineated by a sharp transition. The width of this zone was determined from transects (Figure 12) of concentration in the vicinities of Daytona Beach and Charleston. The transects extend from the coast to the 30-m and 40-m isobaths, respectively. Figure 13 provides two examples of transects off Charleston. These two examples indicate that the nearshore pigment front was 25 km further offshore on March 15 than it was on February 2. The following section provides an interpretation.

Region 1: East Florida Shelf

The number of scenes for region 1 is 37. Of course, partial coverage and clouds limit the amount of data contained in a

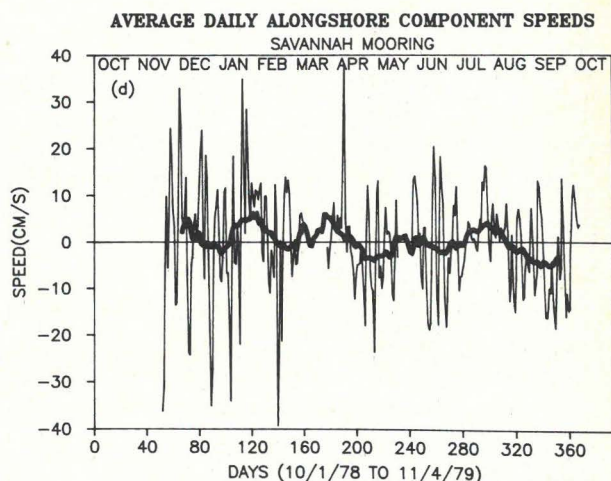
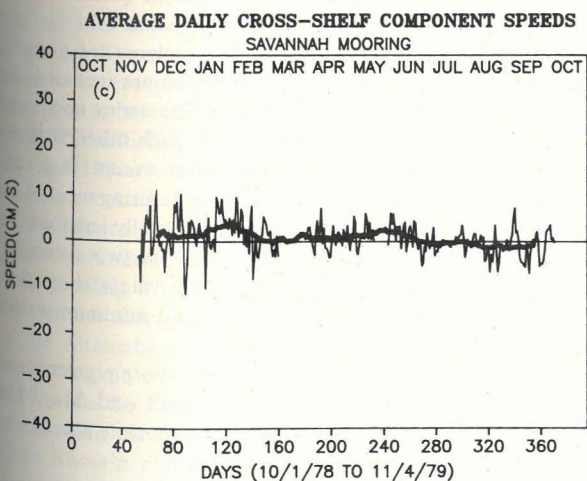
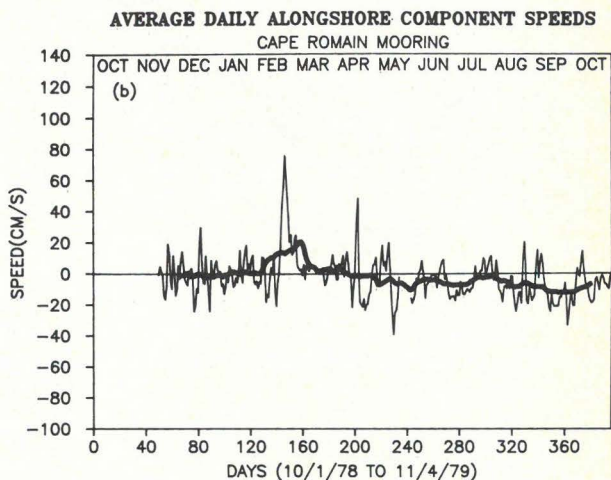
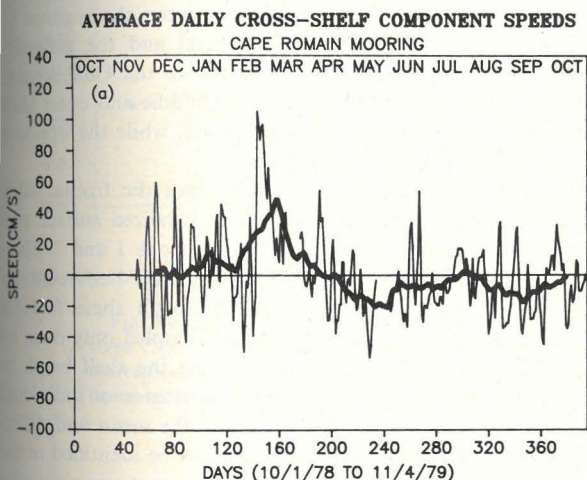


Fig. 11. Surface current meter plots of cross-shelf and alongshore components (daily and 30-day running mean values) from the Cape Romain and Savannah moorings. The data have been 40-hr low-pass filtered. (a) Cape Romain cross-shelf component. (b) Cape Romain alongshore component. (c) Savannah cross-shelf component. (d) Savannah alongshore component.

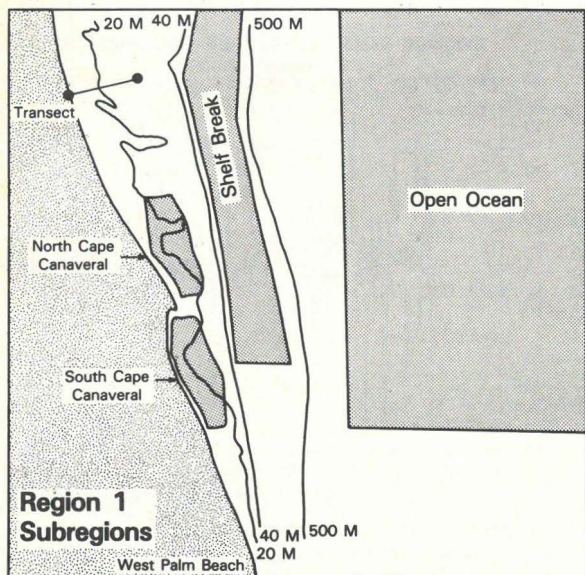
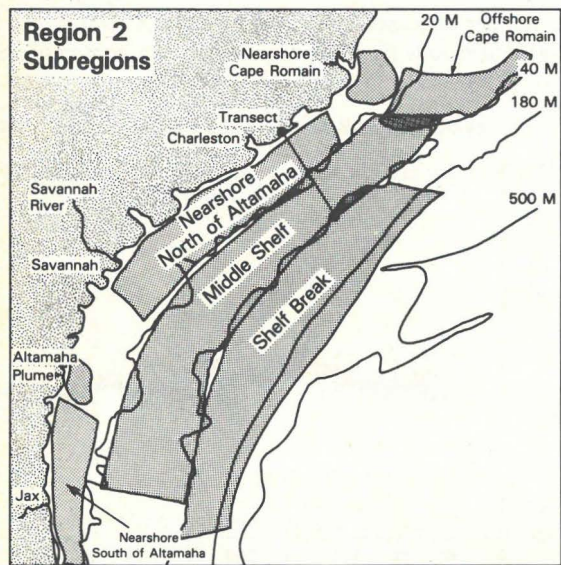
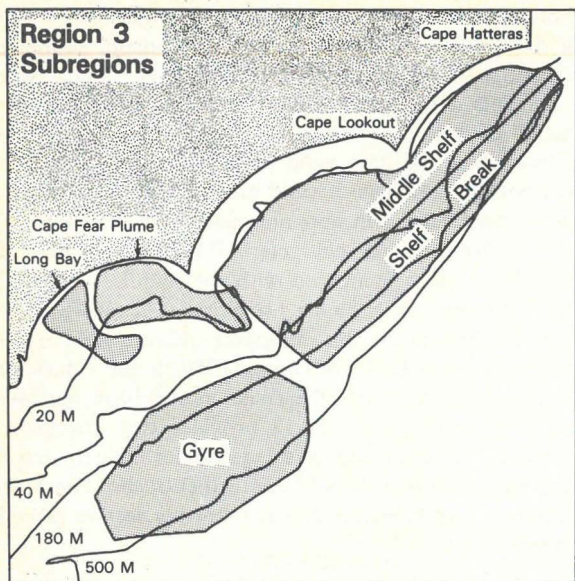


Fig. 12. Subregions (with labels) for the three regions.

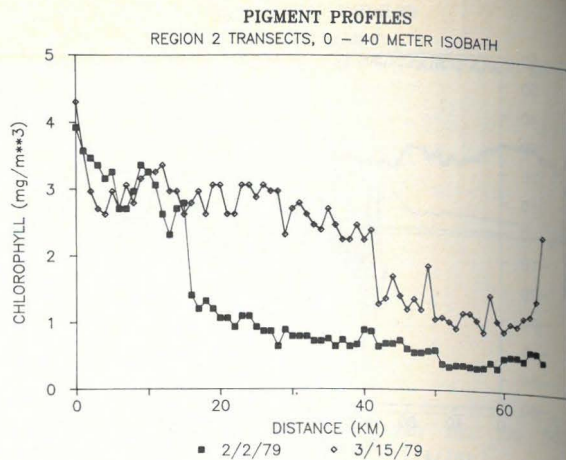


Fig. 13. Pigment profiles from the Charleston transect on February 2 and March 15, 1979.

given scene. The winter (21 scenes) and summer (16 scenes) composites and the difference image (winter minus summer) are given in Plates 1a, 1b, and 1c, respectively. The color bars for pigment and pigment differences are defined in the figure caption. Overlaid on the images are the 20-, 40-, 180-, and 500-m isobaths. The two most striking features are the abrupt transition in pigment concentration between the regimes to the north and south of Cape Canaveral and the generally higher concentrations during the winter in the Gulf Stream. North of Cape Canaveral, most of the middle and outer shelf had higher concentrations in the summer, while the opposite was true to the south of the cape.

The shelf break area is subject to sporadic frontal eddy upwellings which often have very high localized surface pigment levels, especially in the spring in regions 1 and 2. Shingles in region 3 were usually elongated and had relatively weak surface pigment expressions. Although these features propagate northward, they are usually sampled only once by the CZCS, causing the composites along the shelf break to appear patchy. In regions 1 and 2, signatures of individual events at the shelf break can be seen in the mean and difference images, and the particular events can be identified in the time series. While this makes the mean value at any particular location along this portion of the shelf break questionable, it does confirm that this domain is highly variable.

The time series of the region 1 subregions are given in Figure 14. Monthly mean values (triangles) are included and connected with a line to show trends. The series north and south of Cape Canaveral tended to track each other, with the concentrations to the north being higher except that concentrations to the south trended downward during most of the year. The shelf break concentrations were usually less than 0.5, but three strong events are evident (there are two events between days 200 and 250). The open ocean values show peak concentrations in February and March and minimum values in May, June, and July.

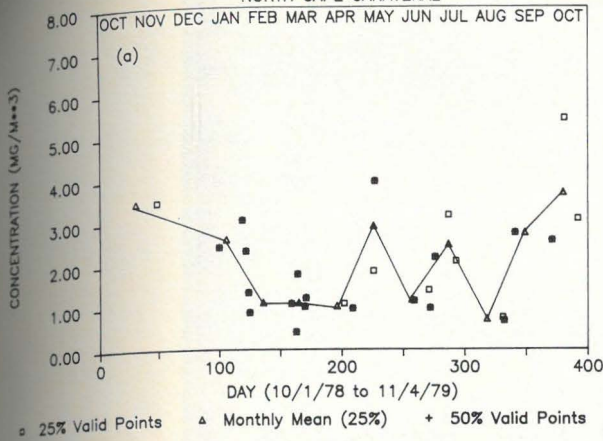
Figure 15 shows the highly variable nearshore pigment zone width, which had a minimum during April and May. The mean value corresponding to the winter composite was 22 km, while the mean for the summer was 30 km.

Region 2: Georgia and South Carolina

Plate 2 presents the composite and difference images for region 2. The inner and middle shelf regimes (0-40 m) were

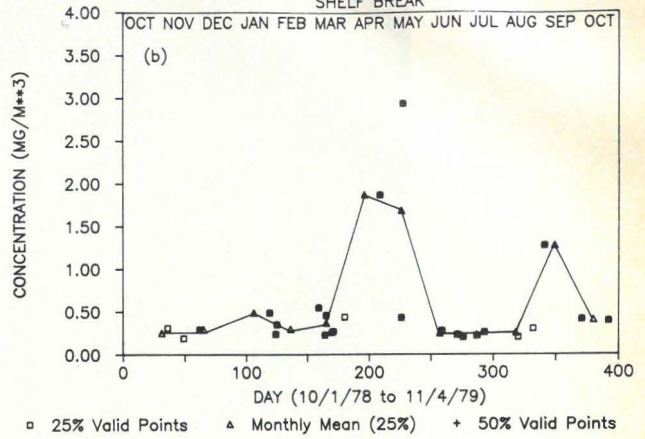
EAST FLORIDA SHELF

NORTH CAPE CANAVERAL



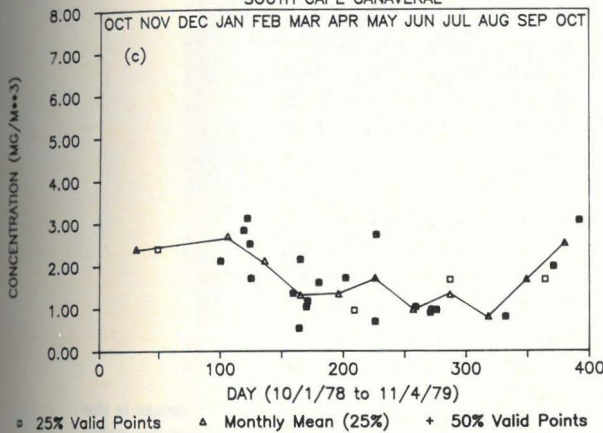
EAST FLORIDA SHELF

SHELF BREAK



EAST FLORIDA SHELF

SOUTH CAPE CANAVERAL



EAST FLORIDA SHELF

OPEN OCEAN

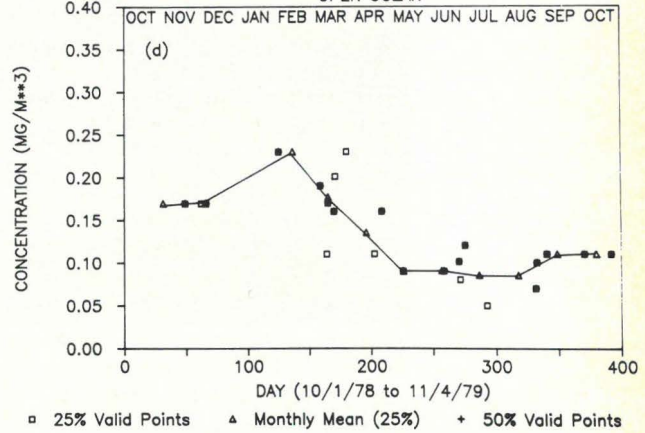


Fig. 14. Region 1 subregion pigment concentration time series: (a) north Cape Canaveral, (b) shelf break, (c) south Cape Canaveral, and (d) open ocean. Pluses indicate scenes where more than 50% of the pixels had valid values, and boxes correspond to scenes where more than 25% of the pixels within the subregion were valid. Pluses necessarily are superimposed on boxes. Triangles are monthly mean values of the 25% values and are connected.

predominantly richer in pigment during the summer except in the vicinities of the St. Johns, Altamaha, and Pee Dee rivers (Plate 2c). The mean isopleths were tightly aligned with the bathymetry except offshore of Cape Romain in the winter. As in region 1, individual events are clearly evident at the shelf break. Nonetheless, the pigment concentrations between the 40- and 180-m isobaths were consistently higher in winter. Therefore because the inner shelf concentrations were higher in the summer, the mean cross-shelf pigment gradient was greater in summer than in winter.

Progressing from south to north in the discussion of the subregional time series (Figure 16), the nearshore area south of the Altamaha River (Figure 16g) indicates no particular trends but did have a maximum concentration in the fall of 1979, while the Altamaha plume (Figure 16e) increased sharply following the late winter runoff maximum (Figure 8). The Cape Romain plume (Figures 16a and 16b) also had lower concentrations in the fall of 1978 than during the summer and fall of 1979. The coastal zone between the Altamaha plume and Cape Romain (Figure 16c) trended toward higher concentrations in the summer, as did the middle shelf (20–40 m,

Figure 16d). The shelf break (Figure 16f) indicates distinct peaks in the spring and fall of 1979. The Cape Romain nearshore and offshore regions had concentration peaks coinciding with the runoff maximum in late winter but did not have a similar peak associated with the fall runoff peak. The transect for region 2 is between Charleston and Cape Romain (Figure 12). The width of the nearshore pigment zone (Figure 17), although it had large variations, definitely trended toward higher values in the summer with the seasonal mean values for winter and summer being 21 km and 26 km, respectively.

Region 3: The Carolina Capes

Examination of Plate 3 clearly indicates that the seasonality of region 3 was quite different from that of region 2. Indeed, the trend was for higher concentrations in the winter at all locations except for a small area in Long Bay between the Pee Dee River and Cape Fear River plumes. The difference image (Plate 3c) shows a well-defined winter enhancement situated inshore of the 40-m isobath that extended from Cape Romain to Cape Hatteras. This enhancement was clearly associated with capes Romain, Fear, and Lookout and is independent of

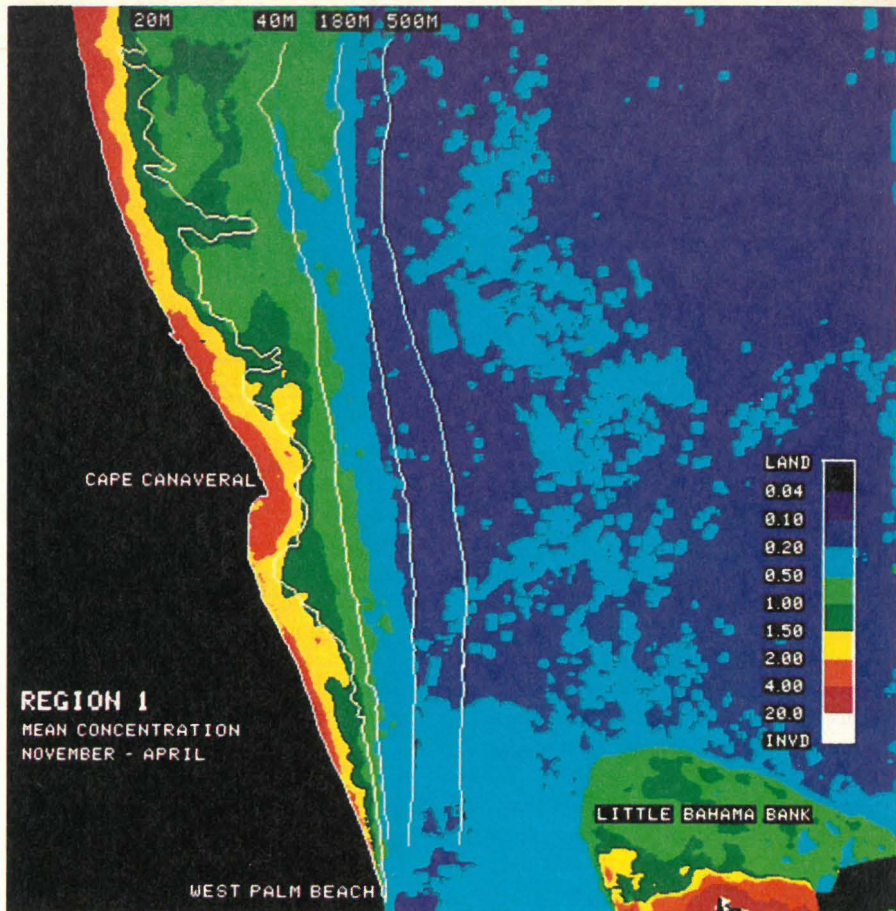


Plate 1a

Plate 1. (a) Winter composite, (b) summer composite, and (c) difference images for region 1. The difference image is the winter mean minus the summer mean values. The pigment color bar is the following, with values in milligrams per cubic meter; black, land; dark blue, 0.04 to 0.10; medium blue, 0.10 to 0.20; light blue, 0.20 to 0.50; light green, 0.50 to 1.0; dark green, 1.0 to 1.5; yellow, 1.5 to 2.0; amber, 2.0 to 4.0; red, 4.0 to 20.0; white, >20.0 or clouds present in all scenes. The pigment difference color bar is the following, with values in milligrams per cubic meter: black, land; dark blue, -2.0 to -1.0; medium blue, -1.0 to -0.5; light blue, -0.5 to -0.25; purple, -0.25 to 0.0; green, 0.0 to 0.25; yellow, 0.25 to 0.5; amber, 0.5 to 1.0; red, 1.0 to 2.0. The high values around Little Bahama Bank should be ignored, since they are a result of anomalous water radiances due to bottom reflection.

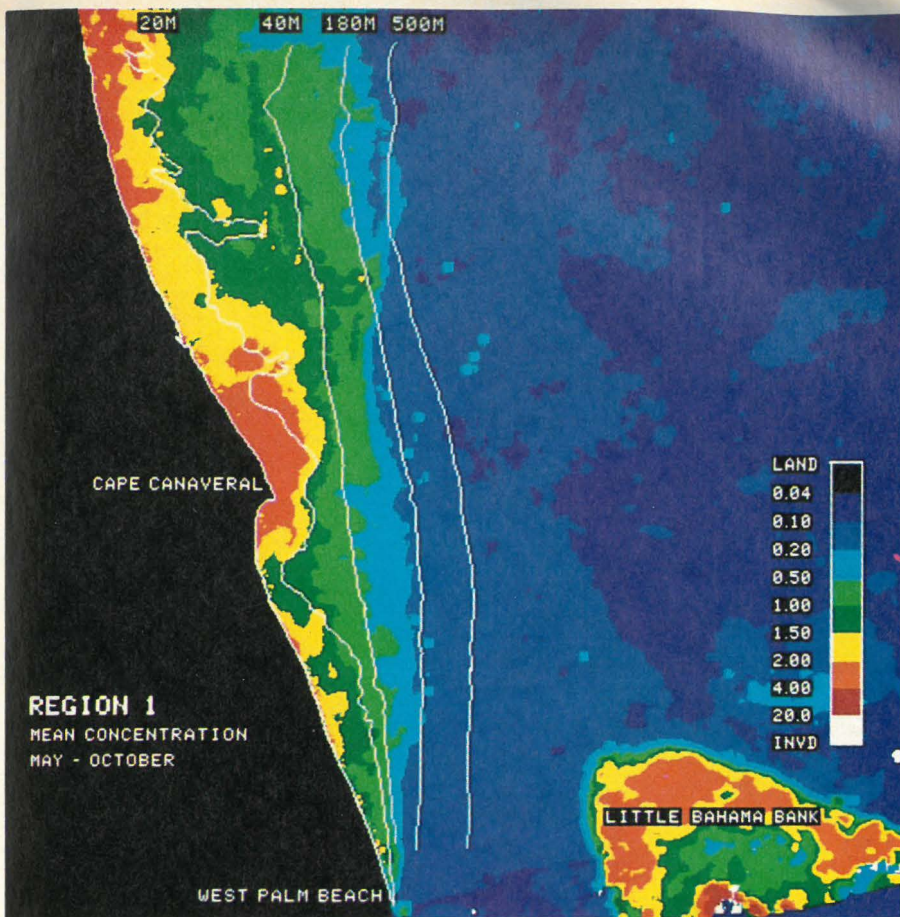


Plate 1b

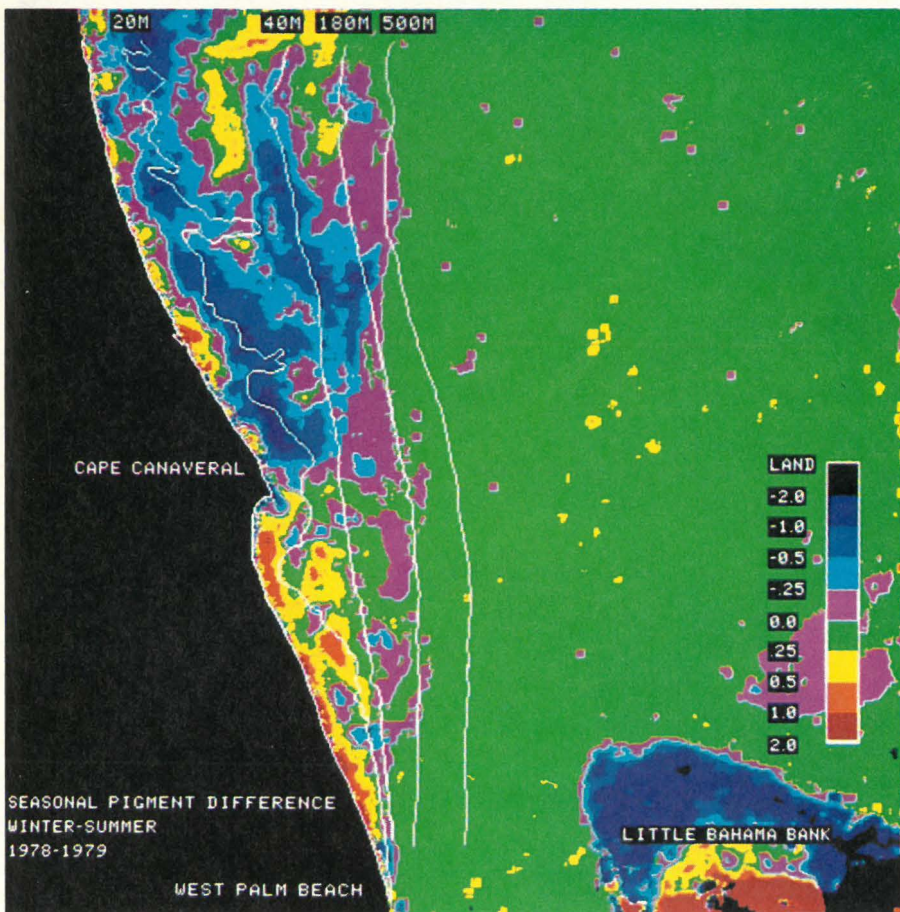


Plate 1c

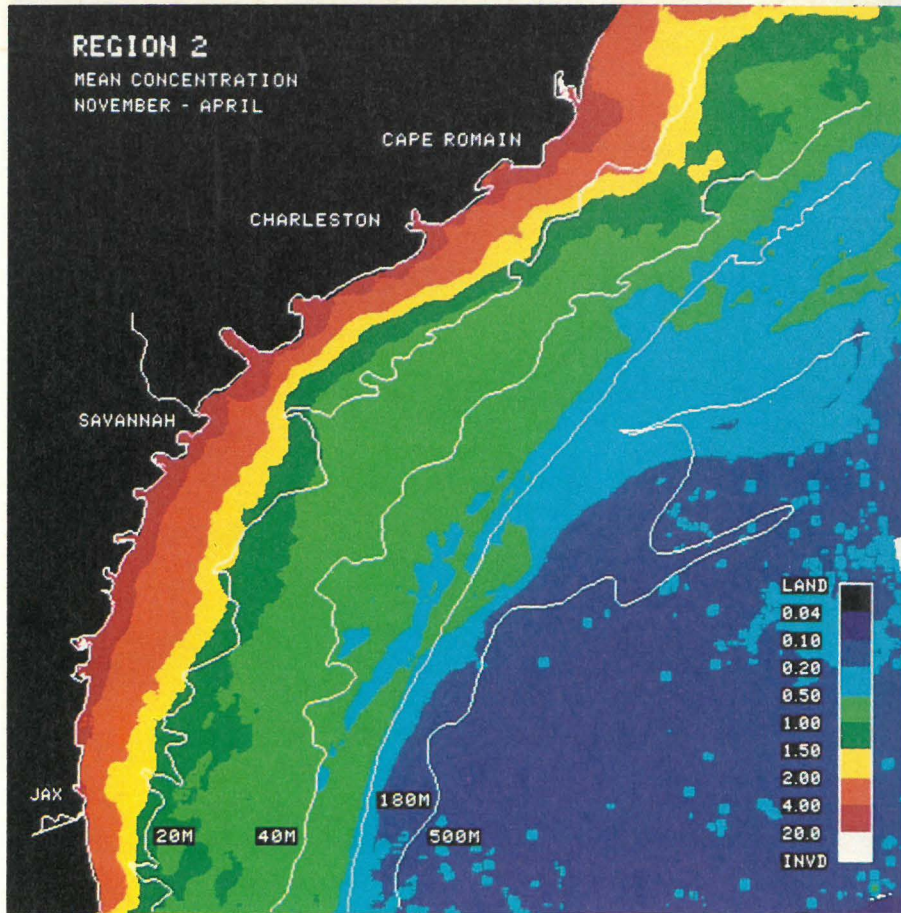


Plate 2a

Plate 2. (a) Winter composite, (b) summer composite, and (c) difference images for region 2.

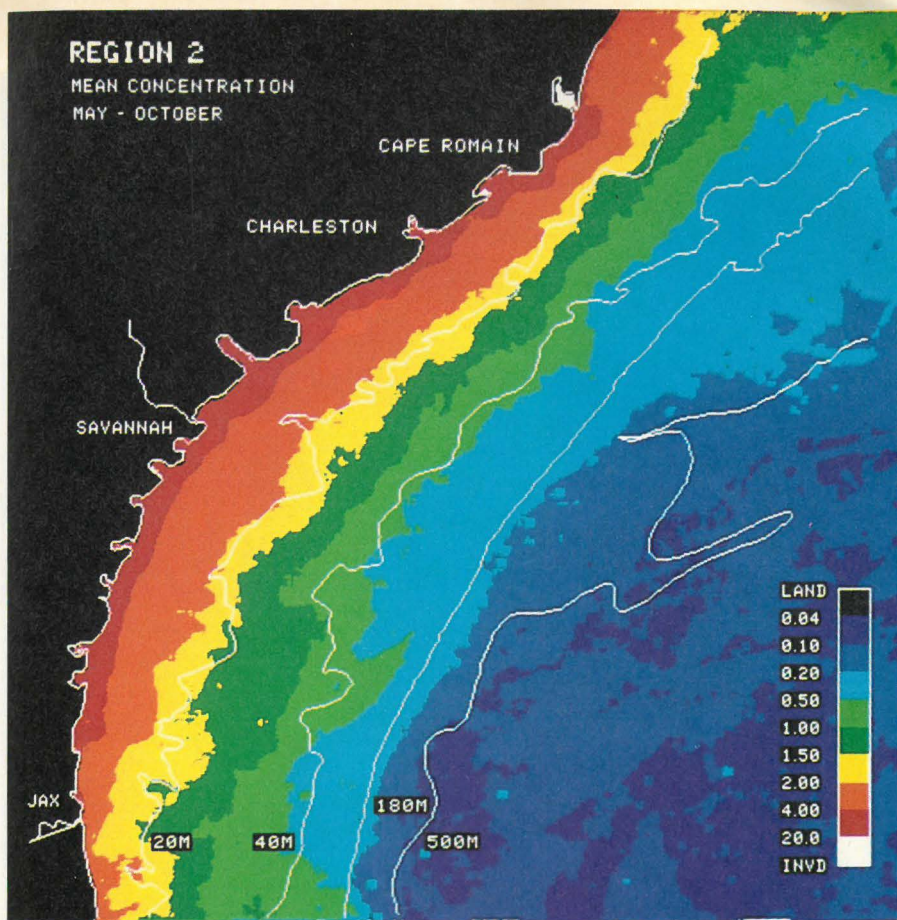


Plate 2b

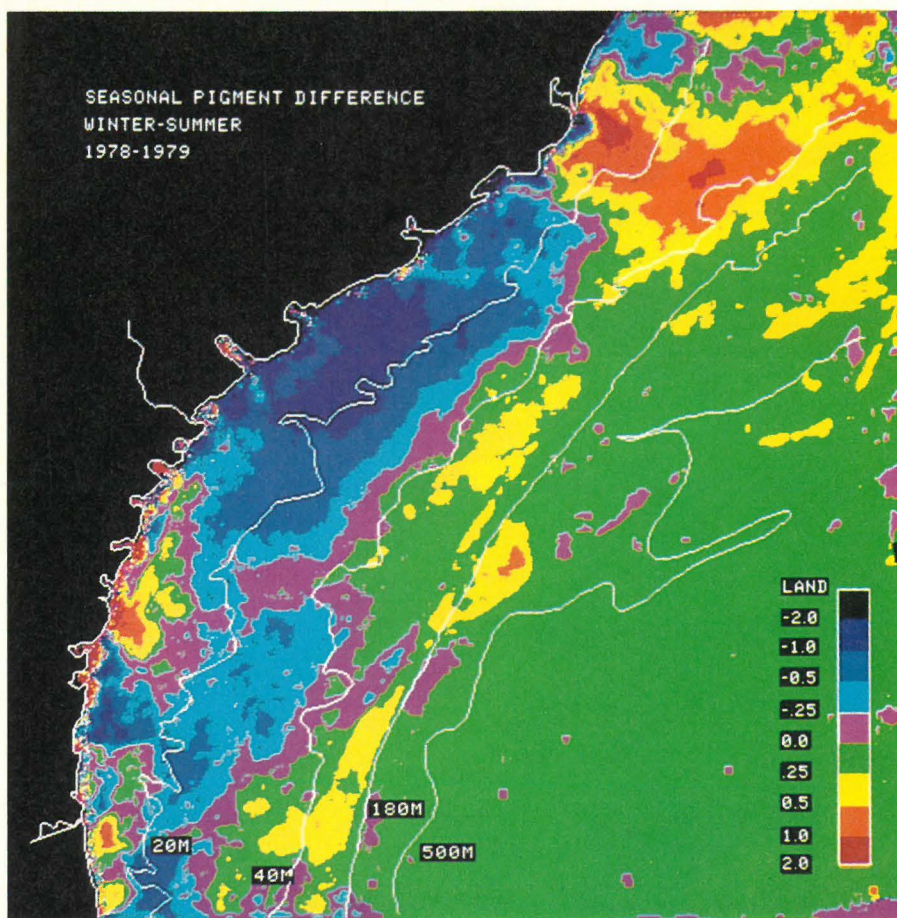


Plate 2c

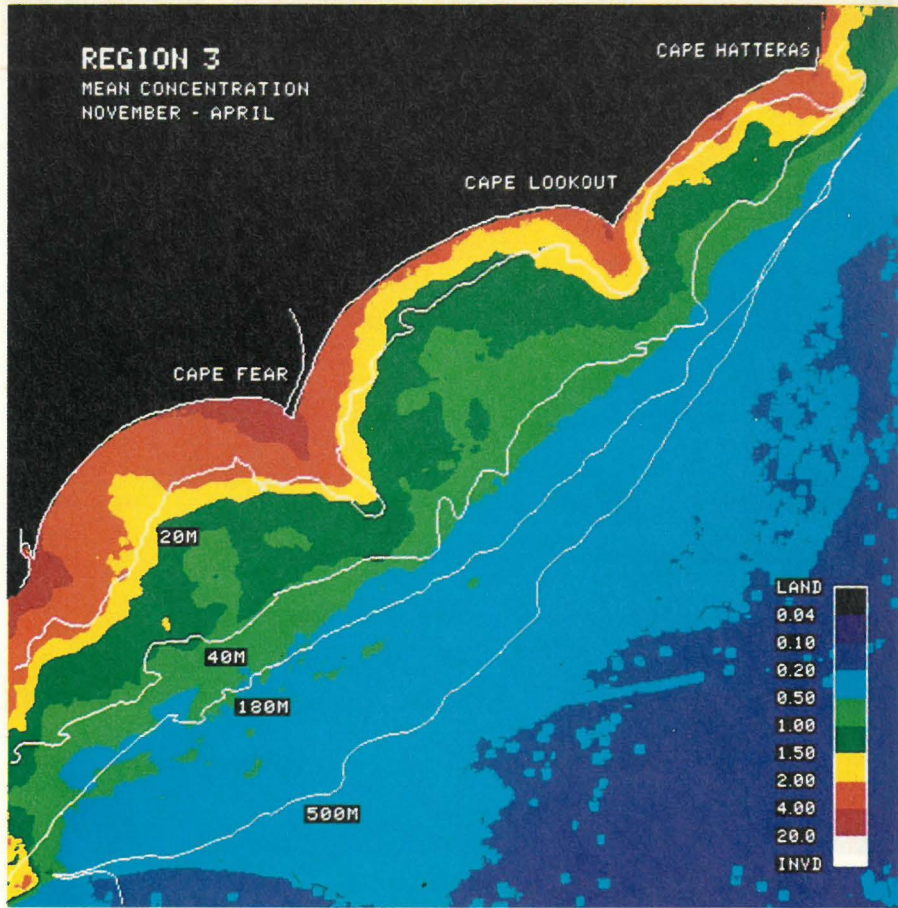


Plate 3a

Plate 3. (a) Winter composite, (b) summer composite, and (b) difference images for region 3.

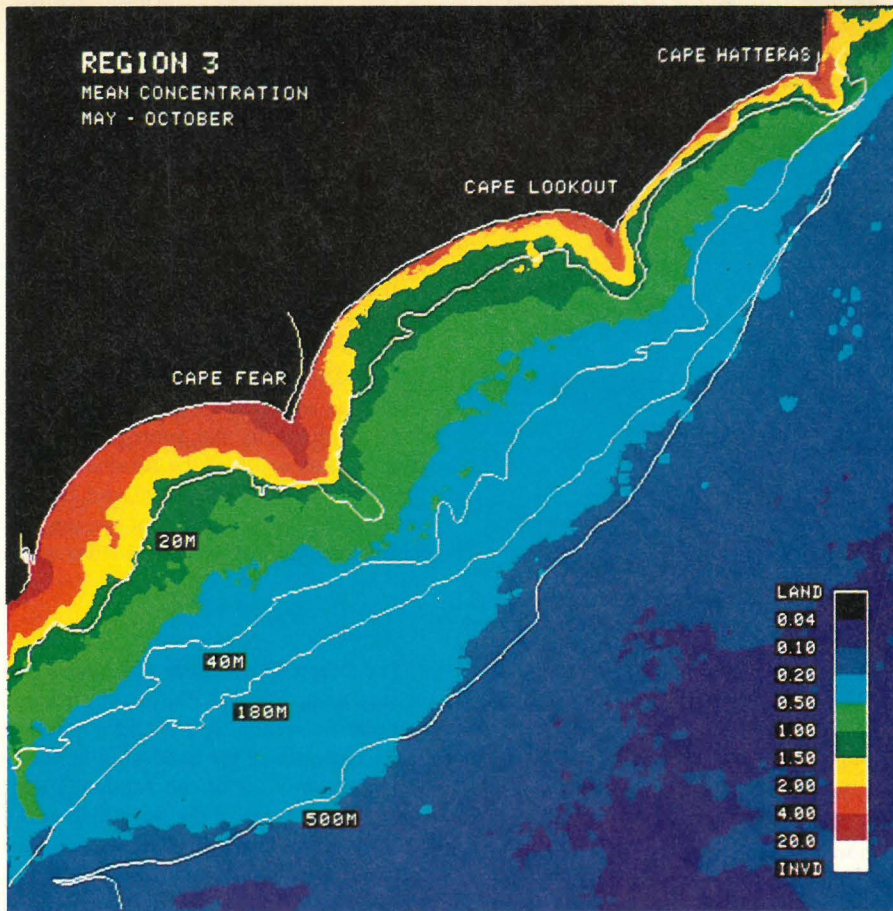


Plate 3b

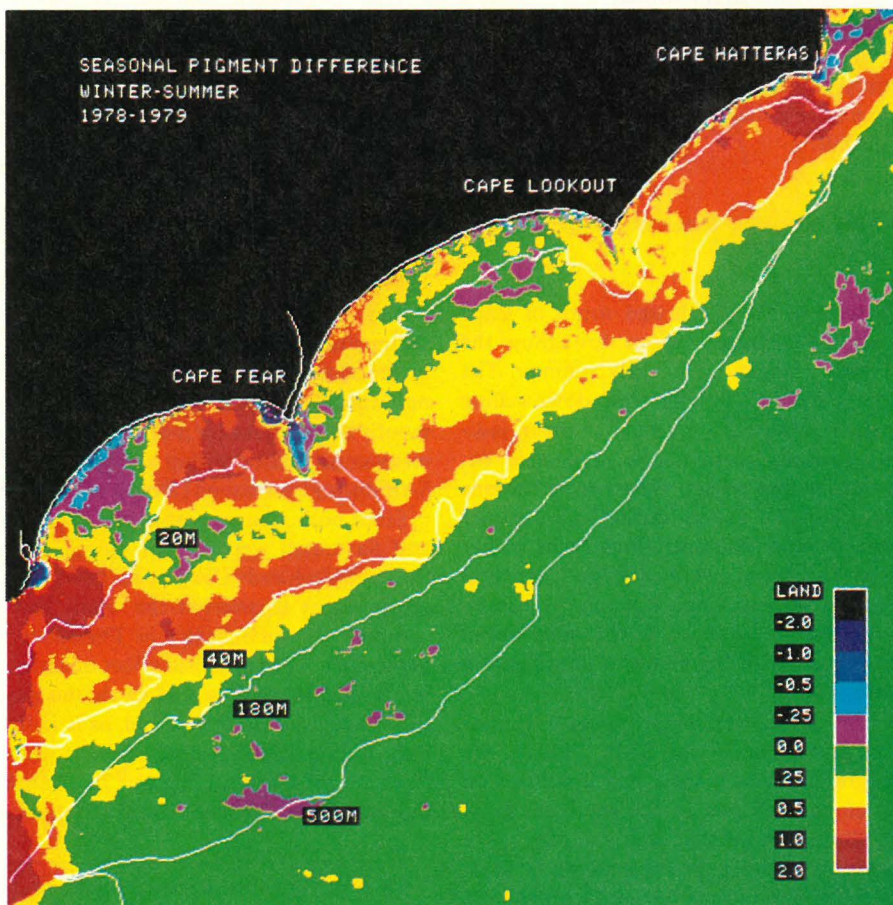


Plate 3c

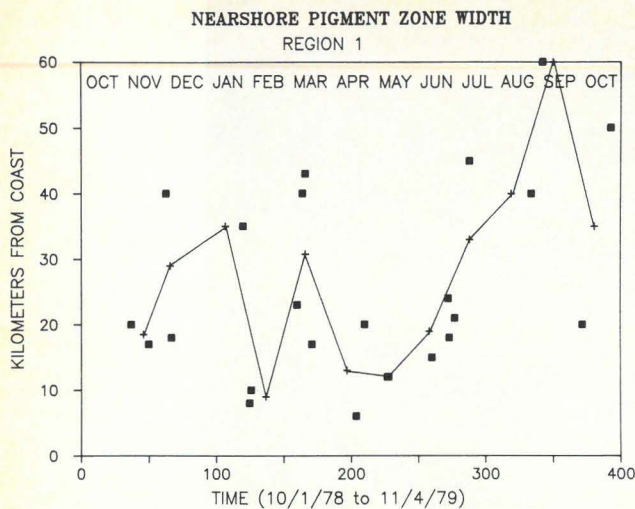


Fig. 15. Width of the nearshore zone of high pigment concentration. Monthly mean values (triangles) are connected. The width is defined as the distance from the coast to the point where the concentration is one-half of its maximum value near the coast.

the Charleston Gyre region, which is situated to the southeast of the 40-m isobath. The gyre domain concentrations were rather constant during the summer. However, in the winter composite the gyre region exhibited more structure and higher concentrations. Also, there is a progression toward greater winter-summer pigment concentration differences in the embayments going from Long Bay to Raleigh Bay. As elsewhere, the open ocean was slightly richer in the winter.

The pigment concentration time series are presented in Figure 18. Long Bay shows a definite increase throughout the winter and rather steady monthly mean values the rest of the year. All other locations have a similar peak in late winter and a secondary peak in the fall.

INTERPRETATION OF RESULTS

Region 1

Overall, the CZCS data to the north and south of Cape Canaveral indicate a decline in concentrations throughout the winter-spring period with a minimum in early summer. The winds at Daytona Beach and Jacksonville were downwelling favorable during this time but reversed by early summer, indicating that intrusion processes north of the cape were enhanced by the wind during that season. The concentrations north of the cape indicate two events during the summer which caused the mean summer concentrations to be higher than during the winter. This trend north of Cape Canaveral extended over most of the shelf to Cape Romain. The minimum concentrations during the summer in the open ocean observed in all three regions were the result of stratification and reduced wind mixing.

There was little correlation between pigment concentrations and river discharge in this sector of the SAB. Only in the November 1979 hydrographic data is there any indication of fresh water extending along the coast to the south of 30°N. Freshwater discharge during September and October 1979 was substantially greater than during the same period in 1978. The winds at Jacksonville and Savannah during October 1978 and 1979 were similar. However, the alongshore component at Daytona Beach was negative in the fall of 1978 but was posi-

tive in 1979. Thus at Daytona Beach the winds were downwelling favorable during October 1978 but were upwelling favorable during September and October 1979. While there is no indication of alongshore flow to the south in 1978, southward flow occurred in the fall of 1979. Therefore the combination of upwelling favorable winds and increased discharge during the fall of 1979 resulted in greater concentrations and nearshore pigment zone widths off Florida than were observed during the fall of 1978, when discharge was low and the winds were downwelling favorable. This also implies that much of the fall 1979 discharge exited the shelf off Florida. This conclusion is supported by the concurrent increases in pigment concentrations in the subregions north of Cape Canaveral (Figure 14a), south of the Altamaha River (Figure 16g), and at the shelf break (Figure 14b) and by the absence of any substantial increases in pigment concentrations or pigment zone widths north of the Altamaha River during the fall of 1979.

Region 2

The effects of a variety of physical mechanisms are evident in this area. Perhaps the most striking result is the winter-summer differences which had a minimum between Savannah and Charleston. This band of minimum difference is interrupted at the mouths of the Altamaha and St. Johns rivers but not at the mouths of the Savannah and Cooper rivers. This is striking because major blooms associated with summertime intrusions are normally observed at depth and not in the surface layer. Also, intrusions are generally thought to occur in the southern end of the Georgia Bight and exit the shelf offshore of Savannah.

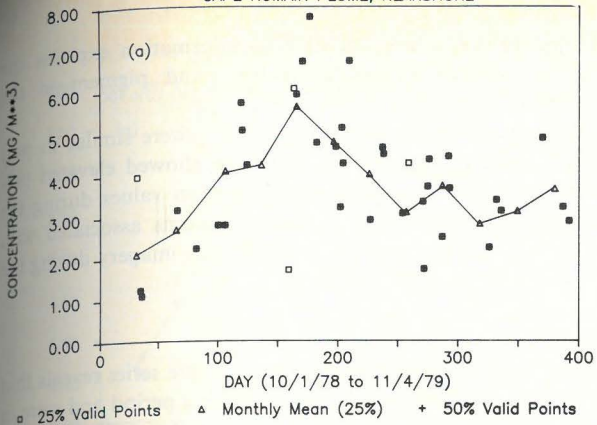
The concentrations in the vicinities of the Altamaha River and Cape Romain track freshwater discharge with maximum values during the discharge peak. Note that the nearshore values to be south of the Altamaha River (Figure 16g) were nearly uniform throughout the year, while those to the north of the river gradually increased throughout the winter and spring and remained relatively high during the summer. There was no concentration peak north or south of the plume corresponding to the discharge maxima. This implies either that the high CZCS-derived concentrations in the Altamaha plume during the runoff maximum were an artifact of suspended sediments which settled out before being transported very far in the alongshore direction or that the uptake of riverborne nutrients was rapid, resulting in an intense bloom near the mouth of the river (or both). In general, dissolved inorganic nitrogen is utilized within a few kilometers of the coast in the SAB during all seasons [Bishop *et al.*, 1984; Yoder, 1985].

Since both components of the wind impulse at Jacksonville and Savannah were benign during the discharge maximum, the wind-induced alongshore flow would have been weak. However, at Charleston the winds had a strong northward component which began in December and continued until September. The combined effect of high discharge and upwelling favorable winds would cause the nearshore pigment zone to broaden during this period, as is indicated in pigment profiles (Figure 13), the March salinity field (Figure 6b) and the pigment zone width (Figure 17). The offshore translation of the nearshore pigment front continued through October.

Fig. 16. (Opposite) Region 2 subregion time series: (a) nearshore Cape Romain plume, (b) offshore Cape Romain plume, (c) nearshore north of Altamaha River, (d) middle shelf, (e) Altamaha River plume, (f) shelf break, and (g) nearshore, south of Altamaha River.

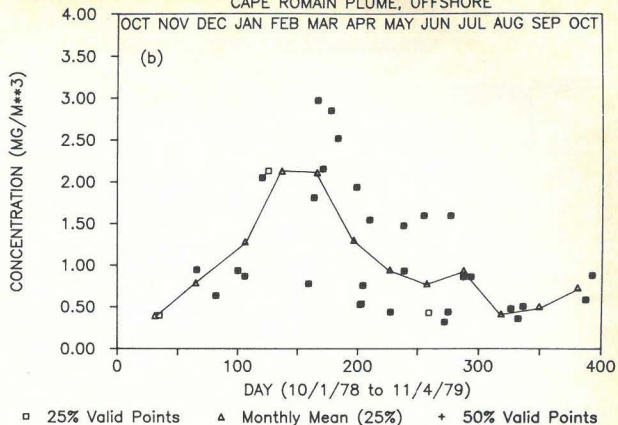
SOUTH CAROLINA - GEORGIA

CAPE ROMAIN PLUME, NEARSHORE



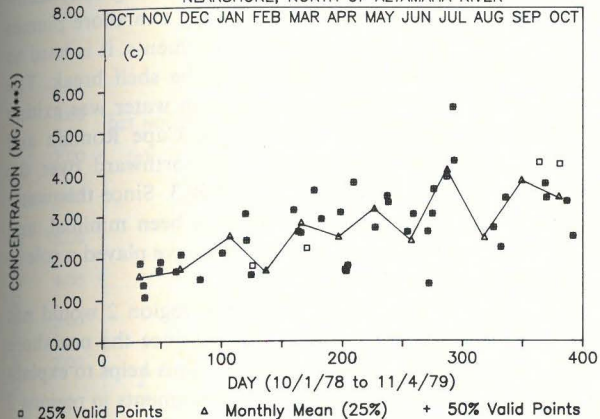
SOUTH CAROLINA - GEORGIA

CAPE ROMAIN PLUME, OFFSHORE



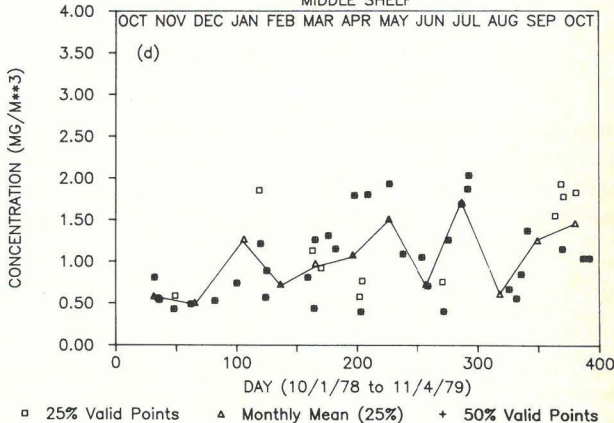
SOUTH CAROLINA - GEORGIA

NEARSHORE, NORTH OF ALTAMAHA RIVER



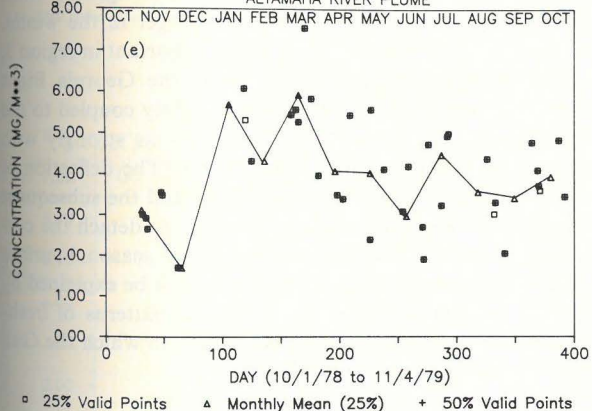
SOUTH CAROLINA - GEORGIA

MIDDLE SHELF



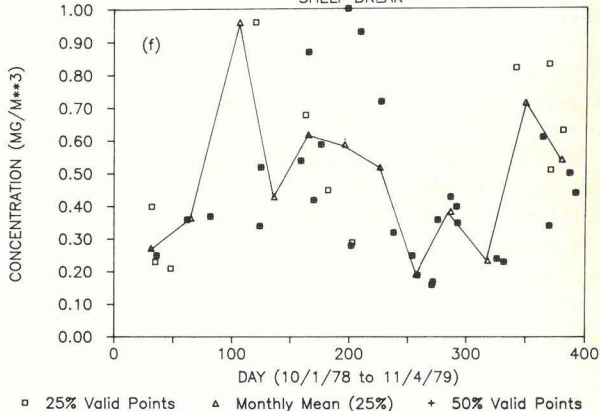
SOUTH CAROLINA - GEORGIA

ALTAMAHA RIVER PLUME



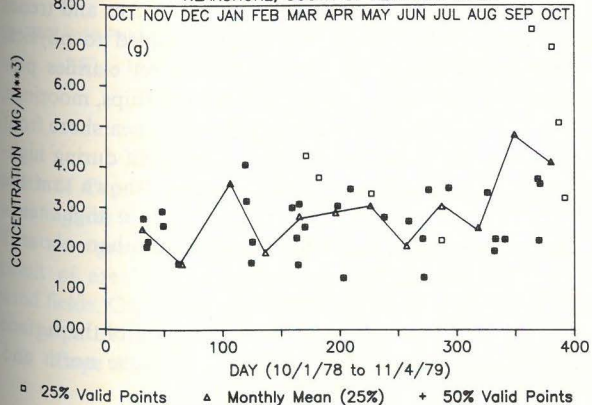
SOUTH CAROLINA - GEORGIA

SHELF BREAK



SOUTH CAROLINA - GEORGIA

NEARSHORE, SOUTH OF ALTAMAHA RIVER



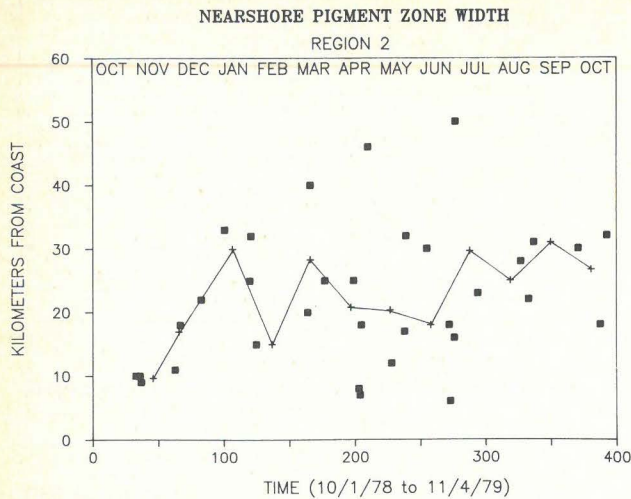


Fig. 17. Region 2 nearshore pigment zone width.

though there is an indication of a minimum in May and June. This also points out the fact that the pigment front may not always be associated with a salinity front [Yoder, 1985]. The salinity data imply the greatest expanse of fresh water in May with a minimum in August, but the pigment front during the summer followed the opposite trend. In the winter months, the correlation was more positive.

The data from the Cape Romain plume clearly indicate the effects of the discharge maximum. The concentration time series showed that the concentrations in the offshore portion of the plume declined more rapidly than did those in the nearshore portion, although the peaks occurred nearly simultaneously. The currents at the Cape Romain mooring were predominantly offshore throughout the winter and spring, but were onshore in the summer and fall of 1979. The currents off Savannah were predominantly northward and offshore for the first period but had no strong trends during the summer. The conclusion is that the elevated pigment concentrations caused by the winter-spring discharge was transported offshore and to the north at Cape Romain.

The midshelf concentrations behaved similarly to the nearshore concentrations in that they were low in the fall of 1978 and increased throughout the winter and spring. In the summer, as Figure 5d indicates, much of the inner shelf can be vertically homogeneous as a result of upwelling favorable winds causing the isopycnals to outcrop just offshore of the nearshore front. In comparing Figures 5d and 6d, low-salinity water was limited to a small area along the coast which coincided with relatively high stratification values. Examination of the temperature transects (not shown) revealed that intruded water was present in the five southernmost transects. In the two centermost transects off Brunswick and Savannah, the nearshore front was well defined and the temperature was nearly constant at 28°C throughout the water column between the 20- and 30-m isobaths. At Cape Romain the intruded water extended across the entire shelf. These facts indicate that subsurface intrusion water was the nutrient source that supported the summertime phytoplankton production. This conclusion is somewhat surprising, since it is generally thought that intruded waters exit the shelf offshore of Savannah. On the other hand, Charleston winds were the most strongly upwelling favorable of all stations south of Cape Romain. If the nutrient source in the summer was the estuaries, it is not

reflected in the salinity data. This information explains the lack of correlation between salinity and pigment in the summer.

The concentrations at the shelf break were similar in pattern to those in region 1 in that both showed elevated pigments from March to May and minimum values during the summer. No intense phytoplankton blooms associated with frontal eddies were observed in the CZCS imagery during the summer in region 2.

Region 3

Examination of the region 3 pigment time series reveals that all subregions peaked in the winter-spring period and were in phase with the discharge of the rivers to the south. Since the discharge during this period was twice the normal winter-spring discharge, shelf flushing must have been greatly facilitated. While the high concentrations in the nearshore plumes may have been affected by suspended sediments, it is hard to argue that the effect was significant at the shelf break. The only explanation is that nutrient-rich fresh water was exiting the nearshore regime in the vicinities of Cape Romain and Cape Fear and was being transported northward over the middle and outer shelf portions of region 3. Since this water was buoyant, vertical mixing would have been minimal, and nutrient recycling by phytoplankton may have played a role in sustaining the surface blooms.

The middle and outer shelf sections of region 2 would not have benefited from this nutrient source, since the nearshore front tended to retard offshore transport. This helps to explain why the seasonal modulations in surface pigments in regions 2 and 3 are opposite. In region 3 the winds were upwelling favorable during all of 1979, while they were not in region 2. Also, while there was no seasonal reversal in alongshore winds as in region 2, the winds were much stronger in the winter. Second, intrusion processes, while being important in region 3, may not be as persistent as they are in the Georgia Bight because the Gulf Stream front is not as tightly coupled to the shelf break and therefore does not interact as strongly with Cape Fear as it does with Cape Canaveral. The deflection of the Gulf Stream by the Charleston Bump and the subsequent enhanced meandering off the Carolinas act to detach the current from the shelf. Thus the reversal in the seasonal surface pigment maxima between regions 2 and 3 can be explained by differences in (1) the wind regimes, (2) the patterns of freshwater nutrient transport, and (3) the degree to which the Gulf Stream interacts with the capes.

CONCLUSIONS

In this work, a variety of environmental data have been merged with a time series of satellite-derived surface pigment concentration images, confirming that the patterns and trends in the pigment time series are strongly coupled to physical processes in the SAB. The combined data set clarifies processes that are difficult to observe solely from ships, moorings, and aircraft. Examples are the behavior of the nearshore front and the exchange of fresh water across the shelf during high-discharge conditions. In addition, it has been shown that the pigment retrievals are representative, although a slight tendency to underestimate concentrations greater than about 1 mg/m³ was suggested by the data set.

Specific results include the following:

1. There was a definite seasonal modulation of the surface pigment fields, which tended to be out of phase north and

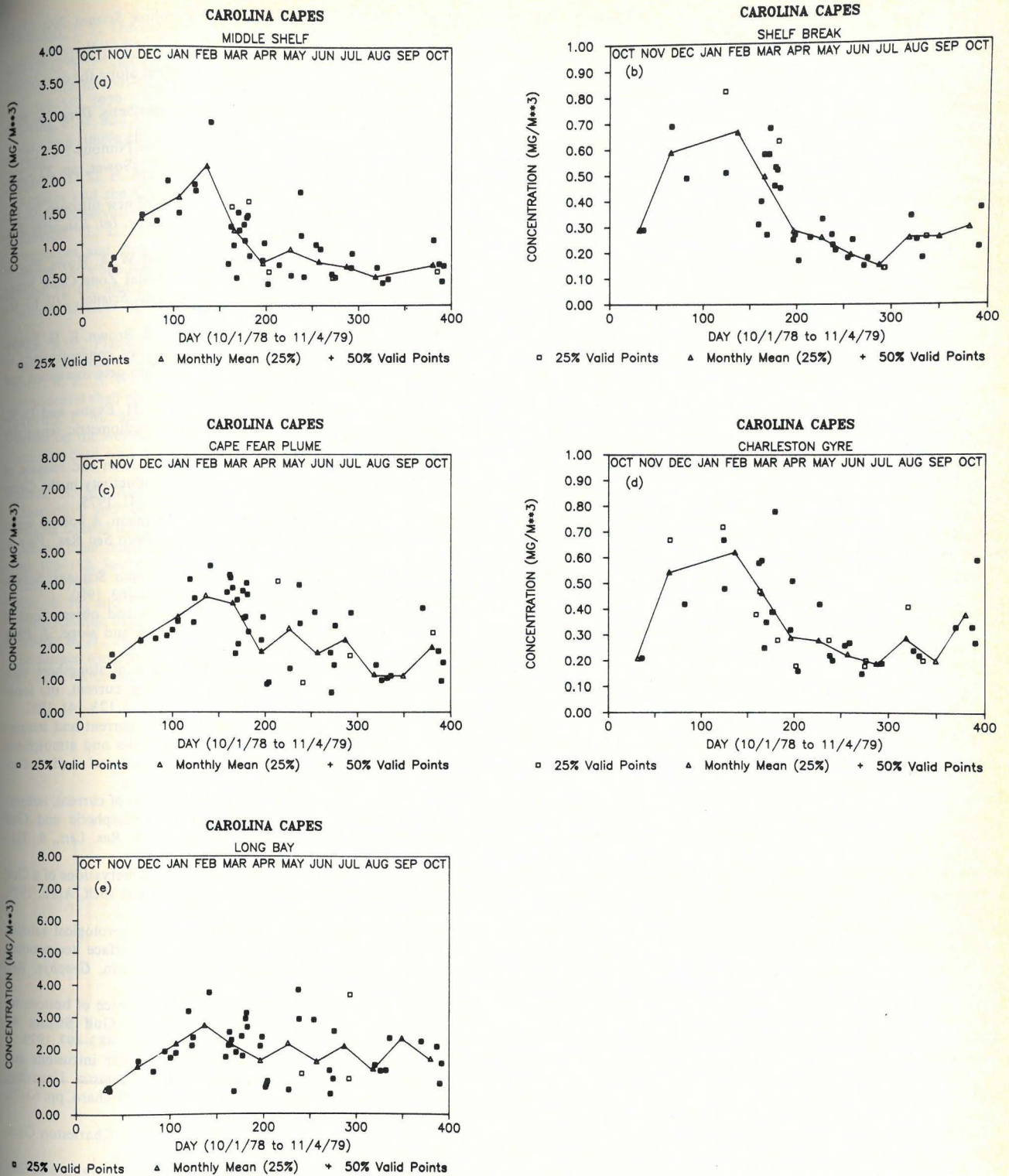


Fig. 18. Region 3 subregion pigment concentration time series: (a) middle shelf, (b) shelf break, (c) Cape Fear plume, (d) Charleston Gyre, and (e) Long Bay.

south of Cape Romain. Concentrations in the Georgia Bight were highest in the summer, while concentrations off the Carolinas were greatest in the winter. This phase difference was the result of areal variations in physical processes, namely the wind fields, Gulf Stream-shelf interactions, and freshwater discharge patterns.

2. Cape Romain and Cape Fear were sites of cross-shelf

exchange of fresh water during the period of the winter-spring runoff maximum, the fresh water in the Georgia Bight having been effectively confined to the inner and middle shelf domains between Jacksonville and Cape Romain during this period. However, the major site of removal in fall of 1979 appears to have been the east Florida shelf just north of Cape Canaveral.

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