Coupling of Coastal Zone Color Scanner Data to a Physical-Biological Model of the Southeastern U.S. Continental Shelf Ecosystem

1. CZCS Data Description and Lagrangian Particle Tracing Experiments

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Nine Coastal Zone Color Scanner (CZCS) images from the southeastern U.S. continental shelf area during April 1980 were processed, and the resulting chlorophyll distributions were analyzed in conjunction with concurrent flow and temperature fields which were obtained from an optimal interpolation of current meter measurements from 17 m. The chlorophyll distributions obtained from the CZCS showed high chlorophyll concentrations over the shelf and low chlorophyll concentrations over the offshore shelf region. The variance of the CZCS-derived chlorophyll distributions was highest at the shelf break region. The chlorophyll patterns at the shelf break varied with time and space and showed shapes characteristic of typical Gulf Stream frontal eddies, high-chlorophyll bands that were oriented along-shelf, isolated high-chlorophyll patches, and simple waveforms. Each event observed in the chlorophyll patterns corresponded with a Gulf Stream frontal eddy event that could be identified in the optimally interpolated flow and temperature fields. Lagrangian particle tracing experiments were also conducted to track the movement of the features observed in the CZCS images. The particles traced in these experiments showed movement that was consistent with the evolution of the patterns observed in the CZCS chlorophyll distributions. Results of the Lagrangian experiments indicate that the optimal interpolation of the current meter measurements reproduced the flow between successive CZCS images. These experiments provide evidence that the high-chlorophyll bands seen in the CZCS chlorophyll distributions were produced by the passing of Gulf Stream frontal eddy events.

1. Introduction

The Coastal Zone Color Scanner (CZCS) provided the first synoptic observations of surface phytoplankton biomass over wide areas. Because of the synoptic coverage, these data have been used to study a variety of topics in a variety of environments. However, most of the studies that used CZCS data have been descriptive or statistical; few studies have attempted dynamically based explanations for the chlorophyll distributions detected by the CZCS. Numerical models are a developing tool that can be used to understand the dynamics in the ocean. Recent advances in computer technology allow for the solution of large numbers of simultaneous equations over a large range of parameter space. Physical models reproduce the basic dynamics of water motion, and biological models coupled with physical models can be used to explain the dynamics of space- and time-dependent biological properties. It has been suggested [Nihoul, 1984] that satellite data are useful for the initialization and verification of numerical models, because satellites represent the only means for obtaining large-scale time- and space-dependent measurements of the ocean. It is natural, then, that physical-biological models can be used to understand and explain the processes producing the phytoplankton distributions detected by the CZCS. It is also reasonable to expect that the CZCS-derived phytoplankton distributions can provide a mechanism for the initialization and verification of physical-biological models.

The southeastern U.S. continental shelf (Figure 1) ecosystem is influenced primarily by two different types of physical forcing: Gulf Stream frontal eddy upwelling and wind-induced bottom intrusions of Gulf Stream water. These two upwelling mechanisms are the major source of nutrients for this ecosystem. Gulf Stream frontal eddies are associated with waves that propagate along the Gulf Stream front. These features have wavelengths that are typically 100 km and widths of 20 km in the region between Florida and Georgia. The waves propagate northward with speeds of about 35 cm s\(^{-1}\) (30 km d\(^{-1}\)) and have frequencies of 2–24 days [Lee et al., 1981; Lee and Atkinson, 1983]. There is strong upwelling within the trailing portion of the wave crest of Gulf Stream water (region of anticyclonic curvature), while downwelling exists along the trailing edge of the meander trough (region of cyclonic curvature) [Osgood et al., 1987]. The crest of these waves often folds back over the outer continental shelf and develops a warm tongue-like structure and the trough of the wave becomes a cold-core eddy that is situated between the warm tongue and the Gulf Stream front [Lee et al., 1981] (Figure 2). In many cases, the warm tongue and cold-core eddies form elongated bands along the Gulf Stream front. The frontal eddies occur over most of the year but are most frequent in winter and spring. The wind-induced Gulf Stream bottom intrusions occur mainly during summer when winds are predominantly from the south, which is favorable for upwelling. The bottom intrusion transports a large volume of subsurface Gulf Stream water to the midshelf region and these events can persist for several weeks.

During the spring of 1980 and the summer of 1981, two multidisciplinary oceanographic programs, Georgia Bight Experiment (GABEX) I and II, occurred on the southeastern U.S. shelf [Blanton et al., 1984; Atkinson et al., 1985]. The oceanographic data resulting from these experiments provided a basis for the development of a two-dimensional...
time-dependent model of the lower trophic levels of this ecosystem [Hofmann, 1988]. This physical-biological model, which consisted of optimally interpolated flow and temperature fields from the GABEX I and II current meter data [Ishizaka and Hofmann, 1988] and a 10-component biological model [Hofmann and Ambler, 1988], successfully reproduced the time-dependent horizontal plankton distributions at a nominal depth of 37-45 m on the southeastern U.S. continental shelf. The model results showed that frontal eddies and bottom intrusions have different effects on the southeastern U.S. shelf ecosystem. Two of the major conclusions drawn from the model are that the time scale of the frontal eddy upwelling is short relative to the time scale needed for the zooplankton to respond to the primary production increase resulting from the frontal eddy upwelling and that a significant amount of organic carbon is exported offshore at a depth of 37-45 m along the continental shelf, especially during the spring months.

McClain et al. [1984] processed and analyzed several CZCS images from the southeastern U.S. continental shelf for the GABEX I period and found several high-chlorophyll patches and bands along the inshore side of the Gulf Stream front. They compared the chlorophyll distributions seen in the CZCS images to ship observations and to current meter data and found that these patches and bands were related to Gulf Stream frontal eddy events and wind events and that the features were being advected to the north.

This paper and the two following present a series of studies that were conducted with a sequence of CZCS derived chlorophyll distributions for the southeastern U.S. continental shelf and with a physical-biological model similar to that used by Hofmann [1988]. Since the CZCS can detect chlorophyll in only the upper few tens of meters of water, the physical-biological model was recalibrated for a horizontal plane located at a depth of 17 m. These studies are focused on the GABEX I period, when upwelling is predominantly the result of Gulf Stream frontal eddies rather than wind induced bottom intrusions.

First, the sequence of CZCS-derived chlorophyll distributions are compared with the temperature and flow fields obtained for 17 m from an optimal interpolation of the GABEX I current meter data. The optimally derived circulation fields are used in Lagrangian particle tracing experiments to investigate the role of advective effects on the evolution and fate of the features seen in the CZCS chlorophyll distributions. Second, a four-component physical-biological model [Ishizaka, this issue(a)] was constructed for the southeastern U.S. continental shelf ecosystem. The chlorophyll distributions obtained from the model are compared statistically to those obtained from the CZCS to provide a quantitative verification of the model output. The sensitivity of these statistics to model parameter values is also tested. Finally, phytoplankton and nutrient fluxes are calculated from the model distributions [Ishizaka, this issue(b)] and compared with the fluxes obtained at 37-45 m by Hofmann [1988]. The CZCS data were also assimilated into the model to improve the phytoplankton flux calculation.

This, the first in the series of papers, has two primary objectives. The first is to describe the features seen in a sequence of nine CZCS images from April 1980 and to compare these features with those seen in the temperature and flow fields obtained from optimal interpolation of the GABEX I current meter data for the same time period. The second objective is to perform a series of Lagrangian particle tracing experiments, similar to those given by Ishizaka and Hofmann [1988], to track several of the features seen in the CZCS distributions. Some of the CZCS images from the GABEX I time period (April 1980) have already been processed, analyzed, and compared with current meter and ship observations by McClain et al. [1984]. Several additional CZCS images from April 1980 were processed for this study, and the images used by McClain et al. [1984] were repro-
cessed using different sensor decay correction factors. This new set of CZCS-derived chlorophyll distributions are interpreted using the information obtained from the optimally derived flow and temperature distributions and the particle trajectories obtained from the Lagrangian experiments.

2. METHODS

Model Domain

The model domain used in this study is located approximately 100 km offshore of Georgia, and the southern boundary is just north of Cape Canaveral (Figure 1). Dimensions of the model region are 200 km along-shelf ($y$; north-south) and 45 km across-shelf ($x$; east-west). The shallowest portion of the model domain is found in the southwest corner where depths are less than 30 m. The deepest part is found at the middle of the offshore (eastern) boundary where depths are more than 200 m. This model domain was determined by the GABEX I current meter mooring locations, which form the basis of the flow and temperature fields used in this and the following studies.

CZCS Data

Nine CZCS images, obtained for the southeastern U.S. continental shelf during April 1980, were processed using the facilities at NASA Goddard Space Flight Center. Some of the images had been previously processed by McClain et al. [1984] with a “clear water radiance” algorithm for the atmospheric correction [Gordon and Clark, 1981; Gordon et al., 1983a] and with a sensor sensitivity decay correction [Gordon et al., 1983b]. However, the resultant pigment concentrations overestimated the surface chlorophyll of this region. The reasons for the overestimation are unclear, but it may be the result of short-term variability in the calibration factors, contamination by onshore freshwater, or reflectance from a subsurface chlorophyll maximum [McClain et al., 1984]. For this study, the same CZCS images and some additional images were processed with a new linear sensor sensitivity decay correction from Gordon’s unpublished results, which is a revised formulation of Gordon et al. [1983b]. The formulations are as follows:

$$f_1(N) = 1.06(1 + 1.70 \times 10^{-5}N)$$

$$f_2(N) = 0.978(1 + 0.68 \times 10^{-5}N)$$

$$f_3(N) = 0.955(1 + 0.426 \times 10^{-5}N)$$

where $f_1$, $f_2$, and $f_3$ are the decay factors of the sensor sensitivity for bands 1–3 and $N$ is the orbit number.

The steps in image processing are as follows. First, low-resolution subsampled images were used to manually search for cloud-free regions with low constituent waters, which are used to derive a set of atmospheric correction factors (Angstrom exponents) in the manner described by Barale et al. [1986]. In general, waters in the region offshore of the Gulf Stream, near the outer edge of the model domain, contained less chlorophyll and land material than the shelf waters and were chosen as the clear water region for calculation of the atmospheric correction factors. After the correction factors were calculated, a full resolution image (a level 1 image), which included the model domain, was processed with the atmospheric correction and chlorophyll calibration factors to produce a level 2 image. The chlorophyll images were then remapped to a standard transverse Mercator projection that covered the region from 28.0° to 32.1°N and from 77.2° to 82.0°W (a level 3 image). Finally, the remapped images were fitted to the eastern coast line of the United States with a linear shift that corrected the small errors associated with the remapping process.

For later comparison to model chlorophyll distributions, the CZCS-derived chlorophyll was averaged with a binomial weighting scheme over $6 \times 6$ pixels around a model grid point. The model grid size is 5 km, and the distance covered in a pixel is about 0.9 km; consequently, averaging does not result in overlapping of the CZCS pixels relative to the model grid points.

Flow and Temperature Fields

Ishizaka and Hofmann [1988] applied an optimal interpolation technique to current meter data obtained during GABEX I to construct flow and temperature fields at a nominal depth of 37–45 m for the southeastern U.S. continental shelf waters. A general discussion of the GABEX I current meter moorings is given by Lee and Atkinson [1983]. Optimal interpolation is a method for interpolating and extrapolating a discrete data set with information on the extent to which the variables are statistically correlated at certain separation distances. The mathematical basis for optimal interpolation is given by the Gauss-Markov theorem. Optimal interpolation was introduced to physical oceanography by Bretherton et al. [1976]. A simplified description of the method is given by Karweit [1980], and a more detailed mathematical discussion is given by Gandin [1965]. The use of optimal interpolation techniques for obtaining circulation patterns on continental shelves is discussed by Denman and Freeland [1985].

For this study, flow and temperature fields at 17 m were obtained from the GABEX I current meter data with an optimal interpolation technique that is an improvement over the one described by Ishizaka and Hofmann [1988]. The 17-m fields are the shallowest fields which can be obtained from the GABEX I current meter data. The shallowest fields are necessary to interpret and compare chlorophyll distributions observed by the CZCS with those obtained from the model because the CZCS can only detect about one optical depth, where the surface light decreases to $1/e$. An interpolated circulation field is used in this study rather than one obtained from a theoretical circulation model because the dynamics responsible for the Gulf Stream frontal eddies are still not clear and, at present, no theoretical circulation model exists for the southeastern U.S. shelf that is adequate for coupling to a biological model. Furthermore, the interpolated circulation obtained from the field measurements makes possible direct comparisons between the model chlorophyll distributions and those obtained from the CZCS because of exact time and space correspondence.

The moorings used for the optimal interpolation are listed in Table 1, and the mooring locations are indicated on Figure 1. At some of the moorings, current meter measurements at 17 m were missing. Thus temperature and velocity values for this depth were estimated with a linear regression of the temperature and velocity measurements available from current meters at other depths. The combinations of the current meters used for this estimation are shown in Table 1. The
TABLE 1. Current Meter Mooring Numbers and Parameters Used for the Optimal Interpolation

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Parameter</th>
<th>Used for Estimation</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U, V, T</td>
<td>3 (17 m)</td>
<td>...</td>
</tr>
<tr>
<td>3</td>
<td>U, V</td>
<td>4 (45 m)</td>
<td>...</td>
</tr>
<tr>
<td>4</td>
<td>T</td>
<td>10 (17 m ~ 72 m)</td>
<td>0.759</td>
</tr>
<tr>
<td>5</td>
<td>U</td>
<td>9 (17 m ~ 37 m)</td>
<td>4.11</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>9 (17 m ~ 37 m)</td>
<td>7.19</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>9 (17 m ~ 37 m)</td>
<td>0.680</td>
</tr>
<tr>
<td>6</td>
<td>U</td>
<td>4 (45 m ~ 72 m)</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>4 (45 m ~ 72 m)</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>6 (17 m)</td>
<td>...</td>
</tr>
<tr>
<td>7</td>
<td>U, V, T</td>
<td>8 (17 m)</td>
<td>...</td>
</tr>
<tr>
<td>8</td>
<td>U, V, T</td>
<td>9 (17 m)</td>
<td>...</td>
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<tr>
<td>9</td>
<td>U, V, T</td>
<td>10 (45 m)</td>
<td>...</td>
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<tr>
<td>10</td>
<td>U, V</td>
<td>10 (17 m)</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>11 (17 m)</td>
<td>...</td>
</tr>
<tr>
<td>11</td>
<td>U, V, T</td>
<td>10 (45 m ~ 72 m)</td>
<td>6.04</td>
</tr>
<tr>
<td>12</td>
<td>U</td>
<td>10 (45 m ~ 72 m)</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>10 (45 m ~ 72 m)</td>
<td>0.759</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>10 (17 m ~ 72 m)</td>
<td>...</td>
</tr>
</tbody>
</table>

For some moorings, a linear relationship between current meters at two depths was used to estimate the velocity and temperature. The moorings and depths for which the linear relationship is used are indicated in column 3. The root mean square errors (RMSE) associated with these correlation analyses are also listed. Those moorings at which the 45-m data were used are indicated by (45 m). Those moorings at which a linear relationship between 17-m and 72-m current meters was used are indicated by (17 m ~ 72 m). The units for the RMSE are cm s\(^{-1}\) for the u velocity (U; across-shelf) and v velocity (V; along-shelf) and øC for temperature (T).

This was then subtracted from the velocity and temperature time series before performing the optimal interpolation. Because the time mean of the u velocity was more strongly dependent on the along-shelf distance rather than across-shelf distance (Figure 4), the u velocity mean was subtracted from the velocity time series as a linear function of along-shelf distance.

Optimal interpolation also requires homogeneity in the variance of the variable to be interpolated. Figures 3 and 4 indicate that the variances associated with the velocities and the temperature were slightly dependent on location. However, this heterogeneity was ignored in this study because the differences of the variances were small.

The least rigorously defined step in an optimal interpolation is the choice of a correlation function and a correlation length scale. In the study by Ishizaka and Hofmann [1988], correlation length scales for the temperature and velocity root mean square errors (RMSE) associated with the correlations are also listed in Table 1. Velocity measurements at 17 m were unavailable at all of the outer shelf (75-m isobath) moorings; consequently, the 45-m velocity measurements were used. The use of velocity observations from a different depth will introduce error into the optimally interpolated flow fields. It would be appropriate to include these errors in the interpolation of the velocity field; however, quantification of these errors is uncertain. Thus these errors were not explicitly included in the optimal interpolation, and it was further assumed that the velocity measurements contained no error as a result of the estimation.

One of the difficulties in using an optimal interpolation technique to obtain circulation and temperature distributions for the outer southeastern U.S. continental shelf is the strong gradient in temperature and velocity that exists across the Gulf Stream front or across the continental shelf. The optimal interpolation method implicitly assumes an unknown spatially constant mean value for the field being interpolated [Bretherton et al., 1976]. Thus this method does not allow for a spatially variable mean, which can be associated with the circulation and temperature distributions on a continental shelf that are produced by different forcings at different locations. For this study, the time means of the temperature and u (across-shelf) and v (along-shelf) velocities were calculated for each mooring location and plotted as a function of across-shelf distance (Figure 3). Temperature and the v velocity component were significantly increasing with distance from the shore. Since both temperature and v velocity are expected to be nearly constant away from the Gulf Stream front, a second-order polynomial was used to give an estimate of the across-shelf variation of the means.

Fig. 3. Variations in the time mean and standard deviation of the GABEX I temperature and velocities as a function of across-shelf distance.
interpolations were obtained by plotting cross correlations of the time series of current meter data versus separation distance between the current meters. These data were then fit with a two-dimensional Gaussian function of the form

$$ F(x, y) = e^{-\frac{(x/L_x)^2}{2}}e^{-\frac{(y/L_y)^2}{2}} \tag{2} $$

where $F$ is the correlation function which depends on the across- ($x$) and along- ($y$) shelf distance. The correlation length scales in each direction are given by $L_x$ and $L_y$, respectively. The resultant correlation length scales derived from the GABEX I current meter data were 25, 35, and 35 km for the $u$ velocity, $v$ velocity, and temperature in the across-shelf direction and 35, 150, and 150 km in the along-shelf direction for each variable, respectively. However, optimal interpolation with the correlation length scales obtained by Ishizaka and Hofmann [1988] tends to overestimate the velocities and temperature, and for some times the maximum and minimum values are out of the range of values measured by the current meters. This may be because the analysis of the time correlations between the current meters includes long time scale fluctuations that may tend to overestimate the instantaneous length scale which is required for the optimal interpolation.

Yoder et al. [1987] applied a variogram technique to CZCS data from the southeastern U.S. shelf and obtained an along-shelf length scale for chlorophyll patchiness in this region. This study yielded average along-shelf length scales of 32 km for the inner shelf and 84 km for outer shelf; however, these length scales were highly variable with time and with location. A variogram is a plot between the separation distance and the average of the squared difference of the parameter of interest at two locations. This method had been originally suggested as an approach for obtaining the correlation function for optimal interpolation techniques, and it has been called a structure function by Gandin [1965]. More recently, Bretherton et al. [1976] and Denman and Freeland [1985] have used this method. Unfortunately, the data sets from the GABEX I moored current meters are not sufficient for this analysis to be used to obtain the correlation function for the optimal interpolation because the separation distances between the moorings are too large. Thus, for this study, an along-shelf length scale of 60 km and an across-shelf length scale of 30 km were used with the Gaussian function given in (2). These length scales are close to those obtained by Yoder et al. [1987] and are approximately equal to the mooring separation distances.

Since velocities are vector quantities, it is reasonable to apply dynamic constraints that relate the $u$ and $v$ velocities. For example, Bretherton et al. [1976] used a geostrophic nondivergent horizontal flow assumption to constrain an optimal interpolation of discrete velocity measurements. However, as Ishizaka and Hofmann [1988] found from their correlation analysis and as is obvious from the satellite images, the strong Gulf Stream flow at the outer shelf results in velocity and temperature distributions that are not isotropic. Therefore, constraints, such as those used by Bretherton et al. [1976] which assumed isotropy, could not be adopted for this analysis. Thus the $u$ and $v$ velocities were interpolated as independent scalars, and the derived circulation is horizontally divergent.

Similar to the optimal interpolation of the GABEX II data by Ishizaka and Hofmann [1988], the optimal interpolation of the quantities at 17 m was done after transformation to a parabolic coordinate system which fits the bathymetry of the southeastern U.S. continental shelf. Velocity and temperature values corresponding to the 5 km by 5 km mesh grid points of the model domain were linearly interpolated from the curvilinear coordinate system.

The error field associated with the correlation function and correlation length scales is shown in Figure 5. Local errors of some of the mooring data discussed before (cf. Table 1) are not shown in this error field. The error in this analysis is slightly larger than that obtained with the longer correlation length scales used by Ishizaka and Hofmann [1988]. However, the error over most of the area was less than 25%, with only the north and south inshore corners of the model domain being poorly extrapolated. The strong flow of the Gulf Stream is predominantly from the southeast to the
Particle Tracing Experiments

Several Lagrangian particle tracing experiments were conducted to follow the features seen in the CZCS images. These experiments can be used to verify the optimally interpolated flow fields as well as to understand the movement of the chlorophyll patches. The method employed is the same as that described by Ishizaka and Hofmann [1988]. The new particle position is calculated by

\[
X_{\text{new}} = X_{\text{old}} + u \Delta t \\
Y_{\text{new}} = Y_{\text{old}} + v \Delta t
\]

where \(u\) and \(v\) are the velocities at the old position and time and are specified from the optimally interpolated fields. These velocities are calculated from the nearest four velocity values at the previous and next time level. The time interval \((\Delta t)\) is 0.5 hours and is chosen so that the particle moves less than half of the grid size, even when maximum velocities \((150 \text{ cm s}^{-1})\) are encountered.

3. RESULTS

Time Series of CZCS Images

The CZCS can detect chlorophyll to about one optical depth, which is about 10 m on the southeastern U.S. continental shelf [Yoder et al., 1983, 1985]. The optimally derived flow and temperature fields used in this study correspond to a nominal depth of 17 m, which is deeper than one optical depth. Thus it is first necessary to determine whether the CZCS chlorophyll measurements agree with the chlorophyll concentrations measured at 17 m in this area.

The CZCS pigment concentrations were compared with the ship-observed total chlorophyll measured at the surface and at 17 m during GABEX I, which was coincident with the images. Only ship-observed chlorophyll concentrations that were obtained within 6 hours of the time of the CZCS data (about noon local time) were used for the comparison. The stations at which the depth was shallower than 20 m were excluded from the analysis because of possible contamination with terrestrial dissolved organic and suspended materials. Because water samples were not taken exactly from 17 m, the chlorophyll concentration at this depth was obtained by linear interpolation of the chlorophyll values at the two nearest depths.

As reported by McClain et al. [1984], the CZCS-derived chlorophyll values overestimated the surface chlorophyll values obtained by ship observations during the April 1980 period (Figure 6a). McClain et al. [1984] suggested that the freshwater outflow was one of the possible causes of the overestimation of surface chlorophyll by the CZCS; however, the overestimation was not only in the area covered by low-salinity water (<36.00%), indicating that the overestimation may not be only the result of freshwater discharge. Low-chlorophyll water (0.1–0.2 \(\mu\)g L\(^{-1}\)) tends to be overestimated by the CZCS. The observed chlorophyll concentra-
tions at 17 m were generally higher than those at the surface, and the CZCS-derived chlorophyll slightly underestimated the concentrations at 17 m (Figure 6b). The overestimation of surface chlorophyll concentration by the CZCS was compensated by the higher subsurface chlorophyll concentration. But the correlation coefficients for the comparisons at the surface and 17 m were both $r = 0.85$ on a log-log scale, which are acceptable given the active advective character of this region. These results indicate that the CZCS chlorophyll can be used to represent the pattern as well as the magnitude of the 17-m chlorophyll.

The nine CZCS images for April 1980 are shown in Plate 1. The most distinctive pattern apparent in these images is the strong across-shelf gradient in chlorophyll concentration. The chlorophyll concentration was high over the shelf, reaching values of $3 \mu g L^{-1}$ and occasionally more than $5 \mu g L^{-1}$. The inshore waters (shallower than 20 m) had chlorophyll concentrations that were mostly higher than those at the midshelf region. However, the high inshore chlorophyll concentrations are probably the result of overestimation due to the presence of terrestrial dissolved organic or suspended materials as well as the effects of aerosols that originate from land. Chlorophyll concentrations offshore were low, less than 0.5 $\mu g L^{-1}$. The chlorophyll concentrations decreased sharply at the shelf break, which is also the region where the chlorophyll distributions showed the most time variability.

The CZCS images show a number of high-chlorophyll patches and band structures which are associated with the frontal eddy events, and these features are shown schematically in Figure 7. A frontal eddy event is seen clearly in the CZCS image from April 5 (2 in Figure 7b). At this time, a high-chlorophyll region extended northeast along the shelf break, and a low-chlorophyll region intruded from the north to the west of the high-chlorophyll region. This orientation of high- and low-chlorophyll regions is very similar to the cold-core and warm-tongue structure of a frontal eddy (cf. Figure 2) described by Lee et al. [1981], respectively. By April 10, the typical frontal eddy structure had moved out of the model region, and a small high-chlorophyll plume is seen in the middle portion of the model domain (3 in Figure 7c). An isolated high-chlorophyll patch is also located at the north of the model domain (2 in Figure 7c).

The images for April 11, 12, 15, and 16 were analyzed previously by McClain et al. [1984]. These same images, reprocessed for this study, showed basically the same features as described by McClain et al. [1984]. On April 11, a small high-chlorophyll plume, which is also seen on April 10, extended to the north in the model domain (3 in Figure 7d). This frontal eddy event was identified as filament A by McClain et al. [1984]. There was another high-chlorophyll patch south of the model region at this same time (4 in Figure 7d). This event was identified as filament B by McClain et al. [1984]. This high-chlorophyll patch is elongated in the April 12 image (4 in Figure 7e). On April 15 and on April 16, two high-chlorophyll bands extended northeastward at the north of model domain (3 and 4 in Figures 7f and 7g). Another small high-chlorophyll patch is seen in the south of the model domain on April 16 (5 in Figure 7g).

Another typical eddy structure is also seen at the south of the model domain on April 23 (7 in Figure 7h). Several wave structures are seen in the April 16 image (Figure 7i). These nine CZCS images showed a number of features that have different shapes and forms. However, the images themselves do not indicate interrelations between events because most of the images were separated by more than 1 day and the movement and deformation of the chlorophyll features are relatively fast given the high advective speeds that characterize this region.

The strong across-shelf gradient and high variance of chlorophyll at the shelf break are clear from the spatial distributions of the mean and standard deviation calculated from the nine CZCS chlorophyll distributions. The mean and standard deviation were calculated without (Figure 8) and with (Figure 9) a log-transformation of the chlorophyll concentration. The resultant mean fields are very similar to each other. Both distributions show mean chlorophyll values that are less than 0.25 $\mu g L^{-1}$ in the southeast corner of the model domain and mean values of more than 1.75 $\mu g L^{-1}$ in the southwest model domain. Chlorophyll concentrations in the northwest model region were also high. The distribution of the isopleths of mean chlorophyll concentration is remarkably similar to the distribution of the isobaths over the model domain (cf. Figure 1).

The spatial distributions of the standard deviations for the with and without log-transformed chlorophyll are different from one another. The standard deviation, calculated without first taking a log transformation of the chlorophyll, shows the across-shelf gradient in chlorophyll, which was seen in the mean field distributions, whereas the standard deviation distribution calculated after taking a log transformation of the chlorophyll shows a pattern that is high at the shelf edge and low for the onshore and offshore regions. This is consistent with the lognormal distribution of phytoplankton suggested by Harris [1986] on the basis of time series of phytoplankton concentration. In other words, the variance of the chlorophyll is high when the mean chlorophyll concentration is high, and variance is low when the mean chlorophyll concentration is low. Smith and Baker [1982] and Denman and Abbott [1988] found a more nearly Gaussian distribution of chlorophyll concentration derived from CZCS data after taking a log transformation, and Campbell [1987] suggested the importance of log transformations for the analysis of CZCS data.

**Flow and Temperature Fields**

Flow and temperature fields over the model domain for March 15 to April 30, 1980, were constructed by applying an optimal interpolation technique to the GABEX I moored current meter data (Figures 10 and 11). The use of different length scales from Ishizaka and Hofmann [1988] reduced the overestimation of the fields between the current meters; however, the over all pattern was almost the same as the results of the previous study. The strong northward flow (>75 cm s$^{-1}$) and high temperatures (>22.5°C) at the offshore edge of the model region indicate the presence of the Gulf Stream. Inshore of the Gulf Stream, the shelf waters were cold and the flow was slow and did not exhibit a persistent direction. The optimally derived fields show that several frontal eddy events propagated northward through the model domain during April 1980. These events can be identified by the presence of cold water and a reversal in velocity direction at the outer shelf.

One typical frontal eddy event was observed during April 1-7 (Figures 10 and 11), and this event can be seen clearly in the April 5 CZCS image (cf. Figure 7b). On April 2, a Gulf...
Plate 1. Sequence of CZCS images for the southeastern U.S. continental shelf during GABEX I: (a) March 31, (b) April 5, (c) April 10, (d) April 11, (e) April 12, (f) April 15, (g) April 16, (h) April 23, and (i) April 26. Coast line is indicated by the white lines, and current meter locations are indicated by white crosses.
Stream meander, which appears as a small perturbation of the velocities, moved into the southern model region. This perturbation produced a 30 cm s$^{-1}$ southward flow in the shelf region that is southwest of the strong northward flow. By April 4, this perturbation had developed strong westward flow in the middle of the model domain. On April 5 when the low-chlorophyll tongue-like structure and high-chlorophyll eddy can be seen in the CZCS image (Figure 7b), a warm-

Fig. 7. Schematic of the chlorophyll distributions observed in the sequence of CZCS images shown in Plate 1; (a) March 31, (b) April 5, (c) April 10, (d) April 11, (e) April 12, (f) April 15, (g) April 16, (h) April 23, and (i) April 26. Model domain is shown by the box. The frontal eddy events are identified from the velocity and temperature phase diagrams (Figure 12) and are indicated by the arrows and numbers.

Fig. 8. Distribution of the time mean and standard deviation (SD) calculated from the nine CZCS images for April 1980. The contour intervals are 0.25 and 0.2 µg L$^{-1}$ for the mean and standard deviation, respectively. The current meter locations are indicated by the circles.

Fig. 9. Same as Figure 8, except that the mean and standard deviation were calculated after taking a log transformation of the CZCS data and then transformed back to normal space. The contour intervals are 0.25 and 0.2 µg L$^{-1}$ for the mean and standard deviation, respectively.
tongue structure and a cold-core (<21°C) eddy were fully developed in the model domain. The eddy continued to propagate to the north and moved out of the domain on April 7. At this time, the most offshore portion of the model domain was covered with warm (>22.0°C) water and was characterized by northward flow.

The propagation of frontal eddy events through the model domain can be visualized with phase diagrams of the temperature and velocities from approximately the 75-m isobath (Figure 12). The previously mentioned chlorophyll features in the nine CZCS images correspond to the frontal eddy events. The typical frontal eddy event on April 5 can be recognized in the southern model domain on April 2 (event 2) as a cold (<22.5°C) southward flow that follows westward flow. This event moved through the middle of the model domain on April 5 and exited the region on April 7. Because of the limited model region, it is not possible to continue tracking this feature after April 7. However, if the eddy continued to move with almost the same speed as in the model domain, it is expected that the eddy moved to the region north of the model domain that showed a high-chlorophyll patch in the April 10 CZCS image (2 in Figure 7c).

The phase diagram shows several cold temperature and decreased-velocity events that propagated northward. The frequency of these events was about once per every 4-5 days, although some of the events were not very intense. In particular, the propagation of the eddies was difficult to identify during April 10-20 when two high-chlorophyll bands were formed and when strong southerly winds dominated [McClain et al., 1984]. Because of the elongated band structures, the position of the cold-core eddy may be easily mistaken in current meter records placed along a given isobath. Assuming the same phase speed of the April 5 event, a total of eight events were recognizable during April 1980. This is consistent with the events observed in the optimally interpolated fields at a depth of 37-45 m [Ishizaka and Hofmann, 1988]. This is also consistent with the analysis of the events passing individual moorings [Lee and Atkinson, 1983]. However, Ishizaka and Hofmann [1988] skipped a small event (event 5), and Lee and Atkinson [1983] did not identify events 5 and 8 [cf. Figure 8 of Ishizaka and Hofmann, 1988].

The frontal eddy seen in the April 5 CZCS image (2 in Figure 7b) was obvious in the GABEX I current meter data.
However, the other high-chlorophyll bands and patches also seem to be related, but less obviously so, to the events detected by the current meters. The features corresponding to events shown in the phase diagram are numbered in Figure 7. On April 10 when the small high-chlorophyll plume was seen in the CZCS image (3 in Figure 7c), the third frontal eddy event was located in the middle of the model domain, which is close to the plume. This event moved northward and exited from the model domain on April 12 (Figure 12) when the northern model domain was covered by clouds (Figure 7e). On April 15 (Figure 7f), a high-chlorophyll band extended to the northeast in the northern portion of the model domain. This event was explained by McClain et al. [1984] as a freshwater outflow that was entrained from the inner shelf into event 3. The high-chlorophyll patches detected in the southern model domain on April 12, 16, 23, and 26 (Figures 7e, 7g, 7h, and 7l) correspond to the dates of entrance into the model domain of the events 4, 5, 7, and 8, respectively. Event 4, which corresponds to the southern chlorophyll patch seen on April 12 (4 in Figure 7e), moved northward and exited from the model domain on April 16 when another high-chlorophyll band developed at the south of the high-chlorophyll band described previously. In the next section, the relationships between the high-chlorophyll bands and frontal eddy events are examined using numerical Lagrangian particle tracing experiments.

**Lagrangian Particle Tracing**

The comparisons between the velocity and temperature phase diagrams (Figure 12) and the CZCS chlorophyll distributions indicate correspondences between the features observed in the CZCS images and the frontal eddy events. However, the CZCS images provide sporadic realizations and the phase diagrams show only one-dimensional time series of velocity and temperature. After obtaining the time series of the flow and temperature fields, it is possible to use a numerical model to reconstruct time series of the chlorophyll distributions that then gives explanations of the interactions between the features observed in the CZCS images.
and the frontal eddy events. However, an Eulerian model includes uncertainties that arise from the assumptions that are made for boundary conditions, eddy diffusion coefficients, and upwelling terms, for example. Therefore it is useful to first test the accuracy of the flow field with Lagrangian particle tracing experiments, which do not include many a priori assumptions. Tracking of some of the features seen in the CZCS chlorophyll distributions allows checking the accuracy of the flow fields as well as testing hypotheses about the movement of features.

The first tracing experiment was designed to investigate whether or not the northern high-chlorophyll band (3 in Figure 7f), seen on April 15, developed from the small plume observed in the model domain on April 10 (3 in Figure 7c). Particles were placed in the high-chlorophyll region in the southern model domain that is seen in the April 10 CZCS image (Plate 2a). The particles moved northward during the next day (Plate 2b). Some of the particles continued to move to the northeast and followed the orientation of the northern high-chlorophyll band (3 in Figure 7f) seen in the April 15 CZCS images (Plate 2c). These results indicate that the high-chlorophyll band seen on April 15 developed from the small plume observed in the model domain on April 10 and are consistent with the hypothesis of McClain et al. [1984] and with the feature movement suggested by the phase diagram (cf. Figure 12).

The second particle tracing experiment was focused on the low-chlorophyll water observed on April 10 (north of 3 in Figure 7c). Particles were placed in the low-chlorophyll region at the middle to northern part of the model domain (Plate 2d). Most of these particles were moved to the northeast by the strong flow associated with the Gulf Stream (Plate 2e) and exited from the northeast corner of the domain (Plate 2f). These trajectories indicate that the low-chlorophyll water, which is a warm-tongue structure of an eddy event (cf. Figure 2), was trapped between the high-chlorophyll shelf water and the high-chlorophyll band which developed from the small plume. These results are also consistent with the feature development suggested by McClain et al. [1984] and the phase diagram (cf. Figure 12). Furthermore, some of the particles around the low-chlorophyll water moved toward the west, following the anticyclonic circulation of this feature suggested by McClain et al. [1984].

A third particle tracing experiment was conducted to consider the fate of the high-chlorophyll patch (4 in Figure 7e) that appeared in the southeast model domain on April 12 (Plate 2g). After three days, the particles moved to the northeast (Plate 2h) and the trajectories were slightly south of the trajectories traced in the first experiment (Plate 2c). Although most of the high-chlorophyll band is located outside of the model domain, the location of the trajectories corresponds to the southern high-chlorophyll band observed in the April 15 CZCS image (4 in Figure 7f). These results are consistent with the movement of event 4 on the phase diagram (Figure 12), and suggest that the southern high-chlorophyll band was formed by event 4.

4. DISCUSSION

In this study, a sequence of CZCS images from the southeastern U.S. continental shelf was processed and compared with flow and temperature fields obtained from optimal interpolation of current meter measurements made in this region. Lagrangian particle tracing experiments were then conducted to trace the features seen in the CZCS images. The sequence of CZCS images showed distinct across-shelf gradients and high variability at the shelf break area in chlorophyll concentration. Comparison of the CZCS chlorophyll distributions to phase diagrams of the flow and temperature fields showed correspondences between features in the chlorophyll fields and the Gulf Stream frontal eddies. The Lagrangian particle tracing experiments interpolated between the unequally spaced CZCS distributions and illustrated that the high-chlorophyll bands seen in the CZCS images were formed by frontal eddy events. The consistency of the CZCS chlorophyll distributions, the interpolated flow and temperature fields, and the Lagrangian particle tracing experiments shows the importance of the Gulf Stream frontal eddies in producing variability in chlorophyll distributions on the southeastern U.S. continental shelf. These results also demonstrate the usefulness of optimal interpolation and Lagrangian particle tracing experiments for interpreting CZCS data, even though each technique contains possible errors.

The patches and bands of high chlorophyll concentration detected by the CZCS showed considerable variability in shape and size with time and location. The length scales and structure of the high-chlorophyll patch that extended to the northeast and the low-chlorophyll water that intruded to the southwest, as seen in April 5 image (2 in Figure 7b) are very similar to those of the cold-core and warm-tongue structures, respectively, that was described by Lee et al. [1981, Figure 2]. The velocity and temperature phase diagrams indicate that this fronted eddy moved northward and that this typical frontal eddy form became the isolated patch of chlorophyll observed on April 10 (2 in Figure 7c). The small high-chlorophyll plume seen on April 11 evolved into the elongated high-chlorophyll band that was observed on April 15 and 16 (event 3). An additional high-chlorophyll band was formed from an isolated patch of high-chlorophyll water that is seen on April 11 (event 4). On April 26, simple wave structures can be seen in the chlorophyll distributions detected by the CZCS (event 8).

At present, it is still not clear what conditions are required for the development of the warm-tongue-like structure from a simple waveform. However, numerical modeling studies of this circulation suggest that the triggering mechanism is a mixed baroclinic-barotropic instability [Luther and Bane, 1985; Oey, 1988]. The sequence of CZCS images and the optimally interpolated flow and temperature fields indicate that the warm-tongue and cold-core structure observed on April 5 persisted for only a short period (a few days). It is possible that this structure may be just a temporary phenomenon associated with a developing instability on the Gulf Stream front.

On April 15 and 16, two bands of high-chlorophyll water were formed along the outer portion of the model domain (events 3 and 4). This period corresponds to the time when the frontal eddy events were weak (cf. Figure 12) and southerly winds prevailed [McClain et al., 1984]. Wind effects on frontal eddy events are not well understood [Lee and Atkinson, 1983], but weakening of the eddy may be associated with southerly winds. Given the possible merging of the warm-filament into the cyclonic vortex [cf. Lee et al., 1981] and the downwelling in the trailing portion of the frontal eddy [cf. Osgood et al., 1987], a weakened eddy may
Plate 2. CZCS chlorophyll concentration and particle trajectories from the Lagrangian particle tracing experiments. (a), (b), and (c) The trajectories followed by particles that were started in the high-chlorophyll region observed in the southern model domain on April 10. (d), (e), and (f) The trajectories taken by particles that were started in the low-chlorophyll region on April 10. (g) and (h) The trajectories followed by particles that were started offshore in the high-chlorophyll patch observed on April 12. Dotted lines are contours of chlorophyll concentration with a contour interval of 0.25 μg L⁻¹, and blue, green, yellow, and orange regions correspond to the chlorophyll concentrations of <0.25, 0.25-0.50, 0.50-0.75, >0.75 μg L⁻¹, respectively. Triangles represent the position of the particles. Solid lines are the trajectory followed by the particles during 1 day.
result in the retention of the effects of previous eddy events which could contribute to the formation of high-chlorophyll band structures along the outer shelf.

McClain et al. [1984] suggested that the northern high-chlorophyll band seen in the April 15 CZCS image (3 in Figure 7f) was caused by freshwater outflow that was entrained into a frontal eddy event. The results of the first and second Lagrangian particle tracing experiments support the suggestion that this band structure was caused by the entrainment of mid-shelf water into frontal eddy event 3. However, the comparison between the CZCS chlorophyll and ship-observed surface chlorophyll indicates that surface freshwater does not necessarily result in overestimation of the surface chlorophyll concentrations. The CZCS chlorophyll concentrations correlated well with the 17-m chlorophyll, and the magnitude of the concentration is closer to the 17-m chlorophyll than to the surface chlorophyll, especially when the surface chlorophyll concentration is low. Ship observations indicate that there is a large amount of chlorophyll just below the surface of this band structure [Singer et al., 1981a, b]. The CZCS can detect to depths of approximately one optical depth which is generally only about 7-10 m in this area; however, the optical thickness of the surface water may be deeper because of low chlorophyll concentrations. Since the subsurface chlorophyll concentrations in this area were sometimes very high and were found at relatively shallow depths, reflectance from the subsurface chlorophyll may be another possible reason for the overestimation of the surface chlorophyll by the CZCS. In fact, McClain et al. [1988] also found that the CZCS-derived chlorophyll concentrations off Georgia were high during the summer when Gulf Stream summer bottom intrusions enhance the subsurface chlorophyll concentration. These facts indicate that the northern band seen on April 15 is the band of subsurface chlorophyll maximum caused by the frontal eddy event 3, although the possibility of freshwater outflow cannot be neglected.

The particle trajectories computed with the Lagrangian model illustrate the general usefulness of these models for tracing the development and the fate of features observed in satellite images. Lagrangian models provide a mechanism for interpolating between satellite images, thereby, giving a more accurate description of how features form. This can be important for areas, like the southeastern U.S. continental shelf, that are characterized by large advective velocities and exhibit considerable space and time variability. Features can significantly change in size, concentration, and location even with a 1-day interval between satellite realizations. Furthermore, even if ocean color measurements are available at frequent intervals, some portion of the image is frequently partially obscured by cloud cover. Lagrangian particle tracing experiments provide a means for extrapolating feature movement in the obscured portions of an image.

For the study presented here, three different particle tracing experiments were conducted. The first and second experiments showed that the northern high-chlorophyll band seen on April 15 and April 16 (3 in Figures 7f and 7g) was formed by event 3 which is at the middle of the model domain on April 10 and April 11 (3 in Figures 7c and 7d) and identified as filament A by McClain et al. [1984]. These results were consistent with the hypothesis of McClain et al. [1984] in the sense that the band was formed by event 3. However, the results from the third experiment indicate that the southern high-chlorophyll band seen on April 15 and 16 (4 in Figures 7c and 7d) was formed from the high-chlorophyll patch that entered the model domain on April 11 to April 12 (4 in Figures 7d and 7e). McClain et al. [1984] identified this high-chlorophyll band to be the result of wind-induced shelf-break upwelling and assumed that it was an independent feature from the chlorophyll patch seen on April 12, which they referred to as filament B. McClain et al. [1984] also suggested that the filament B moved slowly and was identical to the southern chlorophyll patch observed on April 16 (5 in Figure 7g). The phase diagrams (Figure 12) show unclear movements of the eddy events between April 12 and 16, which makes interpretation of the current meter and CZCS measurements difficult. The results of the particle tracing experiments show northward movement of filament B, which corresponds to event 4 in Figure 12. Thus the use of Lagrangian tracing experiments clarified the interpretation of the development, movement, and correspondence of features observed in CZCS, ship, and current meter mooring measurements.

The correspondences between the computed particle trajectories and the features observed in the CZCS images also show the accuracy of the optimally interpolated flow fields. The comparisons between the CZCS data and the Lagrangian particle trajectories illustrate a method for checking the accuracy of surface or near-surface circulation distributions that are derived from techniques such as optimal interpolation. On the basis of these comparisons, it is clear that the interpolated flow fields reproduced the circulation on the southeastern U.S. continental shelf. This is an important point because the optimally derived temperature and circulation fields are used in conjunction with the CZCS data and a physical-biological model to investigate frontal eddy upwelling effects on biological production along the outer southeastern U.S. continental shelf.

In this study, the chlorophyll features seen in the CZCS images were assumed to be conservative. However, phytoplankton can grow, sink, and be grazed by zooplankton. Infrared images of event 4 [McClain et al., 1984] showed a cold core associated with the high-chlorophyll patch on April 11, but no cold water corresponding to the high-chlorophyll band on April 15, although the phase diagrams and the Lagrangian particle tracing experiment indicate these high-chlorophyll features were associated with the same event. The difference between the infrared and the ocean color images for event 4 on April 15 [McClain et al., 1984] may be caused by differences in the dynamics that control the patterns of the temperature and chlorophyll distributions. Local production of chlorophyll supported by upwelled nutrients may allow the high-chlorophyll band to persist longer than the cold core. Moreover, the second Lagrangian particle tracing experiment (Plates 2d and 2e) showed a significant decrease of the chlorophyll concentration along the trajectories followed by the particles between April 10 and 11. This decrease in chlorophyll concentration may be the result of error introduced by the image processing algorithms or the exclusion of vertical circulation processes in the optimally derived flow fields. However, the role of biological processes in effecting this decrease may be important. Further investigation of the interaction between biological production and physical processes is given in the following paper.
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