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Plankton dynamics on the outer southeastern U.S. continental shelf. Part I: Lagrangian particle tracing experiments

by Joji Ishizaka¹ and Eileen E. Hofmann¹

ABSTRACT

The residence time and flow patterns of plankton populations on the outer southeastern U.S. continental shelf were studied with Lagrangian particle tracing experiments. Flow and temperature fields used for these experiments were constructed by applying optimal interpolation methods to current meter data obtained during the Georgia Bight Experiment I and II which took place 25 February to 18 June 1980 and 10 June to 24 September 1981, respectively. The interpolated fields reproduced the flow and temperature structures associated with Gulf Stream frontal eddies and bottom intrusions, which are the upwelling mechanisms of interest in this region.

The general particle tracing results showed that plankton residence time and flow trajectory are controlled primarily by the Gulf Stream location and wind direction. During times when the Gulf Stream is located near the shelf break, plankton are transported rapidly to the north with little onshore flow. Residence times are short, being on the order of three to four days. When the Gulf Stream is located offshore of the shelf break and wind patterns are variable, particle transport shows no preferred direction and residence times on the outer southeastern U.S. shelf are long; sometimes in excess of thirty days.

Tracing of particles in waters upwelled in frontal eddies and bottom intrusions showed considerable differences in the fate of plankton associated with these features. Residence times of waters and particles upwelled in frontal eddies are short, four to six days, and transport is northward with the Gulf Stream. Bottom intrusion waters, by contrast, remain on the continental shelf for more than twenty days and transport of these waters and of associated particles is across the shelf to the inshore regions.

The particle tracing experiments showed that the different upwelling regimes and changing physical environment greatly affect the transport of material from and across the outer southeastern U.S. continental shelf. This in turn implies that these physical processes are a major component influencing the structure of plankton communities of this region.

1. Introduction

Recent studies of the oceanography of the outer southeastern U.S. continental shelf (Fig. 1) show that the plankton dynamics of this region are controlled by frequent inputs of upwelled, nutrient-rich, subsurface Gulf Stream water. The primary mecha-

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nisms responsible for this upwelling have been identified as: Gulf Stream frontal instabilities which are manifested as warm-core filaments and cold-core eddies, and bottom intrusions of subsurface Gulf Stream water. The cold-core frontal eddies occur throughout the year, but are most frequent between November and April (Lee et al., 1981; Lee and Atkinson, 1983). Bottom intrusions occur primarily during summer months when shelf waters are stratified and when southeasterly, upwelling-favorable winds prevail (Stefánsson et al., 1971; Blanton, 1971; Hofmann et al., 1981; Atkinson et al., 1984). These two types of upwelling are characterized by different length and time scales and, consequently, their net effect on the organisms and ecosystem of the outer southeastern U.S. shelf is also different.

To investigate the processes associated with frontal eddy and bottom intrusion upwelling, two large multidisciplinary experiments were conducted on the outer southeastern U.S. continental shelf. The first of these, Georgia Bight Experiment I
(GABEX I), occurred February to June 1980 and was designed to investigate Gulf Stream frontal eddies. The second, GABEX II, which occurred June to October 1981, focused on bottom intrusion processes. As a result of GABEX I and II, extensive biological, chemical and hydrographic data sets are available for Gulf Stream frontal eddies and bottom intrusions. These data have provided descriptions of the hydrographic characteristics of frontal eddies (Lee and Atkinson, 1983) and bottom intrusions (Atkinson et al., 1987) and their effects on primary (Yoder et al., 1983, 1985) and secondary (Paffenhöfer et al., 1987) productivity. Also, as part of GABEX I and II, a current meter mooring array was deployed on the outer and mid-shelf region between Cape Canaveral, FL and Cape Romain, SC. As a result, four-month time series of velocity and temperature at specific locations were obtained from each experiment. These data have yielded information on propagation speeds, frequency of occurrence and dynamics associated with upwelling events on the outer southeastern U.S. shelf. Results from the GABEX I mooring array are presented in Lee and Atkinson (1983); the GABEX II current meter data are described by Lee and Pietrafesa (1987). An overview of the southeastern U.S. shelf studies is given by Blanton et al. (1984).

Using the GABEX I and II data as a basis, we conducted a series of Lagrangian calculations and constructed two mathematical models with the overall objective of understanding and quantifying biological responses to the upwelling associated with the frontal eddies and bottom intrusions. Each set of calculations is designed to investigate different aspects of these upwelling processes. The first considers circulation effects on the transport of plankton along and across the outer southeastern U.S. shelf. The time-dependent behavior of biological interactions among the lower trophic levels is treated in the second, and the third investigates coupling between physical and biological processes. The first, a series of Lagrangian particle tracing experiments, is presented in this paper. The biological and coupled physical-biological models are subjects of the following two papers.

The circulation of the outer southeastern U.S. shelf is dominated by the northward-flowing Gulf Stream. Thus, the first step in our studies was to determine the extent to which the flow is responsible for the biological distributions observed in this region. The Lagrangian particle tracing experiments provide a straightforward approach for this purpose. Specifically these experiments were designed to determine

- the general patterns in the along- and across-shelf transport of particles,
- the fate of upwelled waters,

and

- the residence time of particles on the outer southeastern shelf.

Although the Lagrangian experiments focus on circulation effects in a specific area, the results have relevance to the more general questions of particle transport from
continental shelves (e.g., Smith et al., 1983; Walsh and McRoy, 1986), particularly for those continental shelves influenced by intense currents, such as western boundary currents.

The following section presents a description of frontal eddies and bottom intrusions. Section 3 describes the construction of the flow and temperature fields used in the Lagrangian particle tracing experiments. The methods and results of these experiments are presented in Section 4. Section 5 gives a discussion of the results and conclusions.

2. Description of frontal eddies and bottom intrusions

a. Frontal eddies. In satellite and hydrographic data, Gulf Stream frontal instabilities are seen as warm-core, tongue-like filaments extending southward from the Gulf Stream over the outer continental shelf region. Between the warm-core filament and Gulf Stream front is a dome of cold upwelled water. A schematic of one of these phenomena is shown in Figure 2a. The average along- and across-shelf dimensions of the cold-core eddy are 100 km and 20 km, respectively. The warm-core filaments extend 35 to 40 km across the outer shelf. The along-shelf dimension of these features varies with location, but is usually 100 to 200 km in the region from northern Florida to South Carolina (Lee et al., 1981). These events have average northward propagation speeds of approximately 35 km d$^{-1}$ and occur with a time scale of 2 days to 2 weeks (Lee et al., 1981; Lee and Atkinson, 1983).

The circulation within the frontal eddy is cyclonic and Lee and Atkinson (1983) report upwelling velocities of approximately $10^{-2}$ cm s$^{-1}$ in the cold core. The type of circulation associated with the warm-core filament has not yet been well defined. On the basis of hydrographic and mooring data, Lee et al. (1981) argue that flow in the warm-core filament is to the south and that this flow eventually merges with the cyclonic flow of the eddy. Chew (1981), however, uses conservation of potential vorticity arguments to suggest that upwelling in the cold core can produce anticyclonic flow in the filament which would result in northward flow on the western side of the feature. The existing data support both flow hypotheses (e.g., McClain et al., 1984). The circulation that is observed at any given time in the warm-core filament is most likely the result of a particular combination of the across-shelf density gradient and Gulf Stream and wind effects (McClain et al., 1984).

The processes underlying the development and formation of the filament-eddy structure have been investigated with modeling studies. Luther and Bane (1985) used a linear stability model which included vertical and horizontal shear in current velocity and a sloping bottom to study instabilities of a boundary current. Their model solutions revealed several unstable waves, one of which had a period of 7 to 8 days and showed patterns corresponding to those observed for the filament-eddy structures. This wave resulted from a mixed barotropic-baroclinic instability. However, the actual triggering mechanism could not be inferred from the model.
Figure 2. (a) Schematic of a cold-core Gulf Stream frontal eddy and warm-core filament in the Georgia Shelf (from Lee et al., 1981). Stippled area indicates the upwelling associated with the cold-core eddy. Arrows indicate the direction of flow. (b) Schematic showing the time development of a bottom intrusion of Gulf Stream water (from Blanton, 1971). Solid lines represent isopycnals.
Recently Oey (1988) used a three-dimensional, time-dependent primitive equation model to investigate the initial development of Gulf Stream frontal instabilities. Model calculations were done on an $f$-plane and in a constant depth, periodic channel and geometry. After ten days of integration, features that resemble the cold-core eddy and warm-core filament structure were observed in the simulated velocity fields. Oey concluded that the growth of the initial perturbation is predominantly baroclinic, deriving its energy source from the across-frontal density gradients. The simulated velocity fields show anticyclonic flow in the warm-core filament.

b. Bottom intrusions. In contrast to the frontal eddies, the dynamics underlying the development of bottom intrusions of subsurface Gulf Stream water are better defined. The prevailing wind pattern and the position of the Gulf Stream relative to the shelf break are the important mechanisms for the bottom intrusion process. Offshore (easterly) movement of the Gulf Stream results in an upward movement of isotherms which presents cold water at the shelf break (Atkinson, 1977). When this coincides with periods of southerly winds, the result is Ekman-like upwelling of subsurface Gulf Stream water onto the continental shelf. Subsequent onshore (westerly) movement of the Gulf Stream discontinues the cold water source at the shelf break and strands the newly upwelled water on the continental shelf. A schematic of the bottom intrusion process, as described by Blanton (1971), is shown in Figure 2b.

The magnitude of the intrusion is determined by the intensity and duration of the wind event (Hofmann et al., 1981; Atkinson et al., 1984). During periods of sustained southerly winds, bottom intrusions can extend shoreward to the 20 m isobath (Atkinson et al., 1987). Bottom intrusions occur with a frequency of 14 to 40 days and have been observed to remain on the southeastern U.S. shelf for periods of 5 to 6 weeks. Moreover, waters with temperatures less than 22.5°C upwelled by these events cover areas of approximately 3280 km$^2$ and occupy volumes of 38 km$^3$ (Atkinson et al., 1984). Because of their large volume and frequency, it has been suggested (Blanton and Pietrafesa, 1978; Atkinson and Pietrafesa, 1980) that bottom intrusions play a significant role in property exchanges and flushing of the southeastern U.S. continental shelf.

The role of wind and Gulf Stream location in producing bottom intrusions on the southeastern U.S. continental shelf was investigated with a two-layer finite element circulation model (Lorenzetti et al., 1987, 1988). The model was successful in reproducing wind-driven upwelling observed in the region north of Cape Canaveral, FL. The upwelling observed in the simulated circulation fields was strongest when the Gulf Stream was onshore, which was imposed as an along-shelf sea level slope, and northward wind stress prevailed. Model results suggested that maximum upwelling occurs when forcing from the wind and Gulf Stream act in unison.
3. Construction of flow and temperature fields

a. Approach. The first step in this research was the construction of a circulation system that reproduces the flow variability observed on the outer southeastern U.S. continental shelf. One approach is to use a theoretical circulation model. However, the existing circulation models for the southeastern U.S. shelf-ocean region are inadequate for the purposes of our modeling studies. Orlanski and Cox (1973) modeled the large-scale instabilities associated with the Gulf Stream front, but the spatial grid of their model was too coarse to resolve the filament-eddy structures on the western edge of the Gulf Stream. The diagnostic calculations of the general circulation in the southeastern U.S. shelf region presented in Kantha et al. (1982) captured the large-scale features of the flow, but failed to resolve bottom intrusions as well as the filament-eddy events. Again, their model resolution was too coarse and the averaged density fields used as model input smeared or excluded these smaller scale flow features. The previously mentioned model by Oey (1988) has the spatial resolution to reproduce the filament-eddy structures, but is limited in application by the exclusion of bottom topography and wind effects and by the short duration of the simulations. Further, this model does not consider bottom intrusion processes. Also, as Oey notes, implementation of his simplified model requires considerable computer resources. The model presented by Lorenzzetti et al. (1987, 1988) considers bottom intrusions, but not frontal eddies. Further, it should be noted that it is difficult to produce from a theoretical circulation model flow fields that correspond to the conditions that were observed when the biological and chemical field measurements were made. Therefore, for this study, we have constructed flow and temperature fields directly from current meter measurements by use of an optimal interpolation technique (Bretherton et al., 1976). A readable discussion of the optimal interpolation method can be found in Karweit (1980). With this approach, the specifics of the physical dynamics are not a concern because they are represented in the current meter measurement. Also, the spatial and temporal variability of the circulation during the period of the field observations is provided by the derived fields.

As will be discussed in the following section, the placement of and data return from the GABEX I and II current meters was such that the best estimates of the circulation and temperature distributions are in a horizontal plane at a nominal depth of 37 m. Consequently, the Lagrangian particle tracing experiments and the coupled physical-biological model discussed in Part III consider only processes operating in the across- and along-shelf directions at a single level. It could be argued that neglecting the vertical dimension compromises the model results. However, the large volume of hydrographic data from the outer southeastern U.S. continental shelf shows that in frontal eddies and bottom intrusions, cold, nutrient-rich waters are uplifted at the shelf break a depth up to 50 m and then advected horizontally onshore for distances of up to 50 km. Alongshore movement of the upwelled waters is on the order of approximately...
200 km. Our models are constructed to investigate the processes that occur as the upwelled waters move across and along the shelf.

The 37-m depth used in the models intersects approximately the center of the upwelling features. Lee and Atkinson (1983) show that the maximum onshore transport of nutrients occurs at this depth. Thus, a major pathway for the transport of upwelled waters on the outer southeastern U.S. continental shelf is across-shelf. The depth placement of the GABEX I and II current meters was designed to capture this onshore flow.

Obviously, our results and conclusions are limited by the exclusion of the vertical dimension. A three-dimensional, time-dependent model would be preferable and more accurate. However, given the available data and existing circulation models such a study is not presently feasible.

b. Data and model domain. The portions of the GABEX I and II current meter arrays used in this study are shown in Figure 1. The GABEX I array, located on the 40-m and 75-m isobath, was designed to investigate the propagation of Gulf Stream frontal disturbances along the outer shelf. The horizontal separation of the moorings was set to be at approximately the correlation scale of the frontal eddies (Lee and Atkinson, 1983). These moorings were used to define a model domain (solid line, Fig. 1) with along- and across-shelf dimensions of 200 km and 45 km, respectively. This domain is also the area in which the GABEX I shipboard surveys were made in April, 1980.

The GABEX II array extended inshore to also include the 30-m isobath and was designed to capture the across-shelf movement of the bottom intrusions. The larger horizontal spacing of these moorings reflects the longer length scales of the bottom intrusions. The model domain (dashed line, Fig. 1) encompassing the GABEX II moorings is 200 km and 75 km in the along- and across-shelf dimensions, respectively. As with the GABEX I domain, this region also includes the area surveyed during the shipboard studies phase of GABEX II which occurred July and August 1981.

Current meters on the 30-m and 40-m isobath moorings were located at depths of 17 m and three meters off the bottom. The 75-m isobath moorings had an additional meter at 45 m. The meter depths and data record lengths for each of the GABEX I and II moorings are shown in Table 1. Details of the current meter moorings and data reduction methods are given in Lee and Atkinson (1983) and Lee and Pietrafesa (1987).

The 40-hour, low-pass $u$ (across-shelf) velocity, $v$ (along-shelf) velocity and temperature derived from the data obtained from the current meters located at 27 m, 37 m, and 45 m on the 30-, 40- and 75-m isobaths formed the basis for the optimally-interpolated, two-dimensional fields used in this model. As shown in Table 1, the 17-m depth did not have sufficient data return to construct circulation and temperature fields at this level. The deeper 72-m observations are available only at the outer shelf moorings.
Table I. Current meter depths and length of the velocity and temperature records for the GABEX I and II moorings that are included in the model domain. Current meters from which no data were obtained are indicated as nd. Mooring locations are shown in Figure 1.

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In general, data return from the 27- to 45-m level was mostly excellent, with complete data records obtained for all but a few meters. Exceptions were moorings 6 and 12 from GABEX I and 8 and 14 from GABEX II which were missing data from either the 27 m or 45 m level (cf. Table 1). For the purpose of the optimal interpolation, velocity and temperature data were estimated at these locations from information obtained at nearby current meters. Linear regression coefficients were obtained between the 72 m and 45 m data from moorings 4 and 10 (GABEX I) and between the 17 m and 27 m data from mooring 2 (GABEX II). These relationships were then used to project the 72 m data at moorings 6 and 12 to 45 m and the 17 m data at moorings 8 and 14 to 27 m. The root mean square error associated with these estimations are 6 cm s\(^{-1}\), 16 cm s\(^{-1}\) and 1 °C for \(u\) velocity, \(v\) velocity and temperature, respectively for GABEX I and 6 cm s\(^{-1}\), 3 cm s\(^{-1}\), and 1 °C for GABEX II. Such a procedure increases the error of the data at the estimated locations relative to the other mooring locations; however, the results of the optimal interpolation are improved when the additional information is included, i.e., large gaps in the spatial distribution of the data are avoided.

c. Correlation function. Before applying an optimal interpolation technique to a data set, it is first necessary to know the scales over which the variables are correlated and how this correlation behaves as a function of spatial location. To address these points, zero time-lag cross-correlations for the \(u\) velocity, \(v\) velocity and temperature were calculated from the GABEX I and GABEX II mooring data. The correlation coefficients were then plotted against the separation distance of each mooring pair for the across- and along-shelf directions (Fig. 3). Each point represents the correlation for the three month mooring period. Sciremammano et al. (1980) used a similar method to estimate the vertical and horizontal scales of temperature and velocity from current meter measurements made in Drake Passage. Fandry and Pillsbury (1979) estimated geostrophic volume transport using an optimal interpolation method based upon the correlation functions derived by Sciremammano et al. (1980).

Most of the mooring data pairs were positively correlated and decreased with increasing separation length. Thus, a correlation function of the general form

\[
F(x) = e^{-\left(\frac{x}{L}\right)^2},
\]

where \(L\) is the correlation length scale and \(x\) is the separation length, was fit to these data using a nonlinear curve fitting routine. Data from the 17-m moorings were included to improve the accuracy of the regression. The resultant curves and associated error bars are shown in Figure 3. As can be seen, this type of correlation function fits the characteristics of the data.

The decay scale of the correlation function gave across-shelf length scales of 25 to 35 km for the \(u\) and \(v\) velocities and temperature, which did not differ between GABEX I and II (Fig. 3a, b, c). The along-shelf correlation length scales, by contrast,
are on the order of 100 km to 250 km (Fig. 3d, e, f). The along-shelf correlation length for the $u$ velocity is 35 km for GABEX I and 60 km for GABEX II (Fig. 3d). The shorter along-shelf scales occur because of the existence of several negative correlations. Also, the temperature correlations in the along-shelf direction showed significant differences between GABEX I and II (Fig. 3f) and significant correlations were observed at separation distances greater than 200 km. The across- and along-shelf length scale values for GABEX I and II are summarized in Table 2.

Denman and Freeland (1985) studied the sensitivity of optimally-derived maps to different correlation functions, length scales and noise levels. They found that a simple Gaussian correlation function fit only the initial portion of their data; whereas, a Gaussian function multiplied by a Bessel function provided the best fit to the data. However, they concluded that if sampling of the variable was well distributed, then the patterns obtained in the objective fields changed little with differing input functions. Because of the existence of negative correlations, along-shelf $u$ velocity data were also fit with an exponentially decaying cosine function of the general form

$$F(x) = e^{-\left(x/L\right)^2} \cos \left(\pi \left(x/L\right)^2\right),$$

(2)
Table 2. Across-($L_x$) and along-($L_y$) shelf velocity and temperature correlation length scales obtained from the GABEX I and GABEX II current meter observations. Numbers in parentheses indicate the number of mooring pairs available during each experiment for the nonlinear regression. The correlation lengths denoted by * were obtained by combining the mooring pair data from GABEX I and II.

<table>
<thead>
<tr>
<th></th>
<th>GABEX I</th>
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<th>GABEX II</th>
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<tr>
<td></td>
<td>$L_x$ (km)</td>
<td>25 (6)*</td>
<td>50 (10)*</td>
</tr>
<tr>
<td></td>
<td>$L_y$ (km)</td>
<td>35 (30)</td>
<td>150 (30)*</td>
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where $L$ and $x$ are as previously defined. The correlation length scales obtained with this function were slightly longer than those obtained with Eq. (1), however, the overall values of the two correlation functions were very close. The only exception was that Eq. (2) gave slightly negative values at larger separation distance. However, as found by Denman and Freeland (1985), the flow fields constructed with the correlation functions given in Eqs. (1) and (2) were not significantly different.

d. Interpolation procedure and coordinate system. The optimal interpolation procedure used a Gaussian correlation function of the form

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

(3)

where $L_x$ and $L_y$ are the across- and along-shelf correlation length scales and $x$ and $y$ are separation lengths in the across- and along-shelf directions, respectively. Values of $L_x$ and $L_y$ are different in the two directions (Table 2).

Bretherton et al. (1976) and Freeland and Gould (1976) discussed methods to implement the geostrophic, nondivergent assumption in optimal interpolation of velocity fields. In their techniques, they assumed that the velocity field is homogeneous and isotropic. The assumption of isotropy is not appropriate for the Gulf Stream frontal eddies because these structures are elongated along their north-south axis. Cross-correlation analysis (Fig. 3 and Table 1) shows that the velocity field is anisotropic on the outer southeastern U.S. shelf. Our attempts to interpolate the GABEX I and II velocity data with the method suggested by Bretherton et al. (1976) resulted in unrealistic across-shelf jets. Thus, we chose to apply the optimal interpolation to the $u$ and $v$ velocity components individually and to treat these as scalar quantities.

The mean flow on the outer southeastern U.S. shelf is essentially parallel to the isobaths (Lee and Atkinson, 1983; Lee and Pietrafesa, 1987). This preferred flow trajectory was included as an additional constraint on the correlation function used in the optimal interpolation of the GABEX II current meter data. The isobath curvature was fitted with a parabolic function and the mooring locations were transformed to this curvilinear coordinate system. The optimal interpolation was then done in this curvilinear
e. Error fields. From the optimal interpolation procedure, error variance fields are produced. These fields show that the optimal interpolation of the GABEX I and II mooring data gives good estimates of velocity and temperature on the outer southeastern shelf (Figs. 4, 5). Error variances associated with the estimates of $v$ velocity and temperature were less than 50% over the entire model domain for GABEX I and II. The largest error variance was associated with the $u$ velocity which is not unexpected.
because this variable has the shortest correlation length scale relative to the mooring spacing. Overall, 84.4% (GABEX I) and 71.3% (GABEX II) of the model domain had an error variance of less than 50%. The largest error variance and hence poorest interpolation occurred in the southwest corner of the model domain. However, the effect of this region on the Lagrangian calculations is small.

f. Optimally-interpolated temperature and flow fields. Flow and temperature fields were constructed in horizontal planes on a 5-km grid at six-hour intervals for the periods 25 February to 18 June, 1980 (GABEX I) and 10 June to 24 September, 1981 (GABEX II).

An example of the flow and temperature fields obtained from the GABEX I data is shown in Figure 6. The strong southward flow and cold, 16°C, water along the outer part of the model domain are characteristic of a frontal eddy. Maximum velocities in the eddy are in excess of 50 cm s⁻¹, which agree with direct current observations. Inshore of the cold-core frontal eddy, the warm-core filament is well defined in the temperature field. The along- and across-shelf dimensions of this feature are approximately 150 km and 30 km, respectively, which are in agreement with satellite (McClain et al., 1984) and hydrographic observations (Lee et al., 1981; Lee and Atkinson, 1983). Flow within the warm filament is weak, being less than 15 cm s⁻¹, and in this particular feature it is directed southward along the outer shelf. The eddy-filament structure shown in Figure 6 is very similar to that described by Lee et al. (1981) and shown in Figure 2a. The intense northward flow and warm water directly
north of this region are representative of the Gulf Stream front. Subsequent fields showed this event to propagate northward along the outer shelf and to move out of the model domain in approximately three days.

As mentioned previously, the circulation within the warm-core filament is a controversial point. The example shown in Figure 6 indicates strong southward flow at the eastern side. And weak southward flow at the western edge of the filament. However, some of the filament features seen in the optimally-interpolated fields have northward velocity along the western side. Also, the flow in a single filament can change direction quickly as the event moves through the model region. The actual flow in a warm-core filament is dynamic, which makes it difficult to define a typical flow regime.

Representative flow and temperature fields derived from the GABEX II data are shown in Figure 7. The flow field shows strong northward flow along the outer shelf which turns to onshore flow over most of the inner model domain. The temperature
fields show warm, 22°C, water associated with the northward flow and a large band of cold water, minimum temperature of 16°C, over the inner model domain. These fields show an intense bottom intrusion that has been stranded on the shelf by onshore movement of the Gulf Stream. This particular event was surveyed extensively during GABEX II and the patterns shown in Figure 7 agree well with those seen in hydrographic data (Atkinson et al., 1987).

A summary of the events identified in the GABEX I and II optimally-derived fields and comparison of these to the Gulf Stream position and shelf wind direction is given in Figure 8. During March and April, velocities along the outer shelf region were in excess of 50 cm s⁻¹, indicating that the Gulf Stream was located close to the shelf break. Numerous eddy or eddy-like features were observed in the flow and temperature fields for this time period. However, at this time of year shelf waters are cold and it is sometimes difficult to distinguish cold shelf water from upwelled water. Thus, the
Figure 8. Summary of the frontal eddies and bottom intrusions identified in the optimally-constructed temperature and flow fields. Onshore-offshore indicates the approximate location of an event. Numbers are a comparison with the events identified by (a) Lee and Atkinson (1983) (b) Lee and Pietrafesa (1987), and (c) Atkinson and Lee (1987). The location of the Gulf Stream relative to the shelf break is indicated by the dotted (onshore) and solid (offshore) lines. The Gulf Stream position was determined as offshore when the 10-day averaged $v$ velocity at 45 m was less than 25 cm s$^{-1}$. Periods of predominant southerly or random wind direction are shown by dotted or solid lines, respectively. The wind direction was taken to be consistently from the south when the $v$ component of the wind was positive for more than five days.

criteria for identification of eddy-like structures was a decrease in temperature accompanied by diminished or reversed $v$ velocity. During May and June, velocities on the outer shelf decreased indicating that the Gulf Stream moved offshore and the frequency of eddy-like structures diminished somewhat.

For comparison, the frontal eddies identified by Lee and Atkinson (1983) are also shown in Figure 8. Each event noted by Lee and Atkinson (1983) was recognizable in the interpolated fields. The only discrepancy is that they identified a fewer number of eddies, 14 vs. 22. One explanation for the difference may be the criteria used for frontal eddy identification in this analysis and that used by Lee and Atkinson (1983). Recently Oey et al. (1987) described a transient shelf break upwelling that occurs on the outer southeastern U.S. continental shelf in winter months in response to either a southward
wind pulse or Gulf Stream meander. These forcings provide perturbations that break down the shelf break front that is produced by the presence of the Gulf Stream. As a result, intrusions of warm Gulf Stream water move onshore across the shelfbreak in the upper layer. The warmer water then mixes with the cooler shelf water to form a front on the continental shelf. Downwelling occurs at the shelf front. Coincident is the development of a region of upwelling over the shelf break/slope region which has divergent flow. These upwellings are short lived with time scales on the order of the wind events (3–10 days) and meander cycles (8 days). This mechanism was not included in the eddy count made by Lee and Atkinson (1983). Our event criteria may have also included these transient upwelling events. Because the optimally-interpolated fields represent only one level in the vertical, it is sometimes difficult to separate the eddy-induced and transient upwellings.

The optimally-interpolated fields from GABEX II showed two large bottom intrusions and several frontal eddy events. The first intrusion was already in the model domain on 10 June and remained in this area until 7 July. The second intrusion started on 1 July and moved onshore and northward and remained in the model domain until 5 August. The occurrence of the second intrusion coincided with onshore movement of the Gulf Stream and a period of sustained southerly winds. These two intrusions were observed in the GABEX II hydrographic data (Atkinson et al., 1987).

Concurrent with the intrusions, several frontal eddy events were observed. On August 8 and 18 two of these eddies developed into small intrusions. However, these events persisted for only a few days and did not extend very far onshore. The wind direction at this time was fluctuating, which may have prevented the development of a large intrusion. Lee and Pietrafesa (1987) identified 17 frontal eddies in the GABEX II velocity and temperature records. All of these events are observed in the optimally-interpolated fields, but again a few additional events were identified.

4. Lagrangian particle tracing experiments

a. Methods. The preceding discussion illustrates that the circulation characteristics of the outer southeastern shelf change over the year. These changes are large and consequently the effect on plankton residence time in this region can be rather dramatic. To investigate the effect of the changing advective circulation on plankton residence time, we calculated the trajectories of many particles using the relationships

\[ X_n = X_0 + U\Delta t \]  \hspace{1cm} (4)

and

\[ Y_n = Y_0 + V\Delta t \]  \hspace{1cm} (5)

where \( X_n \) and \( Y_n \) are the spatial locations of the particle and \( U \) and \( V \) are the across- and
along-shelf velocities, respectively. The velocity coordinate system is defined such that $U$ is positive offshore (eastward) and $V$ is positive along-shore to the north. The velocities are specified with the optimally-derived fields. The parameters $X_o$ and $Y_o$ represent the spatial location of the particle at the previous time and $U\Delta t$ and $V\Delta t$ represent the displacement of the particle from this location by the advective field. The advective velocities were linearly interpolated to the location of the particle using velocities from the four nearest grid points at the previous and succeeding time levels. The time interval, $\Delta t$, was set at 0.5 hours, which ensured that particles did not move more than half of the grid interval (5 km) in one time step, even at maximum (150 cm s$^{-1}$) current speeds. Some Lagrangian models include a stochastic term to mimic diffusive processes (e.g., Walsh et al., 1981); however, the calculations presented here did not include an explicit stochastic diffusion.

b. Results of general particle tracing. The general particle movement pattern was obtained by placing 52 particles at various grid locations and tracking these particles until they moved out of the model domain. Examples of particle trajectories for three time periods, which represent different flow conditions, are shown in Figure 9.

In early April 1980, particles on the outer southeastern shelf would have followed the trajectories shown in Figure 9a. These trajectories indicate significant differences between paths followed in the inner and outer model domain. Along the outer region, flow is from south to northeast and particles are retained on the outer shelf for at most 3 days. Obviously these particles were entrained in the Gulf Stream which was located along the outer shelf region during this time (cf. Fig. 8).

However, the Gulf Stream effects do not penetrate inshore to the 40-m isobath and particles in the inner model domain have larger residence times (7 days). Circulation at the 40-m isobath is predominately wind driven (Lee et al., 1984) and mid-shelf waters are well mixed during the spring. The GABEX I period was characterized by strong northward wind stress but with intermittent, frequent reversals to southward winds (Lee and Atkinson, 1983). Consequently, the mid-shelf circulation is primarily to the northeast, but with occasional reversals to southward flow in response to changes in the direction of the wind stress. These flow reversals result in the longer particle residence times in inner model domain. However, most of the particles eventually flow out through the northern model boundary. The mid-shelf particle trajectories are very similar to those obtained from a vertically-integrated, two-dimensional model of wind-driven flow on the southeastern shelf during winter (Kourafalou et al., 1984), the only difference being tidal effects which are filtered from the 40-hour low pass current meter data used to construct the velocity fields.

Particles started on 22 July (Fig. 9b), during a bottom intrusion, show a much different pattern. Flow direction in the southern model region tends to be from offshore to inshore. Particle residence time is still short (3 to 5 days), but particles now leave
Figure 9. Trajectories followed by particles started on (a) April 10, 1980, (b) July 22, 1981, and (c) August 1, 1981. Arrows on the trajectories indicate particle positions in days and particle flow direction.

through the western (onshore) model boundary, reflecting the effect of the onshore flow associated with the bottom intrusion.

Particle trajectories from August (Fig. 9c) show random particle motion and long (30 days) residence times. During this period bottom intrusions were absent, the Gulf Stream was offshore, and the winds showed no predominant pattern (cf. Fig. 8). Hence, flow on the outer shelf was weak and essentially wind-forced.

To quantify and compare seasonal differences in particle movement, frequency diagrams of particle residence time and average Lagrangian flow direction (direction from starting to final position) were produced for particles started inshore and offshore (Fig. 10). In general the particle patterns showed the greatest correspondence to the Gulf Stream position and wind direction (cf. Fig. 8).

From 2 March to 30 April particle motion was similar to the patterns depicted in Figure 9a. The Gulf Stream was located along the outer shelf, and particles started in the outer model domain followed trajectories that were controlled by the Gulf Stream (Fig. 10b). Residence times were mostly less than 5 days and particle transport was to the northeast. In the onshore portion of the model region, a northward, but not always
consistent, wind produced predominately northward flow and particle residence times approaching 10 days for the well mixed waters on the mid-shelf (Fig. 9a). The Gulf Stream moved offshore in early May, which resulted in longer residence times and variable flow directions for both inshore and offshore particles.

The particle motion for the GABEX II time period shows a more complex pattern (Figs. 10c and 10d). From 12 June to 1 July, the Gulf Stream was close to the shelf break and northward winds prevailed. Particles started inshore and offshore moved primarily northward and had maximum residence times of about 10 days. This pattern changed on 2 July when the Gulf Stream shifted offshore. Particle transport reversed to the southeast and residence times increased. Particles started on 12 July followed primarily westward trajectories because of the constant northward upwelling-favorable wind.

The consistent northward wind ceased at the beginning of August, and the Gulf
Figure 11. Example of particle movement associated with a frontal eddy. Particles are denoted by X’s and contour lines are temperature (°C). Particle trajectories are shown by the solid lines and the arrows indicate the direction of particle flow. The model was started on midnight of May 23, 1980. Particles moved into the model domain on 23 and 24 May. See text for explanation.

Stream remained offshore until mid-September. Particle movement during this time was essentially random because of the fluctuating wind. Particles remained in the model domain for more than 30 days and eventually moved out to offshore.

c. Tracing of eddies and bottom intrusions. To address the fate of particles associated with the upwelled waters of the frontal eddies and bottom intrusions, a second series of numerical experiments was performed. We assumed that newly upwelled water flowed into the model domain from the eastern (offshore) boundary and that the upwelled water was colder than 20°C. Particles were started at fifteen grid points on the boundary at 6 hour intervals when the temperature at the grid point was less than 20°C. These particles were traced until they moved out of the model domain.

Particles traced in a frontal eddy are shown in Figure 11. Only a few particles were advected onshore during this event because the cold, upwelled water associated with the eddy covers only a small part of the offshore boundary. Also, currents on the southern side of the feature were directed offshore. The particles advected into the model domain were transported northward along the outer shelf with the eddy or the following warm-core filament. None of the particles moved inshore, and residence times on the outer shelf were about 3 to 5 days.
Figure 12. Example of particle movement associated with a bottom intrusion. Particles are denoted by X's and contour lines are temperature (°C). Particle trajectories are shown by the solid lines and the arrows indicate the direction of particle flow. The model was started on midnight 15 July 1981 and results at five day intervals are shown. Particles moved into the model domain on 15 and 16 July. See text for explanation.
Figure 13. Percent particles transported into the model domain by upwelling events during (a) GABEX I and (b) GABEX II. Maximum number of particles is 15 particles per six hours or 60 particles per day. The direction followed by the particles when leaving the model domain is shown for (c) GABEX I and (d) GABEX II.

The bottom intrusion, by contrast, covered the entire offshore boundary (Fig. 12) and many particles were brought into the model domain by this feature. These particles initially moved southward then abruptly reversed direction and moved gradually onshore and northward. The residence time of the particles in the cold intruded waters was long, with some particles remaining for more than 20 days.
The percent of particles transported into the model domain by frontal eddies and bottom intrusions is shown in Figure 13. Most of the peaks in particle time series correspond to the frontal eddy and intrusion events identified in Figure 8. Comparison of GABEX I and II shows that almost twice as many particles were advected onshore in bottom intrusions as in frontal eddy events.

The residence time of the upwelled water also shows significant differences between these two periods (Fig. 13a, 13b). Residence time of upwelled particles during GABEX I was short, less than 5 days, and very few particles remained for more than 20 days. During GABEX II more than one-third of the upwelled particles had
residence times longer than 20 days. This is particularly evident for the periods 20 to 23 June and 14 July to 2 August, when intrusion-favorable southerly winds prevailed. In fact some of the particles upwelled during July remained in the model domain for more than 60 days because wind patterns became variable during August. The long residence times of these particles results partially from the larger across-shelf dimension used for the GABEX II model domain. However, as shown by the general particle tracing results (cf. Figs. 9, 10) the flow patterns observed during GABEX I and II are different. It is the slower onshore flow associated with the summer bottom intrusions that gives the longer particle residence times.

The direction by which the upwelled particles leave the model domain also differs between GABEX I and II (Fig. 13c, 13d). Upwelled particles are flushed out to the east during GABEX I, with very few particles moving to the west. During GABEX II many particles also moved eastward out of the model domain. However, a large percentage of particles were transported westward for the periods 20 to 24 June and 13 to 25 July. These times coincide with the bottom intrusions. The model domain for GABEX II was 1.6 times larger in the westward direction than that for GABEX I. Hence, this particle movement reflects strong westward transport.

5. Discussion

The optimally-interpolated flow and temperature fields from GABEX I showed northward movement of eddy-like features (Figs. 6 and 8) which had a structure similar to that described by Lee et al. (1981). The GABEX II fields showed the onshore intrusion of cold, Gulf Stream water which was coincident with a period of sustained northward wind stress in late June and July, 1981 (Figs. 7 and 8). The length and time scales, velocities and temperatures associated with the features depicted in the interpolated fields agree with those observed in hydrographic and satellite data. Thus, the optimal interpolation procedure accurately reproduced the characteristics of the flow on the outer southeastern shelf. Furthermore, particles placed in the eddies and intrusions were advected with the region of cold water (Figs. 11 and 12), which gives additional support for the accuracy of the interpolated fields. This latter point also supports the accuracy of the Lagrangian calculations. These calculations do not resolve small scale diffusive motions which in some instances can overwhelm model solutions. However, the correspondence between the interpolated temperature fields and particle trajectories indicates that this was not a serious problem for the time periods considered in the study.

Both the general particle tracing and tracing of particles in upwelled water masses show that particle movement on the outer southeastern U.S. continental shelf is controlled strongly by the location of the Gulf Stream relative to the shelf break and the prevailing wind direction. When the Gulf Stream is close to the shelf break, particles are transported rapidly to the north and out of the model domain. Offshore
movement of the Gulf Stream and random wind patterns favor retention of particles on the outer shelf.

It is difficult to determine the ultimate fate of the upwelled waters because the model domain encompasses only a small portion of the outer southeastern U.S. continental shelf and the Lagrangian experiments do not include a vertical dimension. However, from the particle trajectories it is apparent that the behavior of waters upwelled in frontal eddies and bottom intrusions is different. Waters upwelled in frontal eddies have short (5 days) residence times and are transported northward and offshore. Upwelled waters associated with bottom intrusions are transported across the outer shelf to inshore areas and remain in the model region for as long as one month.

The particle tracing experiments indicate that most of the particles upwelled in the frontal eddies remained in and moved with or followed the feature. Thus, it is reasonable to expect that phytoplankton populations would also remain in the frontal eddy and be transported northward. Yoder et al. (1981) found that the horizontal scales of phytoplankton patchiness on the outer southeastern U.S. continental shelf correspond to those of frontal eddies. Further, the results presented in this paper show that even though the residence times associated with frontal eddy upwelling are short, some of the particles do remain in the model domain more than 5 days (cf. Fig. 13a). This suggests that waters and associated nutrients upwelled in an eddy may affect subsequent events.

Verification of the patterns observed in the GABEX II particle tracing experiments (Fig. 12) is given by observations of the space and time development of phytoplankton (Yoder et al. 1985; Paffenhöfer and Lee, 1987) and zooplankton (Paffenhöfer et al., 1987) distributions associated with the bottom intrusion that began 15 July 1981. The particle trajectories indicate that newly upwelled water appeared at the outer shelf break on July 15–23 and moved gradually to the mid-shelf region. Repeated transects through this bottom intrusion show the onshore movement of the intruded waters and development of patches of high chlorophyll (Yoder et al., 1985) and zooplankton (Paffenhöfer et al., 1987) concentration in the mid- to inner-shelf region in late July and early August.

The results of Lagrangian particle tracing experiments showed that waters upwelled in frontal eddies have short residence times on the outer southeastern U.S. shelf and that there is little onshore transport of the waters. Intruded waters, by contrast, move onshore during periods of sustained southerly winds and remain in the mid-shelf region for up to a month. These results imply that the plankton populations would respond differently to the two physical regimes.

Klein and Steele (1985) investigated the role of physical effects in marine ecosystems with a simple model. Their general results for three different physical regimes zero-, one-, and two-dimensional flow, show that as water exchange is increased, primary production increases but secondary production does not. From the different particle trajectory patterns in frontal eddies and in summer intrusions, we
would expect that the primary and secondary production associated with these features would be different.

Klein and Steele (1985) also concluded that knowledge of the details of the advection and diffusion is required to understand the physical environment contribution to biological production. Our Lagrangian experiments show the complex and dynamic flow regime of southeastern U.S. continental shelf area to be controlled by the Gulf Stream and wind events. Part II of this series of papers (Hofmann and Ambler, 1988, this volume) describes a time-dependent biological model for this area, and the effect of the physical regime on biological systems is investigated in Part III (Hofmann, 1988, this volume).

Finally, the methods used in this study are not new to physical oceanography; however, optimal interpolation and Lagrangian particle tracing experiments can supply important information to biological oceanographers. These models allow investigation of the effects of physical processes on marine ecosystems and provide a method to estimate the trajectory followed by a water mass. The latter point may be of interest to biological oceanographers when designing sampling programs. In the future, real time acquisition of current meter data (e.g., Brooks, 1984) will make it possible to construct real time flow maps and water mass trajectories. Coupling to a biological model then supplies a time-space model for the biological system.

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