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Variability in surface chlorophyll $a$ at a shelf-break front

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ABSTRACT

We report an extensive underway sampling of temperature and chlorophyll $a$ in the region of the shelf/slope front in the New York Bight in early spring. Variability in chlorophyll $a$ and frontal structure is analyzed at three spatial scales. At the largest scale (50-100 km), warm core rings are implicated in causing an offshore displacement of the front and a divergence in the flow field. This temporal variation in large-scale frontal structure smooths out large-scale variability in chlorophyll and obscures an overall relationship between water column stability and surface chlorophyll distributions. At scales of 10-50 km, and inshore of the front, variability in chlorophyll concentration at the surface appears to be determined by variations in mixed layer depth. At scales of 1-10 km, variability in surface chlorophyll $a$ is consistent with preferred patch sizes predicted by a theory of the chlorophyll fluctuation spectrum in the sea.

1. Introduction

An oceanic front roughly coincident with the shelf break throughout the Middle Atlantic Bight forms the boundary between coastal water characteristic of the shelf and oceanic slope water. In winter, this front is baroclinic and extends from surface to bottom (Beardsley and Flagg, 1976). Shelf water has a temperature range of 3-6°C and a salinity range of 30-33.5‰, and in the slope water, seaward of the front, temperature and salinity are 12-14°C and 35‰.

Physical forcing of the frontal regime imposes variability on a wide range of temporal and spatial scales. Over the shelf there is a mean drift of 3-6 cm s$^{-1}$ to the southwest (Beardsley et al., 1976; Butman et al., 1982). Wind stress will tend to move the upper layer of shelf water as a slab; the prevailing wind will move this slab to the northeast, opposite the mean drift. Wind events have a periodicity of 2-4 days (Beardsley et al., 1976) and thus the flow over the shelf, especially in the winter and spring, will consist of a series of reversals in an along-shelf direction with a weaker cross-shelf component superimposed on the southwest drift. The frontal region is subject to additional forcing of oceanic origin, primarily from Gulf Stream meanders and warm core rings. These are probably the source of frontal meandering.

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which has wavelengths of ~80 km (Beardsley and Flagg, 1976; Halliwell and Mooers, 1979; Mooers et al., 1979) and which propagates southwest along the shelf.

The impact of these physical forcings on phytoplankton dynamics in the region of shelf/slope front is not well understood (cf. Fournier et al., 1979). Neither are there enough data for the shelf break region in the Middle Atlantic Bight which might support the contention (Fournier, 1978) that shelf/slope fronts are sites of enhanced productivity. Three factors, therefore, motivated our collection of data on the surface distribution of chlorophyll $a$ and temperature at the shelf/slope front in the Middle Atlantic Bight. First, such data should provide a way to study detailed relationships between the distribution of physical properties and phytoplankton at the front. It is important to establish this relationship since it may provide clues to physical mechanisms responsible for the hypothesized high relative productivity. Second, intensive underway sampling programs of biological and physical variables at oceanic fronts are rare (cf. Herman and Denman, 1979). Thus, we would have the opportunity, hypothetically at least, to study further spatial distributions in chlorophyll under conditions of horizontal mixing not parameterized in present models relating phytoplankton biomass to the physical environment (Denman and Platt, 1977). Third, we hoped to characterize large-scale changes in the surface expression of the front. Although important phenomena occur over spatial scales of one to a few kilometers (e.g., Herman and Denman, 1979), these phenomena are difficult to evaluate without reference to larger scale frontal dynamics.

The data were obtained on cruise “SWIG I” aboard RV Eastward which took place from 21 March to 4 April, 1979. (The study area is shown in Fig. 1.) The cruise was designed as a joint biological and physical investigation of the front, and sampling was designed to observe chlorophyll $a$ and physical variable distributions at large (~100 km) and small (1-10 km) scales. Since temperature and salinity were strongly correlated for that time of year, temperature correlated directly with density and was adopted as the primary physical scalar. Following studies of Wright (1976) and Beardsley and Flagg (1976) we took the 10°C isotherm to denote the frontal boundary.

The results will be presented according to a length scale. The identification of this scale is somewhat arbitrary but is supported by examination of spatial heterogeneity of phytoplankton in coastal areas (Platt et al., 1977). Accordingly, large-scale variability is defined as encompassing the ~100 km wide area of the frontal region near the shelf break. Data collected at this scale include maps of the surface distribution of chlorophyll $a$ and temperature at the beginning and end of the cruise, and a series of transects coincident with a cross-shelf array of current meters to determine the vertical structure of the front and chlorophyll distribution. Transects along which surface mapping was done and the current meter line are shown in Figure 1. Medium scale variability is defined as that occurring on length scales of
Figure 1. The shelf-break region of the New York Bight south of Long Island, showing the transects comprising the surface maps and the NSFE79 current meter array (N1-N6). The first surface map, solid line, was completed at the beginning of SWIG I (21-22 March 1979). The second map (dashed line), end of SWIG I (1-2 April 1979). The small scale map (29 March 1979) (Figs. 5, 6) is shown as the dotted line. Isobaths indicate depth in meters.

10-50 km. Data at this scale consists of a surface map of a confined area near the front in which we were able to achieve finer resolution of surface variability than in the other two maps (Fig. 1). Small scales are defined at 1-10 km, the smallest lengths resolved by our measurement techniques. Results at this scale consist of detailed examinations of individual transects comprising the large-scale surface maps.

2. Methods

a. Underway sampling. The underway sampling system consisted of a fluorometer (Turner Design Model 10), a thermistor (Fenwal GV34MM 132, glassbead), a conductivity cell (Beckman CEL-VH10-T), bridge and amplification circuits, and a triple-x-time strip-chart recorder. The thermistor and conductivity cell were housed in a four-outlet PVC connector immediately after the fluorometer outflow. Seawater was supplied by the ships in-line seawater system (hull inlet at 2 m depth) and passed
through a bubble-trap before arriving at the sensors. The sensors were calibrated each hour. The thermistor was checked against a thermometer at the outflow. Water from the outflow was used to calibrate the conductivity cell against a Guildline Model 8400A Autosalinometer and to calibrate the fluorometer against another laboratory calibrated fluorometer. Calibration samples for chlorophyll $a$ were filtered through Gelman A/E glass fiber filters and were either processed immediately according to the method of Holm-Hansen et al. (1965), or the filters were frozen and processed within a few hours of collection.

**b. Physical measurements.** Vertical distribution of temperature, salinity, and dissolved oxygen was obtained from a Neil Brown Mark III CTD/O$_2$ system attached to a rosette with twelve 1.2 liter water samplers. Comparison with reversing thermometers (+0.01°C) and with bottle salinities analyzed on a Model 8400A Guildline autosalinometer (+0.005%) resulted in no correction to the CTD temperature and salinity values.

Our study area was situated adjacent to the Nantucket Shoals Flux Experiment (NSFE79), an array of current meters (N1-N6 in Fig. 1) deployed collectively by Woods Hole Oceanographic Institution, National Marine Fisheries Service, U.S. Geological Survey and the University of New Hampshire. This array produced a continuous time series of temperature and current velocity on a section across the shelf from 40-1000 m water depths.

**c. Other measurements.** Samples were drawn from the rosette Niskins for chlorophyll $a$ analysis by the method of Holm-Hansen et al. (1965) and for nitrate, phosphate and silicate according to Garside et al. (1976).

**d. Data reduction and spectral analysis.** Surface variables recorded on the strip-chart recorder (in millivolts) were digitized and stored on computer disk. These data were converted from engineering units and the various calibration relationships applied to obtain degrees C, mmhos, and chlorophyll $a$. This data set was subsampled for spectral analysis. We calculated a minimum sampling interval to be 5 m; the spacing between points for the purposes of analysis was 10 m. Conductivity data was not used in the final data analysis. However, the conductivity data proved valuable on a few occasions when electronic noise from the ship's radiotelephone interfered with the thermistor signal. During such times, the conductivity signal, which is a strong function of temperature, was used to regenerate the lost temperature data.

The spectral analysis programs were based on the fast Fourier transform algorithm (Bendat and Piersol, 1971). The data were detrended, and spectral coefficients averaged over five frequency bands to reduce the variance of the spectral estimates. For our purposes, the resulting wavenumber resolution was adequate. Although our transects were generally longer than is assumed prudent in studies of this kind
Figure 2. (a) Surface distributions of temperature (solid lines) and chlorophyll \(a\) (toned areas) for the first mapping (See Fig. 1). (b) Same as (a) but for the second mapping 12 days later. The easternmost leg on (b) is the NSFE79 current meter line.

(Platt and Denman, 1975) we chose not to split up the transects into shorter segments because of the way chlorophyll was distributed in the frontal region (see below). It took \(\sim 5\) h to complete a single transect, which given alongshore advection of \(\sim 5\) cm s\(^{-1}\) means that data for each transect are synoptic.

3. Results

\textit{a. Variability at large scale.} Surface temperatures on SWIG I ranged from 3-14°C in the frontal region (see Fig. 1), with the maximum temperature gradient occurring between \(\sim 8-12°C\). Surface chlorophyll \(a\) values typically ranged from \(<1-6\) \(\mu g\) \(l^{-1}\). Occasionally, values up to 25 \(\mu g\) chlorophyll \(a\) \(l^{-1}\) were recorded. Chlorophyll \(a\) measured by the underway sampling system was found to be proportional to chlorophyll \(a\) integrated over the top 30 m of the water column \((r^2 = 0.79)\).

The large-scale spatial distribution of surface chlorophyll \(a\) and surface temperature, based on data from the individual transects, is shown in Figure 2. At the
beginning of the cruise (Fig. 2a) the relative distributions of temperature and chlorophyll $a$ are complex. There is considerable alongshore variability in both chlorophyll $a$ and temperature and from this map apparently no relationship between areas of high values of surface chlorophyll $a$ ($>3 \mu g \, m^{-3}$) and gradients in temperature. Generally, however, chlorophyll $a$ ranges to higher values on the shoreward side of the $10^\circ C$ isotherm. Concentrations of chlorophyll $a$ exceeding $\sim 3 \mu g \, m^{-3}$ are $\sim 10-40 \, km$ wide in the cross-shelf direction.

Twelve days later (Fig. 2b), the distribution of surface temperature is much changed. In the northern portion of this map, the temperature gradients are reduced, and there is a broad area $\sim 60 \, km$ wide, of near isothermal water at $\sim 8-9^\circ C$, where previously (Fig. 2a) there existed sharper gradients and along-shelf variability. A sharp front at $9-14^\circ C$ now exists further offshore and is oriented in a more north-south direction than at the beginning of the cruise. (The position of this front was later verified by examining temperature distributions on the ocean frontal analysis maps supplied by the Naval Oceanographic Office.) Average surface chlorophyll $a$ concentrations by this time (Fig. 2b) are diminished, and near the $9-14^\circ C$ front, chlorophyll $a$ variability is considerably smoothed. Despite the offshore movement and re-orientation of surface isotherms $>9^\circ C$, however, some of the gross structure in surface chlorophyll $a$ remains unchanged. Areas of high chlorophyll are still located between $6-8^\circ C$. The center of the low chlorophyll ($<3 \mu g \, m^{-3}$) around latitude $40^\circ 20'N$ and longitude $70^\circ 20'W$ has moved westward only about $20 \, km$ in 12 days, corresponding to an apparent average current speed of $\sim 2 \, cm \, s^{-1}$.

Repeated hydrographic sections along the NSFE79 current meter array (Fig. 3) provide a record of the changing frontal structure at the shelf break and continuity between the two surface maps (Fig. 2). The frontal structure shown in Figure 3a is typical for this time of year (Beardsley and Flagg, 1976). The front is baroclinic and inclined seaward as it rises from the ocean bottom near the shelf break. The $10^\circ C$ isotherm is close to the historical mean for winter conditions (Wright, 1976). Chlorophyll $a > 1 \mu g \, m^{-3}$ occurs in the top $40 \, m$ and on the shoreward side of the front. Concentrations $>4 \mu g \, m^{-3}$ are found not at the front itself, but $30-60 \, km$ inshore.

Two days later (Fig. 3b) the frontal structure has changed markedly. The $8^\circ C$ isotherm has been displaced $\sim 50 \, km$ seaward, and at depths of $30-50 \, m$, the boundary has become flattened across the shelf break ($\sim 150 \, m$ isobath). By 1 April (Fig. 3c), two distinct temperature fronts have been established connected by nearly horizontal isotherms. The $8^\circ C$ isotherm, which marks the outer front, has moved back shoreward during the previous three days (cf. Fig. 3b).

Throughout the period 25 March-1 April, there has been no displacement of the $6^\circ C$ isotherm. Likewise the core of high chlorophyll $a$ at $\sim 40N$ in Figure 3 remains relatively stationary (cf. Fig. 2b). These facts suggest a divergence in the alongshore
Figure 3. Depth vs distance plots of temperature (left) and sigma-t (right) for the NSFE79 current meter line for three transects during SWIG I. Toned areas in temperature plots indicate shelf water. Chlorophyll a values are superimposed on the sigma-t plots; lightest tone corresponds to 1-2 µg 1⁻¹ and darkest is >4 µg 1⁻¹. No vertical chlorophyll a data were obtained for the plot shown in c where the toned areas here represent surface values from the easternmost leg of the second map (Fig. 2b) which coincides with this transect. The dashed line indicates the historical mean frontal position according to Wright (1976). Inverted triangles above each panel indicate the location of CTD stations.
flow field during this period. Although there were 2-3 day periods of strong winds (>10 m s\(^{-1}\)) during SWIG I, the timing and direction cannot account for these observed frontal movements. Also, the stability of the high chlorophyll \(a\) zones and the 6°C isotherm throughout this period are not consistent with the effects of wind.

Figure 4 shows a progressive vector diagram of the flow at the 10 m depth current meters at N4, N5, and N6. The positions of these current meters relative to the front are shown above Figure 3a. Overall (20 March-1 May) there is a strong lateral shear between N4 and N5, and N6, and alongshore convergence. However, an offshore flow is apparent for N6 from late March to 1 April (indicated by an arrow in Fig. 4) creating the divergence between N5 and N6. This divergence coincides with the time period shown in the hydrographic sections (Fig. 3). Cross-shelf velocities inferred from isotherm displacements in the hydrographic sections are consistent with direct current measurements. For example, the net movement of the 9°C isotherm between 26 March and 1 April gives an offshore velocity of \(\sim 4\) cm s\(^{-1}\), while the current meter record for N6 (10 m depth) for the same period gives an average offshore velocity of \(\sim 5\) cm s\(^{-1}\).

Warm core rings are apparent in the Naval Oceanographic Office frontal analysis maps for late March and early April, 1979, and are a probable cause of the advection recorded at N6. Although these rings have length scales on the order of 100 km, their boundaries are very sharp and they are capable of producing large lateral shears up to 40 cm s\(^{-1}\) (R. C. Beardsley, personal communication) and, apparently divergent flow over regions less than 10 km wide. Some of the surface chlorophyll variability at the beginning of the cruise (Fig. 2a) is smoothed out by the displacement of the front (Fig. 3), but the divergence between N5 and N6 (\(\sim 8°C\) isotherm) could explain why inshore much of the surface and vertical structure of the chlorophyll \(a\) distribution is relatively stable.

b. Variability at 10-50 km length scales. The large-scale changes in the surface front obscures an overall relationship between chlorophyll and vertical stability.
Chlorophyll $a$ concentrations are higher on the shoreward more vertically stable side of the front (Figs. 3a, 3b), but beyond that we have found no relationship between integrated values of chlorophyll $a$ and vertical gradients in sigma-$t$ or mixed layer depth for the frontal region as a whole (cf. Fournier et al., 1979). If there was an overall effect of water column stability, then one would expect to find the highest chlorophyll $a$ values very near the surface expression of the front, but this is not observed.

During the cruise we completed a smaller scale map (see Fig. 1) to characterize better variability between 6 and 10°C, where surface chlorophyll (based on the first large-scale map) was generally highest. This mapping occurred in an area about 40 km inshore of the surface expression of the front and was therefore largely unaffected by the cross-shelf divergence documented in Figure 3. CTD-0$_2$ casts were done at the ends of each of the long legs, and expendable bathythermographs (XBT's) were launched at approximately 10 km intervals. Making use of the high correlation between temperature and salinity for the mixed shelf/slope water, and the better spatial resolution compared to the large-scale maps, it was possible to estimate density from the XBT traces and to contour the spatial variations in density surfaces.

Figure 5 shows the variability of surface chlorophyll $a$ and surface temperature for this map, and Figure 6 isopleth of the depth of the 26.7$\sigma_t$ surface ($\sim$8.3°C). This $\sigma_t$ value was chosen because it marks the mixed layer depth near the front. Comparing Figures 5 and 6, surface chlorophyll $a$ is highest in areas where mixed layer depths are shallow. A regression between the depths to the 26.7$\sigma_t$ surface for each XBT and CTD station and the surface chlorophyll $a$ concentration at those stations produces a significant inverse relationship ($r^2 = 0.43, n = 28$). Since surface chlorophyll $a$ is indicative of total mixed layer values, these data suggest that for this area, variations in mixed layer depth contribute to the development of biomass gradients. For this relationship to hold in the Lagrangian sense, the variations in mixed layer depth must be persistent long enough for the surface patch structure to develop. A rough calculation, using an increase in chlorophyll $a$ from 1 to 6 $\mu$g $1^{-1}$ and an exponential growth rate of $\sim$0.5 day$^{-1}$ (see below), implies a persistence in features favorable to phytoplankton accumulation of $\sim$2-3 days.

Further support for the idea that variations in mixed layer depth contribute to biomass gradients at this spatial scale comes from examination of biological characteristics of the phytoplankton. Malone and Neale (1981) have reported that light-saturated chlorophyll specific photosynthesis ($P_{R_{\text{max}}}$) does not vary significantly between sampling locales on SWIG I. The $P_{R_{\text{max}}}$ data are from a large range (1-9 $\mu$g $1^{-1}$) of chlorophyll $a$ concentrations and a variety of temperatures (5-10°C) and nutrient concentrations (e.g., 1-20 $\mu$g at N $1^{-1}$). The lack of significant variation in $P_{R_{\text{max}}}$ suggests that variability in chlorophyll concentrations are not due to temperature- or nutrient-induced differences in phytoplankton growth.
Figure 5. Surface distributions of chlorophyll a and temperature for the small-scale map shown as the dotted line in Figure 1. Legend as in Figure 2a. This mapping was performed on 29 March, 1979.

c. Variability at 1-10 km. Selected transects from the first map (Fig. 2a) are shown in Figures 7 and 8. Here the greater complexity of the distributions which could not be shown in Figure 2 because of spatial-averaging, is revealed. For example, a finer scale variability is superimposed on regions of higher than average chlorophyll a concentrations (i.e., the >3 µg 1−1 area at 10-50 km distance along the transect in Fig. 7). The cross-shelf variability in chlorophyll seen in the large-scale maps thus contains additional structure at the 1-10 km length scale. Most of the highest chlorophyll concentrations occur between the 6 and 8°C surface isotherms, inshore of the surface expression of the front (10°C isotherm). As shown in the maps and vertical sections, this zone of high chlorophyll is bounded shoreward and seaward by areas where chlorophyll is relatively low. The temperature distribution shows the region to be dominated not by a single front, but by several smaller temperature discontinuities. On the basis of these transects, and as seen in the surface maps, there appears to be no simple relationship between surface temperature and chlorophyll a as suggested for example, in the data of Pingree et al. (1975).

A useful way to examine the variability in chlorophyll a and temperature distri-
Figure 6. Isopleths of the depth (in meters) of the 26.7σ, isopycnal to be compared with the surface distributions of chlorophyll a shown in Figure 5. Closed circles are locations during the mapping where XBT's were launched, and open circles are CTD stations.

butions in detail is to compute variance spectra of these two variables, whereby the total variance on a particular transect is partitioned according to wavenumber. Thus the transects and variables may be more easily compared by means of a few characteristics of the spectrum. Also, spectral analysis can be used as an interpretative tool. The relative relationships between the variance of chlorophyll and temperature at particular scales can help determine whether distributions at those scales are under the control of biological or physical phenomena (Platt and Denman, 1975). According to Denman (1976), where variance spectra of chlorophyll a and temperature are similar, it is possible to infer a common source of variability. Since the distribution of temperature variance is determined by physical processes, agreement in the shapes of variance spectra for chlorophyll a and temperature are interpreted as evidence for physical processes as a common source of variability for those length scales, whereas differences are attributed to biological sources of variability.

As an example, Figure 9 shows temperature and chlorophyll a variance spectra for the transect pictured in Figure 7. Despite detrending, both temperature and
Figure 7. Temperature (T, °C) and chlorophyll a (C, µg l⁻¹) variations with distance (km) for leg 1, the westernmost leg of the first map (Fig. 2a). Only 69 km of the total of 93 km are shown here.

Figure 8. Same as Figure 2, for the fourth leg of the first map. (Note different distance scale and chlorophyll scale). The temperature change from ~38-45 km was computed from conductivity data.
chlorophyll spectra are 'red', that is most of the variance occurs at low wavenumbers, or at large scales. Variability at high wavenumbers (>0.5 km\(^{-1}\)), on the other hand, contributes little to the total variance. Typical for the spectra computed for SWIG I is the presence of a significant \((P < 0.05)\) peak at wavelengths of \(~1-5\) km in the chlorophyll variance spectrum, with no corresponding peak in the temperature spectrum. Pre-whitening the data before running the spectral analysis (labelled "P" in Fig. 9) de-emphasizes the large-scale variance so these peaks are more easily discerned.

The significant chlorophyll variance peak at the 1-5 km scale suggests a preferred scale of chlorophyll variability. This preferred scale arises from the difference between biological processes (i.e., growth) which produce chlorophyll and physical processes which dissipate it. These peaks can be evaluated in terms of the theoretical spectrum developed by Denman et al. (1977) where a maximum variance in wave-
number space ($k_m$), identified as a preferred scale for chlorophyll variance occurs at

$$k_m = \left[ \frac{6re^{-0.33}}{5} \right]^{1.5}$$

(1)

where $r$ is the rate of growth of phytoplankton and $\epsilon$ is the dissipation rate of turbulent energy.

Given average assimilation ratios for surface samples from SWIG I (Malone and Neale, 1981) and the carbon: chlorophyll ratios measured, an average doubling time on the order of a day or an exponential growth rate of $\sim 0.8$ day$^{-1}$ can be calculated (after Eppley, 1972). This is probably a maximum value; euphotic zone-averaged growth rates because of the lower averaged irradiance are probably much less. Assuming therefore, a phytoplankton growth rate of 0.5 day$^{-1}$, and with $\epsilon$ as $10^{-7}$-$10^{-9}$ m$^2$ s$^{-3}$ (Denman et al., 1977), Eq. (1) gives a $k_m$ range of 4-0.4 km$^{-1}$ or $\sim 0.2$-2 km. This is slightly low, but is otherwise roughly consistent with the maxima observed in the chlorophyll spectrum shown in Figure 9. The fine-scale peaks on the transects are on average $\sim 2$ km. Aside from the fact that $\epsilon$ cannot be further constrained, the lack of precision in the estimate of $k_m$ comes from the low number of bands chosen to smooth the spectral estimates. Greater bandwidth resolution, however, means a noisier spectrum (see Platt and Denman, 1975). Also, there are uncertainties and systematic errors in estimating $r$. Choosing the maximum calculated value increases $k_m$ to $\sim 0.5$-5 km.

The above calculation of preferred patch sizes for chlorophyll $a$ is for transect data from before the large-scale displacement of the front (Fig. 3).

4. Discussion

For March and early April on the continental shelf of the New York Bight, Walsh et al. (1978) report that zooplankton biomass is relatively low and that nutrient levels are not yet depleted. We did not make zooplankton observations, although nitrate, phosphate, and silicate data for SWIG I agree with that assessment. For example, nitrate-nitrogen which becomes undetectable later in the season (Walsh et al., 1978) was typically 6, and never less than 1 µg-at l$^{-1}$ at the surface in shelf and slope water alike. In the absence of grazing and nutrient depletion, therefore, mechanisms which maintain phytoplankton in the euphotic zone will lead to accumulation of biomass. The shelf/slope front, with its inclined isopycnals near the surface, would provide stability and favor development of enhanced biomass levels. Broadly speaking, this analysis holds for the results from SWIG I. Chlorophyll $a$ concentration ranges to higher values on the shoreward side of the shelf/slope front (Figs. 2, 3), and areas where surface chlorophyll is low on that side co-occur with areas exhibiting deep mixed layers (Figs. 5, 6).
However, the evidence that vertical stability is an important factor comes only from observations for a locale a considerable distance inshore of the surface expression of the front. The fact that nutrients are not depleted argues against there being an optimal vertical stratification, as suggested by Pingree et al. (1975), where stability is sufficient to maintain a population in the euphotic zone but not great enough to prevent the vertical flux of nutrients to an otherwise nutrient-depleted surface layer. Instead, what obscures any possible overall relationship between vertical stability and depth-integrated or surface chlorophyll $a$ in the region of the front is the dominance of large-scale events, perhaps abetted by variability at small scales. At large scales, the temporal alongshore variability of the front (Figs. 2, 3) can prevent the development of phytoplankton blooms, even though on any one transect across the front, vertically, conditions appear favorable.

Superimposed on the 10-50 km surface chlorophyll patch structure is a smaller scale variability, (Figs. 7, 8) which being consistent with a theory of chlorophyll fluctuation in the sea (Denman et al., 1977) probably arises from phytoplankton growth. To our knowledge this is the first observational evidence supporting that theory.

While it is clear from Figures 2 and 3 that, for SWIG I, large-scale displacements of the front are most important to the biological dynamics, as yet, processes leading to the on- and off-shore movements of the front are difficult to evaluate in general. First, although eddy-induced distortions of the front ($\sim$3-6 yr$^{-1}$ according to Halliwell and Mooers, 1979) observed on SWIG I would be rare events given the time scale for phytoplankton blooms, there are perturbations of the front occurring from week to week with cross-frontal amplitudes of 10-50 km (Voorhis et al., 1976; Beardsley and Flagg, 1976; Flagg, 1977). Presumably these perturbations are forced by local winds or by low frequency energy propagating onto the shelf from the deeper ocean. Second, the detailed interaction of the front to external forcings is not sufficiently well known that its effect on the distribution of phytoplankton can be predicted. Third, the response of the front to external forcing will necessarily change as the front progresses from the baroclinic winter-spring structure to the density-compensated thermohaline front characteristic of summer.

The variability of the surface expression and vertical structure of the front can be compared to other frontal systems. On the Scotian Shelf, for example, in addition to alongshore variability documented here, large-scale slope water intrusions onto the shelf have been implicated in altering the vertical structure of the shelf/slope front with drastic consequences for phytoplankton production (Fournier et al., 1979). In contrast, in tidal fronts at the approaches to the English Channel, the relatively stable conditions and regularity of tidal cycles produce more of an equilibrium situation with phytoplankton occupying a zone, in the front, between highly stable and vertically mixed regimes (Pingree et al., 1975).

To summarize our results, first, we have been able to separate to a fair degree,
variability arising from physical and biological sources. Overall variability in chlorophyll \( a \) in the region of the shelf/slope front can only be interpreted with reference to large-scale frontal dynamics. In the absence of large-scale displacements of the front, there is evidence that variations in mixed layer depth contribute to large-scale (10-50 km) variability in chlorophyll \( a \). On the other hand, small-scale variability (1-10 km) in chlorophyll can be attributed to phytoplankton growth.

Second, we now have greater perspective on how the front influences productivity in the shelf break region in a seasonal context. Our results show that for the winter-spring months before nutrients have been depleted from the surface layer, water column stability is important and there is no need to involve some elusive mixing mechanism or cross-frontal exchange process to account for variations in productivity across the front. Later in the season, after nutrients have been depleted in the surface layer but before the front loses its density contrast, tidally-driven intrusions of slope water onto the shelf, documented by Herman and Denman (1979), may be important mechanisms for nutrient enrichment. Still later in the season, when the front is thermohaline, diffusive fluxes become factors in determining the distribution and variability of phytoplankton biomass (Houghton and Marra, in preparation). The variety of physical phenomena and forcings will have to be better understood, before it is possible to make an assessment of the importance of the shelf-break region to annual continental shelf primary production.

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