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Space-time structure of a continental shelf ecosystem measured by a towed porpoising vehicle

by Kenneth L. Denman^{1,2} and Alex W. Herman²

ABSTRACT

During August, 1975, an experiment was carried out in the eastern Gulf of Maine with the Batfish, a towed undulating body, on which were mounted an *in situ* fluorometer and a conductivity-temperature-depth probe. The Batfish cycled between depths of about 4 and 40 m with a cycle length of order 0.6 km. Six transects were completed, five along and one across the continental shelf, giving a picture of the space-time structure of the chlorophyll, temperature and salinity fields. An anomaly of relatively high chlorophyll concentration, with a linear dimension of order 10 km, persisted in a lens of warm light surface water for 6 days, the duration of the experiment. The anomaly was advected back and forth by the tide and was spreading horizontally. Although maximum chlorophyll values in the anomaly were decreasing, salinities were increasing, suggesting that deeper waters were rising to the surface possibly as a result of the local upwelling thought to be driven by the tidal currents. T-S analysis shows that much of the water at the base of the anomaly was derived from Slope Water, known to be nutrient-rich, that flows periodically at depth from the Atlantic Ocean through the Northeast Channel into the basins of the Gulf of Maine. During the observations this water apparently had risen onto the continental shelf where it was being mixed with waters more characteristic of the surface layer.

1. Introduction

A considerable effort in recent years has been focussed on the influence of physical processes on the organization and functioning of the marine ecosystem. In such studies, for example those of patchiness or of upwelling systems, the investigators have attempted to marry theory with observations, but with limited success. In studies of phytoplankton patchiness (see, for example, the review by Platt and Denman, *in press*), theoretical models that relate the patchiness to turbulence or to grazing assume horizontal homogeneity over scales to hundreds of kilometers, an assumption not borne out by observations. In studies of upwelling ecosystems, present simulation models (e.g., Wroblewski, 1977; Walsh, 1975), although they may be driven or forced by time-dependent hydrographic models based on observations, are

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not directly validated with matching biological observations. Rather, the observations are usually interpreted separately (e.g., Walsh *et al.*, 1974, 1977; Kelley, 1975).

Further progress in coupling models and observations is hampered by our inability to obtain three-dimensional synoptic data sets that can be repeated to give time series. Such data sets must not only extend over many tens of kilometers, but they must also retain sufficient resolution to discriminate structure on the patchiness scales (~ 1 to 10 km). Recently, at least two vehicles have been developed that will undulate along a sawtooth pattern in the vertical plane when towed from a moving ship. When equipped with appropriate sensors, they have the potential to acquire the multidimensional data necessary to study the structure and interactions in the marine ecosystem and its environment. One of these, the Undulating Oceanographic Recorder (UOR), designed to be towed by "ships of opportunity", can traverse a pattern that repeats every 3 to 30 km (Bruce and Aiken, 1975; Aiken *et al.*, 1977).

The other vehicle is the Batfish (Dessureault, 1976). It can traverse a pattern that repeats every 0.3 to 3 km, enabling the resolution of scales of 1 to 10 km. We (Herman and Denman, 1977) have demonstrated the capability of the Batfish as a research tool when equipped with a CTD probe and an *in situ* fluorometer. The fluorometer, used to measure phytoplankton chlorophyll, was a Variosens model (Impulsphysik GmbH, Hamburg, West Germany) modified to give a rapid response time (~ 0.3 s) with minimum noise fluctuations. The lower detection limit varies between 0.1 and 0.5 mg m^{-3} according to the calibration for relative fluorescence per unit of extractable chlorophyll. The CTD probe, a prototype of the model 8700 digital model now manufactured by Guildline Instruments (Smith Falls, Canada), has accuracy specifications of $\pm 0.01\%$, $\pm 0.01^\circ\text{C}$ and ± 1 dbar for the conductivity, temperature and pressure sensors.

In this paper, we use data acquired with the Batfish equipped as in Herman and Denman (1977) to explore the biological and physical structure in a dynamic continental shelf region whose physical oceanography is characterized by large amplitude tidal currents, internal waves, rough bottom topography and local upwelling. We do not expect unequivocal answers. Rather we will demonstrate that the Batfish system allows us to gain a new perspective on the processes acting in such a complex biological/physical region.

2. The eastern Gulf of Maine

The experiment was conducted during August, 1975, over the continental shelf in the eastern Gulf of Maine adjacent to the western end of Nova Scotia (Fig. 1). The general circulation of the Gulf of Maine, first treated extensively by Bigelow (1927), has been reviewed recently by Bumpus (1973). The surface flow in the Gulf of Maine is dominated by a slow cyclonic (counterclockwise) eddy with speeds on its outside margins reaching values of order 15 cm s^{-1} during the spring. Bigelow

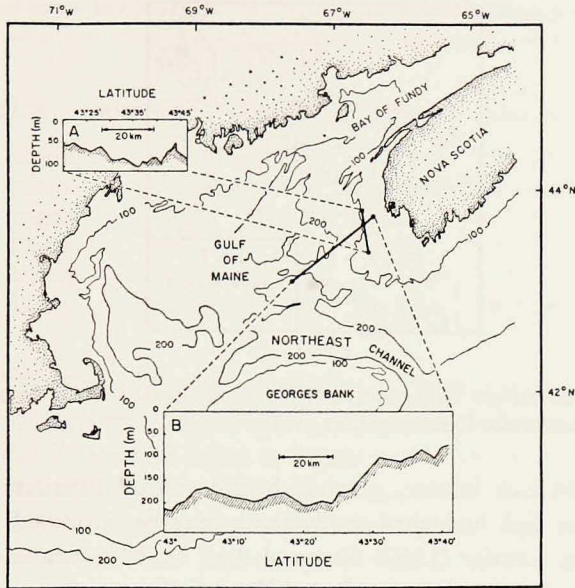


Figure 1. Chart of the Gulf of Maine showing the Batfish transect lines with bottom topography. Yarmouth, N.S. is located by the solid square.

(1927) found evidence that, during spring and summer months, low temperature water from the Nova Scotian shelf often flows around the southern tip of Nova Scotia, then northwards into the Gulf of Maine. This flow into the Gulf of Maine eddy was also suggested by Bumpus and Lauzier (1965) who estimated northerly speeds averaging 6 cm s^{-1} from surface drift bottle data. Another important aspect of the general circulation of the Gulf of Maine is the exchange of subsurface waters with the Atlantic Ocean through the deep Northeast Channel (Fig. 1). Bigelow (1927) suggested that such exchanges are episodic; data of Pawlowski and Schlitz (personal communication) indicate a time scale of days or weeks, possibly corresponding to atmospheric events.

The Bay of Fundy/Gulf of Maine basin is also the site of the world's highest observed tides (Neumann and Pierson, 1966). As a result, the tidal currents in the area of our observations have an amplitude of about 1 m s^{-1} and a direction roughly parallel to the coast of Nova Scotia (Greenberg, 1977 and in press). Hence, intense tidal mixing may be expected. The modulation of the intensity of tidal mixing by variable bottom depth in shallow seas results in areas of well-mixed and stratified waters separated by frontal discontinuities (Simpson and Hunter, 1974; Fearnhead, 1975); such effects are relevant in the eastern Gulf of Maine and are currently under investigation (C. Garrett, personal communication).

The waters off the southwest end of Nova Scotia are interesting biologically be-

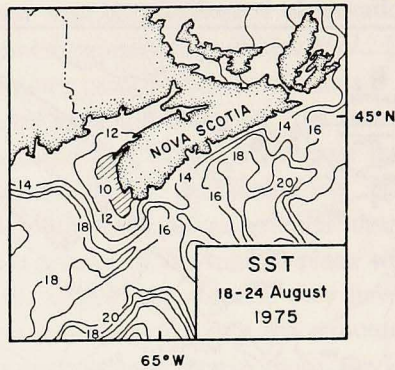


Figure 2. Map of sea surface temperatures (SST) for the period 18-24 August 1975. Prepared by Canadian Forces Metoc Center, Halifax, N.S.

cause they contain rich lobster, groundfish and scallop fisheries (Brinkhurst and Hord, 1976). This high biological productivity may be attributed, at least in part, to local upwelling. Lauzier (1967) observed that, over the whole continental shelf region off western Nova Scotia, sea bed drifters indicate a shoreward bottom convergence of approximately 2 cm s^{-1} consistently throughout the seasons. The consequent upwelling along the coast, coupled with tidal mixing in shallow areas, results in a pronounced region of anomalously low sea surface temperature at the western end of Nova Scotia, especially during the late summer. The dashed area in Figure 2 shows that such a regime existed during our observations. Garrett and Loucks (1976) argued that the upwelling mechanism is similar to the centrifugal effect that induces a secondary circulation as a river flows round a bend. Unlike upwelling driven by the Coriolis force, centrifugal upwelling would be produced by currents flowing in either direction along the coast, a condition well-suited to the strong tidal currents observed in the region.

3. Calibration data

Our experiment consisted primarily of a set of Batfish transects carried out during the period 25-30 August, 1975. During the transects, a submersible pump was towed at roughly 3 m depth to obtain chlorophyll calibration samples, and between the transects validation data were obtained for an airborne remote sensing experiment and have been published separately (Denman *et al.*, 1977b). They included vertical profiles with the towed pump, vertical profiles with an attenuation meter (Larsen, 1973) and with a meter that measured downwelling and upwelling irradiance, and Secchi depths.

At sea the Variosens fluorometer can only be calibrated indirectly: water samples for chlorophyll extraction are obtained by means of a towed pump at roughly regular intervals along the transects (Herman and Denman, 1977). During the period

Table 1. Summary of times and positions for the Batfish transects. Times are in Atlantic Daylight Time. (Solar noon is at 1326 ADT at the intersection of lines A and B).

Transect	Date	Start		Stop		Mean Speed (m s ⁻¹)
		Time	Latitude	Time	Latitude	
A ₁	25 August	1740	43°27'N	2040	43°45'N	3.1
A ₂	26 August	1925	43°22'N	2235	43°45'N	3.8
A ₃	27 August	1440	43°27'N	1820	43°48'N	3.0
A ₄	28 August	2030	43°43'N	2355	43°18'N	3.8
A ₅	30 August	0600	43°52'N	0935	43°26'N	4.0
B	29-30 August	1900	43°00'N	0355	43°40'N	3.4

25-30 August, 1975, the extracted chlorophyll *a* from the phytoplankton was linearly related to fluorescence measured on a Turner 111 fluorometer coupled to the towed pump. For 72 samples taken at depths from 2 to 18 m, the linear correlation coefficient was 0.945. The chlorophyll:fluorescence relationship was even more constant on a single transect: for the 5 transects along line A, the mean correlation coefficient was 0.988 for an average 12 samples per transect. The mean standard error of the estimate was 0.30 mg m⁻³. No dependence of the chlorophyll:fluorescence relationship on depth was found.

4. Spatial observations

The dates and times of the Batfish transects are summarized in Table 1; line A in Figure 1 was completed 5 times, and line B once. The obvious method for displaying Batfish data is by drawing isopleths of each parameter on a section of depth against horizontal distance. Such a plot for chlorophyll *a* concentration and specific density (expressed in sigma-t units) is shown in Figure 3 for the second transect of line A (designated section A₂). High concentrations of chlorophyll *a* (~5 mg m⁻³) appear in a lens of light surface water between 43°35' and 43°40'N. Lighter water also occurs at the northern end of the transect in shallower water (see Fig. 1), but it is less stratified and supports much lower (<2 mg m⁻³) concentrations of chlorophyll *a*. Throughout the transect, but especially in the stratified central portion, large vertical undulations occur with typical amplitudes of about 15 m and typical wavelengths of about 2 km. These undulations do not result from the response characteristics of the instruments; rather, they probably result from internal waves.

From the high degree of linearity in the chlorophyll:fluorescence relationship, we have confidence that the observed chlorophyll variations were real. Further evidence is obtained by comparing extracted chlorophyll values directly to the Batfish derived values. During transect A₂ for example, duplicate samples were taken from the pump towed at 2.5 m at two positions indicated by the solid circles in Figure 3 (representing areas of relatively high and low chlorophyll concentrations but with small horizontal gradients to make the comparisons more valid). The extracted

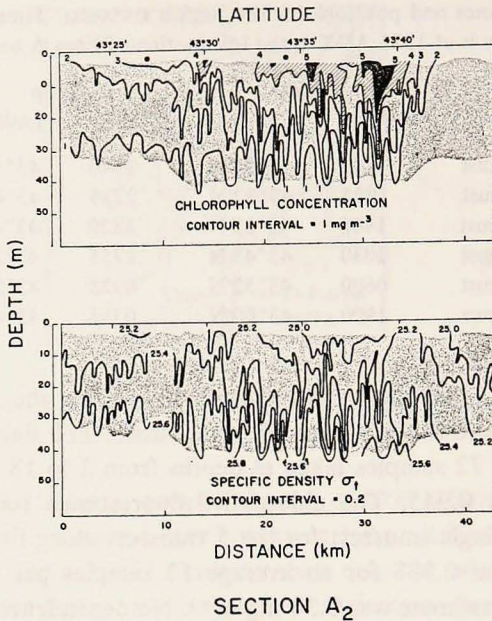


Figure 3. Contour plots of chlorophyll *a* concentration and sigma- t on graphs of depth against distance for transect A₂. The shaded area represents the limits of the Batfish cycling. There were 80 cycles or 19 every 10 km. The solid black areas in the upper panel represent chlorophyll concentrations between 5 and 6 mg m⁻³ and two solid black circles near the surface indicate positions of duplicate extracted chlorophyll *a* samples.

chlorophyll *a* concentrations were 3.6 mg m⁻³ at 43°27'N and 4.5 mg m⁻³ at 43°34'N, in good agreement with the Batfish values, especially as the minimum depth of the Batfish cycling was about 4 m.

Equivalent plots to those in Figure 3 for the first transect of line A (section A₁) one day earlier (Table 1) were displayed for temperature and salinity as well as chlorophyll and sigma- t in Figure 9 of Herman and Denman (1977). The pronounced undulations also dominated that transect, and were present in all four parameters. Both the warm surface lens with its characteristic high chlorophyll concentration and the large undulations were evident in all 5 transects along line A.

Larger scale patterns in the data, such as the area of high chlorophyll concentration in Figure 3, tend to be confounded or masked by the shorter scale vertical undulations. If the undulations result from internal wave-like displacements, then isopleth plots with sigma- t rather than depth as the vertical coordinate should show the larger scale features more clearly. In Figure 4 we have plotted for section A₂ isopleths of chlorophyll *a* concentration, temperature and salinity all on graphs of sigma- t against horizontal distance. One can readily see that the kilometer-scale vertical undulations are much reduced; now they show up as a highly variable posi-

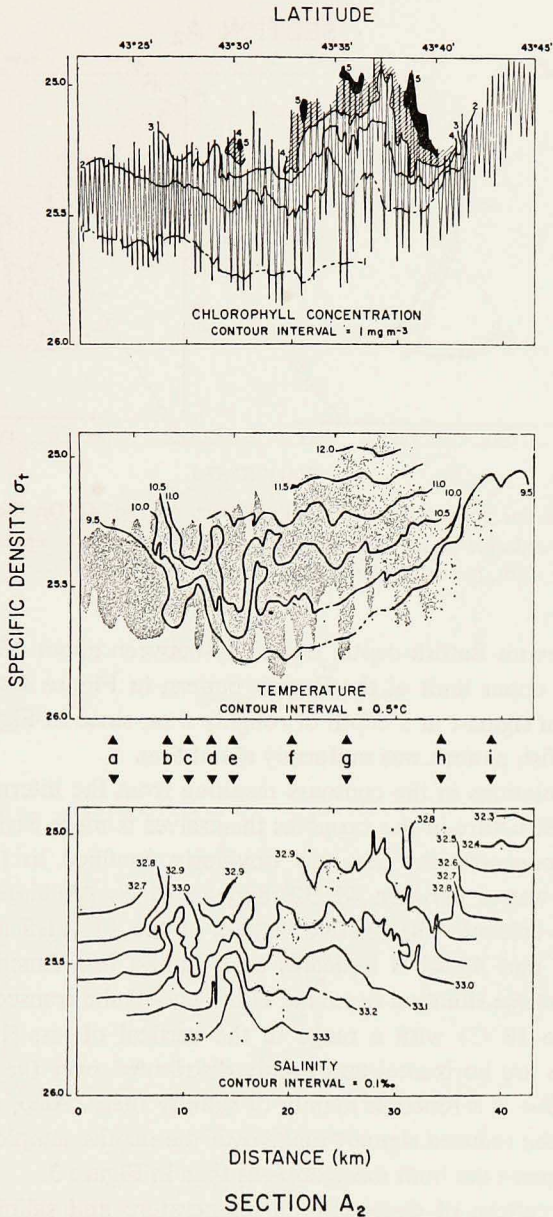


Figure 4. Contour plots of chlorophyll, temperature and salinity on graphs of sigma-t against distance for transect A₂. The sawtooth pattern in the upper panel represents the Batfish track. The depth of the 1% surface light level (where a phytoplankter's photosynthesis and respiration rates are roughly equal, Parsons and Takahashi, 1973) varied from about 20 m at the ends of the transect to less than 10 m in the center where the surface chlorophyll was a maximum. These depths were estimated from the light attenuation measurements given in Denman *et al.* (1977b).

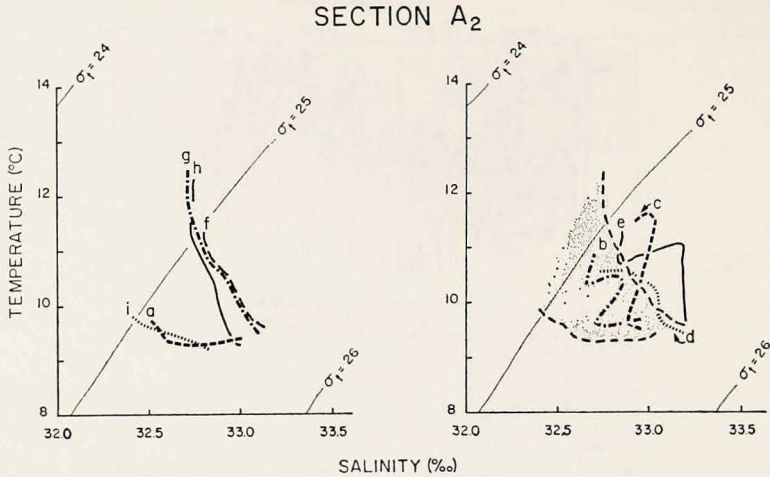


Figure 5. T-S plots for positions *a* to *i* along transect A (Fig. 4). On the left, profiles *a* and *i* represent the boundaries of the anomaly and profiles *f*, *g* and *h* represent the center of the anomaly. On the right, the other profiles are plotted.

tion of the maximum Batfish depth, especially between about $43^{\circ}27'$ and $43^{\circ}40'N$. In addition, the upper limit of the Batfish pattern in Figure 4 traces out the horizontal gradient in sigma-t at a depth of roughly 5 m, since in Figure 3 the minimum depth of the Batfish pattern was uniformly about 5 m.

With the undulations in the contours resulting from the internal waves no longer so pronounced, structure in the variables themselves is more easily visible. The high chlorophyll *a* concentrations are now obviously confined to the "dome" of low sigma-t surface waters between $43^{\circ}32'$ and $43^{\circ}41'N$. A chlorophyll "front" near $43^{\circ}42'N$ is also evident. The relative flatness of the 11, 11.5 and $12^{\circ}C$ isotherms between $43^{\circ}32'$ and $43^{\circ}41'N$ indicates that sigma-t is a function mainly of temperature. The reverse situation occurs at either end of the transect: the temperatures are cooler (9 to $10^{\circ}C$) with a range in the vertical of less than $0.5^{\circ}C$, and the salinity contours are horizontal and evenly distributed over the sigma-t range indicating that sigma-t is a function mainly of salinity there. Also, at the northern end of the transect, the reduced sigma-t range over the depths sampled and the relatively low values of sigma-t are both more obvious than in Figure 3.

The striking pattern of distortions in temperature and salinity (but not chlorophyll) between $43^{\circ}26'$ and $43^{\circ}33'N$ in Figure 4 is rather unexpected since horizontal lines now represent levels of constant density. As these distortions are therefore density-compensated, they probably are indicative of horizontal, rather than vertical, intrusions.

The contrast in the physical characteristics between the edges of the transect and the high chlorophyll central region can best be illustrated by plots of temperature

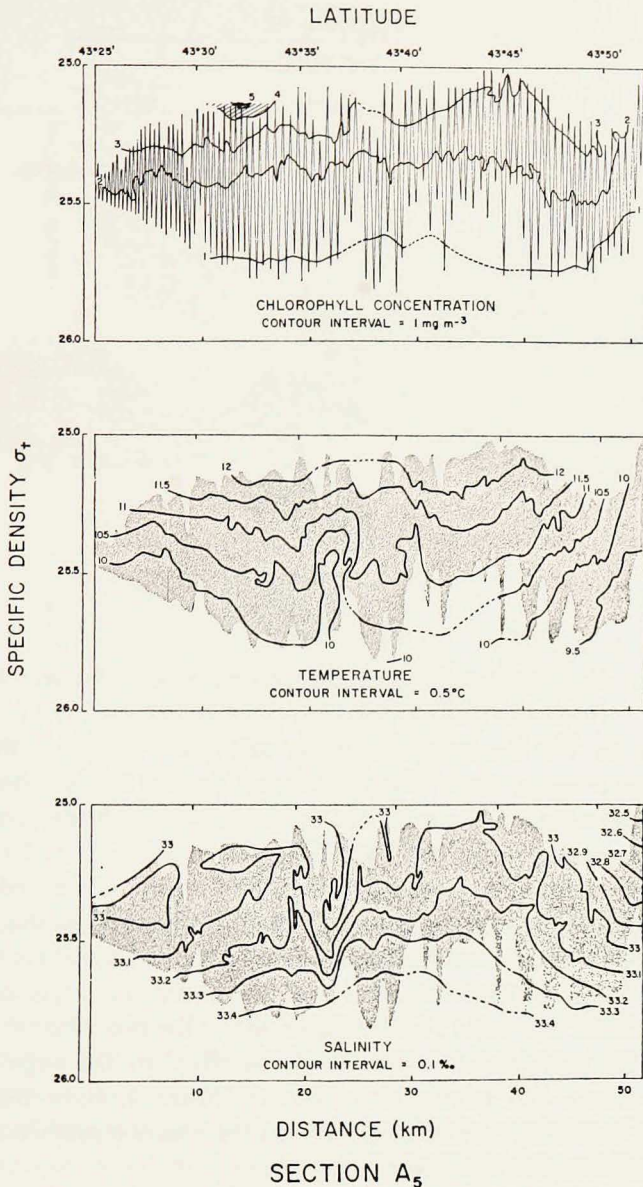


Figure 6. Contour plots of chlorophyll, temperature and salinity on graphs of sigma-t against distance for transect A₅.

versus salinity (T-S curves) for selected points along the transect. T-S curves for Section A₂ are shown in Figure 5, each created from half a Batfish cycle at the points along the section labelled *a* to *i* in Figure 4. In the left-hand plot, curves *a*

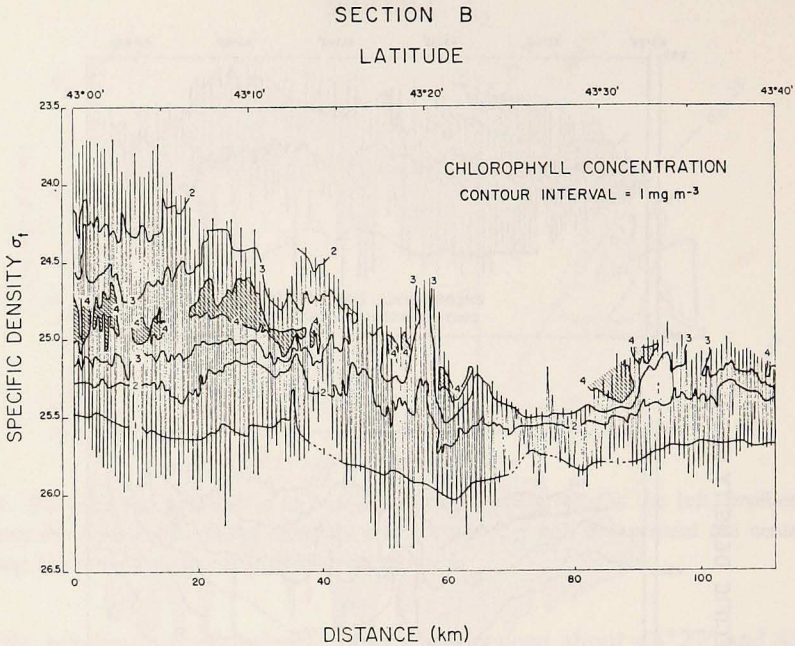


Figure 7. Contour plot of chlorophyll on a graph of sigma-t against distance for transect B.

and *i* represent the T-S characteristics of the well-mixed waters at the south and north ends of the transect. Both curves are almost parallel to the salinity axis, and curve *i* is displaced toward lower salinities, consistent with its being farther from the open ocean. Curves *f*, *g* and *h* are located in the stratified central region of the transect: they show the surface waters there to be warmer, saltier and lighter than the waters near the ends of the transect. In the right-hand plot, the dashed lines represent the T-S characteristics inside and outside of the anomalous water, as defined by the curves in the left-hand panel, and the shaded area represents the range of T-S characteristics that could result from mixing of the two water masses. Curves *b* to *e*, taken from that part of section A_2 characterized by the large density-compensated temperature and salinity distortions in Figure 4, show that water was present at some depth with higher salinities than the waters characterized by any of the more regularly-shaped T-S curves.

Isoleth contours on graphs of sigma-t versus distance have also been plotted for section A_5 in Figure 6. Plots of the section on depth-distance graphs are not shown, but the Batfish pattern was similar to that for Section A_2 (Fig. 3). The general characteristics of the plots are similar to Figure 4, but the surface chlorophyll *a* concentrations are lower, the high chlorophyll lens has shifted to the south and is spread over a larger portion of the transect, and the minimum sigma-t is not as low as for section A_2 (25.0 compared to 24.8). Subsurface distortions of the temperature

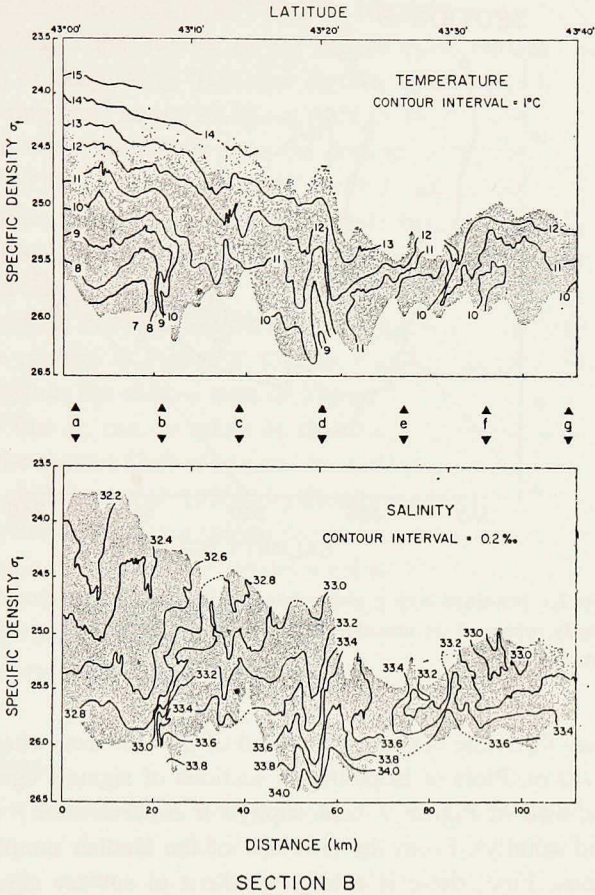


Figure 8. Contour plots of temperature and salinity on graphs of sigma-t against distance for transect B.

and salinity contours again occur (between 43°34' and 43°40'N) with no corresponding distortions in the chlorophyll data (see the 2 mg m⁻³ contour of chlorophyll concentration, for example).

The region of high surface chlorophyll concentration could be identified on all 5 transects along line A. As it was associated with the highest surface temperatures and salinities along the line and tended to be bounded by zones with high horizontal temperature gradients, it is convenient to refer to it as an anomaly for the rest of the paper. Repeated transects along a single line cannot of course confirm that the anomaly was an identifiable parcel of water. To determine its extent perpendicular to the coastline, we made one transect offshore to onshore along line B (Fig. 1) immediately before doing section A₅ (Table 1). The Batfish cycling pattern was uniform over most of the line between depths of 6 m and 50 m, except for 2 sections

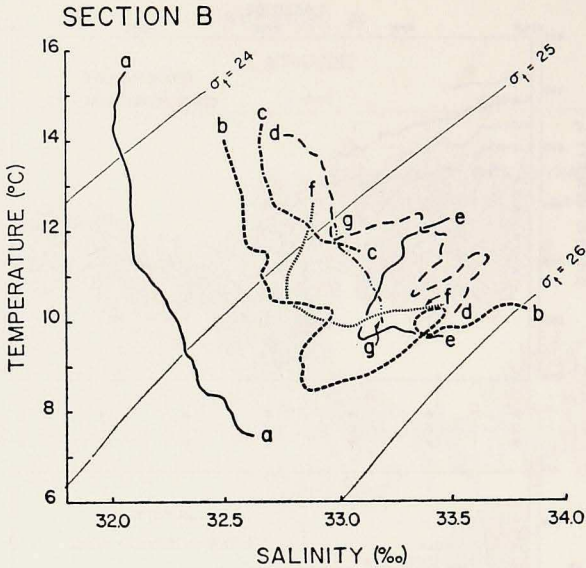


Figure 9. T-S plots for positions *a* to *g* along transect B (Fig. 7). The closed loop on profile *b* does not necessarily represent an unstable inversion as the Batfish travels obliquely, not vertically, through the water.

of about 5 km length, at the beginning and end of the transect, where the maximum depth was only 40 m. Plots of isopleths on sections of sigma-t against distance for transect B are shown in Figure 7 (chlorophyll *a* concentration) and in Figure 8 (temperature and salinity). From the envelope of the Batfish sampling pattern, two points are obvious. First, there is a large gradient in surface sigma-t from about 23.7 at 43°N to 25.5 at 43°26'N. Inshore from that is a dome of lighter surface water. Since line B intersects line A at 43°38'N, we interpret this water to be the same light surface water found in Figures 3, 4 and 6. Second, the density range over depth varies from over 2 sigma-t units between 43° and 43°05'N down to about 0.25 units at 43°26'N. The vertical density gradient over the upper 50 m, then, varies by about a factor of 8 in a distance of only 60 km.

The chlorophyll *a* section of Figure 7 can be divided into two regions. Inshore of 43°25'N, the higher chlorophyll concentrations are found in the light, warm surface waters, as they were in Figures 4 and 6 near the center of line A. Offshore of 43°25'N however, a subsurface chlorophyll maximum layer, typical of open temperate waters during summer, is shown between 24.5 and 25.0 sigma-t units. On depth-distance sections this layer corresponds to the bottom of the seasonal thermocline (or pycnocline) between depths of about 15 and 20 m.

In Figure 8, the near-surface temperature decreases from about 15.5°C at 43N to about 10°C at 43°30'N. The vertical range of temperature, 10C° (6.5° to 15.5°C)

at $43^{\circ}05'N$, decreases to only $0.5C^{\circ}$ (9.5 to $10.0^{\circ}C$) at $43^{\circ}30'N$; there, the $10^{\circ}C$ isotherm, often below the bottom of the Batfish cycle pattern, rises almost to the minimum depth of the cycling. The near surface salinity also has a large horizontal gradient, increasing from about 32.1‰ at $43N$ to 33.7‰ at $43^{\circ}22'N$. Strong frontal regions occur in both parameters near the bottom of the sections at about $43^{\circ}08'$, $43^{\circ}20'$ and $43^{\circ}30'N$. As in Figures 4 and 6, the 1 and 2 $mg\ m^{-3}$ contours of chlorophyll concentration near the bottom, and hence below the 1% surface light level (10 to 20 m depth), do not reflect at all the high horizontal gradient structure in temperature and salinity.

T-S curves formed from the Batfish data of section B at the points labelled *a* to *g* in Figure 8 are plotted in Figure 9. Curves *f* and *g*, located within the anomaly, would also lie within the shaded area of Figure 5. Curve *a*, located at the extreme offshore end of line B, can be taken as characteristic of the summer surface layer (0 to 50 m) in the eastern Gulf of Maine. According to an interpretation of the summer 1966 data of Colton *et al.* (1968) by Hopkins and Garfield (personal communication), curve *a* lies within an envelope designated as Maine Surface Water (MSW). Progressing from *a* to *g*, the water becomes saltier but less stratified. Curves located in zones of pronounced temperature and salinity structure (*b*, *d* and *e*), are themselves more structured, and (in common with Fig. 5) have the highest salinities (and largest salinity ranges) anywhere along the transect.

5. Temporal changes

From the data presented in the previous section, a picture has emerged of an anomaly of warm light water, with a linear dimension of order 10 km, sitting in the upper 20 m of the ocean adjacent to western Nova Scotia. This anomalous water persisted in roughly the same geographic position for at least a week, supporting surface chlorophyll *a* concentrations up to $6.9\ mg\ m^{-3}$ (Denman *et al.*, 1977b), relatively high for the region during summer. Going offshore, a narrow region of well-mixed water separated the anomaly from warmer highly stratified surface waters typical of the central Gulf of Maine.

The strong horizontal gradients observed in temperature, salinity, and, especially, surface sigma-t suggest that the structure was not static, however. To obtain some information on the temporal changes in the system and possibly on the dynamic processes operating, we have attempted to map, from the 5 transects A_1 to A_5 , the position of the anomaly along line A as a function of time. In the upper two panels of Figure 10 selected isopleths of salinity and chlorophyll *a* concentration at 5 m depth are plotted. On the vertical axis, the position along line A, and on the horizontal axis, the time at which the ship passed $43^{\circ}35'N$ are plotted. In the bottom panel of Figure 10 the tidal height at Yarmouth, Nova Scotia (see Fig. 1) is plotted for the corresponding times. Three features can be observed in the figure: the posi-

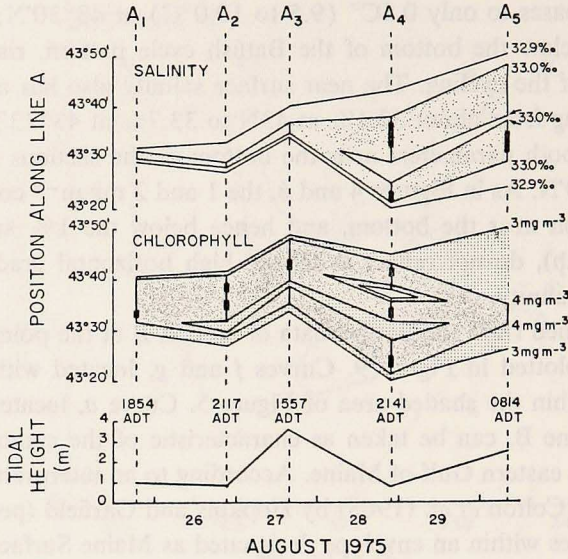


Figure 10. Time history of the position of the anomaly along line A as measured at a depth of 5 m. The heavy vertical bar represents, in the upper panel, salinities in the range 33.1-33.2‰, and, in the middle panel, chlorophyll concentrations greater than 5 mg m^{-3} . Transect times were taken at $43^{\circ}35'N$. In the bottom panel is the tidal height at Yarmouth, N.S., at the times of the 5 transects.

tion of the anomaly along line A was clearly correlated with the tide, the anomaly was apparently spreading out along line A, and, although the chlorophyll *a* concentrations were decreasing, the salinity maximum was increasing, in both magnitude and horizontal extent.

The phase of the tide anywhere along line A should be within $\pm 20^{\circ}$ of the tidal height measured at Yarmouth, Nova Scotia (Greenberg, 1977). Thus, the horizontal tidal excursion of the water along line A, which lies roughly parallel to the major axis of the tidal ellipses there, should be nearly in phase with the tide at Yarmouth. Since the time for transects A_2 , A_3 and A_4 each falls within 0.5 h of a low, a high and a low tide respectively, and since there is no perceptible mean advection of the anomaly along line A during the 5-day period of Figure 10, we can estimate the tidal excursion from the differences in the position of the center of the anomaly (defined as the point halfway between either the 32.9‰ or the 3 mg m^{-3} contours) between successive transects given in Table 2. For the orientation of line A relative to north, $5.3'$ latitude equals 10 km. Between sections A_2 and A_3 , the salinity center moved north 13 km and the chlorophyll center 11 km; between sections A_3 and A_4 , the salinity retreated south 10 km and the chlorophyll 15 km, for an overall average of 12 km. To compare with this value, the tidal current can be integrated over one-half a tidal period. From Greenberg's model, the tidal current amplitude in the grid

Table 2. Time history of the anomaly on line A at a depth of 5 m. Center of anomaly is half-way between the outside boundaries, 32.9‰ for salinity and 3 mg m⁻³ for chlorophyll *a* concentration. Recorded time is the time (Atlantic Daylight Time) that the ship passed 43°35'N.

Transect	Date	Time (ADT)	Tidal Height at Yarmouth (m)	Position of Center		Ratio Salinity Patch Width: Chlorophyll Patch Width
				Salinity	Chlorophyll	
A ₁	25 August	1854	1.0	43°30.5'N	43°35'N	0.3
A ₂	26 August	2117	0.8	43°30'N	43°34.5'N	0.4
A ₃	27 August	1557	3.6	43°37'N	43°40.5'N	0.4
A ₄	28 August	2141	0.9	43°31.5'N	43°32.5'N	0.9
A ₅	29 August	0814	2.6	43°37'N	43°38'N	1.1

spaces containing line A is about 0.9 m s⁻¹ to give a calculated tidal excursion of 13 km, consistent with the observed movement of the anomaly.

In addition to the tidal advection, the anomaly was spreading with time along line A, probably as a result of some combination of horizontal diffusion, horizontal divergence, or horizontal advection perpendicular to line A. From chlorophyll, one might conclude that the spreading was due to horizontal diffusion or advection since the areas of concentration greater than 5 mg m⁻³ had disappeared by the fifth transect (A₅) and the area between 4 and 5 mg m⁻³ had shrunk to about 20% of the width of the anomaly from over 80% on earlier transects. However, the salinity anomaly was not only spreading horizontally, but the maximum salinity at the center of the patch increased from just over 33‰ to over 33.1‰, and the ratio of the width of the salinity anomaly to the width of the chlorophyll anomaly increased almost fourfold. This behavior suggests that higher salinity water was entering the central region of line A. T-S analysis of the transects A₁ to A₅ is consistent with this hypothesis. In Figure 11 envelopes of T-S curves for sections A₁, A₃ and A₅ are plotted (where each envelope has been drawn around 7 to 9 T-S curves taken along the Batfish transect of line A as shown for section A₂ in Fig. 5). There is a progression in time toward more saline water going from A₁ to A₅. A mean horizontal advection of saltier water shoreward along line B (perpendicular to line A) alone could not account for the increased salinities since, in Figures 8 and 9, the near-surface salinity decreases markedly with increasing distance offshore beyond a salinity maximum at the 60 km position along the transect. There, the salinity at the bottom also represents a maximum for the transect, highly suggestive of upwards vertical advection of high salinity waters from that point shoreward. Referring back to Figures 4, 6 and 8 (to the right of 43°30'N), the higher salinity waters at depth bulge upwards near the center of the anomaly, also suggesting an upward flow into that region.

Finally, the position of the salinity center (Table 2) was consistently south of the chlorophyll center by an average of 3' latitude or about 5 km. If the subsurface

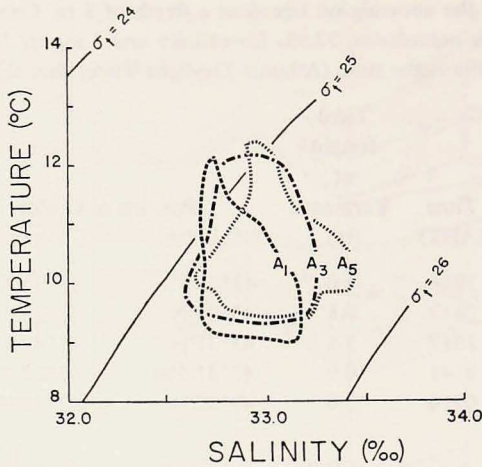


Figure 11. Temperature-salinity (T-S) envelopes for transects A₁, A₃ and A₅. Each envelope is drawn around 7 to 9 T-S profiles distributed along line A (for example, at points *a* to *i* in Fig. 4 for A₂).

waters were rising to the surface, the center of the salinity anomaly should indicate more accurately the point of origin for the divergence or spreading in the surface waters along line A. Because phytoplankton chlorophyll is much less of a conserved quantity and because the reproductive doubling time for phytoplankton (1 to 3 days) usually results in a delay of the occurrence of peak biomass after upwelled water enters the euphotic zone (e.g. Wroblewski, 1977), finding the center of the chlorophyll anomaly consistently to the north of the salinity anomaly might be evidence for a slow northward drift of surface waters (observed by Bumpus and Lauzier, 1965) despite the absence of any obvious net advection of the anomaly along line A in Figure 10.

6. Oceanographic interpretation

The temporal changes that were described in the previous section suggest a spreading out and diffusing of the observed anomaly, but the salinity data show a tendency toward enhancement or strengthening of the anomaly. In this section we interpret the data in terms of the water mass characteristics of the Gulf of Maine; then we suggest several mechanisms that could create, maintain and erode the anomaly.

Hopkins and Garfield (personal communication) and Brown and Beardsley (1978) have summarized the seasonal evolution of the water mass characteristics of the Gulf of Maine. During the late summer there are three main water types. Maine Surface Water (MSW) dominates the upper 50 m, with nearly constant salinity (32.0-32.5‰) but vertically stratified temperature (9-16°C). Maine Intermediate Water (MIW) with properties near 32.0-33.0‰ and 3-7°C is found around the 100 m

level; it is formed in the western Gulf of Maine by convective sinking of winter-cooled surface waters. Upper Slope Water (USW), with high salinities (34.5-35.5‰) and medium temperatures (9-14°C), is thought to enter the main basin of the Gulf of Maine via the Northeast Channel (Fig. 1) from the outer continental slope. A fourth water type, Maine Bottom Water (MBW), with properties 33.5-34.5‰ and 5-7°C, is thought to be a mixture of MIW and USW. In Figure 9 the upper half of curve *a* lies within the envelope of MSW. Curves *b* to *g* have temperatures similar to MSW but salinities 0.5 to 1.0‰ higher. USW waters with similar temperatures but higher salinities are the likely source of higher salinity: the water found in curves *b* to *g* of Figure 9 could be a mixture of MSW and USW in a ratio of about 3:1. Evidence for the other water types can be found near the bottom of the Batfish pattern in Figure 8. Between curves *a* and *b* water was present (6.5°C and 33.9‰) that can be identified as MBW. Between curves *d* and *e* was water (11°C and 34.1‰) that must have been largely USW with some MSW and MBW mixed in. However, a factor that complicates determining the origins of the various parcels of water is that, during the summer, Scotia Shelf Water (SSW) has similar characteristics to Maine Surface Water but with lower surface temperatures. The analysis of historical data by Sutcliffe *et al.* (1976) suggests that MSW is formed from SSW. They traced a low salinity pulse associated with spring runoff of the St. Lawrence River out through Cabot Strait, down the Scotian Shelf and up into the upper reaches of the Gulf of Maine (St. Andrews, New Brunswick and Portland, Maine) where it usually arrives in May of the following spring.

The important conclusion to be drawn from the water mass analysis is that during August 1975 the waters on the continental shelf adjacent to the western end of Nova Scotia were more saline than waters of the same depth range off the shelf in the main basin of the Gulf of Maine. Furthermore, these waters contained a significant fraction (~30%) of Upper Slope Water. Evidence for the intrusion of slope water along the eastern side of the Northeast Channel during summer can be found in Bigelow (1927). His sections in that region showed consistently that the highest salinities (>33‰ at 40 m and >34‰ at 100 m) were found bulging upwards against the eastern continental slope through the Northeast Channel up into the Gulf of Maine basin. During the spring and summer of 1975 a similar salinity regime existed; on 14 August for example a CTD section across the Northeast Channel between 42°22'N, 65°52'W and 42°09'N, 66°02'W showed 35‰ salinity water bulging up to 100 m on the northeastern half of the transect (Pawlowski and Schlitz, personal communication). Surface salinities also were higher, going from 34.4‰ at the northeastern station to 32.0‰ at the southwestern station. Before and during our observations, the subsurface high salinity water apparently mixed with Maine Surface Water and Maine Bottom Water, and was possibly drawn eastward onto the shelf by the centrifugal upwelling suggested by Garrett and Loucks (1976). It then formed the anomaly observed with the Batfish, which appeared to have been

topographically fixed over a depression on the shelf between two shallows along line A (Fig. 1).

Many questions remain. First, centrifugal upwelling ought to produce a steady-state situation. Yet, the long series of data analyzed by Wright and Pawlowski (personal communication) suggests that the intrusions are episodic with time scales of order days to weeks, corresponding to variations in atmospheric forcing. Furthermore, two current meters moored about 6 m above the bottom for 25 days in 1969 near the southern end of line A did not show consistent residual flow toward the coast. Our data, while over too short a period to be definitive, show increasing salinity, decreasing chlorophyll and a spreading of the anomaly over a 6-day period. There is some evidence that the upwelling off the western end of Nova Scotia was affected by the winds during the summer of 1975. For the period 14 to 27 July, weekly sea surface temperature (SST) charts similar to Figure 2 showed a consistent cold water anomaly ($<8^{\circ}\text{C}$) off the western end of Nova Scotia. On July 28, Hurricane Blanche passed over the Gulf of Maine and up the length of Nova Scotia with recorded winds over 110 km h^{-1} at Halifax, N.S. The SST chart for the period 29 July-3 August showed that the cold water anomaly had completely disappeared, with warm 14°C water reaching almost to the coast of Nova Scotia. It was not until three weeks later (in the SST chart shown in Fig. 2) that the cold water anomaly had clearly reappeared.

A second question concerns the existence of this small anomaly of warm chlorophyll-rich surface water in a region of predominantly cold water. Was it a remnant of offshore water blown into the area by Hurricane Blanche, or did it form from steady phytoplankton growth in waters warming by solar heating during the several-week-long period of low winds between Hurricane Blanche and the observation period? The data base used in the construction of the SST maps like Figure 2 is too sparse to show the development of such small mesoscale features.

It is also possible that the centrifugal upwelling is of minor importance. Garrett and Loucks (1976) calculated that the observed 2 cm s^{-1} bottom convergence would be contained in a layer $\sim 5\text{ m}$ thick. If the return surface flow offshore were in a layer 25 m thick, it would take ~ 30 days to travel 10 km , a rather slow rate of advection. On the other hand, in coastal regions with large tidal currents, topographically-fixed areas of stratified waters often coexist with areas of well-mixed waters separated by sharp frontal boundaries. Simpson and Hunter (1974) and Simpson (1976) studied the location and distribution of such summer fronts around the British Isles by mapping a diagnostic number h/u_s^3 where h is the bottom depth and u_s is the surface tidal current amplitude. They found that fronts tended to occur parallel to h/u_s^3 contours with values between 50 and 100. For h/u_s^3 less than this critical range the water column was well-mixed, for h/u_s^3 greater it was stratified. Fearnhead (1975), for a related parameter, also found fronts to coincide with contours of the same range of values.

We have used tidal currents calculated for the Gulf of Maine by Greenberg (1977) to estimate h/u_s^3 along line A. It increases from about 20 (below the critical value) at the two shallowest points ($43^\circ 22'$ and $43^\circ 44'N$) to about 270 (above the critical value) at the deepest point ($43^\circ 36'N$). Gross estimates of h/u_s^3 along line B increase rapidly from about 190 where it intersects line A ($43^\circ 38'N$) to over 2.5×10^3 at the offshore end ($43^\circ N$) (everywhere above the critical value, suggesting stratification can be maintained). Our physical data are not inconsistent with such a picture, and our biological data are similar to those of Pingree *et al.* (1975, 1976) who found high chlorophyll layers in stratified waters immediately adjacent to well-mixed regions. Thus we believe that the high salinity (and high nutrient) waters were transported up onto the shelf by centrifugally-driven bottom convergence but that tidal mixing modulated by variable bottom depth was an important factor in the creation and maintenance of the observed surface anomaly. However, the h/u_s^3 criterion does not account for the well-mixed region observed along line B between $43^\circ 25'$ and $43^\circ 30'N$ (Figs. 7 and 8), right over the region of sharpest dropoff from the nearcoastal shelf (Fig. 1).

The Batfish sections on graphs of sigma-t against distance suggest possible mechanisms for the mixing. In each plot, between $43^\circ 25'$ and $43^\circ 35'N$ in Figure 4, between $43^\circ 35'$ and $43^\circ 40'N$ in Figure 6, and at $43^\circ 08'$, $43^\circ 20'$ and $43^\circ 30'N$ in Figure 8, distinct temperature-salinity features were observed near the bottom of the Batfish pattern. On the transects A_2 and A_5 (Figs. 4 and 6), the structures had a width of about 3 to 5 km. That they had the same density characteristics as the surrounding water suggests that the motions associated with these intrusive features were predominantly horizontal.

We thus hypothesize a large-scale version of the classical concept of stirring followed by mixing (Eckart, 1948). The passive scalar fields of temperature and salinity are convected and distorted along sigma-t surfaces by the large-scale motions of the fluid into the observed intrusive structures. The high gradient regions thus become stronger and more extensive until such time as tidally-driven turbulent diffusion can accomplish the mixing. Since these processes appear to occur over time and space scales similar to those operating in the ecosystem under study (days to weeks; kilometers to tens of kilometers), it seems unlikely that they can be effectively parameterized by simple turbulent diffusion coefficients.

7. Biological implications

The shelf region off southwest Nova Scotia supports several productive fisheries (Brinkhurst and Hord, 1976). That the marine food chain there has relatively high productivity can be inferred from the observations of Sutcliffe and Brodie (1977) that feeding marine mammals converge on the region especially in spring and autumn. Our observations of high surface chlorophyll *a* biomass concentrations

along line A imply that the area is potentially one of high primary productivity. Subba Rao (1975), in a large-scale survey conducted in the eastern Gulf of Maine during August 1974, found relatively high values of nutrients, especially nitrates, phosphates and silicates, off the southwestern tip of Nova Scotia. These nutrients probably originate in the Slope Water that was found from T-S water mass analysis to form a significant fraction of the water in the surface anomaly observed along line A. Fournier *et al.* (1977) and Denman *et al.* (1977a) found the Slope Water to be high in nutrients further east out at the edge of the Scotian shelf. The supply of the nutrient-rich slope water onto the continental shelf in the eastern Gulf of Maine and the subsequent phytoplankton production are most likely controlled by a combination of centrifugal upwelling, wind events and tidal mixing.

The complexity of the physical and biological structure revealed by the Batfish would have remained undetected with either conventional point sampling or single depth underway surveys. The necessity for such a rapid survey instrument that gives high spatial and temporal resolution becomes obvious once such data has been acquired. With the planned addition of an electronic zooplankton counter, the Batfish or a similar system should become an essential tool of biologists if they are to understand the ecosystem dynamics of such energetic and variable continental shelf areas.

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