

The importance of a plume of tidally-mixed water to the biological oceanography of the Gulf of Maine

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ABSTRACT

During the warmer months of the year the eastern Gulf of Maine features a plume of cold water which extends from the tidally well-mixed area adjacent to Grand Manan Island at the mouth of the Bay of Fundy southwest along the Maine coast to well beyond Penobscot Bay. Near Grand Manan Island the plume waters are cold (ca. 10°C), nearly vertically isothermal and carry high concentrations of dissolved inorganic nutrients. The analysis of temperature-salinity diagrams and hydrographic vertical section plots indicate that the deeper waters in Jordan Basin, of slope water origin, upwell and contribute a significant fraction of the high nutrient concentrations. The plume waters become increasingly stratified as they flow to the southwest which leads to a phytoplankton bloom downstream. Nitrate concentrations within the euphotic zone of the plume decrease approximately linearly (ca. 194 mg-at NO₃-N · m⁻²) along a distance of about 130 km travelled after its exit from the Grand Manan area (ca 7.5 days transit time). Cross frontal mixing and tidal flushing along the south and north sides of the plume could account for ca. 18% of this decrease. Total chlorophyll concentrations increase nearly linearly with distance along the first 80 km and then decrease in the following 50 km, presumably the result of phytoplankton being grazed by zooplankton which apparently propagate in response to the increasing chlorophyll levels. Over the distance of increasing chlorophyll concentrations (80 km) the nitrate decrease, corrected for physical losses laterally, would support a "new" primary production of 1.46 gm C m⁻² d⁻¹. Our analyses suggest that as much as 44% of the new nitrate which enters the Gulf of Maine at depth through the Northeast Channel upwells in the eastern Gulf becoming part of the plume, and hence this feature appears to be very important to the nutrient budget and general biological oceanography of the inner Gulf of Maine.

1. Introduction

The Gulf of Maine is a semi-enclosed continental shelf sea situated on the east coast of North America between the United States and Canada. Its waters have for centuries supported rich fisheries, due in large part to the complex physical and biological processes associated with tidal mixing; tides have been known for a long time to represent an important modifying force acting on the general hydrographic and

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biological features of the Gulf of Maine (Bigelow, 1926, 1927). Tidal ranges in the Gulf increase from west to east along the northern coast, from about 2 to 3 m in the western sectors, to 6 m in Eastport, Maine, and to greater than 10 m in the Bay of Fundy (Fig. 1). These large tides give rise to swift tidal current velocities and significant turbulent mixing relative to the increase in range (Garrett *et al.*, 1978; Greenberg, 1979; 1983). Bigelow (1927) noted that the major areas of tidal mixing, as indicated by summertime areal distributions of sigma-*t* differences between 0 and 40 m, were Georges Bank, the southwestern Nova Scotian shelf, the Bay of Fundy and the eastern Maine coast. The transition from these mixed areas to stratified waters is marked by often sharp thermal surface fronts (Yentsch and Garfield, 1981).

The implications of the opposing effects of tidal mixing and thermal stratification in shelf seas, and the frontal boundaries which result, have been the subject of considerable attention in recent years, especially as they augment biological production (Bowman and Esaias, 1978; Bowman *et al.*, 1986). Given the apparent significance of tidal mixing in the Gulf of Maine the biological importance of tidal fronts would seem likely but with few exceptions (Yentsch and Garfield, 1981; Townsend *et al.*, 1983) such features in the Gulf have as yet received little attention. One of the more conspicuous features of the inner Gulf of Maine is the slug of cold water which extends from entrance to the Bay of Fundy along the Maine coast to well beyond Penobscot Bay. This plume was first documented by Apollonio and Applin (1972, 1973), but it is apparent in the plankton distributions reported from much earlier biological studies in the Gulf (Bigelow, 1926; Fish and Johnson, 1937). Although it is clearly visible in infrared satellite images of sea surface temperature during the warmer months of the year (Yentsch and Garfield, 1981; Townsend *et al.*, 1986), it is not predicted by numerical models of vertical mixing by wind and tides (Garrett *et al.*, 1978; Greenberg, 1983; Loder and Greenberg, 1986) and appears to represent the effects of coastal upwelling or horizontal advection, or both, rather than local mixing. Such a movement of nutrient-rich, tidally-mixed waters away from their source may have important consequences for the biological oceanography of Gulf of Maine waters to the west. We examine these processes in this communication in light of more recent measurements in the inner Gulf of Maine and present data which serve to underscore the probable importance of tidal mixing and the formation of the plume feature to the nutrient budget and ensuing plankton production in the Gulf of Maine.

2. Materials and methods

The data presented here were collected on two research cruises in the Gulf of Maine, 8–9 Sept., 1984, on the R/V *Cape Hatteras*, and 16–24 July, 1985, on the R/V *Gyre*. The station locations for each are shown in Figure 1. We also present current meter data collected in Sept., 1985. The details of each set of data follow.

On the Sept., 1984, cruise we sampled 24 stations in the eastern Maine area for herring larvae, zooplankton, chlorophyll, nutrients and physical structure (Fig. 1b).

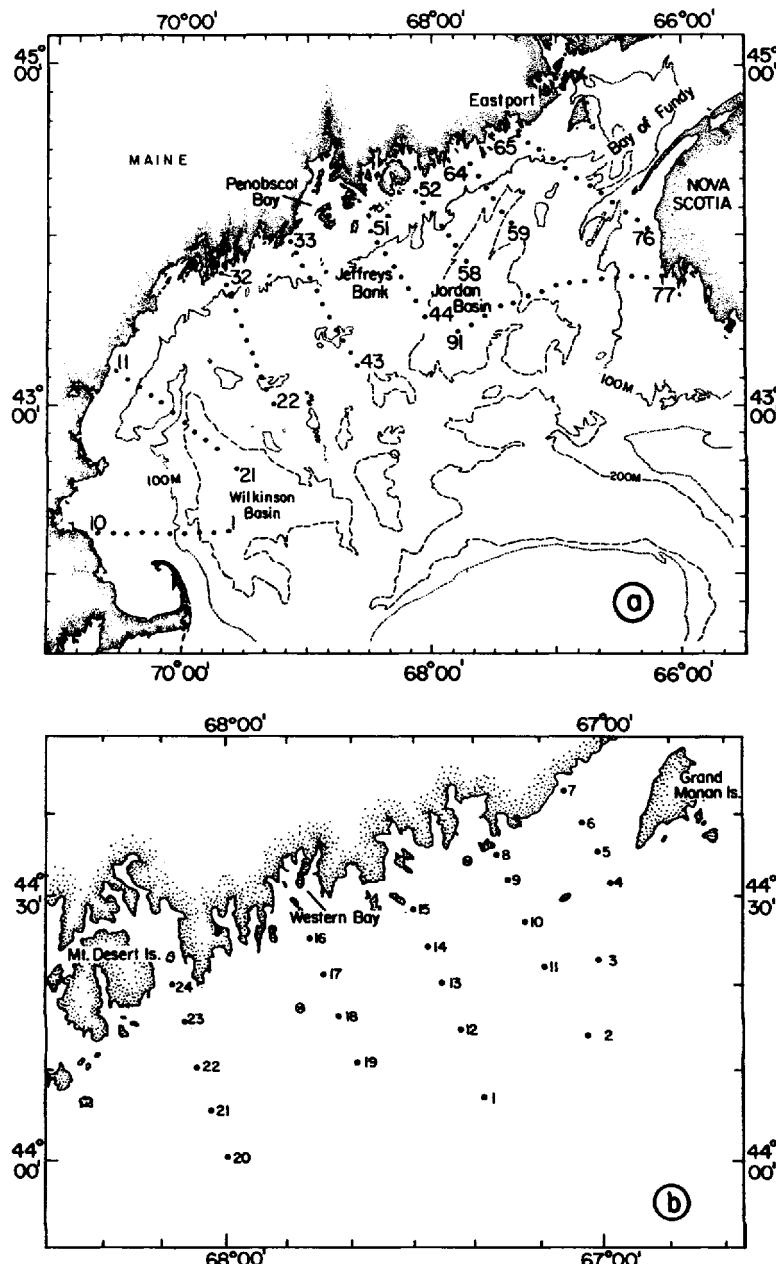


Figure 1. (a) Map of the Gulf of Maine showing locations referred to in the text and the stations sampled on the R/V *Gyre* cruise, 16–24 July, 1985. The station numbers at the ends of each transect are indicated. The Bay of Fundy nutrient station from Bailey *et al.* (1954) is indicated (X). (b) Map of stations sampled on the R/V *Cape Hatteras* cruise 8–9 Sept., 1984. The locations of the two current meter mooring deployments are indicated (◎).

This site was chosen because it has been known to be an important spawning ground for herring (Boyar *et al.*, 1973; Graham, 1982) and we were interested in the dynamics of plankton in this important region of the Gulf. Conductivity, temperature and depth data were collected with the ship's Neil Brown Smart CTD, and water samples for chlorophyll and nutrients were collected on the same hydrocast using a General Oceanics rosette sampler. Chlorophyll and phaeopigment concentrations were determined by the method of Holm-Hansen *et al.* (1965); nutrient concentrations were determined back at the laboratory, employing a three-channel autoanalyzer (Strickland and Parsons, 1972), on samples frozen at sea. Larval herring were collected with a 1 m² Tucker trawl equipped with 505 µm mesh nets. Replicate samples were collected by towing the sampler at 3.5 kts obliquely from the surface to the deepest point (100 m or about 5 m above the bottom, whichever was deeper; depth was recorded using a maximum depth recorder) at which time the first net was closed and the second net opened using a messenger-activated release. The sampler was then collected by retrieving the net in the same manner. Each tow lasted about 5–15 min. Zooplankton samples were collected using a 20 cm diameter Bongo net frame fitted with 80 µm mesh nets. This sampler was attached just above (0.5 m) the Tucker trawl on the same wire and therefore sampled the same waters as for larval herring, with the exception that only a single double-oblique tow was made without replicates. All samples were preserved in 5% buffered formalin. The zooplankton samples were enumerated by examining one ml subsamples using 100× magnification; a minimum of 100 organisms were identified and counted. Only one side of the Bongo was examined. These cruise data are presented in their entirety elsewhere (Townsend, 1985).

On the July, 1985, cruise we sampled 91 stations for chlorophyll, nutrients and physical structure (Fig. 1a). Zooplankton samples were collected at selected stations using the 20 cm, 80 µm mesh Bongo nets and analyzed as described above; additional samples of macrozooplankton were collected on the same tow using a 61 cm, 505 µm mesh Bongo net attached above the smaller sampler. These samples were used to estimate the biomass, in terms of displacement volume, of the macrozooplankton. No herring larvae were collected on this second cruise because it preceded the spawning season which begins in August. The physical data were collected with the ship's Neil Brown Mark III CTD, and water samples for the chlorophyll and nutrient analyses were collected on the same hydrocast using a General Oceanics rosette sampler. Chlorophyll and phaeopigment concentrations were determined according to the method of Holm-Hansen *et al.* (1965). The nutrient concentrations were determined at sea with a 6-channel autoanalyzer using the methods in Strickland and Parsons (1972). These data are presented in their entirety elsewhere (Townsend and Christensen, 1986).

A single current meter mooring consisting of two ENDECO type 105 recording current meters (Environmental Services Corp., Marion, Mass.), one situated 5 m from the surface and the other 5 m from the bottom, was deployed once at each of two

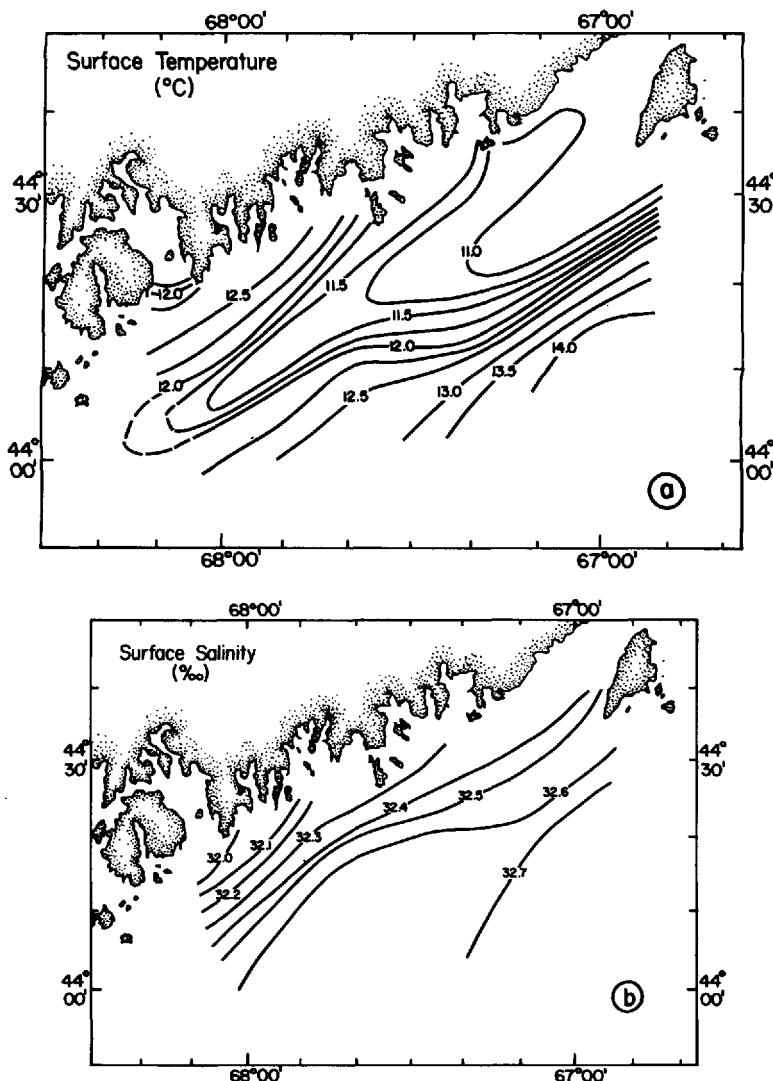


Figure 2. Areal contour maps for the Sept., 1984, cruise of: (a) surface temperature, (b) surface salinity, (c) density differences (σ_t) from 0–35 m, (d) surface chlorophyll *a*, (e) integrated (0–35 m) total chlorophyll (chlorophyll *a* plus phaeopigments), (f) surface $\text{NO}_3 + \text{NO}_2$ concentrations, (g) catch rates of herring larvae, (h) densities of copepod nauplii, and (i) densities of post-naupliar copepods.

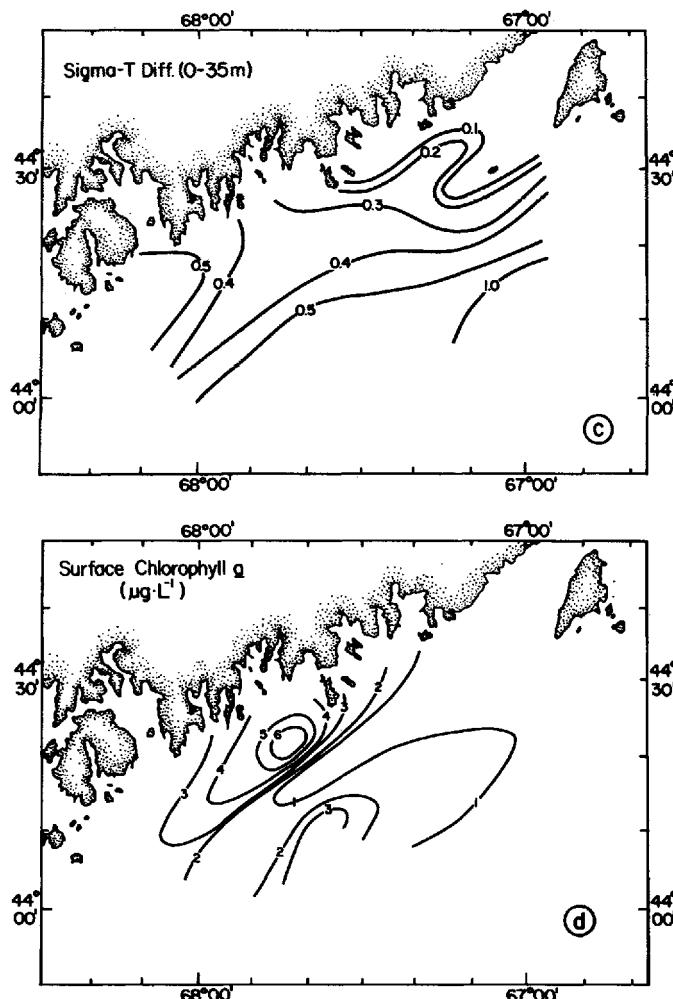


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stations during the period 2–26 Sept., 1985 (Fig. 1). Each current meter was recalibrated by the manufacturer in August of that year. A full account of these data is presented in Townsend *et al.* (1985).

3. Results

Contour plots of surface temperature, salinity, stratification, chlorophyll concentrations (surface and integrated), nitrate plus nitrite, and areal distributions of larval herring, and zooplankton during the period 8–9 Sept., 1984, are presented in Figures 2a–h. These show that vertical mixing is greatest toward the east in the Grand Manan area, that the surface waters there are coldest, and the nutrient concentrations the

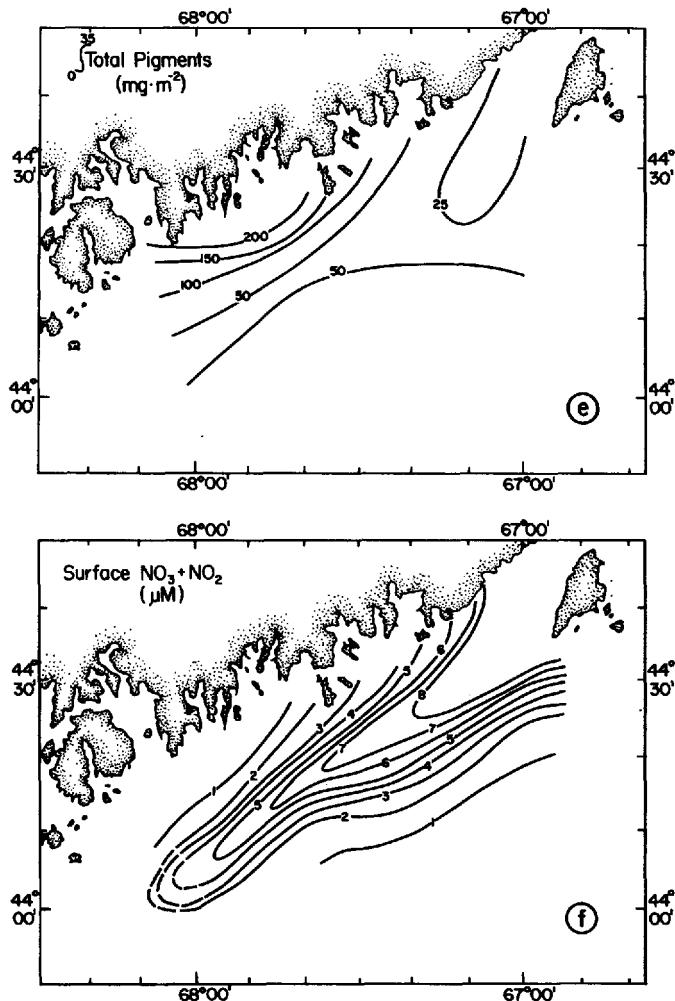


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highest throughout the inner Gulf of Maine. Both the surface temperatures and nutrient concentrations show what appears to be a plume of relatively cold, mixed water being advected away from the Grand Manan area and toward the southwest, assuming a somewhat offshore trajectory. The plume becomes defined by warmer waters to the north and south, with the coldest waters at the core not hugging the coast, but perhaps heading offshore some distance downstream in the vicinity of Western Bay on the eastern Maine coast. This general current pattern along the Maine coast has been documented before (Bumpus and Lauzier, 1965; Apollonio and Applin, 1972, 1973; Graham, 1970; Townsend *et al.*, 1986) and the plume feature is clearly visible in satellite infrared images of sea surface temperature (Yentsch and Garfield, 1981; Townsend *et al.*, 1986). The reasons why it departs the coast and heads offshore are not

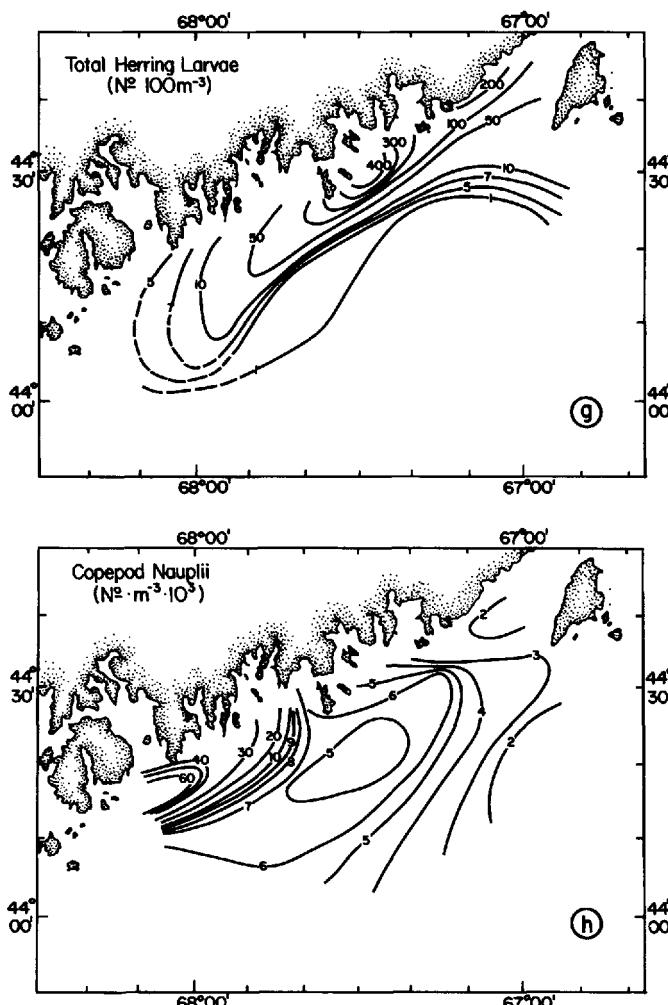


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well understood but may include the introduction of lower salinity waters nearshore, simple topographic control, and the general, geostrophic balance with doming slope waters in Jordan Basin which contribute to a cyclonic gyre offshore (Brooks, 1985). The south side of the plume is delineated by a sharp thermal front between the mixed plume waters and the offshore stratified waters. The northern edge of the plume is less sharply defined as a surface front, especially east of Western Bay.

The surface chlorophyll concentrations on the September cruise increased to the southwest and "downstream" from the area of mixing, becoming maximal along the north side of the plume at a point off Western Bay where the thermal front becomes better developed (Figs. 2a and d). There is also an indication of increasing chlorophyll

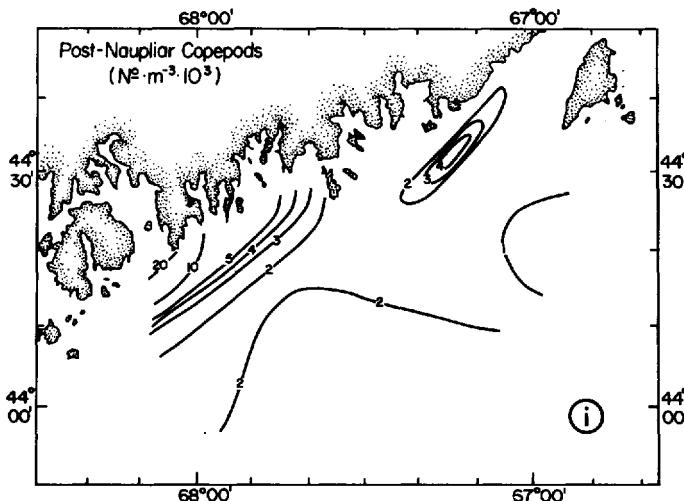


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levels in the front to the south of the plume; like the chlorophyll distributions on the northern side, this patch occurs downstream from the Grand Manan area. Vertical section plots of temperature, chlorophyll and nitrate-nitrite along two transects (Fig. 3) suggest that the thermal front to the north of the plume is better developed west of Western Bay (Fig. 1); this may be due to the added buoyancy effect of increased fresh water discharge west of Western Bay, as inferred from the salinity distribution in Figure 2b and may also be due to the waters simply being shallower there, thus facilitating warming. The vertical section plots also illustrate that the critical depth for net phytoplankton growth is met by both the depth of the pycnocline in the stratified waters within the front to the south of the plume as well as by the bottom depth inshore of the plume. The highest concentrations of copepod nauplii also appear to correspond to the northern front, but these occur even farther downstream to the west than that of the chlorophyll (Fig. 2g), implying a propagation response by the copepods to the phytoplankton growth. It is along this northern front that the greatest abundances of herring larvae are found, apparently having been transported away from the eastern Maine spawning grounds adjacent to the coast as has been reported earlier (Graham and Townsend, 1985; Townsend *et al.*, 1986). It appears that phytoplankton growth, and the ensuing response by the zooplankton, is augmented more effectively to the north of the plume in shallow water than to the south where stratification results from a pycnocline.

Though it should be noted that the second cruise is not a true replicate, due to differences in coverage and season, a broader and better resolved picture of these patterns is revealed in the surface contour plots of temperature, salinity, stratification, dynamic height, nitrate, chlorophyll and zooplankton from the 16–24 July, 1985,

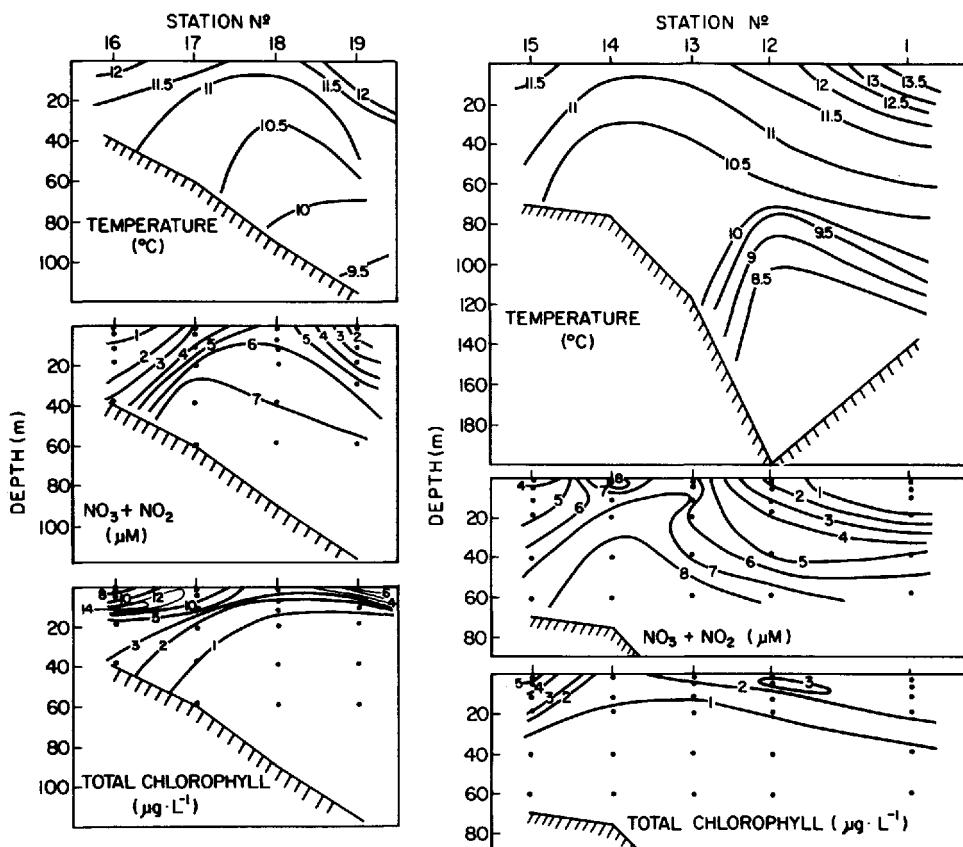


Figure 3. Vertical section plots of temperature, nitrate + nitrite, and total chlorophyll (chlorophyll *a* plus phaeopigments) for the stations shown for the Sept., 1984 cruise, and given in Figure 1b.

cruise (Figs. 4a–k). We again see a well-defined plume-like feature of colder, high nitrate water, apparently produced in the Grand Manan—Bay of Fundy area, which extends to the southwest and then offshore. The influence of the salinity field in directing this flow offshore can be seen; the lowest salinities are adjacent to the coast, decreasing at a point just to the east of Mount Desert Island, while the highest salinities occur offshore over Jordan Basin (Fig. 4b). The sea surface height which results suggests that this flow pattern of the coastal plume may be in geostrophic balance, as shown by the inferred geostrophic current streamlines (Fig. 4d), and that it begins to depart the Maine coast in the vicinity of Western Bay. These contours of dynamic topography also suggest the northern halves of two gyres in the Gulf of Maine which have been previously described (Brooks, 1985), one over Jordan Basin and another over Wilkinson Basin, possibly separated by an anticyclonic eddy over Jeffreys Bank. Surface nitrate concentrations are greatest in the areas of mixing, in and near Grand Manan Channel and off Nova Scotia (Fig. 4e). The surface contour maps show

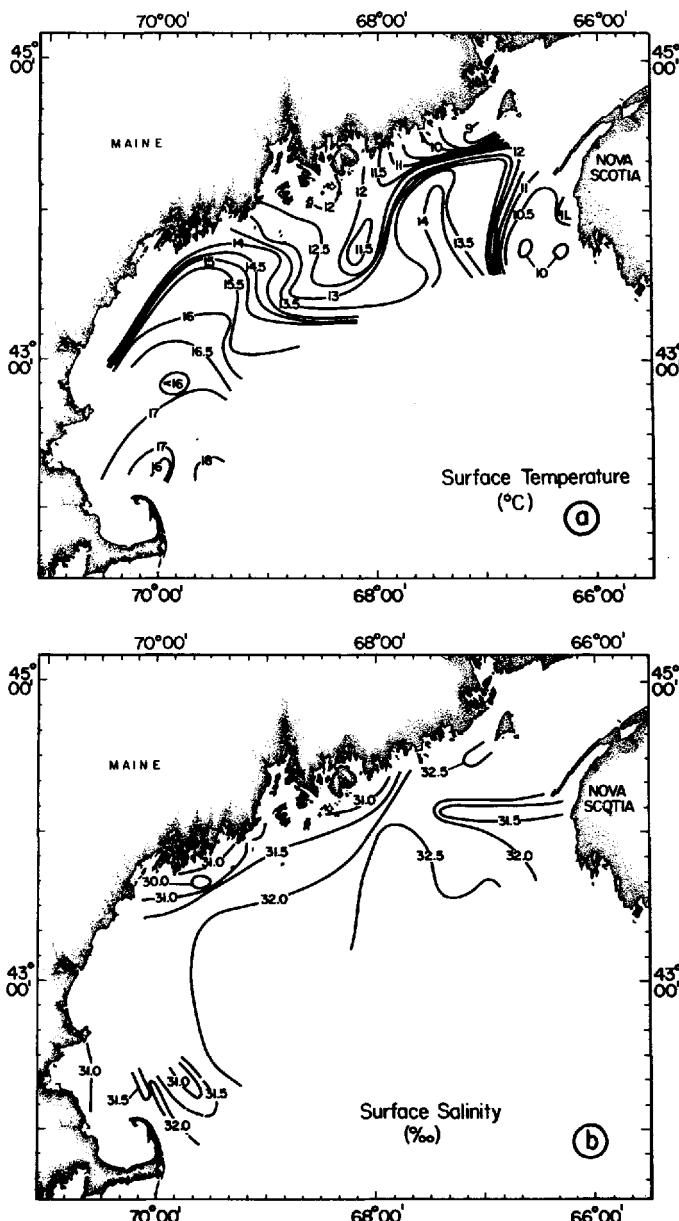


Figure 4. Areal contour maps for the July, 1985, cruise of: (a) surface temperature, (b) surface salinity, (c) density differences ($\sigma_0 - \sigma_{35}$ m), (d) dynamic height relative to 100 m, (e) surface nitrate concentrations, (f) integrated (0–35 m) nitrate concentrations, (g) surface chlorophyll *a* concentrations, (h) integrated (0–35 m) total chlorophyll (chlorophyll *a* plus phaeopigments), (i) densities of copepod nauplii, (j) post-naupliar copepods, (i and j each representing the 80 μm mesh Bongo Samples), and (k) displacement volumes of macrozooplankton caught in 505 μm mesh 61 cm Bongo nets. The stations are indicated for the zooplankton samples.

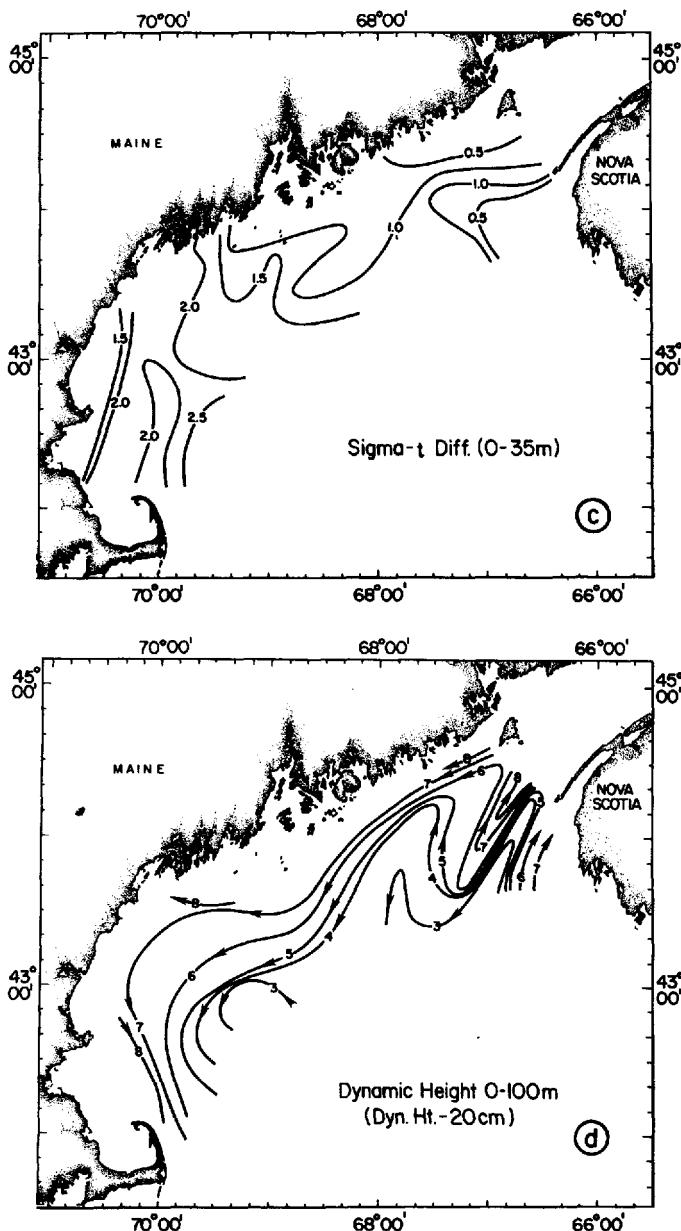


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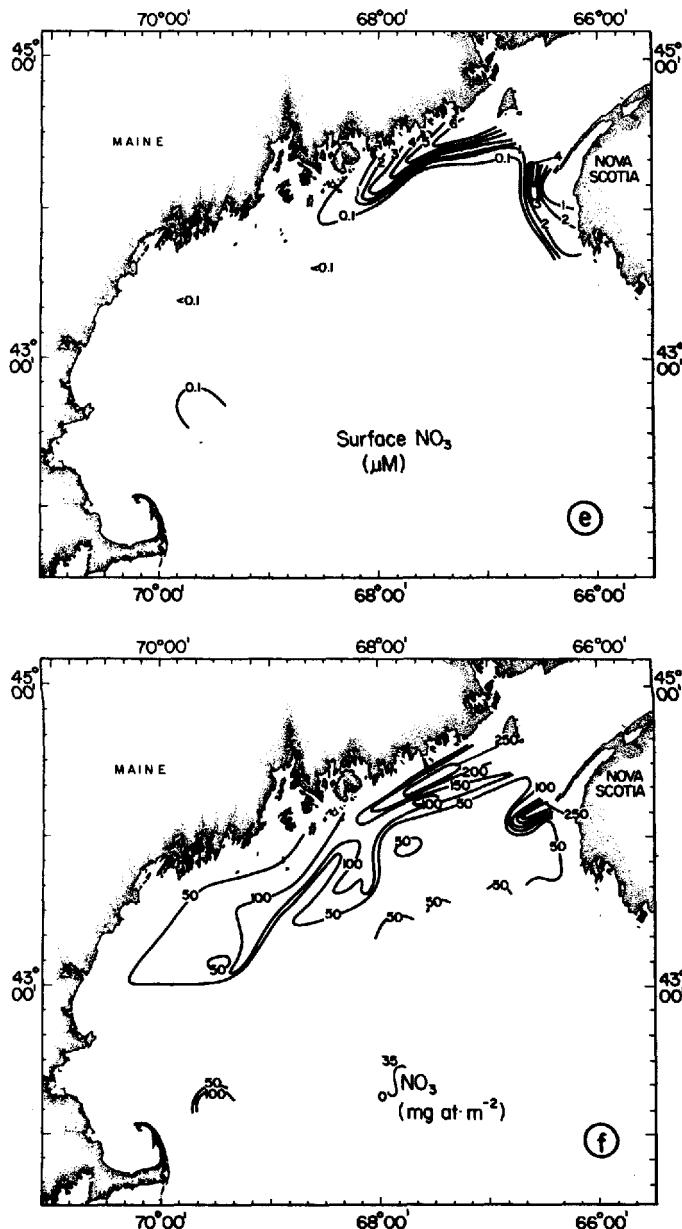


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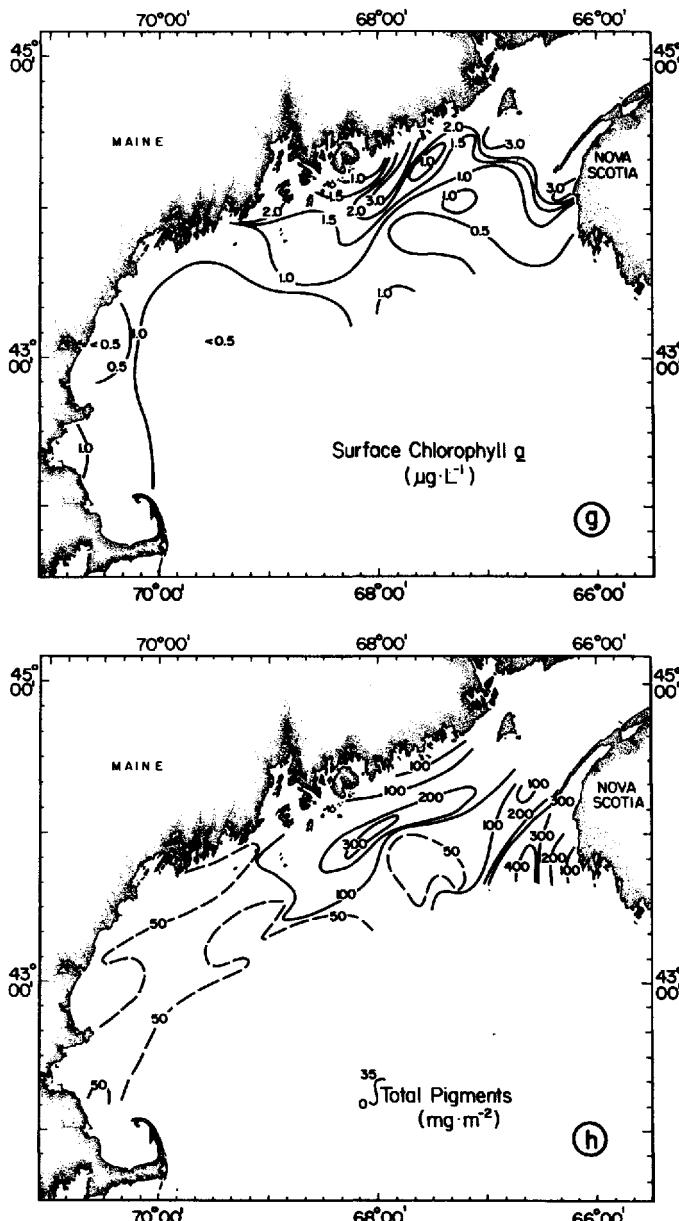


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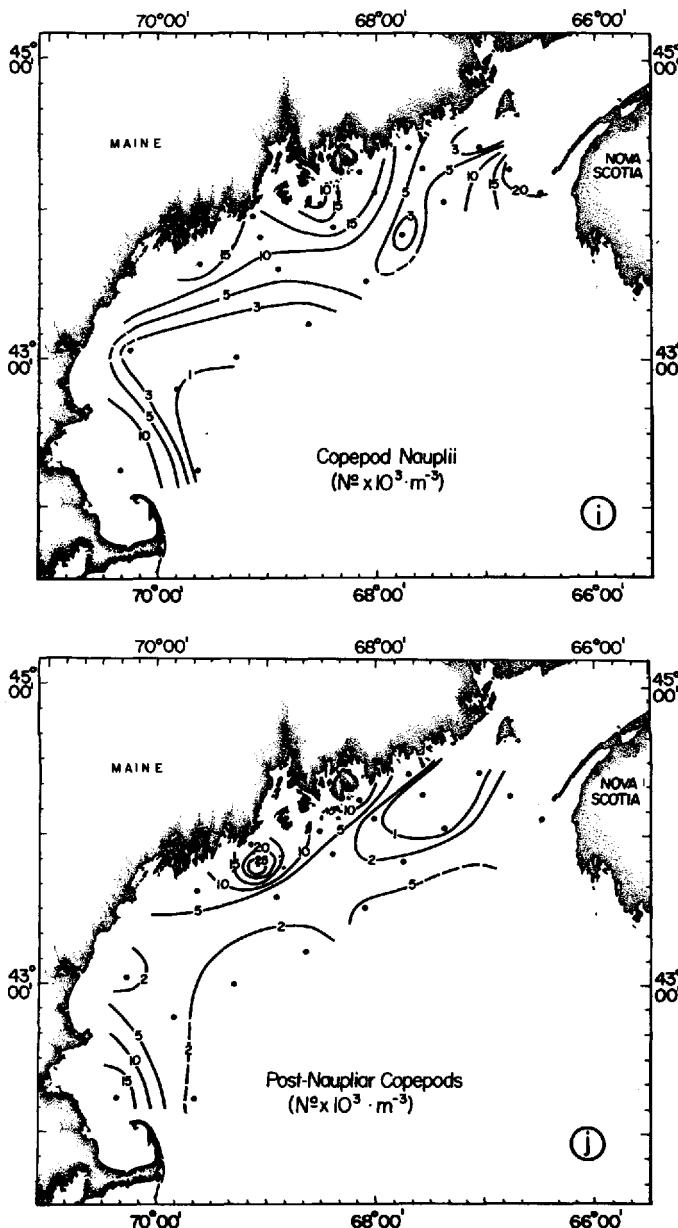


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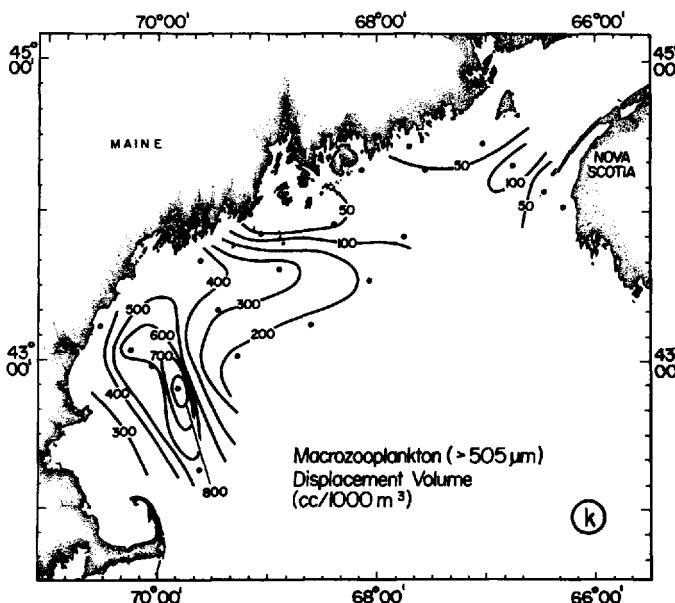


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the high nitrate water in the plume being advected to the southwest, with concentrations decreasing appreciably along the way to less than 0.1 μM at the surface throughout the remainder of the inner Gulf. Areal contours of integrated (0–35 m) nitrate (Fig. 4f), along with the surface contours of temperature, illustrate the influence of the anticyclonic eddy over Jeffreys Bank in bifurcating the plume off Penobscot Bay, at the southwestern end of the plume. The distributions of surface and integrated chlorophyll each become maximal downstream as the surface nitrate diminishes (Fig. 4g and 4h).

The vertical section plots in Figure 5 illustrate the importance of both bathymetry and thermal fronts in the distribution of chlorophyll. Peaks in chlorophyll occur both as a subsurface maximum in the front to the south of the plume as well as throughout the water column in the shallower waters to the north. Apparently, the water column inshore of the plume is shallower than the critical depth, thus supplying sufficient illumination for net phytoplankton production throughout the water column. The situation south of the plume is somewhat different, with nutrients apparently limiting production above the pycnocline; this may also be the case along the northern edge of the plume but not until a weak thermal front develops at the western extreme.

The densities of copepod nauplii and post-naupliar copepods collected with the 80 μm mesh Bongo nets show the lowest densities in the east, with the numbers of nauplii greatest along a coastal band extending to the west of the chlorophyll maximum (Fig. 4h and 4i). The greatest abundances of post-naupliar copepods

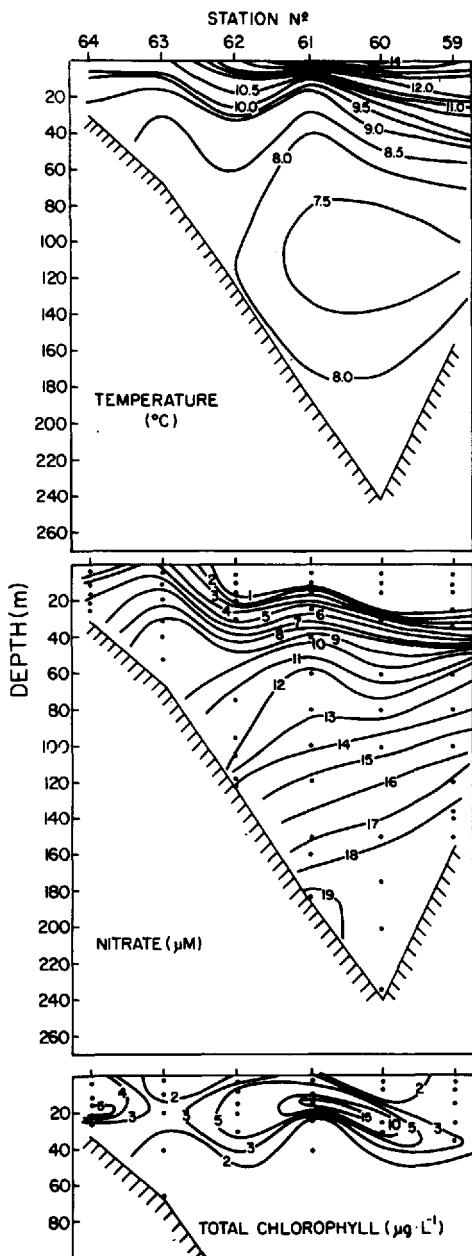


Figure 5. Vertical section plots of temperature, nitrate and total chlorophyll (chlorophyll *a* plus phaeopigments) for the stations shown for the July, 1985 cruise, and given in Figure 1a.

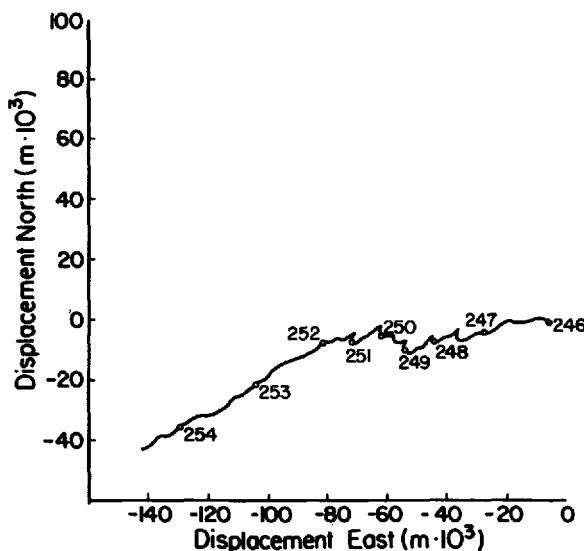


Figure 6. Progressive vector diagram for the surface (5 m) current meter at the station indicated in Figure 1 for the period 2 to 11 Sept., 1985; Julian day numbers are indicated (from Townsend *et al.*, 1985).

(primarily species of *Pseudocalanus*, *Oithona*, *Acartia*, and *Centropages*) occur even farther west (Fig. 4j). The biomass of macrozooplankton, primarily *Calanus finmarcchicus*, becomes maximal farther still to the west (Fig. 4k), thus suggesting a sequence of trophic events as the high-nitrate waters are advected from east to west in the interior Gulf. It would appear that the *Calanus* populations in the western Gulf are subsisting on recycled primary production.

Our calculations of geostrophic velocity (relative to 100 m) in the area of maximum sea surface slope suggest a current of about 5 cm s^{-1} to the southwest. This speed is somewhat lower than that calculated during June for this area by Brooks (1985) who found speeds of 5 to 10 cm s^{-1} during the year of his study, a relatively wet year with greater freshwater discharge into the nearshore waters which likely explains this difference. It is also lower than the presumed transport rates of herring larvae (ca. 12 km d^{-1} , or 14 cm s^{-1}) determined by Graham and Townsend (1985). We emphasize, however, that these geostrophic calculations are only approximate—they assume a balance between the pressure gradient and Coriolis only, and no other forcing functions—and should be interpreted with caution. Also, the choice of 100 m as the reference depth, or level of no motion, is one of convenience only; a deeper reference depth would increase our estimated current speeds. Our current meter record (Fig. 6) at the offshore station shown in Figure 1 indicates that the mean surface flow very near the core of the plume is also directed toward the southwest, but at about 20 cm s^{-1} , or about 17 km day^{-1} (Townsend *et al.*, 1986). Thus, as pointed out by Loder and

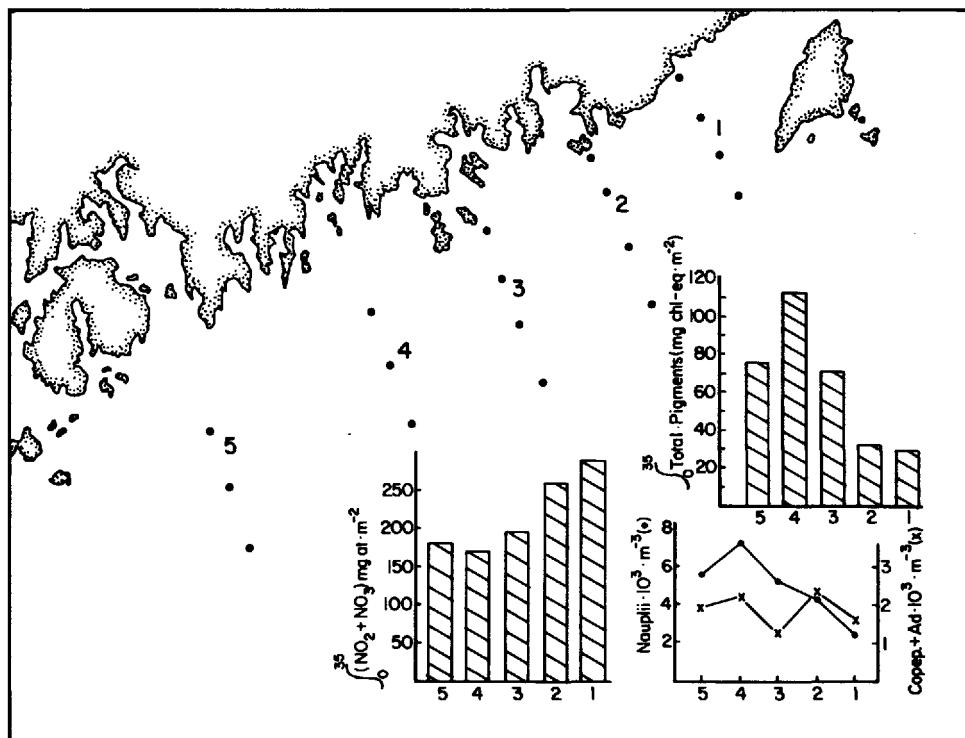


Figure 7. Summary plot for the Sept., 1984, cruise illustrating the changes in nitrate plus nitrite, total chlorophyll and zooplankton for each of the transects shown. The nitrate plus nitrite and the total chlorophyll histograms represent the mean integrated concentration, from the surface to 35 m, for the stations shown on each transect. The zooplankton data represent the mean concentration for the stations shown on each transect; data are for densities of copepod nauplii and post-naupliar stages.

Greenberg (1986), the influence of the mean horizontal circulation would appear to be very significant in displacing the expected position of the mixed waters produced in the Grand Manan area.

4. Discussion

a. Chlorophyll-nutrient relations in the plume. Recently, Loder and Greenberg (1986) examined the positions of tidal fronts as predicted by numerical models which incorporate mixing by both tides and wind. They found that the positions of cold waters and thermal fronts along the coast of Maine, such as those seen in satellite images, are not predicted accurately by their mixing models and that other processes, including wind-driven coastal upwelling and displacement of fronts by the horizontal mean circulation, may be important in determining position. This is especially true for the eastern coastal Gulf of Maine which typically exhibits the plume-like tongue of cold

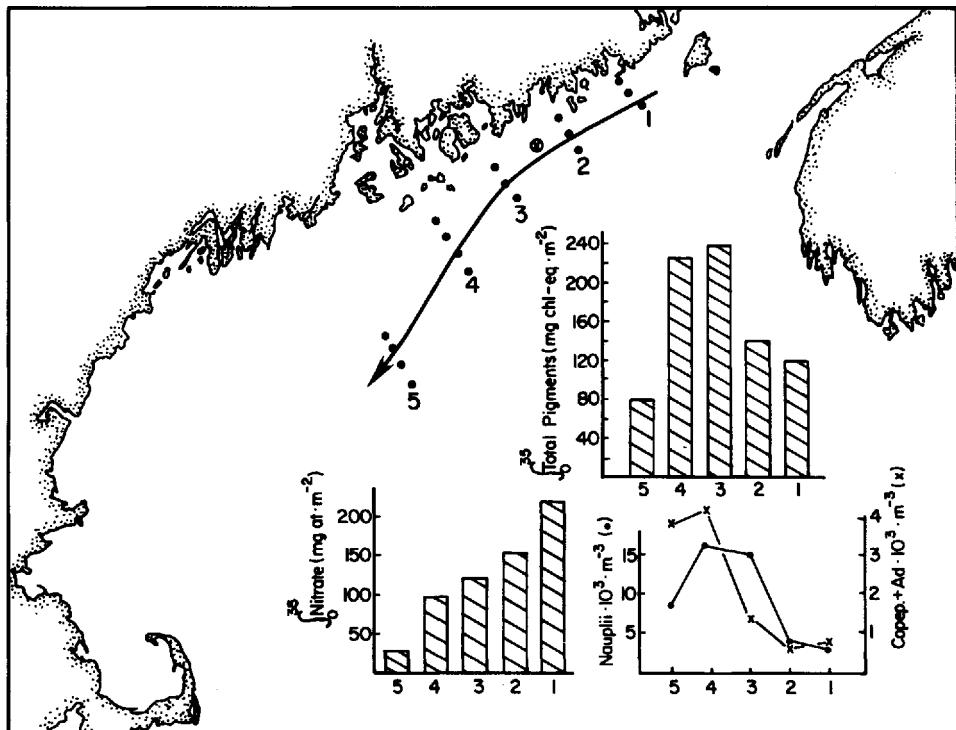


Figure 8. Summary plot for the July, 1985, cruise illustrating the changes in nitrate, total chlorophyll and zooplankton for each of the transects shown. The arrow represents the assumed path of the plume and corresponds with the dynamic height streamlines in Figure 5d. The location of the current meter (Fig. 7) is shown (x). The histograms represent the mean integrated concentration for nitrate and total chlorophyll for the stations shown for each transect. The zooplankton data are for a single station only for each transect.

water extending from the Grand Manan area to well off Penobscot Bay (Fig. 1; Townsend *et al.*, 1986). As we will discuss in the sections that follow, this plume is very important to the biological oceanography of much of the interior Gulf of Maine.

Figures 7 and 8 present graphically the processes which appear to be occurring during both our Sept. 1984 and July 1985 cruises as the plume of mixed water is advected away from its source in the Grand Manan area. Figure 7 shows that for the Sept. 1984 cruise the average integrated nitrate-nitrite concentrations (integrated to 35 m, the approximate depth of the euphotic zone) decrease with distance "downstream," dropping from 290 mg at-N · m^2 at the eastern-most transect to 181 mg at-N · m^2 at transect no. 5 in the west. The concentrations of phytoplankton pigments, on the other hand, increase to a maximum at transect no. 4, reflecting growth of the phytoplankton populations as they flow to the southwest. The integrated total pigment concentrations decrease between no. 4 and no. 5, most likely in response to increases in

potential zooplankton grazing with distance downstream, particularly along the northern, inshore edge of the plume. While the abundances of copepod adults and copepodites do not change appreciably with distance downstream, there is an apparent increase in naupliar stages (Fig. 7; Table 1).

A similar plot (Fig. 8) for the more complete July 1985 cruise shows these processes more clearly and affords a first-order calculation of some rates. To analyze these rates we have selected those stations sampled in July which coincide with the calculated geostrophic current streamlines (Fig. 4d) within the plume, and have presented the average integrated concentrations of nitrate and total phytoplankton pigment concentrations along this presumed trajectory of plume waters. These data are presented in Table 1. The pigment concentrations increase from a low at transect no. 1 in the east to a maximum at transect no. 3; the concentrations level off at nos. 3 and 4 before dropping to their lowest values at transect no. 5. The nitrate concentrations, on the other hand, show a nearly steady reduction from transect no. 1 in the east to transect no. 5, a reduction of about 194 mg at $\text{NO}_3\text{-N} \cdot \text{m}^2$. This pattern suggests that zooplankton grazing becomes important at transect no. 3, where the pigment concentrations begin to level off, and indeed it is at this point that the numbers of copepod nauplii increase, followed by the adult and copepodite stages (Fig. 8, Table 1). Direct current measurements within this apparently quasi-geostrophic flow, indicated that the residual flow at the surface along these streamlines is about $20 \text{ cm} \cdot \text{s}^{-1}$, or about $17 \text{ km} \cdot \text{day}^{-1}$. The apparent rate of nitrate uptake, assuming the losses between transect no. 1 and transect no. 5 reflect uptake by phytoplankton, is therefore 25.8 mg at $\text{NO}_3\text{-N} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. Using the Redfield ratio of 6.625 for carbon:nitrogen, this uptake rate would correspond to a new primary production rate of about $2 \text{ gC} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, an impressive value. We emphasize that this calculation, and those that follow, represent only "new production" based on nitrate (Dugdale and Goering, 1967; Eppley and Peterson, 1979) and considering nutrient recycling these estimates would likely be much greater. We also point out that our calculations are based on our current meter data (20 cm s^{-1}); should this value be off, so would each of our calculated values which use it.

b. Cross frontal mixing and tidal flushing. A simple linear uptake of nitrate in the plume with increasing distance downstream and along the trajectory in Figure 8 is an oversimplification, since it is likely that nutrients are lost laterally from the center of the plume to both the shallow inshore waters to the north as well as to the stratified side of the front to the south by a variety of mechanisms.

Loder and Platt (1985) have examined the relative importance of a number of physical mechanisms which can transfer materials across tidal fronts. The more important mechanisms include: (a) the variation in the position of a front between spring and neap tides, and (b) cross frontal mixing by baroclinic eddies. Loder and Greenberg (1986) have examined the variations in the positions of tidal fronts between

Table 1. Summaries of data used in Figures 7 and 8 and for calculations referred to in the text. Values given are averages for the stations listed unless otherwise indicated.

(a) 8–9 Sept. 1984 R/V Cape Hatteras:

Transect	Stations	$\int_0^{35\text{ m}}$ Chl. <i>a</i> (mg · m ⁻²)	$\int_0^{35\text{ m}}$ Phaeopigments (mg · m ⁻²)	$\int_0^{35\text{ m}}$ Total Pigments** (mg · Chl.- equivalents · m ⁻²)	$\int_0^{35\text{ m}}$ $\text{NO}_3 + \text{NO}_2 - \text{N}$ (mg-at N · m ⁻²)	$\int_0^{35\text{ m}}$ Nauplii (No. · m ⁻³)
1	4, 5, 6, 7	8.4	15.5	31.8	290	2561
2	8, 9, 10, 11	11.6	15.4	34.8	259	4134
3	12, 13, 14, 15	30.0	28.0	72.0	194	5223
4	17, 18, 19	40.7	48.3	113.5	169	7185
5	20, 21, 22	33.0	28.0	75.0	181	5592

(b) 16–24 July 1985 R/V Gyre:

Transect	Stations	$\int_0^{35\text{ m}}$ Chl. <i>a</i> (mg · m ⁻²)	$\int_0^{35\text{ m}}$ Phaeopigments (mg · m ⁻²)	$\int_0^{35\text{ m}}$ Total Pigments** (mg · Chl.- equivalents · m ⁻²)	$\int_0^{35\text{ m}}$ $\text{NO}_3 - \text{N}$ (mg-at N · m ⁻²)	$\int_0^{35\text{ m}}$ Nauplii* (No. · m ⁻³)
1	65, 66, 67	56.5	43.5	122	224	2577
2	64, 63, 62	63.9	50.3	140	150	3643
3	53, 54, 55	113.0	83.0	238	120	14937
4	50, 49, 48, 47	107.0	77.9	224	96	1375
5	40, 41, 42, 43	39.5	25.6	78	30	16726

*Zooplankton samples (80 µm mesh bongo) from a single station only for each transect.

** Equals (mg phaeopigment × 1.508) + (mg chlorophyll *a*)

spring and neap tides for the Gulf of Maine and showed that only the waters within the immediate vicinity of Grand Manan Island are affected. The maximum and minimum extensions of the predicted positions of tidal fronts due to fortnightly and monthly variations in mixing are within the area east of Western Bay (i.e. east of about 67° 30' W) and hence are not likely to be responsible for nutrient exchanges across the plume edges west of this area, which is where we see the nutrient concentrations dropping (Figs. 2f and 4e).

We can evaluate the importance of cross-frontal mixing via baroclinic eddies using the formulations in Loder and Platt (1985). They showed that the magnitude of this exchange can be estimated using a semi-empirical expression, developed by Green (1970) for meteorological applications, and used by Pingree (1979) to estimate the transfer of heat across fronts in the Celtic Sea. For nitrate the expression is:

$$Q_e = \gamma \left[\frac{(g\Delta\rho D)}{\rho} \right]^{1/2} \cdot D\Delta C$$

where Q_e is the exchange rate of nitrate in mg at $\text{m}^{-1} \cdot \text{s}^{-1}$, g is gravitational acceleration, $\Delta\rho$ is the surface density difference across the front, ρ is the average density, D is the depth of the pycnocline on the stratified side of the front, ΔC is the difference in nitrate concentration across the front, and γ is a dimensionless constant which Green (1970) found to be 0.0055. Loder and Platt (1985), however, point out that their analysis of the Ushant front and laboratory experiments by Griffiths and Hopfinger (1984) suggest that this value for γ may be as much as an order of magnitude too low.

Using $\Delta\rho = 0.8 \times 10^{-3}$, $\rho = 1.024$, $D = 20 \text{ m}$, $\Delta C = 4 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^3$, and, as a conservatively high estimate, $\gamma = 0.055$, we calculate the flux of nitrate by baroclinic eddies per unit length of front to be ca. $1.72 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ from the plume to the stratified waters on the south. With a current velocity of 17 km d^{-1} and a frontal length of 130 km this mixed water will be in contact with the front 7.5 days. We calculate that $1.45 \times 10^{11} \text{ mg at } \text{NO}_3\text{-N}$ will be lost from the plume to the stratified waters south of the front. If we approximate the area of the plume to be $130 \text{ km} \times 40 \text{ km} = 5.2 \times 10^9 \text{ m}^2$, this loss averages out to $27.8 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^{-2}$ over 7.5 days, or $3.7 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^{-2} \text{ d}^{-1}$. If the total loss of nitrate in this bolus of mixed water over the 7.5 day period is $194 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^{-2}$ over 7.5 days, or $25.8 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, then the loss due to cross-frontal mixing by baroclinic eddies could be as much as 14% of that overall during the 7.5 days it would take for waters to travel from the Grand Manan area to the end of the plume. This suggests in turn that we should see significantly high chlorophyll levels along the front and not just at the downstream end, and this is indeed the case as revealed by the areal distribution of pigments integrated to 35 m, and the vertical section plots which show the presence of subsurface chlorophyll maxima in the pycnocline at the front (Fig. 5).

The subsurface chlorophyll maximum may also be receiving nutrients from vertical

mixing across the pycnocline, delivering nutrient-rich deeper waters to the near-surface layers. As Loder and Platt (1985) point out, this process can only be quantified if one knows the vertical eddy diffusivity, a value which has a wide range of reported values (Kullenberg, 1982). Using Loder and Platt's (1985) equation:

$$Q_v = K_v \cdot \left(\frac{\Delta C}{\Delta Z} \right) \cdot L_w$$

where, K_v (the vertical eddy diffusivity) = 10^{-4} m² s⁻¹, $\Delta C/\Delta Z$ (the vertical nitrate concentration gradient across the pycnocline) = ca. 10 mg at NO₃-N m⁻³/30 m = .33 mg at m⁻³ m⁻¹, and L_w (the width of the front along which there is transfer) = ca. 10 km, gives a value of Q_v = 0.33 mg at NO₃-N m⁻¹ s⁻¹. This addition of nutrients to the pycnocline and near-surface waters is about 20% of that supplied as a horizontal loss from the plume (1.72 mg at NO₃-N m⁻¹ s⁻¹).

Losses of nitrate from the plume to the shallow waters to the north are more likely due to simple tidal flushing rather than baroclinic eddies, since the thermal front inshore is only weakly developed, especially east of Western Bay during our July, 1985, cruise (Fig. 4a). The elevated chlorophyll concentrations inshore suggest that the bottom serves as the base of the mixed layer, which is shallower than the critical depth in these waters (ca. 60 m, Townsend and Spinrad, 1986), and that net growth of phytoplankton can occur once nutrients are supplied. The rate of transfer of nutrients from the plume to the inshore waters to the north can be estimated by invoking simple tidal flushing as the principal mechanism, if we assume: (a) that the volume of water exchanged across the northern plume boundary is equal to the product of the mean tidal range (ca. 3 m), the approximate length of the boundary (ca. 120 km), and the inshore-offshore, or cross-isobath, component of the tidal excursion, and (b) that these waters become completely mixed during each tidal cycle. Current meter records at the stations shown in Figure 1 (Townsend *et al.*, 1985) indicate that the tidal currents are strongly oriented alongshore, with excursions of 10 to 15 km at the nearshore station. Cross-isobath excursions are much less: 3 to 4 km at the nearshore station and less offshore, where there is little evidence of flow reversal with changing tide (Fig. 6). For the purposes of these analyses we have taken 3 km as a representative value for the cross-isobath (north-south) tidal excursion along the eastern portions of the plume. The flux of nutrients from the plume to the inshore waters on each tide can then be calculated as:

$$Q_f = \frac{V_t \left(\frac{N_p + N_i}{2} \right) - N_i}{12.4 \text{ hrs}}$$

where, V_t = the exchange volume (= 3 km · 120 km · 3 m), N_p = the mean nitrate concentration in the plume (ca. 5 mg at NO₃-N · m⁻³), and N_i = the mean nitrate concentration of the inshore waters (ca. 2 mg at NO₃-N · m⁻³). This comes out to

$1.62 \cdot 10^9$ mg at $\text{NO}_3\text{-N}$ per tide being mixed from the plume to the inshore waters along a 120 km length; in units similar to our estimate of cross frontal mixing to the south by baroclinic eddies, this is 0.3 mg at $\text{NO}_3\text{-N} \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ length, or about 0.62 mg at $\text{NO}_3\text{-N} \cdot \text{m}^{-2}$ over 7.5 days. This is about one-fifth that calculated for cross frontal mixing to the south and about 4% of the overall loss during a 7.5 day transit for waters in the plume.

c. Primary and secondary production in the plume. Accepting these estimates of nitrate losses out the sides of the plume (totalling ca. 4 mg at $\text{NO}_3\text{-N} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) we can proceed with estimates of the resulting production of phytoplankton downstream from the area of mixing, as well as the probable transfer of this production to zooplankton. If we assume that the phaeopigments we measured were produced from chlorophyll *a* by degradation (Lorenzen, 1965) and that the phaeopigments measured fluorometrically are predominantly phaeophorbide *a*, we can convert these measures back to chlorophyll-equivalents by multiplying mg phaeopigments times (894/593), which is the ratio of molecular weights for chlorophyll *a* and phaeophorbide *a* (Welschmeyer *et al.*, 1984). Thus, if we assume that there is little or no loss of phytoplankton due to either sinking of cells or grazing by zooplankton in the well-mixed Grand Manan area, then we can relate the apparent "loss" of nitrate to production of chlorophyll. These assumptions appear to be met for the first 3 transects (Fig. 8) presented in Table 1 for our July cruise. For example, the change in total phytoplankton pigments (in chlorophyll-equivalents) from transect no. 1 to no. 3 is 116 mg · m⁻², while the apparent uptake of nitrate is 104 mg at $\text{NO}_3\text{-N} \cdot \text{m}^{-2}$. Since about 18% of this apparent uptake may be due to cross frontal mixing and tidal flushing out the sides of the plume, the change in nitrate due to biological uptake would be 85 mg at $\text{NO}_3\text{-N} \cdot \text{m}^{-2}$; converting this to carbon produced, by multiplying by the Redfield ratio of 6.625, and converting from mg atoms to mg, reveals a primary production rate of 6.8 g C · m⁻² between transect no. 1 and no. 3. Multiplying this value by the current velocity (17 km · d⁻¹) divided by the distance (80 km) gives a production rate of 1.44 g C · m⁻² · d⁻¹. Dividing this carbon production (6.8 g C · m⁻²) by the chlorophyll production (0.116 g chlorophyll-equivalents · m⁻²) gives a carbon:chlorophyll ratio of 59, a reasonable value well within published ranges (Welschmeyer *et al.*, 1984; Welschmeyer and Lorenzen, 1984). If we assume that "downstream" from transect no. 3 departures of the carbon-produced:chlorophyll-produced ratio from a value of 59 reflect either sinking of cells, which would be unlikely in such a high energy environment, or losses of phytoplankton carbon by respiration or assimilation into a higher trophic level, we can assess relative secondary production. For example, new primary production between transects no. 3 and no. 4, calculated using 82% of the total change in nitrate, is about 1.5 gm C · m⁻². Without losses due to grazing we would expect the carbon-produced to chlorophyll-produced ratio to equal 59 and thus we should see a positive change in chlorophyll of 26.5 mg · m⁻². Instead, we see (Table 1) a decrease in chlorophyll of 14 mg · m⁻². This

difference of 40.5 mg chlorophyll-equivalents · m⁻² between that expected and that observed corresponds, then, to a value of about 2.4 gm C · m⁻² for respiration and gross secondary production, meaning that grazing likely exceeds production. Similar numbers are obtained between transects no. 4 and no. 5. This chain of events, from the Grand Manan area to the western sectors of the inner Gulf of Maine, helps to explain the overall greater biomass of zooplankton, especially macrozooplankton, toward the west as has been noted by earlier workers (Bigelow, 1926; Fish and Johnson, 1937; Sherman, 1970).

5. Probable sources of plume waters

One question which remains outstanding is where do these nutrients in the Grand Manan area come from? The two logical sources are the Bay of Fundy and the deep waters of Jordan Basin which derive from slope water (Bigelow, 1927). While it is probable that both are important sources, average nutrient levels measured during August at the mouth of the Bay of Fundy to the northeast of Grand Manan Island, presumably "upstream" from the plume origin, are only 0.33 mg at NO₃-N · m⁻³ (Keizer *et al.*, 1984), while the deep waters of Jordan Basin are much higher (Fig. 5). It would seem that upwelling of deep Jordan Basin waters, as indicated by the upward-bending isopleths in Figure 5, is an important process and that the high nitrate waters in the plume represent a significant mix of deep Jordan Basin water with the Bay of Fundy water which enters the Gulf at the surface.

This interpretation appears tenable in examining the T-S relations (Fig. 9) of water types available for mixing both in the immediate vicinity of Grand Manan Island, where the nutrient concentrations were the highest (Fig. 2f and 4e), as well as along the axis of the plume. The T-S envelope for mixed water (MW) near Grand Manan (Fig. 9) represents the near-center of the T-S envelope for the plume water (PW), which in turn shows the T-S signatures for Maine coastal water (CW) and the mixture of deeper slope water and Maine intermediate water as represented by station 61. This mixed water also corresponds to the deeper water sections of the Bay of Fundy water (BFW). We would conclude, therefore, that similar to observations off southwest Nova Scotia (Denman and Herman, 1978), upwelling of the deeper waters of Jordan Basin, which derive from intrusions of slope water into the Gulf, make an important contribution to the nutrient dynamics of the plume.

6. Conclusions

Our analyses of the plume of cold, high-nitrate, water which originates in the Grand Manan area suggest to us that this feature may be extremely important to the biological oceanography of the entire inner Gulf of Maine. The plume feature appears to represent significant upwelling and mixing of deep Jordan Basin waters, which ultimately derive from slope water entering the Gulf of Maine through the Northeast Channel. In fact the 200 m isobath comes closer to shore in the vicinity of eastern

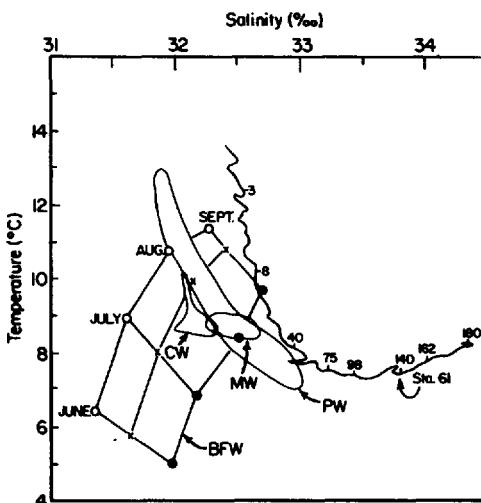


Figure 9. Temperature-salinity diagram illustrating the probable mixing of the various water types for the July, 1985 cruise along the plume axis from the Grand Manan area toward the southwest where the surface nitrate levels disappear (Fig. 5e). MW – the mixed water with the highest nitrate concentrations, comprising stations 67 and 68 in the immediate vicinity of Grand Manan Island; PW – the plume water and comprises stations 62, 63, 54, 55, 48 and 49 along the axis of the plume. CW – Maine coastal water and comprises stations 64, 65 and 66. BFW – Bay of Fundy water for the surface (open circles; less than 25 m), mid-depth (x's; between 25 and 75 m), and bottom (solid dots; between 75 and 90 m) for each season, as presented by Bailey *et al.* (1954) for the station shown in Figure 1a. Station 61 illustrates the three water layers typical for the offshore Gulf of Maine (Hopkins and Garfield, 1979): the warmer and less saline Gulf of Maine surface water, the relatively fresh and cold Maine intermediate water, and the warmer, saltier Maine bottom water which results from the intrusion of slope water into the Gulf. Depths in meters are indicated for Station 61.

Maine than anywhere else in the Gulf of Maine (Fig. 1a). As Bigelow (1927; Figs. 95 and 152) first observed, the warm and salty slope waters that enter the Northeast Channel at depth hug the shelf edge along Nova Scotia, filling Jordan Basin and hence making high-nutrient slope waters available for mixing and upwelling off southwest Nova Scotia and in the Grand Manan area. It is important to note that aside from the southwestern Nova Scotian shelf the plume feature is the only area where summer nitrate levels can be seen to exceed 0.1 μM at the surface; the areal plot of integrated nitrate shows that this feature in the eastern Gulf can be traced well into the western sectors, and, as was noted by Bigelow (1926) and Fish and Johnson (1937) it is toward the west that zooplankton biomass is greatest (Figs. 5i and 9). We would assume, therefore, that production in the western Gulf is greatly dependent upon nutrient recycling by zooplankton, rather than on new nitrate, and that this process is in turn driven by the dynamics of the plume feature in the eastern Gulf, as perhaps modified by a mesoscale eddy over Jeffreys Bank. A simple calculation serves to underscore the importance of these plume waters to the nutrient budget of the inner Gulf of Maine.

The flux of nitrate into the Gulf via the plume can be estimated by taking an average nitrate concentration at the origin of the plume in the Grand Manan area (ca. 5 mg at $\text{NO}_3\text{-N} \cdot \text{m}^3$) and multiplying by the volume transport of plume waters (ca. $30 \text{ km wide} \times 60 \text{ m deep} \times 17 \text{ km} \cdot \text{d}^{-1}$); this gives a flux of $1.51 \times 10^{11} \text{ mg at } \text{NO}_3\text{-N} \cdot \text{d}^{-1}$. Dividing this value by the approximate area of the inner Gulf of Maine (inside a line from Cape Cod to Nova Scotia; $57,500 \text{ km}^2$) gives an average Gulf-wide flux of nitrate of $2.6 \text{ mg at } \text{NO}_3\text{-N} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$. This converts to a new primary production of $0.21 \text{ g C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ or $76 \text{ g C} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$. Schlitz and Cohen (1984) report that the flux of nitrate through the Northeast Channel is about $3.97 \times 10^9 \mu\text{g at N sec}^{-1}$, or $3.43 \times 10^{11} \text{ mg at N} \cdot \text{d}^{-1}$. This means that about 44% of the nitrate which enters the Gulf of Maine system through the Northeast Channel makes its way into the surface waters of the Gulf via the plume, leaving winter convective overturn, diffusion through the pycnocline and coastal upwelling to account for the remaining 56%.

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