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Fluorescence structure in the region of the tidal mixing front on the southern flank of Georges Bank

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Abstract—Transects of fluorescence measurements were made across the region of the tidal-mixing front on the southern flank of Georges Bank in 1992, 1993 and 1994. The fluorescence distribution exhibited three characteristic patterns: (i) a subsurface maximum associated with the pycnocline in stratified water columns; (ii) a spatially incoherent variability with a characteristic spectral slope, believed to be related to the local vertical mixing processes; and (iii) a higher level of fluorescence within the front on some transects. This latter pattern was observed when the tidal current amplitude had recently increased with the local fortnightly/monthly variability. Published by Elsevier Science Ltd

INTRODUCTION

On the southern flank of Georges Bank, seasonal stratification develops in the late spring and summer due to the seasonal increase in surface warming and decrease in the mean wind stress. In the shallow, central region of the bank, strong tidal currents keep the water column well mixed year round. The boundary between the well-mixed and stratified regions is determined by a balance between buoyancy input from surface heating and the intensity of local tidal mixing or tidal energy dissipation (Simpson and Pingree, 1978). The boundary often is referred to as the tidal mixing front, and on Georges Bank it is located at about the 60 m isobath (Garrett *et al.*, 1978).

The characteristic chlorophyll distributions in the two regions of the bank have been summarized by O'Reilly *et al.* (1987). In the well-mixed waters, the chlorophyll values are relatively uniform through the water column, while in the stratified region a subsurface maximum in chlorophyll exists in the spring, associated with the development of the seasonal density stratification. The chlorophyll levels and the measured rates of primary production generally are greater in the well-mixed region than in the stratified water columns on the southern flank of the Bank. The well-mixed central region of the Bank also is characterized by a higher percentage of large phytoplankton cells compared to the stratified region. The species complex in the well-mixed waters is dominated by diatoms, while the stratified waters are dominated by flagellates (Cura, 1987).

Tidal mixing exerts an important influence on the growth and distribution of phytoplankton by affecting the availability of light and of nutrients. Tidal-mixing fronts are often associated with high levels of chlorophyll, particularly on the stratified side of the front where the stratification can provide sufficient light conditions and local mixing can provide a source of nutrients (Simpson and Pingree, 1978; Demers *et al.*, 1986). Horne *et al.*

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(1989) measured a higher nutrient demand within the frontal region on the northern edge of Georges Bank than in the stratified or the well-mixed regions on either side of the front. They also estimated that the nitrate flux across the front was sufficient to support the phytoplankton production within the entire well-mixed region of the Bank. The distribution of chlorophyll or fluorescence within the region of the tidal-mixing front on the southern flank of Georges Bank, however, has not been well described.

The purpose of this paper is to characterize the structure of fluorescence in the region of the tidal mixing front on the southern flank of Georges Bank during spring and to identify the processes that determine that structure.

DATA AND METHODS

Cruises were conducted during the first two weeks of May 1994 and last two weeks of May 1992, 1993 and 1994. Temperature, salinity and fluorescence data were collected by a Neil Brown Instrument Systems MK5 CTD instrument with a SeaTech fluorometer. The data were processed to 1 db average values. The fluorescence data are reported here in volts. On the 1993 cruise water samples were filtered, and chlorophyll values were determined to compare with the fluorescence data.

The primary objective of the cruises was to compare conditions on the southern flank of the Bank, where seasonal stratification was beginning to develop, with those in the nearby well-mixed region. As a result, sampling was focused at one or more sites in the deeper stratified region and at a nearby site in the shallower, well-mixed region. In addition, on each of these cruises one or more transects of observations was made across the tidal front region from stratified to well-mixed conditions. A total of 10 transects were made.

On 1992 transects, a CTD profile was made every 12 min as the vessel steamed at about 2.5 knots, resulting in a profile about every 900 m horizontally. In 1993 and 1994, profiles were made approximately every 5 min, or about every 300–350 m horizontally, along transect lines. On transects in 1992 the instrument was lowered for one profile and held at depth to be raised at the time of the next profile, such that profiles alternated between up and down casts. A potential bias in the up cast fluorescence was identified after the cruise (see Appendix), and for transects in 1993 and 1994 the instrument was retrieved immediately at the end of each cast and only down cast data are used to construct the transects.

In 1992 three transects (nos 1, 2, and 3) were completed from the stratified to the well-mixed region, each about a day apart. In 1993, transect sampling was timed such that the water column would be at the on-bank or off-bank extreme of the tidal displacement ellipse during the sampling. Transects 4 and 6 were made from south to north during the on-bank tide, while 5 and 7 were made from north to south on the off-bank extreme of the tide. A transect took about 4 h to complete and was timed to begin 2 h before and to extend 2 h after the extreme in the tidal displacement. The speed of the vessel relative to the water was about 1.5 knots, such that the horizontal spacing of the profiles was about 200–250 m in the reference frame of the water. Transect 4 had to be terminated due to electrical problems before reaching well-mixed water. In 1994 one pair of on-bank/off-bank transects (8 and 9) was made on the early May cruise, and a single transect (10) was made on the later cruise in May. The locations of the transects conducted in the different years are shown in Fig. 1 and are listed in Table 1. Currents were measured on a mooring on the southern flank of the Bank in 1993 (see Fig. 1), allowing the tidal displacement during the 1993 transect sampling to be estimated.

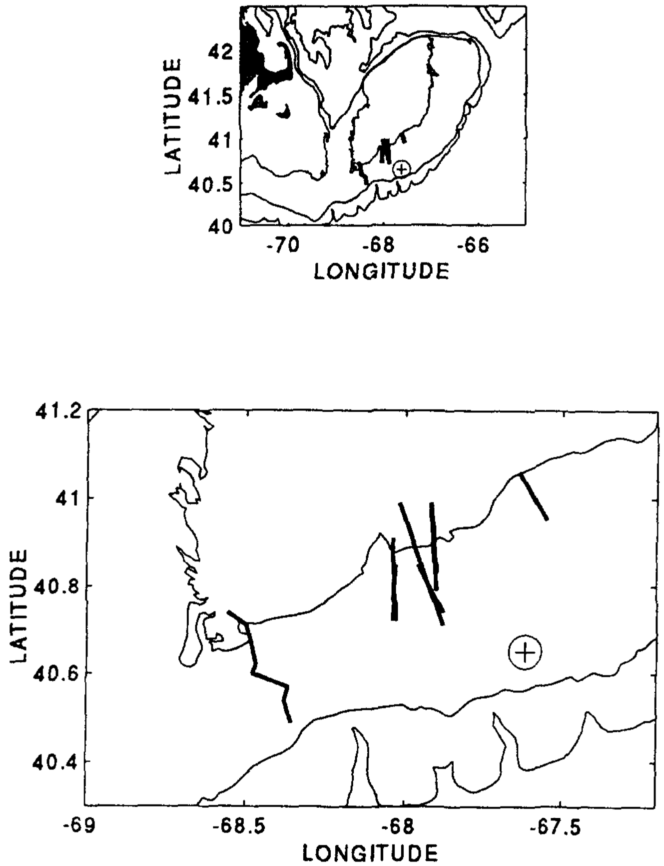

Fig. 1. Location of the CTD/fluorometer transects occupied in 1992, 1993 and 1994 (see Table 1). The ⊕ indicates the location of a current meter mooring during the 1993 cruise.

Table 1. *CTD/fluorometer transects through the region of the tidal mixing front*

Year	Month/ Day	Transect	Start Position	End Position	Start Depth (m)	End Depth (m)
1992	5/25	1	40°44.4 N 67°52.7 W	40°50.8 N 67°57.5 W	73	51
1992	5/26	2	40°42.6 N 67°52.7 W	40°59.4 N 68°01.2 W	76	49
1992	5/27–5/28	3	40°29.3 N 68°21.8 W	40°44.2 N 68°33.7 W	97	62
1993	5/23	4	40°43.1 N 68°02.2 W	40°50.3 N 68°01.9 W	79	66
1993	5/26	5	40°42.9 N 68°02.1 W	40°54.4 N 68°02.4 W	79	47
1993	5/26	6	40°54.7 N 68°02.6 W	40°43.3 N 68°01.9 W	47	77
1993	5/26–5/27	7	40°44.0 N 68°02.3 W	40°54.3 N 68°02.2 W	76	47
1994 (I)	5/12	8	40°47.2 N 67°54.2 W	40°58.1 N 67°55.2 W	68	56
1994 (I)	5/12	9	40°59.8 N 67°55.2 W	40°49.6 N 67°54.1 W	53	66
1994 (II)	5/24	10	40°57.0 N 67°32.9 W	41°03.5 N 67°38.6 W	70	56

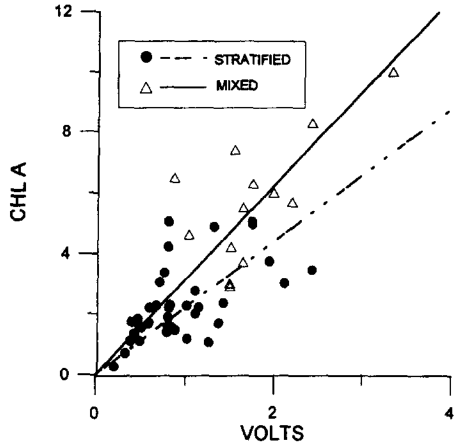

Fig. 2. Regression relationships between fluorescence value from the CTD fluorometer and the abundance of chlorophyll determined by acetone extraction, for water samples from stratified (- – -) and well-mixed (—) regions during the cruise in May 1993.

To determine the spatial structure of the vertical variability in fluorescence data, variance spectra were calculated. To do this a group of 20 casts from the stratified region and 20 casts from the well-mixed region in 1993 were reprocessed to 0.5 db average values (rather than the 1 db depth bins used in the standard data processing). A fast Fourier transform (FFT) was calculated using the fluorescence from the deepest 32 m (64 points) of each cast. The spectral estimates were averaged from the different casts in each region to yield average spectrum. Since the spectra may provide insight into the source of the fluorescence variability, only the deepest values were used to exclude from the spectral calculations the variance associated with the subsurface fluorescence maximum, a characteristic feature of the pycnocline in the stratified water columns (see below). The subsurface fluorescence maximum and the fluorescence variability away from the maximum are believed to have different causes, and therefore, it was important to exclude the maximum region from the spectral calculations.

RESULTS

Chlorophyll/fluorescence relationship

Significant linear relationships exist between the measured fluorescence and extracted chlorophyll values in 1993 from both the stratified and the well-mixed regions (Fig. 2). While the regression lines for the two regions are significantly different, there is considerable scatter in each case, and no attempt is made to convert the fluorescence data to chlorophyll values. The cause of the different regression lines for the two regions is believed to be due to different dominant species in the two regions (Cura, 1987). Other comparisons of SeaTech fluorometer data with extracted chlorophyll values also have indicated a linear relationship, which changed seasonally, likely with changes in the species composition (Townsend *et al.*, 1991).

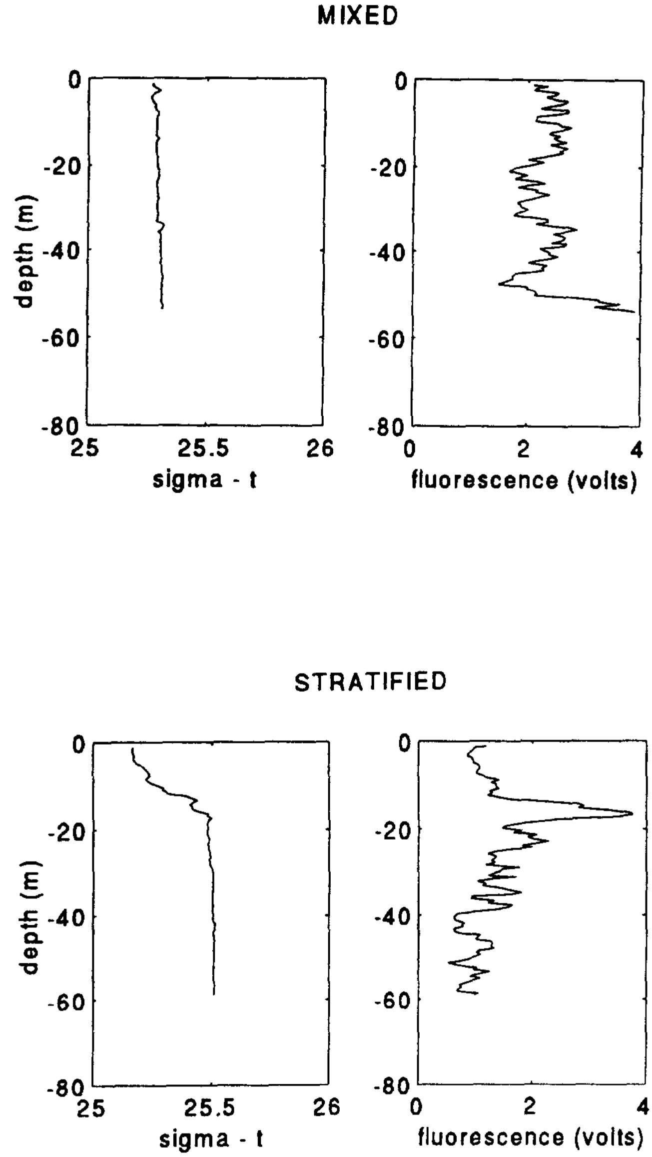

Fig. 3. Density (left) and fluorescence (right) profiles for representative stations in the well-mixed (top) and stratified (bottom) areas of the southern flank of Georges Bank.

Vertical structure and spectra

Representative profiles of the fluorescence and density (σ_t) in the stratified region show a subsurface maximum in fluorescence often occurred in or around the pycnocline (Fig. 3). Below the maximum, considerable variability existed, but with no apparent pattern. Profiles from the well-mixed region generally showed no characteristic vertical pattern, although there was considerable variability in fluorescence (Fig. 3). The variance spectra for the vertical profiles in fluorescence in both the stratified and the well-mixed regions have slopes

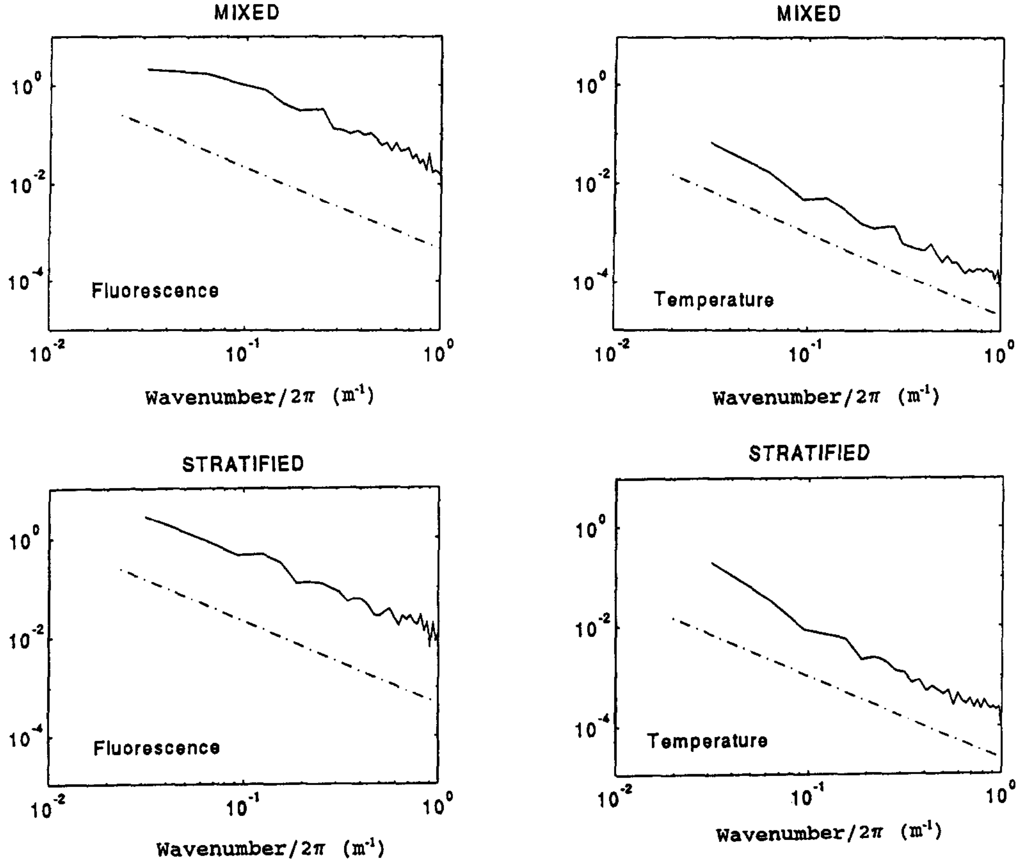

Fig. 4. Averaged variance spectra for the vertical variations in fluorescence (left) and temperature (right) from 20 stations in (top) the well-mixed and (bottom) stratified regions (see text for an explanation). The dashed lines represent a slope of −5/3.

of approximately −5/3 (Fig. 4). The spectra for the corresponding temperature data in both regions also have spectra with slopes of approximately −5/3 (Fig. 4).

Spatial variability—transects

The 10 transects through the front illustrate the characteristic structure of the frontal region (Figs 5–14). The temperature, salinity and density are stratified, particularly over the upper 30 m of the water column, at the southern end of the sections and are vertically uniform at the northern end. The transition between the two regions (i.e. the front) occurs over a distance of about 10 km, with the isolines (isotherms, isohalines and isopycnals) from the surface layer intersecting the surface and those from within the pycnocline and below intersecting the bottom. Section pairs made during subsequent on-bank/off-bank extremes of the tidal ellipse [transects 6 and 7 (Figs 10 and 11) and transects 8 and 9 (Figs 12 and 13)] suggest that the front is sharper (narrower) at the on-bank extreme and more gradual

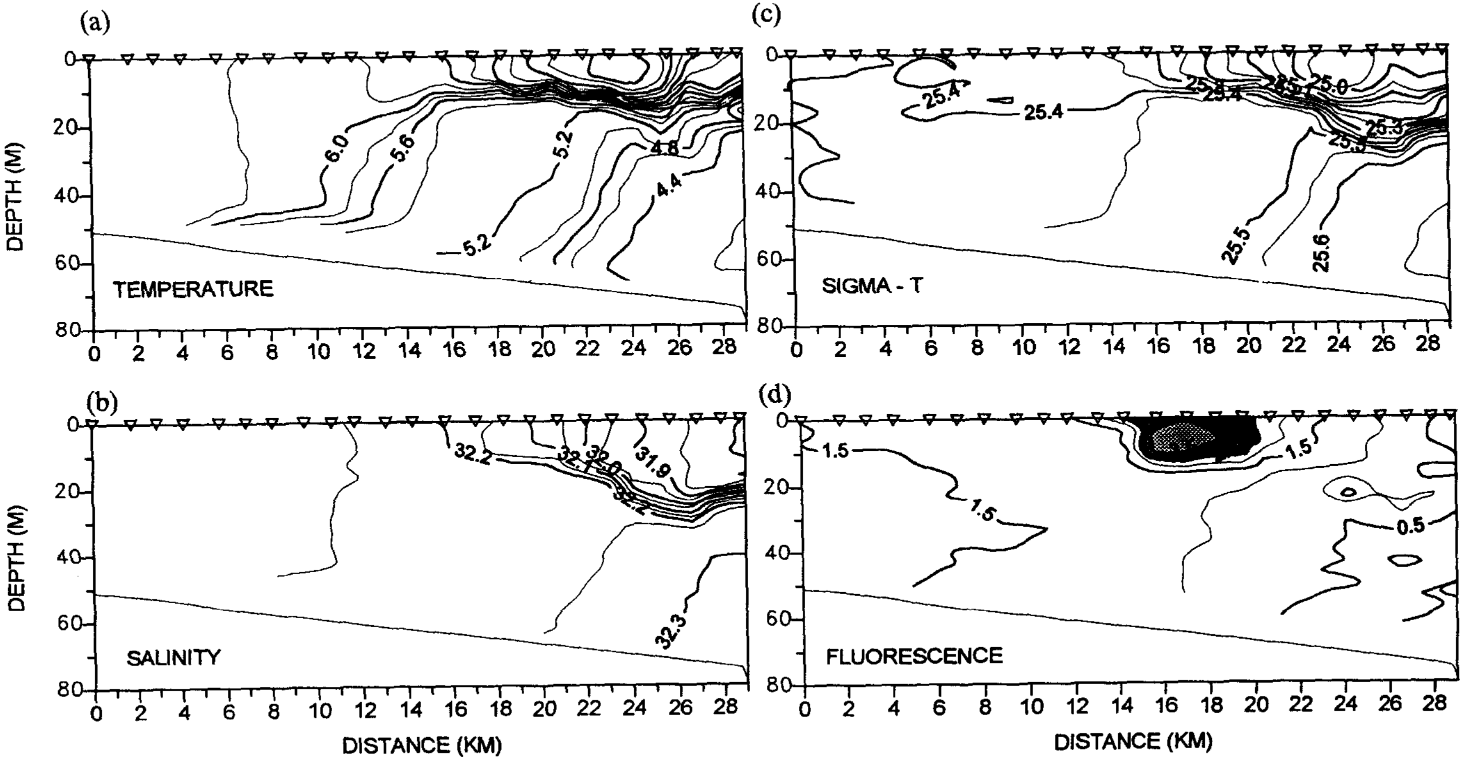

Fig. 5. Cross-sections of (a) temperature, (b) salinity, (c) σ_t and (d) fluorescence for the first transect 1 (May 1992). See Table 1 for location and time information. Station locations are indicated by ∇ along the top axis. North is to the left, south to the right. The line sloping down from the left to the right represents the bottom. Fluorescence values > 2.5 are shaded.

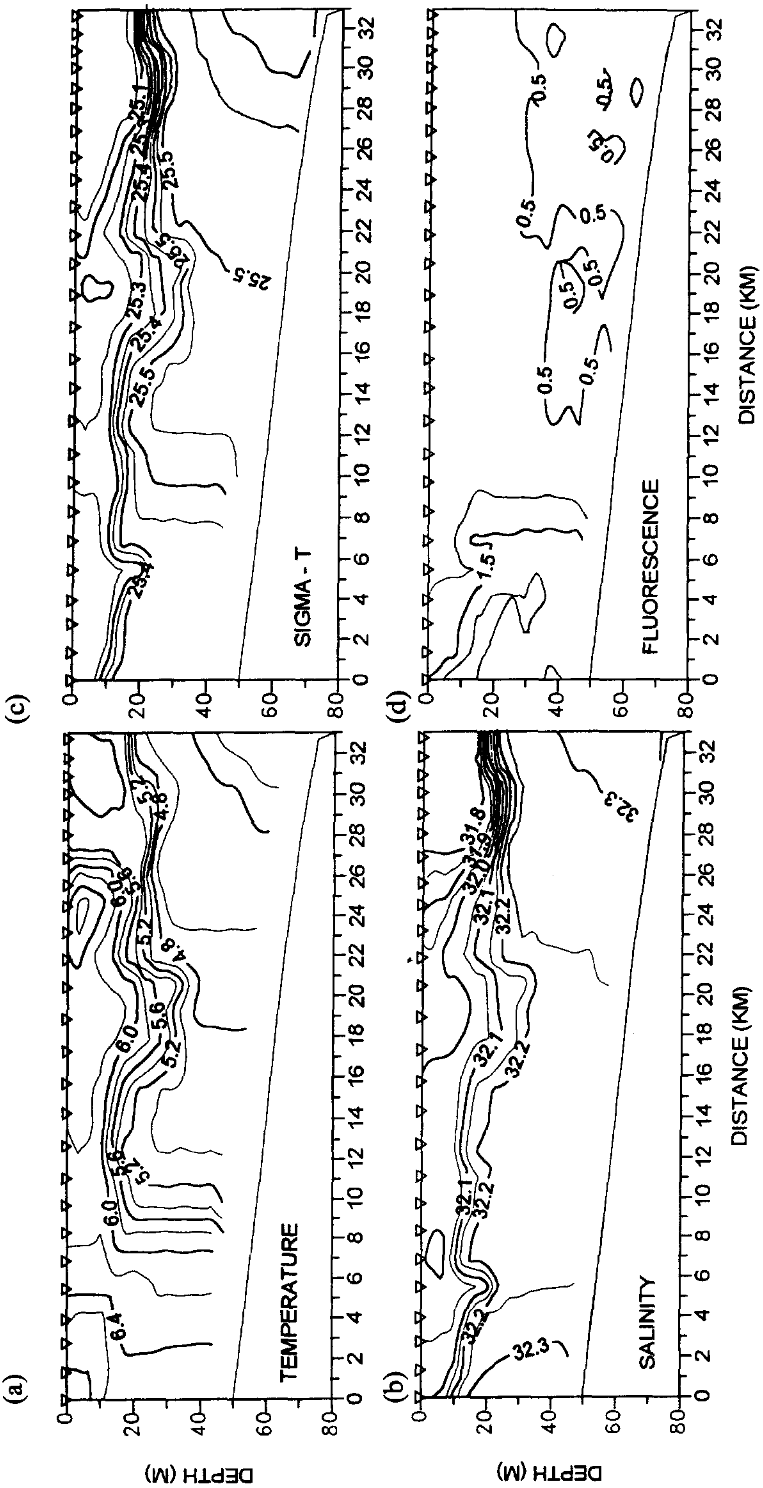

Fig. 6. As Fig. 5 but for transect 2 (May 1992).

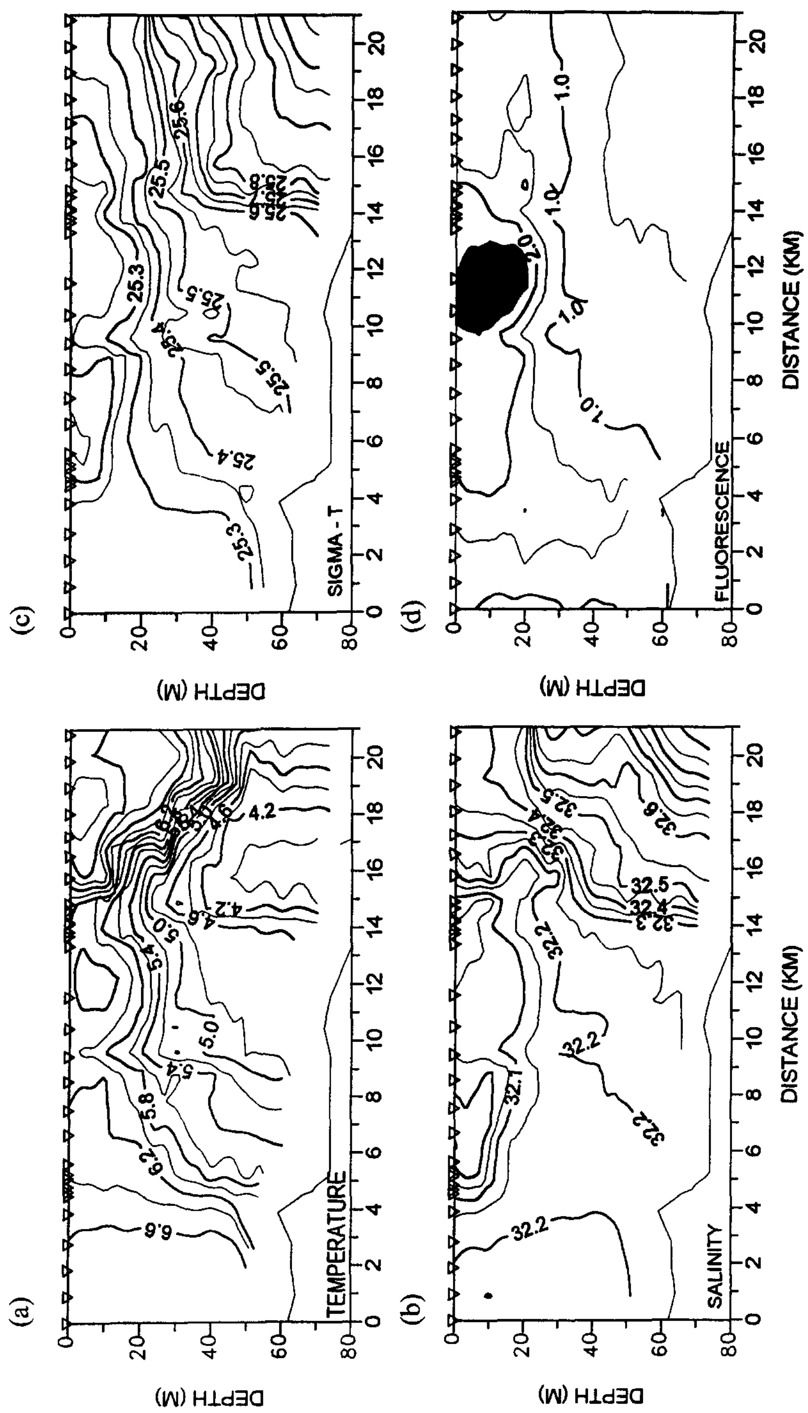

Fig. 7. As Fig. 5 but for transect 3 (May 1992).

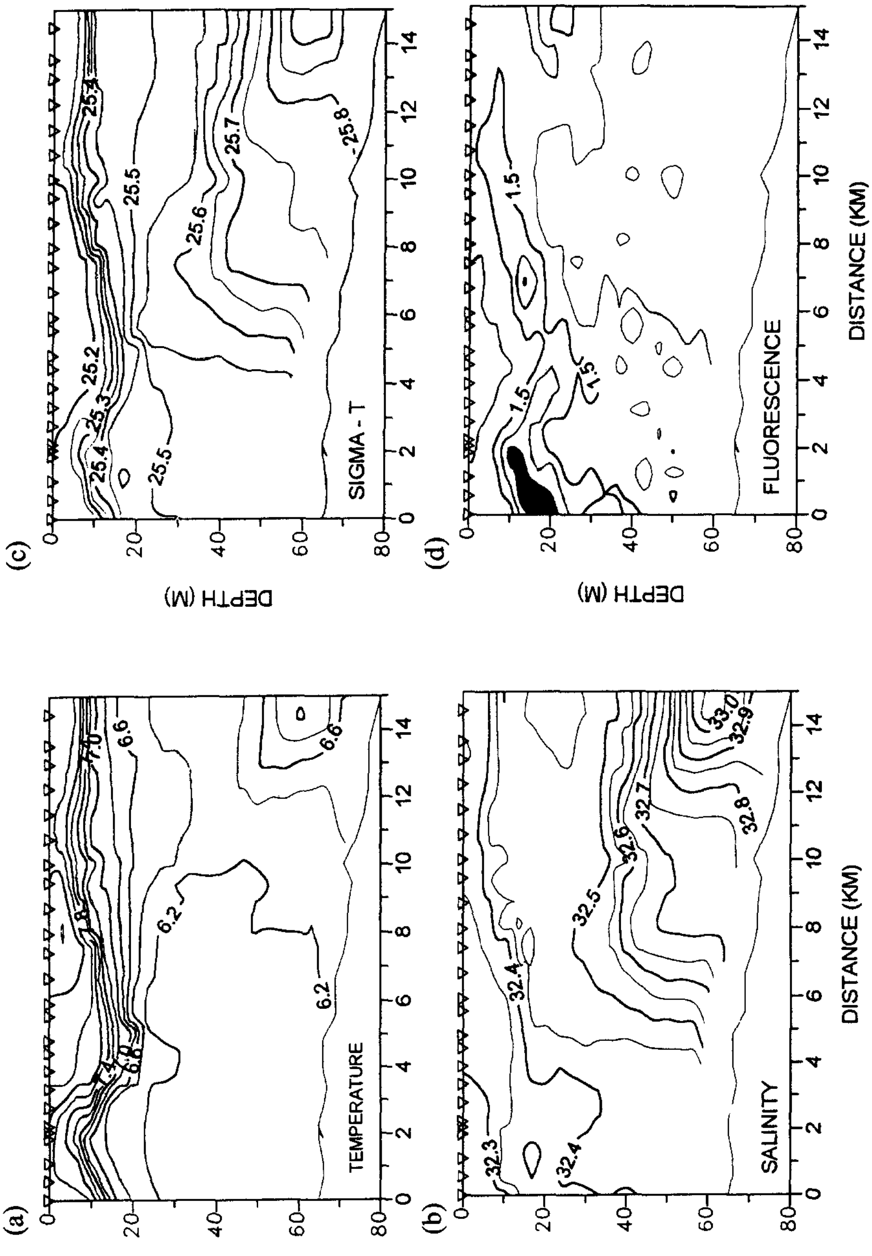

Fig. 8. As Fig. 5 but for transect 4 (May 1993), made during the on-bank extreme of the tidal ellipse.

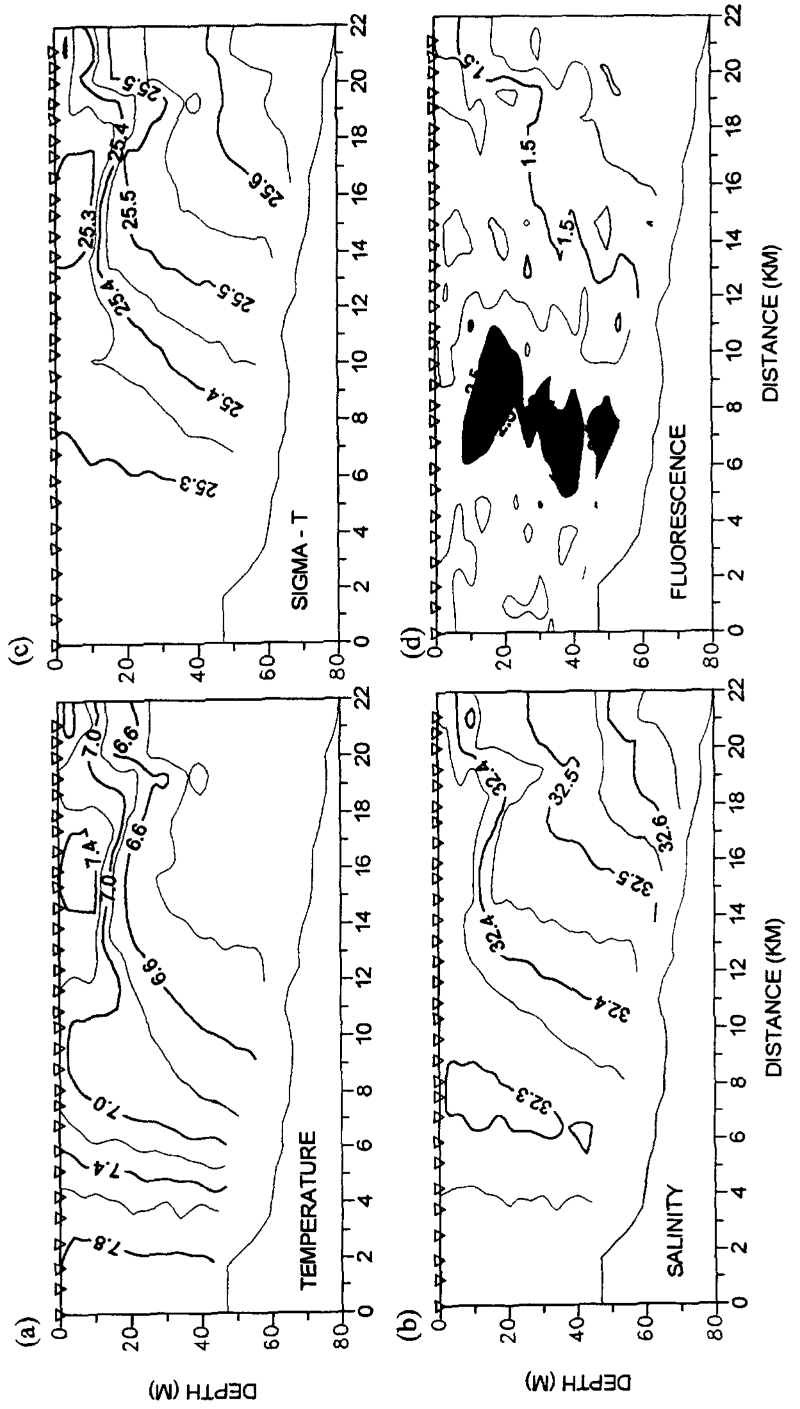

Fig. 9. As Fig. 5 but for transect 5 (May 1993), made during the off-bank extreme of the tidal ellipse.

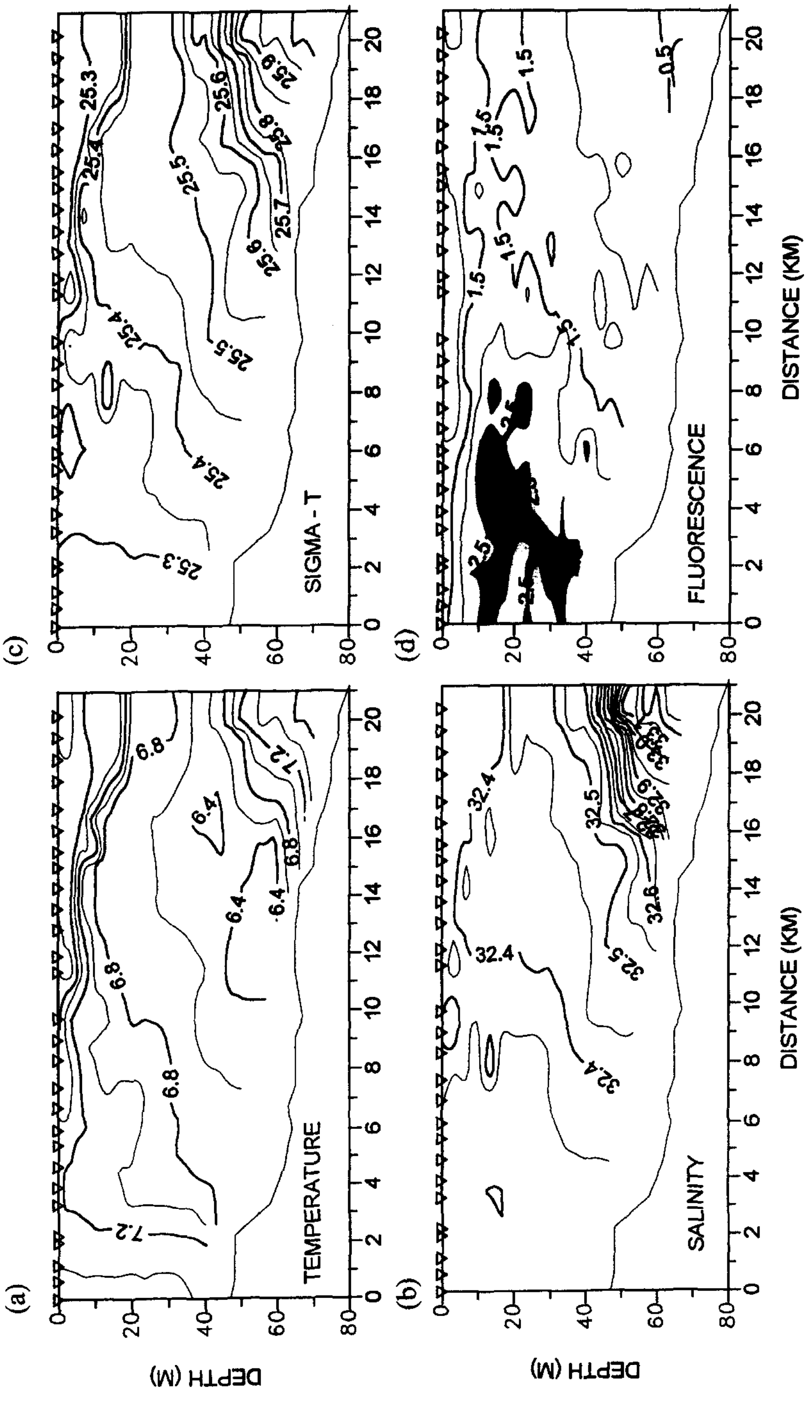

Fig. 10. As Fig. 5 but for transect 6 (May 1993), made during the on-bank extreme of the tidal ellipse.

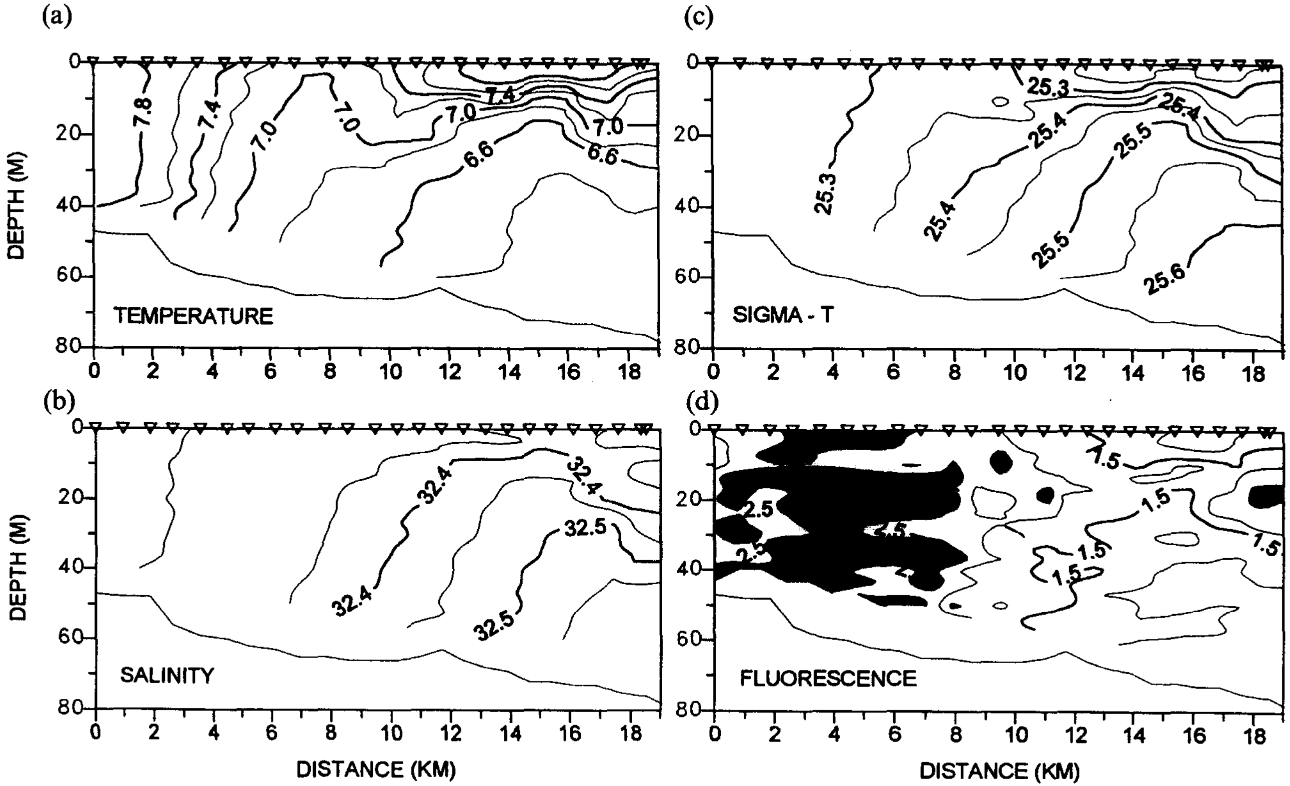

Fig. 11. As Fig. 5 but for transect 7 (May 1993), made during the off-bank extreme of the tidal ellipse.

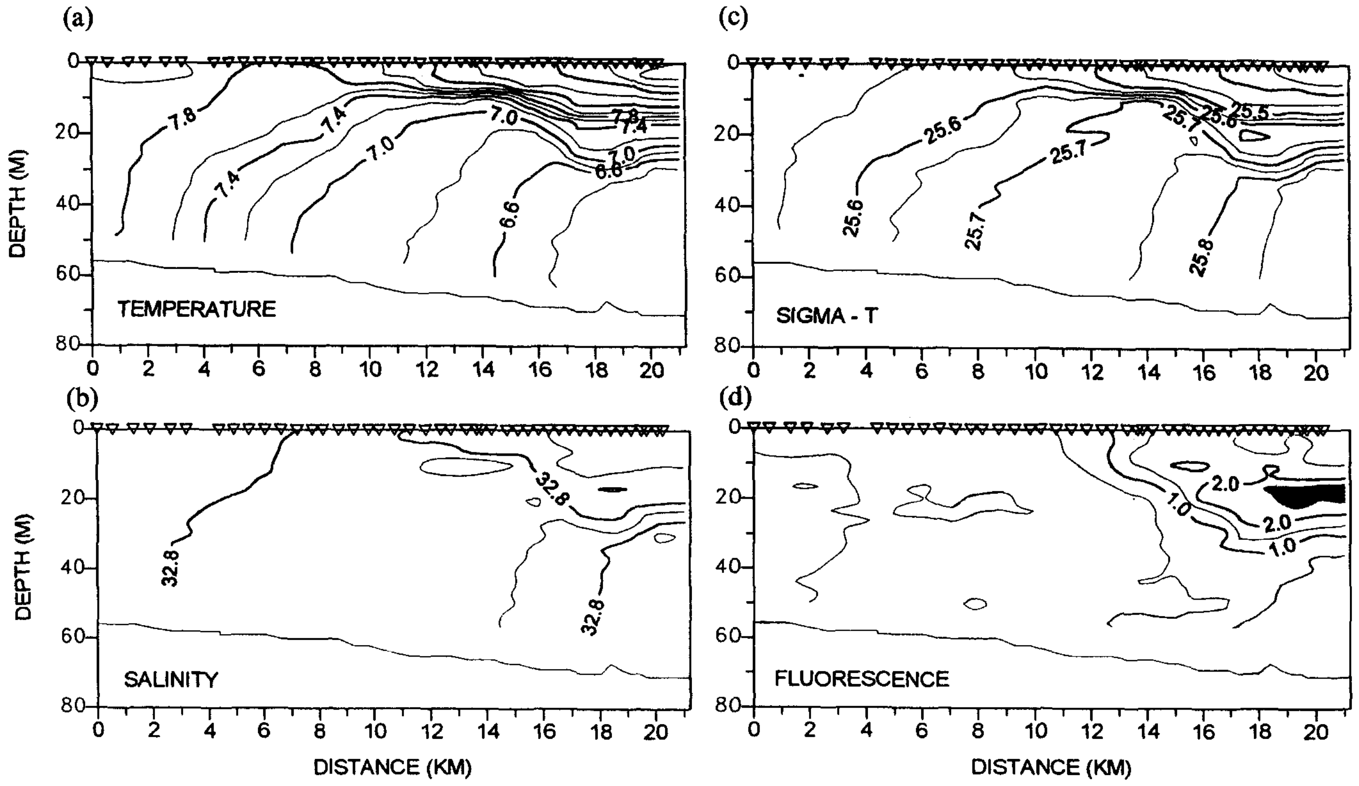

Fig. 12. As Fig. 5 but for transect 8 (May 1994), made during the on-bank extreme of the tidal ellipse.

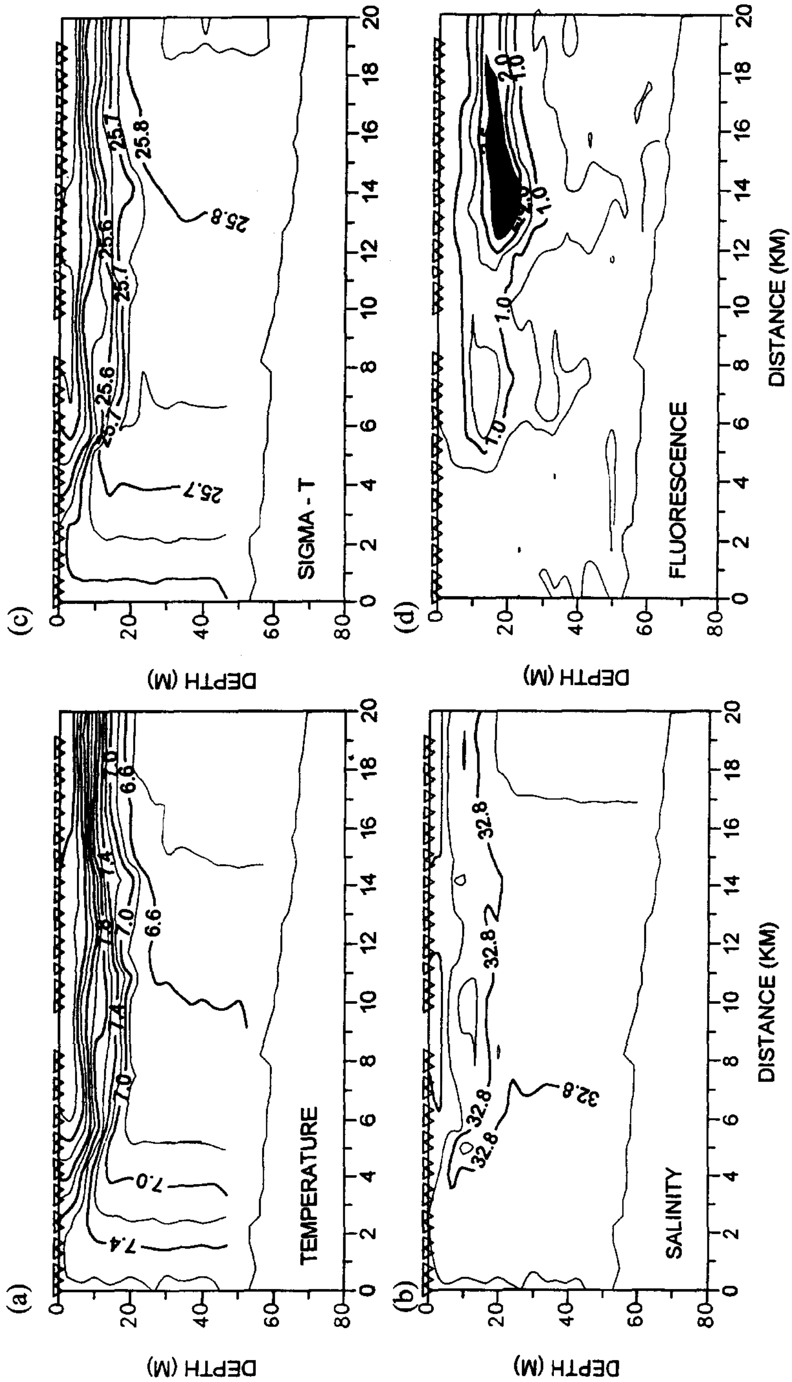

Fig. 13. As Fig. 5 but for transect 9 (May 1994), made during the off-bank extreme of the tidal ellipse.

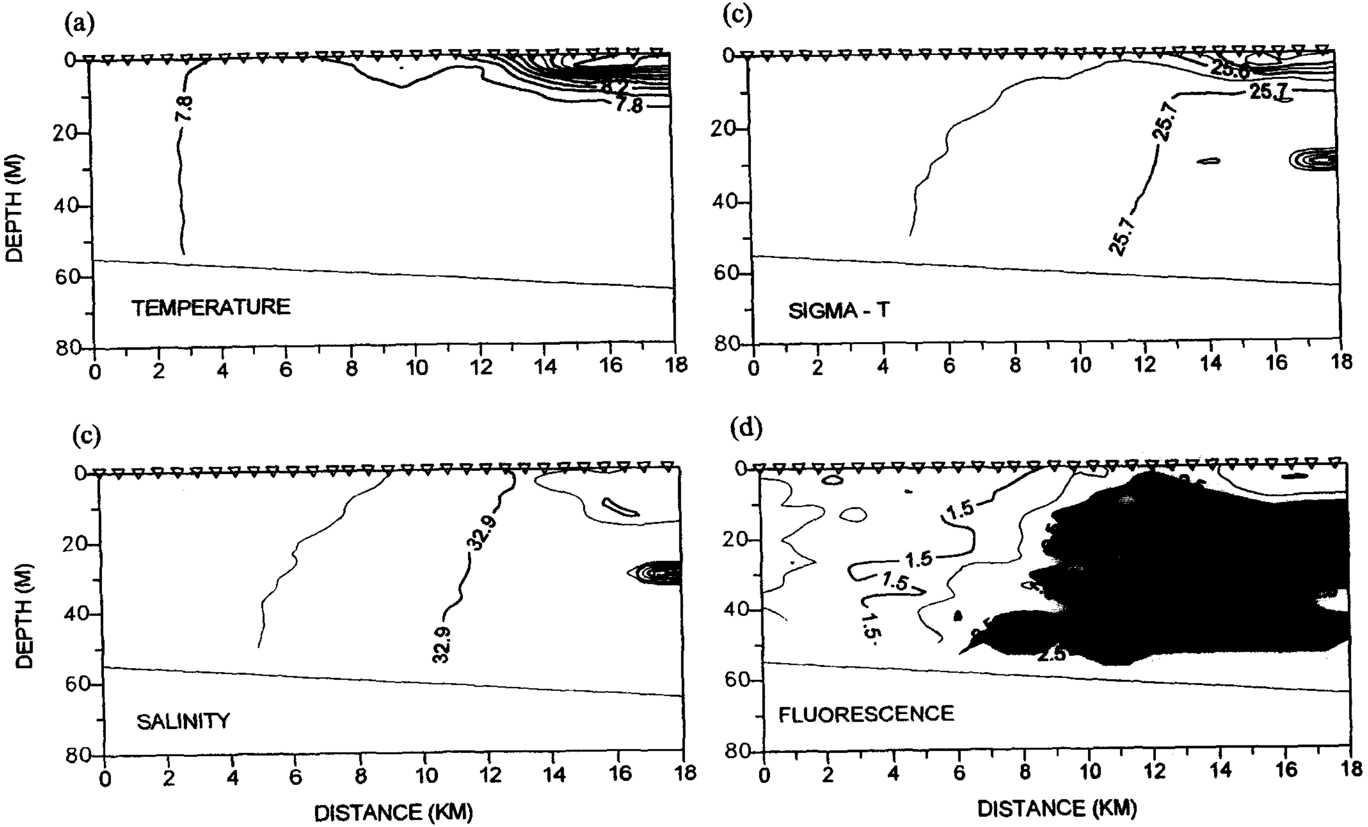

Fig. 14. As Fig. 5 but for transect 10 (May 1994).

(wider) at the off-bank extreme. The frontal transition also occurs more sharply in the stratified surface layer than in the lower layer.

The subsurface fluorescence maximum characteristic of individual profiles in the stratified region (Fig. 3) is a coherent feature in the pycnocline across the stratified region south of the front in most of the transects. The fluorescence variability in the lower part of the stratified water column and through the whole mixed water column in Fig. 3 is not spatially coherent across the transects, but is evident as numerous, small closed contours in the transects. Another characteristic of the fluorescence sections is a region of higher fluorescence, throughout the water column, within the front on some transects [e.g. transects 5, 6, 7 and 10 (Figs 9–11 and 14)].

Progressive vector diagrams for the currents measured at 15 m and 45 m depth at the mooring location (Fig. 1) were constructed for the periods when transects 5, 6 and 7 were conducted (Fig. 15a–c). The transects were done during the intended half of the tidal excursion, indicating that they do represent sequential off-bank, on-bank and off-bank extremes of the tidal excursion.

DISCUSSION

The fluorescence distribution in the region of the tidal mixing front on the southern flank of Georges Bank exhibits three characteristic patterns: (i) a subsurface maximum associated with the pycnocline on the stratified side of the front; (ii) away from the subsurface maximum variability that does not appear coherent horizontally but in the vertical does have a characteristic spectral slope; and (iii) a high level of fluorescence within the front on some transects. A subsurface maximum in chlorophyll or fluorescence is commonly observed in stratified water columns and is generally attributed to a balance of the pycnocline inhibiting vertical mixing, providing good light conditions and nutrients in the deeper waters slowly mixing into the pycnocline region (Pingree *et al.*, 1975) to sustain the production. A subsurface chlorophyll maximum in the pycnocline is a common feature on the southern flank of Georges Bank (O'Reilly *et al.*, 1987).

The spectra of the fluorescence and temperature variability away from the pycnocline are approximately straight lines with slopes of about $-5/3$ (Fig. 4). While the $-5/3$ spectral slope is characteristic of the inertial subrange in turbulent mixing (Tennekes and Lumley, 1972), the spectral calculations presented here (Fig. 4) extend to length scales (10s of meters) that are longer than expected for the inertial subrange for the local turbulent field. Still, the similarity of the fluorescence and temperature spectra suggests that the spatial structure of the fluorescence is determined by the same physical process controlling the temperature variability. The dominant physical process is the strong vertical mixing associated with the dissipation along the bottom of the energy in the large tidal currents. The conclusion is that the spatial structure of the vertical variability in fluorescence is determined primarily by the physical mixing process, not by biological processes. Similar results have been found for the horizontal variations in fluorescence (e.g. Fasham and Pugh, 1976). Wiebe *et al.* (1996), using near surface fluorescence measured underway on the May 1992 cruise, found a spectral slope of approximately $-5/3$ in the stratified region of the bank. In the well-mixed region, however, they found a break from that pattern that also was observed in acoustic backscatter data and that is attributed to presence of Langmuir-like circulation cells.

The third characteristic pattern of the fluorescence field is higher values within the front on some occasions. High phytoplankton concentration within a tidal front has been

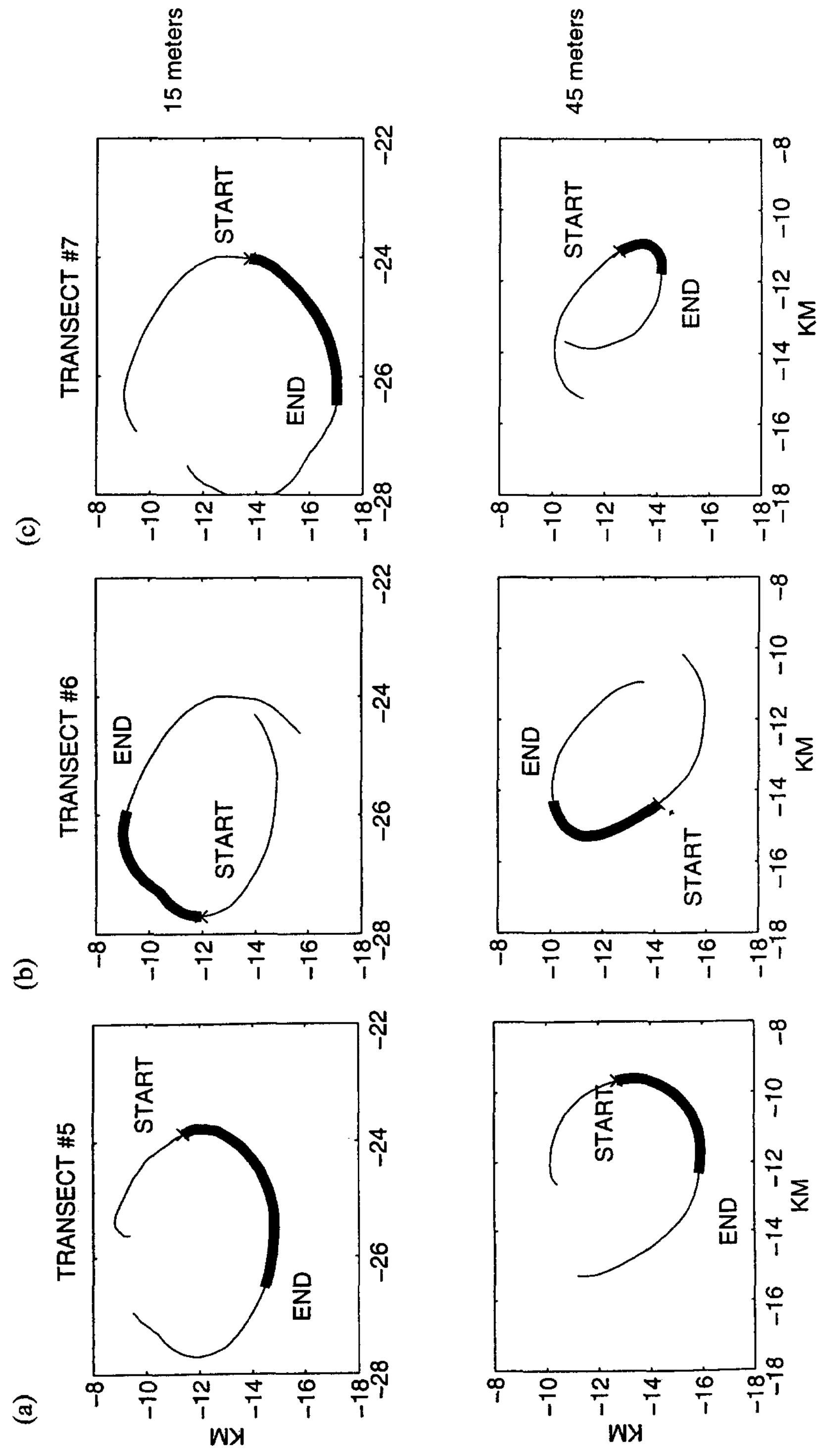

Fig. 15. Progressive vector diagrams for the currents at 15 m and 45 m depths during transects (a) 5, (b) 6 and (c) 7 (Figs 9, 10, 11) in 1993. The heavy portion of the curves indicates the times during which the transects were conducted. The currents were measured on a mooring indicated in Fig. 1.

observed in other areas, e.g. the Ushant front in the English Channel (Loder and Platt, 1985) and on the northern side of Georges Bank (Horne *et al.*, 1989). Garrett and Loder (1981), Loder and Platt (1985) and Horne *et al.* (1989) identified a number of possible physical mechanisms that could cause a flux of nutrients into and across a tidal front and support higher primary production there: (i) movement of the frontal position due to spring–neap changes in tidal current amplitude; (ii) shear-flow dispersion; (iii) mean residual flow; and (iv) baroclinic eddies in the frontal region.

The steepening and flattening of the front with the on-bank/off-bank movement of the tidal ellipse identified above implies some degree of vertical current shear over a tidal cycle. This shear could supply nutrients to the frontal region through shear-flow dispersion and support increased production within the front. Direct measurements of currents in this general region (Moody *et al.*, 1984), however, do not indicate a significant vertical shear in the tidal currents. Shear-flow dispersion would not account for the higher fluorescence being observed in the front at some times and not at others.

Periodic increases in tidal current amplitude with the spring–neap cycle could cause the well-mixed region on Georges Bank to expand and the tidal front to migrate to deeper water, where the water column has been stratified. Nutrients at depth in the stratified column (e.g. Walsh *et al.*, 1987), would be mixed into the frontal region and support a

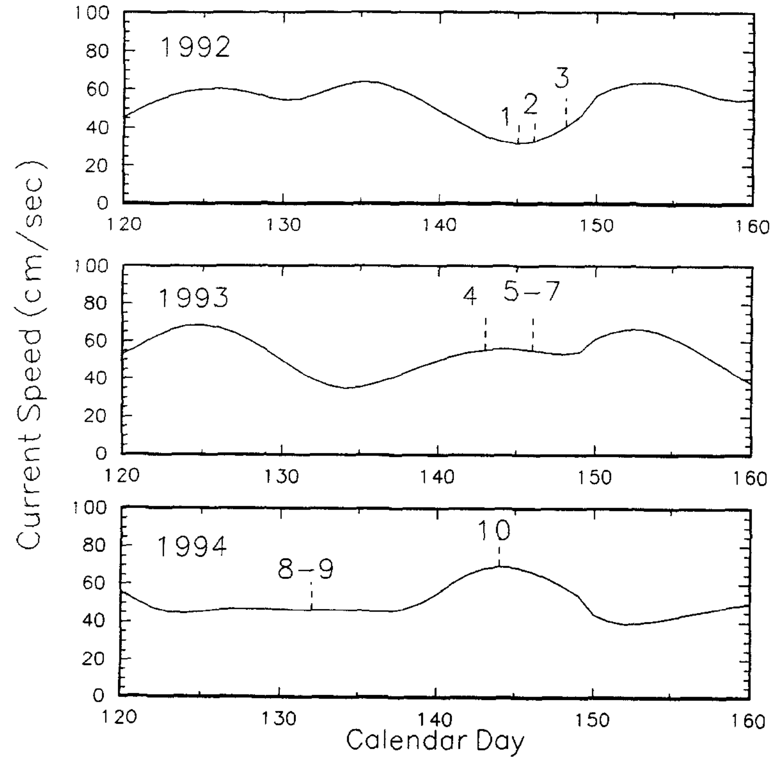

Fig. 16. Calculated tidal current amplitude during the cruises in 1992, 1993 and 1994. The dashed lines indicate the times of the transects during each year with the numbers above each line corresponding to the transect number in Table 1.

localized, short-term increase in primary production within the front. Sea surface temperature changes associated with increased tidal mixing caused by the spring–neap current variations on Georges Bank have been observed by Bisagni and Sano (1993). To investigate this as a possible mechanism, the amplitude of the tidal current was recreated for the time periods of the transects using the method of Shureman (1941) and tidal current coefficients reported by Moody *et al.* (1984). The hourly current values were calculated for the location 41°20′N, 67°15′W (the same location used by Bisagni and Sano, 1993) and averaged to daily mean values (Fig. 16). The 1992 transects (nos 1, 2 and 3) occurred at a low in the tidal velocity, although the speed was increasing by the time of transect 3; the 1993 sections were occupied after the current had increased from 35 to 55 cm s^{-1}; and in 1994 the first two transects (8 and 9) occurred during a period of constant current amplitude while the last (no. 10) occurred after the current increased from 45 to 70 cm s^{-1}. The increase in tidal current amplitude before the 1993 sections and the last section in 1994 could have caused the tidal front to extend to deeper water and caused the increased fluorescence observed within the newly formed frontal region. The subtle maximum in fluorescence within the front on the third section in 1992 (transect no. 3, Fig. 7d), when the tidal current was beginning to increase, may represent the beginning of this process.

The available data are not sufficient to estimate the nutrient flux associated with either the potential shear dispersion or movement of the front, nor to estimate the nutrient demand represented by the observed increased fluorescence in the frontal region. Whether the enhanced production in the tidal front is caused by processes that have a tidal or a fortnightly/monthly time scale would have significant implications for the importance of production to higher trophic levels—whether it represents a steady or an intermittent food source. The time scale of forcing also could have important implications for the physiology of the phytoplankton (Auclair *et al.*, 1982; Frechette and Legendre, 1982; Demers *et al.*, 1986). The apparent absence of the increased fluorescence in the front when the tidal currents were low or not changing gives support to the fortnightly/monthly variations in tidal current amplitude being the primary causal factor.

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APPENDIX—UP CAST/DOWN CAST BIAS IN FLUORESCENCE

While data were being recorded in 1992, it appeared that the fluorescence on some up casts was noticeably higher than on the immediately preceding down cast. To investigate the possibility of an up cast bias in the fluorescence, the water column average fluorescence value was determined on the down and up casts for each profile of transects 5, 6 and 7 in 1993. Since the up cast often began a few meters shallower than the down cast preceding it (due to the rise of the instrument through the water with the movement of the vessel), for each up/down pair the averaging was done over the common depth range. The ratio of the up to down value for the stations on the transects and the density difference between the surface and 50 m depth were both calculated (Fig. A1). In the stratified water columns the ratio was near 1. In the well-mixed columns, however, the ratio was consistently greater than 1, with values often of 1.2–1.3.

In June 1994 a plankton and hydrographic survey of Georges Bank was conducted using the same CTD/fluorometer instrument system. The up/down fluorescence ratio (Fig. A2a) and the density difference between 0–50 m (Fig. A2b) were calculated for the data from the bank wide survey. In the shallow central region of the bank the ratio is highest (greater than 1.05) and the density difference is less than 0.05 σ_t units. An up cast bias in the fluorescence values appears to be a characteristic feature of well-mixed region of Georges Bank.

The cause of up cast bias in fluorescence in the well-mixed region is unknown. Since the bias is regional, it does not appear to be a systematic bias of the CTD/fluorometer instrument. The regionalization of the bias is similar to that of the dominant phytoplankton species—with diatoms generally dominant where the bias exists and flagellates where there is no bias. The water sensed by the fluorometer on the up cast has been disturbed and mixed by the CTD housing and the rosette with bottles above the fluorometer sensor, while the water sensed on the down cast has not

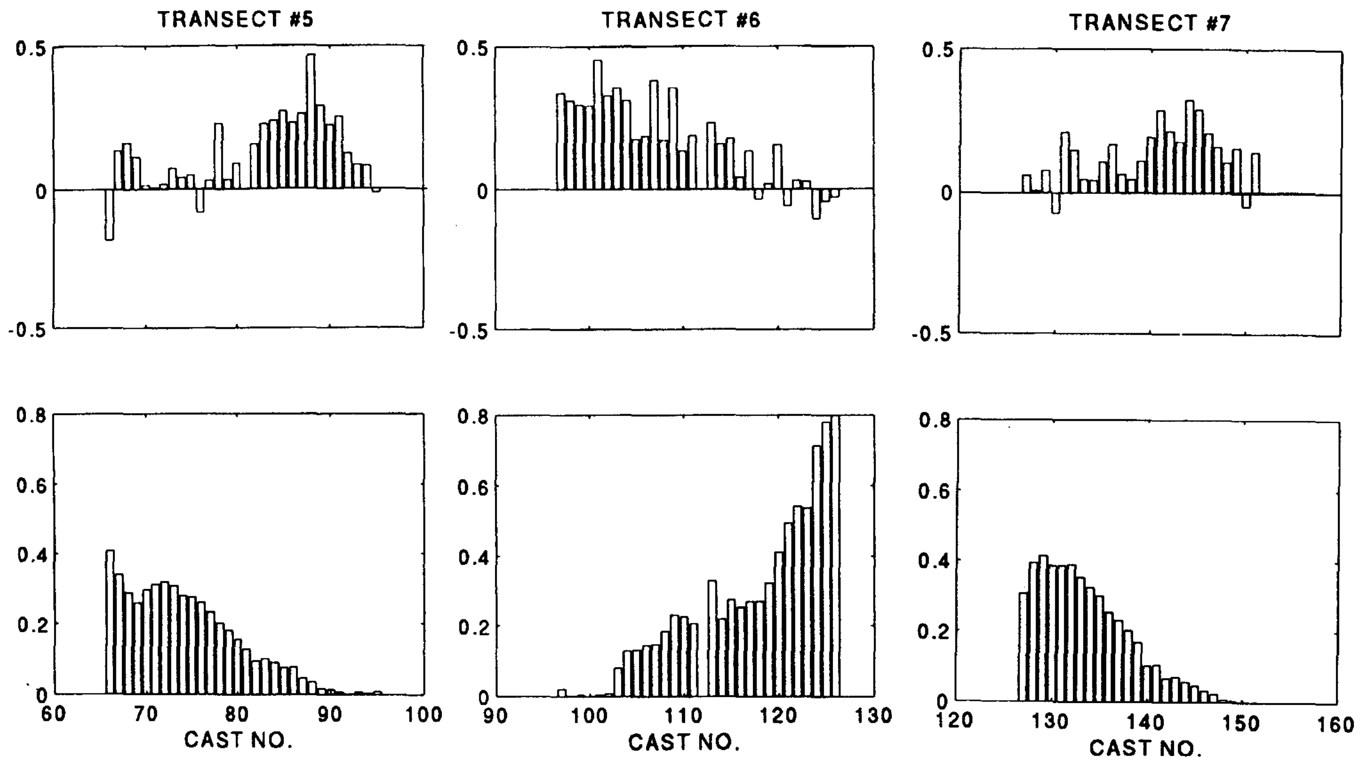

Fig. A1. Top: the ratio of average fluorescence during the up cast to that during the down cast (minus 1); bottom: the difference in σ_t between 50 m and the surface for CTD casts along transects 5, 6 and 7 in 1993.

been similarly disturbed. No evidence or explanation for increased fluorescence by diatoms at increased levels of turbulence or for a difference in response to turbulence by flagellates and diatoms could be found in the literature. The cause of the bias and any important implications it may hold are unclear. At a minimum, the existence of the bias is important to consider when fluorescence data from the region are analyzed and interpreted.

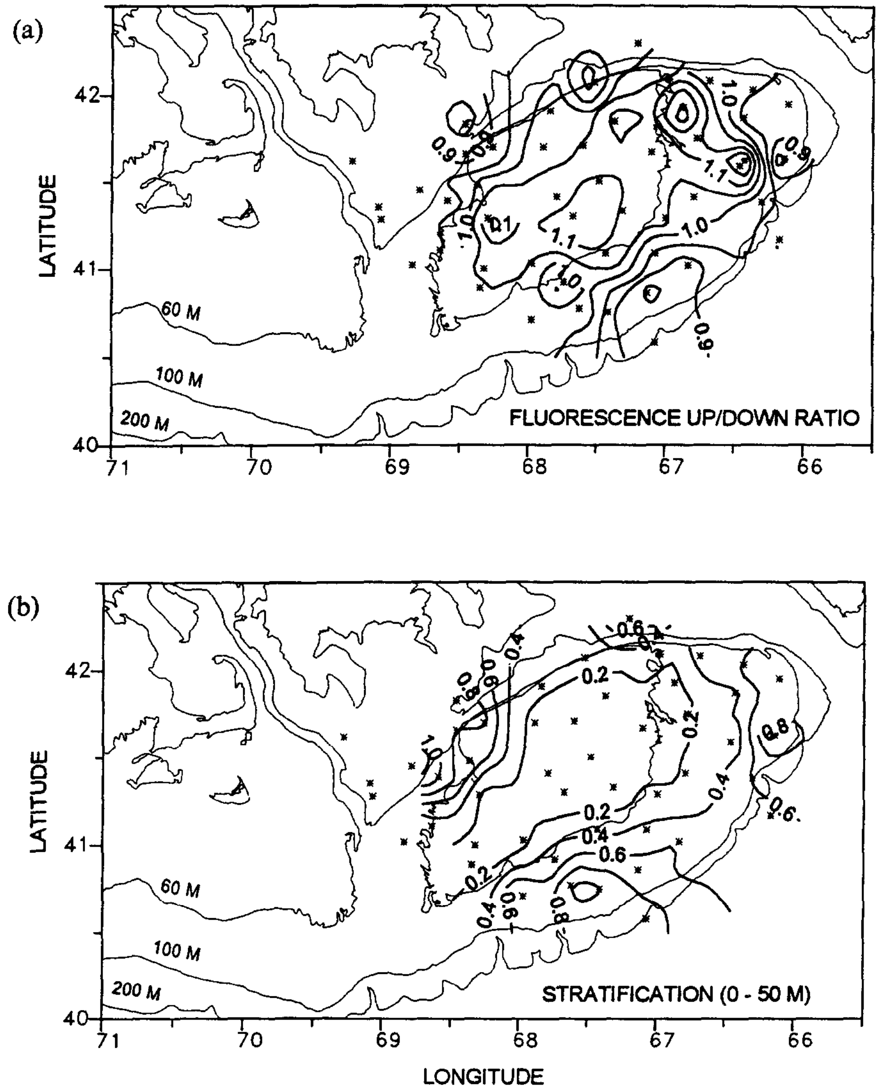

Fig. A2. The spatial distribution of (a) the ratio of the average fluorescence during the up cast to that during the down cast and (b) the difference in σ_t between 50 m and the surface for a survey of the Bank in June 1994.