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ENTRAINMENT OF REDFISH (*SEBASTES* SP.) LARVAE OFF THE SCOTIAN SHELF

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Satellite images indicate that a large volume of cold shelf water lay offshore of the Scotian Shelf in the spring of 1991. The seaward boundary of the shelf water was highly convoluted and suggested shelf water was being entrained into the offshore slope water region by warm-core Gulf Stream eddies. An interdisciplinary field study of this region in late April and May found relatively high concentrations of redfish larvae in the entrained shelf waters, up to 100 kilometres offshore of the edge of the continental shelf. Historical data indicate that these larvae were most likely spawned along the edge of the Scotian Shelf. Satellite data together with hydrographic information collected during the field program are used to discuss the entrainment feature. The distribution and condition of redfish larval are described and we speculate upon their possible fate.

INTRODUCTION

The exchange of water between the northwest Atlantic continental shelf and the offshore slope waters induced by the presence of Gulf Stream eddies is well documented (Morgan and Bishop 1977; Smith 1978; Trites 1981; Churchill et al. 1986). This exchange not only plays a significant role in the heat and salt balance for the shelf region (Smith 1978) but also affects biological distributions and production. Eddies transport tropical and sub-tropical fish species onto the shelves (Wroblewski and Cheney 1984) and, more importantly, it has been suggested that the shelf water entrained by these warm core rings may carry enough fish eggs and larvae offshore to significantly reduce the recruitment of those fish whose larvae normally reside on the shelf (Wroblewski and Cheney 1984; Flierl and Wroblewski 1985). Evidence in support of this hypothesis was provided by Myers and Drinkwater (1989). Using a correlative approach, they found reduced recruitment was associated with increased eddy activity for 16 out of 17 groundfish stocks examined. These stocks included 5 separate species including Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), pollock (*Pollachius virens*), redfish (*Sebastes* sp.) and yellowtail flounder (*Limanda ferruginea*). Observations of fish larvae of shelf origin in offshore entrainment features are still relatively rare, however. Wroblewski and Cheney (1984) found substantial numbers of larval and juvenile white hake (*Urophycis tenuis*) 140 km seaward of the continental shelf break off the southwestern tip of the Scotian Shelf. Friedlander and Smith (1983) observed sand lance (*Ammodytes* sp.) larvae in an entrainment feature approximately 136 km offshore of Hudson Canyon in the mid-Atlantic Bight. To our knowledge significant numbers of eggs or larvae in entrainment features for any of the 5 species of groundfish examined by Myers and Drinkwater have not previously been reported.

In April and May 1991 we conducted an interdisciplinary field study of the circulation and the distribution of cod larvae on Western Bank (Fig. 1). During the course of the study the opportunity arose to investigate possible offshore entrainment features. Although no cod were found offshore, substantial numbers of redfish larvae were collected. Over the course of the following month we visited one entrainment feature three times, each time finding significant numbers of redfish larvae.

The present paper focuses upon the redfish larvae in the offshore feature. In the next section we describe the sampling procedures, the data sets, and the analysis methods. The physical characteristics of the entrainment feature are then presented, followed by a discussion of the distribution and condition of the redfish larvae. A summary of the results and the conclusions of the study appear in the last section, including the implication of our observations on redfish biology.

DATA AND DATA METHODS

During April to mid-May, 1991, a two-ship (CSS DAWSON and the PETREL V) multidisciplinary field study of the circulation and cod larvae distributions was conducted on Western Bank, a shallow (60 m) submarine plateau on the outer edges of the Scotian Shelf, off Nova Scotia. Low numbers of cod larvae lead to speculation at the time that maybe they had been swept off the Bank through entrainment by Gulf Stream eddies. Our speculation was heightened by several eddies and entrainment-like features in the area, including some just offshore of Western Bank (Fig. 2). The eddies had been visible in thermal satellite imagery for upwards of two months prior to the study. In an attempt to test the hypothesis that the larvae may have been entrained off the shelf, we began a larval and CTD survey of the offshore waters from the DAWSON on 20 April. Realizing the likelihood that cod larvae may not be able to tolerate the higher offshore temperatures (above 10°C) we searched offshore for shelf water characteristics (i.e. having temperature and salinity similar to those on Western Bank; <4°C, <33.5). Guided by satellite imagery, we proceeded approximately south-southeast from Western Bank taking CTD profiles and reached 42.5°N but found no water of the appropriate characteristics. We then turned northeastward, proceeded to 43°N and shifted to an eastward track. Finding cool shelf waters in the vicinity of 59.3°W, we conducted a larval and CTD survey for 24 hr. Net tows revealed relatively abundance redfish larvae but no cod.

On 30 April the DAWSON returned offshore, undertaking further CTD and larval measurements through 1 May. Shelf waters containing redfish larvae were again located in the same general vicinity. A third visit to this area was conducted on 8-9 May by the PETREL during which 6 miniBIONESS stations were conducted. In addition, the PETREL sampled another offshore feature further to the southwest on 29-30 April and conducted a larval survey on the shelf over Western Bank during 1-4 May.

Vertical profiles of temperature and salinity were taken from the DAWSON using a Seabird digital CTD (Conductivity-Temperature-Depth) profiler. Water densities were calculated from the temperature and salinity using the UNESCO 1980 formulation and expressed as sigma-t (σ_t). Initially, reversing thermometer temperatures and salinity samples from Niskin bottles were obtained for calibration purposes at two depths per cast using a rosette attached to the CTD. Technical problems with the rosette and CTD unit resulted in replacement of the CTD during the second half of the cruise. No *in situ* calibration samples could be collected for the new instrument because of the difficulties with the rosette, hence laboratory calibrations were applied to the data from this instrument.

Satellite imagery of the positions of the Gulf Stream, warm-core eddies and the shelf/slope front were taken from the National Oceanic and Atmospheric Administration (NOAA) oceanographic analysis charts published 3 times per week. Additional satellite imagery were available from Cribb (1993) who processed all available NOAA-11 AVHRR (Advanced Very High Resolution Radiometer) sea surface temperature (SST) images covering the period February to May, 1991.

Larval sampling was conducted from both the DAWSON and PETREL using a half scale version of the BIONESS (Sameoto et al. 1980), a multiple opening and closing net. Each miniBIONESS was fitted with 333 μm nets of 0.25 m^2 area, a CTD unit, flowmeters, digital pitch and roll sensors and towed at approximately 1.5 m s^{-1} (3 kt) for 1 h. The DAWSON miniBIONESS contained seven nets. The instrument was usually lowered to 60 m depth, the first net opened and towed diagonally upwards and closed at 40 m. Additional samples were obtained in the 40-20 m and 20-0 m depth ranges. The instrument was then lowered while being towed to obtain an integrated sample of the 0-60 m depth range. The procedure used for the first three nets was repeated for the last three nets in order to obtain replicate samples. The PETREL miniBIONESS contained 10 nets. Sample depth ranges varied with the tow, usually covering a vertical distance of 10 to 20 m per net tow. Maximum depths were typically 60 to 80 m but at times reached 100 m. As on the DAWSON, replicate samples were generally taken for each depth range.

The net samples were sorted at Dalhousie University upon the ship's return. Because of the difficulties in identification of redfish species and consistent with most other redfish studies, larvae were identified to the genus level only. Two redfish species are known to occupy the Scotian Shelf region, *S. fasciatus* and *S. norvegicus mantella*. Larval numbers collected in the miniBIONESS tows were converted to concentrations using estimates of the volume filter based upon the flow meter attached to the miniBIONESS. The length and weight of each larvae were also recorded.

RESULTS

Satellite Imagery

On the 19 April the shelf/slope front off the Scotian Shelf was highly convoluted, including a large hammerhead-shaped entrainment feature to the south of Western Bank (Fig. 2). These entrainment features formed in March in response to the presence of Gulf Stream eddies as suggested by the NOAA frontal analysis charts. Two Gulf Stream eddies remained in the slope water region between the Gulf Stream and the shelf water on 19 April (Eddies A and B, Fig. 2). This region is highly dynamic as indicated by changes in positions of the shelf/slope front, the Gulf Stream and warm-core eddies between 19 April and 8 May, the period corresponding to our sampling (Fig. 2,3). For example, by the 22 April, the eastward extension of the hammerhead was wrapped around Eddy B and pulled further offshore towards the Gulf Stream. By the 26 April this feature disappeared, apparently mixed into the slope water, while the remainder of the hammerhead was being entrained around Eddy A.

Hydrographic Data

20-21 April. During our first offshore survey, we first occupied a CTD section through the hammerhead feature to the south of Western Bank and then turned eastward into the shelf water (Fig. 4,5). The hammerhead contained water with temperatures of 5-8°C and salinities 33.5-34.5, slightly warmer and saltier than the waters over Western Bank (T<5°C, S<33.5; Fig. 5). This feature was approximately 50 m deep and lay above warm slope waters (T>8°C, S>34.5). To the east lay surface waters of slope water origin, while even farther east we passed through the shelf/slope front into shelf water of similar hydrographic characteristics to those found over Western Bank (Fig. 5,6). We immediately began miniBIONESS tows (discussed below) and took additional CTD profiles in this area. An approximate north-south transect along 59.2°W indicated the southern limit of the shelf/slope front was located near 42.8°N (Fig. 4,7) while additional measurements further east along 43°N showed shelf water extended at least to 58°W (Fig. 4,6).

There was good agreement in the surface thermal structure measured by the CTD and the NOAA image of 22 April, although some details did differ (Fig. 4). East of 60°W, both data sets revealed slope water characteristics separating the hammerhead feature from shelf water farther east. The southern extent of the shelf water was located in the same general vicinity by both methods, although the CTD measurements placed it slightly south of that on the NOAA chart. The largest difference was the absence of slope water at the surface west of 60°W based upon the CTD measurements when the NOAA representation suggested slope water separated the western arm of the hammerhead from the main body of shelf water.

An interesting oceanographic feature was the presence of Labrador slope water (6-8°C, >34.5) in the deep waters (below 150 m) east of 58.5°W (Fig. 6). These waters originate from Labrador Current waters to the northeast and are separate from the warm slope waters (T>10°C) off Western Bank.

30 April-1 May. We returned to the offshore area slightly over 1 week later. A CTD transect was run southeastward off Western Bank, then northeastward before running eastward along 43°N in an attempt to locate the same feature we had sampled previously (Fig. 8). On the western end of the transect, we traversed the former hammerhead feature which showed temperatures had warmed to 6.5-8°C (Fig. 9). Warm slope water still separated this water from the cold shelf waters farther to the east; temperatures in the latter had generally risen by 0.5-1°C since our earlier visit although salinities remained relatively the same. Two north-south transects were also run, one along 59.2°W (Fig. 10) and 58.8°W (Fig. 11). Along the former, the southern extension of the shelf-slope front was located to the south of 42.7°N and slightly south of its position on 21 April. Good agreement was again found between the position of the shelf/slope front from the CTD measurements and the NOAA charts (Fig. 8).

Redfish Larvae

Vertical Distribution. Redfish larvae were collected in the miniBIONESS tows during the three occupations of the offshore feature. They were primarily located in the top 40 m in temperatures <5°C (Fig. 12) and salinities <33.5, physical characteristics corresponding to shelf waters. Concentrations reached maximum values of up to 30/100 m^3. The depths and temperatures in Fig. 12 refer to averages over the length of the tows.

Horizontal Distribution. Biological sampling was concentrated east of 60°W within waters of temperature and salinity characteristics to those found over the shelf. During the first visit, 4 miniBIONESS stations were taken along 43°N with 2 additional samples to the north and south of this line along 59.2°W (Fig. 13A). Redfish larval concentrations were maximum (6.65/100 m^3) near 43°N, 59°W (tow stn. 227) and decreased to the east and west. Concentrations refer to the average over the top 40 m only. The lowest concentrations were observed in slope waters with temperatures >10°C immediately to the south of the shelf/slope front.

During our second visit we repeated biological sampling along 43°N as well as south towards the shelf/slope front. Larval concentrations increased relative to our first visit with maximum values exceeding 11 larvae/100 m^3 in shelf waters at 2 sites along approximately 42.8°N (Fig. 13B). The lowest concentrations (0.3 larvae/100 m^3) were again recorded in slope water near the shelf/slope front.

All miniBIONESS stations on the third and last visit were taken in shelf waters of temperatures varying from 2°C to less than 6°C based upon CTD measurements from the BIONESS. Larval concentrations were lower than on the 2nd visit but similar to those recorded during the first visit. They ranged from a high of just over 10 larvae/100 m^3 to <0.1/100 m^3 (Fig. 13C). Redfish larval concentrations during the 1st and 3rd visits were similar to those recorded over Western Bank at the beginning of May.

Size and Condition. Histograms of weight and length expressed as percent frequency show little overall difference between the 3 visits (Fig. 14). The sizes ranged from just under 4 mm to over 9 mm and weights of <0.1 gm to over 1.0 gm. While the lengths were approximately normally distributed, weights were skewed with the majority laying between 0.1 and 0.4 gm. The last two visits showed more larger, heavier fish and the first visit showed the largest percentage of shorter fish. For the same length distribution, there were more heavier fish on Western Bank (not shown) than offshore. Weight/length relationships showed a significant increase from the first to the second visit but no difference between the 2nd and 3rd visits. The weight/length relationship during the latter 2 visits to the offshore was similar to that observed on Western Bank.

Additional Offshore Sampling. PETREL also conducted 5 miniBIONESS stations south of Western Bank on 29-30 April in the area of the former hammerhead feature. All stations were run along 61.3°W between 42.15°N and 41.75°N. Temperature, as measured on the miniBIONESS CTD was in the range of 6-8°C suggesting the water was a mixture of shelf water and slope water. This is consistent with the gradually disappearance from the satellite imagery of the hammerhead. Redfish larvae were collected but in much reduced numbers (total of 27 larvae and an average concentration over the top 40 m of < 0.3 larvae/100 m^3) compared to the other offshore location. The tows were dominated by myctophids which accounted for 71% of the larvae while redfish constituted only 26%. This contrasts with the other feature were redfish dominated almost exclusively. The myctophids are mesopelagic fish which occupy the slope waters and are generally not found in shelf water. This provides further evidence of mixing of the two water masses. The length of the redfish larvae were primarily 7-9 mm and the weights 0.3-1 gm. The weight per unit length relationship was similar to that recorded in the other offshore feature during the 2nd and 3rd visits and also on Western Bank. It is most likely that the redfish larvae were originally within the hammerhead feature and may have been as old as one or two months (based upon an assumed size of 4-6 mm and a growth rate of 1% per d). The relatively low numbers of larvae collected may be due to larval mortality caused by increased temperatures, an initial low concentration of larvae, or to dispersion due to mixing of water masses.

DISCUSSION

Three surveys conducted off the Scotian Shelf during a 20 d period in April and May of 1991 revealed redfish larvae over 100 km from the edge of the continental slope at concentrations comparable to those measured on the shelf. The redfish larvae were predominantly found in the top 40 m of the water column in waters <5°C, temperatures characteristic of waters found on the shelf. Shelf water normally extends out beyond the continental slope and its southern boundary (called the shelf/slope front) is highly convoluted due to the presence of Gulf Stream eddies and the Gulf Stream (Drinkwater et al., 1994). Similar conditions were observed during our study.

Previous investigations had observed few redfish larvae off the shelf. The most extensive study of redfish in the area was carried out by Kenchington (1984) from samples collected during 34 cruises between 1976 and 1982, known as the Scotian Shelf Ichthyoplankton Program (SSIP). Although most sampling was restricted to the shelf area, he noted that no redfish larvae were caught in the tows taken over oceanic depths away from the continental slope. During the 1914-1915 Fisheries Expedition in Atlantic waters led by J. Hjort, larval sampling showed redfish distributed throughout the Scotian Shelf (Dannevig 1919). Of 21 stations taken off the shelf, only two contained redfish larvae and these were few in number. They were located off the northeastern edge of the Scotian Shelf in temperatures characteristic of shelf water. Templeman (1959) in his extensive review of redfish in the North Atlantic notes the lack of larvae seaward of the 200 m line off the Scotian Shelf and attributes it to a lack of suitably low temperatures. To our knowledge, our measurements are the first to show significant concentrations of redfish larvae seaward of the continental shelf.

Redfish are ovoviviparus which means they release their larvae near the end of the yolk-sac stage. Newly-released larvae tend to range in length from 4 to 9 mm (Kenchington 1984) and rise towards the surface. For those species on the Scotian Shelf, newly-released *S. mantella* typically are in the 7-9 mm range while *S. fasciatus* are generally smaller than 7 mm. Lengths of from 4 to 9 mm observed during our study indicate the redfish larvae were newly-released and the preponderance of lengths < 7 mm suggest that they were most likely *S. fasciatus*. An increase in the maximum lengths and weights of larvae from our 1st to our 2nd visit is consistent with growth. In addition, increase in the median (and mean) larval length of from 6 to 6.5 mm matches closely the expected growth rate of redfish larvae using the measured rate of approximately 1% per day (Anderson 1984). However, a smaller mean length observed subsequently on the third visit suggests either we were sampling a different patch of larvae or newly hatched larvae were imported into our original patch. The weight/unit length relationship was significantly smaller during the first visit, while during the last two visits it was comparable to that on the shelf. This suggests that if we were sampling the same larval patch, the larvae were growing at a rate similar to that on the shelf and were not stressed over the period of our observations.

What was the source of these larvae? They were found almost exclusively in shelf-type waters at temperatures < 5°C. Redfish on the Scotian Shelf release their larvae from March to September with the majority from May to August (Kenchington 1984). In April the releases are primarily along the shelf edge but by May they begin to release their larvae throughout the Scotian Shelf. We believe that the larvae we observed offshore were likely released near the shelf edge into shelf waters. These waters and the larvae within were then transported seaward through entrainment of the shelf water by Gulf Stream rings, perhaps aided by other processes, such as wind forcing.

A more important question is, what happens to these larvae? Larvae tend to metamorphose at 40-50 mm which at the measured growth rates means they would be in the larval stage for approximately 4.5 months (Kenchington 1984; he also gives an extreme range of 2 to 6 months). Those larvae that metamorphose offshore in depths of 2000-4000 m of water would presumably die. However, newly-released larvae near the shelf/slope front are unlikely to persist there for 4-5 months. As revealed by the satellite imagery, the region is highly dynamic. The shelf/slope front is constantly pushed and pulled by eddies and the Gulf Stream. The eddies and Gulf Stream entrain shelf water seaward which then is quickly mixed into the surrounding slope water. Any redfish larvae that were transported into these warm slope water along with the cold shelf water would likely die due to the abrupt temperature change, such as observed by Colton (1959) for cod larvae off Georges Bank. If any larvae did survive initial contact with warm slope water, the concentration, species, and particle-size of available prey in the slope water would be significantly different to that in the shelf waters. This would probably result in deteriorating condition of the larvae. We believe that the larvae observed offshore of the Scotian Shelf were likely to be eventually lost to the population. The low numbers of larvae found in the slope water during our study is consistent with this hypothesis.

Are losses of larvae through offshore transports an important component of recruitment variability for redfish? The relationship of redfish recruitment to the presence of eddies as found by Myers and Drinkwater (1989) suggests that it is important. They found that recruitment was never high when there were large numbers of Gulf Stream eddies near the shelf during the time when larvae were normally present whereas recruitment could be either high or low during years of low numbers of eddies. Our observations of larvae well off the continental shelf where they are released lend support to the hypothesis proposed by Myers and Drinkwater (1989) that recruitment is influenced by eddies entraining larvae off the shelf.

SUMMARY

High concentrations of redfish larvae in shelf waters up to 100 km from the continental shelf were found off the Scotian Shelf. These larvae are believed to have been released near the shelf edge and transported offshore, mostly likely due to entrainment of shelf water offshore by the Gulf Stream eddies. The condition of the larvae found offshore during our study suggests that they were growing at a rate similar to that observed on the shelf. However, in the event of significant warming of the waters in which the larvae were found through mixing with slope water, could lead to larval stress and ultimately their death. Such mixing is suggested from the satellite images that show a highly dynamic region due to the presence of the Gulf Stream eddies. Our results are consistent with the hypothesis of Myers and Drinkwater (1989) that these eddies affect redfish recruitment.

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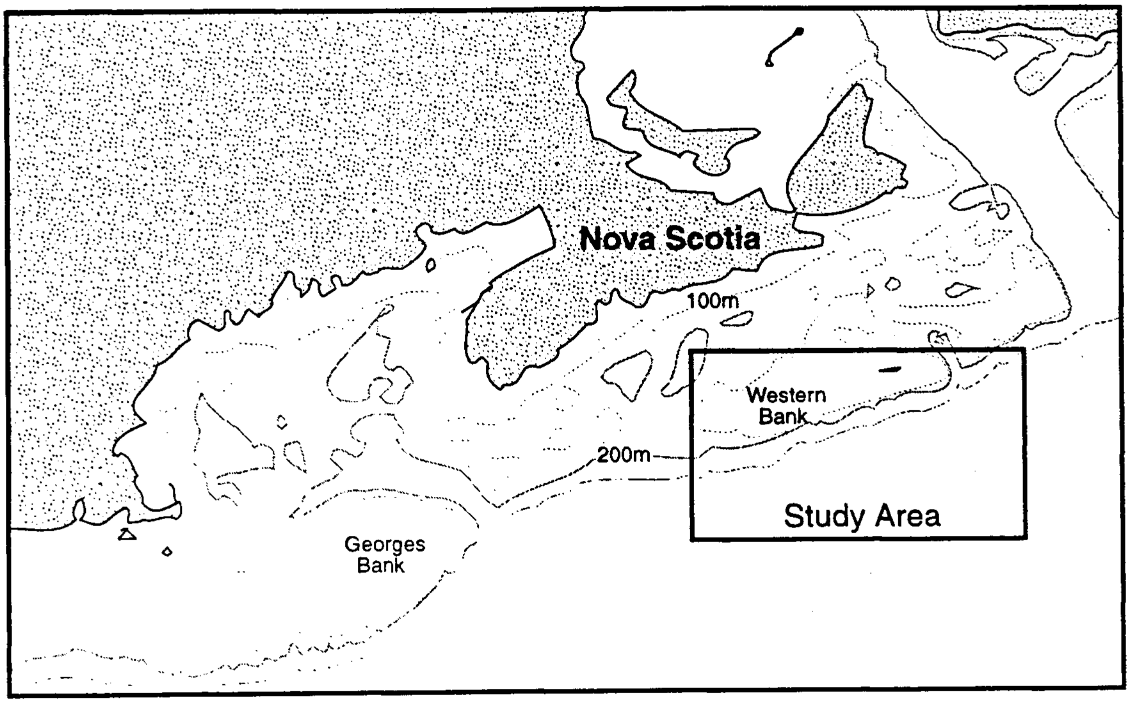


Fig. 1. Map of the Scotian Shelf showing Western Bank and the offshore study area.

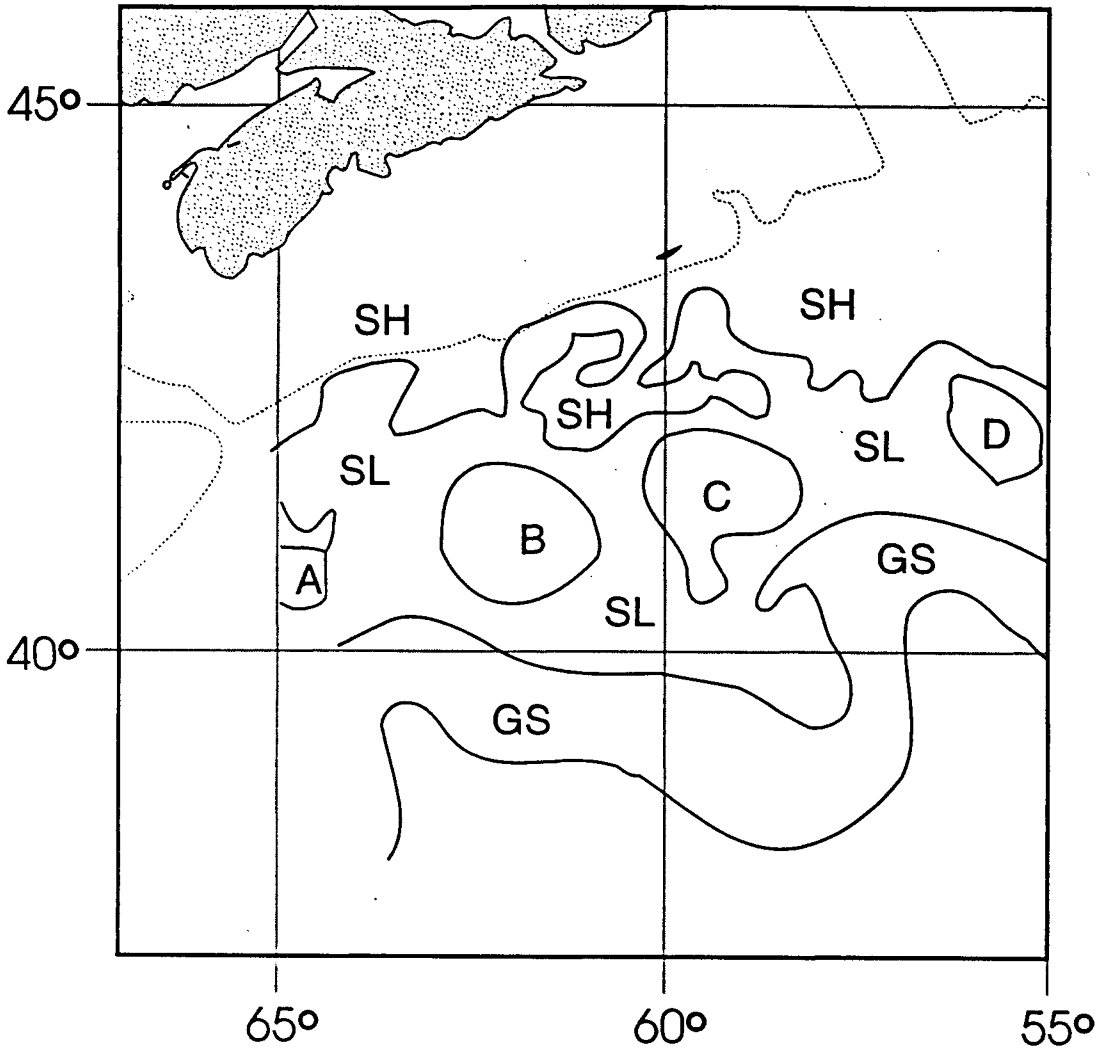


Fig. 2. Satellite image-based representations from NOAA of the shelf/slope front, the Gulf Stream and Gulf Stream eddies on 19 April, 1991. The shelf water is designated by SH, the slope water by SL, the Gulf Stream by GS and the eddies by separate letters.

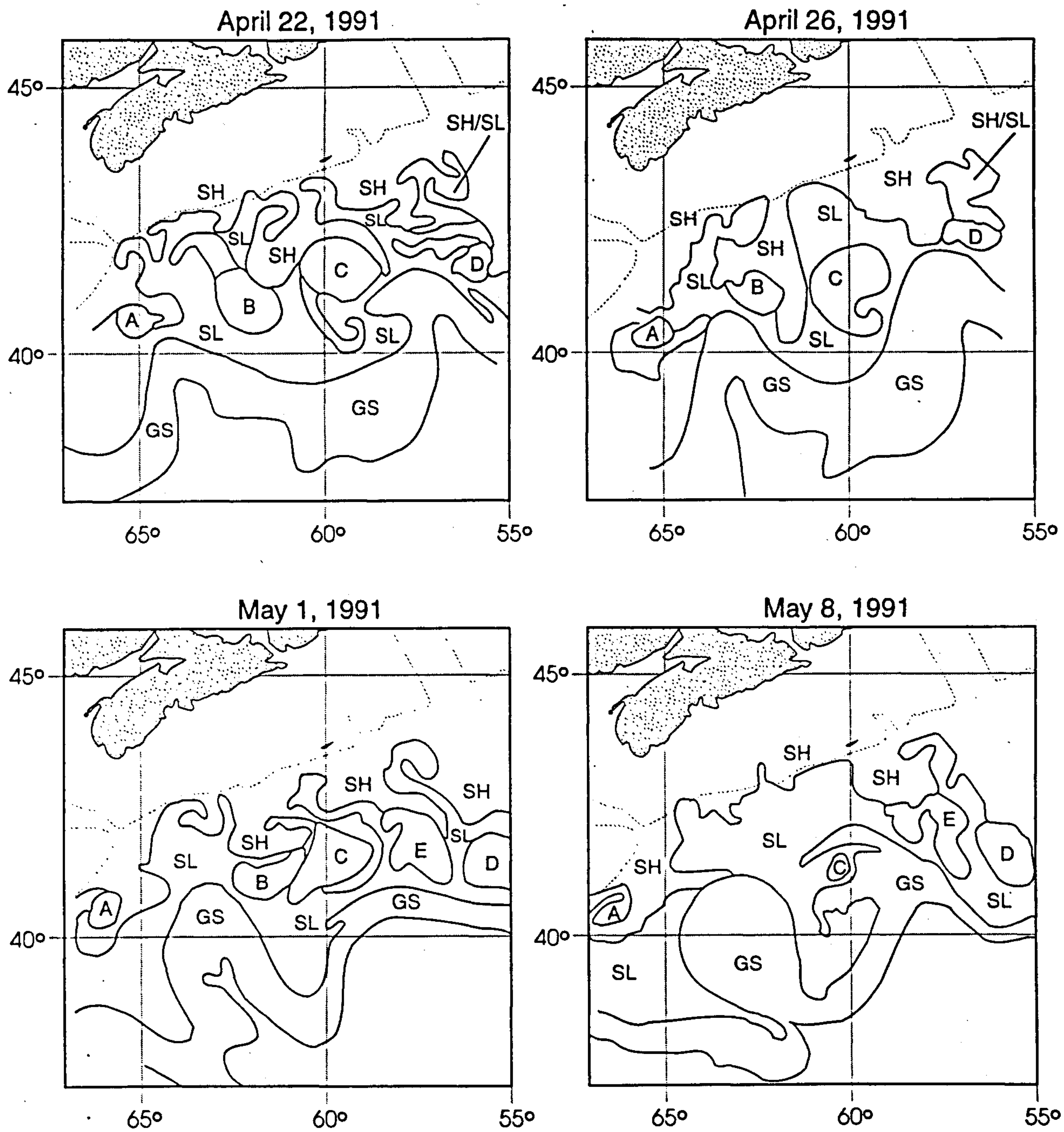


Fig. 3. Four NOAA images of the thermal fronts between 22 April and 8 May, 1991. The shelf water is designated by SH, the slope water by SL, the Gulf Stream by GS and the eddies by separate letters.

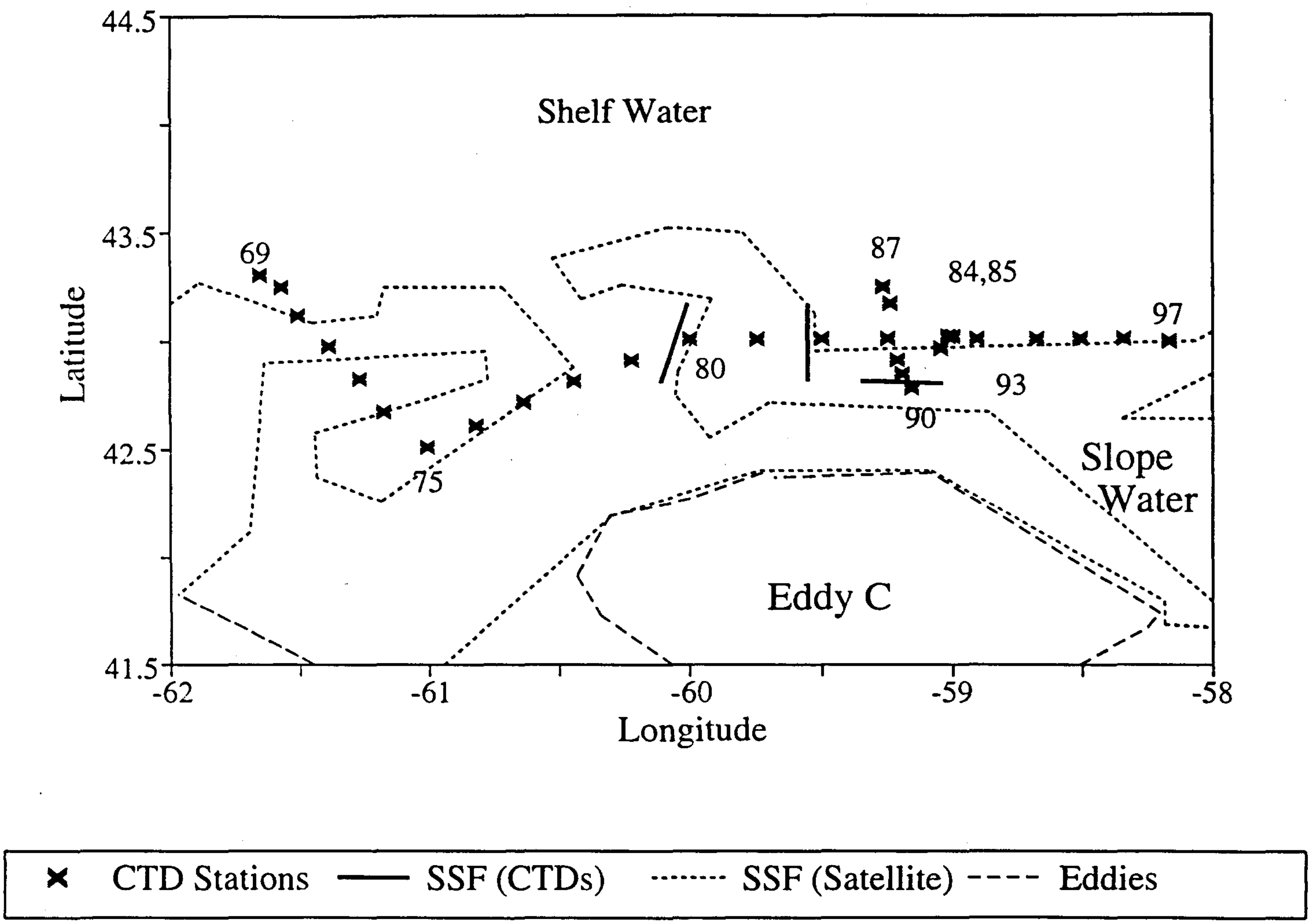


Fig. 4 CTD locations taken during 20-21 April shown relative to the position of the shelf/slope front (SSF) and Gulf Stream eddies from the NOAA analysis for April 22. The location of the SSF based upon the CTD measurements are marked by a heavy solid line. The numbers denote the CTD station identifiers.

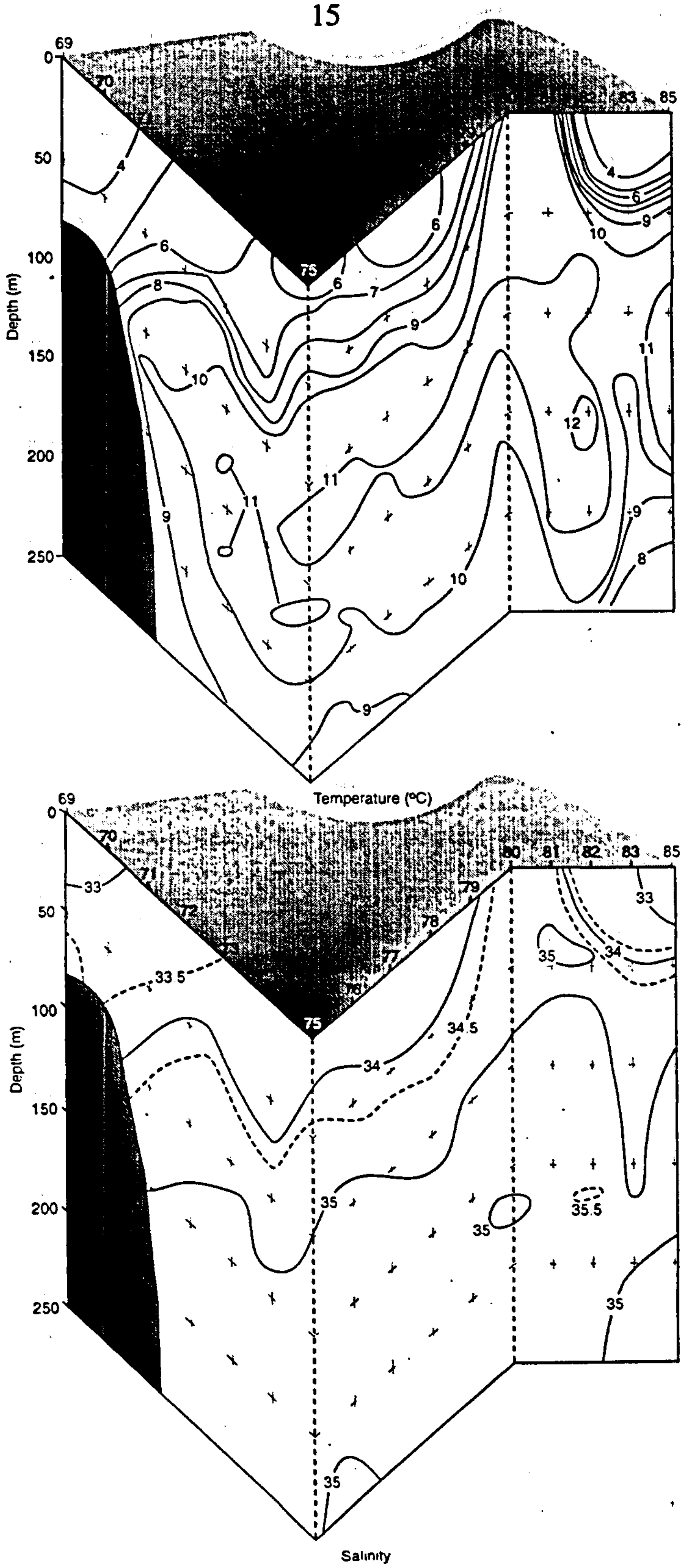


Fig. 5. Temperature and salinity transects offshore of Western Bank (see Fig. 4 for station positions) during our first visit to the offshore during 20-21 April.

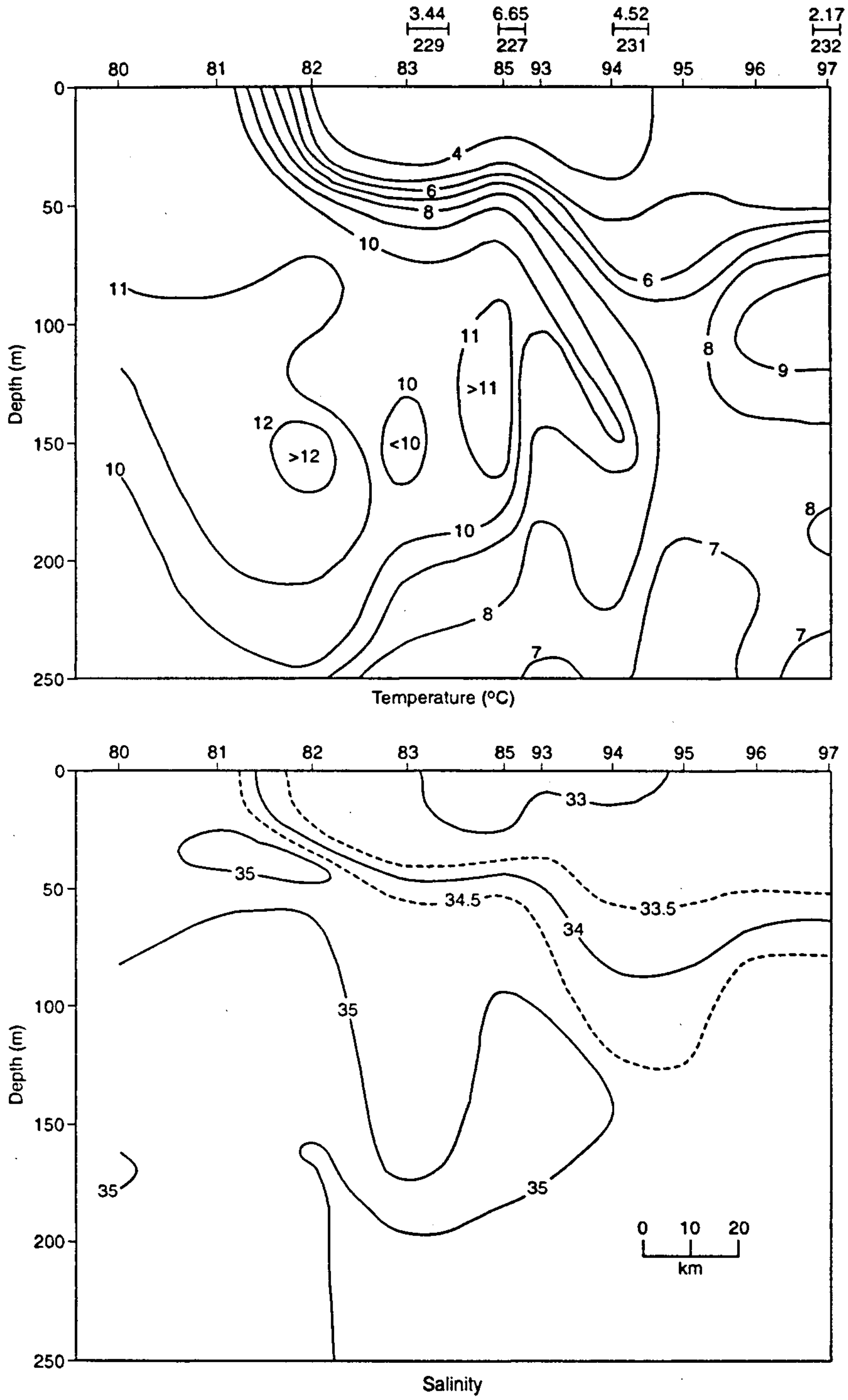
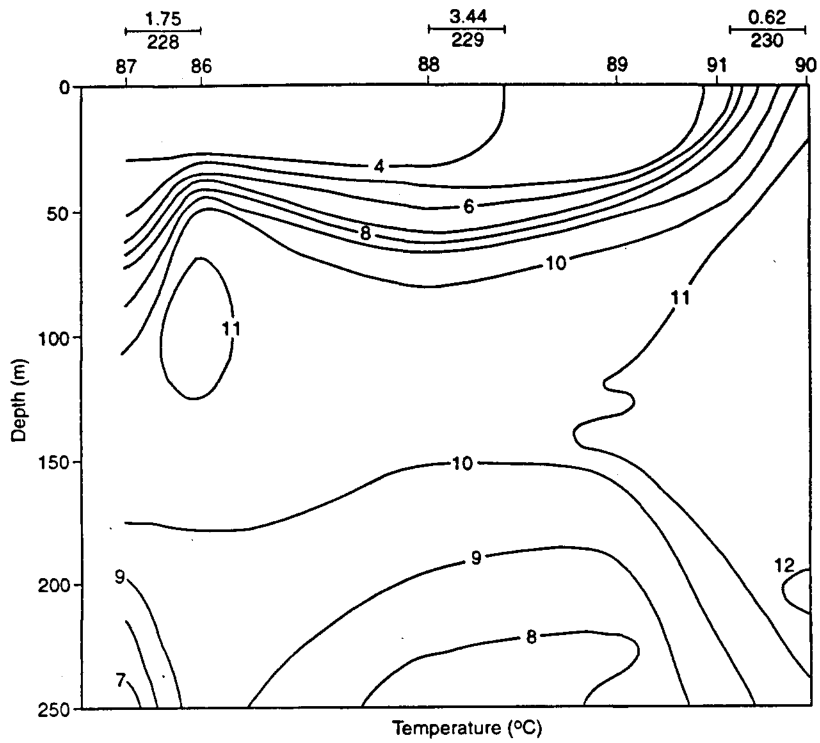


Fig. 6. Temperature and salinity transects along 43°N during 20-21 April. CTD station numbers are provided directly above the plots. The horizontal lines at the top of the diagram indicate the location of the miniBIONESS tows. The number below the line is the miniBIONESS station number identifier and the number above the line is the concentration of redfish larvae in the top 40 m in numbers per 100 m^3.



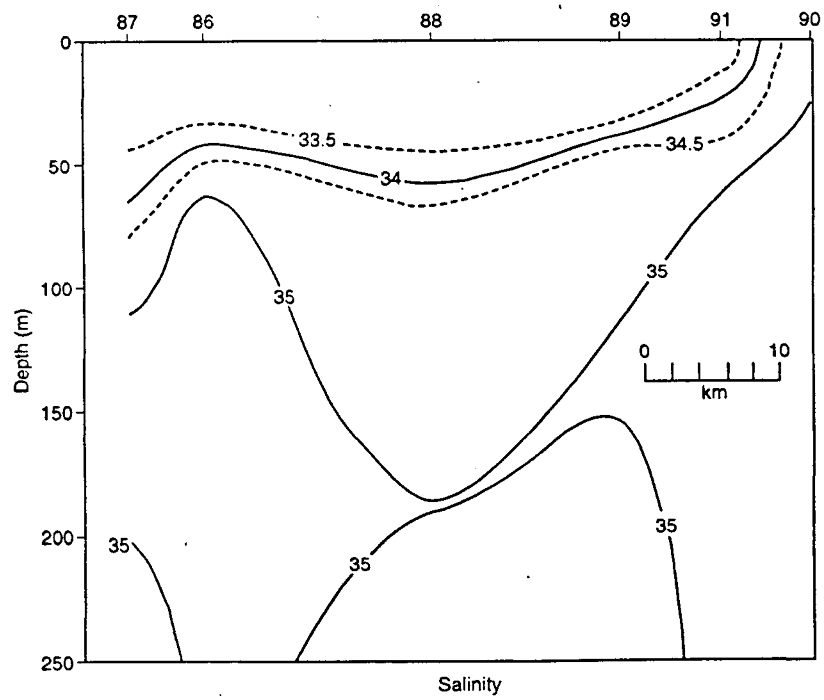


Fig. 7. Temperature and salinity transects along 59.2°W during 21 April. CTD station numbers are provided directly above the plots. The horizontal lines at the top of the diagram indicate the location of the miniBIONESS tows. The number below the line is the miniBIONESS station number identifier and the number above the line is the concentration of redfish larvae in the top 40 m in numbers per 100 m^3.

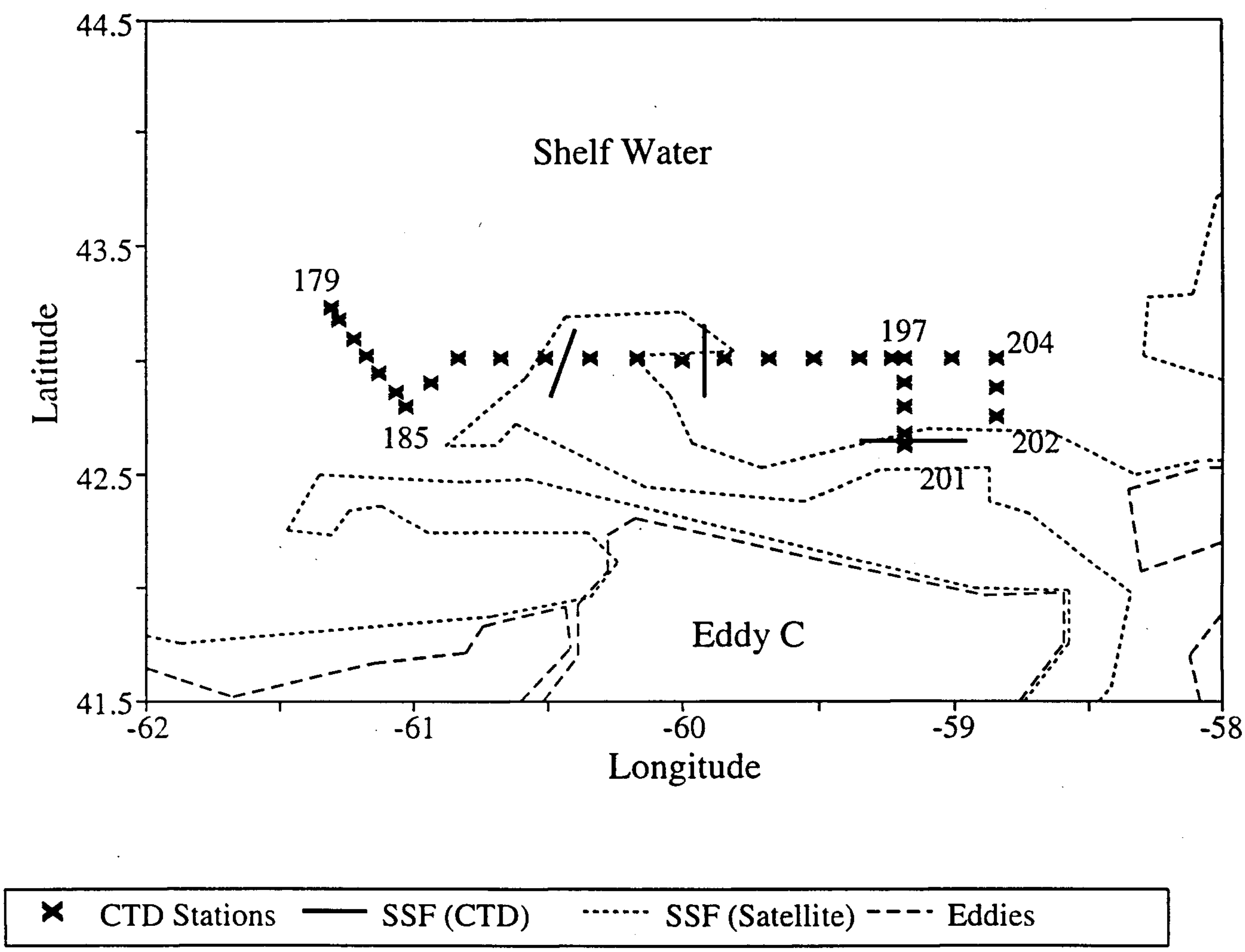


Fig. 8 CTD locations taken during 30 April-1 May shown relative to the position of the shelf/slope front (SSF) and Gulf Stream eddies from the NOAA analysis for 1 May. The location of the SSF based upon the CTD measurements are marked by a heavy solid line. The numbers denote the CTD station identifiers.

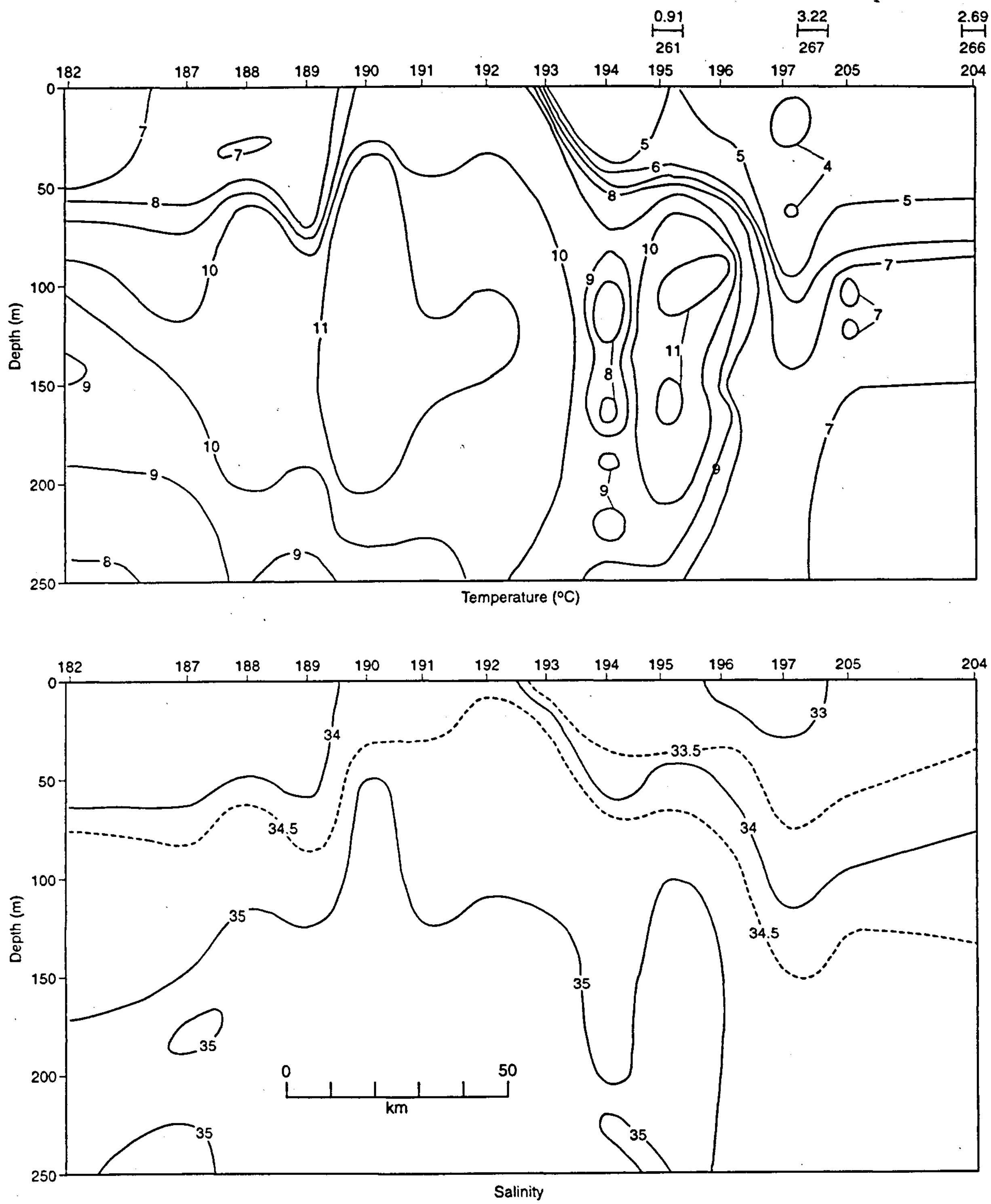


Fig. 9. Temperature and salinity transects along 43°N during 30 April. CTD station numbers are provided directly above the plots. The horizontal lines at the top of the diagram indicate the location of the miniBIONESS tows. The number below the line is the miniBIONESS station number identifier and the number above the line is the concentration of redfish larvae in the top 40 m in numbers per 100 m^3.

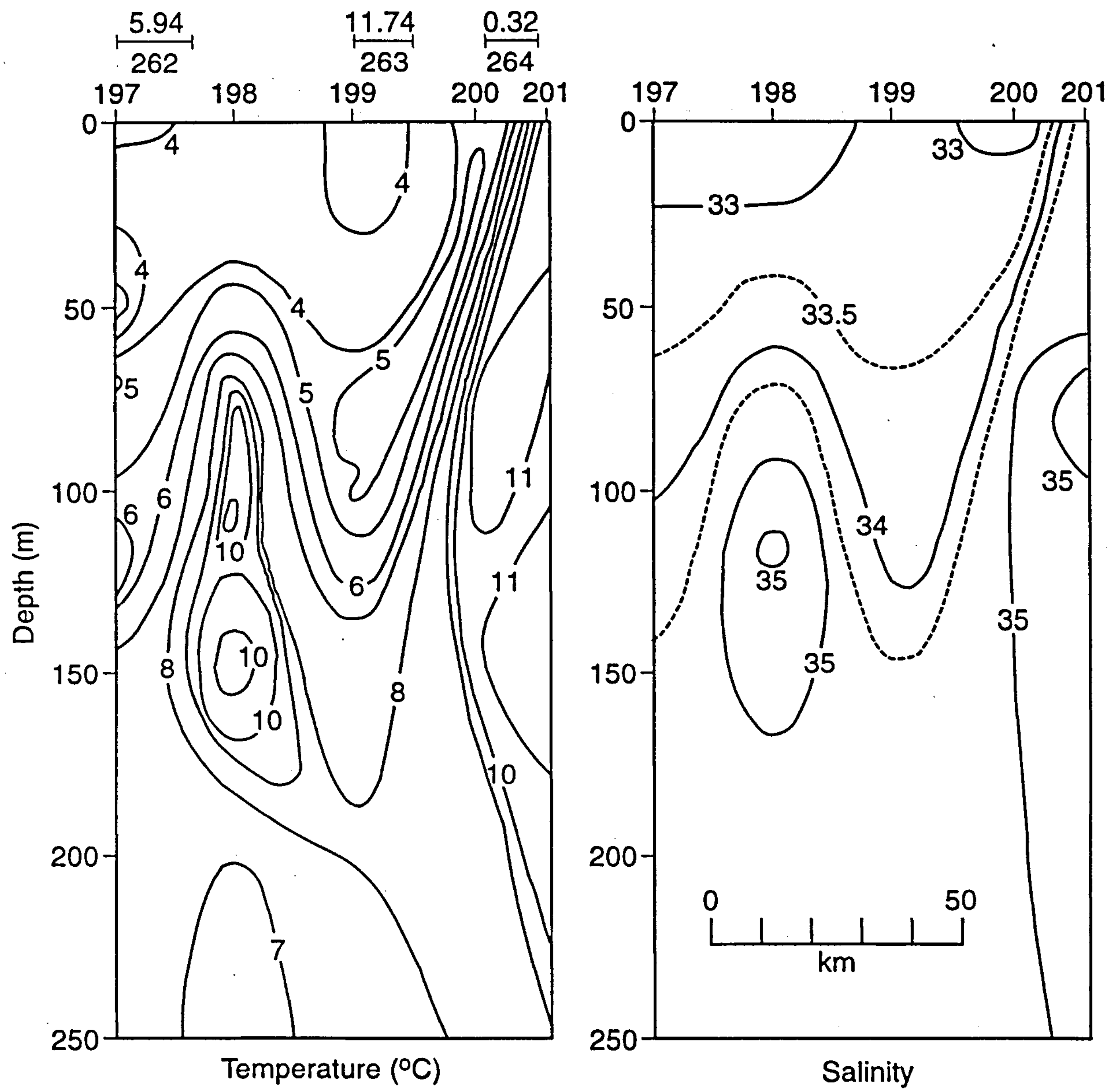


Fig. 10. Temperature and salinity transects along 59.2°W during 30 April. CTD station numbers are provided directly above the plots. The horizontal lines at the top of the diagram indicate the location of the miniBIONESS tows. The number below the line is the miniBIONESS station number identifier and the number above the line is the concentration of redfish larvae in the top 40 m in numbers per 100 m^3.

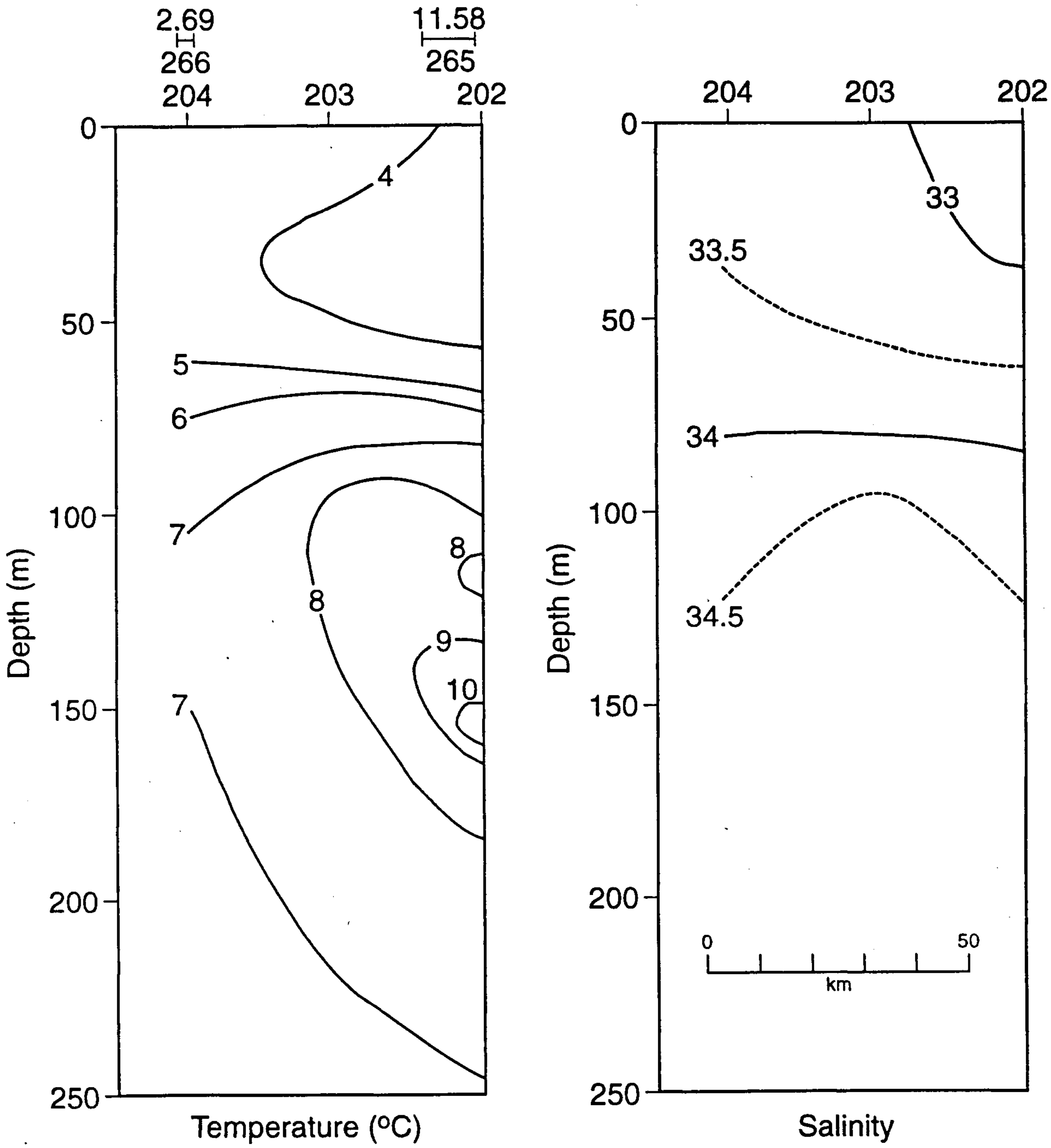
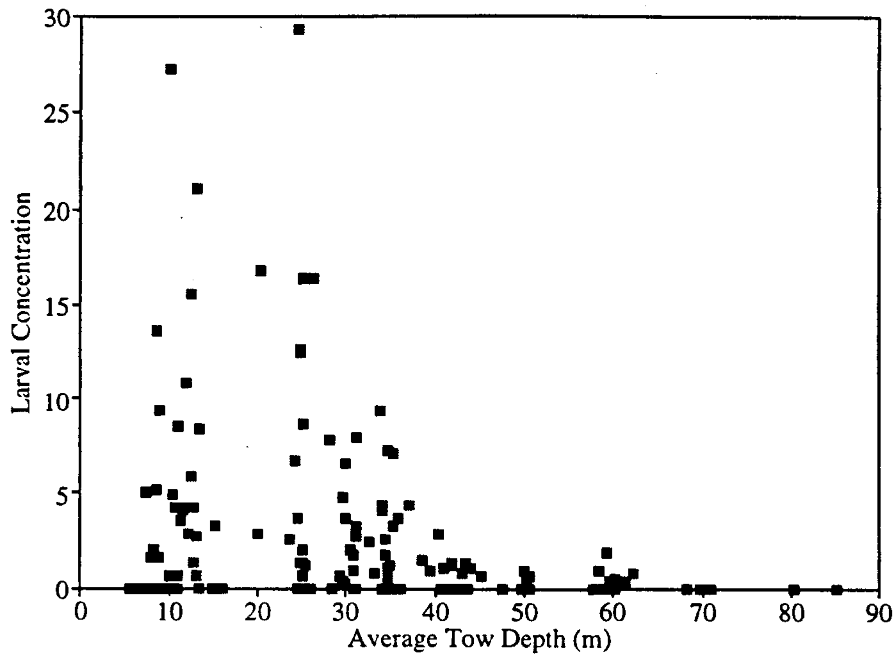


Fig. 11. Temperature and salinity transects along 58.8°W during 30 April. CTD station numbers are provided directly above the plots. The horizontal lines at the top of the diagram indicate the location of the miniBIONESS tows. The number below the line is the miniBIONESS station number identifier and the number above the line is the concentration of redfish larvae in the top 40 m in numbers per 100 m^3.



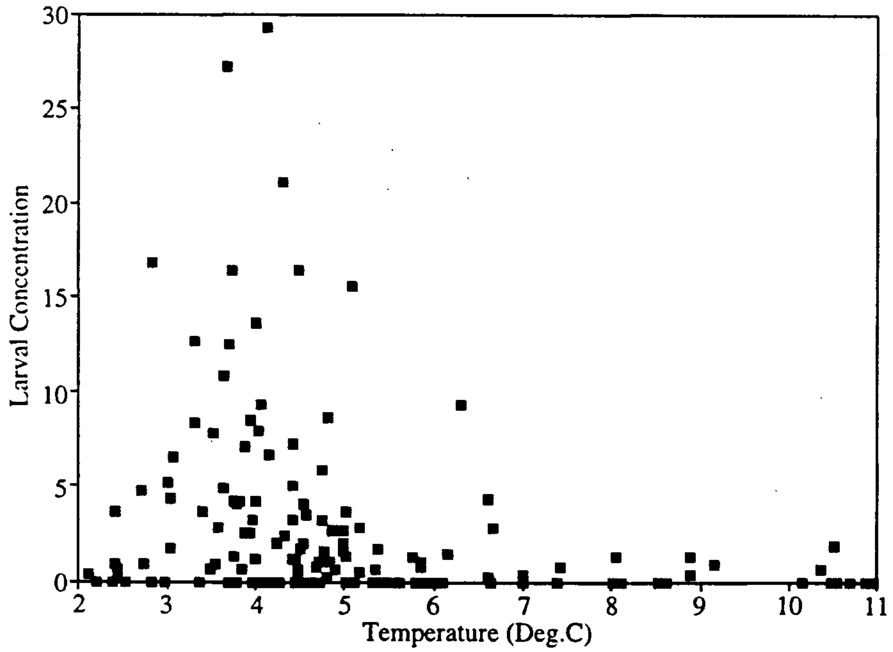


Fig.12 Redfish larval concentrations as a function of average tow depth (top) and average temperature (bottom) over the tow.

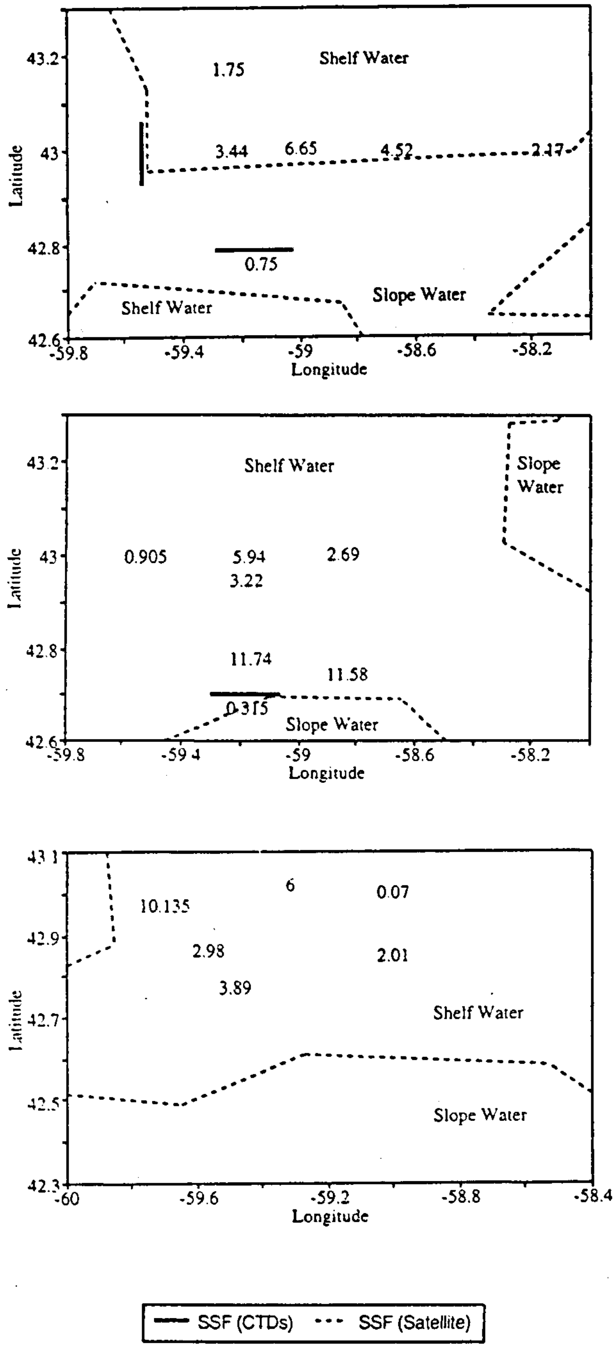
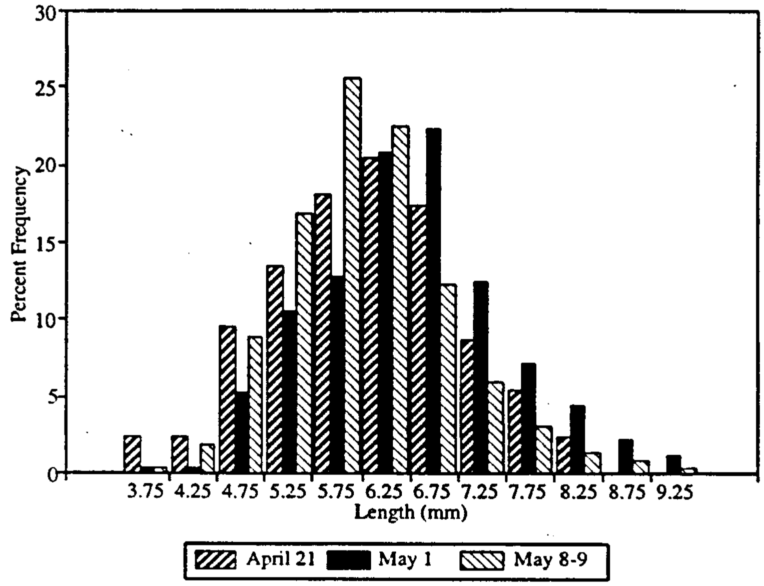


Fig.13 Average concentration of redfish larvae in the top 40 m at each BIONESS station for (A) 21 April, (B) 1 May and (C) 8-9 May. The dashed lines indicate the position of the shelf/slope front from the NOAA satellite analysis and the heavy solid line denotes the position of the front based upon the CTD measurements.



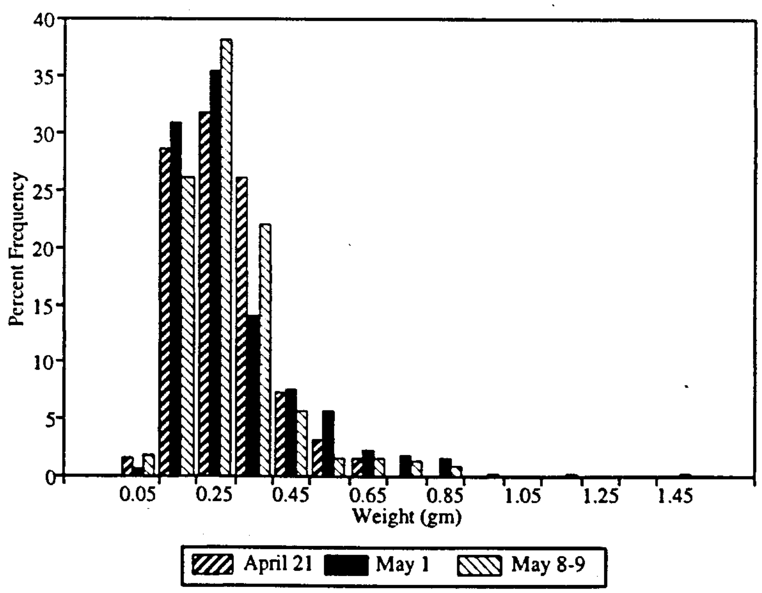


Fig.14 The length (top) and weight (bottom) of the redfish larvae expressed as percent frequencies for each of the visits to the offshore feature.