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The role of frontal currents in larval fish transport on Georges Bank

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Abstract—The hydrography and distributions of cod larvae on Georges Bank were surveyed during two research cruises in April and May 1993 in order to relate larval drift between cruises to the vernal intensification of the frontal component of the residual circulation. We observed the transport of two patches of cod larvae. One patch, which had maximum larval cod densities of 45 larvae 100 m^{-3} in April, appeared to have been advected south about 75 km between surveys, while the other, which had maximum larval cod densities of 20 larvae 100 m^{-3} in April, appeared to have been advected north-northeast about 25 km. Maximum larval densities in each patch sampled during the second cruise in May were 15 and 18 larvae 100 m^{-3}, respectively, and mean growth in total length for larvae in the two patches was approximately 5.5 mm and 4.5 mm, respectively, between the two cruises. During the April cruise there was a large volume of anomalous cold, fresh water, of Scotian Shelf origin, which occupied much of the eastern third of Georges Bank. During May, relatively cold, fresh water appeared in a band from the Northeast Peak along the Southern Flank, between Georges Bank water on the top of the Bank, and upper Slope Water offshore. The distribution of cold, fresh water suggests its participation in the general clockwise circulation around the Bank. The transport of cod larvae comprising the first patch appeared to become organized within, and move along, the frontal boundary established by the Scotian Shelf-like water mass, while larvae in the second patch, which we assumed to have moved to the north, may have been transported northward in an on-Bank flow of warmer and saltier upper Slope Water, which may have originated from a Gulf Stream Ring. Based upon observed transport of the first patch of larvae in relation to the frontal boundary, we present a conceptual model of frontal mixing currents on Georges Bank, where current velocities may reach 5 cm s^{-1} at the depth of the pycnocline. We suggest that this frontal component of the residual circulation, which is in addition to that resulting from tidal rectification, may be important in the transport of fish larvae, and that interannual variability in the degree of intrusion of extrinsic water masses may contribute to variable larval cod drift patterns, to variable larval cod retention on the Bank, and ultimately, to variable larval fish recruitment to the early juvenile stage. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Studies of the transport of larval fishes in relation to the mean circulation on Georges Bank date to Bigelow (1926) and Walford (1938), who were among the first to document the spawning distributions of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) on Georges Bank, and to describe the general clockwise transport of their larvae from spawning areas on the northern and northeastern parts of the Bank, around to the Southern Flank. While these early works provided a first-order description of larval drift on the Bank, the process remained thinly detailed and poorly understood. Attention was refocused on the transport of larval gadids on the Bank when Colton and Temple (1961) examined the

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physical and biological mechanisms that might control the drift patterns of larvae. They pointed out that, based on drifter studies up to that time, the residual flow of surface waters would be expected to carry fish larvae from Georges Bank to the offshore slope waters to the south and southwest, and thus result in their loss from the system. Despite this potential for offshore drift, Colton and Temple (1961) noted that the young fish were still somehow able to recruit to the Bank.

Much more has since been learned about the circulation on Georges Bank, including the dynamical origins of the anticyclonic mean flow (Loder and Wright, 1985). Recent work, based on results using 3-dimensional circulation models (e.g. Werner *et al.*, 1993; Lough *et al.*, 1994), supports the notion that while fish larvae in the surface waters may be advected off the Bank, especially under the influence of wind events (Lough *et al.*, 1994), larvae that occupy deeper waters may be retained in an on-Bank flow (Lough and Bolz, 1989). However, more recent drifter data suggest that even at 5–10 m depth, drifting particles may be retained on the Bank from late spring through summer (Limeburner and Beardsley, 1996; Pettigrew, unpublished).

Georges Bank cod larvae

The timing and location of spawning of cod and haddock are closely coupled to the vernal intensification of the anticyclonic circulation pattern around Georges Bank (Lough, 1984; Backus, 1987; Buckley and Lough, 1987; Lough and Bolz, 1989). Cod and haddock have overlapping spawning seasons on Georges Bank; each spawns pelagic eggs on the northeast part of the Bank from winter to spring (Fig. 1). The maximum spawning occurs in late February–early March for cod, and early April for haddock (Walford, 1938; Colton *et al.*, 1979; Lough and Bolz, 1989). The eggs and larvae of both species may be found in the water column through the spring and early summer (Colton *et al.*, 1979). Winter hydrographic conditions generally still prevail at the time of spawning, with the water column being vertically well-mixed throughout the region (Mountain and Holzwarth, 1989). The pelagic eggs develop in about 2–3 weeks at the prevailing temperatures (*ca* 4–6°C), and the yolk sac is resorbed in about another week (Marak and Colton, 1961; Laurence and Rogers, 1976). During this time, the eggs and larvae are subject to the general clockwise circulation around the Bank (Sherman *et al.*, 1984), and larval distributions can be followed as the larvae are advected around the Bank at 2–7 km day^{-1} (Lough, 1984).

Physical background

The primary character of the vernal hydrographic structure surrounding Georges Bank is that of a tidal mixing front. While the upper waters of the Gulf of Maine stratify each spring in response to the vernal increase in solar insolation, the waters over the shallower Bank remain vertically homogeneous as a result of vigorous tidal mixing. This lateral variation of vertical tidal mixing intensity gives rise to horizontal density differences between on- and off-Bank locations, and thus to baroclinic pressure gradients and frontal currents. Based on analysis of satellite imagery, Yentsch and Garfield (1981) concluded that the location of the front generally corresponds with the 60 m isobath. More recent numerical predictions of frontal position by Loder and Greenberg (1986) consistently placed the front inside the 50 m isobath, even when the wind-mixing effects were included. We note, however, that only the M_2 component of tidal currents was included in that calculation.

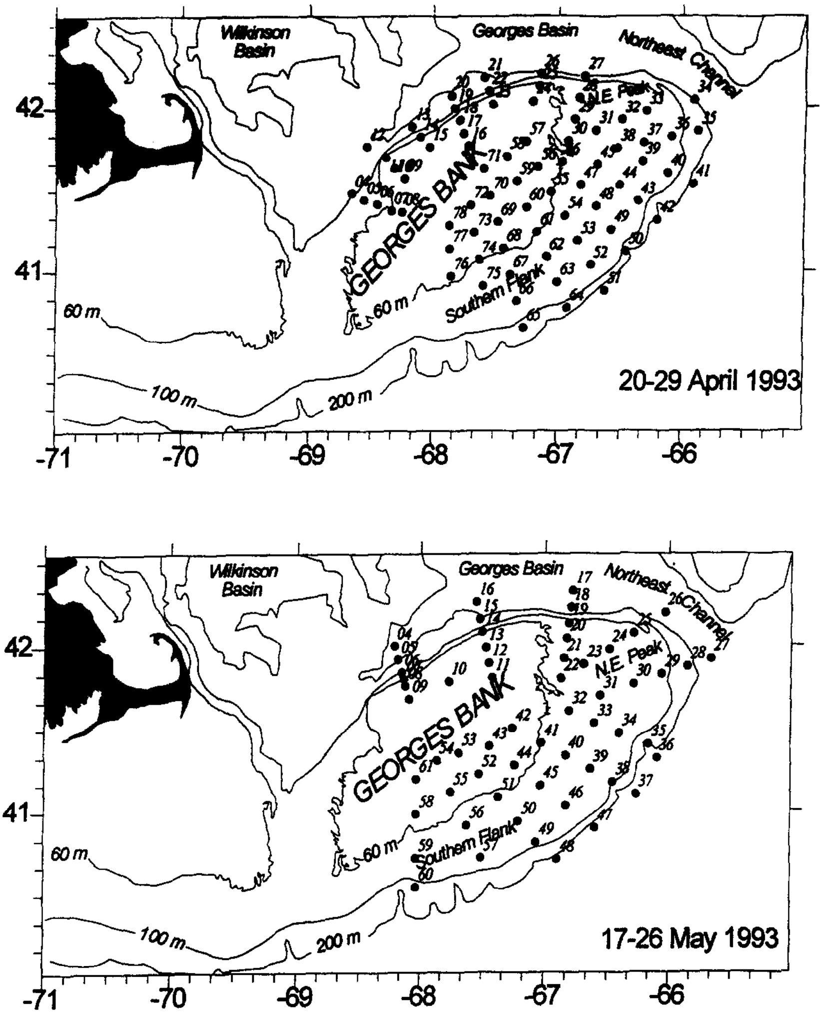

Fig. 1. Location of sampling stations on Georges Bank, for R.V. *Columbus Iselin* cruises, 20–29 April and 17–26 May 1993. The 60, 100 and 200 m isobaths are indicated, as are features referred to in the text.

Although the main features of the Georges Bank frontal system are those of a classic tidal mixing front, and are simply attributable to enhanced mixing over the shallow Bank, the details of the Bank's hydrographic structure reflect other significant factors. In deeper water over the flanks of the Bank, the density contrasts are due primarily to salinity differences between Georges Bank water and surrounding water masses (e.g. Loder *et al.*, 1992). To this background can be added on-Bank advections of waters of Gulf of Maine, Scotian Shelf, or Gulf Stream Ring origin. These episodic incursions distort both the density distributions and the residual circulation pattern. Hopkins and Garfield (1981) suggest that tongues of Scotian Shelf Water commonly intrude between Georges Bank Water and upper Slope Water over the southeastern portion of the Bank during spring and early summer.

It is generally well accepted that the principal cause of the annual mean anticyclonic circulation around Georges Bank is the topographic rectification of tidal currents (Loder, 1980). Detailed numerical calculations by Loder and Wright (1985) show that, due to viscous effects, the maximum currents associated with this barotropic mechanism occur near the surface. On the southern flank, near the 60 m isobath, the model predicts near-surface currents of *ca* 5 cm s^{-1}, decreasing to approximately 2 cm s^{-1} 10 m off the bottom. On the northern flank rectified currents are approximately three times as great. During spring, developing density stratification results in increased anticyclonic circulation around the Bank; the first indirect effect of stratification is due to the reduction of bottom friction acting on the rectified flow. In addition, the vernal formation of the tidal mixing front on Georges Bank gives rise to a density-driven component (e.g. Butman and Beardsley, 1987). It is during this springtime period of intensifying circulation and developing thermal fronts that the larval gadids are present on Georges Bank.

We present here the results of two research cruises to Georges Bank in April and May 1993, during which we surveyed the hydrography and distributions of larval cod in an attempt to relate larval drift patterns between the two surveys to the frontal component of the Georges Bank circulation. We show that the density-driven currents in the frontal region are important in explaining the observed transport of larvae during the period between our two cruises, in that the transport trajectories of one patch of larvae appears consistent with the hydrographic structure and geostrophic currents. Furthermore, we point out that the positions of the fronts, and their intensities, depend upon the incursions of extrinsic water masses of Gulf of Maine, Scotian Shelf and Gulf Stream/Continental Slope origin onto Georges Bank, which likely have both seasonal and interannual variability, and which could be a source of variability in the recruitment of young cod on the Bank.

MATERIALS AND METHODS

Larval cod and hydrographic data were collected during two research cruises on Georges Bank aboard the R.V. *Columbus Iselin*: 20–29 April and 17–26 May 1993. Standard CTD (conductivity, temperature, depth recorder) casts were made at each station (Fig. 1) using the ship's Neil Brown MKIII CTD. Contour plots of temperature and salinity were used to characterize the springtime hydrography of the Bank during the successive (April and May) cruises. Density profiles also were used to calculate geostrophic currents associated with the mixing front located near the 60 m isobath. For these calculations, the thermal wind equation was numerically integrated using the bottom as a zero-velocity reference level.

Ichthyoplankton samples were collected using 60-cm Bongo nets. The Bongo frame was fitted with 505 μm mesh nets, digital flow meters, and a maximum depth recorder; the frame was hauled in a double oblique fashion at a speed through the water of *ca* 1 m s^{-1}, from the surface to *ca* 50 m, or at shallower stations, to within *ca* 5 m of the bottom. Larvae from one side of the Bongo were sorted immediately upon collection and were preserved in ethanol for later otolith analyses; the other side of the Bongo sample was preserved in 5% buffered formalin. The preserved samples were sorted back at the laboratory and all fish larvae removed and identified. All cod larvae collected were measured to the nearest 0.5 mm total length, and larval cod densities at each station were computed as number of larvae per 100 m^3 filtered.

RESULTS

April 1993

Surface water temperatures on the Bank during 20–29 April cruise ranged from low temperatures below 4°C, which are likely the result of an intrusion of Scotian Shelf Water onto the northeastern-most part of the Bank, to high temperatures of about 6.5°C; the higher temperatures were largely confined to the central western portion (Fig. 2). There was much warmer surface water on the southern edge of the Bank at Station 51 (12.9°C; not contoured), which likely represents upper Slope Water possibly associated with a Gulf Stream Ring. The mass of cold water on the Bank, having surface temperatures colder than about 5.3°C, covers a large area that comprises much of the eastern third of the Bank. This cold-water intrusion extends over the Northeast Peak as far west as the 60 m isobath, where topographic control appears to be exerted, effectively directing the flow along the southern flank (Fig. 2).

The surface salinities in April ranged from 31.5 at Station 34 (Fig. 1) to 35.0 at Station 51 (Fig. 3). Both of these stations are beyond the 200 m isobath. There was general spatial coherence between the cold surface waters and the lower salinities; the fresher waters were seaward of the 60 m isobath and extended along the southern flank, similar to the cold temperature pattern.

The *T–S* relations for several stations sampled in April are plotted in Fig. 4. Station 27, located just north of the 200 m isobath in Georges Basin, shows the typical Gulf of Maine *T–S* relationship, with cold waters at intermediate depths and warmer, higher salinity water at depth, representing the influx of deep Slope Water into the Gulf through the Northeast Channel (Hopkins and Garfield, 1979). Station 41, located on the open ocean side of the Northeast Peak (Fig. 1) just beyond the 200 m depth contour, reflects the warmer, saltier Slope Water at depth, but this station also shows a colder and fresher signature that we attribute to Scotian Shelf Water near the surface. The stations on the eastern third of Georges Bank, which we identified as an intrusion of Scotian Shelf Water, are shown

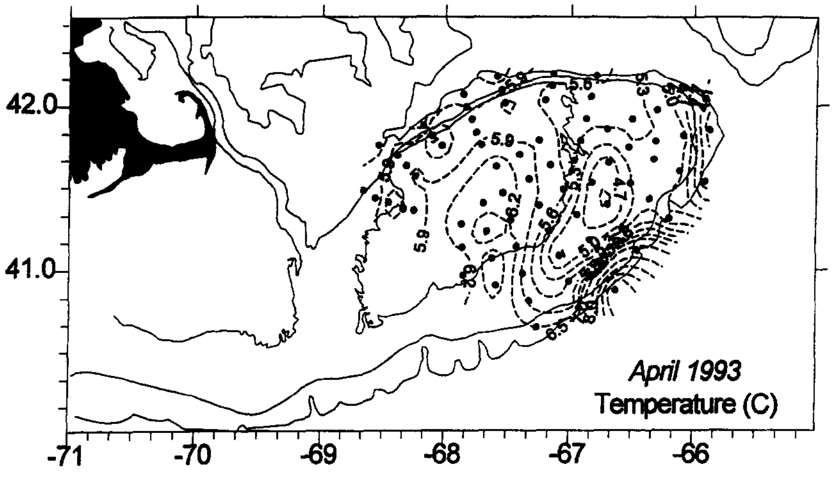

Fig. 2. Contours of surface water temperature on Georges Bank for the period 20–29 April 1993.

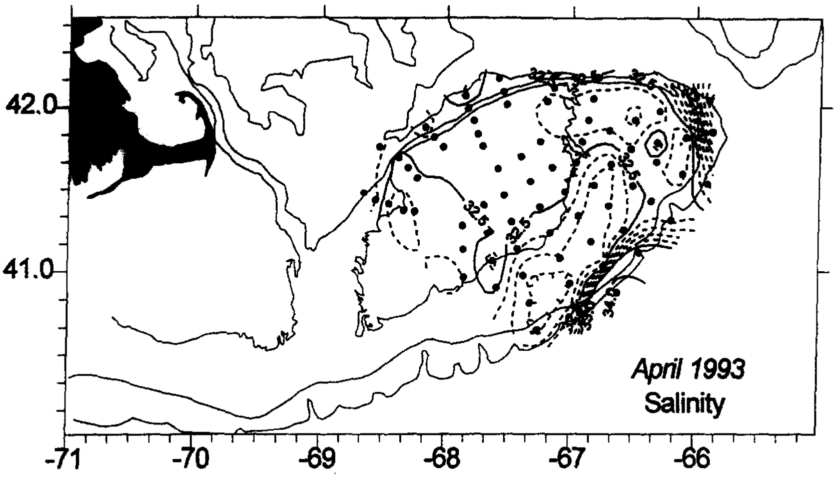

Fig. 3. Contours of surface salinity on Georges Bank for the period 20–29 April 1993.

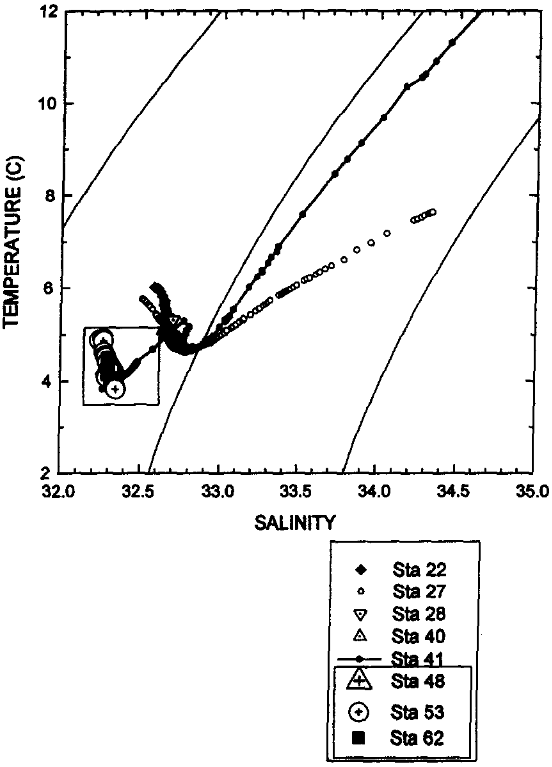

Fig. 4. Temperature–salinity diagram for selected stations for the period 20–29 April 1993. The stations are indicated. T–S data plotted inside the box correspond to the stations indicated in the legend.

enclosed in the box in Fig. 4, and are readily identifiable as having distinct and narrowly-defined *T–S* properties, consistent with earlier definitions (Hopkins and Garfield, 1979).

Referring back to Figs 2 and 3, a clear "break" can be seen in the continuity of the low temperature, low salinity surface waters over the Northeast Peak. The water property distributions appear to be disrupted along a curved path that runs between the 60 and 100 m isobaths. We interpret this pattern to indicate Scotian Shelf Water that had intruded earlier onto Georges Bank and was cut by Gulf of Maine surface water from the northern flank, as part of the general clockwise around-Bank, residual circulation.

The densities of cod larvae in April were generally low (Fig. 5). Nonetheless, we identified two main patches of larvae: one on the Northeast Peak of Georges Bank, which had a peak density of *ca* 45 larvae 100 m^{-3} at Station 31 (Fig. 1), and a second patch on the southwest flank, which had a maximum density of *ca* 20 larvae 100 m^{-3} at Station 76 (Fig. 1). The position of the first patch of larvae is near the northern edge of the cold pool of Scotian Shelf Water on the Northeast Peak (Fig. 2), while the second patch is associated with slightly warmer and saltier waters on the southwestern part of the Bank. We were forced to conclude our April sampling after Station 76, which was when we began to encounter the higher densities of cod larvae that we identified as the second patch.

May 1993

The 17–26 May 1993 cruise results (Figs 6–8) show how the Georges Bank system evolved in the three to four weeks following the April cruise. The surface waters had warmed as much as 2.0°C on the top of the Bank, and by about 1.0°C on the Northeast Peak (Fig. 6). The surface temperatures ranged from 5.0°C at Station 26, which was in Scotian Shelf Water over the Northeast Channel, to > 18°C in the Gulf Stream Ring waters at Station 37 off the Southern Flank of the Bank. The surface salinities ranged from 31.56 at Station 26 to 35.63 at Station 37 (Fig. 7). These data suggest that relatively cold and fresh water was still present in the Northeast Peak region, and between the 60 and 100 m isobaths on the southern flank where it appeared to be entrained in the residual clockwise circulation. There is little or no

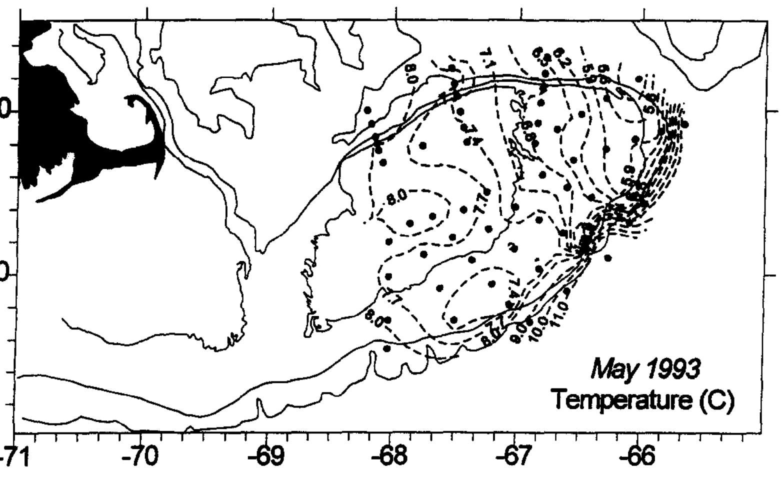

Fig. 6. Contours of surface water temperature on Georges Bank for the period 17–26 May 1993.

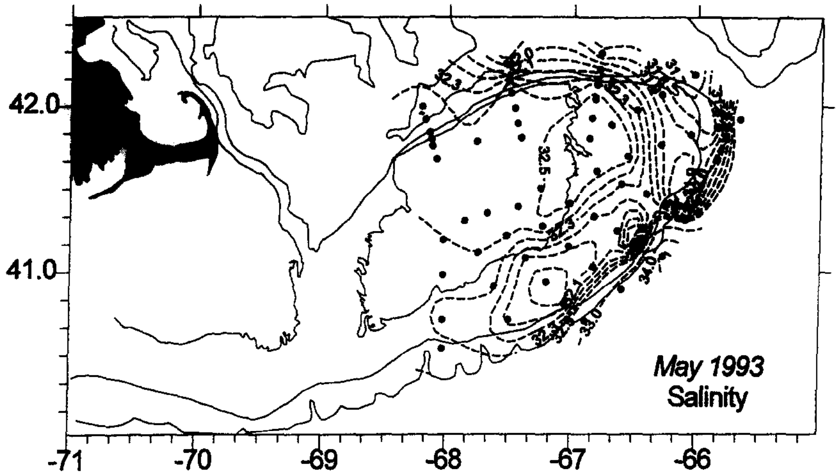

Fig. 7. Contours of surface salinity on Georges Bank for the period 17–26 May 1993.

evidence of a flow of warmer and saltier surface waters from south to north onto the western Bank, as we suspect may have occurred in April.

The densities of cod larvae in May were lower than in April, as is consistent with natural mortality in the intervening period between the cruise legs. At least one of the two patches of cod larvae identified in April could still be identified in May: "patch one", which was on the Northeast Peak in April, appears to have moved almost due south about 75 km; its maximum cod density was reduced to *ca* 15 larvae 100 m^{-3} at Station 39 (Fig. 8). "Patch two", which was on the southwest flank in April, may have moved to the north-northeast about 18–27 km; if this were the case, its maximum cod density was not significantly reduced compared with larvae in patch one. This relatively constant maximum density, or very low larval mortality, may be an artifact of not having sampled completely patch number two in April. Thus, we cannot state with any certainty how far the patch was advected nor determine its decrease in larval density. It is also possible that the second patch we are identifying in May originated from a split of the first patch, in which case those larvae in patch two would have been transported more than 100 km to the southwest. We would argue that this is a less likely scenario.

Although we cannot be certain, we suspect that the larvae in patch two moved to the north from the position noted in April. One line of evidence supporting this point is the change in larval lengths in each suspected patch between the two cruises. The length-frequencies of cod larvae from each of the two patches in April and May (Fig. 9) show that larvae of patch one in April, on the northeast part of the Bank, had a mean length of 6–7 mm, and that they grew *ca* 5–6 mm in the 3–4 week period between the April and May cruises. Larvae of patch two in April were smaller, with a mean length of *ca* 5–6 mm; these larvae grew only *ca* 4–5 mm in the intervening 3–4 weeks between cruises. These growth rates, deduced from approximate changes in modal lengths, are in keeping with published accounts for larval cod (Bolz and Lough, 1983). If, on the other hand, the larvae in the second patch in May were from patch one on the Northeast Peak in April, then that population of larvae would have exhibited a very slow, and unlikely, average growth rate of only *ca* 2 mm in the 3–4 weeks.

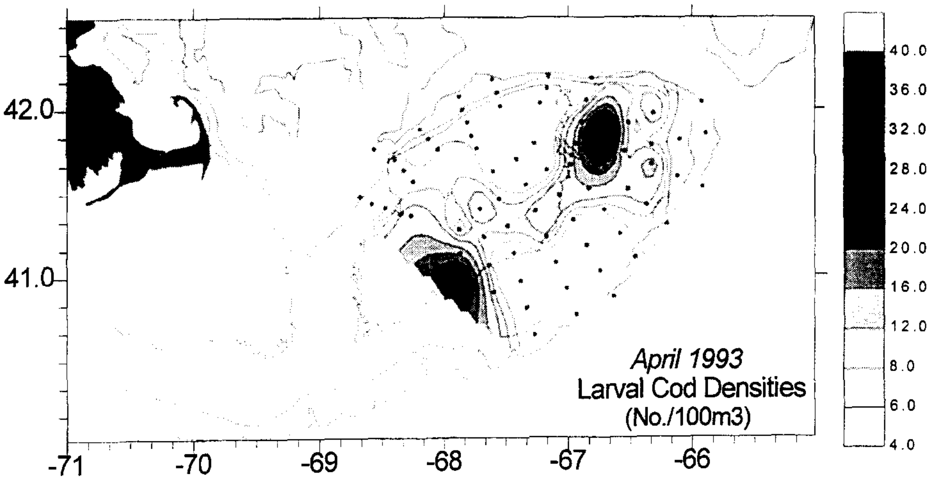

Fig. 5. Contours of larval cod densities, expressed as number of larvae per 100 m^3 water filtered, for the period 20–29 April 1993.

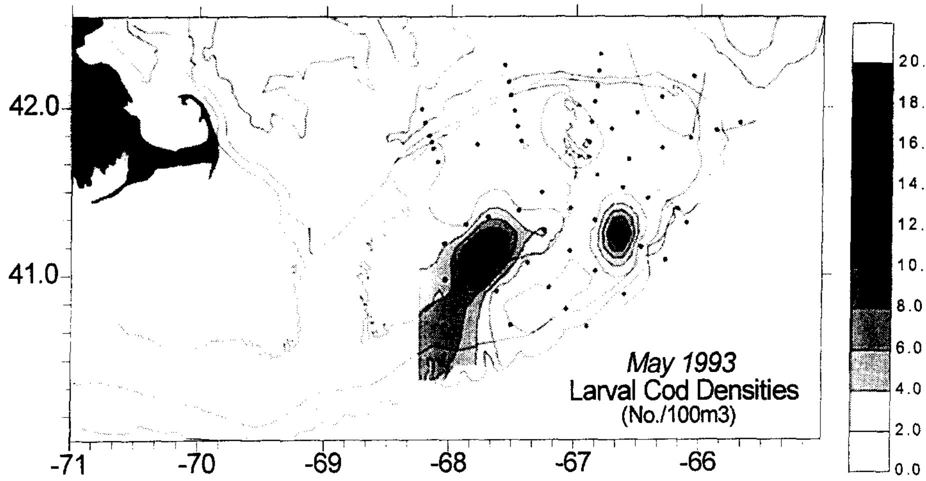

Fig. 8. Contours of larval cod densities, expressed as number of larvae per 100 m^3 water filtered, for the period 17–26 May 1993.

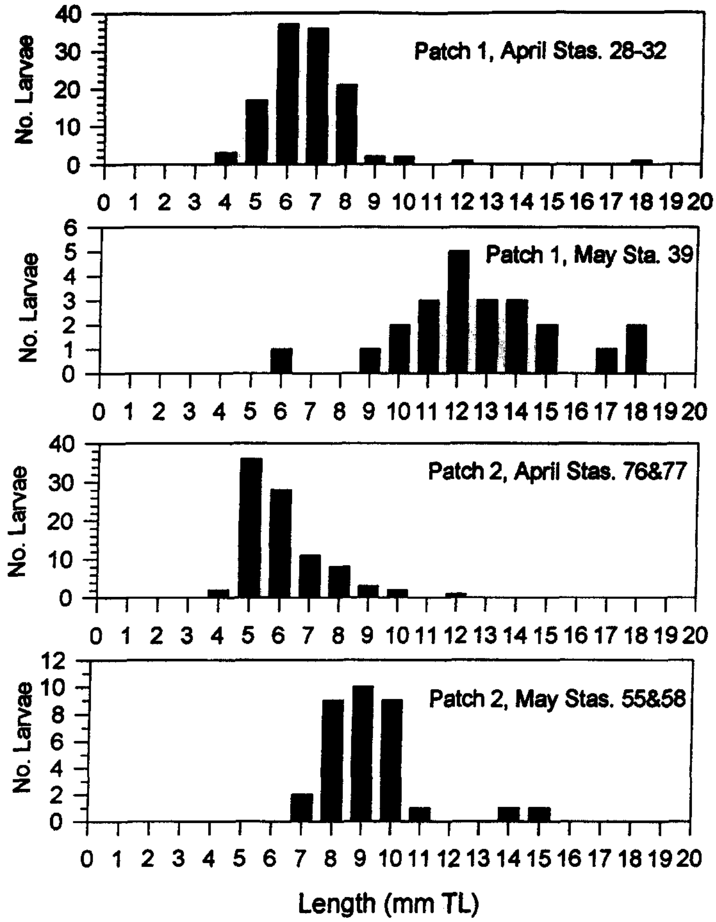

Fig. 9. Length–frequency distributions for cod larvae collected from the two larval patches in Figs 5 and 8; all larvae at the stations listed in each panel were measured to the nearest 0.5 mm total length and plotted in 1 mm length intervals.

Larval transport in relation to fronts

The distribution of the first patch of cod larvae in April appears to be coincident with the eastern-most frontal edge of the Scotian Shelf Water, which tended to hug the 60 m isobath as it flowed toward the southwest and around the shallowest portion of the Bank (Figs 2, 3 and 5). Vertical sections along Stations 46–50 (Fig. 10) show that the core of Scotian Shelf Water was centered at Stations 47 and 48, and that the water column was vertically well-mixed over the Bank. The water mass was bounded by two fronts: a surface-to-bottom front near Station 46, and a stronger bottom front at Station 49. The greatest density of cod larvae was at the on-Bank end of that transect, at Station 46 (Fig. 10), which we identify as the frontal region between Scotian Shelf Water and Georges Bank water. Vertical sections along a transect of stations farther to the southwest on the Bank (Stations 59–64; Fig. 11), which was farther "downstream", show that the core of Scotian Shelf Water was narrower, being confined between Stations 63 and 60 or 61. The core of the Scotian and Shelf Water

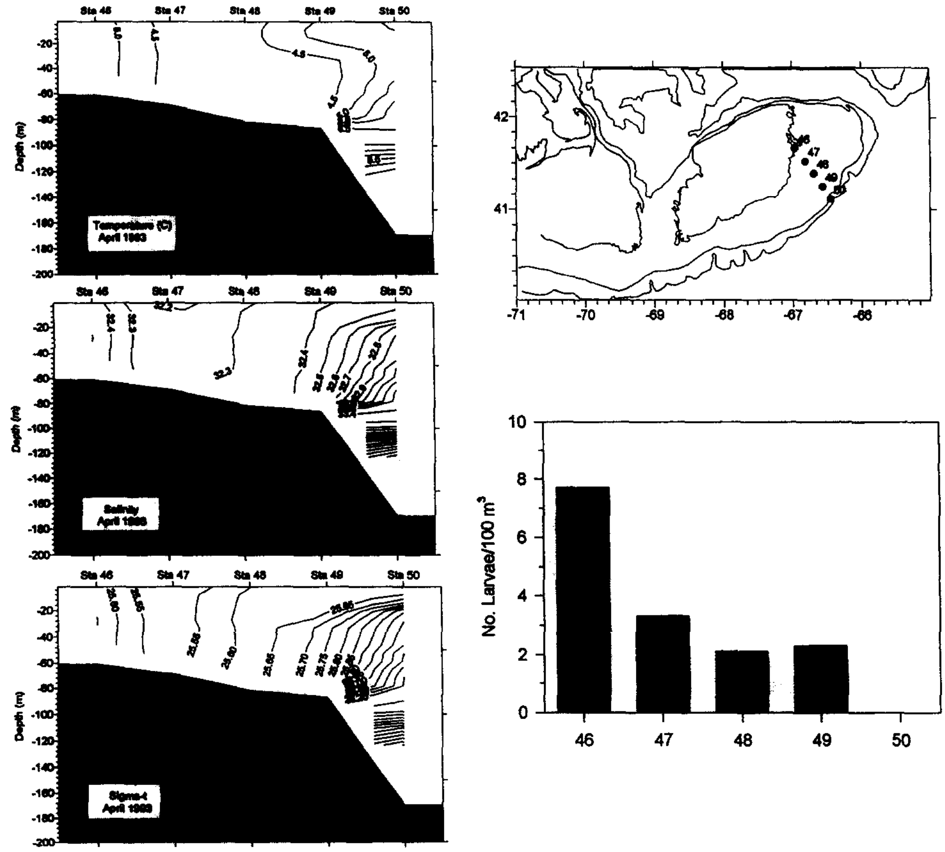

Fig. 10. April 1993. Vertical section contour plots of temperature, salinity and σ_θ for Stations 46–50, as well as map of transect station locations and bar graph of larval cod densities at each station along the transect.

was approximately centered at Station 62, where there was some evidence of the surface waters having become warmed slightly (0.5°C) during their flow to the southwest. The waters are vertically well-mixed to the north of Station 62, and vertically stratified to the south (Fig. 11). The cod larvae were most dense at Station 60, which was once again in the vertically-mixed waters in the frontal edge of the Scotian Shelf Water and Georges Bank water. A little farther offshore along this transect, the density structure showed the development of a "pycnocline fan", where isopycnals opened toward the shallower, tidally-mixed portion of the Bank, and intersect both the surface and bottom at the front. In this instance, the fan occurred in the transition zone between Scotian Shelf Water and the warmer, saltier upper Slope Water.

Examination of Fig. 7 shows that in May a band of relatively low-salinity surface water still wrapped around the shoal central region of the Bank. In fact, salinities were lower than those observed in the April cruise. Although surface temperatures (Fig. 6) warmed considerably, the lowest temperature (<5.6°C) waters on the Northeast Peak appear to have been advected from the Northeast, suggesting a Scotian Shelf contribution, although

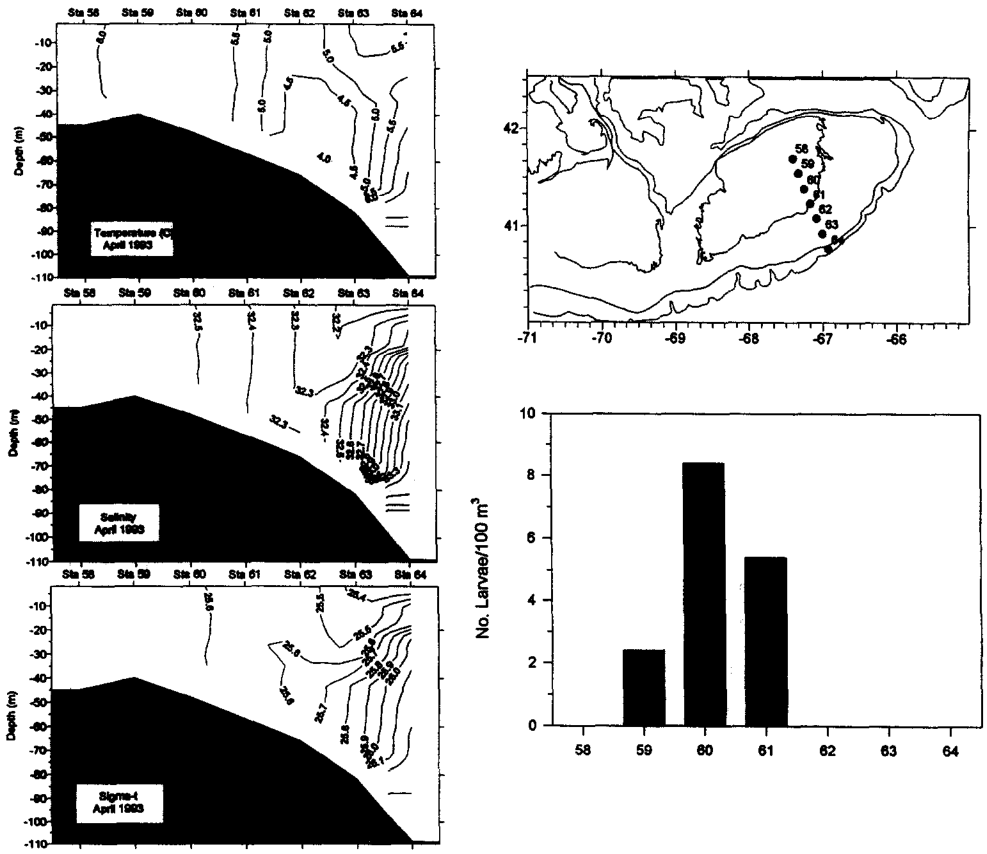

Fig. 11. April 1993. Same as Fig. 10, except for Stations 58–64.

based on T–S properties and the presence of low salinity water on the north flank, it is hard to argue convincingly against a Gulf of Maine surface water origin.

The frontal features had become better developed in May (Figs 12–14). Beginning on the Northeast Peak, or at the upstream end of the Bank, vertical sections along the transect of Stations 22–26 (Fig. 12) show the relatively cool and fresh water mass extending from the Northeast Channel (Station 26) to Station 24 near the 80 m isobath. The density structure exhibits the classical pycnocline mixing fan located at about Station 24. The densities of cod larvae were low and not correlated well with the front at this upstream, Northeast Peak region, the larvae were most dense at Station 22, within the vertically-mixed Georges Bank water (Fig. 12), with a secondary peak seaward of the strongest surface salinity front.

Farther downstream, the cool, fresh water was now identifiable as a distinct band between the Georges Bank water and the much warmer and saltier upper Slope Water (cf. Hopkins and Garfield, 1979), associated in this case with a Gulf Stream Ring at Station 37 (Fig. 13). There is evidence that the cool, fresh surface water (relic Scotian Shelf Water) warmed over the outer portion of the Bank, between Stations 41 and 38, resulting in a cold subsurface feature. This cold subsurface water mass, often referred to as the cold pool, is a common

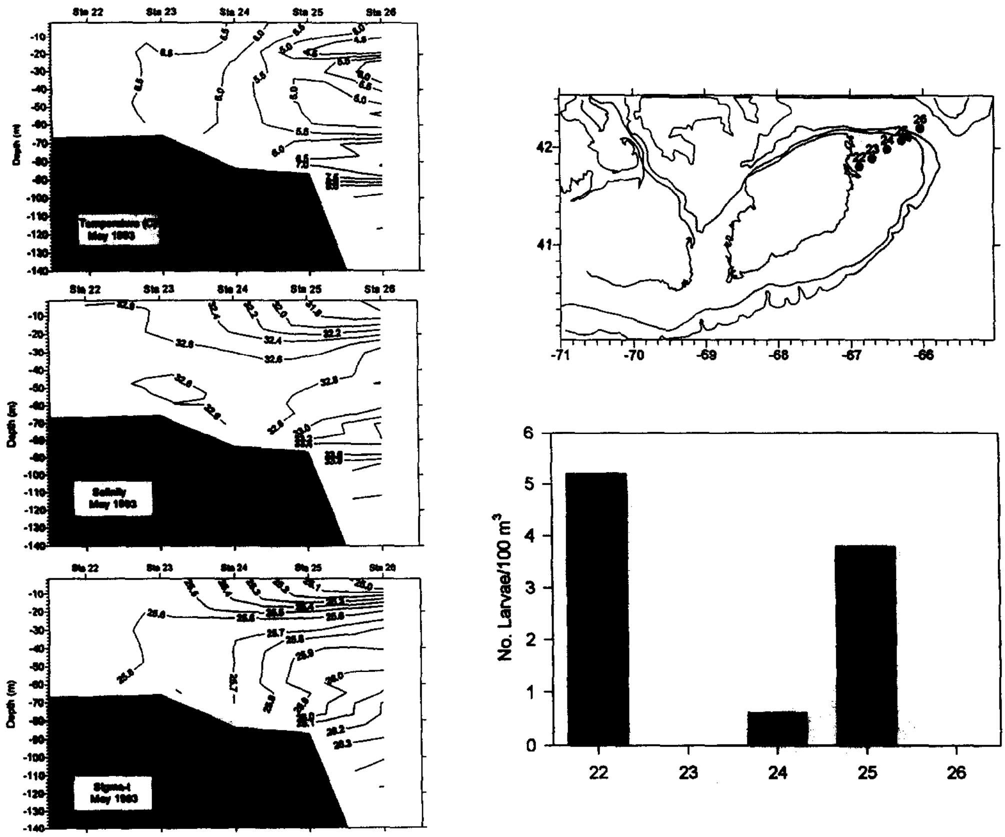

Fig. 12. May 1993. Vertical section contour plots of temperature, salinity and σ_θ for Stations 22–26, as well as map of transect station locations and bar graph of larval cod densities at each station along the transect.

seasonal feature from the south flank of Georges Bank to the Mid-Atlantic Bight (Beardsley *et al.*, 1976; Hopkins and Garfield, 1981). The origin of this feature is usually most closely linked to Gulf of Maine Intermediate Water, although our observations and the analyses of Hopkins and Garfield (1981) suggest a significant admixture of Scotian Shelf Water. The density structure across this transect (Fig. 13) shows a complex frontal structure. While the pycnocline mixing fan appears between Stations 40 and 41, the highest larval cod densities (patch one) appeared at Station 39, in association with a surface salinity front. Although there were strong temperature and salinity fronts between the cold fresh band and upper Slope Water, below the surface layer they compensate, and no frontal structure appeared in the density field. Still farther downstream and toward the southwestern flank of Georges Bank, at the transect of Stations 43–47 (Fig. 14), the cold pool could be seen between Stations 45 and 46, capped by a surface lens of low salinity water. The shallow, on-Bank side of that water mass had a surface front between Stations 44 and 45 (Fig. 14), which again exhibited a pycnocline fan in cross-section. The highest densities of larval cod were found at Station 44, which is at the edge of that tidal mixing surface front.

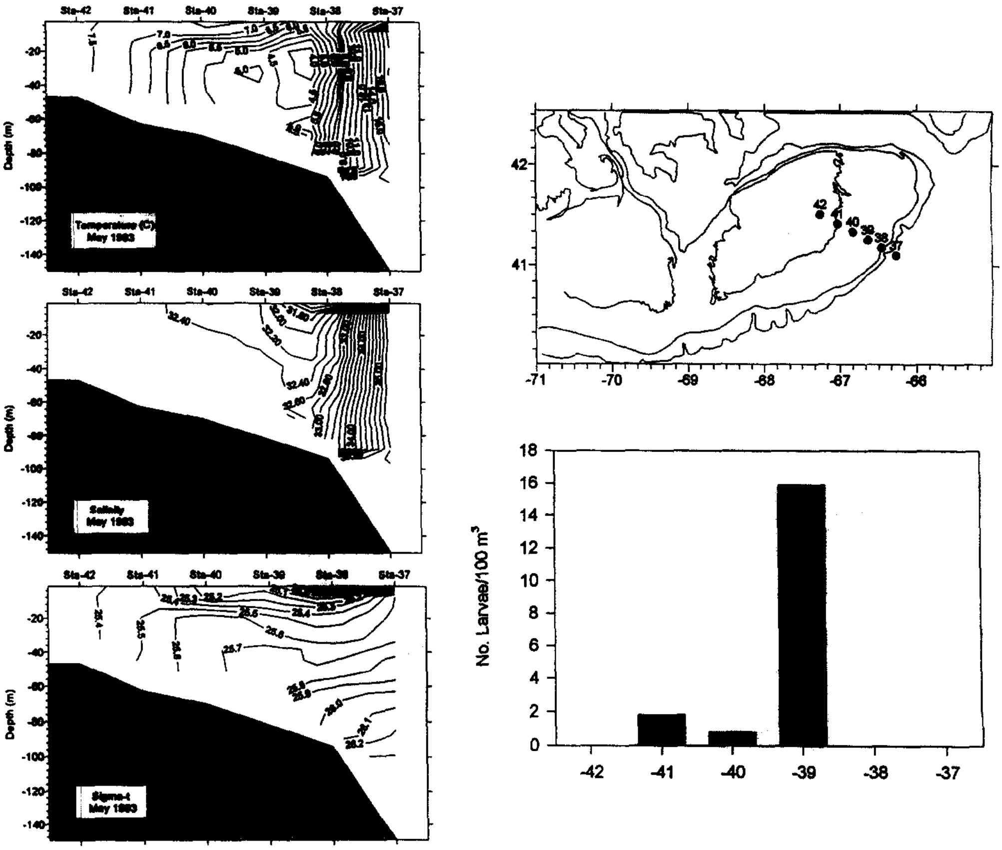

Fig. 13. May 1993. Same as for Fig. 12, except for Stations 37–42.

DISCUSSION

While the residual clockwise circulation on Georges Bank is forced primarily by the topographic rectification of tidal currents (Loder and Wright, 1985), larvae in the vicinity of tidal mixing fronts, especially in the later part of the spring when the density contrasts become enhanced, are likely to gain an additional clockwise advective component. In both April and May, we found some evidence of the larval cod distributions becoming more organized, or concentrated, in relation to the frontal regions as a function of increasing distance downstream from the Northeast Peak. The frontal structures themselves become somewhat better defined in the downstream direction. This interpretation assumes that distance away from the Northeast Peak is the same as increasing distance and time from spawning.

The April hydrographic survey suggests that an earlier intrusion of Scotian Shelf Water onto the Northeast Peak and Southern Flank was bisected by a slightly warmer, saltier water mass, presumably of Gulf of Maine origin, as part of the anticyclonic Bank circulation. During May, a tongue of even fresher surface water than that observed in April occupied the Northern Flank and eastern tip of the Bank. This intrusion displaced the

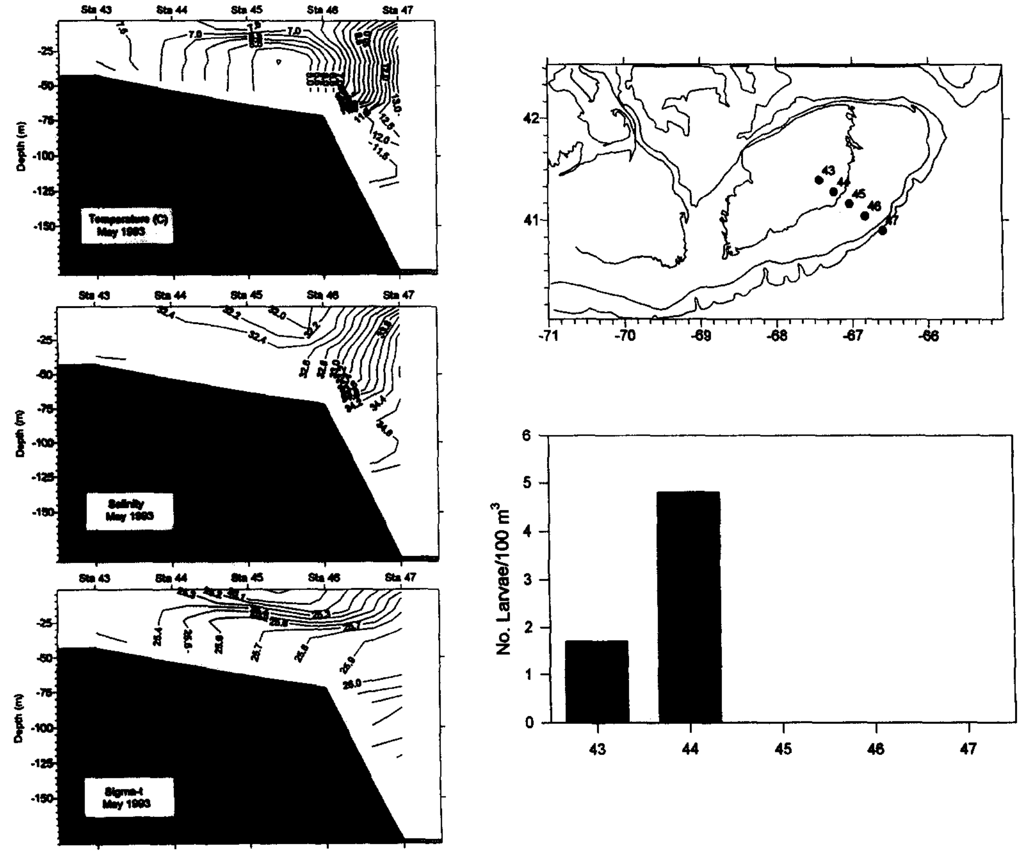

Fig. 14. May 1993. Same as for Fig. 12, except for Stations 43–47.

Scotian Shelf/Gulf of Maine Water observed in April, and the patch of fish larvae, toward the southwest. The result was that throughout the spring, a band of cold, fresh water of Scotian Shelf and Gulf of Maine origin was found between the Georges Bank Water and upper Slope Water farther offshore. The progressive surface warming of these cold fresh waters resulted in a near-bottom cold pool over the Southern Flank in May, suggesting that the cold pool observed over the New England Shelf and Mid-Atlantic Bight (Beardsley *et al.*, 1976) is of mixed (Scotian Shelf/Gulf of Maine) origin.

When the hydrography of Georges Bank is stripped of the complicated structures associated with cross-Bank advection of extrinsic water masses, such as the incursion of Scotian Shelf water observed in this study, the vernal hydrography can be characterized as a classical tidal-mixing frontal system arranged along the perimeter of a shallow submarine bank. While the location of the front varies over seasonal, monthly, meteorological, and tidal timescales, its position is generally around the 60 m isobath. This system can be viewed conceptually by considering an idealized shallow bank in a stratified sea. If we assume that the pycnocline is initially horizontal and centered at approximately mid-depth (e.g., 30 m in a 60 m water column), and we then invoke tidal mixing over the Bank, the overlying pycnocline will be destroyed without changing the mean density of the water column or the hydrostatic pressure at the top of the bank. The resulting hydrographic structure in this idealized situation will be a symmetric pycnocline fan that opens toward the homogenous area over the bank (Fig. 15). Purely as a consequence of the vertical mixing, baroclinic pressure gradients and associated geostrophic currents arise. These baroclinic, frontal mixing currents are greatest at the depth of average density in the stratified portion of the domain where the horizontal pressure gradient is strongest. Thus, in the absence of other circulation processes, mixing alone generates a net anticyclonic circulation around the bank in the northern hemisphere. This component of the circulation has a subsurface maximum and decreases to zero toward the surface and bottom boundaries.

The idealized tidal mixing front in Fig. 15, intended to represent springtime hydrographic conditions on the Northeast Peak and Southern Flank of Georges Bank, is based upon the hydrographic data collected during the April and May cruises in 1993, with two important differences. First, the hydrographic gradients associated with the front were under-resolved by the roughly 20 km station spacing of the CTD surveys, in that the sharp density changes generally occurred between a single pair of stations on each transect. Underway surface temperature and salinity measurements between stations indicated that the surface expression of the front was at times less than 5 km in width. Thus, we have assumed a representative surface-to-bottom frontal width intermediate between these two values (e.g. *ca* 12.5 km; see Fig. 15). Second, the observed frontal regions are not strictly tidal mixing fronts; the density contrast is influenced by the intrusion of buoyant (fresher) Scotian Shelf Water, which also may have introduced a sea-level gradient.

Geostrophic calculations of the currents associated with the idealized front have been superimposed on the density section in Fig. 15. Horizontal displacements in the core flow (5 cm s^{-1}) are about 4 km day^{-1}. It is interesting to consider whether or not the subsurface flow maximum associated with the idealized mixing fan would persist when combined with the around-Bank circulation due to tidal rectification. Loder and Wright (1985) examined this question of relative significance of rectified and baroclinic circulation on Georges Bank

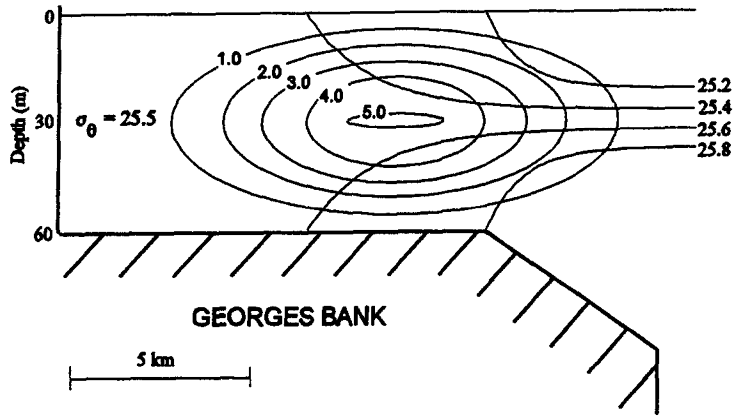

Fig. 15. Density (σ_θ) and velocity (cm s^{-1}) of an idealized tidal mixing front over Georges Bank. The pycnocline fan is characteristic of lateral variation in the degree of vertical mixing. The velocity contours represent geostrophic currents associated with the density distribution. The subsurface maximum velocity occurs at the depth of the mean density of the stratified column (center of the pycnocline) and within the front. Positive velocity values indicate flow out of the page.

using a numerical model, and calculated tidally-rectified residual currents under stratified (low friction) conditions. Their calculations show that at the 60 m isobath on the Southern Flank the maximum (surface) rectified current is 5 cm s^{-1}, while currents at 30 and 50 m depth drop to 4 and 3 cm s^{-1}. Superimposing the frontal mixing currents represented in Fig. 15 results in a subsurface maximum of 9 cm sec^{-1} at mid-depth, falling off to roughly 5 cm sec^{-1} both at the surface and at 50 m depth. Thus, the subsurface maximum associated with the frontal mixing current (Fig. 15) would be preserved. Loder and Wright (1985) came to the opposite conclusion, which perhaps resulted from their using density data from Flagg *et al.* (1982), which were averaged over four summer seasons, thereby broadening the front to approximately 30 km and greatly weakening the calculated frontal circulation.

Our observations of larval cod transport on Georges Bank and our conceptual model of the role of frontal mixing currents in that transport may help to refine earlier interpretations of larval cod dynamics on the Bank (Lough, 1984; Buckley and Lough, 1987; Perry and Neilson, 1988). Clear evidence of the residual, clockwise around-Bank transport of larval cod and haddock was reported by Lough (1984). In a subsequent paper, Buckley and Lough (1987), in studying cod and haddock larvae at both vertically mixed and stratified sites on Georges Bank, reported that larvae sampled at stratified sites were in better physiological condition (had higher RNA/DNA ratios) than those sampled in vertically well-mixed waters. They argued that larval feeding conditions at the stratified sites were more favorable for larval growth and survival, which is similar in general to the findings of others (e.g. Lasker, 1975; Frank and McRuer, 1989). Buckley and Lough also found that the vertical distributions of the larvae had centers of abundance within and just below the thermocline at their stratified sampling sites (e.g. at depths of 10 to 40 m). Such a vertical distribution, it was pointed out (Buckley and Lough, 1987), would be coincident with a presumed (though not measured) subsurface phytoplankton maximum, and higher concentrations of zooplankton prey. While the authors found that larvae were fewer in abundance at the vertically mixed site, the larvae there also were concentrated at mid-depth (between 20 and 40 m), despite the absence of a pycnocline. These general findings of mid-depth distributions were reconfirmed more recently in a thorough analysis of a large data set by Lough and Potter (1994), who reported that even when diel vertical migrations are considered, larval cod less than about 20 mm (standard length) are concentrated primarily between depths of 20 and 40 m on the Southern Flank.

We suggest that the occurrence of cod larvae at and near the depth of the pycnocline in frontal and stratified areas on the Southern Flank of Georges Bank will result in greater advective transport than that resulting from tidal rectification alone. In which case, enhanced frontal transport sheds some light on observations by Buckley and Lough (1987) and Lough and Potter (1994) of the vertical distributions of the larvae, and may explain further the observations by Lough (1984) and Lough and Bolz (1989) that larvae are smaller (younger) in the area of developing stratification around the perimeter of the Bank than in the vertically mixed areas on top of the Bank. That is, we suggest that observations of larvae occupying the area of developing stratification, and with a maximum larval density near the depth of the pycnocline, can be explained in terms of horizontal transport processes that arise from tidal mixing currents. There would be little need to invoke explanations based upon the vertical distributions of zooplankton prey items and probable larval associations with the depth of the developing pycnocline. Indeed, Buckley and Lough's (1987) results (their Fig. 4) show similar deep maxima in the vertical distributions of larvae, independent of vertical water column structure. We would argue that larvae initially distributed vertically and horizontally homogeneously across a developing frontal system shortly after spawning, would, at some distance "downstream", become better organized horizontally about tidal mixing fronts, which we observed in this study; and we suspect that their maximum vertical distribution some distance downstream would be concentrated at the depth of the pycnocline, as shown in Fig. 15. That is, the larvae would be closely associated with the residual current structure within which they are being advected away from their source. Furthermore, such a subsurface depth distribution might enhance the likelihood of the larvae being retained on Georges Bank as part of the recirculating flow around the southwestern part of the Bank, as has already been demonstrated by the modeling results of Werner *et al.* (1993) and proposed even earlier by Lough and Bolz (1989).

Should our interpretation of the importance of frontal currents to larval fish transport be correct, then we must consider the potential for interannual variability in the positions and magnitudes of such currents, and the corresponding differences in larval transport that could arise from episodic intrusions of extrinsic water masses to Georges Bank, such as the Scotian Shelf Water and Gulf Stream/upper Slope Water we observed in 1993. Residual currents due to tidal rectification and, on average, the seasonal warming of the waters that leads to the development of tidal fronts, do not vary among years. However, water mass intrusions likely are not consistent from year to year, and they can distort the positions of the fronts on Georges Bank and affect the intensity of the geostrophic component of the residual circulation. Thus, we pose the question whether such hydrographic variability plays a key role in interannual variability in recruitment of cod on Georges Bank.

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