Springtime ichthyoplankton of the slope region off the north-eastern United States of America: larval assemblages, relation to hydrography and implications for larval transport

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ABSTRACT

Larval transport in the slope region off north-eastern North America influences recruitment to juvenile habitats for a variety of fishes that inhabit the continental shelf. In this study, collections of larval fishes were made during springtime over the continental slope to provide insights into larval distributions and transport. Ichthyoplankton composition and distribution mirrored the physical complexity of the region. Three larval fish assemblages were defined, each with different water mass distributions. A Gulf Stream assemblage was found predominantly in the Gulf Stream and associated with filaments of discharged Gulf Stream water in the Slope Sea. Larvae of this assemblage originated from oceanic and shelf regions south of Cape Hatteras. Several members of this assemblage utilize habitats in the Middle Atlantic Bight (MAB) as juveniles (Pomatomus saltatrix, Peprilus triacanthus) and other members of the assemblage may share this life cycle (Magil curema, Sphyraena borealis, Urophycis regia). A Slope Sea assemblage was found in all water masses, and was composed of epi- and mesopelagic fish larvae, as well as larvae of benthic shelf/slope residents. Larvae of one member of this assemblage (U. tenuis) are spawned in the Slope Sea but cross the shelf-slope front and use nearshore habitats for juvenile nurseries. A MAB shelf assemblage was found in MAB shelf water and was composed of larvae that were spawned on the shelf. Some of these species may cross into the Slope Sea before returning to MAB shelf habitats (e.g. Enchelyopus cimbrius, Glyptocephalus cynoglossus). Previous studies have examined the effect of warm-core rings on larval distributions, but this study identifies the importance of smaller-scale features of the MAB shelf/slope front and of filaments associated with Gulf Stream meanders. In combination with these advective processes, the dynamic nature of larval distributions in the Slope Sea appears to be influenced, to varying degrees, by both vertical and horizontal behaviour of larvae and pelagic juveniles themselves.

Key words: continental slope, Gulf Stream, larval assemblages, larval transport

INTRODUCTION

Large-scale circulation in the slope region off north-eastern North America (termed the Slope Sea, Fig. 1a; Stommel, 1960; Csanady and Hamilton, 1988) is influenced by both the Gulf Stream and the Labrador Current (Csanady and Hamilton, 1988; Berger et al., 1996; Dragos et al., 1996). Cold Labrador shelf water mixes with Slope Sea water in the north-eastern Slope Sea. Most of this cooler water turns to the east, but the remainder forms a westward current south of Nova Scotia. A cyclonic gyre is formed in the western Slope Sea by the west-south-westward flow near the shelf-break and north-eastward flow associated with the Gulf Stream. The gyre closes on the western side near Cape Hatteras, where both Slope Sea and Middle Atlantic Bight (MAB, Cape Hatteras, North Carolina to Cape Cod, Massachusetts) shelf water are entrained into the Gulf Stream. Closure of the gyre on the

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eastern side is periodic and dependent upon the occurrence and location of Gulf Stream meanders and warm-core rings (WCRs), which are anticyclonic eddies that form when meanders ‘pinch-off’ (Auer, 1987). Water drains eastward out of the Slope Sea in a broad zone north of the Gulf Stream and in association with the eastward-flowing Labrador shelf water.

Slope Sea circulation influences both larval distributions and recruitment to juvenile habitats of a variety of fish species. In the vicinity of Cape Hatteras, larval distributions are affected by interactions between Gulf Stream, Slope Sea and shelf water masses (Grothues and Cowen, 1999), and the loss of shelf water in the vicinity of Cape Hatteras may result in lower recruitment of fish spawned in the southern MAB (Hare and Cowen, 1993). North-east of Cape Hatteras, WCRs advect larval fish off the continental shelf into the Slope Sea (Wroblewski and Cheney, 1984; LeBlanc, 1986), and lower groundfish recruitment is related to the export of shelf water into the Slope Sea by WCRs (Flierl and Wroblewski, 1985; Cohen et al., 1987; Myers and Drinkwater, 1989). WCRs also advect larval fish from the Gulf Stream, across the Slope Sea, to the shelf edge (Hare and Cowen, 1991; Cowen et al., 1993) and are linked to higher recruitment of fish spawned south of Cape Hatteras to MAB estuarine habitats (Hare and Cowen, 1996).

Although larval transport into, out of and across the Slope Sea may influence recruitment to juvenile habitats of a variety of fishes, most studies have made this inference from ichthyoplankton surveys conducted over the continental shelf (e.g. Urophycis tenuis; Fahay and Able, 1989; Comyns and Grant, 1994). Our purpose was to study larval distributions in the Slope Sea and to elucidate larval transport mechanisms that result in a subset of larvae being in a spatial and temporal position to recruit to juvenile habitats. We focused on the movement of larvae between the Gulf Stream and the Slope Sea and between the MAB shelf and the Slope Sea. Our emphasis was on larval assemblages, which are groups of larvae that co-occur in space and time. The same physical processes will initially affect distributions of larvae spawned in the same location, yet subsets of these larvae may interact differently with the physical environment owing to differences in vertical or horizontal behaviour. By comparing larval distributions among and within larval assemblages in terms of life history similarities, with concomitant measures of the physical environment, insights can be gained into the processes that affect larval distribution, transport and ultimately, recruitment to juvenile habitats at the level of marine systems (Cowen et al., 1993; Dempster et al., 1997).

MATERIALS AND METHODS

Data collection

Principal data were collected during 8–13 May 1993 in the western Slope Sea. Fifty-four stations were sampled from east of Cape Hatteras to south of Block Island,
from the shelf edge to 125 km offshore of the shelf edge (Fig. 1b). Ichthyoplankton collections were taken with a 0.61-m paired bongo frame fitted with 0.505 mm and 0.333 mm mesh nets, and with a 0.5 x 1.0 m neuston net with 0.947 mm mesh. Bongo tows were made at 1.5 knots in a double-oblique pattern, repeated two or three times, for 15 min; the average maximum depth sampled was 18 m (range = 15–31 m). Volume of water filtered was measured with a General Oceanics flowmeter. Only data from the 0.505 mm net were analysed. The neuston net was towed for 15 min. Volume of water filtered was estimated from the approximate ship speed (3.5 knots), net mouth area (0.5 m²) and tow duration (15 min) (∼ 810 m³ sampled). At each station, temperature and salinity were measured with a SeaBird CTD deployed to 100 m. Water samples (n = 11) were used to calibrate CTD-derived salinity measurements.

Data collected during 1–3 June 1988 were analysed also. Thirty-nine stations were sampled from the coast to 40 km offshore of the shelf edge (Fig. 1b). Ichthyoplankton collections were taken with a 5 m², 2 mm mesh modified-Methot frame trawl towed as a neuston net. Volume filtered was estimated from the approximate speed of the ship (3 knots), approximate net fishing area (∼ 4.5 m²) and tow duration (10 min) (∼ 4000 m³ sampled). At each station, temperature and salinity were measured with a MARTEK Mark VI Multiparameter Recorder deployed to within 10 m of the bottom or to 200 m. These data have been analysed in studies of Gasterosteus aculeatus (Cowen et al., 1991) and Pomatomus saltatrix (Shima, 1989; Hare and Cowen, 1996).

Larval fishes were sorted from collections and identified to the lowest taxonomic level possible (Fahay, 1983; Hare, Fahay and Cowen, unpublished data). Concentration of each taxon was calculated for each station and each gear type (number larvae per 100 m⁻³).

Data analyses

Determination of larval assemblages and analysis of their distributions relative to the physical environment were conducted in six steps, which were modified from Field et al. (1982).

Water mass classification of stations

Stations were assigned to water mass based on an upper 15 m average of temperature and salinity and previously defined water mass boundaries (Atkinson et al., 1983; Csanady and Hamilton, 1988; Churchill et al., 1993). Water mass boundaries were based on data collected in May (Churchill et al., 1993), thereby data collected in May 1993 were directly comparable.

Temperatures at some stations sampled during June 1988 were higher than the May-based water mass boundaries owing to vernal warming (Beardsley et al., 1985); water masses of these stations were determined primarily on the basis of salinity. Water from the southeast United States continental shelf (termed South Atlantic Bight – SAB – by regional convention, Cape Hatteras, North Carolina to Cape Canaveral, Florida) was identified based on Atkinson et al. (1983).

Station ordination based on larval fish

Stations were ordinated using nonmetric multidimensional scaling (MDS) of a Bray–Curtis dissimilarity matrix, which was calculated between stations from root-root transformed larval concentrations (Field et al., 1982). The Kruskal method with a monotonic regression was used and a two-dimensional solution was designated. Station ordinations were then evaluated relative to the water mass classifications of stations to determine how closely larval fish distributions were aligned to water masses. Data collected in different years and gears were analysed separately. Three criteria were set for the inclusion of larval taxa in the ordination of stations: (i) identification to species or larval type; (ii) capture of ≥ 3 individuals; and (iii) capture at ≥ 2 stations. Several exceptions were made to the first criteria. Higher-level taxa collected during May 1993 were included if they were known to originate from south of Cape Hatteras (Fahay, 1975, 1983; Able and Fahay, 1998). Ammodytes sp. were included from the June 1988 data because the collection location indicated the involvement of a single species (Nizinski et al., 1990).

Classification of larval fish assemblages

Larval fish assemblages were classified with a hierarchical cluster analysis of a Bray–Curtis dissimilarity matrix, which was calculated between species using relativized larval concentrations (Field et al., 1982). The same taxa were included as used in step 2. Larval fish assemblages were determined from the results of the cluster analysis and named based on their primary water mass distribution.

Spatial and water mass patterns in larval fish distributions

Spatial and water mass patterns in larval concentrations and larval lengths were quantified for the 1993 data for individual taxa, as well as within larval assemblages. Data from 1988 were excluded because the spatial extent of collections was limited and not all water masses were sampled. Linear regressions were calculated between log-transformed larval concentrations (log[conc. + 1]; dependent) and along-slope and cross-slope position (independent), which were
determined from a curvilinear grid following the
100 m isobath. A Kruskal–Wallace test evaluated
water mass (independent) differences in larval con-
centrations (dependent). When significant differences
were found, pairwise Kruskal–Wallace tests were cal-
culated between all water masses. Taxa were included
if ≥ 20 individuals were collected at ≥ 5 stations and
neuston nets were analysed separately.

Spatial and water mass patterns in larval length
were also examined with linear regression. Lengths
were weighted by the concentration represented by a
larva in that collection. Weights were scaled so that
the sum of weights equalled the number of larvae
measured. Weighted length data from both May 1993
datasets were combined. Linear regressions were cal-
culated between scaled-weighted length (dependent)
and along-slope position, cross-slope position and
water mass (independent). Taxa were included if ≥ 20
individuals were measured from ≥ 5 stations.

Significance of regression and Kruskal–Wallace
tests was determined with α = 0.05. The chance of
Type II errors (Sokal and Rohlf, 1981) is increased at
this significance level owing to the number of tests
conducted. However, the emphasis of these tests was
to evaluate assemblage-wide patterns in larval distri-
butions not taxa-specific patterns and, thus, the taxa-
specific tests are used as a guide to identifying and
describing such assemblage-wide patterns.

Large-scale physical oceanographic features
Large-scale physical oceanography of the western
Slope Sea was examined during the periods of samp-
ling to evaluate links between the physical environ-
ment and larval distributions. Surface physical
oceanographic features were inferred for 1993 from
Oceanographic Feature Analysis (OFA) charts
(NOAA, NOS, Ocean Prediction Center) and
satellite-derived sea surface temperature (SST) images
(NOAA/NESDIS South-east CoastWatch Program,
NOAA Beaufort Laboratory). OFA charts from
January through May 1993 were examined. SST ima-
ges from 1 April to 15 May were also examined. Sur-
face CTD data were compared to SST imagery using
linear regression and based on this comparison,
changes in Gulf Stream-related features (water
> 16°C) were examined from SST imagery by meas-
uring the area of specific features from a time series of
relatively cloud-free images (May 2, 5, 7–13).

Surface physical oceanographic features were
inferred for 1988 from a summary of WCR movement
along the north-eastern North American coast.

Figure 2. Classification of stations by water mass for (a) May 1993 and (b) June 1988. Values shown are the upper 15 m
averages of temperature and salinity. Boundaries of water masses present in the western Slope Sea region (dotted lines) during
springtime are from Churchill et al. (1993). Water mass classifications are shown on the right.
Changes in water mass distributions of larval fish

Taxa that apparently changed water masses were identified through the above analyses and by additional examination of larval distributions relative to SST imagery. (i) Changes in water mass distribution of larval fishes were identified as either a given taxa classified in different assemblages in analyses of different data sets or a given taxa distributed in different water masses in May 1993 bongo and neuston collections. The different gears collected different size fishes (Powell et al., 2000) and thus provide insights into the movement of fish over time. (ii) For the Gulf Stream assemblage, the null hypothesis was tested that presence at a station was independent of the presence of Gulf Stream-derived water (> 16°C). Contingency tables (2 × 2) were used and G-test of independence was calculated (Sokal and Rohlf, 1981). (iii) The relation between water mass and larval length was examined in more detail for certain taxa collected in May 1993. (iv) Larval distributions of select assemblages and taxa were examined relative to synoptic SST imagery for May 1993.

RESULTS

Water mass classification of stations

During May 1993, six water masses were sampled: Gulf Stream, SAB shelf, mixed Gulf Stream/Slope Sea, Slope Sea, frontal and MAB shelf (Fig. 2a). SAB shelf water was identified at one station based on surface salinities < 36 and temperatures > 18°C (Atkinson et al., 1983). This station was grouped with Gulf Stream stations for subsequent analyses, since both water masses originate south of Cape Hatteras. A second station (station 13) had slightly different temperature and salinity characteristics than expected and was separated in subsequent analyses.

Three water masses were sampled in June 1988: Slope Sea, frontal and MAB shelf (Fig. 2b). One station (station 15) was intermediate between Slope Sea and frontal water and was separated for subsequent analyses. Stations classified as Slope Sea water had temperatures above the Slope Sea water mass boundary. Vernal heating during the spring likely caused this increased temperature and classification was based on salinity.

Station-ordination based on larval fish

Station ordinations based on larval fishes distinguished some but not all of the water masses. Ordination of the May 1993 bongo data differentiated stations that sampled Gulf Stream, Gulf Stream/Slope Sea and MAB shelf water (Fig. 3a). Stations in frontal and Slope Sea water overlapped in the ordination with stations in Gulf Stream/Slope Sea and MAB shelf water. Ordination of the May 1993 neuston data distinguished stations that sampled Gulf Stream water from stations that sampled other water masses (Fig. 3b). Stations that sampled Slope Sea water and MAB shelf water were distinct in the ordination of June 1988 neuston data. Stations in frontal water overlapped with stations in both MAB shelf and Slope Sea water (Fig. 3c).

Classification of larval fish assemblages

Three assemblages were identified from classifications of larval fish: Gulf Stream, Slope Sea and MAB shelf. The Gulf Stream assemblage was found in both May 1993 datasets, the Slope Sea assemblage was found in all three data sets and the MAB shelf assemblage was found in June 1988 data (Figs 4, 5 and 6).
Gulf Stream assemblage

The Gulf Stream assemblage included 32 and 9 taxa from the May 1993 bongo and neuston data, respectively (Figs 4 and 5). Three taxa were shared between bongo and neuston Gulf Stream assemblages: *Decapterus punctatus*, *Mugil curema*, and *Mullidae*. All members were likely spawned south of Cape Hatteras and occurred primarily in Gulf Stream/SAB shelf water (Figs 7a and 8a). However, 14 taxa were also collected in cooler and less saline water masses: *Bothus* sp., *Callionymus* sp., *Engraulis eurytoste*, *Epinephelinae*, *Fistularidae*, *Gobiidae* 1, *Lepophidium profundorum*, *Mugil curema*, *Otophidium ostomatum*, *Pepinthus triacanthus*, *Pomatomus saltatrix*, *Sphyraena borealis*, *Syacium papillosum*, and *Trachurus lathami*.

Groups with slightly different water mass distributions were distinguished in the Gulf Stream assemblage. From the May 1993 bongo data (Fig. 4), one group (GS-1) was found primarily in SAB shelf water and at the cooler of the four Gulf Stream stations (Fig. 7b). A second group (GS-2) was found primarily in SAB shelf water (Fig. 7c). A third group (GS-3) was found predominantly at the three warmer Gulf Stream stations (Fig. 7d). From the May 1993 neuston data (Fig. 5), one group (GS-1) was distributed in Gulf Stream, Gulf Stream/Slope Sea and Slope Sea water (Fig. 8b); most of the non-Gulf Stream/SAB shelf water occurrences of...
Figure 5. Classification of larval fish taxa by relative concentration at stations sampled in May 1993 with a neuston net. Two assemblages were defined (Gulf Stream and Slope Sea) and several groups were identified within each assemblage (GS-1, GS-2, SS-1, SS-2, SS-3).

May 1993 - Neuston Collections

Figure 6. Classification of larval fish taxa by relative concentration at stations sampled in June 1988 with a neuston net. Two assemblages were defined (Slope Sea and MAB shelf) and several groups were identified within the Slope Sea assemblage (SS-1, SS-2, SS-3).

June 1988 - Neuston Collections

The Slope Sea assemblage was composed primarily of species that spawn in the Slope Sea, and was dominated by myctophids and *Urophycis tenuis* (Figs 4, 5 and 6). The assemblage included 13, 9 and 13 taxa from May 1993 bongo, May 1993 neuston and June 1988 neuston data, respectively. Three taxa were shared between the May 1993 bongo and neuston assemblages: *Enchelyopus cimbrius*, *Ceratoscopelus maderensis* and *Urophycis tenuis*. *C. maderensis* and *U. tenuis* were shared between May 1993 bongo and June 1988 neuston assemblages and these two and five additional taxa were shared between May 1993 and June 1988 neuston assemblages: *Gonichthys cocco*, *Hygophum hygomi*, *Peprilus triacanthus*, *Scomberesox saurus* and *Symbolophorus veranyi*.

The Slope Sea assemblage occurred in all water masses (Figs 9a, 10a, and 11a), but groups were identified with different water mass distributions. From May 1993 bongo data (Fig. 4), one group (SS-3) was...
Figure 8. Water mass distributions of Gulf Stream assemblage and groups within the Gulf Stream assemblage from May 1993 neuston data (see Figure 5). Symbol size represents the actual concentration of larval fish. Scales for symbol size are provided below figure for reference.
Figure 9. Water mass distributions of Slope Sea assemblage and groups within the Slope Sea assemblage from May 1993 bongo data (see Figure 4). Symbol size represents the actual concentration of larval fish. Scales for symbol size are provided below figure for reference.
Figure 10. Water mass distributions of Slope Sea assemblage and groups within the Slope Sea assemblage from May 1993 neuston data (see Figure 5). Symbol size represents the actual concentration of larval fish. Scales for symbol size are provided below figure for reference.
Figure 11. Water mass distributions of Slope Sea assemblage, groups within the Slope Sea assemblage and MAB shelf assemblage from June 1988 neuston data (see Figure 6). Symbol size represents the actual concentration of larval fish. Scales for symbol size are provided below figure for reference.
found in all water masses but predominated in frontal, Slope Sea and Gulf Stream/Slope Sea water (Fig. 9b). Several taxa in this group (SS-3a) were found in warmer water (Fig. 9c) and several other taxa (SS-3b) were found in cooler water (Fig. 9d). A second group (SS-2) was less common but was also found in all water masses except Gulf Stream water (Fig. 9e). A third group (SS-1) was found in frontal and MAB shelf water (Fig. 9f). A fourth group, represented by a single species, was found in frontal water only (Fig. 9g). From May 1993 neuston data (Fig. 5), one group (SS-1) was abundant in frontal and Slope Sea water and was not found in MAB shelf water (Fig. 10b). A second group (SS-2) was abundant in Slope Sea and Gulf Stream/ Slope Sea mixed water but was not found in Gulf Stream water (Fig. 10c). A third group (SS-3) was present in Slope Sea, Gulf Stream/Slope Sea mixed and Gulf Stream water (Fig. 10d). Two myctophids were aligned with this assemblage (Fig. 7), but were rare (Figs 10e,f).

Water mass differences were less apparent between groups in the Slope Sea assemblage in the June 1988 data (Fig. 6), probably owing to the lack of sampling in Gulf Stream and Gulf Stream/Slope Sea mixed water (Fig. 2b). Two groups were found in MAB shelf, frontal and Slope Sea water, but one group was more widespread (SS-1) than the other (SS-2) (Fig. 11b,c). A third group (SS-3) was found predominantly in frontal water (Fig. 11d). A fourth group, represented by one species, was found in frontal water, but at different stations than the SS-3 group (Fig. 11e).

<table>
<thead>
<tr>
<th>Species</th>
<th>Along-slope</th>
<th>Cross-slope</th>
<th>Water mass comparisons (Kruskal–Wallace test )</th>
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<tr>
<td></td>
<td>b</td>
<td>r²</td>
<td>b</td>
</tr>
<tr>
<td>Analyses of bongo data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bothus sp.</td>
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<tr>
<td>Syacium papillosum</td>
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<td>0.379</td>
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<tr>
<td>Mullidae</td>
<td>-0.033</td>
<td>0.041</td>
<td>0.437***</td>
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*P < 0.05; **P < 0.01; ***P < 0.001.

b = log(larval conc. + 1) · 100 km⁻¹.
Figure 12. Larval densities of members of the Gulf Stream and Slope Sea assemblages by water mass from May 1993 bongo (circles, left axes) and neuston (triangles, right axes) data. Lines indicate the results of Kruskal–Wallace tests comparing larval concentrations between water masses for bongo (solid) and neuston (dashed) data.

Table 2. Summary of the linear regression analyses of fish lengths (dependent variable) and along-slope and cross-slope position, as well as water mass (independent variables). Slope (b) and $r^2$ of each regression are provided. A positive b along-slope means larval lengths increased from south to north. A positive b cross-slope means lengths increased from onshore to offshore. A positive slope b with water mass means that lengths increased from the Gulf Stream to MAB shelf water.

<table>
<thead>
<tr>
<th>Species</th>
<th>Along-slope</th>
<th>Cross-slope</th>
<th>Water mass</th>
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<tr>
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<td>0.422</td>
<td>4.120***</td>
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<td>Mullidae</td>
<td>1.731**</td>
<td>0.068</td>
<td>15.506***</td>
</tr>
<tr>
<td>Syacium papillosum</td>
<td>7.002***</td>
<td>0.928</td>
<td>12.844*</td>
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<td>Peprilus triacanthus</td>
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<td><strong>Taxa in the Slope Sea assemblage</strong></td>
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<td></td>
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<td>0.023</td>
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<td>Urophycis tenuis</td>
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<td>0.015</td>
<td>4.671</td>
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*P < 0.05; **P < 0.01; ***P < 0.001.
b1 = mm/100 km; b2 = mm/water mass.

members within this group (SS-3a) were different (Fig. 12). There were also differences in water mass distributions of *Lophius americanus* and *Benthosema glaciale* (SS-3b, Figs 4 and 12). In neuston collections, larval concentrations of some taxa were greater to the north and offshore, but most taxa did not exhibit significant spatial nor water mass patterns (Table 3). Larval lengths were greater to the north in some taxa (*C. maderensis*, *C. warmingi*) but greater to the south in others (*B. glaciale*). Larval lengths increased from MAB shelf to Gulf Stream water in some taxa (*E. cimbrius*, *L. americanus*) but increased from Gulf Stream to MAB shelf water in other taxa (*B. glaciale*, *C. warmingi*, *U. tenuis*). Larval lengths increased from offshore to onshore for several taxa (*B. glaciale*, *C. maderensis*, *U. regia*) (Table 2).

### Large-scale physical oceanographic features

During April and May 1993, several Gulf Stream meanders, with attached filaments, propagated toward the north-east along the south-western boundary of the Slope Sea (Fig. 13). Three filaments of discharged Gulf Stream water were evident. The surface area of filament 1 and 3 increased from 2 to 13 May, while the surface area of filament 2 decreased (Fig. 13). A WCR formed in late March, south-east of Georges Bank (based on OFA charts) and moved westward. The WCR came into contact with a Gulf Stream meander in early April, resulting in a WCR-streamer. By late April, no Gulf Stream–WCR interaction was apparent and the WCR was fairly stationary. In early May, the WCR interacted with another Gulf Stream meander.

During spring 1988, a filament of discharged Gulf Stream water was associated with a meander crest and a WCR was located to the east of the sampling area (Fig. 14). A WCR-streamer developed as the meander crest contacted the southern margin of the WCR and was evident for a period of about 2 weeks. An area of warm water developed to the west of the ring while the streamer was evident. No other WCRs had passed the area since 1987 (Sano and Fairfield, 1989).

### Changes in water mass distributions of larval fish

#### Gulf Stream assemblage

The distribution of the Gulf Stream assemblage was related to the location of the Gulf Stream and associated filaments (Fig. 15a). The occurrence of the assemblage in bongo collections was significantly related to the occurrence of water > 16°C within 4-days of sampling ($G_{adj} = 16.84$, $P < 0.001$).

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**Table 3.** Summary of linear regression analyses of larval fish densities ($\log(\text{larvae} \ 10^3 + 1)$) on along-slope and cross-slope position for taxa in the Slope Sea assemblages collected in May 1993. Slope ($b$) and $r^2$ for each regression are provided. A positive along-slope $b$ means larval concentrations increased from south to north. A positive cross-slope $b$ means concentrations increased from onshore to offshore. The Kruskal-Wallace Test Statistic for larval fish densities by water mass is provided.

<table>
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<th>Species</th>
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<th>Cross-Slope</th>
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*P < 0.05; **P < 0.01; ***P < 0.001.

$b = \log(\text{larval concentration}) \cdot 100 \ km^{-1}$.
Figure 13. Time series of AVHRR sea-surface temperature images for April and early May 1993. Stations sampled during May 1993 are shown (white circles). Area of the filaments identified from AVHRR sea-surface temperature imagery for May 1993 are shown in bottom right; bar shows period of May 1993 cruise.
Members of the assemblage occurred at six stations that had 4-day temperatures < 16°C; four of these stations were in the vicinity of the filament that was decreasing in area (filament 2; Figs 13 and 15a) and larger larvae occurred in water < 16°C (Fig. 16), suggesting their origin was Gulf Stream water, which had subsequently cooled.

In neuston collections, the distribution of most members of the Gulf Stream assemblage remained linked to the distribution of the Gulf Stream and associated filaments. Decapterus punctatus and other members of the GS-1a group were found only in Gulf Stream water (Fig. 8; with the exception of one Monacanthus hispidus in Gulf Stream/Slope Sea water). Mullidae and Mugil curema (GS-1b, Fig. 5) remained linked to the distribution of Gulf Stream-derived water (\(G_{adj} = 13.121, P < 0.001\); Fig. 15b), but were found in greater concentrations in Gulf Stream/Slope Sea and Slope Sea water compared with bongo collections. All locations < 16°C where these taxa occurred were in the vicinity of the filament that was decreasing in area (Figs 13 and 15b). Peprilus triacanthus, however, was classified in the Slope Sea assemblage (Fig. 5), was independent of the distribution of Gulf Stream-derived water (\(G_{adj} = 1.068, P > 0.05\); Fig. 15c), and was collected at locations < 16°C that were not exclusively near the filament that was decreasing in size. Larval lengths of M. curema, Mullidae and P. triacanthus were greater in water < 16°C, but this pattern was less pronounced for P. triacanthus (Fig. 16). Pomatomus saltatrix exhibited a similar distribution; in bongo collections, larvae were collected only in Gulf Stream water, whereas in neuston collections, larvae were collected in Gulf Stream and Slope Sea water.

Several members of the Gulf Stream assemblage were also found in frontal water during June 1988: Monacanthus hispidus, Peprilus triacanthus, Mugil curema, Pomatomus saltatrix, Sphoeroides sp. and Sphyraena borealis.

\[\text{Slope Sea assemblage}\]

Some members of the Slope Sea assemblage also exhibited differences in water mass associations between gear types and collection times. The SS-1 group of the May 1993 bongo data, of which Enchelyopus cimbrius was a member, was found primarily in the middle of the sampling grid and within 50 km of the shelf/slope front (Fig. 15f). In 1993 neuston collections, most E. cimbrius were collected in the northern half of the sampling grid between two of the Gulf Stream filaments (Fig. 15g) and as far as 125 km from the shelf/slope front. Lengths of E. cimbrius increased from MAB shelf water to Gulf Stream/Slope Sea mixed water (Fig. 17a). The largest individuals, however, were collected in frontal water. During June 1988, most E. cimbrius were found in shelf water but...
several were collected in frontal water. Distributions of *Lophius americanus* were similar to those of *E. cimbrius*. Larvae were found in colder, fresher water in the May 1993 bongo data (Fig. 12) and in warmer, more saline water in the May 1993 neuston net (Fig. 8e vs. 9d). Larval lengths increased from MAB shelf to Gulf Stream water (Table 2).

Distributions of *Urophycis tenuis* were also different between bongo and neuston collections. *U. tenuis* occurred in the northern two thirds of the sampling area in bongo collections, and throughout the sampling area, except in the Gulf Stream, in neuston collections (Figs 15d and 15e). Larval concentrations were higher in Gulf Stream/Slope Sea and Slope Sea water (Fig. 12). There were no spatial patterns in larval length, but lengths increased from Gulf Stream to MAB shelf water (Table 2, Fig. 17b).

**MAB shelf assemblage**

All members of the MAB shelf assemblage were found only in MAB shelf water, except for *Ammodites* sp., *Enchelyopus cimbrius* and *Scomber scombrus*. Larvae of *E. cimbrius* were collected in MAB shelf and frontal water (see above). Larvae of *Ammodites* sp. were also collected in MAB shelf and frontal water during June 1988. Larvae of *Scomber scombrus* were found only in MAB shelf water during June 1988 but were only found in frontal water during May 1993 (Fig. 9g).

**DISCUSSION**

The Slope Sea is an admixture of Labrador Current, local shelf, Gulf Stream and Sargasso Sea water (Stommel, 1960; Csanady and Hamilton, 1988). The composition and distribution of ichthyoplankton reflects this complexity. Larval distributions in the Slope Sea were linked to water masses as found in other marine systems, for example in and around WCRs off eastern Australia (Brandt, 1981, 1983). Likewise, larvae were apparently transported across water mass boundaries, again as observed in other marine systems: the south-eastern US shelf and Gulf Stream (Govoni, 1993) and the shelf/slope front off north-eastern Spain (Sabates and Olivar, 1996). Identifying the mechanisms by which larvae move between water masses and are successfully transported from spawning grounds, through water column habitats, to juvenile nurseries will elucidate recruitment processes for the variety of species whose larvae inhabit the Slope Sea.

Inferences of larval transport in the Slope Sea can be derived from our analyses of larval assemblages and larval distributions in relation to the physical environment. In general, observed larval distributions result from several interacting factors: spawning time, location and intensity; physical transport of eggs and larvae; vertical and horizontal larval behaviour; and larval mortality. We have no basis to assess the role of larval mortality in affecting observed larval distributions in the Slope Sea and thus, assume mortality effects on distribution patterns are negligible. Nor have we directly studied the effects of vertical or horizontal larval behaviour. When spawning location is known, however, larval transport mechanisms (both physical and biological) can be determined from a coupled analysis of larval distributions and measures of the physical environment (Hare and Cowen, 1991). Analysis of larval assemblages complements the above approach by providing comparisons and contrasts within and between groups of larvae with similar distributions (Cowan et al., 1993; Dempster et al., 1997). We use this approach in the following discussion to identify larval transport mechanisms that affected larval distributions in the Slope Sea. We consider each assemblage using individual species or groups of species to exemplify potential larval transport mechanisms. We end with a summary of potential larval transport mechanisms and their role in affecting recruitment in the many species whose larvae inhabit the Slope Sea.

**Gulf Stream assemblage**

All members of the Gulf Stream assemblage are larvae of warm-temperate continental shelf fishes (Briggs, 1974; Robins et al., 1986), most were probably spawned south of Cape Hatteras (Fahay, 1975; Robins et al., 1986; Able and Fahay, 1998) and transported to the southern boundary of the Slope Sea in the Gulf Stream (Figs 15a and 16). During May 1993, the distribution of the Gulf Stream assemblage in the Slope Sea likely resulted from advection in filaments of discharged Gulf Stream water (Figs 15a,b and 16), which are associated with the crests of Gulf Stream meanders (Brooks and Bane, 1983; Lee et al., 1991). Several studies have found that meanders and their associated filaments are important mechanisms of larval transport from the Gulf Stream into shelf waters in regions upstream from the Slope Sea (Florida Keys, Lee et al., 1992, 1994, Carolina shelf, Stegmann and Yoder, 1996). In contrast to these other areas, when members of the Gulf Stream assemblage are advected into the Slope Sea in Gulf Stream filaments, they may be stranded unless subsequently transported to appropriate shelf and coastal habitats (e.g. estuaries).
Figure 15. (a) Distribution of the Gulf Stream assemblage from May 1993 bongo data. Open circles are stations where members of the assemblage were not collected. Small-sized filled circles represent concentrations from > 0–1 larva 100 m$^{-3}$. Intermediate-sized filled circles represent concentrations from 1 to 10 larvae 100 m$^{-3}$. Large-sized filled circles represent concentrations from 10 to 100 larvae 100 m$^{-3}$. Filled triangles identify stations where members of the assemblage were found but water did not exceed 16°C during the four days prior to sampling. (b) Distribution of the Gulf Stream assemblage group GS-1a (Mullidae and Mugil curema) from May 1993 neuston data. Small-sized filled circles represent concentrations from 1 to 10 larvae collected. Intermediate-sized filled circles represent concentrations from 10 to 100 larvae collected. Filled triangles identify stations where members of the assemblage were found but water did not exceed 16°C during the 4 days prior to sampling. (c) Distribution of Peprilus triacanthus from May 1993 neuston data. Symbols same as in panel b. (d) Distribution of Urophycis regia from May 1993 neuston data. Symbols same as panel a, except stations with temperatures < 16°C are not denoted. (e) Distribution of Urophycis tenuis from May 1993 bongo data. Symbols same as panel a, except stations with temperatures < 16°C are not denoted. (f) Distribution of Urophycis tenuis from May 1993 neuston data. Symbols same as panel b, except stations with temperatures < 16°C are not denoted. (g) Distribution of members of the Slope Sea assemblage group SS-1 (Enchelopus cimbrius and Glyptocephalus cynoglossus) from May 1993 bongo data. Symbols same as panel a, except stations with temperatures < 16°C are not denoted. (h) Distribution of Enchelopus cimbrius from May 1993 neuston data. Symbols same as panel b, except stations with temperatures < 16°C are not denoted.
During 1988, WCR-streamers likely resulted in the advection of members of the Gulf Stream assemblage from the Gulf Stream across the Slope Sea to the MAB shelf/slope front. SST imagery showed a WCR–Gulf Stream interaction that resulted in the formation of a WCR-streamer and transport of warmer, Gulf Stream origin water to the MAB shelf/slope front (Fig. 14). Various members of the Gulf Stream assemblage are frequently found at the MAB shelf/slope front in association with WCRs (Table 4), indicating the importance of these mesoscale eddies in transporting larvae across the Slope Sea.

Active vertical or horizontal behaviour may also facilitate the transport of larvae and juveniles from the Gulf Stream into the Slope Sea. For example, Peprilus triacanthus larvae were distributed similar to other Gulf Stream assemblage members in May 1993 bongo collections (Figs 4 and 15a) but were found in cooler and fresher water than other Gulf Stream assemblage members (Mugil curema and Mullidae) in
neuston collections (Figs 5 and 15b,c). Changes in spawning location could be responsible for the observed differences in larval distributions, as *P. triacanthus* spawning progresses northward in the spring (Rotunno and Cowen, 1997; Berrien and Sibunka, 1999). However, larger *P. triacanthus* were collected in water < 16°C, opposite of the pattern expected if these fish were spawned later in the season. As an alternative explanation, vertical distribution of larval *P. triacanthus* may interact with vertical differences in flow and result in differential larval transport (Fortier and Leggett, 1983; Hare et al., 1999). This alternative is supported by observed differences in larval vertical distributions: *P. triacanthus* larvae exhibit vertical migrations of ~10 m (Kendall and Naplin, 1981), whereas *M. curema* and Mullidae are primarily neustonic (Fahey, 1975; Powles, 1981). Horizontal swimming may also contribute solely or in conjunction with vertical movements to effect differential movement of *P. triacanthus* larvae and pelagic juveniles between water masses (sensu Hare and Cowen, 1996; Leis et al., 1996; Stobutzki and Bellwood, 1997).

**Slope Sea assemblage**

Larval distributions of epi- and mesopelagic species were clearly linked to the water mass distribution of adults (see Backus et al., 1970), but larval transport may have interacted with spawning location to affect larval distributions of some mesopelagic species. Lengths of larval *Benthosema glaciale* increased from north to south (Table 2), suggesting either southward larval transport in the general circulation of the Slope Sea or northward progression in spawning. Conversely, lengths of larval *Ceratoscopelus maderensis* and *C. warmingi* increased from south to north (Table 2), indicating either northward transport in Gulf Stream-associated waters or a southward progression in spawning. Interpretation of the larval distributions of mesopelagic species is limited by the emphasis on surface sampling, in addition to the uncertainty of spawning location. Larvae of some

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**Figure 16.** Length frequencies of select members of the Gulf Stream assemblage from May 1993 bongo and neuston data. Below line are lengths of larvae collected in water > 16°C; above line are lengths of larvae collected in water < 16°C.

mesopelagic fishes were missed altogether (sternopychids, Schultz, 1964; Gibbs and Krueger, 1987), and diel and ontogenetic movements of other mesopelagic larvae (Loeb, 1979) may have influenced observed distribution patterns. Similarly, the sampling design missed spatially discrete frontal regions, which can concentrate organisms and have discrete communities associated with them (Olson and Backus, 1985; Olson et al., 1994). These issues are a general limitation to this study, but most likely have their greatest influence on interpretation of the larval distributions of mesopelagic fish. Additional ecological information is required regarding vertical distributions and spawning distributions of mesopelagic species in the Slope Sea before the processes that affect larval distribution and transport can be fully addressed.

The importance of spawning location and larval transport processes in determining larval distributions is also unclear for some non-mesopelagic members of the Slope Sea assemblage. For example, *Urophycis regia* spawns on the MAB shelf in the fall and spring and on the SAB shelf in the winter (Fahay, 1975). Comyns and Grant (1993) collected *U. regia* pelagic juveniles near the MAB shelf edge in early spring and postulated winter spawning on either the MAB or SAB shelf. During May 1993, lengths of larval *U. regia* increased from offshore to onshore (Table 2), and larvae were collected in all water masses but Gulf Stream water (Table 3, Fig. 15d). These results suggest either spawning in the Slope Sea or spawning in the SAB with subsequent transport into the Slope Sea. Without knowing the source of larvae, conclusions regarding larval transport based on larval distributions are equivocal.

Larval and pelagic juvenile distributions, in consideration with the physical environment, indicate that young *Urophycis tenuis* move from the Slope Sea to nearshore areas in the MAB and southern New England. Previous investigators have proposed that *Urophycis tenuis* spawns in the Slope Sea (Fahay and Able, 1989; Comyns and Grant, 1993; Lang et al.,
which was confirmed by our finding of small *U. tenuis* larvae (< 5 mm) in Slope Sea water (Fig. 17b). Larger larvae and pelagic juveniles have been found only on the shelf, and following the pelagic juvenile stage, *U. tenuis* enter estuarine habitats (Table 2, Wroblewski and Cheney, 1984; Fahay and Able, 1989; Comyns and Grant, 1993; Lang et al., 1996; Able and Fahay, 1998). These findings indicate that young *U. tenuis* move from spawning and larval habitats in the Slope Sea, across the shelf/slope front and across the MAB shelf to nearshore estuarine juvenile habitats.

Active horizontal swimming is the most likely mechanism by which *Urophycis tenuis* pelagic juveniles could cross the shelf/slope front and the MAB shelf to nearshore juvenile habitats. The shelf/slope front is a permanent feature along the northern edge of the Slope Sea (Houghton *et al.*, 1988). Mid-level intrusions (15–30 m) of Slope Sea water onto the shelf are common during summer (Mountain *et al.*, 1989; Cowen *et al.*, 1993; Flagg *et al.*, 1994) and slope water can intrude across the front near the bottom (see Csanady and Hamilton, 1988; Flagg, 1988), but neither mechanism explains cross-frontal larval transport in the springtime, nor for larvae near the surface (e.g. *U. tenuis*). Springtime winds in the MAB are not favourable for wind-driven transport across the shelf (Hare and Cowen, 1996). Shelfbreak eddies could mix larvae from the Slope Sea to the shelf (see Garvine *et al.*, 1989), but Dragos *et al.* (1996) found that only two of 56 surface drifters crossed from the Slope Sea onto the MAB shelf and only to a very limited extent, indicating that passive exchange from slope to shelf at the surface is rare. Similar to the arguments of Hare and Cowen (1996) for *Pomatomus saltatrix*, owing to the lack of physical mechanisms and the morphological (slab-sided, counter shaded, large caudal fin) and behavioural (neustonic) characteristics of *U. tenuis*, active horizontal swimming is the most probable mechanism to explain how pelagic juveniles cross the

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**Figure 18.** Summary of physical processes that influence the distribution of fish larvae and pelagic juveniles in the Slope Sea.
shelf/slope front and the shelf to arrive at nearshore juvenile habitats.

MAB shelf assemblage

The shelf/slope front appears to form a substantial barrier to larval transport from the MAB shelf to the Slope Sea during springtime. Most members of the MAB shelf assemblage spawn on the continental shelf (Able and Fahay, 1998) and the occurrence of their larvae in frontal or Slope Sea water suggests shelf-to-slope transport. However, only a subset of larvae in the MAB shelf assemblage were found in frontal and Slope Sea water, and many of the species that spawn on the MAB shelf during spring were not collected during this study (Table 5). These findings indicated limited transport from the MAB shelf to the Slope Sea, similar to observations of limited movement of Slope Sea assemblage members onto the shelf.

Several factors could have affected the larval distributions of the MAB shelf assemblage members that were collected in frontal and Slope Sea water. For several of these species (Scomber scombrus, Enchelyopus cimbrius, Glyptcephalus cynoglossus, Berrien et al., 1999), spawning occurs over the shelf break and may place eggs and larvae in frontal or Slope Sea water, depending on the location of the shelf/slope front. More information is needed regarding spawning of shelf species in waters deeper than 200 m along the MAB shelf break region to resolve questions of larval distribution and transport. SST imagery, however, indicated water movement from the shelf edge into the Slope Sea coincident with the offshore shift in larvae (Figs 13, 15f,g). WCRs can interact with the shelf/slope front resulting in offshore advection of shelf water (Fig. 18; Morgan and Bishop, 1977; Evans et al., 1985), however, no WCRs had passed through the study site for several months in either 1988 or 1993. Frontal waves and small eddies along the shelf/slope front can mix shelf and slope water (Garvine et al., 1999).

Table 4. Members of the Gulf Stream assemblage collected in the vicinity of warm-core rings during other studies. Total number of fish collected in a study are presented. Austin (1975) sampled on the western side of a warm-core ring off Hudson Canyon during May 1974. A 61-cm bongo sampler fitted with both 0.333 mm and 0.505 mm mesh were used and values represent catch in both nets. A 1 x 2 m neuston net with 0.947 mm mesh was also used. Wroblewski and Cheney (1984) sampled off the Scotian shelf on the north side of a warm-core ring during May 1982. Both a bongo net and neuston net with 0.333 mm mesh were used. LeBlanc (1986) sampled on the north-eastern side of a WCR south-west of Hudson Canyon during late June/July 1982. A 1 m³ MOCNESS with 0.333 mm mesh was used. Cowen et al. (1993) sampled on the continental shelf in the New York Bight during the summer of 1988 while a WCR was offshore in the Slope Sea. Data for early July cruise shown. A 1 m³ Tucker Trawl with 0.505 mm mesh was used. Evseenko (1982) collected some of these species in the Slope Sea as well, but in low numbers. Accompanying hydrographic data suggests the presence of a Gulf Stream meander/filament and as a result, this study is not listed here.

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*In late June/early July spawning in the MAB is a possibility (Fahay, 1983; Rotunno and Cowen, 1997). bFrom Austin (1975) identifications made from illustrations and meristics of unknown types. cFrom LeBlanc (1986) 19 unidentified Gobiidae were collected. dAustin (1975) identified as Mugil spp.; LeBlanc (1986) identified as Mugil cephalus. cFrom LeBlanc (1986) 70 unidentified labrids collected – 54 were X. novacula (Hare, unpublished data) material borrowed from Museum of Comparative Zoology (lot numbers).
yet the scale of offshore movements appears larger than shelf break eddies or frontal waves. MAB shelf water exits the shelf in association with the Gulf Stream south of Chesapeake Bay (Ford Water, Ford et al., 1952; Churchill and Berger, 1998) but this mechanism is too distant. Although the mechanisms of off-shelf transport are unresolved, two appear most likely: an unidentified advective mechanism (Fig. 13) or, by default, active swimming. The mechanisms of larval transport from the shelf into the Slope Sea require further study, as for some species this transport may represent a source of larval loss (e.g. Melanogrammus aeglefinus, Cohen et al., 1987; Myers and Drinkwater, 1989), while for other species this transport is necessary to supply larvae to juvenile habitats on the slope (e.g. Glyptocephalus cynoglossus, Powles and Kohler, 1970; Markle, 1975, possibly Enchelyopus cimbrius, Table 2, Fig. 17a).

Larval distributions, larval transport and recruitment
The early life history stages of a variety of fishes occur in the Slope Sea. Predictably, mesopelagic (e.g. Benthosema glaciale, Ceratoscopelus maderensis) species complete their entire life cycle in this oceanic region. More notably, a suite of species spawns south of Cape Hatteras, moves along the southern boundary of the Slope Sea in association with the Gulf Stream, crosses the Slope Sea, and utilizes nearshore or shelf habitats in the MAB as juvenile nurseries before returning to habitats south of Cape Hatteras (Pomatomus saltatrix, Mugil curema, Peprilus triacanthus, Sphyraena borealis, Sphoeroides spp.). This 'strategy' is closely linked with the physical mechanisms that cause the periodic closure of the gyre in the western Slope Sea. Further, there may also be a suite of species that uses the Slope Sea as late-larval or juvenile habitat before returning to adult, shelf habitats (Urophycis regia, U. tenuis, Enchelyopus cimbrius, Glyptocephalus cynoglossus, Lophius americanus).

Multiple mechanisms of larval transport move larvae into, through and out of the Slope Sea (Fig. 18). Determining how these mechanisms combine to affect larval distributions is a necessary step in understanding the role of larval transport in influencing supply of larvae to juvenile habitats. For example, Hare and Cowen (1991) and Cowen et al. (1993) found that the distribution of members of the Gulf Stream assemblage on the MAB shelf was linked to WCR-streamers north of Delaware Bay, whereas south of Delaware Bay, these larvae were also present when no WCRs were nearby. This spatial pattern can be explained by the supply of these larvae from the

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<td>Shelf</td>
<td>Morse et al. (1987)</td>
</tr>
<tr>
<td>Scomber scombrus</td>
<td>3</td>
<td>3</td>
<td>Yes/no</td>
<td>Shelf/slope</td>
<td>Berrien (1978)</td>
</tr>
<tr>
<td>Enchelyopus cimbrius</td>
<td>4</td>
<td>2</td>
<td>Yes/yes</td>
<td>Shelf/slope</td>
<td>Cohen and Russo (1979)</td>
</tr>
<tr>
<td>Cyclopteridae (Liparis spp.)</td>
<td>5</td>
<td>&gt; 10</td>
<td>No/no</td>
<td>Shelf</td>
<td>K.A. Able (pers. comm.)</td>
</tr>
<tr>
<td>Scopthalmus aquosus</td>
<td>6</td>
<td>6</td>
<td>No/no</td>
<td>Shelf</td>
<td>Morse and Able (1995)</td>
</tr>
<tr>
<td>Gadus morhua</td>
<td>7</td>
<td>&gt; 10</td>
<td>No/no</td>
<td>Shelf/slope</td>
<td>Morse et al. (1987)</td>
</tr>
<tr>
<td>Glyptocephalus cynoglossus</td>
<td>8</td>
<td>5</td>
<td>Yes/no</td>
<td>Shelf/slope</td>
<td>MARMAP</td>
</tr>
<tr>
<td>Benthosema glaciale</td>
<td>9</td>
<td>&gt; 10</td>
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<td>Slope/oceanic</td>
<td>MARMAP</td>
</tr>
<tr>
<td>Melanogrammus aeglefinus</td>
<td>10</td>
<td>&gt; 10</td>
<td>No*/no</td>
<td>Shelf</td>
<td>MARMAP</td>
</tr>
<tr>
<td>Lophius americanus</td>
<td>&gt; 10</td>
<td>4</td>
<td>Yes/no</td>
<td>Shelf</td>
<td>Morse et al. (1987)</td>
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<tr>
<td>Merluccius bilinearis</td>
<td>&gt; 10</td>
<td>7</td>
<td>No*/no</td>
<td>Shelf</td>
<td>Fahay (1975)</td>
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<td>Tautogolabrus adspersus</td>
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<td>8</td>
<td>No/yes</td>
<td>Shelf</td>
<td>Morse et al. (1987)</td>
</tr>
<tr>
<td>Hippoglossina obstanga</td>
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<td>No/no</td>
<td>Shelf</td>
<td>MARMAP</td>
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<tr>
<td>Urophycis chuss</td>
<td>&gt; 10</td>
<td>10</td>
<td>No*/no</td>
<td>Shelf</td>
<td>Comyns and Grant (1993)</td>
</tr>
</tbody>
</table>

*During May 1993, one L. ferruginea larva was collected in shelf water and one was collected in frontal water. †During May 1993, one M. aeglefinus and one U. chuss larva were collected in frontal water. ‡During May 1993, one M. bilinearis larva was collected in Slope Sea water.
Gulf Stream to the MAB shelf edge via two mechanisms: WCR streamers to the north and both WCR-streamers and Gulf Stream filaments to the south. WCRs form to the east and move south-westward and thus, these mesoscale eddies and associated streamers are less frequent in extreme western portion of the Slope Sea (Auer, 1987). Gulf Stream filaments and discharges form in association with meanders, which occur along the entire length of the Gulf Stream (Auer, 1987; Olson et al., 1994), but transport across the Slope Sea is more likely along the southern portion of the MAB shelf edge (Churchill et al., 1993). These different transport mechanisms may result in different patterns in the timing and magnitude of recruitment to specific coastal areas in the MAB for the species for which transport across the Slope Sea and onto the MAB shelf is a necessary part of the life history. Similar consequences may result from spatial differences in shelf-to-Slope Sea transport, and require future investigation. We hope that our summary of larval fish distributions, classification of ichthyoplankton communities and identification of potential larval transport processes will serve as a basis for future examinations of the role of the Slope Sea in the life history of the variety of species that use this environment.

In general, oceanic areas between continental shelves and western boundary currents may be more important to shelf fishes than is currently recognized (see Kasai et al., 1996). These areas share complex water mass structure and physical processes causing mixing across water mass boundaries. Other western boundary currents advect warm-temperate and subtropical species to cooler temperate and boreal areas (Miskiewicz, 1989; Beckley, 1995) and there may be a suite of species for which poleward transport is a necessary part of the life history (Miskiewicz et al., 1996). Similarly, warm-core rings and their associated warm (western boundary current-derived) and cold (shelf/slope water-derived) streamers are common to western boundary currents (Lutjeharms et al., 1988; Yasuda et al., 1992). Differences will exist, however, owing to the geographical ‘layout’ of the system. For example the Gulf Stream separates from the continental shelf at Cape Hatteras and flows nearly parallel to the north-eastern US shelf but roughly 100–300 km offshore. In contrast, the separation point of the Brazil Current (south-western Atlantic boundary current) varies over several degrees of latitude, and following separation the current flows directly offshore (Olson et al., 1988). Large-scale anticyclonic circulation is semipermanent just downstream of the separation in the Brazil Current, which may create analogues to larval transport in the Gulf Stream’s WCRs and associated streamers. Thus, information gained on larval distributions, transport and survival in a specific western boundary current system will help refine our understanding of the processes that affect larval distribution, transport and survival is other systems and thereby illuminate the processes that affect variability in recruitment at the level of marine systems.

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