Abstract

WALSH, HARVEY JOSEPH. Distribution of Fall / Winter-Spawned Larval Fish in Relation to Hydrographic Fronts on the North Carolina Shelf: Implications for Larval Transport Mechanisms. (Under the supervision of Drs. Jeffery A. Buckel and Jonathan A. Hare).

Fish population dynamics are partially determined by successful larval transport. Many fish in the southeast U.S. use estuaries as juvenile nursery habitat, but are spawned on the continental shelf. Favorable cross-shelf larval transport pathways for fall / winter-spawned species off North Carolina have been theorized to occur as a result of seasonal circulation patterns of currents and episodic onshore movement of water masses. As a result, hydrographic fronts which separate the water masses; including the outer-shelf front and mid-shelf front have been linked to cross-shelf larval transport for several species. The objective of this study was to determine whether fronts on the continental shelf off the southeast U.S. influence larval fish distribution and cross-shelf transport. Ichthyoplankton and hydrographic data were analyzed in concert to determine if the presence of fronts on the shelf influenced larval distribution patterns or mean distance from shore of larvae. In addition, "average" larval distribution patterns for each species were compared with the results from when fronts were present. Results indicated larval fish were not aggregated at fronts, though abundance and size distribution patterns and mean distance from shore of several species-size classes analyzed were significantly different when the outer-shelf front, mid-shelf front, warm Gulf Stream filament front, or Hatteras front (i.e., intrusions of Virginia coastal water) were present on the shelf. Average cross-shelf distributions of several species and the results of previous studies led to the conclusion that cross-shelf larval transport was predominately driven by seasonal circulation patterns. In addition, my results verify that episodic events, such as fronts modify seasonal transport pathways.

Distribution of Fall / Winter-Spawned Larval Fish in Relation to Hydrographic Fronts on the North Carolina Shelf: Implications for Larval Transport Mechanisms

By

Harvey Joseph Walsh

A thesis submitted to the graduate faculty of
North Carolina State University
in partial fulfillment of the requirements for the
Degree of Master of Science

Zoology

Raleigh, NC

2007

Approved By:

Dr. Cynthia N. Cudaback
Department of Marine Earth and Atmospheric Sciences

Dr. Jeffrey A. Buckel
Department of Zoology
Co-chair of Advisory Committee

Dr. Jonathan A. Hare
Department of Zoology
Co-chair of Advisory Committee

Biography

Education

August 2002 – August 2007. North Carolina State University. Raleigh, NC 27695.
Master of Science, Department of Zoology, Expected date of graduation Fall 2007

August 1987 – May 1991. St. Cloud State University, St. Cloud, MN 56301.
Bachelor of Science, Department of Biology, Aquatic Biology. December 1991

Professional Experience

December 2005 – present: Research Associate II, Biology Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

December 1991 – December 2005: Biological Science Technician, NOAA Beaufort Laboratory, Beaufort, North Carolina

March 1991 – October 1991: Water Quality Research Biologist, Water Research & Management, Inc., Sauk Rapids, Minnesota

Publications

Sullivan, M.C., K.W. Able, J.A. Hare, and H.J. Walsh. 2006. *Anguilla rostrata* glass eel ingress into two, U.S. east coast estuaries: Patterns, processes, and implications for adult abundance. Journal of Fish Biology 69: 1081-1101.

Walsh, H.J., K.E. Marancik, and J.A. Hare. 2006. Juvenile fish assemblages of unconsolidated sediments on the southeast United States continental shelf. Fishery Bulletin 104: 256-277.

Hare, J.A., H.J. Walsh, and M.J. Wuenschel. 2006. Sinking rates of late-stage fish larvae: implications for larval ingress into estuarine nursery habitats. Journal of Experimental Marine Biology and Ecology 330: 493-504.

Hare, J.A., S. Thorrold, H. Walsh, C. Reiss, A. Valle-Levinson, and C. Jones. 2005. Bio-physical mechanisms of larval ingress into Chesapeake Bay. Marine Ecology Progress Series 303: 295-310.

Walsh, H.J., L.R. Settle, and D.S. Peters. 2005. Early life history of blueback herring and alewife in the lower Roanoke River, North Carolina. Transactions of the American Fisheries Society 134: 910-926.

Walsh, H.J., D.S. Peters, and D.P. Cyrus. 1999. Habitat utilization by small flatfishes in a North Carolina estuary. Estuaries 22(3B): 803-813.

Burke, J.S., M. Ueno, Y. Tanaka, H. Walsh, T. Maeda, I. Kinoshita, T. Seikai, D.E. Hoss, and M. Tanaka. 1998. The influence of environmental factors on early life history patterns of flounders. Journal of Sea Research 40: 19 32.

Presentations

Walsh H.J. and J.A. Hare. Distribution of larval fish in relation to hydrographic fronts on the North Carolina shelf. 30th Annual Larval Fish Conference, Sept 10-14, 2006. Lake Placid, NY.

J.A. Hare and H.J. Walsh. Quantifying planktonic linkages among Marine Protected Areas on the south Florida and southeast U.S. continental shelf. 30th Annual Larval Fish Conference, Sept 10-14, 2006. Lake Placid, NY.

Walsh H.J., J.C. Taylor, and J.A. Hare. Relationships between larval ingress and juvenile fish survey data in North Carolina, USA. 28th Annual Larval Fish Conference, May 23-26, 2004. Clemson, SC.

Walsh, H.J., K.E. Marancik, and J.A. Hare. Linking larval fish distributions with juvenile settlement patterns on the Georgia shelf, USA. 27th Annual Larval Fish Conference, August 19-23, 2003. Santa Cruz, CA.

Hare, J.A., H.J. Walsh and K.E. Marancik. Marine Habitats and Protected Areas. SouthEast Coastal Ocean Science Conference and Workshop. January 27-31, 2003. Charleston, SC.

Walsh, H.J., J.C. Taylor, J.P. Monaghan, Jr. and J.A. Hare. Relationships between larval ingress and juvenile fish survey data for three species of flatfish from North Carolina, USA. 5th International Flatfish Symposium. November 2-7, 2002. Isle of Man, UK.

Honors & Awards

National Ocean Service, Employee of the Year, 2001

Professional Affiliations

Early Life History Section of the American Fisheries Society

Acknowledgements

I would like to first thank my committee; Dr. Cynthia Cudaback, Dr. Jeff Buckel, and Dr. Jon Hare for all their work and patience through this long process. They provided guidance and much appreciated help with this endeavor.

Much of the field work took place during cruises for the South Atlantic Bight Recruitment Experiment, and too many individuals were involved to name them all. The Sea Fisheries Institute, Poland and members of the Fish Ecology team of the NOAA Beaufort Laboratory processed the ichthyoplankton samples. I would especially like to thank Larry Settle for providing much of the CTD data.

Several supervisors have allowed me to pursue my research, and I appreciate their support. The list includes; J. Hare, P. Tester, C. Currin of the NOAA Beaufort Lab and S. Thorrold of the Woods Hole Oceanographic Institution.

I thank Dave Peters, Don Hoss, and Jon Hare for initiating and continuing to foster my interest in fisheries oceanography and the early-life history of fish. Without their mentoring I would have probably ended up back in Minnesota, stocking walleyes.

Finally, thanks and appreciation goes to my wife Katey for providing words of advice, countless reviews, and much needed support.

Table of Contents

Page

List of Tables………………………………………………………………………........... vii

List of Figures……………………………………………………………………….... xi

Distribution of Fall / Winter-Spawned Larval Fish in Relation to Hydrographic Fronts on the North Carolina Shelf: Implications for Larval Transport Mechanisms

1.1 Introduction……………………………………………………………….... 1

1.2 Methods…………………………………………………………........... 9

1.2a Ichthyoplankton collection………………………………….. 9

1.2b Hydrographic data collection……………………………….. 9

1.2c Definition of fronts and water masses………………………. 11

1.2d Ichthyoplankton data processing……………………………. 13

1.2e Larval distribution patterns and the presence of fronts……... 14

1.2f Water mass specific larval distribution patterns and the presence of fronts……………………………………........... 15

1.2g Mean distance from shore of larvae and the presence of fronts……………………………………………………… 15

1.2h Average larval cross-shelf distribution……………........... 16

1.3 Results……………………………………………………………........... 16

1.3a Description of fronts and water masses……………………... 16

1.3b Larval distribution patterns and the presence of fronts……... 17

1.3c Water mass specific larval distribution patterns and the presence of fronts……………………………………........... 18

1.3d Mean distance from shore of larvae and with the presence of fronts…………………………….............................. 20

1.3e Average larval cross-shelf distribution……………………… 20

1.3f Atlantic menhaden average cross-shelf distribution…............ 21

1.3g Round herring average cross-shelf distribution……………... 22

1.3h Spot average cross-shelf distribution………………………... 22

1.3i Atlantic croaker average cross-shelf distribution……………. 23

1.3j Summer flounder average cross-shelf distribution…………... 23

1.3k *Paralichthys albigutta / lethostigma* average cross-shelf distribution……………………………………………….... 24

1.4 Discussion……………………………………………………………….. 24

1.4a Larval distribution patterns and the presence of fronts……... 24

1.4b Cross-shelf larval distribution and transport………………... 27

1.4c Conceptual model of the effect of the outer-shelf and mid-shelf fronts……………………………………………... 28

Table of Contents (Cont'd)

Page

1.4d Conceptual model of the effect of the warm filament front… 31
1.4e Conceptual model of the effect of the Hatteras front……….. 32
1.4f Conclusions………………………………………………….. 33

1.5 Literature Cited……………………………………………………….. 67

1.6 Appendixes……………………………………………………............ 74
1.6a Appendix A: Hydrographic data…………………………….. 75
1.6b Appendix B: Larval fish data……………………………….. 100

List of Tables

		Page
Table 1	Ichthyoplankton and hydrographic sampling information for the…….... New River transect which Onslow Bay, North Carolina (Fig. 2). Ichthyoplankton was collected in oblique tows using a 60 cm bongo net fitted with 333 µm mesh nets. Hydrographic data was collected using a conductivity, temperature, and depth (CTD) probe. When available, sea surface temperature (SST) was derived from advanced very high-resolution radar satellite images.	35
Table 2	Definition of water masses in Onslow Bay, North Carolina was…….. based primarily on seasonal surface water temperature, surface salinity, and presence of fronts on the shelf.	36
Table 3	Mean (standard deviation) difference of surface water temperature….. (^oC), salinity, density (σ_t, $kg \cdot m^{-3}$), and sea surface temperature (SST, ^oC) between adjacent sample stations from the New River transect off the coast of North Carolina for December, January, and February 1990-1999. Stations either coincided with a front or not (none). SST data were corrected from advanced very high-resolution radar satellite images.	37
Table 4	Number (n), mean distance from shore (standard deviation), water…... column water temperature (^oC), salinity, density (σ_t, $kg \cdot m^{-3}$), stratification (Φ, $joules \cdot m^{-3}$), and sea surface temperature (SST, ^oC) for six fronts observed on the New River transect off the coast of North Carolina from December, January, and February 1990-1999. SST data were corrected from advanced very high-resolution radar satellite images.	38
Table 5	Total number of larvae collected and number of larvae measured for…. six taxa collected in oblique bongo tows on 27 cruises from the New River transect which bisects Onslow Bay, North Carolina (Fig. 2).	39
Table 6	Seven analyses were conducted on larval abundance and length…….. distributions to determine whether fronts on the continental shelf off North Carolina influence larval fish distributions and cross-shelf transport. The analyses done to address each objective are listed.	40
Table 7	Mean (standard deviation) water column water temperature (^oC),……. salinity, density (σ_t, $kg \cdot m^{-3}$), stratification (Φ), and sea surface temperature (SST, ^oC) for seven water masses defined on the New River transect off the coast of North Carolina from December, January, and February 1990-1999. SST data for each water mass were corrected from advanced very high-resolution radar satellite images. VCW = Virginia Coastal Water.	41

List of Tables (Cont'd)

		Page
Table 8	Location of peak abundance of three size classes for six taxa…………. collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Chi-square analysis was used to determine whether peak abundance for each taxa and size class of larvae occurred at fronts or not at fronts (*** = $p \leq 0.025$, ** = $p \leq 0.05$, * = $p \leq 0.10$).	42
Table 9	Mean (standard deviation) of Green's coefficient (GC) of three size….. classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). A one-way ANOVA was used to determine if GC differed whether or not the mid-shelf, outer-shelf, or warm Gulf Stream filament was present (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$).	43
Table 10	Results from a two-factor ANOVA (degrees of freedom (df), sums….. of squares (SS), mean square (MS)) examining the interaction of the presence of fronts and water mass on standardized larval abundance of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Three continental shelf fronts; mid-shelf (MSF), outer-shelf (OSF), and warm Gulf Stream filament (FIL) were classified as either present or absent and stations were separated into water masses (Table 5). The interaction between water mass and presence / absence of front indicated whether fronts affected larval abundance within water masses (*** = $p \leq 0.001$, ** = $p \leq 0.025$, and * = $p \leq 0.05$).	44
Table 11	Results from a two-factor ANOVA (degrees of freedom (df), sums….. of squares (SS), mean square (MS)) examining the interaction of the presence of fronts and water mass on mean body length (BL, mm) of larvae for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Three continental shelf fronts; mid-shelf (MSF), outer-shelf (OSF), and warm Gulf Stream filament (FIL) were classified as either present or absent and stations were separated into water masses (Table 5). The interaction between water mass and presence / absence of front indicated whether fronts affected larval size distributions within water masses (*** = $p \leq 0.001$, ** = $p \leq 0.025$, and * = $p \leq 0.05$).	46

		Page
Table 12	Results from a one-factor ANOVA (degrees of freedom (df), sums….. of squares (SS), mean square (MS)) examining the effects of the presence of fronts on mean distance from shore (weighted by larval abundance) of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Three continental shelf fronts; mid-shelf (MSF), outer-shelf (OSF), and warm Gulf Stream filament (FIL) were classified as either present or absent and the ANOVA was used to determine if mean distance from shore differed whether or not the MSF, OSF, or FIL was present (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$).	47
Table 13	Results from a two-factor ANOVA (degrees of freedom (df), sums….. of squares (SS), mean square (MS)) examining the effects of season and water mass on larval abundance ($\log_{10}$ (larvae · $1000m^{-3}$ + 1)) of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sample months were separated into two seasons, December and January – February. Stations were separated into water masses (Table 5) based on water temperate, salinity, density, and the presence of fronts on the shelf. A *posteriori* multiple comparisons among seasons and water masses were conducted using Scheffé's S procedure (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$, and ns = not significant). Differences in mean abundance among seasons and water masses[1] are indicated from highest to lowest (IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, GS = Gulf Stream, VCW-IS = Virginia coastal water inner-shelf, and VCW-MS = Virginia coastal water mid-shelf).	49
Table 14	Results from a two-factor ANOVA (degrees of freedom (df), sums….. of squares (SS), mean square (MS)) examining the effects of season and water mass on mean body length (BL, mm) of larvae for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sample months were separated into two seasons, December and January – February. Stations were separated in to water masses (Table 5) based on water temperate, salinity, density, and the presence of fronts on the shelf. A *posteriori* multiple comparisons among seasons and water masses were conducted using Scheffé's S procedure (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$, and ns = not significant). Differences in mean BL among seasons and water masses[1] are indicated from largest to smallest (IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, GS = Gulf Stream).	52

List of Tables (Cont'd)

		Page
Table 15	Summary of results for water mass specific abundance and size……… distribution and the effects of fronts on larval distributions on the continental shelf off North Carolina. Fronts which were present when significant difference in larval distributions occurred are shown for each analysis. MSF = mid-shelf front, OSF = outer-shelf front, FILF = warm filament front, and HF = Hatteras front.	53
Table B1	Location of peak abundance of three size classes for six taxa………… collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Chi-square analysis was used to determine whether peak abundance for each taxa and size class of larvae occurred at fronts or not at fronts (*** = $p \leq 0.025$, ** = $p \leq 0.05$, * = $p \leq 0.10$).	101
Table B2	Mean (standard deviation) of Green's coefficient (GC) of three size… classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). A one-way ANOVA was used to determine if GC differed whether or not the coastal front or Gulf Stream front was present (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$).	102

List of Figures

		Page
Figure 1	A schematic of six fronts that occur in Onslow Bay, North Carolina.. during the winter and resultant current flows are shown. (A) The coastal front (CF) and Gulf Stream front (GSF) commonly bound the continental shelf, and either a three layer cross-shelf current flow pattern (Miller et al. 1984) or northward flow may occur on the mid-shelf (Werner et al. 1999). (B) Surface intrusions of the Gulf Stream water mass (gs) result in the formation of the outer-shelf front (OSF) and mid-shelf front (MSF). (C) A filament front (FILF) often separates mesoscale eddies with warm filaments of Gulf Stream water (fil) from shelf water masses. (D) Intrusions of Virginia Coastal Water (VCW) overlay resident water masses and form the Hatteras front (HF) at the offshore edge.	54
Figure 2	Location of ichthyoplankton stations (black dots) and a satellite…... transect (dotted line) bisecting Onslow Bay, North Carolina. The start and end points of the satellite transect are shown (red dots). Sampling was conducted during December, January, and February 1990-1999 (Table 1).	55
Figure 3	Linear relationship between conductivity, temperature, and depth… (CTD) surface water temperature measurements and satellite sea surface temperatures (SST) from a transect bisecting Onslow Bay, North Carolina (Fig. 2). Sampling conducted during December, January, and February 1990-1999. Circles represent surface water temperature (averaged from 1 to 3 m) from CTD casts and satellite SST from pixels which corresponded to the nominal station locations and were within two days of the sample date (N). The line represents predicted SST values from the CTD values using the linear equation shown on the graph.	56
Figure 4	Monthly cross-shelf water temperature (^{o}C) climatologies for…….. Onslow Bay, North Carolina. Climatologies were created using water temperature casts (n) from the current study and the World Ocean Database 2005 (downloaded from NOAA's National Oceanographic Data Center: http://www.nodc.noaa.gov/ OC5/SELECT/dbsearch/sysinfo.html).	57

List of Figures (Cont'd)

		Page
Figure 5	Abrupt difference in surface water temperature (^{o}C), salinity, and… density (σ_t, kg·m^{-3}) between stations were used to define the location of fronts on a transect bisecting Onslow Bay, North Carolina (Fig. 2). An example using data from conductivity, temperature, and depth probe casts for 17-18 February 1993 (A) and satellite sea surface temperature derived from advanced very high-resolution radar satellite images for 18-19 January 1999 (B) show the location of fronts. CF = coastal front, MSF = mid-shelf front, OSF = outer-shelf, and GSF = Gulf Stream front.	58
Figure 6	Visual analysis of the cross-shelf temperature (^{o}C), salinity, and….. density (σ_t, kg·m^{-3}) sections from stations (circles) on a transect bisecting Onslow Bay, North Carolina (Fig. 2) were used to verify the location of fronts (black triangles). An example from 17-18 February 1993 shows the location of four fronts, and stations classified as adjacent to the MSF and OSF enclosed by dotted boxes. CF = coastal front, MSF = mid-shelf front, OSF = outer-shelf, and GSF = Gulf Stream front.	59
Figure 7	Average water column temperature (^{o}C) and salinity of the seven… water masses defined for the North Carolina shelf for December (A) and January-February (B) shown with lines of equal density (σ_t, kg·m^{-3}) at a pressure of 0 dbar. VCW = Virginia Coastal Water.	60
Figure 8	Atlantic menhaden (*Brevoortia tyrannus*) mean (standard………… deviation) standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a mid-shelf front (MSF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.	61
Figure 9	Round herring (*Etrumeus teres*) mean (standard deviation)……….. standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a mid-shelf front (MSF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.	62

List of Figures (Cont'd)

Page

Figure 10 Atlantic menhaden (*Brevoortia tyrannus*) mean (standard………… deviation) standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a warm filament front (FILF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream. 63

Figure 11 Spot (*Leiostomus xanthurus*) mean (standard deviation)…………… standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a mid-shelf front (MSF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream. 64

Figure 12 Mean (standard deviation) distance from shore (km) of small (A),... medium (B), and large (C) size classed larvae of six taxa when the outer-shelf front (OSF) was present and absent. Differences within size class among presence/absence of the fronts were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. 65

Figure 13 Mean (standard deviation) distance from shore (km) of small (A),... medium (B), and large (C) size classed larvae of six taxa when the warm filament front (FILF) was present and absent. Differences within size class among presence/absence of the fronts were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. 66

List of Figures (Cont'd)

Page

Figure A1 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 30 January 1990. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 76

Figure A2 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 7 February 1991. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 77

Figure A3 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 18-19 December 1991. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 78

List of Figures (Cont'd)

		Page
Figure A4	Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 11-12 January 1992. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).	79
Figure A5	Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 20-21 December 1992. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).	80
Figure A6	Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 11-12 February 1993. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).	81

List of Figures (Cont'd)

Page

Figure A7 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 13-14 February 1993. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 82

Figure A8 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 17-18 February 1993. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 83

Figure A9 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 7-8 December 1993. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 84

List of Figures (Cont'd)

Page

Figure A10 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 1-2 February 1994. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg \cdot m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 85

Figure A11 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 13 December 1994. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg \cdot m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 86

Figure A12 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 5-6 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg \cdot m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 87

List of Figures (Cont'd)

Page

Figure A13 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 7-8 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 88

Figure A14 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 9-10 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 89

Figure A15 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 12-13 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 90

List of Figures (Cont'd)

Page

Figure A16 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 18-19 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg{\cdot}m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 91

Figure A17 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 30-31 January 1996. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg{\cdot}m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 92

Figure A18 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 1-2 February 1996. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg{\cdot}m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 93

List of Figures (Cont'd)

Page

Figure A19 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 3-4 February 1996. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 94

Figure A20 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 19 February 1998. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 95

Figure A21 Hydrographic data from a cross-shelf transect bisecting Onslow….. Bay, North Carolina (Fig. 2) sampled 25-26 February 1998. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F). 96

List of Figures (Cont'd)

Page

Figure A22 Mean (standard deviation) surface water temperature (^{o}C) from…... CTD cast and satellite sea surface temperature used to define water masses for transects with out CTD casts for December (A) and January – February (B). IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, and GS = Gulf Stream. 97

Figure A23 Satellite sea surface temperature (SST, ^{o}C) data from a cross-shelf... transect bisecting Onslow Bay, North Carolina (Fig. 2). Transects shown are for 18 January 1994 (A, B), 6-7 December 1994 (C,D), 7 February 1995 (E, F), and 15-16 February 1996 (G, H). SST were used to define water masses and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled circles (Water masses; A, C, E, G). Locations of fronts were detected by abrupt differences in SST between stations (B, D, F, H). 98

Figure A24 Satellite sea surface temperature (SST, ^{o}C) data from a cross-shelf... transect bisecting Onslow Bay, North Carolina (Fig. 2). Transects shown are for 18-19 January 1999 (A, B) and 28-29 January 1999 (C,D). SST were used to define water masses and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled circles (Water masses; A, C). Locations of fronts were detected by abrupt differences in SST between stations (B, D) and are shown with filled black triangles. 99

Figure B1 Mean (standard deviation) body length (A, mm) and abundance…... of small (B), medium (C), and large (D) Atlantic menhaden (*Brevoortia tyrannus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream. 103

List of Figures (Cont'd)

Page

Figure B2 Mean (standard deviation) body length (A, mm) and abundance…... of small (B), medium (C), and large (D) round herring (*Etrumeus teres*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and log_{10} transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream. 104

Figure B3 Mean (standard deviation) body length (A, mm) and abundance…... of small (B), medium (C), and large (D) spot (*Leiostomus xanthurus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and log_{10} transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream. 105

Figure B4 Mean (standard deviation) body length (A, mm) and abundance…... of small (B), medium (C), and large (D) Atlantic croaker (*Micropogonias undulatus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and log_{10} transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream. 106

List of Figures (Cont'd)

		Page
Figure B5	Mean (standard deviation) body length (A, mm) and abundance…... of small (B), medium (C), and large (D) summer flounder (*Paralichthys dentatus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.	107
Figure B6	Mean (standard deviation) body length (A, mm) and abundance…... of small (B), medium (C), and large (D) *Paralichthys albigutta / lethostigma* larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.	108

1.1 Introduction

Along the southeast United States coast, there are a number of commercially and recreationally important species of fish that spawn on the shelf yet use estuaries as juvenile nursery habitats. These species are considered estuarine-dependent, and late stage larvae enter inlets along the coast and settle to various habitats within the estuary. For many estuarine-dependent species, ingress variability may be a dominant factor generating variability in recruitment (Jenkins and Black 1994, Hare and Cowen 1996, Garvine et al. 1997, Quinlan and Crowder 1999). Consequently, determining physical mechanisms of larval transport is important in understanding year-class survival (Norcross and Shaw 1984, Epifanio and Garvine 2001) and subsequent population size.

Successful transport of estuarine-dependent larvae on the southeast United States shelf has been linked to seasonal physical forcing. Miller et al. (1984) proposed a three layer cross-shelf flow model for the North Carolina shelf during the winter, with onshore flow throughout most of the water column (50 -70 %) and offshore flow in the surface and bottom. This model, coupled with cross-shelf larval distribution patterns and seasonal patterns of ingress and recruitment (Warlen 1982, Warlen and Chester 1985, Warlen 1992), led to the conclusion that cross-shelf larval transport may be a continuous process (i.e., seasonal conveyer belt) from offshore spawning grounds to estuarine juvenile nursery habitats (Miller et al. 1984, Govoni and Pietrafesa 1994).

During the 1990's, the South Atlantic Bight Recruitment Experiment (SABRE), an interdisciplinary research project was conducted to investigate the link between recruitment variability of estuarine-dependent fish and environmental variability along the southeast U.S.

shelf (Ortner et al. 1999). Biological sampling on the continental shelf during SABRE focused on determining the distribution and abundance of eggs on the shelf and examining larval transport across the shelf of Atlantic menhaden (Brevoortia tyrannus), a fall / winter spawning species (Ortner et al. 1999). Consequently, most sampling occurred on cross-shelf transects from offshore spawning habitats to inshore nursery grounds. A physical oceanographic model was also developed during SABRE, which was forced by a tide and hourly wind stresses (Werner et al. 1999). Along-shelf advection was proposed as the dominant aspect of larval transport with cross-shelf transport occurring mainly near the capes when the physical oceanographic model was linked with seasonal patterns of abundance and recruitment of estuarine-dependent fish species (Hare et al. 1999, Rice et al. 1999, Quinlan et al. 1999). Lagrangian tracking of simulated larvae from spawning location to inlet ingress in the model was compared with actual ingress at three North Carolina inlets (Hare et al. 1999, Rice et al. 1999), with overall conclusions that larval transport from spawning grounds north and south of inlets resulted in successful larval ingress (Quinlan et al. 1999).

However, the SABRE physical oceanographic model underestimated the cross-shelf magnitude of currents (Werner et al. 1999). The model lacked a dynamic Gulf Stream front (i.e., no onshore or offshore movement) and a density component (Werner et al. 1999); these have been found to lead to the formation, persistence, and dispersal of the outer-shelf front and mid-shelf front on the North Carolina shelf (Oey 1986, Oey et al. 1987, Xie and Pietrafesa 1995). Both the outer-shelf front and the mid-shelf front have been correlated to successful onshore transport of larvae on the southeast U.S. continental shelf (Checkley et al. 1988, Stegmann and Yoder 1996, Hettler and Hare 1998). Thus, the results of SABRE, which lacked these outer- and mid-shelf dynamics, may have underestimated the cross-shelf larval transport potential of fronts on the North Carolina shelf.

Fronts are important features in the pelagic environment, frequently having increased levels of biological production (Haney and McGillivary 1985, Kingsford 1990, Franks 1992, Govoni 2005, Bakun 2006). A surface convergent zone occurs at the location of strong horizontal density gradients (Govoni and Spach 1999, Bakun 2006) and high levels of production result from physical and biological processes that occur in this zone where water masses of differing properties interact (Kingsford 1990, Franks 1992, Bakun 2006). Adult fish often spawn larvae in specific water masses (Cowen et al. 1993, Govoni et al. 2000, Munk 2002, Marancik et al. 2005). Over time, mixing of water masses or not mixing of water masses (caused by fronts) influences larval distributions through aggregation, retention, and onshore / offshore movement (Kingsford 1990), resulting in changes in larval fish assemblage composition (Cowen et al. 1993, Grothues and Cowen 1999, Munk et al. 1999, Lee et al. 2005). Consequently, fronts can directly or indirectly affect larval transport pathways (Kingsford 1990).

Fronts are common features in the coastal ocean (Bakun 2006) and their effect on larval transport depends upon frontal type (Kingsford et al. 1990, Bakun 2006). The most frequently observed fronts are coastal upwelling, shallow sea, and shelf break fronts and these can be described by the gradients in water mass properties between and physical forcing mechanisms balancing them (Kingsford 1990).

Coastal upwelling fronts are forced primarily by winds, and separate water masses differing in temperature, salinity, or both temperature and salinity (Chen et al. 1999, Reiss and McConaugha 1999, Cudaback and Largier 2001). Current flows at coastal fronts vary with the slope of the pycnocline. When the pycnocline bends up and intersects the surface (i.e., upwelling), waters pushing towards the surface cause divergent surface flow (Pond and Pickard 1995). During downwelling, the pycnocline bends downward and intersects the bottom, and surface flows converge (Pond and Pickard 1995). Upwelling fronts can move across the shelf with changes in wind direction or a cessation of strong, sustained upwelling (or downwelling) winds (Reiss and McConaugha 1999, Cudaback and Largier 2001). Convergent flow at upwelling fronts may aggregate larval fish (Kingsford 1990), and onshore / offshore transport results from frontal propagation (Reiss and McConaugha 1999).

In stratified coastal oceans, tidal currents can produce significant turbulent mixing. A shallow sea front forms at the boundary between stratified and mixed water masses (Lochmann et al. 1997, Lee et al. 2005). Tidal currents often produce enough turbulent mixing to disrupt stratification. The shallow sea front is a boundary between the stratified and mixed water masses, with a convergent surface zone (Lochmann et al. 1997). Larval assemblages are often separated by shallow sea fronts which limit water mass exchange (Lee et al. 2005). Aggregation in the convergent zone of shallow sea fronts also retains larvae near juvenile nursery habitats (Lochmann et al. 1997).

Coastal ocean water masses are separated from the open ocean by a shelf break front, where strong density gradients occur predominately along the shelf edge (Lee et al. 1991, Gawarkiewicz et al. 1996, Chen et al. 1999). Baroclinic forcing and geostrophic balance cause along isobath (i.e., along-shelf) flow. Shelf break fronts are relatively stable in cross-shelf location (Kingsford 1990), and primarily influence along-shelf larval transport

(Epifanio and Garvine 2001, Sponaugle et al. 2002). Similar to shallow sea fronts, shelf break fronts separate different larval fish assemblages (Munk et al. 1999). However, baroclinic instabilities often cause shoreward intrusions of offshore water masses (Rudnick and Luyten 1996, Sharples 1997, Gawarkiewicz et al. 2001) and mesoscale eddies to spin off the strong boundary currents (Lee et al. 1991, Gawarkiewicz et al. 2001, Sponaugle et al. 2005). Intrusions of offshore water masses can occur at the surface, pycnocline, or near the bottom (Churchill et al. 2003), and can transport plankton across the shelf (Cowen et al. 1993, Sharples 1997). Mesoscale eddies are rotating currents that flow contrary to the main current, and can rapidly mix water masses and associated larval fish across the frontal zone and adjacent continental shelf (Sponaugle et al. 2005, Bakun 2006).

There are five fronts on the southeast U.S. shelf during winter that could influence the cross-shelf transport of estuarine-dependent species. Two fronts are permanent (a coastal front and the Gulf Stream front) and four fronts are transitory (the outer-shelf front, the mid-shelf front, the warm Gulf Stream filament front, and the Hatteras front). The Gulf Stream front separates the northern/western edge of the Gulf Stream from adjacent waters and along the southeast U.S. shelf (Pietrafesa et al. 1985, Xie and Pietrafesa 1995, Govoni and Spach 1999); this front is typically at the shelf edge (Fig. 1A). During the winter, the coastal front separates colder inner-shelf water (Fig. 1A) from warmer shelf waters (Xie and Pietrafesa 1995), and little research has been conducted on the effect of the coastal front on larval transport. The coastal front experiences more upwelling and downwelling north of Cape Hatteras, North Carolina; particularly during summer when the water column is vertically stratified (Austin 1999, Austin and Lentz 1999, Cudaback and Largier 2001). The water column in Onslow Bay, North Carolina, is not usually stratified during the winter (Pietrafesa et al. 1985), and the coastal front does not appear to be an upwelling / downwelling front.

The Gulf Stream front can drive both along-shelf and cross-shelf larval transport. The Gulf Stream front is a transport mechanism to the southeast shelf, delivering larvae from the south (Denit and Sponagule 2004, Hare and Walsh In Press). Mesoscale eddies (Fig. 1B) also mix water masses along the western wall of the Gulf Stream front, which result in the loss of larvae from the southeast U.S. shelf to the northeast U.S. shelf (Hare and Cowen 1991, Govoni and Spach 1999, Hare et al. 2002). However, water masses are sometimes mixed back on to the southeast shelf in warm Gulf Stream filaments (Lee et al. 1991, Hare et al. 2002) along with the entrained larvae (Govoni 1993, Govoni and Pietrafesa 1994, Govoni and Spach 1999) which may result in local retention of recruits (Limouzy-Paris et al. 1997) or supply of new recruits.

The outer-shelf front is a shoreward intrusion of the Gulf Stream front resulting from wind forcing or a meander of the Gulf Stream front (Oey et al. 1987, Xie and Pietrafesa 1995). Warm, salty, less dense Gulf Stream surface water moves shoreward and deep Gulf Stream waters are upwelled near the shelf break (Fig. 1C). Dense shelf waters are subducted beneath the surface intrusion (Rudnick and Luyten 1996), and divergent flow often occurs at the surface over the foot (offshore side) of the sloped front, and convergent flow occurs near the bottom (Fig. 1C) of the frontal zone (Rudnick and Luyten 1996, Gawarkiewicz et al. 2001). On the inshore side of the outer-shelf front, modeling studies indicate a surface convergence zone occurs (Fig. 1C) due to the downwelling shelf waters (Oey et al. 1987).

As Gulf Stream surface water moves onshore it can cool and sink to the bottom, contributing to the formation of the mid-shelf front (Xie and Pietrafesa 1995, Checkley et al. 1988). The mid-shelf front (Fig. 1C) is a vertical front with a surface convergent zone (Oey et al. 1987, Checkley et al. 1988, Xie and Pietrafesa 1995).

The Hatteras front (Fig. 1D) is formed when Virginia Coastal Water intrudes into Onslow Bay (Pietrafesa et al. 1995, Stegmann and Yoder 1996, Savidge 2002). The less dense Virginia Coastal Water overlays resident water masses, and results in onshore surface flow and offshore bottom flow (Savidge 2002), similar to downwelling.

All three fronts which form as the result of intrusions of water masses onto the southeast U.S. shelf (outer-shelf, mid-shelf, and Hatteras fronts) have been correlated to larval transport (Checkley et al. 1988, Stegmann and Yoder 1996, Hettler and Hare 1998). Checkley et al. (1988) hypothesized that the outer-shelf front transports eggs and larvae in surface waters toward shore. Stegmann and Yoder (1996) also suggested that larval ingress of Atlantic menhaden at Beaufort Inlet, North Carolina may increase with onshore meanders of the Gulf Stream front (i.e., outer-shelf frontal genesis) and intrusions of Virginia Coastal Water (i.e., presence of the Hatteras front). The location of the 16 ^{o}C isotherm, an approximation of the mid-shelf front, was correlated to larval abundance and ingress at Beaufort Inlet (Hettler and Hare 1998); larval abundances were higher outside the inlet when the mid-shelf front was closer to shore. Whether this is the result of the propagating outer-shelf front, or the mid-shelf front acting as a retention zone is not known.

Prior studies have found correlations between larval concentrations and fronts, but have not described a mechanism by which fronts aid cross shelf transport. Understanding this mechanism could greatly aid our understanding of recruitment variability among species that spawn on the southeast US shelf and have estuarine nursery habitats. Thus, the link between frontal genesis and onshore movement of fronts and water masses to cross-shelf transport of larval fish needs further examination. The objective of this study was to determine whether fronts on the continental shelf off the southeast U.S. influence larval fish distribution, abundance, and cross-shelf transport. The general hypothesis is that the cross-shelf distribution of abundance and size of estuarine-dependent larval fish are affected by fronts. To test this hypothesis, ichthyoplankton and hydrographic data were analyzed in concert to examine four objectives. 1) Larval distribution patterns were compared when fronts were present and absent to determine whether larval distribution patterns were affected by the presence of fronts. 2) Larval fish abundance and size within water masses were quantified and compared when fronts were present and absent to determine whether water mass specific larval distribution patterns change with the presence of fronts. 3) Larval distance from shore was compared when fronts were present and absent to determine if mean distance from shore of larvae changed with the presence of fronts. 4) Larval fish abundance and size across the shelf were quantified to determine "average" larval distribution patterns. The "average" distributions for each species were compared with the results from objectives one through three to build a conceptual model of horizontal distribution and movement of larvae on the shelf in the Onslow Bay, North Carolina.

The data used in the present study were collected during SABRE. The original sampling plan was not designed to examine the effect of fronts on larval transport, yet previous research (Checkley et al. 1988, Stegmann and Yoder 1996, Hettler and Hare 1998) and many of the results of modeling conducted during SABRE (Rice et al. 1999, Stegmann et al. 1999, Quinlan et al. 1999) implied that fronts could be important. The cross-shelf transect sampling was used to address the above hypotheses and these analyses will hopefully inform future process-oriented studies that directly examine the effect of fronts on larval transport.

1.2 Methods

1.2a Ichthyoplankton collection

Larval fish were sampled along a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sampling was conducted on 27 cruises during December, January, and February from 1991 to 1999 (Table 1). The transect began approximately 6 km from New River Inlet, North Carolina and ended up to 160 km offshore (Fig. 2), and the number of stations sampled during each cruise varied with a maximum of 14 (Table 1). Standard sampling techniques (Powell et al. 2000) were used to collect ichthyoplankton using a 60 cm bongo net fitted with two 333 μm mesh nets. Oblique tows sampled the water column from the surface to within 1 m of the bottom or 200 m, which ever was shallower. All tows were a minimum of 5 minutes and the volume of water filtered was estimated using flowmeters (General Oceanics, Inc.; model 2030) mounted in the mouths of the nets.

1.2b Hydrographic data collection

A CTD (STD-12, Applied Microsystems, Inc.) cast was made at most ichthyoplankton stations (Table 1). Casts were made from just below the water's surface to within 1 m of the bottom or to 200 m. The CTD recorded depth (m), temperature (^{o}C), and conductivity (mS·cm^{-1}) every second. Salinity and density (σ_t, kg·m^{-3}) were calculated during post processing of the cast using the manufacturer's software, and all five variables were averaged into 1 m bins. To avoid bias owing to equilibration time at the surface, data from 0-1 m depth were discarded, and data from 1-3 m were averaged for the surface value. The average water column values for water temperature, salinity, and density were the mean from 2 m to within 1 m of the bottom or to 50 m. Vertical stratification was estimated using Simpson's stratification parameter (Simpson and James 1986), Φ (joules·m^{-3}), which is a measure of the resistance of water to mixing.

The cross-shelf CTD data was supplemented with SST data derived from advanced very high-resolution radar (AVHRR) satellite images (Table 1) (data obtained from http://rs.gso.uri.edu/avhrr-archive/archive.html). Images from five days on either side of each sampling date were examined to determine if they were cloud free. SST data were extracted from the cloud free images for each pixel along the transect starting at the coast out to a distance of 167 km (Fig. 2), with a pixel resolution of 1.2 km (Ullman and Cornillon 2001). For transects with water temperature data available from both CTD measurements and SST satellite estimates, a correction factor was calculated to reduce bias caused by using two temperature data collection methods. Sample date (± 2 d) and station location combinations for the CTD data overlapped with the SST data sets 324 times. A significant positive linear relationship existed between surface water temperature measured using CTD casts and satellite SST from corresponding station locations ($df = 323$, $f = 3623$, $p \leq 0.001$; Fig. 3). For transects without CTD data, the linear equation (T (^{o}C) = SST – 3.1373 / 0.93104) was used to estimate surface water temperature (T) to define water masses and locations of fronts (Table 1). The 3.1^{o}C degree difference between the CTD and satellite water temperature data may be due several factors including; the depth differences of the two measurements, separation in days between the measurements, estimated location of the station data, and pixel size of the satellite data.

1.2c Definition of fronts and water masses

Strong density gradients (i.e., fronts) frequently separate water masses on the North Carolina shelf (Oey et al. 1987, Lee et al. 1991, Xie and Pietrafesa 1995, Govoni and Spach 1999, Savidge 2002) and are primarily due to differences in water temperature (Pietrafesa et al. 1985). Six fronts were defined as part of this study and in the context of prior research in the region: coastal front, mid-shelf front, outer-shelf front, Gulf Stream front, warm Gulf Stream filament front, and Hatteras front. Seven water masses were defined based on water temperate, salinity, density, and the presence of fronts: inner-shelf, mid-shelf, outer-shelf, Gulf Stream, warm filament, VCW inner-shelf, and VCW mid-shelf (see Appendix A).

Water temperature in Onslow Bay was consistently 2-3 ^{o}C warmer in December than in January and February (Fig. 4); thus December water masses were defined separately (Table 2). The inner-shelf water mass was defined by the lowest surface water temperature and salinity < 36 (Table 2; Pietrafesa et al. 1985). The mid-shelf water mass was a mixture of inner-shelf and outer-shelf waters and had intermediate temperature and salinity (Table 2; Pietrafesa et al. 1985, Xie and Pietrafesa 1995, Hettler and Hare 1998). The outer-shelf water mass had salinity >36 and warm temperatures (Table 2; Pietrafesa et al. 1985, Xie and Pietrafesa 1995). Gulf Stream water was highest in surface water temperature (Table 2; Xie and Pietrafesa 1995, Govoni and Spach 1999). The warm filaments occasionally advected onshore due to onshore and offshore meandering of a warm Gulf Stream filament (Lee et al. 1991) were defined as a water mass (Table 2). The presence of the Hatteras front in Onslow

Bay, with less saline (<33) VCW overlaying the more saline resident water masses (Pietrafesa et al. 1995, Stegmann and Yoder 1996, Savidge 2002), was also used to define two water masses: VCW inner-shelf and VCW mid-shelf (Table 2).

Abrupt changes in water mass characteristic were used to define the location of fronts. The location of a 0.2 ^{o}C change in water temperature (Ullman and Cornillon 1999), 0.05 in salinity, 0.05 σ_t in density, or 0.2 ^{o}C change SST per 1 km between stations was noted as a possible front (Table 3, Fig. 5). Since fronts coincided with horizontally compacted isotherms, isopycnals, and / or isobars, careful visual analysis of the cross-shelf temperature, salinity, and density sections or SST for each transect were used to verify the presence and location of fronts (Fig. 6; see Appendix A). Fronts were named based on the water masses they separated and the vertical structure (Table 4) following Oey et al. (1987), Lee et al. (1991), Xie and Pietrafesa (1995), Govoni and Spach (1999), and Savidge (2002). The coastal front separated inner-shelf water from mid-shelf water (Fig. 1A). The mid-shelf front was a vertical front which separated less dense water masses on either side of the front (Fig. 1C). The outer-shelf front was a sloped front with warmer water overlaying cooler water (Fig. 1C). The outer-shelf front either separated mid-shelf water from outer-shelf water, or outer-shelf water from Gulf Stream water when the Gulf Stream front was imbedded in the front. The Gulf Stream front was a vertical front which separated shelf water from Gulf Stream water (Fig. 1A). The inner edge of warm Gulf Stream filament front separated eddies from shelf water masses (Fig. 1B). When Virginia coastal water (VCW) was present in Onslow Bay, the surface convergence front at the offshore extent of the VCW was termed the Hatteras front (Fig. 1D).

1.2d Ichthyoplankton data processing

Ichthyoplankton samples were sorted and the larval fish identified to the lowest possible taxonomic level. One bongo net was processed for all stations from all the cruises. Larval abundance was expressed as the number of larvae per 1000 m^{-3} of water filtered. For some stations, both bongo nets were processed, and the larval abundances for the two nets were added together. A maximum of 20 individuals of Atlantic menhaden (*Brevoortia tyrannus*), round herring (*Etrumeus teres*), spot (*Leiostomus xanthurus*), Atlantic croaker (*Micropogonias undulates*), summer flounder (*Paralichthys dentatus*), and *Paralichthys albigutta / lethostigma* (either gulf flounder or southern flounder) from each net were measured to the nearest 0.1 mm body length (BL; Table 5). Frequency distributions of all BL for a given taxa were used to define three size classes, and abundances were calculated for each size class separately. The smallest size class was larvae in the first quartile (0 – 25 %) of the BL distribution, referred to as small larvae. The middle sized larvae were those in the 26 – 75 % BL distribution (medium larvae), and the largest size class were in the BL distribution > 75% (large larvae). BL was also averaged for each taxa, at each station. A weighting factor (W_{is}) was calculated for each individual larva measured at each station to minimize the bias associated with a large number of non-measured larvae (i.e., 20 of 600 larvae measured) and the variability in volume of water filtered for each sample. $W_{is} = (C_s / M_s) / V_s$, where W_{is} is the weight of a measured individual i in sample s, C_s is the total number of a taxa in sample s, M_s is the number of individuals of a taxa measured in sample s, and V_s is the volume of water filtered for sample s. Abundance of each size class for each taxa of larvae was then calculated for each station by summing the weights (W_{is}) for that station. Larval abundance of each size class for each transect was then standardized to mean of zero and a standard deviation of one. Finally, mean distance from shore (km) was calculated for each size class for each taxa on every transect by averaging station distances from shore, weighted by larval abundance.

1.2e Larval distribution patterns and the presence of fronts

Two analyses were used to determine whether larval distribution patterns change in the presence of fronts (Table 6). If fronts concentrate larval fish, the peak abundance of larvae should occur near the front, and the larvae would be spatially aggregated. Peak abundance for each taxa-size class on each transect was classified as at the front (occurring at a frontal station or a station inshore or offshore of the front) or not at the front (Fig. 6). Transects with a mid-shelf or outer-shelf front were examined separately. A Chi-square analysis ($p \leq 0.10$) was used to determine if the resulting 1 x 1 table for each front and size class was significantly different than random. The null hypothesis was peak abundance occurred at fronts.

Larvae could have also been spatially aggregated without the peak abundance occurring at fronts. Green's coefficient of dispersion (Haney and McGillivary, 1985), a measure of the degree of spatial aggregation, was calculated on larval abundances for each taxa-size class for each transect. Values for Green's coefficient range from 0 to 1, where 0 = random dispersion and 1 = maximum aggregation. Separate ANOVAs were conducted on Green's coefficient (GC) for each taxa and size class, with the independent variable based on the presence / absence of fronts (Table 6). The analyses tested mid-shelf front present ($n = 5$) versus absent ($n = 22$), outer-shelf front present ($n = 9$) versus absent ($n = 18$), and warm filament front present ($n = 3$) versus absent ($n = 24$). The null hypothesis was the distributions were aggregated when fronts were present. Differences in GC, with or with out the presence of a front, were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$).

1.2f Water mass specific larval distribution patterns and the presence of fronts

Larval abundance and size in relation to water masses and the presence of fronts was evaluated to determine if water mass specific larval distribution patterns changed with the presence of fronts. Two-way ANOVAs, with an interaction term, were used to analyze the data with all water masses and presence / absence of the mid-shelf, outer-shelf, and warm filament fronts as the independent variables (Table 6). Standardized larval abundance data for each taxa-size class and mean BL of each taxa in each water mass were the dependent variables (Table 6). Standardized larval abundance was used to minimize the possibility that a large concentration of larvae from a single transect would over influence the analysis. The mid-shelf, outer-shelf, and warm filament fronts were analyzed separately and the interaction between water mass and presence / absence of a front indicated whether larval abundance or size distributions changed when fronts were present. The null hypotheses were there were differences in larval abundance or mean BL among water masses with presence of fronts on the shelf. Differences in larval abundance and mean BL, with or with out the presence of a front, were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$).

1.2g Mean distance from shore of larvae and the presence of fronts

A one way ANOVA was used to determine if distance from shore changed when fronts were present on the shelf. Weighted mean distance from shore for each taxa-size class was the dependent variable and front category was the independent variable (Table 6). The mid-shelf, outer-shelf, and warm filament fronts were analyzed separately. The null hypothesis was mean distance from shore decreased with the presence of fronts. Differences among mean distance from shore, with or with out the presence of a front, were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$).

1.2h Average larval cross-shelf distribution

Average cross-shelf patterns were described by examining larval abundance for each taxa-size class and mean BL among water masses. Patterns in abundance and size within water masses provided an overall average distribution to compare with distributions when fronts were present on the shelf. Two-way ANOVAs were used to analyze the data with season and water mass as the independent variables (Table 6). The dependent variables, larval abundance and mean BL, were used to determine if larvae of certain size classes were associated with specific water masses. Larval abundance was $\log_{10}$ transformed (larvae per 1000 m^{-3} + 1) to achieve variance homogeneity (Box et al. 1978). The null hypotheses were that there were no differences in larval abundance or BL among seasons (December, January and February) or water masses. Differences in larval abundance and mean BL among seasons and water mass were detected a *posteriori* using Scheffé's S procedure, derived from the F distribution ($p \leq 0.05$).

1.3 Results

1.3a Description of fronts and water masses

Fronts were common on the North Carolina shelf, occurring on 23 of the 27 transects (Table 4). The coastal front (n = 16 of 27) was the most common, and the other fronts occurred less frequently: mid-shelf front (n = 5 of 27), outer-shelf front (n = 9 of 27), Gulf Stream front (n = 6 of 27), warm filament front (n = 3 of 27), and Hatteras front (n = 2 of 27). The coastal, mid-shelf, and Hatteras fronts occurred in the same general location, varying less than 13 km from their mean distance from shore (Table 4). The outer-shelf, Gulf Stream, and warm filament fronts were more variable in their mean distance from shore, especially in January and February (Table 4).

In general, average water column temperature, salinity, stratification, and SST increased from inshore to offshore and density decreased (Table 7; Fig. 7). Average water column salinity was lower for both the inner-shelf and mid-shelf water masses in January and February (Table 7). Overlap in inner-shelf and mid-shelf water masses was more frequent in December (Fig. 7) when coastal fronts were more sloped (see Appendix A). The filament water mass had the largest variation in water temperature, overlapping the Gulf Stream and the outer-shelf water masses (Fig. 7). The lowest water column temperature, salinity, density, and SST occurred when VCW was present on the shelf (Table 7).

1.3b Larval distribution patterns and the presence of fronts

Peak larval abundance rarely occurred at frontal stations on the North Carolina shelf. Of the 18 taxa-size class combinations, only medium size summer flounder larvae were more abundant at the mid-shelf front and only medium sized spot were more abundant at the outer-shelf front (Table 8). On the other hand, of these 18 possible combinations two taxa-size classes were more abundant at stations not adjacent to the mid-shelf front and six taxa-size classes were more abundant at stations not adjacent to the outer-shelf front. Based on this analysis there is little evidence in support of the hypothesis that larvae are more abundant at fronts.

Larvae were also not spatially aggregated when the mid-shelf, outer-shelf, or warm filament fronts were present on the shelf (Table 9). Using Green's coefficient as a measure of aggregation, none of the 18 taxa-size classes were significant aggregated when fronts were present on the shelf. The only significant result was that small round herring were significantly aggregated in the absence of the mid-shelf front. Therefore, larvae do not appear to aggregate at the mid-shelf, outer-shelf, or warm filament fronts.

1.3c Water mass specific larval distribution patterns and the presence of fronts

There were a few significant interactions between the presence of fronts and the abundance and size distributions of larvae in specific water mass. Distributions changed with the presence of the mid-shelf front (Table 10), warm filament front (Table 10), and Hatteras front (Appendix B). Of the 18 taxa-size class combinations, the water mass abundance of only two was significantly different with the occurrence of the mid-shelf front (Table 10). Standardized larval abundance of medium sized Atlantic menhaden was greater in the mid-shelf water masses when the mid-shelf front was present (Fig. 8B) and medium sized round herring were less abundant in Gulf Stream water when the mid-shelf front was present (Fig 9B).

Water mass abundance of one of the 18 taxa-size classes was different when a warm filament front was present on the shelf (Table 10). Large Atlantic menhaden were more abundant in the outer-shelf water mass when a warm filament front occurred (Fig. 10C).

Standardized larval abundance decreased for all three size classes of Atlantic menhaden in inner-shelf water (Fig. 10A-C), but the change was not statistically significant.

Of the three fronts analyzed, mean BL in specific water masses was only different when the mid-shelf front was present on the shelf. Two of six taxa had significant interactions between the presence of the mid-shelf front and size distribution of larvae in specific water masses (Table 11). Mean BL of Atlantic menhaden larvae was larger in inner-shelf water and smaller in outer-shelf water when a mid-shelf front was present on the shelf (Fig. 8D). Larval spot mean BL was larger in inner-shelf, mid-shelf, and Gulf Stream waters when a mid-shelf front was present (Fig. 11D).

Two water masses (VCW inner-shelf and VCW mid-shelf) were only present when the Hatteras front was present on the shelf. For all taxa except summer flounder, mean abundance and size were not significantly different in VCW water masses than resident Onslow Bay water masses (see Appendix B, Figs. B1 – B6). However, all three size classes of summer flounder were more abundant in the VCW mid-shelf water mass (see Appendix B, Fig. B5).

The analyses of the interaction between the presence of fronts and the abundance and size distribution of larvae in specific water mass support the hypotheses that both abundance and size within water masses change with the presence of fronts on the shelf. Specifically, abundance and size of four taxa was different when the mid-shelf, warm filament, and Hatteras fronts were present on the shelf.

1.3d Mean distance from shore of larvae and with the presence of fronts

Mean distance from shore of larvae was different when two types of fronts were present on the North Carolina shelf. Five of 54 taxa-size class combinations / front interactions were significantly different when the outer-shelf and warm filament fronts were present (Table 12). When the outer-shelf front was present, medium sized Atlantic menhaden larvae were closer to shore (Fig. 12B). Three taxa-size classes were further from shore when a warm filament front was on the shelf, large Atlantic menhaden (Fig. 13C) and medium and large *Paralichthys albigutta* / *lethostigma* (Fig 13B and C). On the other hand, large round herring larvae were closer to shore when a filament front was present on the shelf (Fig. 13C). Consequently, taxa-specific patterns indicate mean distance from shore decreases with the presence of some fronts and increases for others.

1.3e Average larval cross-shelf distribution

Average larval abundance and size distributions in Onslow Bay, North Carolina varied among season and water mass. Three seasonal patterns in larval abundance occurred. Atlantic croaker and *Paralichthys albigutta* / *lethostigma* were more abundant earlier in the sample season, with December abundances greater than January and February (Table 13). Round herring, spot, and summer flounder were more abundant later in the season (Table 13), while abundance of Atlantic menhaden varied with size. Small sized Atlantic menhaden were more abundant in December, and large larvae were more abundant in January and February (Table 13). Larval size for all taxa was greatest in January and February (Table 14), probably due to spawning beginning earlier in the year than December.

Taxa-specific distribution patterns in larval abundance of size classes and mean BL among seasons and water masses indicated patterns likely related to larval transport processes (including fronts), as well as, spawning location of adults and location of juvenile nursery habitat (estuarine and shelf). Taxa-specific patterns and potential effects of fronts are described below.

1.3f Atlantic menhaden average cross-shelf distribution

Atlantic menhaden average distribution exhibited a cross-shelf pattern of outer-shelf spawning to estuarine ingress. Water mass specific abundance and size distributions and mean distance from shore were affected by the outer-shelf front, mid-shelf front, and warm filament front (Table 15). Mean BL was smallest in the Gulf Stream and increased steadily to the largest mean BL in the inner-shelf water mass (Table 14; Appendix B, Fig. B1), indicating spawning probably occurred primarily in outer-shelf water masses. However, small size class larvae were common across the shelf, with no significant cross-shelf abundance pattern (Table 13), suggesting spawning occurred in several water masses. Medium sized larvae were most abundant in the outer-shelf and mid-shelf water masses, and large in the mid-shelf (Table 13). Mean distance from shore of medium sized larvae decreased when the outer-shelf front was present (Fig. 12B) indicating larvae were probably transported onshore in the propagating outer-shelf front. Changes in water mass specific abundance and mean BL when the mid-shelf front was present (Figs. 8B and 8D) may also have been an indication of onshore transport by the outer-shelf front, since the mid-shelf front is the result of outer-shelf frontal genesis. Another possibility was the mid-shelf front acted as a barrier to larval exchange, limiting movement of larvae between water masses.

Similarly, warm filament fronts possibly act as a barrier to cross-shelf exchange or a mixing event (Figs. 13C), due either to restriction of cross-shelf exchange or mixing of water masses onshore.

1.3g Round herring average cross-shelf distribution

Distribution of round herring larvae was indicative of outer-shelf spawning and shelf nursery habitat use. The mid-shelf front affecteded the spatial and abundance distributions and the warm filament front influenced mean distance from shore of larval round herring (Table 15). The location of small larvae and mean BL indicated round herring spawning occurred predominately in the Gulf Stream water mass (Table 13 and 14; Appendix B, Fig. B2). Medium and large larvae were most abundant and mean BL was highest in the outer-shelf water mass (Table 13 and 14). The spatial distribution of small round herring larvae was more dispersed when the mid-shelf front was present (Table 9), an indication of cross-shelf exchange. Onshore movement of small larval round herring may have occurred as a result of outer-frontal genesis, and was indicated by lower abundance in Gulf Stream waters when the mid-shelf front was present (Fig. 9B). Large larval round herring may also have been advected onshore by warm filament fronts (Fig. 13C) or the front could have been a barrier to cross-shelf movement, limiting offshore movement of larger larvae.

1.3h Spot average cross-shelf distribution

The average distribution pattern of spot larvae was typical of offshore-spawned estuarine-dependent species, and was influenced by the outer-shelf front and mid-shelf front (Table 15). Mean BL increased from offshore to inshore (Table 14; Appendix B, Fig. B3), and spawning occurred predominately in outer-shelf and Gulf Stream water masses. Small larvae were more abundant in Gulf Stream and outer-shelf waters, medium in the outer-shelf water mass, and large in the mid-shelf water mass. Peak abundance of medium sized spot larvae was more frequent at the outer-shelf front than chance (Table 8); however, the front occurred in the same water mass in which the larvae were most abundant (Table 13). Mean spot BL was greater in three water masses when the mid-shelf front was present (Fig. 11D), an indication larvae may have been advected offshore during outer-shelf frontal genesis or the mid-shelf front acted as a barrier to cross-shelf exchange.

1.3i Atlantic croaker average cross-shelf distribution

Atlantic croaker average distribution was similar to the other estuarine-dependent species, but was not influenced by fronts (Table 15). Mean BL increased from offshore to inshore, though abundance of small larvae was similar across the shelf (Table 14; Appendix B, Fig. B4) suggesting spawning occurred in several water masses. Medium sized Atlantic croaker were more abundant in outer-shelf water and large larvae were more abundant in the mid-shelf water mass (Table 13).

1.3j Summer flounder average cross-shelf distribution

Average larval distributions of summer flounder varied with size class and the presence of the Hatteras and mid-shelf fronts (Table 15). There were no significant differences in summer flounder mean BL or abundance of small larvae among resident Onslow Bay water masses (Table 13 and 14; Appendix B, Fig. B5). Abundance of medium sized larvae was highest in mid-shelf and outer-shelf water masses (Table 13). Large larvae were more abundant in the mid-shelf water mass (Table 14). When the Hatteras front was present in Onslow Bay, overall abundance of small, medium, and large summer flounder larvae either increased or larvae were concentrated in the VCW mid-shelf water mass (Table 14; Appendix B, Fig. B5). Medium sized summer flounder peak abundance was more frequent at the mid-shelf front (Table 8). However, the mid-shelf front separated the two water masses with the highest abundances of larvae (Table 14).

1.3k *Paralichthys albigutta / lethostigma* average cross-shelf distribution

Average distributions of *Paralichthys albigutta / lethostigma* were broadly distributed across the shelf and affected by the warm filament front (Table 15). *Paralichthys a* / *l* spawning probably occurred mainly in outer-shelf and Gulf Stream water masses, where mean BL was smallest (Table 14; Appendix B, Fig. B6). Abundance among water masses of small and medium sized larvae was not different (Table 13). Large *Paralichthys a* / *l* larvae were more abundant in inner-shelf and mid-shelf water (Table 13). The warm filament front either mixed medium and large *Paralichthys a* / *l* offshore or acted as a barrier to cross-shelf exchange (Figs. 13B and 13C).

1.4 Discussion

1.4a Larval distribution patterns and the presence of fronts

Larval abundance and size distributions of five estuarine-dependent taxa and one continental shelf taxa were affected by fronts on the shelf off North Carolina. Taxa-size class specific evidence was correlative, and not overwhelming. However, abundance, size, or mean distance from shore of at least one taxa-size class was significantly different when the outer-shelf front, mid-shelf front, warm filament front, or Hatteras front were present (Table 15). The effect of fronts was both species and size specific and the physical mechanisms which led to frontal genesis of the transient fronts; outer-shelf front, mid-shelf front, warm filament front, and Hatteras front resulted in larval transport or larval exchange among water masses.

Comparison of larval distribution patterns when fronts were present and absent indicated most species-size classes were not aggregated at the fronts. Medium sized spot and summer flounder peak abundance occurred more frequently at the outer-shelf and mid-shelf front respectively (Table 15). However, those results may be correlative, resulting from the overlap of species specific water mass associations and locations of where the fronts occur on the shelf. Convergent zones at persistent fronts like river plumes (Govoni and Grimes 1992), edges of boundary currents (Govoni et al. 2000), and shelf break fronts (Lochmann et al. 1997, Munk 2002, Gonzalez-Quiros et al. 2004) frequently aggregate larval fish. Transient fronts, which are the result of wind or baroclinic forcing, often do not aggregate larvae (Reiss and McConaugha 1999). Regardless, larvae do not have to be aggregated by a front to be transported across the shelf (Reiss and McConaugha 1999, Helfrich and Pineda 2003).

Larvae of most species-size classes were more abundant in specific water masses, consistent with the results of previous studies from the U.S. east coast (Cowen et al. 1993, Grothues and Cowen 1999, Reiss and McConaugha 1999, Hare et al. 2001, Marancik et al. 2005). Mixing of larval assemblages among different faunal regions (Grothues and Cowen 1999) and shelf and oceanic waters (Cowen et al. 1993, Hare et al. 2001) may be used to determine larval transport along the U.S. east coast. Smaller scale cross-shelf larval assemblages also occur, and can be used to examine potential cross-shelf larval transport mechanisms (Reiss and McConaugha 1999, Marancik et al. 2005). Atlantic menhaden, spot, and Atlantic croaker had typical cross-shelf patterns (Tables 13 and 14) of shelf spawned estuarine-dependent species; outer-shelf spawning to estuarine ingress, and may be used examine the effects of fronts on cross-shelf larval transport.

Water mass specific abundance and size of Atlantic menhaden, round herring, spot, and summer flounder varied between the presence / absence of the mid-shelf front, warm filament front, and Hatteras front (Table 15). Water masses associated with persistent fronts often have higher abundances of larvae, and when the fronts are disrupted by mixing forces, larvae are often dispersed (Munk et al. 1999, Lee et al. 2005). The presence of transient fronts on the North Carolina shelf probably indicates larval exchange among water masses is occurring or has recently occurred (Dempster et al. 1997).

The change in mean distance from shore with the presence / absence of fronts was the most direct measure of fronts being a possible cross-shelf transport mechanism. Medium sized Atlantic menhaden were closer to shore when the outer-shelf front was present on the shelf (Table 15), corroborating the propagating front as a cross-shelf transport mechanism (Checkley et al. 1988). Atlantic menhaden and *Paralichthys albigutta / lethostigma* were further from shore, and round herring were closer when the warm filament front was present (Table 15), indicating meandering of the western wall of the Gulf Stream may either directly transport larvae onshore and offshore or larvae may be exchanged in cross-frontal mixing of water masses (Bower and Rossby 1989, Govoni and Pietrafesa 1994, Govoni and Spach 1999). Direct and correlative measures of onshore larval transport have been shown for both propagating fronts (Kingsford 1990, Checkley et al. 1988) and mesoscale eddies (Sponaugle et al. 2005). Offshore transport away from juvenile nursery habitats, due to mixing of water masses, also occurs due to both types of fronts (Hare and Cowen 1991, Govoni and Spach 1999, Reiss and McConaugha 1999, Hare et al. 2002). Thus, species-specific patterns exist for cross-shelf transport for both the outer-shelf front and warm filament front. The outer-shelf front transported larval Atlantic menhaden closer to shore, and potential ingress to estuarine juvenile nursery habitats. Whereas, the warm filament front potentially transported Atlantic menhaden (offshore), *Paralichthys albigutta / lethostigma* (offshore), and round herring (onshore) away from juvenile habitats.

1.4b Cross-shelf larval distribution and transport

Larval size distributions of Atlantic menhaden, spot, and Atlantic croaker were similar to previous results (Warlen 1982, Warlen and Chester 1985, Warlen 1992) which led to the conclusion that larval transport was predominately a cross-shelf process (Miller et al. 1984). Smaller larvae of fall / winter spawning, estuarine-dependent species were more abundant offshore, and size increased with decreased distance from shore. However, the increase in size with a decrease in distance from shore of larvae could be the result of cross-shelf differences of other factors including; spawning, growth, and predation.

Variation in cross-shelf spawning location during the season could lead to an increase from offshore to onshore in larval size. If adults begin spawning near-shore, and continue to spawn and move offshore during the winter, a similar cross-shelf pattern could result with no cross-shelf movement of larvae. Information on cross-shelf spawning locations of fall / winter spawning, estuarine-dependent species is limited for the southeast U.S. shelf. Based on the location of eggs, Atlantic menhaden spawning is reported to occur in primarily on the mid-shelf (20 – 60 m water depth) during the winter on the North Carolina shelf (Checkley et al. 1999). Offshore winter spawning is also inferred for spot and Atlantic croaker, based on collections of small (recently hatched) larvae (Govoni 1993, Able and Fahay 1998). A fall to winter offshore movement in spawning location of Atlantic menhaden and spot could be interpreted for off the coast of Georgia due to the distribution of small larvae, though cross-shelf larval transport could not be ruled out (Marancik et al. 2005).

Cross-shelf differences in larval growth and predation could also result in cross-shelf differences of size that may be interpreted as cross-shelf larval transport. However, even less is known about larval growth and predation rates on the southeast U.S. shelf than spawning. Nevertheless, larval transport may still be an important factor in the cross-shelf pattern. Data from the 27 cruises occurred during the winter, when changes in cross-shelf spawning location may be limited; and the data was averaged over nine years, potentially averaging out differences in growth and predation rates on the shelf.

1.4c Conceptual model of the effect of the outer-shelf and mid-shelf fronts

The outer-shelf and mid-shelf fronts affect larval transport and water mass exchange on the southeast U.S. shelf. Physical processes that cause the outer-shelf front result in cross-shelf transport of larvae (Checkley et al. 1988), and the formation of a mid-shelf as a result of outer-shelf frontal genesis results in larval exchange among water masses. Circulation of the outer-shelf front advects warm, salty outer-shelf and Gulf Stream surface water shoreward and southward, and the colder mid-shelf water mass is advected seaward and northward (Oey 1986, Oey et al. 1987, Xie and Pietrafesa 1995, Checkley et al. 1988). Larval fish are advected onshore and offshore, depending on water mass in which they reside. Atlantic menhaden were closer to shore when the outer-shelf front was present on the shelf. During winter months, a mid-shelf front can form when the warm, salty outer-shelf and Gulf Stream water masses are cooled at the surface and sink to the bottom (Xie and Pietrafesa 1995, Checkley et al. 1988). As a result, the offshore water masses mix with shelf water and larval exchange occurs. Thus, when the mid-shelf front was present; Atlantic menhaden were more abundant in mid-shelf water masses, and larval size decreased offshore and increased inshore, round herring abundance decreased in the Gulf Stream water mass, and average size of spot increased in inner-shelf, mid-shelf, and the Gulf Stream waster masses. At the end of outer-shelf frontal genesis, a fully developed mid-shelf front may act as a barrier to larval exchange due to the surface convergence and bottom divergent current flow of the mid-shelf front (Oey 1986, Oey et al. 1987, Checkley et al. 1988).

Vertical distribution of larvae is an important component of cross-shelf transport; larvae at different depths are transported at different rates, and even different directions (Reiss and McConaugha 1999, Sponaugle et al. 2002, Paris and Cowen 2004, Hare and Govoni 2005). During outer-shelf front onshore propagation, surface water is transported onshore and bottom water offshore (Checkley et al. 1988, Xie and Pietrafesa 1996). Therefore, surface oriented larvae such as the clupeids Atlantic menhaden and round herring (Hoss and Burke 2002, Hare and Govoni 2005) should be transported onshore and deeper species like spot (Hare and Govoni 2005) should be transported offshore. Therefore, spot larvae could be transported offshore and Atlantic menhaden and round herring onshore during outer-shelf frontal genesis.

Evidence for the outer-shelf front transporting Atlantic menhaden onshore was found. If the results found during the presence of the mid-shelf front are assumed to occur because of outer-shelf frontal genesis, round herring larvae were also transported onshore, though differences in diel vertical migration probably result in estuarine ingress of Atlantic menhaden and shelf residence of round herring (Hoss and Burke 2002). In contrast, spot larvae may have been transported offshore, as indicated by the increase in mean size of spot in three water masses. Hare and Govoni (2005) found that the center of mass of larval distributions on the North Carolina shelf varied among species groups and potentially influences cross-shelf larval transport direction; Atlantic menhaden were significantly higher in the water column, exported shelf species next highest, and other estuarine-dependent species (including; spot, Atlantic croaker, and *Paralichthys* spp.) lowest in the water column. Variation in cross-shelf transport of larvae fish also occurred in water masses off the mouth of Chesapeake Bay, where near-shore larvae in the surface water were transported offshore, and distributions of shelf species were dispersed across the shelf, during upwelling wind events (Reiss and McConaugha 1999). Thus, species-specific patterns of vertical distribution result in different cross-shelf transport mechanisms and water mass exchange during mixing events on the southeast U.S. shelf.

Differences in water mass specific abundance and size with the presence of the mid-shelf front may have been the result of water mass exchange due to outer-shelf frontal genesis or the mid-shelf front acting as a barrier, limiting cross-shelf movement of larvae. Unfortunately, the original ichthyoplankton sampling was not designed to look at effects of fronts on larval distributions. Fronts were not specifically targeted and vertically discreet ichthyoplankton samples were not collected. Therefore, it is not possible to determine whether larval distributions that occurred during the presence of the mid-shelf front were the result of cross-shelf transport or specific frontal properties of the mid-shelf front. The mid-shelf front could act as a barrier for estuarine-dependent species, unfavorably restricting onshore transport or favorably limiting offshore advection. Compounding the difficulty was the fact that multiple events occurred at the same time, and the presence of an existing mid-shelf front may affect the cross-shelf propagation of an outer-shelf front. Future research should target both the outer-shelf and mid-shelf fronts and describe the mechanisms affecting larval distributions for both. Concurrent horizontal current flow measurements and vertically discreet ichthyoplankton samples across frontal features would allow for estimations of onshore / offshore larval transport rates, determine whether the mid-shelf front limits these movements, and determine species-specific differences in larval transport.

1.4d Conceptual model of the effect of the warm filament front

The warm Gulf Stream filament front stirs the shelf, and disperses larvae in both directions across the shelf via either direct transport or water mass mixing (Govoni 1993, Govoni and Pietrafesa 1994). The largest size classes of three species were advected further from preferred locations. The two estuarine-dependent taxa, Atlantic menhaden and *Paralichthys albigutta / lethostigma*, were further from shore when the filament was present. While the shelf species, round herring, were closer to shore. Round herring could be transported onshore, as the leading edge of the warm filament front moves onshore (Lee et al. 1991). The estuarine-dependent species may be entrained in offshore water masses during cross-frontal mixing (Bowers and Rossby 1989). Stegmann and Yoder (1996) theorized that warm filament fronts may transport Atlantic menhaden onshore. However, current results indicate the cross-shelf transport mechanism may be more complicated. Warm filament fronts may have an adverse affect on some estuarine-dependent species, resulting in a loss from the southeast U.S. shelf to the northeast U.S. Shelf in Gulf Stream water (Hare and Cowen 1991, Hare et al. 2002) or increasing the residence time on the shelf.

The ability to infer effects of the warm filament front on larval fish distributions was limited because only a single cross-shelf transect was sampled, and warm filament fronts affect shelf water masses in both the cross-shelf and along-shelf directions (Bowers and Rossby 1989, Lee et al. 1991, Govoni and Spach 1999). Thus, future attempts to determine the mechanisms how warm filament fronts affect larval distributions should examine multiple cross-shelf transects which bisect the front. With multiple transects, analyses investigate cross-shelf and along-shelf transport; and examine both potential mechanisms of cross-shelf transport, onshore movement in the filaments and water mass exchange in the eddy.

1.4e Conceptual model of the effect of the Hatteras front

Most species were not significantly affected by the Hatteras front when it occurred on the North Carolina shelf in February. However, the front may have transported summer flounder larvae from the northeast U.S. shelf to the southeast U.S. shelf, around Cape Hatteras. The other possibility is that summer flounder were more concentrated when the Hatteras front was on the shelf. The Hatteras front is pushed south past Cape Hatteras several (2 -8) times a year, primarily during the winter (October – March) by northeast winds (Stegmann and Yoder 1996, Savidge 2002). During other months the front resides north of Cape Hatteras (Savidge 2002). Whether the front reaches into Onslow Bay depends on the strength and duration of winds (Stegmann and Yoder 1996, Savidge 2002). The width and distance from shore of the intrusion is affected by the distance from shore of the Gulf Stream

(Stegmann and Yoder 1996, Savidge 2002), decreasing in size and distance from the coast with decreasing distance from shore off the Gulf Stream (Savidge 2002). Onshore current flow is associated with the passage of the Hatteras front (Savidge 2002), potentially aiding onshore transport of larvae. As long as larvae are present in water masses on the northeast shelf, transport to the south and onshore could occur. Summer flounder larval distributions on the northeast U.S. shelf indicate spawning during the winter occurs mainly on the southern outer-shelf, just north of Cape Hatteras (Able and Fahay 1998). Hatteras fronts have been theorized to transport Atlantic menhaden south from the northeast shelf (Stegmann and Yoder 1996, Quinlan et al. 1999); however there was probably no Atlantic menhaden spawning north of Cape Hatteras in February (Quinlan et al. 1999), but current results add evidence that the north to south mechanism may work.

Evidence of cross-shelf transport in association with the Hatteras front was not found. However, the front consists of a vertically stratified water column with Virginia coastal water overlaying resident water mass, and current ichthyoplankton samples integrated the entire water column. In the future, vertically stratified sampling would allow more detailed analysis of cross-shelf transport mechanisms.

1.4f Conclusions

Fronts are important factors affecting larval distributions on the southeast U.S. shelf. Both species- and front-specific effects occurred (Kingsford 1990), with evidence for larval retention, cross-shelf transport, offshore advection, and potential supply of new recruits. No mechanisms of how fronts affected larval fish were found during this study. However, results from this research should aid in the design of future research. Future correlative and process-oriented studies of cross-shelf transport mechanisms will need to consider the vertical distributions of species and changes in ontogenetic stage (size) of larvae.

Average cross-shelf distributions of several species and the results of previous studies led to the conclusion that cross-shelf larval transport was predominately driven by seasonal circulation patterns. In addition, my results verify that episodic events, such as fronts modify seasonal transport pathways. Fronts may be aiding in cross-shelf transport or affecting larval exchange among water masses. For fronts to transport larvae across the shelf, the fronts themselves must move (Kingsford 1990). Both the outer-shelf and warm filament fronts moved across the shelf, potentially transporting larvae across the shelf. Variations in water mass specific larval size and abundance concurrent with the presence of the mid-shelf front, warm filament front, and Hatteras front indicated water mass exchange by these fronts as a potential modification of the seasonal transport pathway.

Table 1. Ichthyoplankton and hydrographic sampling information for the New River transect which bisects Onslow Bay, North Carolina (Fig. 2). Ichthyoplankton was collected in oblique tows using a 60 cm bongo net fitted with 333 μm mesh nets. Hydrographic data was collected using a conductivity, temperature, and depth (CTD) probe. When available, sea surface temperature (SST) was derived from advanced very high-resolution radar satellite images.

Date(s)			Number of Stations	Transect distance (km) Min	Max	Range	Hydrographic data
1990	January	30	8	7	109	102	CTD
1991	February	7	9	6	132	126	CTD
	December	18-19	7	38	127	88	CTD
1992	January	11-12	11	6	161	155	CTD
	December	20-21	14	7	125	118	CTD
1993	February	11-12	12	6	107	100	CTD
		13-14	14	9	125	116	CTD
		17-18	14	7	125	118	CTD
	December	7-8	14	7	125	118	CTD
1994	January	18	11	7	97	90	SST
	February	1-2	14	7	125	118	CTD
	December	6-7	14	7	125	118	SST
		13	14	7	124	117	CTD
1995	February	7	12	7	107	99	SST
	December	5-6	11	7	99	91	CTD
		7-8	11	8	98	90	CTD
		9-10	11	7	98	90	CTD
		12-13	14	7	125	117	CTD
		18-19	13	7	117	109	CTD
1996	January	30-31	10	7	89	81	CTD
	February	1-2	10	7	89	82	CTD
		3-4	8	7	71	63	CTD
		15-16	6	17	107	90	SST
1998	February	19	8	7	116	109	CTD
		25-26	8	7	116	109	CTD
1999	January	18-19	8	7	135	128	SST
		28-29	6	25	116	91	SST

Table 2. Definition of water masses in Onslow Bay, North Carolina was based primarily on seasonal surface water temperature, surface salinity, and presence of fronts on the shelf.

Water mass	Surface water temperature (^{o}C)		Surface salinity	Presence of front
	December	January - February		
inner-shelf	< 15.5	< 12.5	< 36	
mid-shelf	> 13.0 and < 20.0	> 11.0 and < 16.0		
outer-shelf	> 17.0 and < 23.0	> 15.0 and < 22.0	> 36	
Gulf Stream	> 22.5	> 21.5	> 36	
warm filament			> 36	Gulf Stream filament present
VCW inner-shelf			< 31	Hatteras front present
VCW mid-shelf			> 31 and < 33	Hatteras front present

Table 3. Mean (standard deviation) difference of surface water temperature (°C), salinity, density (σ_t, $kg \cdot m^{-3}$), and sea surface temperature (SST, °C) between adjacent sample stations from the New River transect off the coast of North Carolina for December, January, and February 1990-1999. Stations either coincided with a front or not (none). SST data were corrected from advanced very high-resolution radar satellite images.

Front	Temperature (°C)	Salinity	Density (σ_t)	SST (°C)
none	0.08 (0.07)	0.009 (0.023)	-0.011 (0.025)	0.10 (0.07)
coastal	0.22 (0.07)	0.074 (0.036)	0.012 (0.037)	0.25 (0.12)
mid-shelf	0.30 (0.05)	0.120 (0.031)	0.023 (0.013)	0.14 (0.05)
outer-shelf	0.29 (0.07)	0.006 (0.023)	-0.070 (0.017)	0.11 (0.09)
filament	0.48 (0.47)	0.007 (0.057)	-0.104 (0.057)	0.09 (0.07)
Gulf Stream	0.20 (0.16)	0.002 (0.005)	-0.054 (0.043)	0.08 (0.04)
Hatteras	0.55 (0.15)	0.236 (0.070)	0.054 (0.016)	0.28 (0.11)

Table 4. Number (n), mean distance from shore (standard deviation), water column water temperature (°C), salinity, density (σ_t, $kg \cdot m^{-3}$), stratification (Φ, $joules \cdot m^{-3}$), and sea surface temperature (SST, °C) for six fronts observed on the New River transect off the coast of North Carolina from December, January, and February 1990-1999. SST data were corrected from advanced very high-resolution radar satellite images.

Month	Front	n	Distance from shore (km)	Temperature (°C)	Salinity	Density (σ_t)	Stratification (Φ)	SST (°C)
December	coastal	7	17.9 (3.4)	15.1 (1.6)	35.63 (0.29)	26.46 (0.28)	1.0 (1.9)	16.4 (3.4)
	mid-shelf	2	43.4 (12.2)	18.5 (0.9)	36.43	26.43	4.5	20.4 (1.4)
	outer-shelf	3	67.4 (4.6)	20.7 (1.1)	36.06 (0.20)	25.40 (0.40)	16.1 (3.9)	21.9 (3.3)
	filament	1	51.2	19.0	35.78	25.62	0.1	21.4
	Gulf Stream	2	79.2 (13.2)	22.5 (1.4)	36.28 (0.04)	25.05 (0.36)	8.4 (1.8)	24.0 (0.7)
	Hatteras							
January-February	coastal	9	20.2 (6.8)	12.7 (1.3)	35.37 (0.94)	26.75 (0.70)	1.6 (3.1)	13.3 (2.3)
	mid-shelf	3	55.5 (10.6)	17.6 (0.6)	35.96 (0.11)	26.13 (0.19)	0.4 (0.2)	17.9 (1.0)
	outer-shelf	6	67.6 (23.1)	19.2 (2.8)	36.25 (0.09)	25.91 (0.80)	20.7 (12.5)	19.3 (1.8)
	filament	2	53.6 (40.1)	19.7 (0.9)	36.05 (0.04)	25.66 (0.21)	1.6 (2.6)	16.8 (7.9)
	Gulf Stream	4	101.3 (20.9)	20.5 (1.8)	36.14 (0.14)	25.50 (0.42)	122.5 (154.1)	22.0 (1.6)
	Hatteras	2	115.8 (0.1)	19.6 (1.9)	36.02 (0.28)	25.67 (0.30)	106.2 (4.0)	19.3 (0.3)

Table 5. Total number of larvae collected and number of larvae measured for six taxa collected in oblique bongo tows on 27 cruises from the New River transect which bisects Onslow Bay, North Carolina (Fig. 2).

			Brevoortia tyrannus Atlantic menhaden		*Etrumeus teres* round herring		*Leiostomus xanthurus* spot		*Micropogonias undulatus* Atlantic croaker		*Paralichthys dentatus* summer flounder		*Paralichthys albigutta / lethostigma* gulf / southern flounder	
Date(s)			Total	Measured	Total	Measured	Total	Measured	Total	Measured	Total	Measured	Total	Measured
1990	January	30	349	64	14	14	100	75	8	8	5	5	1	1
1991	February	7	323	60	42	26	105	63	5	4	3	3	4	4
	December	18-19	7	7	38	35	89	39	69	34	5	5	2	2
1992	January	11-12	245	136	145	54	215	160	4	4	1	0	2	2
	December	20-21	538	130	23	22	177	137	11	10	14	14	3	3
1993	February	11-12	191	127	114	112	897	200	16	16	70	67	22	22
		13-14	46	44	29	25	571	137	26	26	112	105	21	20
		17-18	146	121	58	54	601	222	9	9	80	78	15	15
	December	7-8	536	216	11	11	45	45	65	63	15	7	108	108
1994	January	18	77	72	50	43	141	125	4	4	22	22	39	38
	February	1-2	2307	303	224	199	1049	215	54	53	99	99	72	70
	December	6-7	321	62	41	33	113	105	41	41	31	30	113	103
		13	186	72	39	34	325	172	52	51	32	31	140	129
1995	February	7	190	56	29	29	103	101	30	30	12	12	25	25
	December	5-6	192	35	0	0	14	13	5	4	1	1	13	13
		7-8	246	45	14	14	13	13	6	5	1	1	5	5
		9-10	305	70	7	7	10	10	16	14	1	1	7	7
		12-13	105	26	40	39	18	18	13	13	1	1	9	9
		18-19	42	41	11	11	133	55	18	18	0	0	10	10
1996	January	30-31	949	120	64	37	130	91	7	7	17	17	14	14
	February	1-2	530	103	115	66	103	75	0	0	20	20	17	17
		3-4	1084	100	13	11	33	33	4	4	22	22	15	15
		15-16	414	95	113	60	35	35	1	1	3	3	0	0
1998	February	19	34	29	17	17	14	14	1	1	76	56	5	5
		25-26	60	57	23	19	18	17	3	3	137	100	1	1
1999	January	18-19	87	54	39	36	135	73	1	1	33	27	21	21
		28-29	9	9	43	38	220	142	0	0	10	10	15	14
Total			9519	2254	1356	1046	5407	2385	469	424	823	737	699	673

Table 6. Seven analyses were conducted on larval abundance and length distributions to determine whether fronts on the continental shelf off North Carolina influence larval fish distributions and cross-shelf transport. The analyses done to address each objective are listed.

Objective	Variables		Statistic	Null hypothesis
	Dependent	Independent		
Determine whether larval distribution patterns were affected by the presence of fronts	Larval abundance - peak abundance in relation to fronts	at front versus not at front	Chi-square	peak abundance occurred at fronts
	Spatial aggregation - Green's coefficient	presence/absence of front	one way ANOVA	distributions aggregated when fronts present
Determine whether water mass specific larval distribution patterns change with the presence of fronts	Larval abundance - standardized larval abundance	water mass and presence/absence of front	two way ANOVA	larval abundance within water masses changes with the presence of fronts
	Larval size - mean body length (BL, mm)	water mass and presence/absence of front	two way ANOVA	larval size distribution within water masses changes with the presence of fronts
Determine if mean distance from shore of larvae changed with the presence of fronts	Mean distance from shore - weighted by larval abundance	presence/absence of front	one way ANOVA	mean distance from shore decreases with the presence of fronts
Determine "average" larval distribution patterns	Larval abundance - $\log_{10}$(abundance + 1)	season and water mass	two way ANOVA	no differences among seasons or water masses
	Larval size - mean body length (BL, mm)	season and water mass	two way ANOVA	no differences among seasons or water masses

Table 7. Mean (standard deviation) water column water temperature (°C), salinity, density (σ_t, $kg \cdot m^{-3}$), stratification (Φ), and sea surface temperature (SST, °C) for seven water masses defined on the New River transect off the coast of North Carolina from December, January, and February 1990-1999. SST data for each water mass were corrected from advanced very high-resolution radar satellite images. VCW = Virginia Coastal Water.

Month	Water mass	Temperature (°C)	Salinity	Density (σ_t)	Stratification (Φ)	SST (°C)
December	inner-shelf	13.3 (1.4)	35.25 (0.38)	26.55 (0.27)	0.7 (0.7)	13.9 (2.9)
	mid-shelf	16.0 (1.4)	35.85 (0.31)	26.43 (0.29)	3.5 (6.5)	17.4 (2.8)
	outer-shelf	19.9 (1.3)	36.21 (0.21)	25.70 (0.37)	4.8 (7.1)	21.0 (3.1)
	filament	21.1 (2.8)	35.94 (0.42)	25.11 (0.77)	134.5 (214.5)	24.2 (0.7)
	Gulf Stream	23.5 (1.0)	36.23 (0.12)	24.73 (0.27)	164.0 (300.7)	23.8 (2.1)
	VCW inner-shelf					
	VCW mid-shelf					
January-February	inner-shelf	10.2 (0.9)	34.66 (0.95)	26.68 (0.75)	1.0 (1.3)	10.3 (1.5)
	mid-shelf	13.6 (1.3)	35.54 (0.85)	26.70 (0.66)	2.2 (3.0)	14.7 (1.8)
	outer-shelf	18.3 (1.7)	36.16 (0.12)	26.11 (0.44)	13.8 (25.1)	19.3 (1.7)
	filament	20.0 (2.2)	36.15 (0.16)	25.64 (0.57)	80.4 (132.4)	19.9 (5.9)
	Gulf Stream	22.4 (1.3)	36.26 (0.10)	25.08 (0.44)	201.4 (205.8)	23.4 (1.1)
	VCW inner-shelf	10.3 (0.4)	30.08 (0.58)	23.09 (0.48)	11.8 (4.8)	11.5 (0.2)
	VCW mid-shelf	13.4 (1.5)	32.94 (1.12)	24.72 (0.58)	48.2 (13.7)	12.5 (1.6)

Table 8. Location of peak abundance of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Chi-square analysis was used to determine whether peak abundance for each taxa and size class of larvae occurred at fronts or not at fronts (*** = $p \leq 0.025$, ** = $p \leq 0.05$, * = $p \leq 0.10$).

		small larvae		medium larvae		large larvae	
Taxa	Front	at front	not at front	at front	not at front	at front	not at front
Atlantic menhaden	mid-shelf	3	2	2	3	0	5 **
	outer-shelf	4	4	3	6	1	8 ***
round herring	mid-shelf	0	5 **	1	4	3	2
	outer-shelf	3	5	3	5	3	2
spot	mid-shelf	2	3	2	3	1	3
	outer-shelf	3	6	7 *	2	4	2
Atlantic croaker	mid-shelf	2	2	4	1	3	2
	outer-shelf	2	2	0	6 ***	0	6 ***
summer flounder	mid-shelf	2	1	3 *	0	2	2
	outer-shelf	4	5	2	6	1	5
Paralichthys spp.	mid-shelf	1	3	2	3	1	4
	outer-shelf	0	5 *	2	7 *	2	7 *

Table 9. Mean (standard deviation) of Green's coefficient (GC) of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). A one-way ANOVA was used to determine if GC differed whether or not the mid-shelf, outer-shelf, or warm Gulf Stream filament was present (*** = p ≤ 0.001, ** = p ≤ 0.025, * = p ≤ 0.05).

		small larvae		medium larvae		large larvae	
Taxa	Front	present	absent	present	absent	present	absent
Atlantic menhaden	mid-shelf	0.44 (0.19)	0.62 (0.32)	0.31 (0.20)	0.36 (0.20)	0.72 (0.29)	0.51 (0.31)
	outer-shelf	0.57 (0.32)	0.59 (0.30)	0.40 (0.19)	0.33 (0.19)	0.45 (0.27)	0.60 (0.33)
	warm filament	0.48 (0.25)	0.60 (0.31)	0.23 (0.10)	0.37 (0.20)	0.78 (0.38)	0.52 (0.30)
round herring	mid-shelf	0.30 (0.17)	0.59 (0.30) *	0.30 (0.11)	0.41 (0.25)	0.55 (0.41)	0.70 (0.27)
	outer-shelf	0.49 (0.33)	0.55 (0.29)	0.45 (0.19)	0.35 (0.19)	0.51 (0.29)	0.72 (0.31)
	warm filament	0.48 (0.25)	0.53 (0.31)	0.31 (0.23)	0.39 (0.24)	0.61 (0.34)	0.67 (0.32)
spot	mid-shelf	0.48 (0.33)	0.39 (0.21)	0.46 (0.32)	0.41 (0.18)	0.43 (0.39)	0.50 (0.28)
	outer-shelf	0.31 (0.14)	0.46 (0.26)	0.39 (0.24)	0.43 (0.24)	0.40 (0.31)	0.52 (0.29)
	warm filament	0.26 (0.08)	0.43 (0.24)	0.49 (0.27)	0.41 (0.20)	0.72 (0.26)	0.44 (0.28)
Atlantic croaker	mid-shelf	0.71 (0.35)	0.53 (0.35)	0.48 (0.33)	0.53 (0.30)	0.31 (0.21)	0.65 (0.33)
	outer-shelf	0.40 (0.19)	0.64 (0.38)	0.53 (0.29)	0.51 (0.29)	0.61 (0.35)	0.54 (0.34)
	warm filament	0.34 (0.28)	0.64 (0.35)	0.63 (0.44)	0.50 (0.29)	0.48 (0.12)	0.57 (0.36)
summer flounder	mid-shelf	0.35 (0.21)	0.54 (0.34)	0.12 (0.04)	0.42 (0.30)	0.42 (0.40)	0.61 (0.37)
	outer-shelf	0.54 (0.28)	0.49 (0.37)	0.37 (0.31)	0.39 (0.31)	0.50 (0.43)	0.60 (0.36)
	warm filament	0.58 (0.59)	0.51 (0.31)	0.43 (0.33)	0.38 (0.30)	0.24	0.58 (0.38)
Paralichthys spp.	mid-shelf	0.58 (0.28)	0.38 (0.37)	0.59 (0.32)	0.48 (0.37)	0.38 (0.23)	0.52 (0.39)
	outer-shelf	0.36 (0.17)	0.50 (0.42)	0.47 (0.38)	0.53 (0.38)	0.53 (0.39)	0.46 (0.35)
	warm filament	0.10	0.47 (0.34)	0.59 (0.58)	0.50 (0.35)	0.72 (0.48)	0.45 (0.34)

Table 10. Results from a two-factor ANOVA (degrees of freedom (df), sums of squares (SS), mean square (MS)) examining the interaction of the presence of fronts and water mass on standardized larval abundance of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Three continental shelf fronts; mid-shelf (MSF), outer-shelf (OSF), and warm Gulf Stream filament (FIL) were classified as either present or absent and stations were separated into water masses (Table 5). The interaction between water mass and presence / absence of front indicated whether fronts affected larval abundance within water masses (*** = $p \leq 0.001$, ** = $p \leq 0.025$, and * = $p \leq 0.05$).

Taxa	Size class	Front	df	SS	MS	F	P < F
Atlantic menhaden	small (≤ 7.5 mm)	MSF	3	0.21233	0.0708	0.0813	
		OSF	3	1.9388	0.6463	0.7483	
		FIL	3	0.36457	0.1215	0.1397	
	medium (> 7.5 to ≤ 14.5 mm)	MSF	3	9.1703	3.0568	3.6759	**
		OSF	3	1.8528	0.6176	0.7201	
		FIL	3	2.5382	0.8461	0.9942	
	large (> 14.5 mm)	MSF	3	2.4687	0.8229	0.995	
		OSF	3	3.4072	1.1357	1.3791	
		FIL	3	9.6015	3.2005	4.0292	**
round herring	small (≤ 6.8 mm)	MSF	3	0.15147	0.0505	0.0621	
		OSF	3	0.71247	0.2375	0.293	
		FIL	3	0.62337	0.2078	0.2584	
	medium (> 6.8 to ≤ 16.3 mm)	MSF	3	6.5451	2.1817	2.971	*
		OSF	3	0.38678	0.1289	0.1703	
		FIL	3	0.88975	0.2966	0.3955	
	large (> 16.3 mm)	MSF	3	0.11211	0.0374	0.0496	
		OSF	3	2.601	0.867	1.1726	
		FIL	3	0.06993	0.0233	0.031	
spot	small (≤ 3.9 mm)	MSF	3	0.26034	0.0868	0.1054	
		OSF	3	0.62682	0.2089	0.2544	
		FIL	3	0.90042	0.3001	0.3695	
	medium (> 3.9 to ≤ 7.5 mm)	MSF	3	0.48327	0.1611	0.2179	
		OSF	3	0.88408	0.2947	0.3999	
		FIL	3	0.38508	0.1284	0.1736	
	large (> 7.5 mm)	MSF	3	1.209	0.403	0.4741	
		OSF	3	4.7061	1.5687	1.8874	
		FIL	3	1.8701	0.6234	0.7459	

Table 10. continued.

Taxa	Size class	Front	df	SS	MS	F	P < F
Atlantic croaker	small (≤ 4.5 mm)	MSF	3	3.6735	1.2245	1.3846	
		OSF	3	0.18753	0.0625	0.0692	
		FIL	3	3.054	1.018	1.1465	
	medium (> 4.5 to ≤ 7.2 mm)	MSF	3	0.70827	0.2361	0.2714	
		OSF	3	1.0486	0.3495	0.4025	
		FIL	3	3.7567	1.2522	1.4644	
	large (> 7.2 mm)	MSF	3	5.3241	1.7747	2.6395	
		OSF	3	0.635	0.2117	0.3041	
		FIL	3	3.1888	1.0629	1.5766	
summer flounder	small (≤ 3.0 mm)	MSF	3	1.0416	0.3472	0.3802	
		OSF	3	0.24669	0.0822	0.0897	
		FIL	3	2.6723	0.8908	0.9859	
	medium (> 3.0 to ≤ 4.9 mm)	MSF	3	3.3023	1.1008	1.3307	
		OSF	3	0.38279	0.1276	0.152	
		FIL	3	0.67591	0.2253	0.269	
	large (> 4.9 mm)	MSF	3	2.6032	0.8677	1.0491	
		OSF	3	1.2065	0.4022	0.4809	
		FIL	2	1.5483	0.7741	0.9388	
Paralichthys spp.	small (≤ 2.6 mm)	MSF	3	5.249	1.7497	1.8643	
		OSF	3	3.0898	1.0299	1.0797	
		FIL	2	2.1026	1.0513	1.102	
	medium (> 2.6 to ≤ 4.5 mm)	MSF	3	0.43298	0.1443	0.1615	
		OSF	3	5.7306	1.9102	2.1876	
		FIL	3	0.34395	0.1147	0.1285	
	large (> 4.5 mm)	MSF	3	0.24046	0.0802	0.0933	
		OSF	3	1.1423	0.3808	0.4449	
		FIL	3	5.9388	1.9796	2.3635	

Table 11. Results from a two-factor ANOVA (degrees of freedom (df), sums of squares (SS), mean square (MS)) examining the interaction of the presence of fronts and water mass on mean body length (BL, mm) of larvae for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Three continental shelf fronts; mid-shelf (MSF), outer-shelf (OSF), and warm Gulf Stream filament (FIL) were classified as either present or absent and stations were separated into water masses (Table 5). The interaction between water mass and presence / absence of front indicated whether fronts affected larval size distributions within water masses (*** = $p \leq 0.001$, ** = $p \leq 0.025$, and * = $p \leq 0.05$).

Taxa	Front	df	SS	MS	F	P < F
Atlantic menhaden	MSF	3	151.92	50.639	3.7449	**
	OSF	3	25.472	8.4906	0.594	
	FIL	3	26.167	8.7224	0.6108	
round herring	MSF	2	43.159	21.58	1.0073	
	OSF	2	22.645	11.322	0.5427	
	FIL	2	43.323	21.661	1.0292	
spot	MSF	3	76.7	25.567	5.8614	***
	OSF	3	26.956	8.9853	1.8604	
	FIL	2	3.9787	1.9893	0.4021	
Atlantic croaker	MSF	3	2.4243	0.8081	0.3253	
	OSF	3	2.5674	0.8558	0.3363	
	FIL	2	1.5575	0.7787	0.3077	
summer flounder	MSF	2	1.0678	0.5339	0.1646	
	OSF	3	1.5742	0.5247	0.1602	
	FIL	2	2.1461	1.0731	0.3298	
Paralichthys spp.	MSF	3	1.1788	0.3929	0.2467	
	OSF	3	5.7867	1.9289	1.2272	
	FIL	3	4.3062	1.4354	0.9089	

Table 12. Results from a one-factor ANOVA (degrees of freedom (df), sums of squares (SS), mean square (MS)) examining the effects of the presence of fronts on mean distance from shore (weighted by larval abundance) of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Three continental shelf fronts; mid-shelf (MSF), outer-shelf (OSF), and warm Gulf Stream filament (FIL) were classified as either present or absent and the ANOVA was used to determine if mean distance from shore differed whether or not the MSF, OSF, or FIL was present (*** = p ≤ 0.001, ** = p ≤ 0.025, * = p ≤ 0.05).

Taxa	Size class	Front	df	SS	MS	F	P < F
Atlantic menhaden	small (≤ 7.5 mm)	MSF	1	51.644	51.644	0.0724	
		OSF	1	549.33	549.33	0.7955	
		FIL	1	19.851	19.851	0.0278	
	medium (> 7.5 to ≤ 14.5 mm)	MSF	1	1343.1	1343.1	2.7185	
		OSF	1	2305.9	2305.9	5.0615	*
		FIL	1	200.12	200.12	0.3707	
	large (> 14.5 mm)	MSF	1	801.03	801.03	3.5579	
		OSF	1	371.1	371.1	1.5268	
		FIL	1	1115.7	1115.7	5.2618	*
round herring	small (≤ 6.8 mm)	MSF	1	189.06	189.06	1.3869	
		OSF	1	490.07	490.07	4.0176	
		FIL	1	211.81	211.81	1.5663	
	medium (> 6.8 to ≤ 16.3 mm)	MSF	1	591.66	591.66	4.1565	
		OSF	1	77.019	77.019	0.4702	
		FIL	1	24.299	24.299	0.1464	
	large (> 16.3 mm)	MSF	1	43.208	43.208	0.2549	
		OSF	1	117.62	117.62	0.7135	
		FIL	1	749.57	749.57	5.9801	*
spot	small (≤ 3.9 mm)	MSF	1	130.1	130.1	0.542	
		OSF	1	536.05	536.05	2.4103	
		FIL	1	122.72	122.72	0.5105	
	medium (> 3.9 to ≤ 7.5 mm)	MSF	1	0.07438	0.0744	0.0006	
		OSF	1	325.38	325.38	3.0908	
		FIL	1	94.368	94.368	0.8183	
	large (> 7.5 mm)	MSF	1	10.048	10.048	0.0609	
		OSF	1	196.45	196.45	1.2747	
		FIL	1	5.9187	5.9187	0.0358	

Table 12. continued.

Taxa	Size class	Front	df	SS	MS	F	P < F
Atlantic croaker	small (≤ 4.5 mm)	MSF	1	93.632	93.632	0.2438	
		OSF	1	10.357	10.357	0.0265	
		FIL	1	35.223	35.223	0.0907	
	medium (> 4.5 to ≤ 7.2 mm)	MSF	1	866.33	866.33	3.6341	
		OSF	1	497.19	497.19	1.9358	
		FIL	1	83.607	83.607	0.3013	
	large (> 7.2 mm)	MSF	1	0.03112	0.0311	0.0001	
		OSF	1	17.853	17.853	0.0774	
		FIL	1	462.06	462.06	2.2605	
summer flounder	small (≤ 3.0 mm)	MSF	1	0.28116	0.2812	0.0012	
		OSF	1	80.785	80.785	0.3376	
		FIL	1	218.51	218.51	0.9432	
	medium (> 3.0 to ≤ 4.9 mm)	MSF	1	131.23	131.23	1.0207	
		OSF	1	105.17	105.17	0.8098	
		FIL	1	13.351	13.351	0.0993	
	large (> 4.9 mm)	MSF	1	568.02	568.02	1.4759	
		OSF	1	278.35	278.35	0.6864	
		FIL	1	24.842	24.842	0.0586	
Paralichthys spp.	small (≤ 2.6 mm)	MSF	1	930.32	930.32	1.1555	
		OSF	1	18.862	18.862	0.0212	
		FIL	1	9.5957	9.5957	0.0108	
	medium (> 2.6 to ≤ 4.5 mm)	MSF	1	234.97	234.97	0.3369	
		OSF	1	215.31	215.31	0.3083	
		FIL	1	3030.2	3030.2	5.3119	*
	large (> 4.5 mm)	MSF	1	58.676	58.676	0.0866	
		OSF	1	22.601	22.601	0.0333	
		FIL	1	2606.1	2606.1	4.6845	*

Table 13. Results from a two-factor ANOVA (degrees of freedom (df), sums of squares (SS), mean square (MS)) examining the effects of season and water mass on larval abundance ($\log_{10}$ (larvae · 1000m^{-3} + 1)) of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sample months were separated into two seasons, December and January – February. Stations were separated into water masses (Table 5) based on water temperate, salinity, density, and the presence of fronts on the shelf. A *posteriori* multiple comparisons among seasons and water masses were conducted using Scheffé's S procedure (*** = p ≤ 0.001, ** = p ≤ 0.025, * = p ≤ 0.05, and ns = not significant). Differences in mean abundance among seasons and water masses[1] are indicated from highest to lowest (IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, GS = Gulf Stream, VCW-IS = Virginia coastal water inner-shelf, and VCW-MS = Virginia coastal water mid-shelf).

Taxa	Size class	Source	df	SS	MS	F	P < F	Difference in mean abundance
Atlantic menhaden	small (≤ 7.5 mm)	season	1	8.099	8.0991	13.52	***	December > January - February
		water mass	6	8.234	1.3723	2.29	*	
		error	280	167.767	0.5992			
	medium (> 7.5 to ≤ 14.5 mm)	season	1	3.279	3.2785	3.87	ns	
		water mass	6	28.728	4.788	5.66	***	OS, MS, IS, FIL, GS
		error	280	237.07	0.8467			
	large (> 14.5 mm)	season	1	16.988	16.988	31.66	***	January - February > December
		water mass	6	28.297	4.7161	8.79	***	MS, IS, OS, FIL, GS
		error	280	150.236	0.5366			
round herring	small (≤ 6.8 mm)	season	1	0.3809	0.3809	2	ns	
		water mass	6	10.6103	1.7684	9.29	***	FIL, GS, OS, MS, IS
		error	280	53.2877	0.1903			
	medium (> 6.8 to ≤ 16.3 mm)	season	1	5.035	5.0352	17.11	***	January - February > December
		water mass	6	34.418	5.7363	19.49	***	OS, FIL, GS, MS, IS
		error	280	82.393	0.2943			
	large (> 16.3 mm)	season	1	3.9665	3.9665	20.76	***	January - February > December
		water mass	6	13.2586	2.2098	11.57	***	OS, FIL, MS, GS, IS
		error	280	53.4929	0.1911			

Table 13. continued.

Taxa	Size class	Source	df	SS	MS	F	P < F	Difference in mean abundance
spot	small (≤ 3.9 mm)	season	1	0.535	0.5347	1.33	ns	
		water mass	6	22.837	3.8062	9.46	***	GS, OS, FIL, MS, IS
		error	280	112.614	0.4022			
	medium (> 3.9 to ≤ 7.5 mm)	season	1	8.972	8.9717	18.51	***	January - February > December
		water mass	6	59.995	9.9992	20.63	***	OS, FIL, MS, GS, IS
		error	280	135.721	0.4847			
	large (> 7.5 mm)	season	1	26.229	26.229	80.29	***	January - February > December
		water mass	6	19.76	3.2934	10.08	***	MS, FIL, OS, IS, GS
		error	280	91.468	0.3267			
Atlantic croaker	small (≤ 4.5 mm)	season	1	1.837	1.837	15.06	***	December > January - February
		water mass	6	2.5691	0.4282	3.51	***	
		error	280	34.1508	0.122			
	medium (> 4.5 to ≤ 7.2 mm)	season	1	3.3097	3.3097	15.43	***	December > January - February
		water mass	6	5.7037	0.9506	4.43	***	OS, MS, FIL, IS, GS
		error	280	60.0782	0.2146			
	large (> 7.2 mm)	season	1	0.0905	0.0905	0.72	ns	
		water mass	6	9.03	1.505	11.9	***	MS, IS, FIL, OS, GS
		error	280	35.4177	0.1265			

Table 13. continued.

Taxa	Size class	Source	df	SS	MS	F	P < F	Difference in mean abundance
summer flounder	small (≤ 3.0 mm)	season	1	0.4736	0.4736	2.52	ns	
		water mass	6	6.9265	1.1544	6.15	***	VCW-MS, VCW-IS, OS, MS, IS, GS, FIL[1]
		error	280	52.5287	0.1876			
	medium (> 3.0 to ≤ 4.9 mm)	season	1	4.61	4.6104	18.25	***	January - February > December
		water mass	6	17.854	2.9756	11.78	***	VCW-MS, VCW-IS, MS, OS, FIL, IS, GS[1]
		error	280	70.719	0.2526			
	large (> 4.9 mm)	season	1	3.3778	3.3778	21.13	***	January - February > December
		water mass	6	5.7025	0.9504	5.94	***	VCW-MS, VCW-IS, MS, FIL, OS, IS, GS[1]
		error	280	44.7682	0.1599			
Paralichthys spp.	small (≤ 2.6 mm)	season	1	0.4128	0.4128	2.15	ns	
		water mass	6	1.6936	0.2823	1.47	ns	
		error	280	53.6844	0.1917			
	medium (> 2.6 to ≤ 4.5 mm)	season	1	2.3302	2.3302	8.59	**	December > January - February
		water mass	6	5.267	0.8778	3.24	**	
		error	280	75.9259	0.2712			
	large (> 4.5 mm)	season	1	0.5573	0.5573	2.72	ns	
		water mass	6	7.8035	1.3006	6.35	***	IS, MS, FIL, OS, GS
		error	280	57.3644	0.2049			

1. Summer flounder were more abundant in VCW mid-shelf water mass (Appendix B; Fig. 5B). For all other taxa, mean abundance of all size classes were not significantly different in VCW water masses than resident water masses (Appendix B; Figs. 1B – 6B). Therefore, results with VCW were only shown for summer flounder.

Table 14. Results from a two-factor ANOVA (degrees of freedom (df), sums of squares (SS), mean square (MS)) examining the effects of season and water mass on mean body length (BL, mm) of larvae for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sample months were separated into two seasons, December and January – February. Stations were separated in to water masses (Table 5) based on water temperate, salinity, density, and the presence of fronts on the shelf. A *posteriori* multiple comparisons among seasons and water masses were conducted using Scheffé's S procedure (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$, and ns = not significant). Differences in mean BL among seasons and water masses[1] are indicated from largest to smallest (IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, GS = Gulf Stream).

Taxa	Source	df	SS	MS	F	P < F	Difference in Mean BL
Atlantic menhaden	season	1	417.73	417.73	35.83	***	January - February > December
	water mass	6	1084.70	180.78	15.50	***	IS, MS, FIL, OS, GS[1]
	error	167	1947.21	11.66			
round herring	season	1	152.70	152.69	7.89	**	January - February > December
	water mass	4	729.17	182.29	9.42	***	OS, MS, FIL, GS[1]
	error	118	2284.62	19.36			
spot	season	1	199.88	199.88	58.80	***	January - February > December
	water mass	6	704.08	117.35	34.52	***	IS, MS, FIL, OS, GS[1]
	error	189	642.50	3.40			
Atlantic croaker	season	1	42.63	42.62	21.03	***	January - February > December
	water mass	6	183.49	30.58	15.09	***	IS, MS, FIL, OS, GS[1]
	error	106	214.87	2.03			
summer flounder	season	1	25.08	25.08	8.29	**	January - February > December
	water mass	6	54.49	9.08	3.00	**	
	error	115	347.77	3.02			
Paralichthys spp.	season	1	12.44	12.44	8.34	**	January - February > December
	water mass	5	70.47	14.09	9.45	***	MS, IS, FIL, OS, GS[1]
	error	117	174.42	1.49			

1. Mean sizes were not significantly different in Virginia coastal water masses than resident water masses (Appendix B, Figs. 1B – 6B). Therefore, only results for resident Onslow Bay water masses are shown.

Table 15. Summary of results for water mass specific abundance and size distribution and the effects of fronts on larval distributions on the continental shelf off North Carolina. Fronts which were present when significant difference in larval distributions occurred are shown for each analysis. MSF = mid-shelf front, OSF = outer-shelf front, FILF = warm filament front, and HF = Hatteras front.

		Water mass specific distribution		Fronts that affect larval distributions: Peak abundance		Fronts that affect larval distributions: Distribution spatially aggregated[1]		Fronts that affect larval distributions: Water mass specific distribution		Fronts that affect larval distributions: Mean distance from shore (km)
Taxa	Size class	Abundance	Size[1]	At front	Not at front	Present	Absent	Abundance	Size[1]	
Atlantic menhaden	small	*	***					MSF	MSF	
	medium	***								OSF
	large	***			MSF, OSF			FILF		FILF
round herring	small	***	***		MSF		MSF			
	medium	***						MSF		
	large	***								FILF
spot	small	***	***						MSF	
	medium	***		OSF						
	large	***								
Atlantic croaker	small	***	***							
	medium	***			OSF					
	large	***			OSF					
summer flounder	small	***	**					HF[2]		
	medium	***		MSF				HF[2]		
	large	***						HF[2]		
Paralichthys a / l	small		***		OSF					
	medium	**			OSF					FILF
	large	***			OSF					FILF

1. Analysis of water mass specific size and spatial aggregation and were conducted on taxa only, not taxa-size classes. Results were displayed in the first row (small) for convenience.
2. Results for the effect of the Hatteras front on water mass specific abundance were shown in Appendix B.

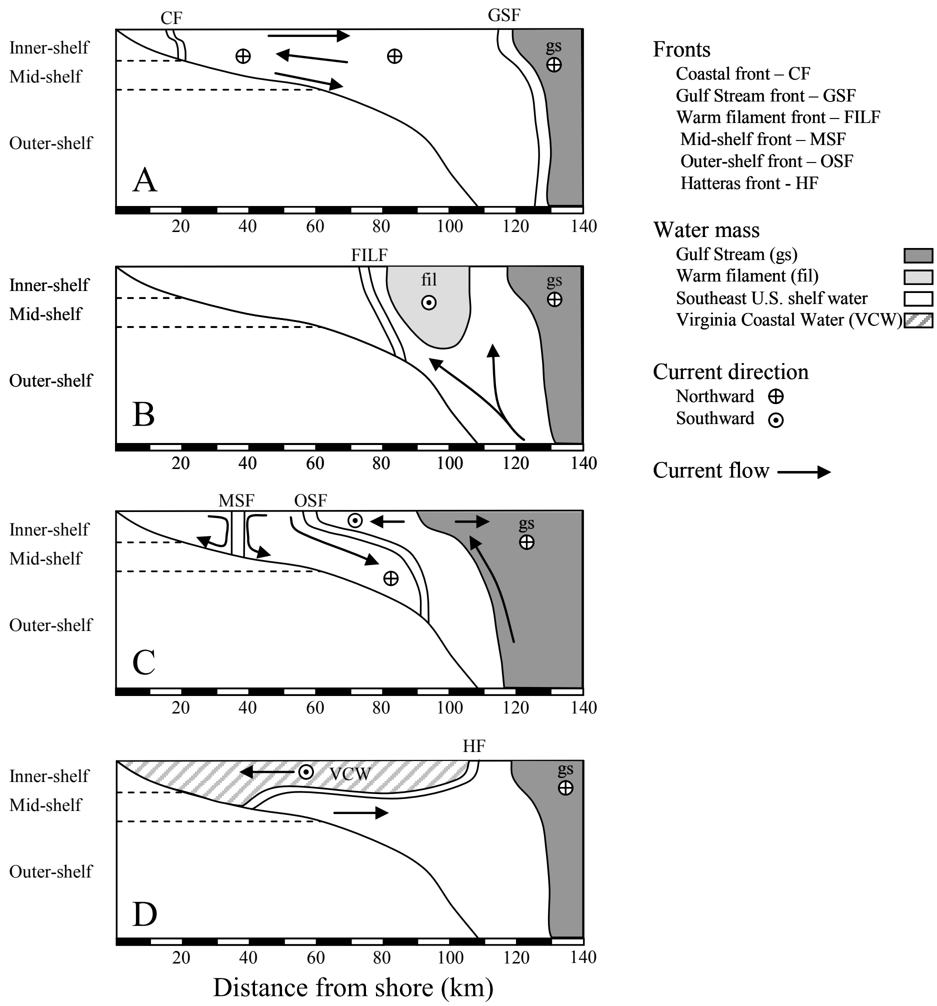

Figure 1. A schematic of six fronts that occur in Onslow Bay, North Carolina during the winter and resultant current flows are shown. (A) The coastal front (CF) and Gulf Stream front (GSF) commonly bound the continental shelf, and either a three layer cross-shelf current flow pattern (Miller et al. 1984) or northward flow may occur on the mid-shelf (Werner et al. 1999). (B) Surface intrusions of the Gulf Stream water mass (gs) result in the formation of the outer-shelf front (OSF) and mid-shelf front (MSF). (C) A filament front (FILF) often separates mesoscale eddies with warm filaments of Gulf Stream water (fil) from shelf water masses. (D) Intrusions of Virginia Coastal Water (VCW) overlay resident water masses and form the Hatteras front (HF) at the offshore edge.

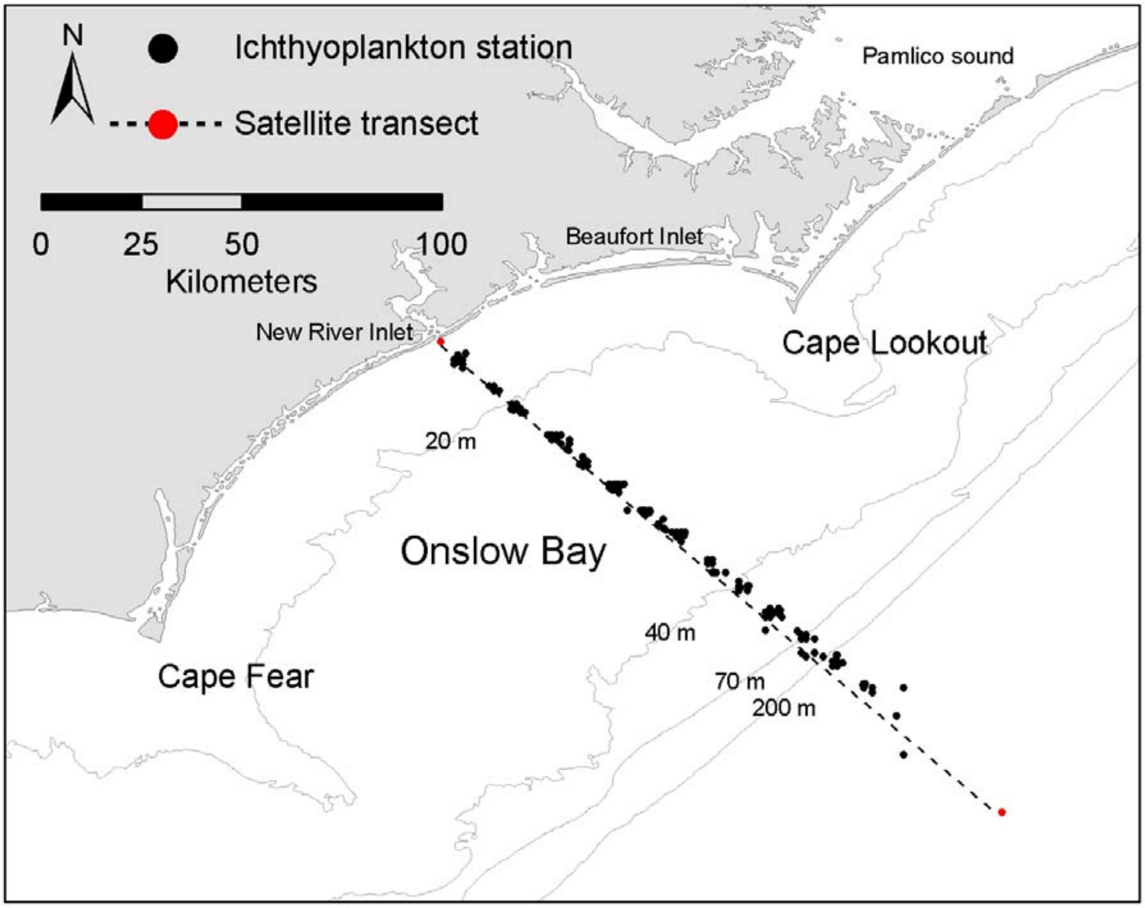

Figure 2. Location of ichthyoplankton stations (black dots) and a satellite transect (dotted line) bisecting Onslow Bay, North Carolina. The start and end points of the satellite transect are shown (red dots). Sampling was conducted during December, January, and February 1990-1999 (Table 1).

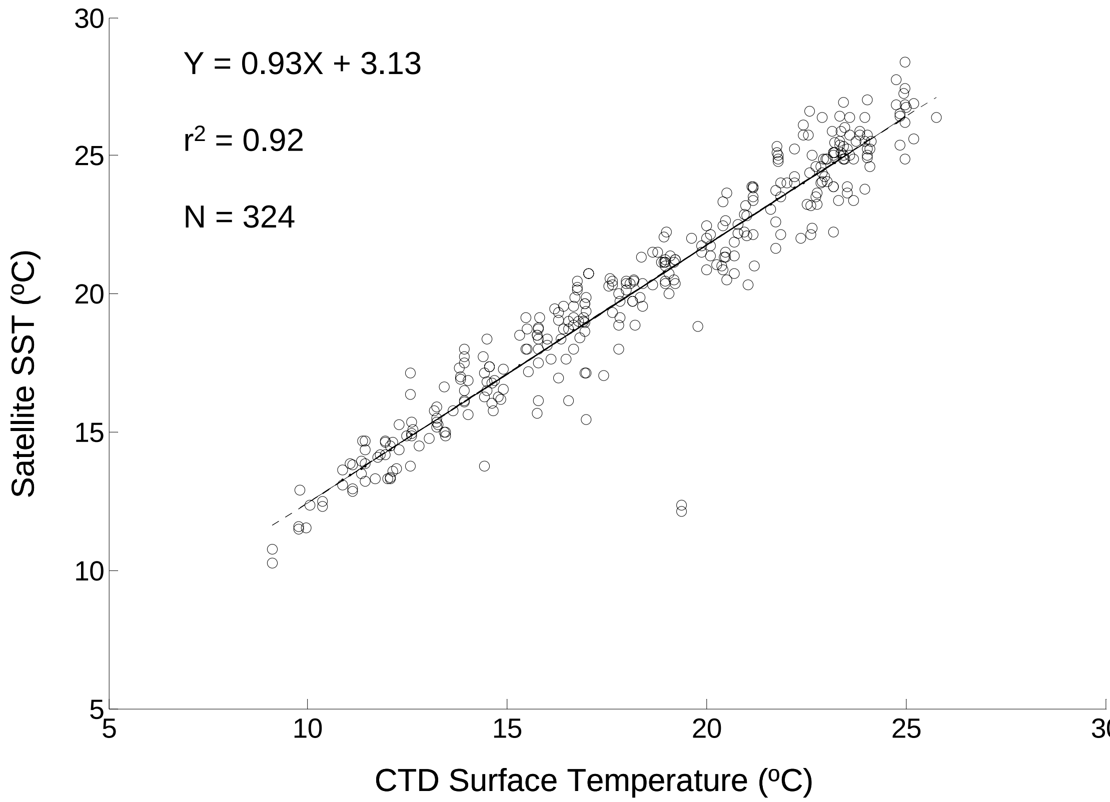

Figure 3. Linear relationship between conductivity, temperature, and depth (CTD) surface water temperature measurements and satellite sea surface temperatures (SST) from a transect bisecting Onslow Bay, North Carolina (Fig. 2). Sampling conducted during December, January, and February 1990-1999. Circles represent surface water temperature (averaged from 1 to 3 m) from CTD casts and satellite SST from pixels which corresponded to the nominal station locations and were within two days of the sample date (N). The line represents predicted SST values from the CTD values using the linear equation shown on the graph.

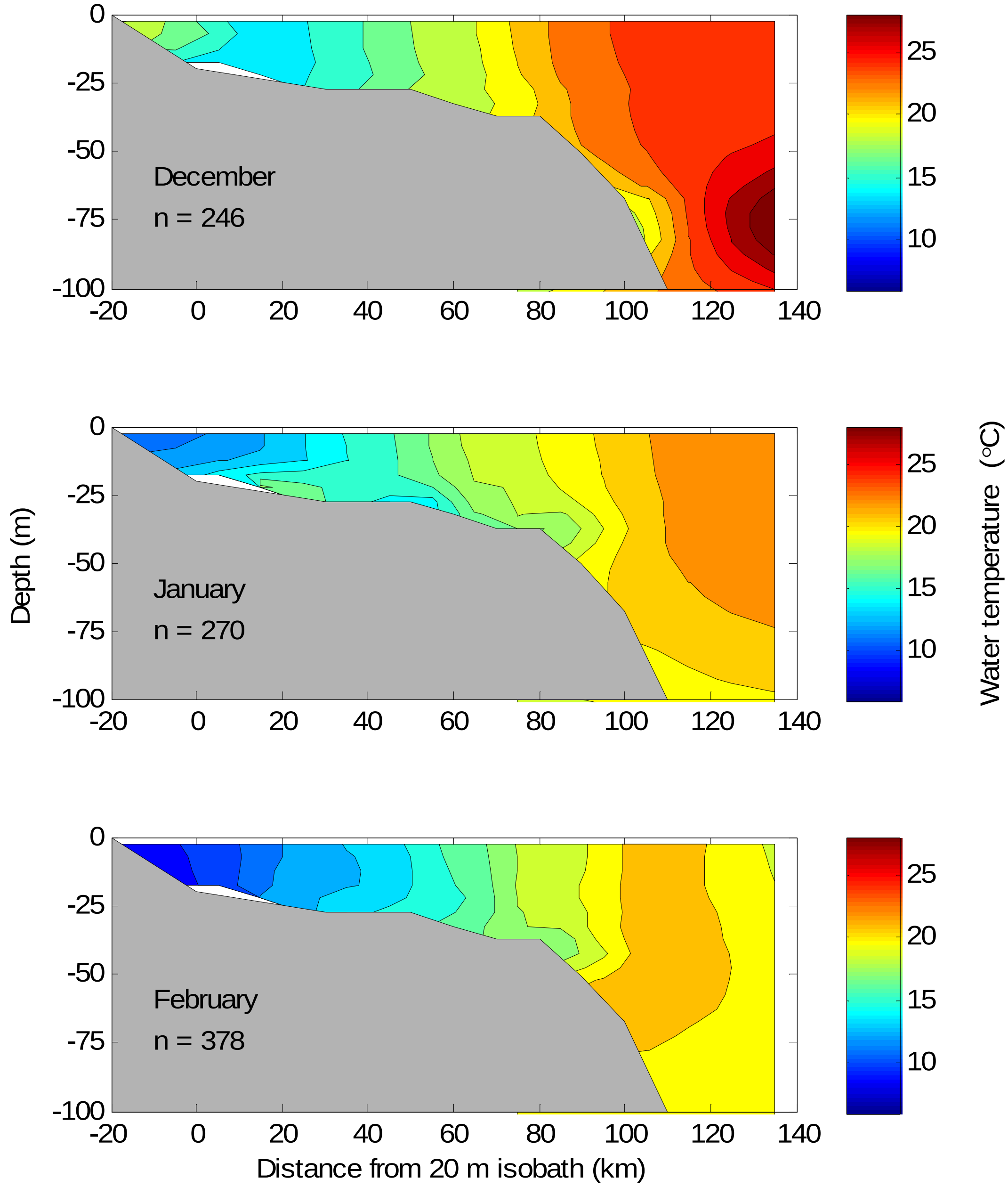

Figure 4. Monthly cross-shelf water temperature (°C) climatologies for Onslow Bay, North Carolina. Climatologies were created using water temperature casts (n) from the current study and the World Ocean Database 2005 (downloaded from NOAA's National Oceanographic Data Center: http://www.nodc.noaa.gov/OC5/SELECT/dbsearch/sysinfo.html).

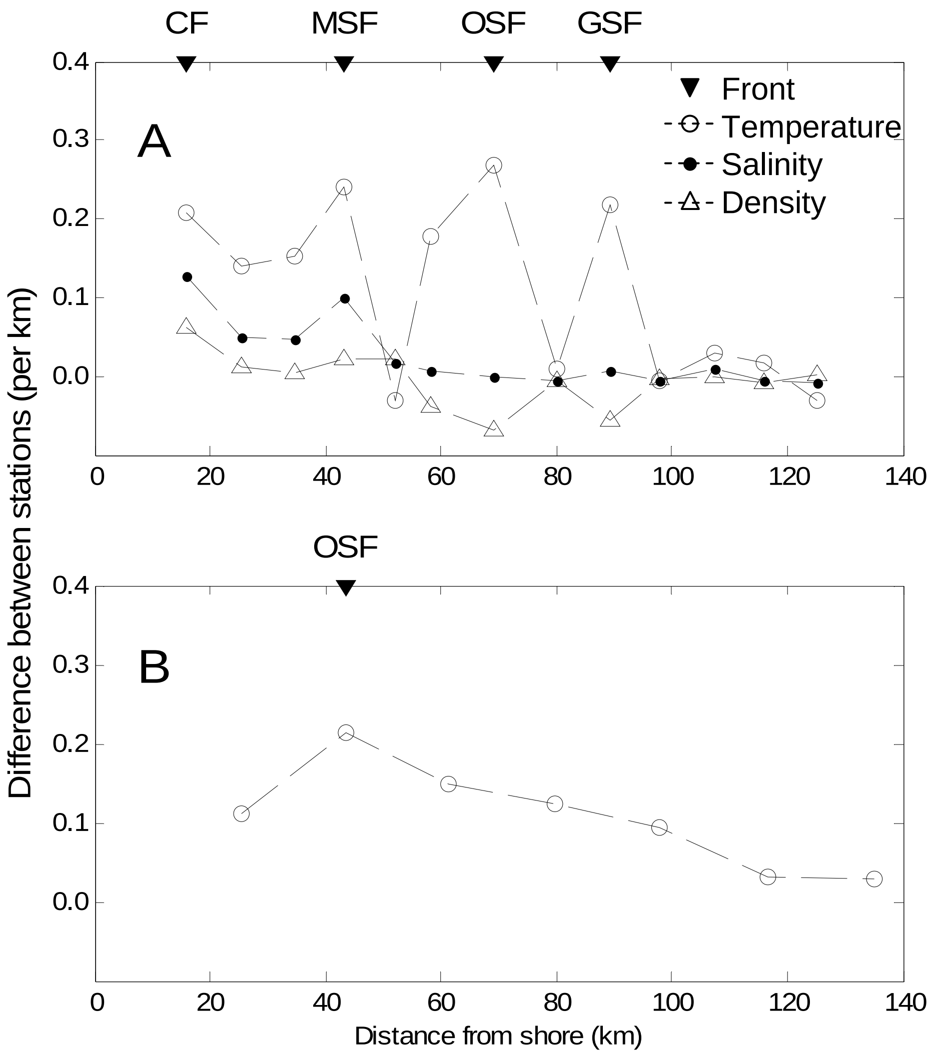

Figure 5. Abrupt difference in surface water temperature (°C), salinity, and density (σ_t, $kg \cdot m^{-3}$) between stations were used to define the location of fronts on a transect bisecting Onslow Bay, North Carolina (Fig. 2). An example using data from conductivity, temperature, and depth probe casts for 17-18 February 1993 (A) and satellite sea surface temperature derived from advanced very high-resolution radar satellite images for 18-19 January 1999 (B) show the location of fronts. CF = coastal front, MSF = mid-shelf front, OSF = outer-shelf, and GSF = Gulf Stream front.

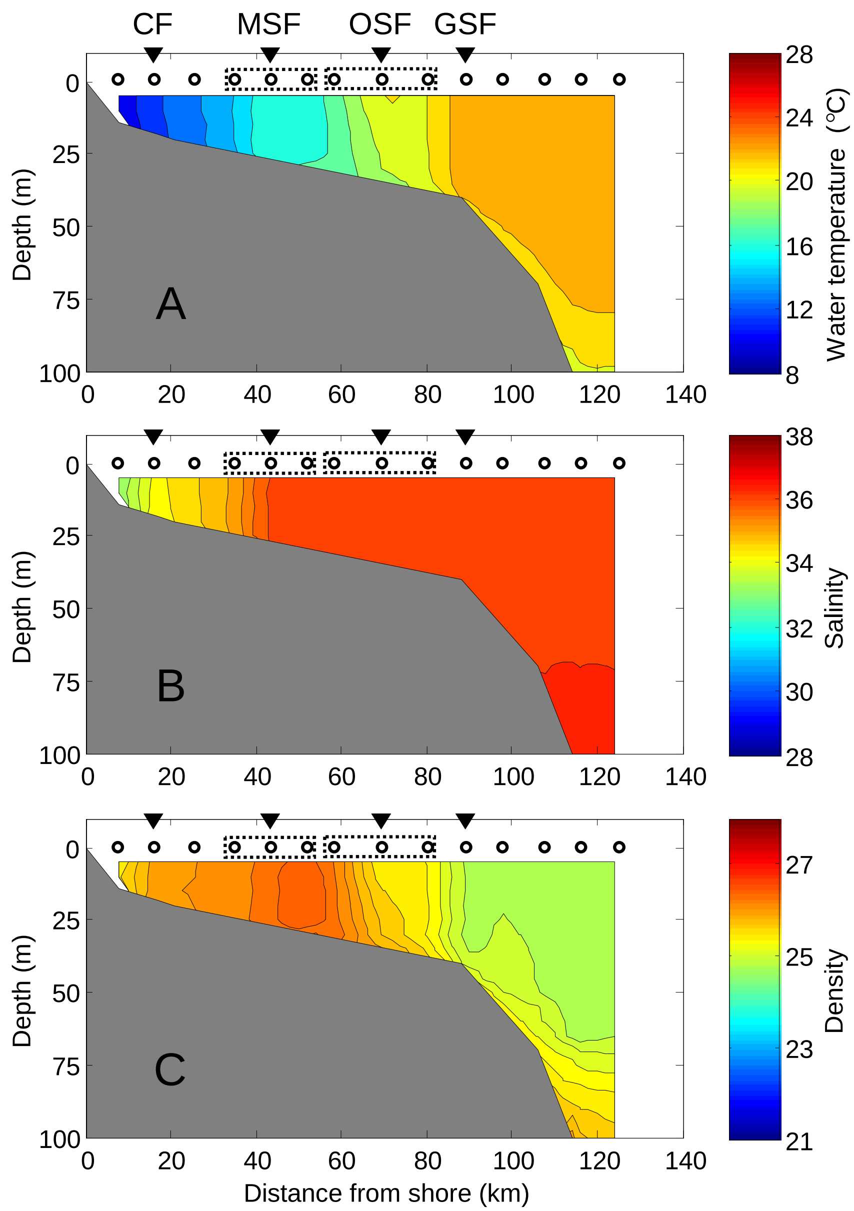

Figure 6. Visual analysis of the cross-shelf temperature (°C), salinity, and density (σ_t, kg·m^{-3}) sections from stations (circles) on a transect bisecting Onslow Bay, North Carolina (Fig. 2) were used to verify the location of fronts (black triangles). An example from 17-18 February 1993 shows the location of four fronts, and stations classified as adjacent to the MSF and OSF enclosed by dotted boxes. CF = coastal front, MSF = mid-shelf front, OSF = outer-shelf, and GSF = Gulf Stream front.

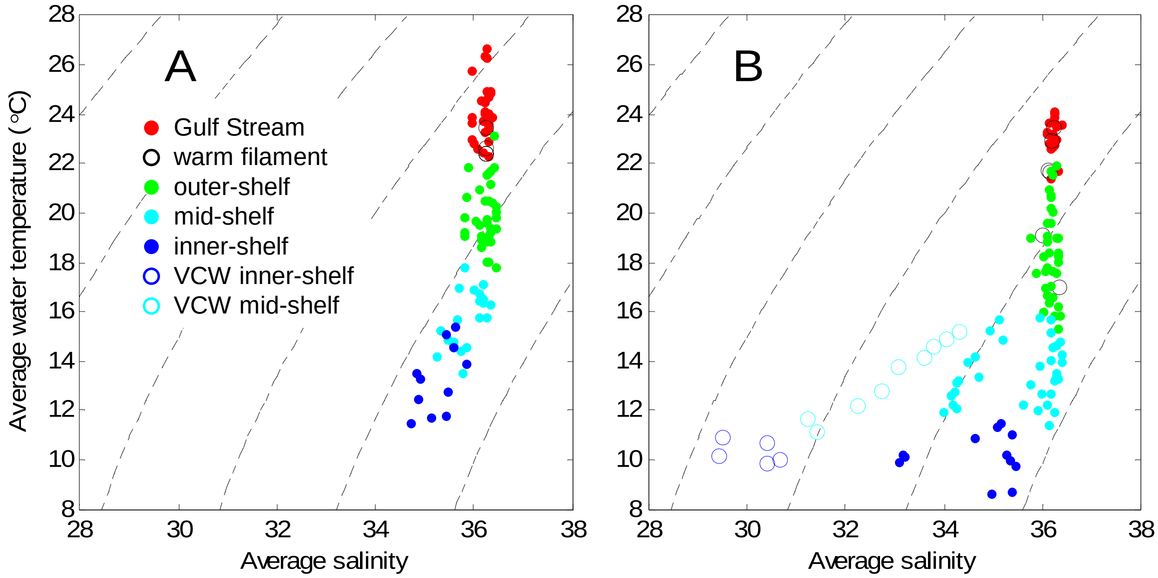

Figure 7. Average water column temperature (°C) and salinity of the seven water masses defined for the North Carolina shelf for December (A) and January-February (B) shown with lines of equal density (σ_t, kg·m^{-3}) at a pressure of 0 dbar. VCW = Virginia Coastal Water.

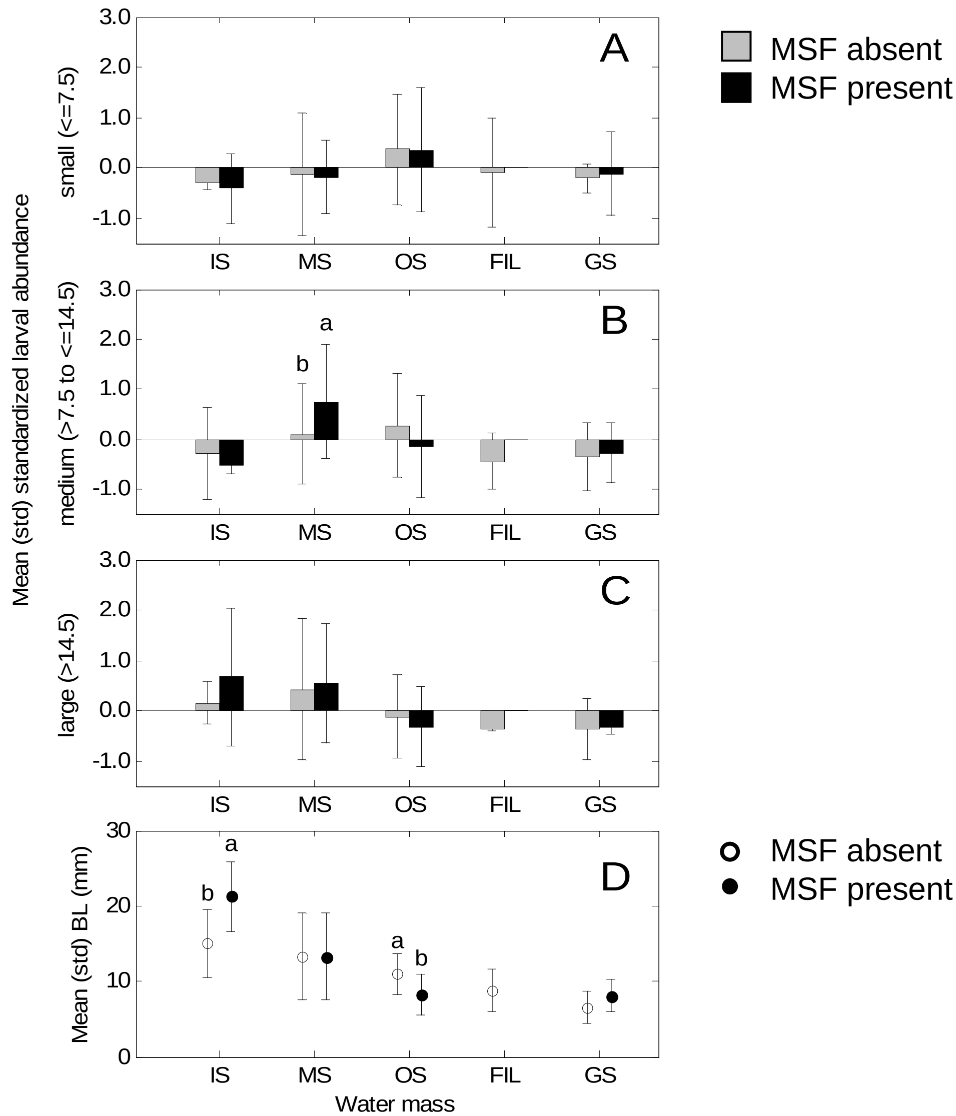

Figure 8. Atlantic menhaden (*Brevoortia tyrannus*) mean (standard deviation) standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a mid-shelf front (MSF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

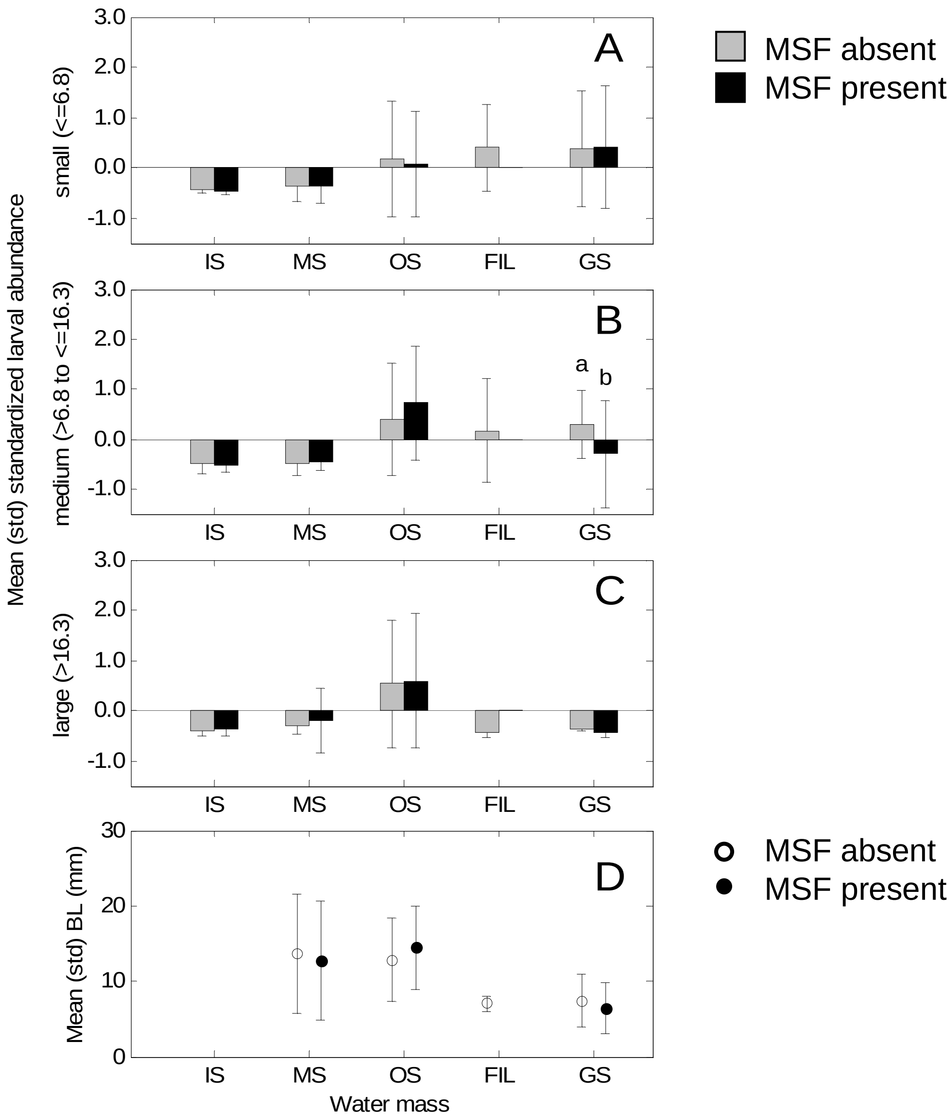

Figure 9. Round herring (*Etrumeus teres*) mean (standard deviation) standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a mid-shelf front (MSF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

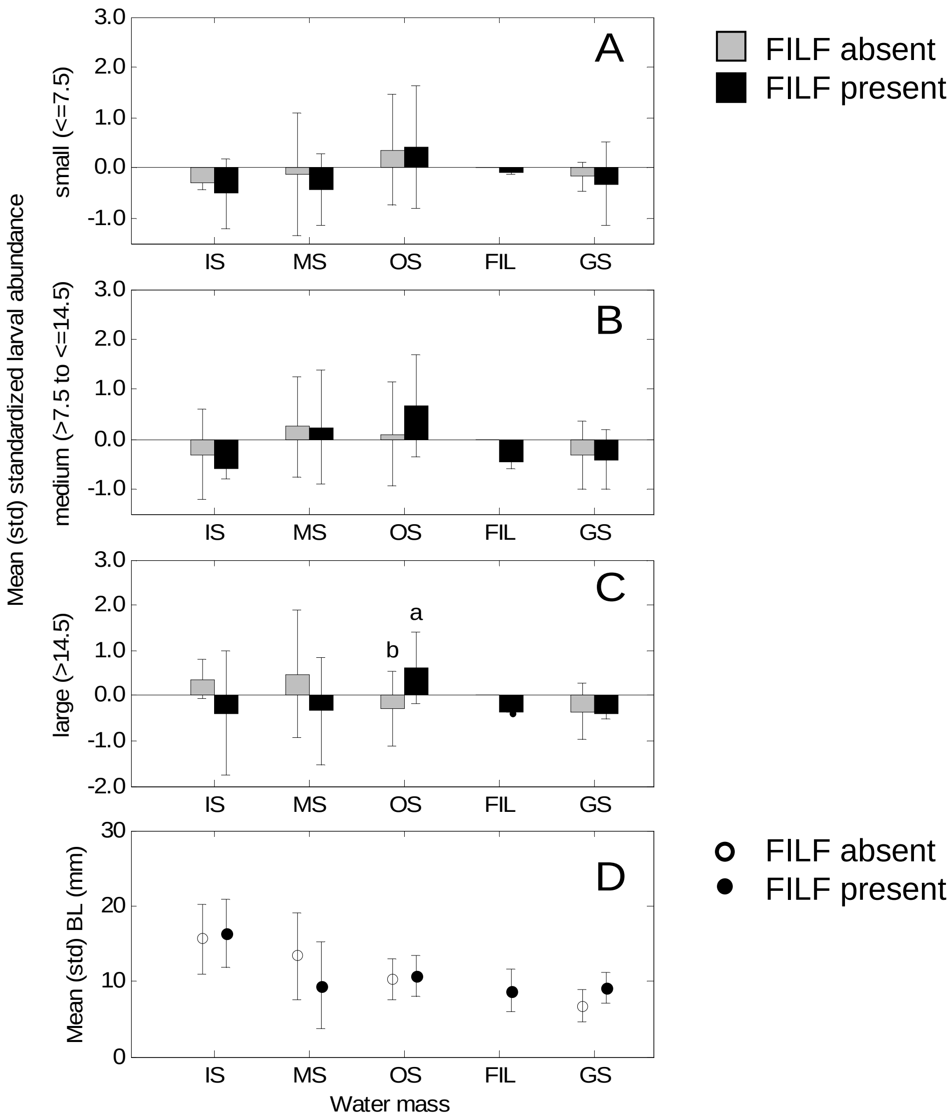

Figure 10. Atlantic menhaden (*Brevoortia tyrannus*) mean (standard deviation) standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a warm filament front (FILF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

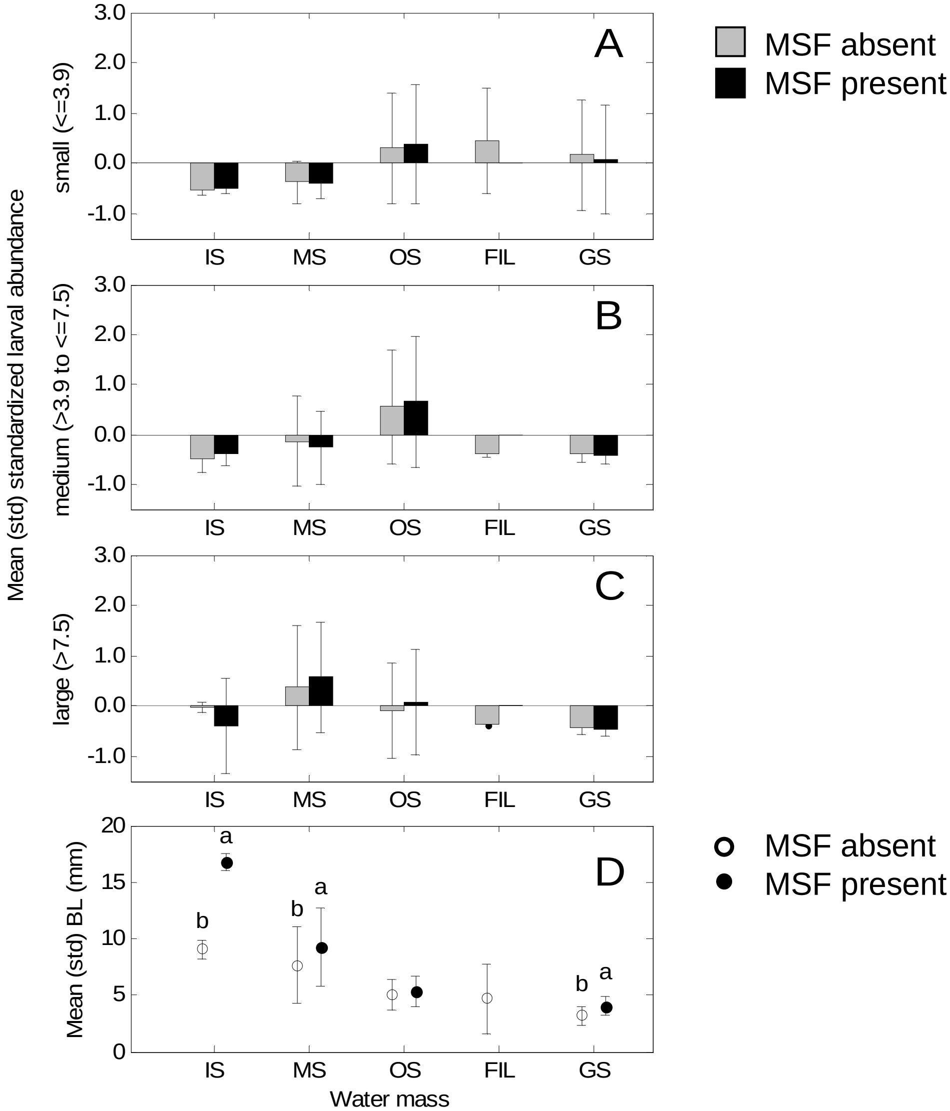

Figure 11. Spot (*Leiostomus xanthurus*) mean (standard deviation) standardized abundance of small (A), medium (B), and large (C) larvae and Mean (standard deviation) body length (BL; D) when a mid-shelf front (MSF) was present and absent. Differences within water masses of and standardized larval abundance and mean BL among presence/absence of the MSF were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

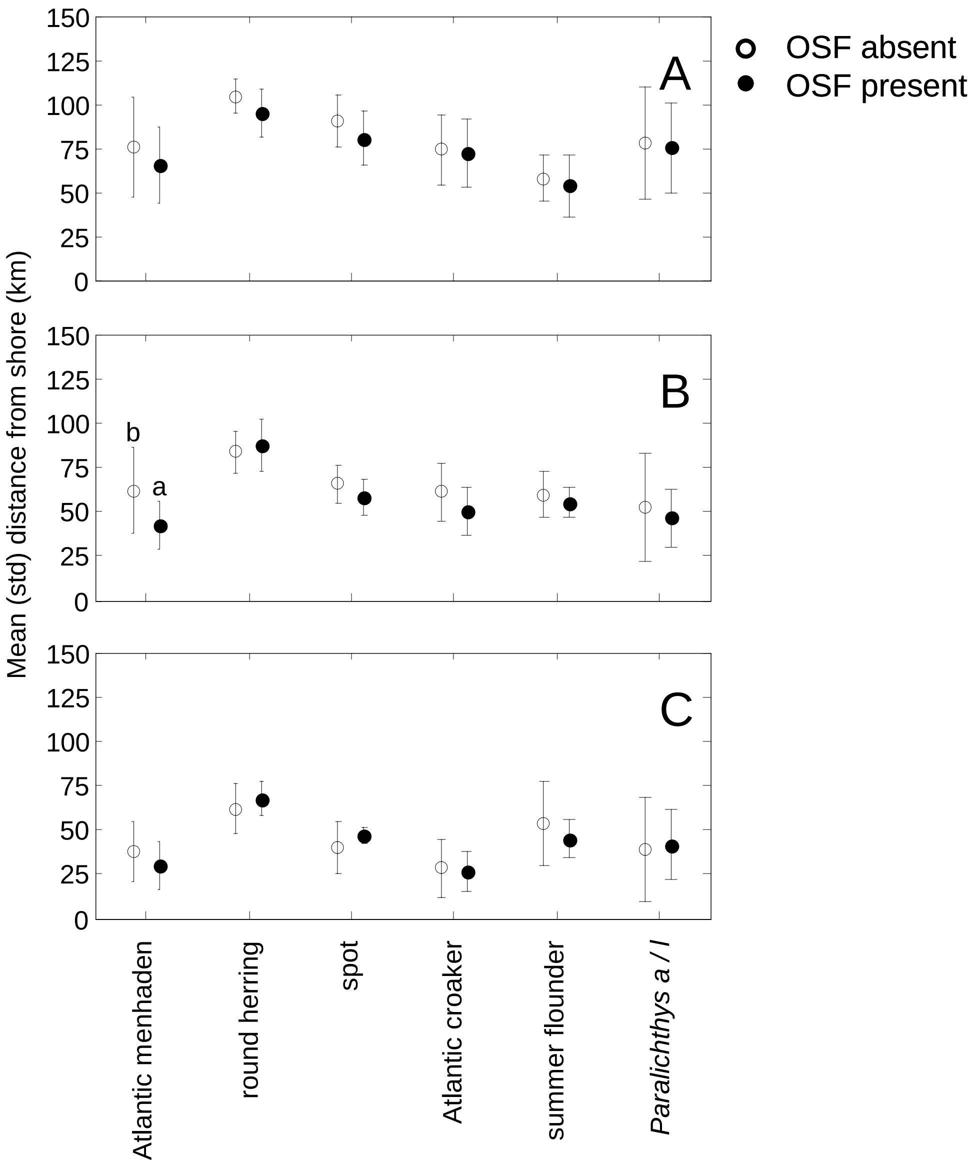

Figure 12. Mean (standard deviation) distance from shore (km) of small (A), medium (B), and large (C) size classed larvae of six taxa when the outer-shelf front (OSF) was present and absent. Differences within size class among presence/absence of the fronts were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters.

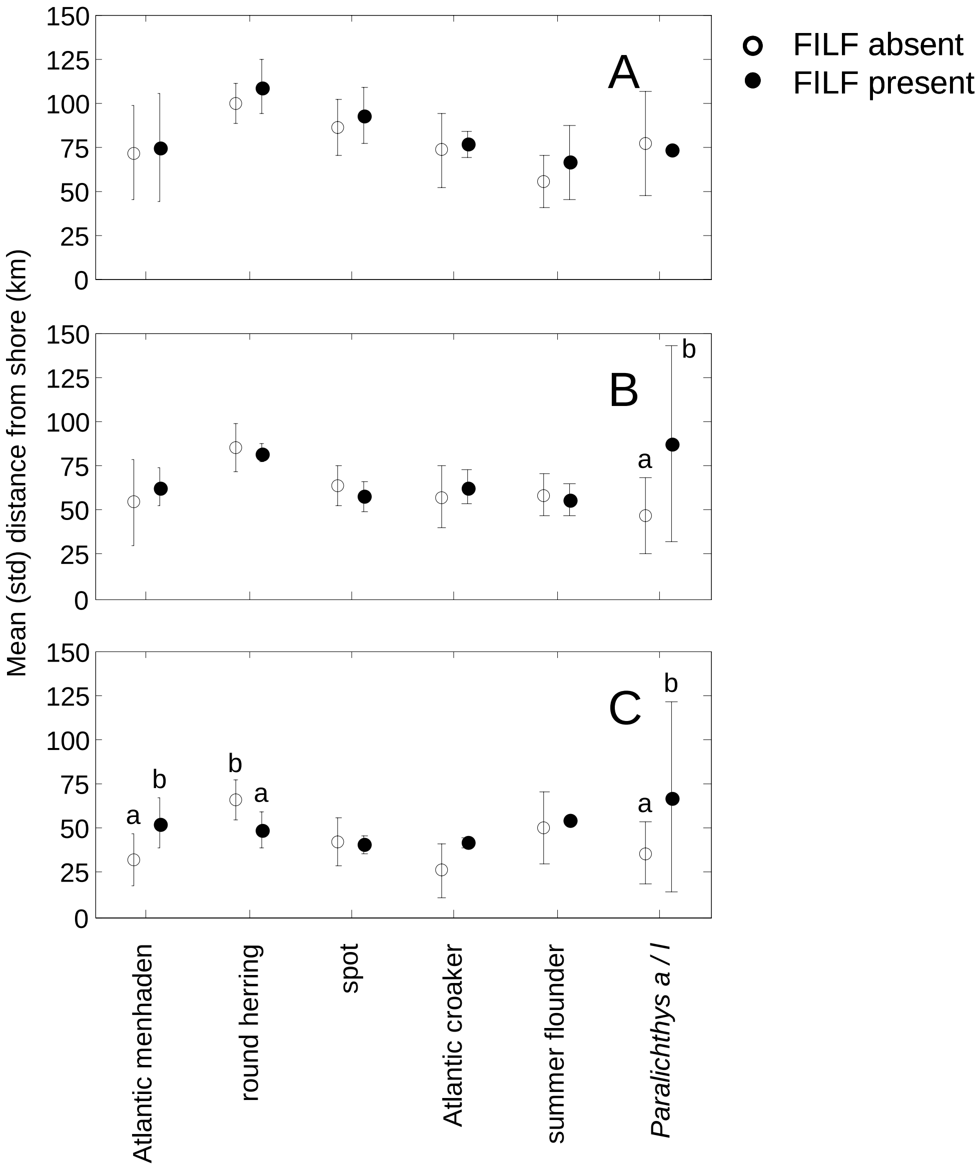

Figure 13. Mean (standard deviation) distance from shore (km) of small (A), medium (B), and large (C) size classed larvae of six taxa when the warm filament front (FILF) was present and absent. Differences within size class among presence/absence of the fronts were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters.

1.5 Literature Cited

Austin, J.A. 1999. The role of the alongshore wind stress in the heat budget of the North Carolina inner shelf. Journal of Geophysical Research. 104: 18187-18203.

Austin, J.A. and S.J. Lentz. 1999. The relationship between synoptic weather systems and meteorological forcing on the North Carolina inner shelf. Journal of Geophysical Research. 104: 18159-18185.

Able, K.W. and M.P. Fahay. 1998. The first year in the life of estuarine fishes in the Middle Atlantic Bight. Rutgers University Press. New Brunswick, New Jersey.

Bakun, A. 2006. Fronts and eddies as key structures in the habitat of marine larvae: opportunity, adaptive response and competitive advantage. Scientia Marina. 70(S2): 105-122.

Bower, A.S. and T. Rossby. 1989. Evidence of cross-frontal properties in the Gulf Stream based on isopycnal RAFOS float data. Journal of Physical Oceanography. 19: 1177-1190.

Box, G.E.P., W.G. Hunter and J.S. Hunter. 1978. Statistics for experimenters: an introduction to design, data analysis, and model building. John Wiley & Sons, New York.

Checkley, D.M. Jr., S. Ramon, G.L. Maillet, and K.M. Mason. 1988. Winter storm effects on the spawning and larval drift of pelagic fish. Nature. 335: 346-348.

Checkley, D.M. Jr., P.B. Ortner, F.E. Werner, L.R. Settle, and S.R. Cummings. 1999. Spawning habitat of the Atlantic menhaden in Onslow Bay, North Carolina. Fisheries Oceanography. 8(S2): 22-36.

Churchill, J.H., J.P. Manning, and R.C. Beardsley. 2003. Slope water intrusions onto Georges Bank. Journal of Geophysical Research. 108: 8012-8028.

Chen, C., L. Zheng, and J.O. Blanton. 1999. Physical processes controlling the formation, evolution, and perturbation of the low-salinity front in the inner shelf off the southeastern United States: A modeling study. Journal of Geophysical Research. 104: 1259-1288

Cowen, R.K., J.A. Hare, and M.P. Fahay. 1993. Beyond hydrography: can physical processes explain larval fish assemblages within the Middle Atlantic Bight? Bulletin of Marine Science. 53: 567-587.

Cudaback, C.N. and J.L. Largier. 2001. The cross-shelf structure of wind- and buoyancy-driven circulation over the North Carolina inner shelf. Continental Shelf Research. 21: 1649-1668.

Dempster, T., M.T. Gibbs, D. Rissik D, and I.M. Suthers. 1997. Beyond hydrography: daily ichthyoplankton variability and short term oceanographic events on the Sydney continental shelf. Continental Shelf Research. 17: 1461-1481.

Denit, K. and S. Sponaugle. 2004. Growth Variation, Settlement, and Spawning of Gray Snapper across a Latitudinal Gradient. Transactions of the American Fisheries Society. 133:1339–1355.

Epifanio, C.E. and R.W. Garvine. 2001. Larval transport on the Atlantic continental shelf of North America: a review. Estuarine, Coastal and Shelf Science. 51:51-77.

Franks, P.J.S. 1992. Sink or swim: accumulation of biomass at fronts. Marine Ecology Progress Series. 82: 1-12.

Garvine, R.W., C.E. Epifanio, C.C. Epifanio, and K-C. Wong. 1997. Transport and recruitment of blue crab larvae: a model with advection and mortality. Estuarine, Coastal and Shelf Science. 45:99-111.

Gawarkiewicz, G., T.G. Ferdelman, T.M. Church, and G.W. Luther. 1996. Shelfbreak frontal structure on the continental shelf north of Cape Hatteras. Continental Shelf Research. 16: 1751-1773.

Gawarkiewicz, G., F. Bahr, R.C. Beardsley, and K.H. Brink. 2001. Interaction of a Slope Eddy with the Shelfbreak Front in the Middle Atlantic Bight. Journal of Physical Oceanography. 31: 2783-2796.

Grothues, T.M. and R.K. Cowen. 1999. Larval fish assemblages and water mass history in a major faunal transition zone. Continental Shelf Research. 19: 1171-1198.

Gonzalez-Quiros, R., A. Pascual, D. Gomis, R. Anadon. 2004. Influence of mesoscale physical forcing on trophic pathways and fish larvae retention in the central Cantabrian Sea. Fisheries Oceanography. 13: 351-364.

Govoni, J.J. and C.B. Grimes. 1992. The surface accumulation of larval fishes by hydrodynamic convergence within the Mississippi River plume front. Continental Shelf Research. 12: 1265-1276.

Govoni, J.J. 1993. Flux of larval fishes across frontal boundaries: examples from the Mississippi River plume front and the western Gulf Stream front in winter. Bulletin of Marine Science. 53: 538-566.

Govoni, J.J. and L.J. Pietrafesa. 1994. Eulerian views of layered water currents, vertical distribution of some larval fishes, and inferred advective transport over the continental shelf off North Carolina, USA, in winter. Fisheries Oceanography. 3: 120-132.

Govoni, J.J. and H.L. Spach. 1999. Exchange and flux of larval fishes across the western Gulf Stream front south of Cape Hatteras, USA, in winter. Fisheries Oceanography. 8(S2): 77-92.

Govoni, J.J., B.W. Stender, and O. Pashuk. 2000. Distribution of larval swordfish, *Xiphias gladius*, and probable spawning off the southeastern United States. Fishery Bulletin. 98: 64-74.

Govoni, J.J. 2005. Fisheries oceanography and the ecology of early life histories of fishes: a perspective over fifty years. Scientia Marina. 69: 125-137.

Hare, J.A. and R.K. Cowen. 1991. Ecological and evolutionary implications of the larval transport and reproductive strategy of bluefish *Pomatomus saltatrix*. Marine ecology progress series. 98: 1-16.

Hare, J.A. and R.K. Cowen. 1996. Transport mechanisms of larval and pelagic juvenile bluefish (Pomatomus saltarix) from South Atlantic Bight spawning grounds to Middle Atlantic Bight nursery habitats. Limnology and Oceanography. 41:1264-1280.

Hare, J.A., J.A. Quinlan, F.E. Werner, B.O. Blanton, J.J. Govoni, R.B. Forward, L.R. Settle, and D.E. Hoss. 1999. Larval transport during winter in the SABRE study area: results of a coupled vertical larval behaviour-three-dimensional circulation model. Fisheries Oceanography. 8(S2): 57-76.

Hare, J.A., M.P. Fahay, and R.K. Cowen. 2001. Springtime ichthyoplankton of the slope region off the north-eastern United States of America: larval assemblages, relation to hydrography and implications for larval transport. Fisheries Oceanography. 10: 164-192.

Hare, J.A., J.H. Churchill, R.K. Cowen, T.J. Berger. P.C. Crnillon, P. Dragos, S.M. Glenn, J.J. Govoni, and T.N. Lee. 2002. Routes and rates of larval fish transport from the southeast to the northeast United States continental shelf. Limnology and Oceanography. 47: 1774-1789.

Hare, J.A. and J.J. Govoni. 2005. Comparison of average larval fish vertical distributions among species exhibiting different transport pathways on the southeast United States continental shelf. Fishery Bulletin. 103: 728-736.

Hare, J.A. and H.J. Walsh. In Press. Planktonic linkages among Marine Protected Areas on the south Florida and southeast United States continental shelf. Canadian Journal of Fisheries and Aquatic Sciences.

Haney, J.C. and P.A. McGillivary. 1985. Midshelf fronts in the south Atlantic Bight and their influence on seabird distribution and seasonal abundance. Biological Oceanography. 3: 401-430.

Helfrich, K.R. and J. Pineda. 2003. Accumulation of particles in propagating fronts. Limnology and Oceanography. 48: 1509-1520.

Hettler, W.F. Jr. and J.A. Hare. 1998. Abundance and size of larval fishes outside the entrance to Beaufort Inlet, North Carolina. Estuaries. 21: 476-499.

Hoss, D.E. and J.S. Burke. 2002. The importance of vertical movements in the early life history of marine fishes. Fisheries Science. 68(S1): 172-177.

Jenkins, G.P. and K.P. Black. 1994. Temporal variability in settlement of a coastal fish (*Sillaginodes punctata*) determined by low-frequency hydrodynamics. Limnology and Oceanography. 39:1744-1754.

Kingsford, M.J. 1990. Linear oceanographic features: a focus for research on recruitment processes. Australian journal of ecology. 15: 391-401.

Lee, O., R.D.M. Nash, and B.S. Danilowicz. 2005. Small-scale spatio-temporal variability in ichthyoplankton and zooplankton distribution in relation to a tidal-mixing front in the Irish Sea. ICES Journal of Marine Science. 62: 1021-1036.

Lee, T.N., J.A. Yoder, and L.P. Atkinson. 1991. Gulf Stream frontal eddy influence on productivity of the southeast U.S. Continental Shelf. Journal of Geophysical Research. 96: 191-205.

Limouzy-Paris, C.B., H.C. Graber, D.L. Jones, A.W. Roepke, and W.J. Richards. 1997. Translocation of larval coral reef fishes via sub-mesoscale spin-off eddies from the Florida Current. Bulletin of Marine Science. 60: 966-983.

Lochmann, S.E., C.T. Taggart, D.A. Griffin, K.R. Thompson, and G.L. Maillet. 1997. Abundance and condition of larval cod (*Gadus morhua*) at a convergent front on Western Bank, Scotian Shelf. Canadian Journal of Fisheries and Aquatic Sciences. 54: 1461-1479.

Marancik, K.E., L.M. Clough, and J.A. Hare. 2005. Cross-shelf and seasonal variation in larval fish assemblages on the southeast United States continental shelf off the coast of Georgia. Fishery Bulletin. 103: 108-129.

Miller, J.M, J.P. Reed, and L.J. Pietrafesa. 1984. Patterns, mechanisms and approaches to the study of migrations of estuarine-dependent fish larvae and juveniles, pp. 209-225. In Mechanisms of migration in fishes (J.D. McCleave, G.P. Arnold, J.J. Dodson, and W.H. Neill, eds). Plenum Press, New York, NY.

Munk, P, P.O. Larsson, D.S. Danielssen, E. Moksness, E. 1999. Variability in frontal zone formation and distribution of gadoid fish larvae at the shelf break in the northeastern North Sea. Marine Ecology Progress Series. 177: 221-233.

Munk, P. 2002. Larval sand lance (*Ammodytes* sp.) in the diet of small juvenile wolffish (*Anarhichas* spp.): predatory interactions in frontal water masses off western Greenland. Canadian Journal of Fisheries and Aquatic Sciences. 59: 1759-1767.

Norcross, B.L. and R.F. Shaw. 1984. Oceanic and estuarine transport of fish eggs and larvae: A review. Transactions of the American Fisheries Society. 113: 153-165.

Oey, L-Y. 1986. The formation and maintenance of density fronts on the U.S. southeastern continental shelf during winter. Journal of Physical Oceanography. 16: 1121-1135.

Oey, L-Y., L.P. Atkinson, LP, and J.O. Blanton. 1987. Shoreward intrusion of upper Gulf Stream water onto the U.S. southeastern continental shelf. Journal of Physical Oceanography. 17: 2318-2333.

Ortner, P.B., L.B. Crowder, and D.E. Hoss. 1999. The South Atlantic Bight Recruitment Experiment: introduction and overview. Fisheries Oceanography. 8(S2): 1-6.

Paris, C.B., and R.K. Cowen. 2004. Direct evidence of a biophysical retention mechanism for coral reef fish larvae. Limnology and Oceanography. 49: 1964-1979.

Pietrafesa, L.J., G.S. Janowitz, and P.A. Wittman. 1985. Physical oceanography processes in the Carolina Capes region, pp. 23-32. In Oceanography of the southeastern U.S. continental shelf (L.P. Atkinson, D.W. Menzel, and K.A. Bush, eds.). American Geophysical Union, Washington, D. C.

Pond, S. and G.L. Pickard. 1995. Introductory dynamical oceanography, 2nd edition.

Powell, A.B., D.G. Lindquist, and J.A. Hare. 2000. Larval and pelagic juvenile fishes collected with three types of gear in Gulf Stream and shelf waters in Onslow Bay, North Carolina, and comments on ichthyoplankton distribution and hydrography. Fishery Bulletin. 98: 427-438.

Quinlan, J.A. and L.B. Crowder. 1999. Searching for sensitivity in the life history of Atlantic menhaden. Inferences from a matrix model. Fisheries Oceanography. 8 (S2)124-133.

Quinlan, J.A., B.O. Blanton, T.J. Miller, and F.E. Werner. 1999. From spawning grounds to the estuary: using linked individual-based and hydrodynamic models to interpret patterns and processes in the oceanic phase of Atlantic menhaden *Brevoortia tyrannus* life history. Fisheries Oceanography. 8(S2): 224-246.

Reiss, C.S. and J.R. McConaugha 1999. Cross-frontal transport and distribution of ichthyoplankton associated with Chesapeake Bay plume dynamics. Continental Shelf Research. 19: 151-170.

Rice, J.A., J.A. Quinlan, S.W. Nixon, W.F, Jr. Hettler, S.M. Warlen, and P.M. Stegmann. 1999. Spawning and transport dynamics of Atlantic menhaden: inferences from characteristics of immigrating larvae and predictions of a hydrodynamic model. Fisheries Oceanography. 8(S2): 93-110.

Rudnick, D.L. and J.L. Luyten. 1996. Intensive surveys of the Azores Front. 1. Tracers and dynamics. Journal of Geophysical Research. 101: 923-939

Savidge, D.K. 2002. Wintertime shoreward near-surface currents south of Cape Hatteras. Journal of Geophysical Research. 107(C11).

Sharples, J. 1997. Cross-shelf intrusion of subtropical water into the coastal zone of northeast New Zealand. Continental Shelf Research. 17: 835-857.

Simpson, J.H. and I.D. James. 1986. Coastal and estuarine fronts, pp. 63-93. In Baroclinic processes on continental shelves (C. N. K. Mooers, ed.). American Geophysical Union, Washington, D.C.

Sponaugle, S., R.K. Cowen, A. Shanks, S.G. Morgan, J.M. Leis, J.S. Pineda, G.W. Boehlert, M.J. Kingsford, K.C. Lindeman, C. Grimes, and J.L. Munro. 2002. Predicting self-recruitment in marine populations: Biophysical correlates and mechanisms. Bulletin of Marine Science. 70: 341-375.

Sponaugle, S., T. Lee, V. Kourafalou, and D. Pinkard, D. 2005. Florida Current frontal eddies and the settlement of coral reef fishes. Limnology and Oceanography. 50: 1033-1048.

Stegmann, P.M. and J.A. Yoder. 1996. Variability of sea-surface temperature in the South Atlantic Bight as observed from satellite: Implications for offshore-spawning fish. Continental Shelf Research. 16: 843-861.

Stegmann, P.M., J.A. Quinlan, F.E. Werner, B.O. Blanton, and P. Berrien. 1999. Atlantic menhaden recruitment to a southern estuary: defining potential spawning regions. Fisheries Oceanography. 8(S2): 111-123.

Ullman, D.S. and P.C. Cornillon. 1999. Satellite-derived sea surface temperature fronts on the continental shelf off the northeast US coast. Journal of Geophysical Research-Oceans. 104 (C10): 23459-23478.

Ullman, D.S. and P.C. Cornillon. 2001. Continental shelf surface thermal fronts in winter off the northeast US coast. Continental Shelf Research. 21: 1139-1156.

Warlen, S.M. 1982. Age and growth of larvae and spawning time of Atlantic croaker in North Carolina. Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies. 34: 204-214.

Warlen, S.M. 1992. Age, growth, and size distribution of larval Atlantic menhaden off North Carolina. Transactions of the American Fisheries Society. 121: 588-598.

Warlen, S.M. and A.J. Chester 1985. Age, growth, and distribution of larval spot, *Leiostomus xanthurus* , off North Carolina. Fishery Bulletin. 83: 587-600.

Werner, F.E., B.O. Blanton, J.A. Quinlan, and R.A. Jr. Luettich. 1999. Physical oceanography of the North Carolina continental shelf during fall and winter seasons: implications for the transport of larval menhaden. Fisheries Oceanography. 8(S2): 7-21.

Xie, L. and L.J. Pietrafesa. 1995. Shoreward intrusion of upper-layer warm water by prescribed shelf break temperature perturbation and surface wind stress. Geophysical Research Letters. 22: 2585-2588.

Appendixes

1.6 Appendixes

1.6a Appendix A: Hydrographic data

Hydrographic data was sampled along a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sampling was conducted on 27 cruises during December, January, and February from 1991 to 1999 (Table 1). Data from both a conductivity, temperature, and depth (CTD) probe and sea surface temperature (SST) data were used to determine water masses from each station and locate boundaries (i.e., fronts) between water masses along each transect (see Methods section). When CTD casts were available, water temperature, salinity, and density plots were used to define water masses on each transect (Figs. A1 – A21), otherwise SST data from satellite images were used (Figs. A22 – A24).

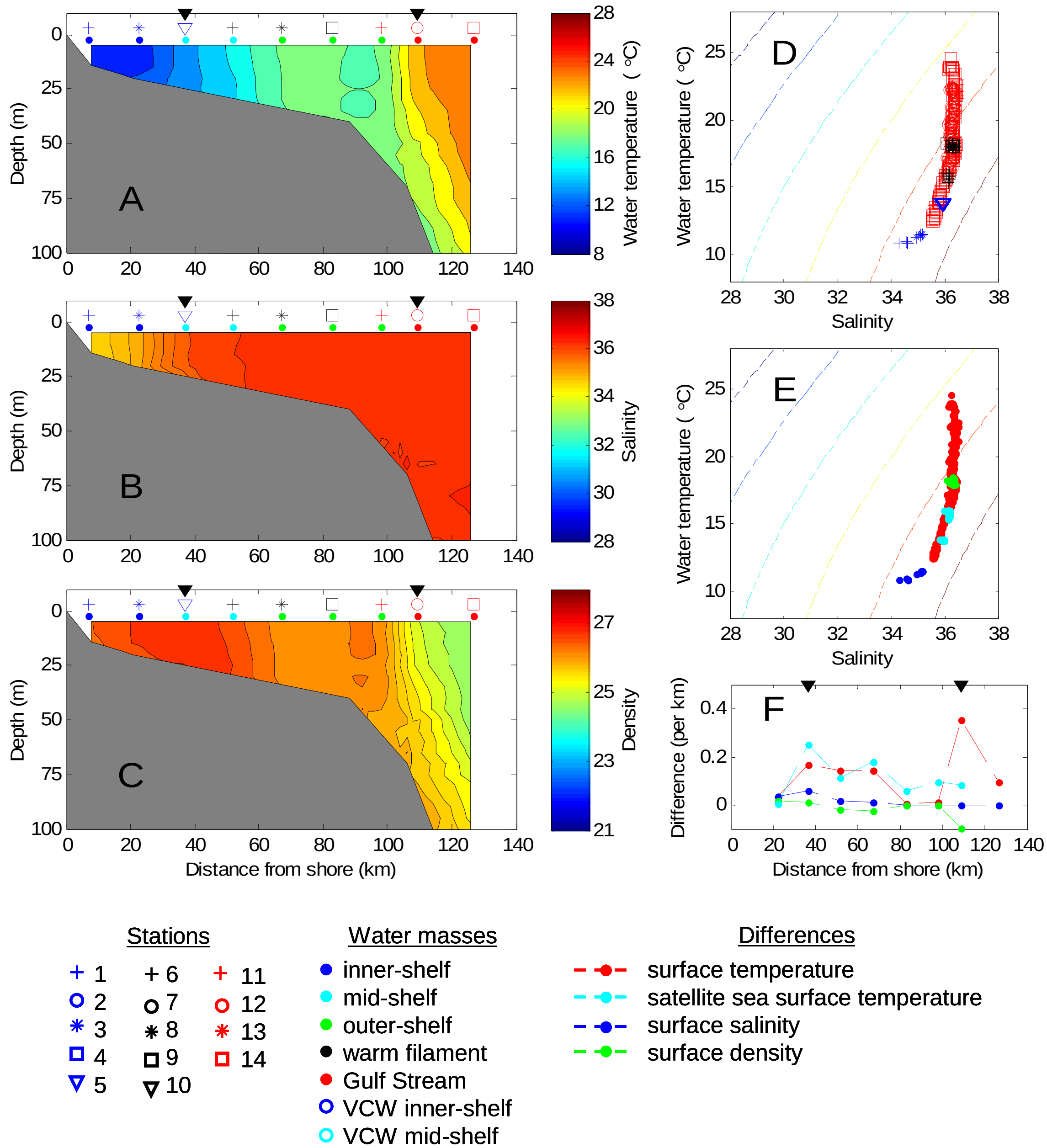

Figure A1. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 30 January 1990. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

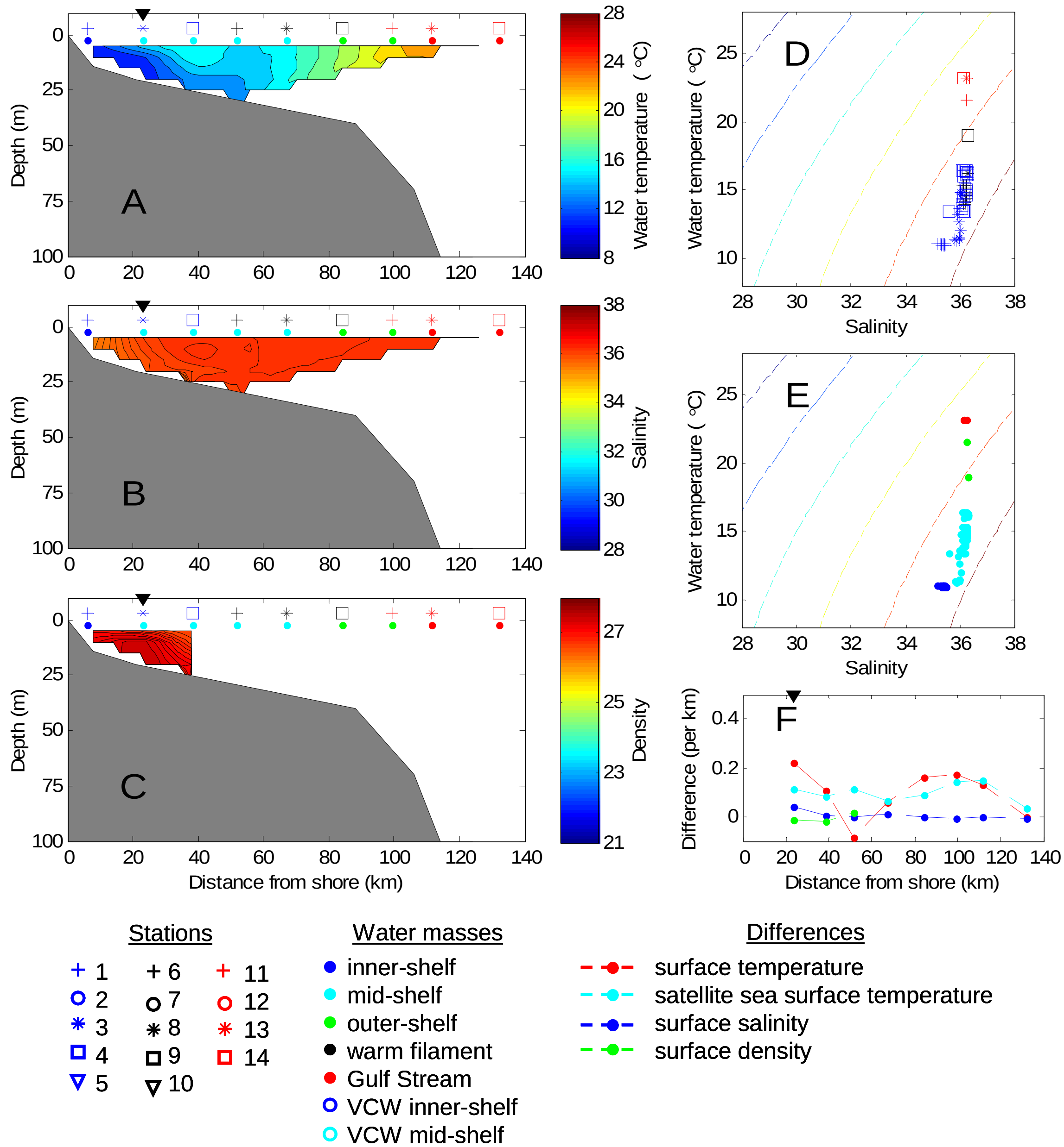

Figure A2. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 7 February 1991. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

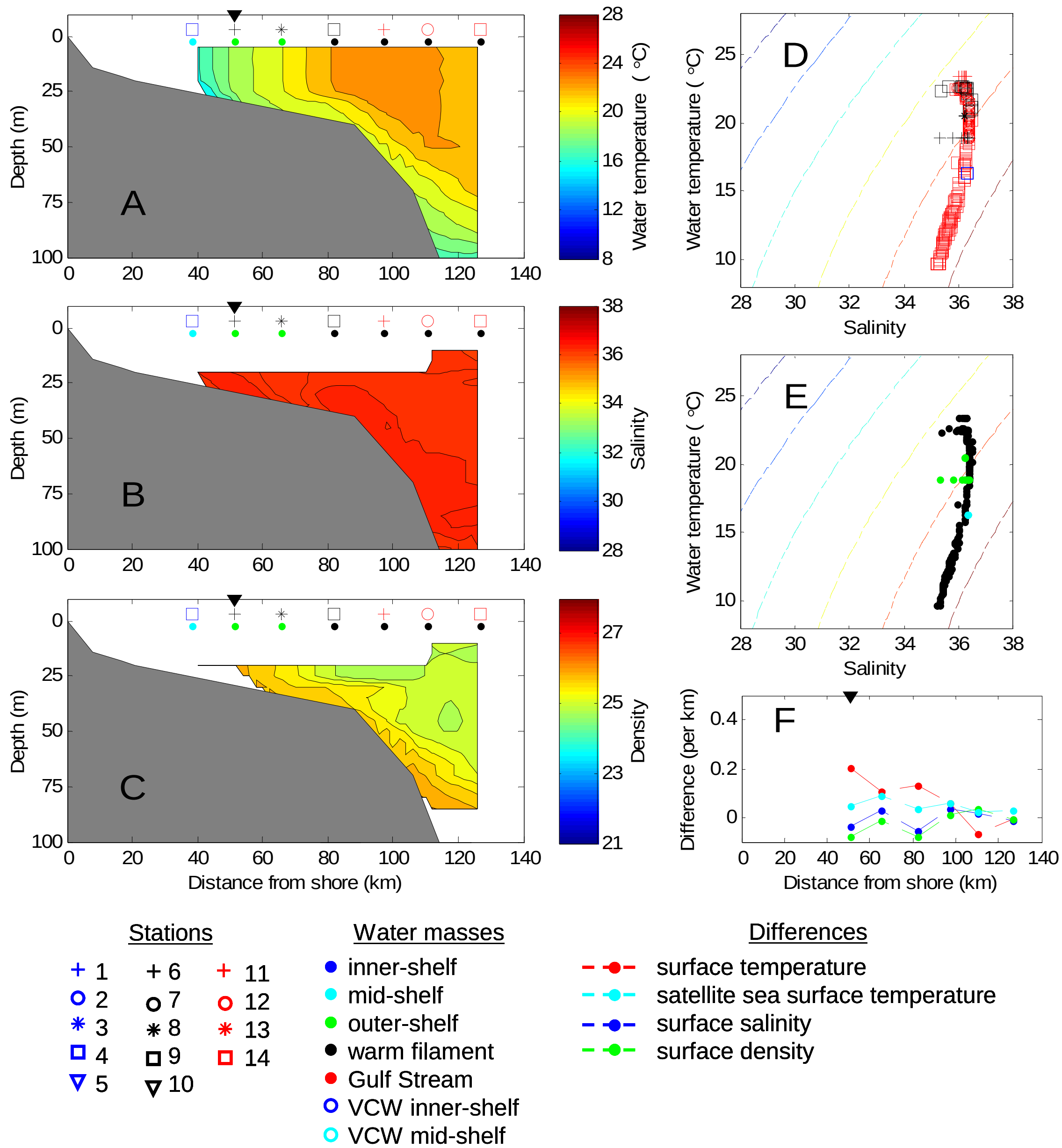

Figure A3. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 18-19 December 1991. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

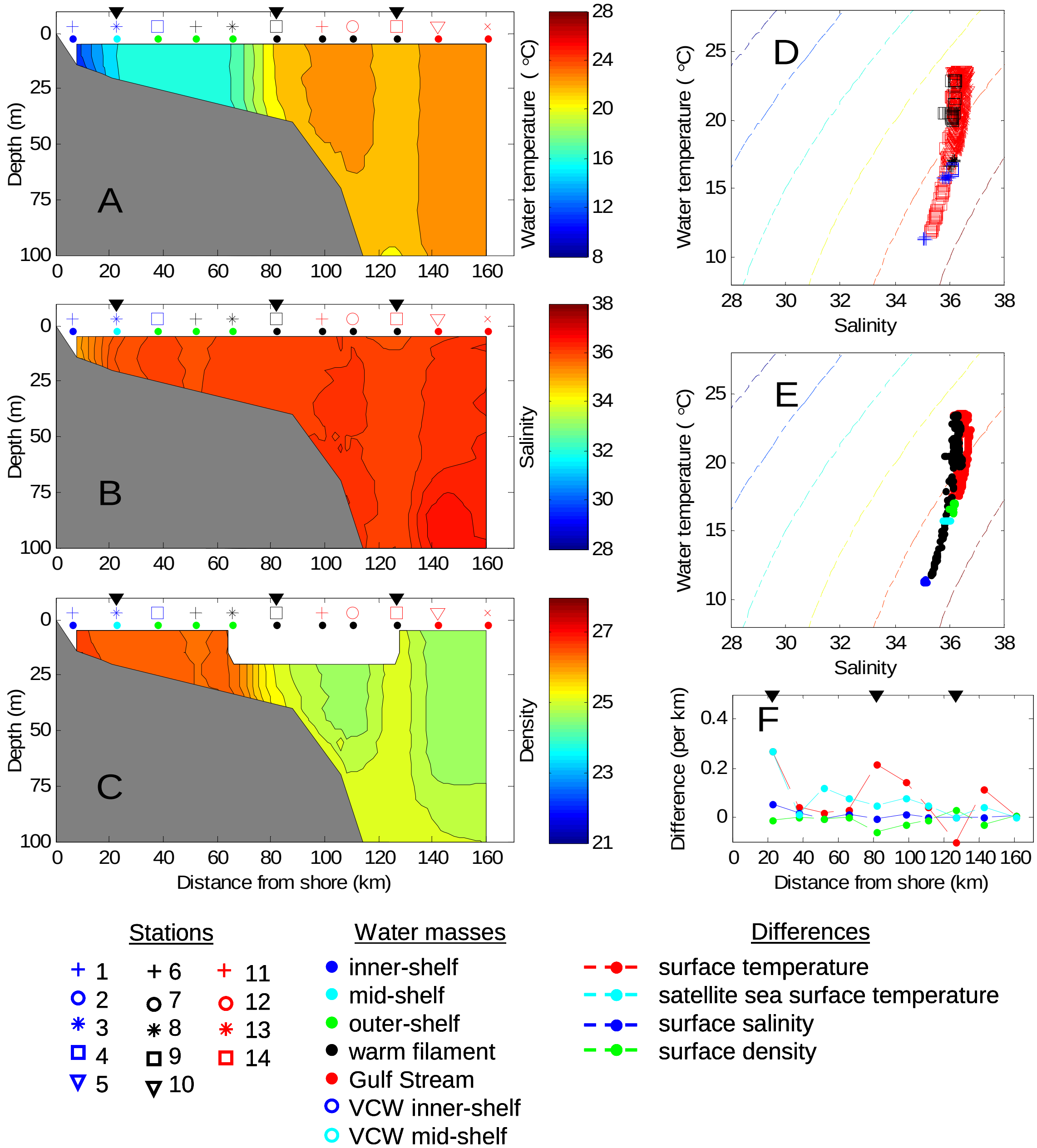

Figure A4. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 11-12 January 1992. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

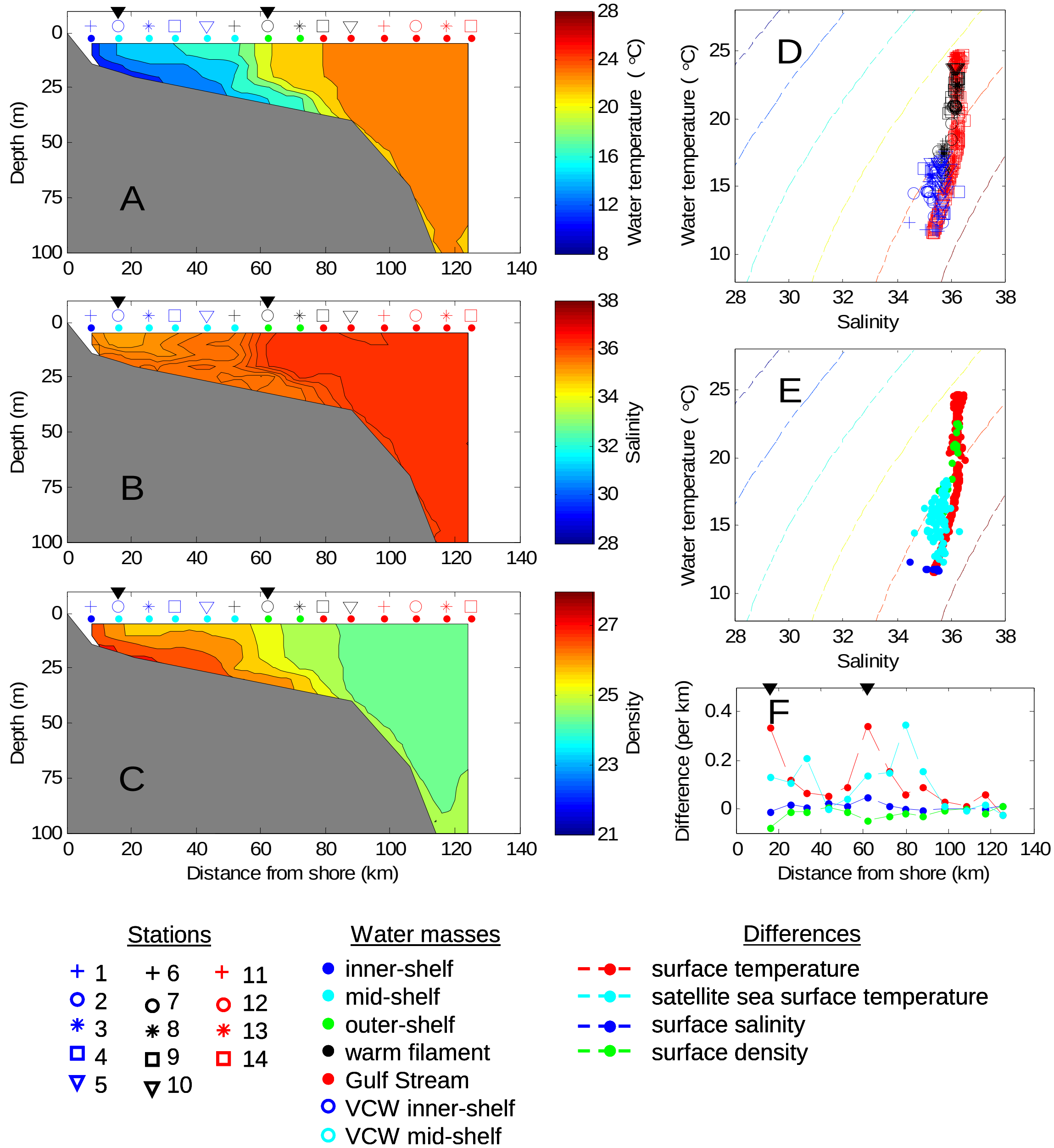

Figure A5. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 20-21 December 1992. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

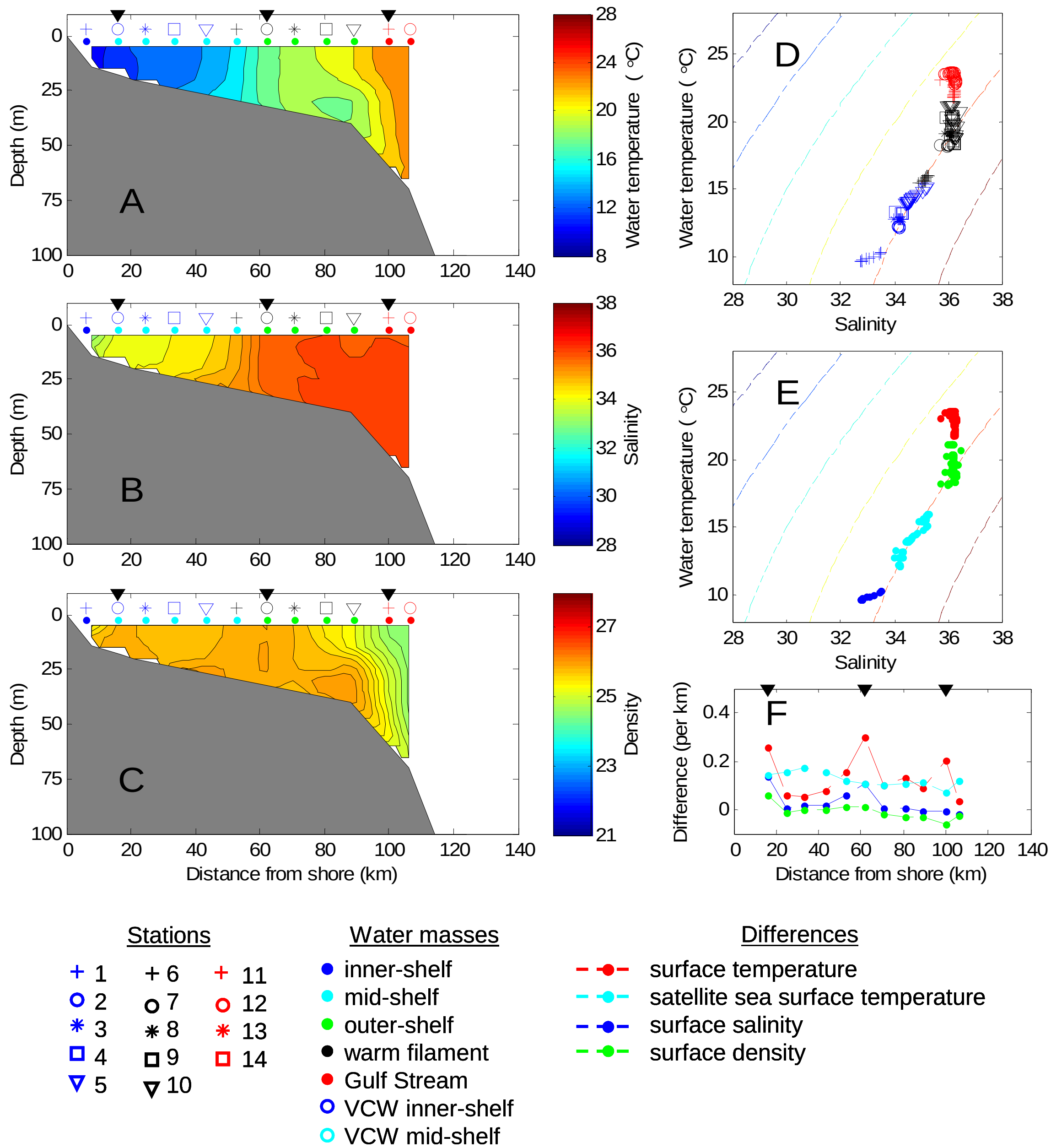

Figure A6. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 11-12 February 1993. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, $kg \cdot m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

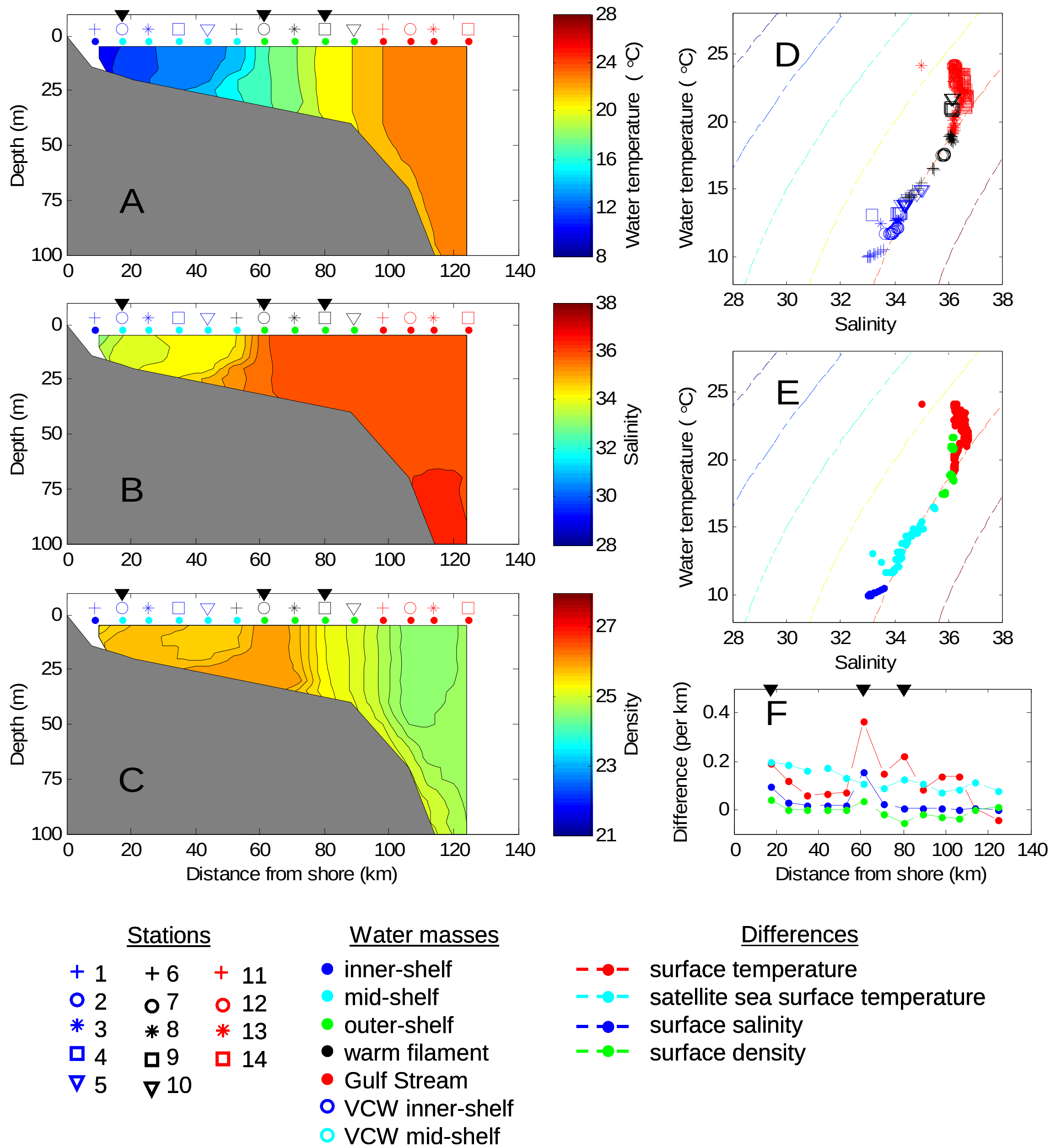

Figure A7. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 13-14 February 1993. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

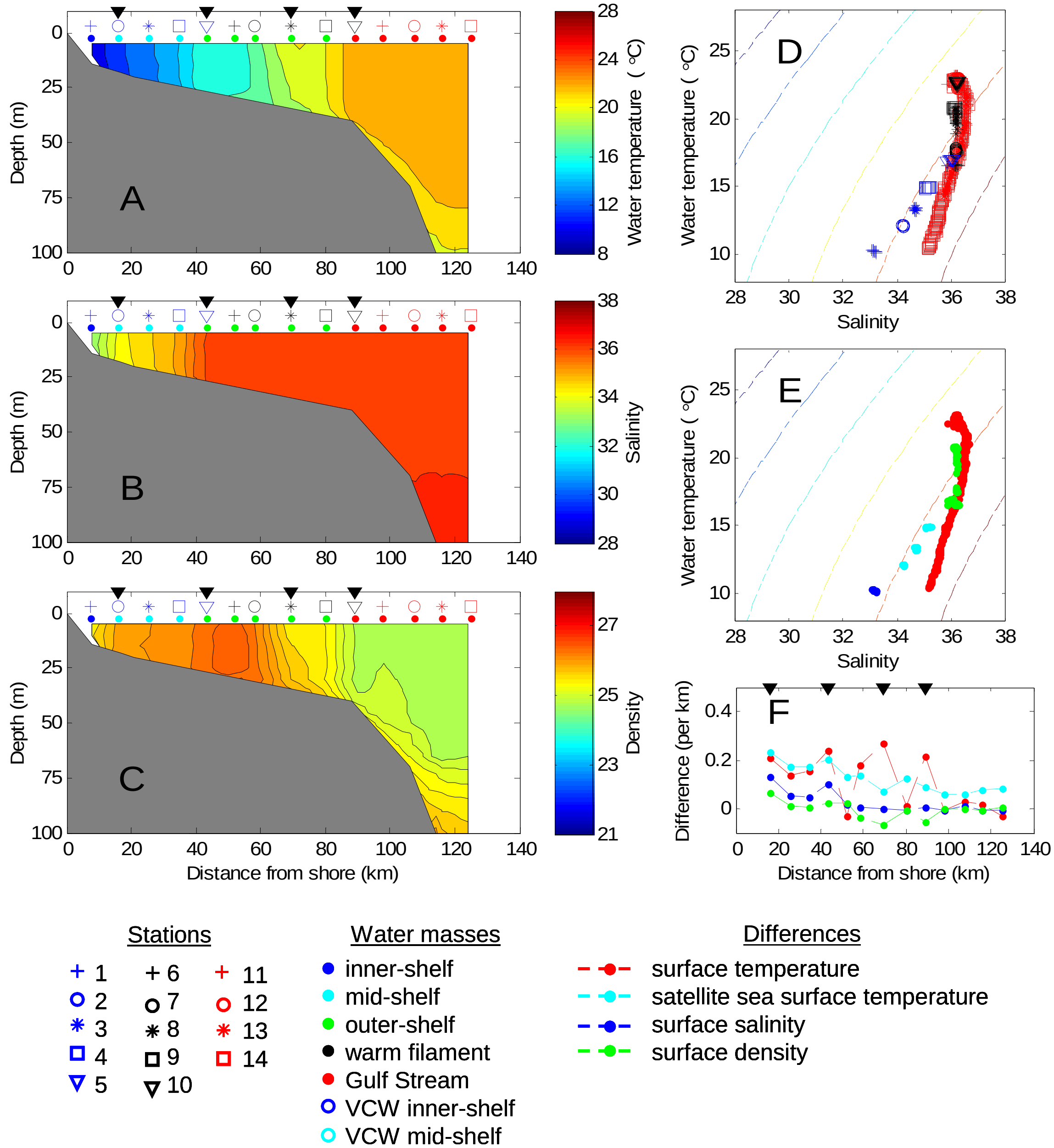

Figure A8. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 17-18 February 1993. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

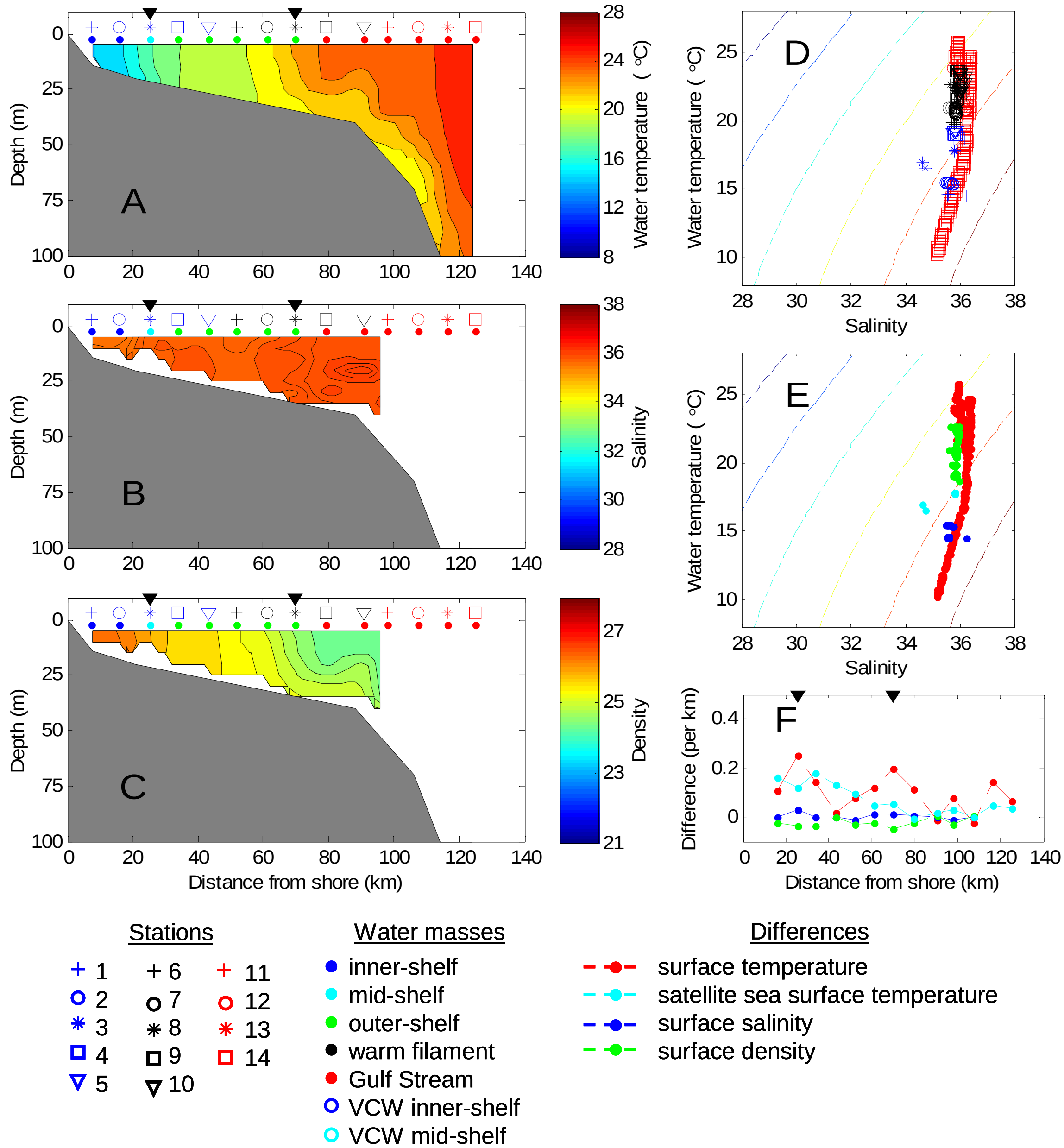

Figure A9. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 7-8 December 1993. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, $kg \cdot m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

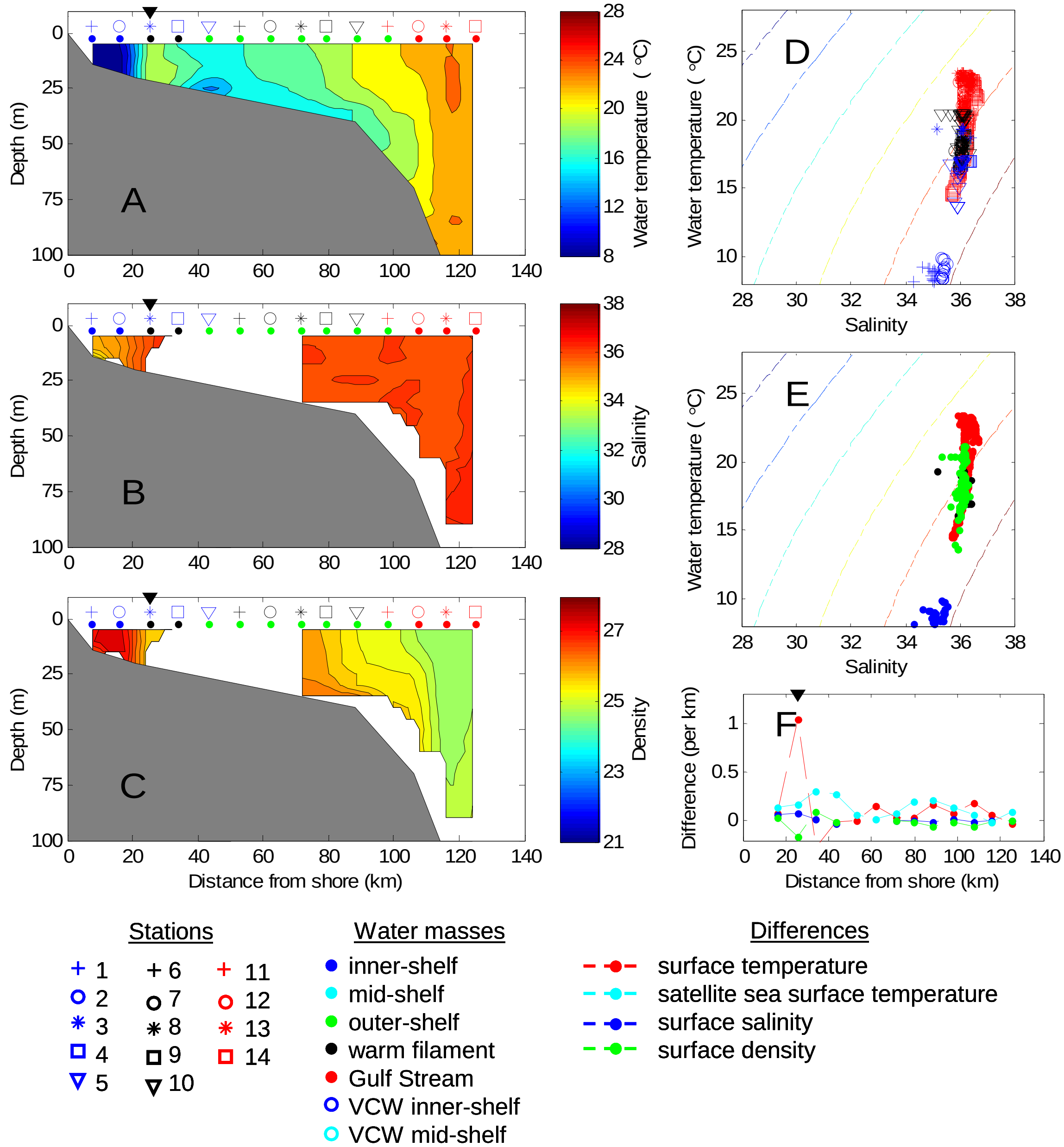

Figure A10. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 1-2 February 1994. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

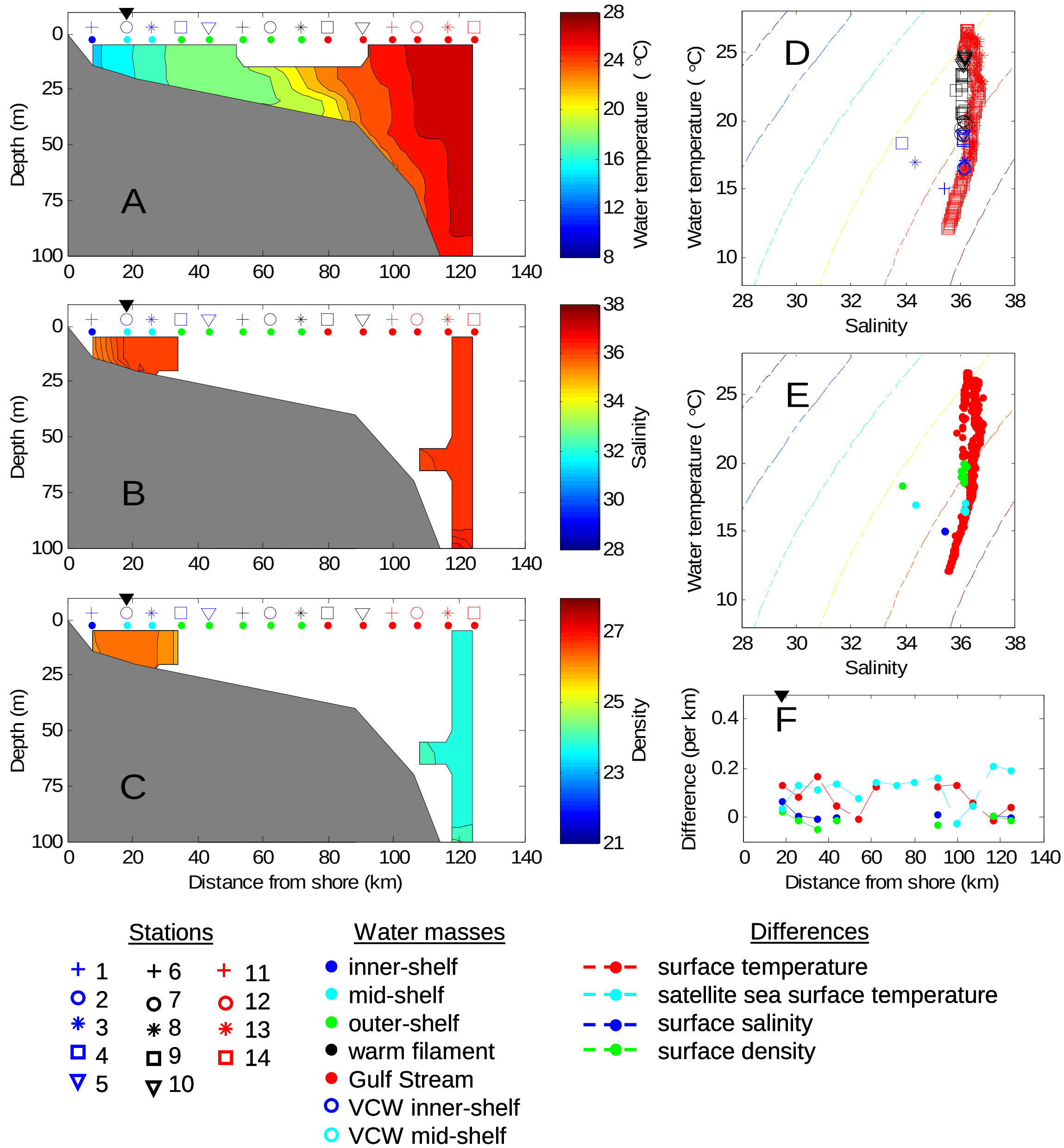

Figure A11. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 13 December 1994. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

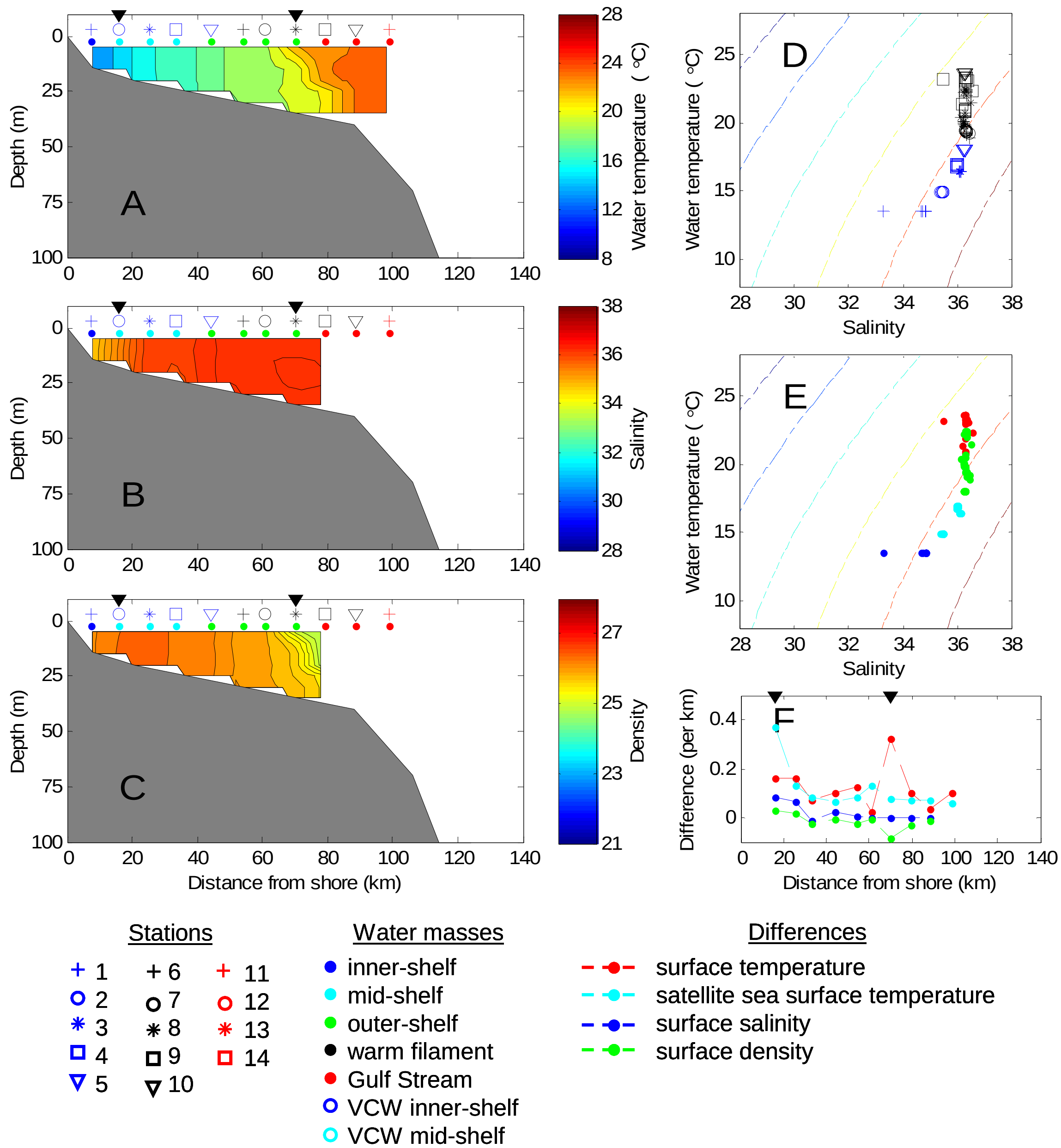

Figure A12. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 5-6 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, $kg \cdot m^{-3}$), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

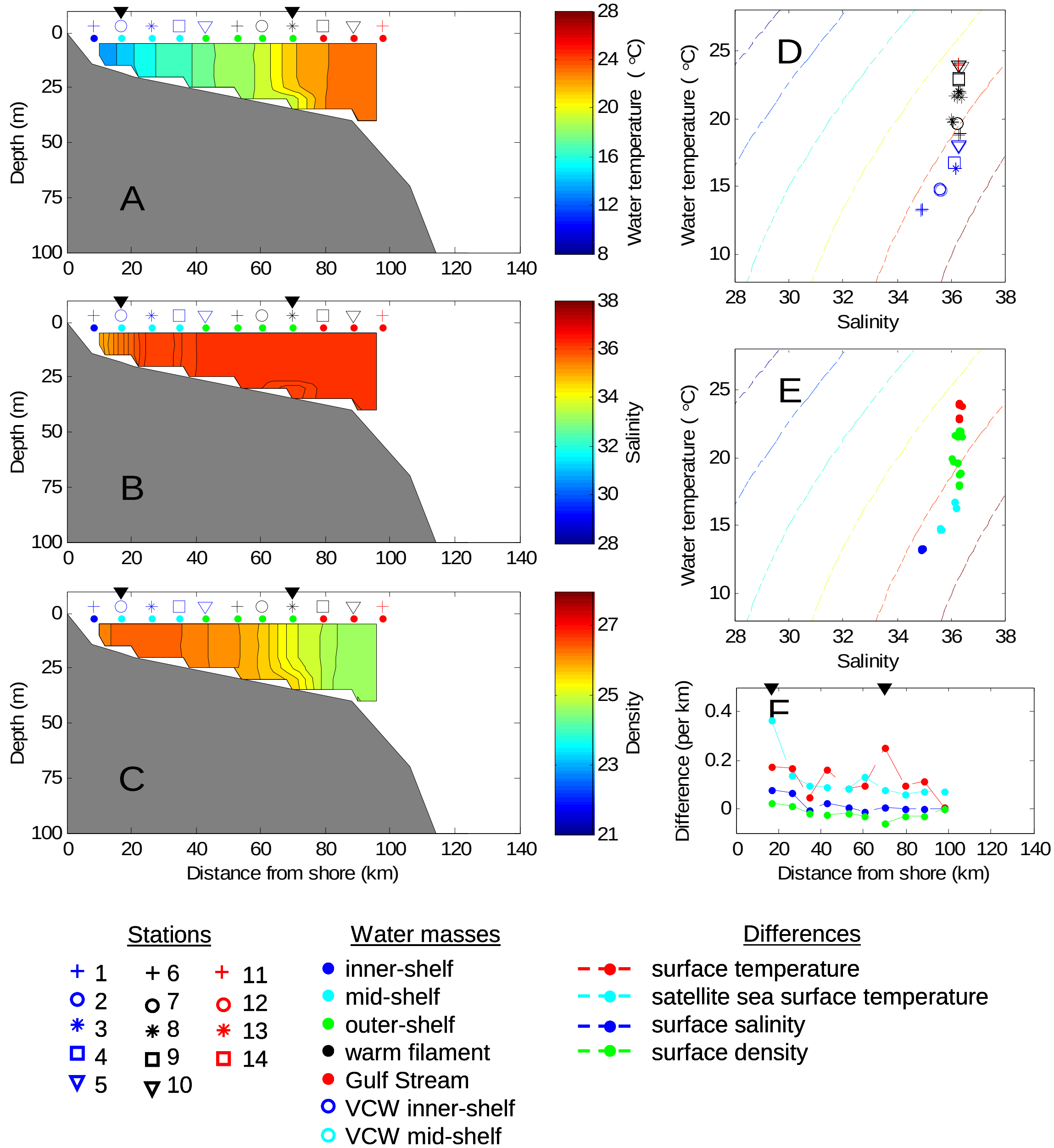

Figure A13. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 7-8 December 1995. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

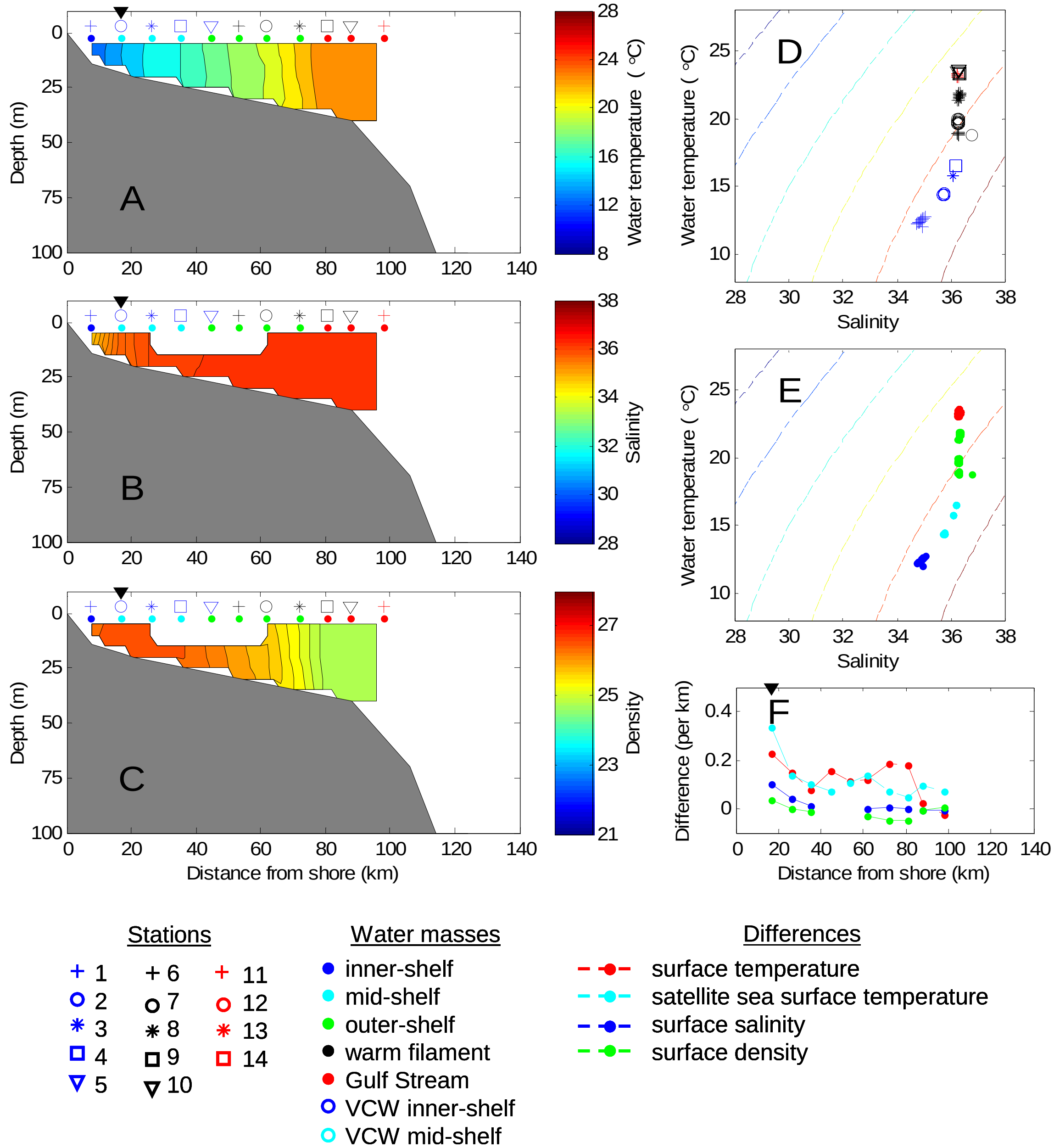

Figure A14. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 9-10 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

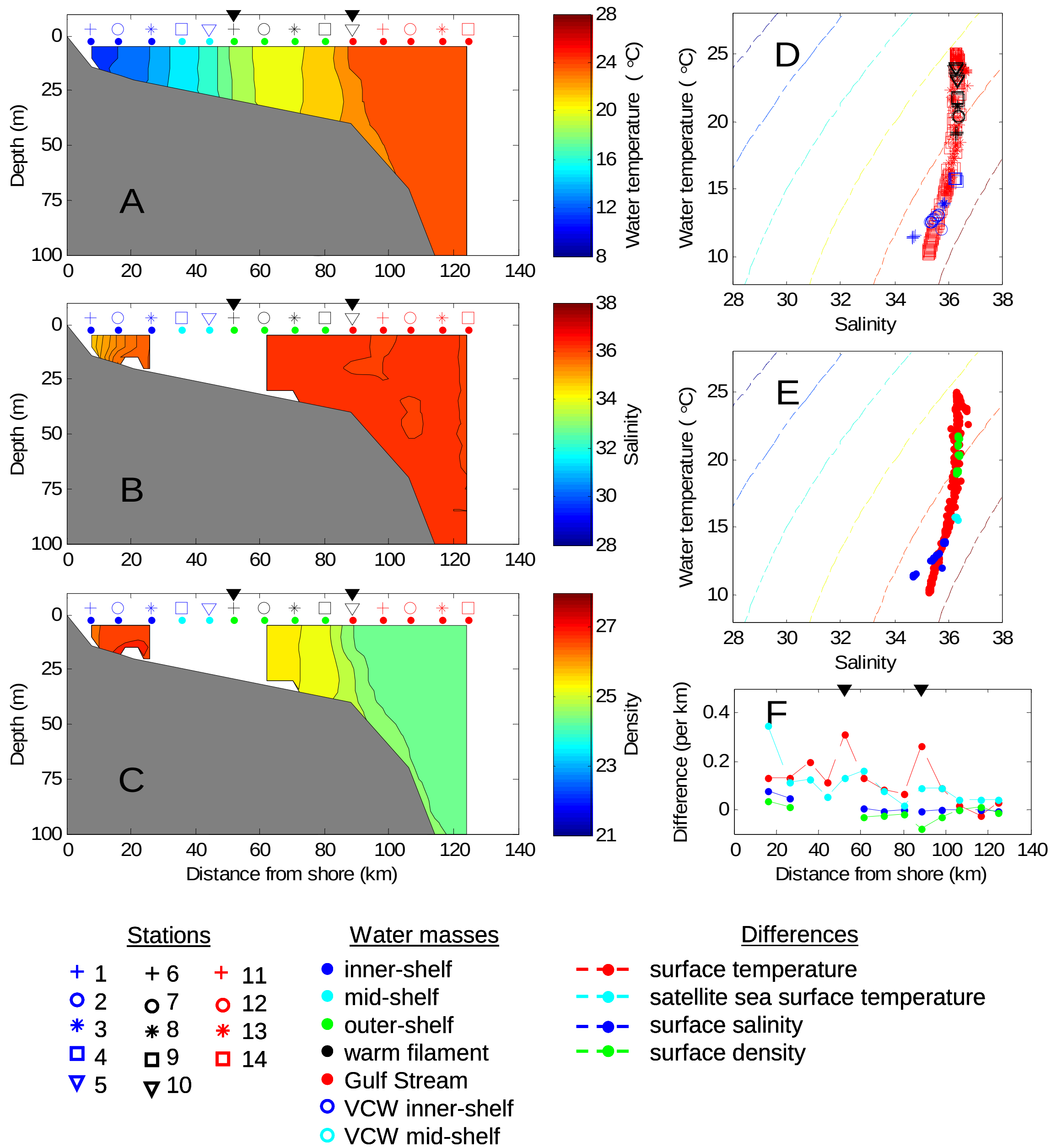

Figure A15. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 12-13 December 1995. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

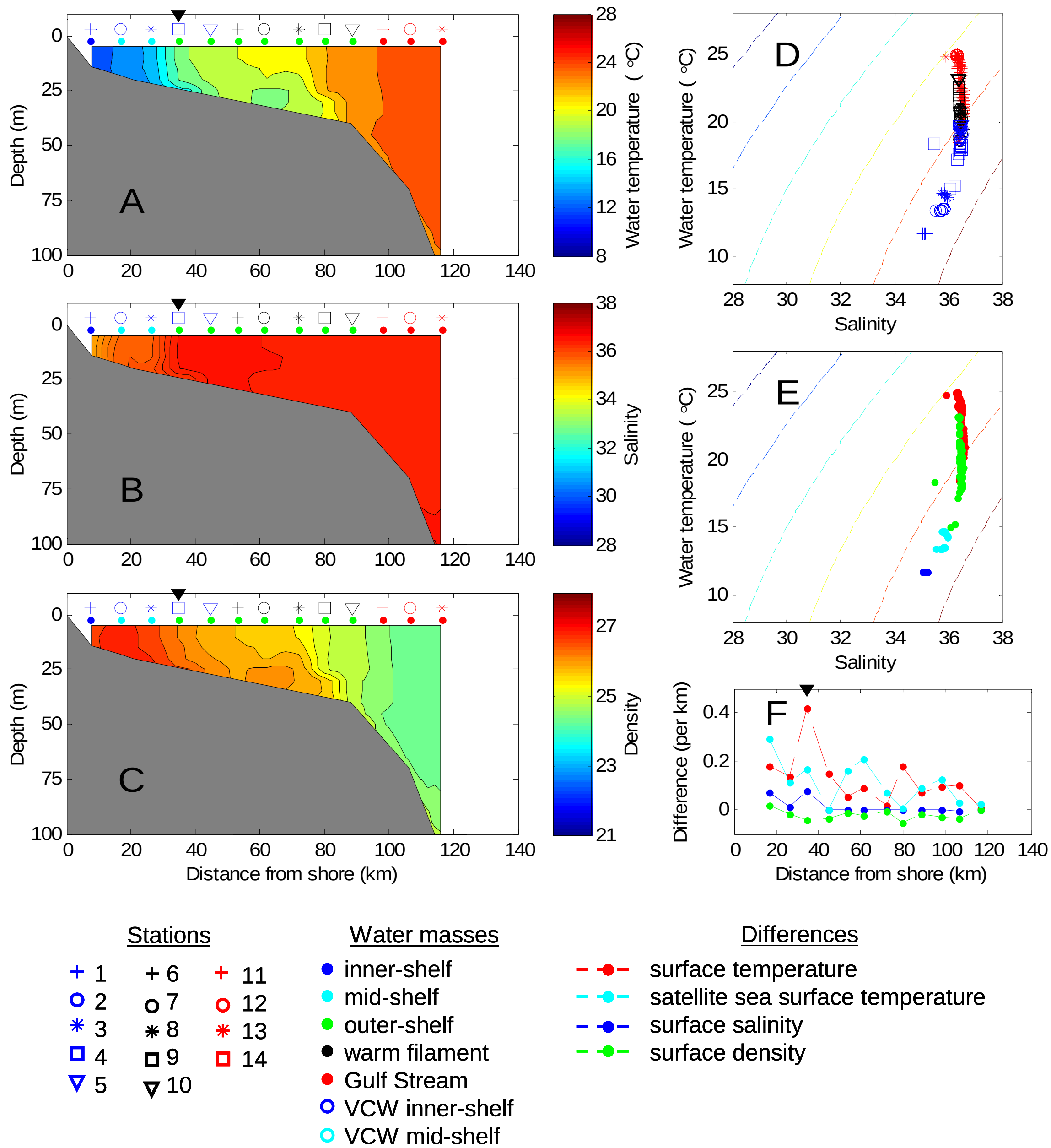

Figure A16. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 18-19 December 1995. Cross-shelf profiles of water temperature (A, ^{o}C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

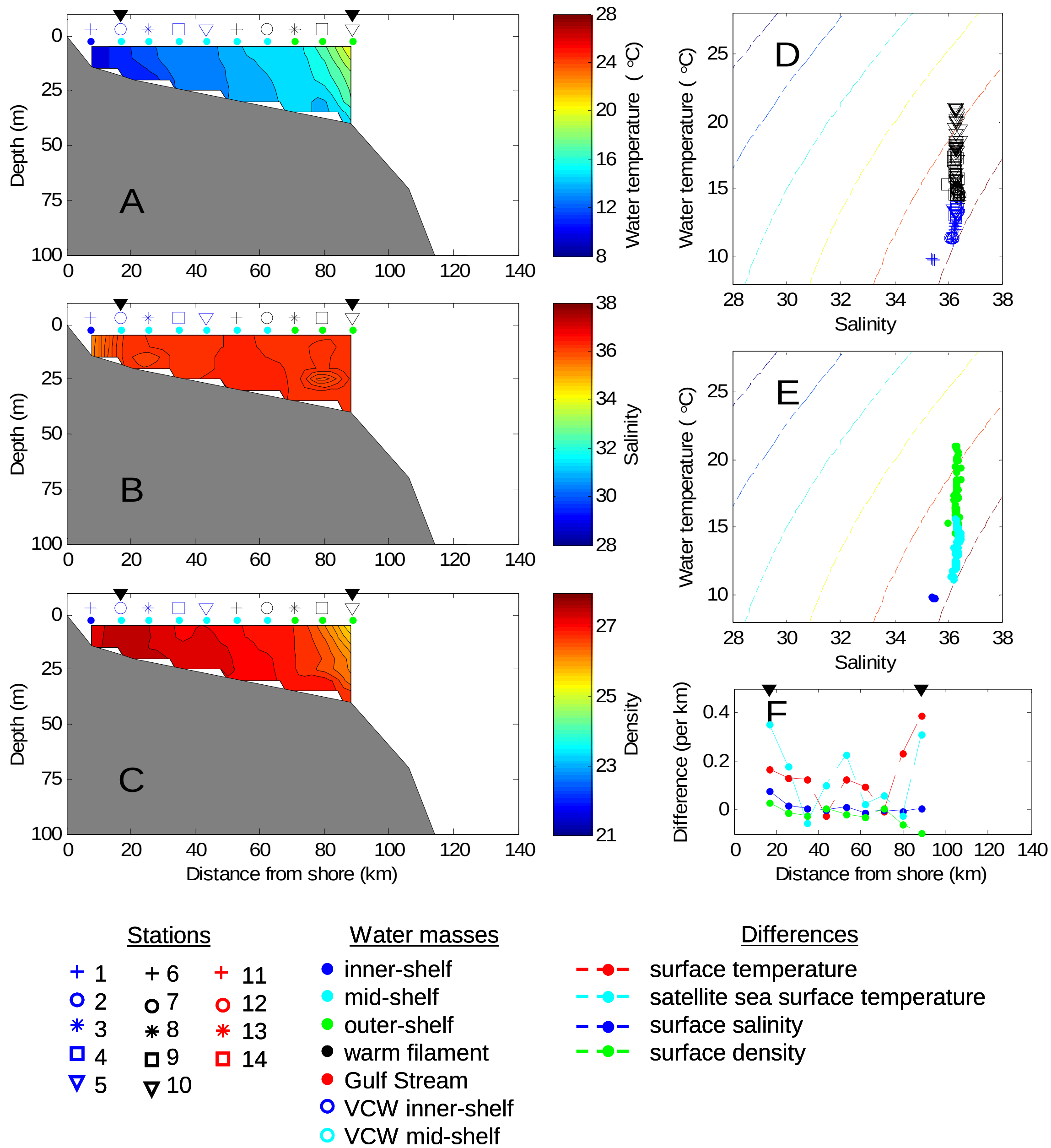

Figure A17. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 30-31 January 1996. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

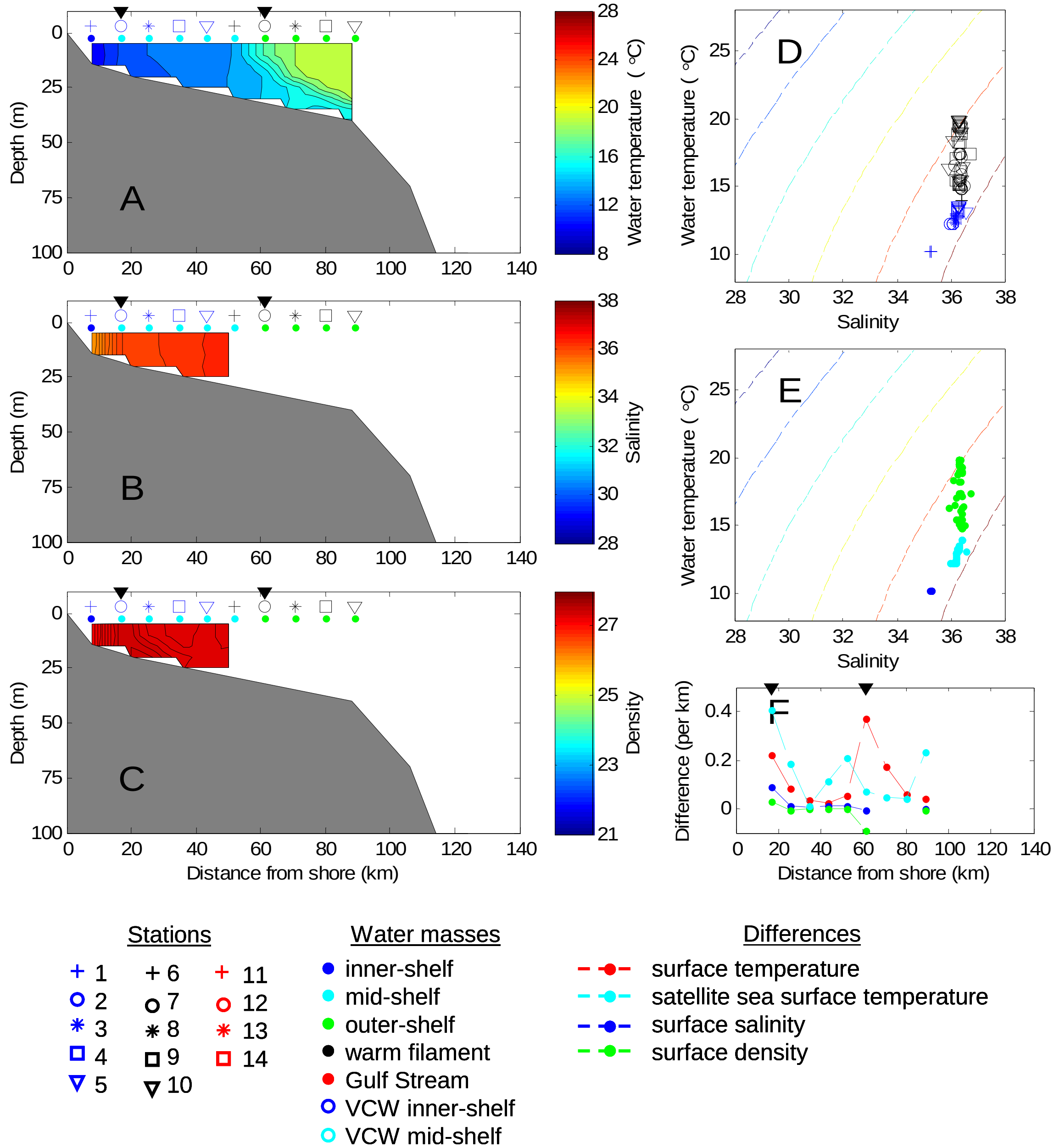

Figure A18. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 1-2 February 1996. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

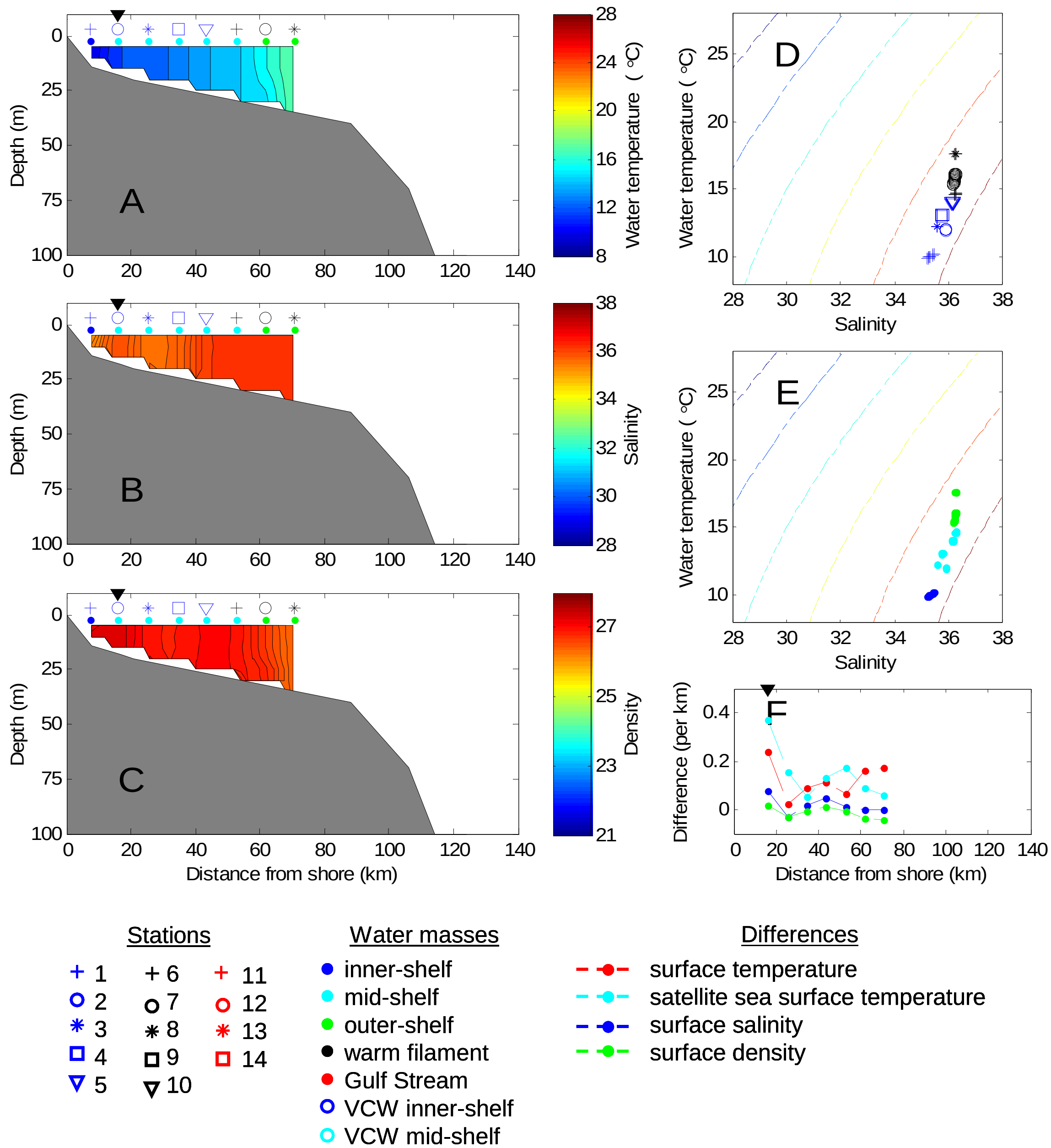

Figure A19. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 3-4 February 1996. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

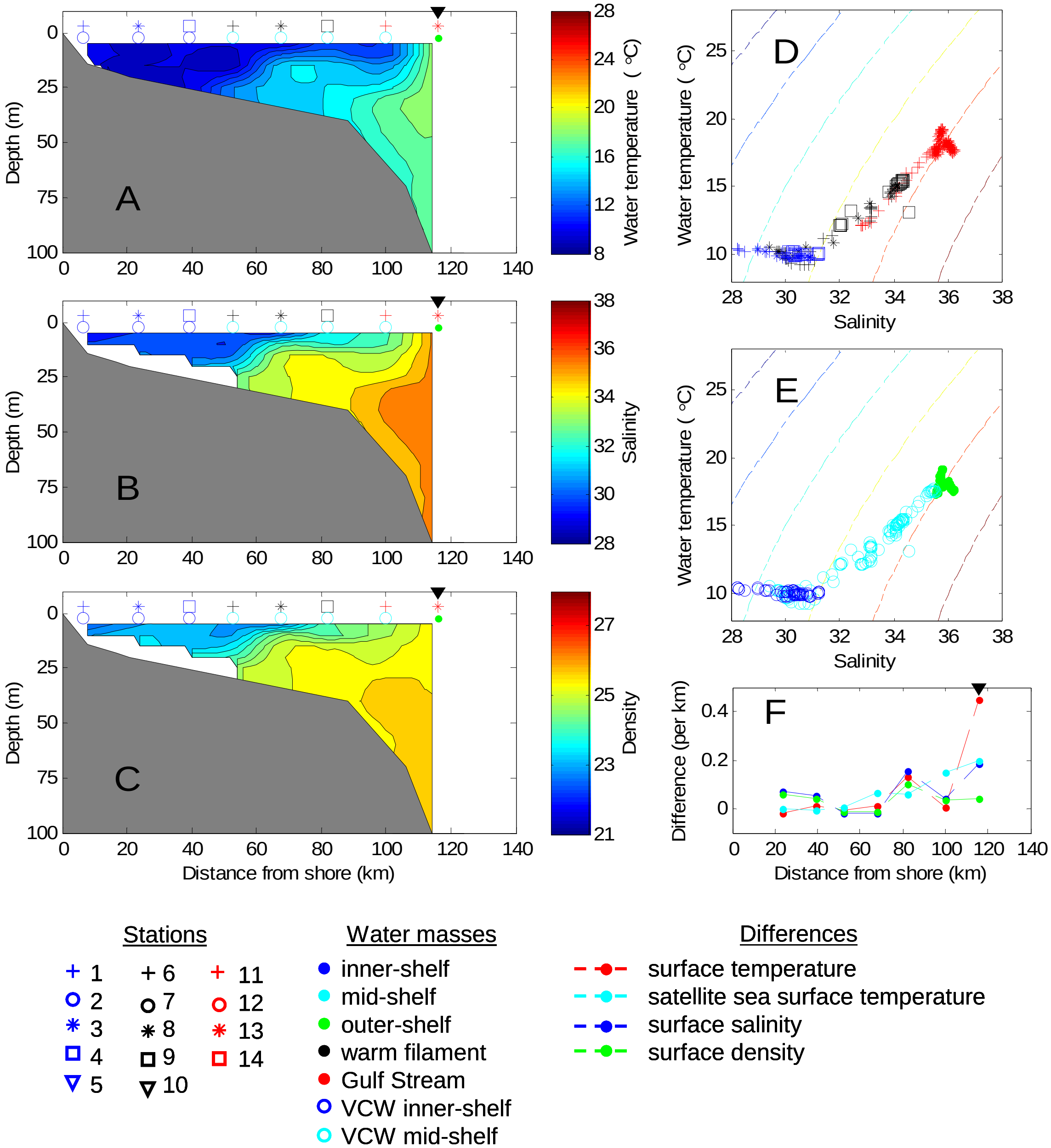

Figure A20. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 19 February 1998. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

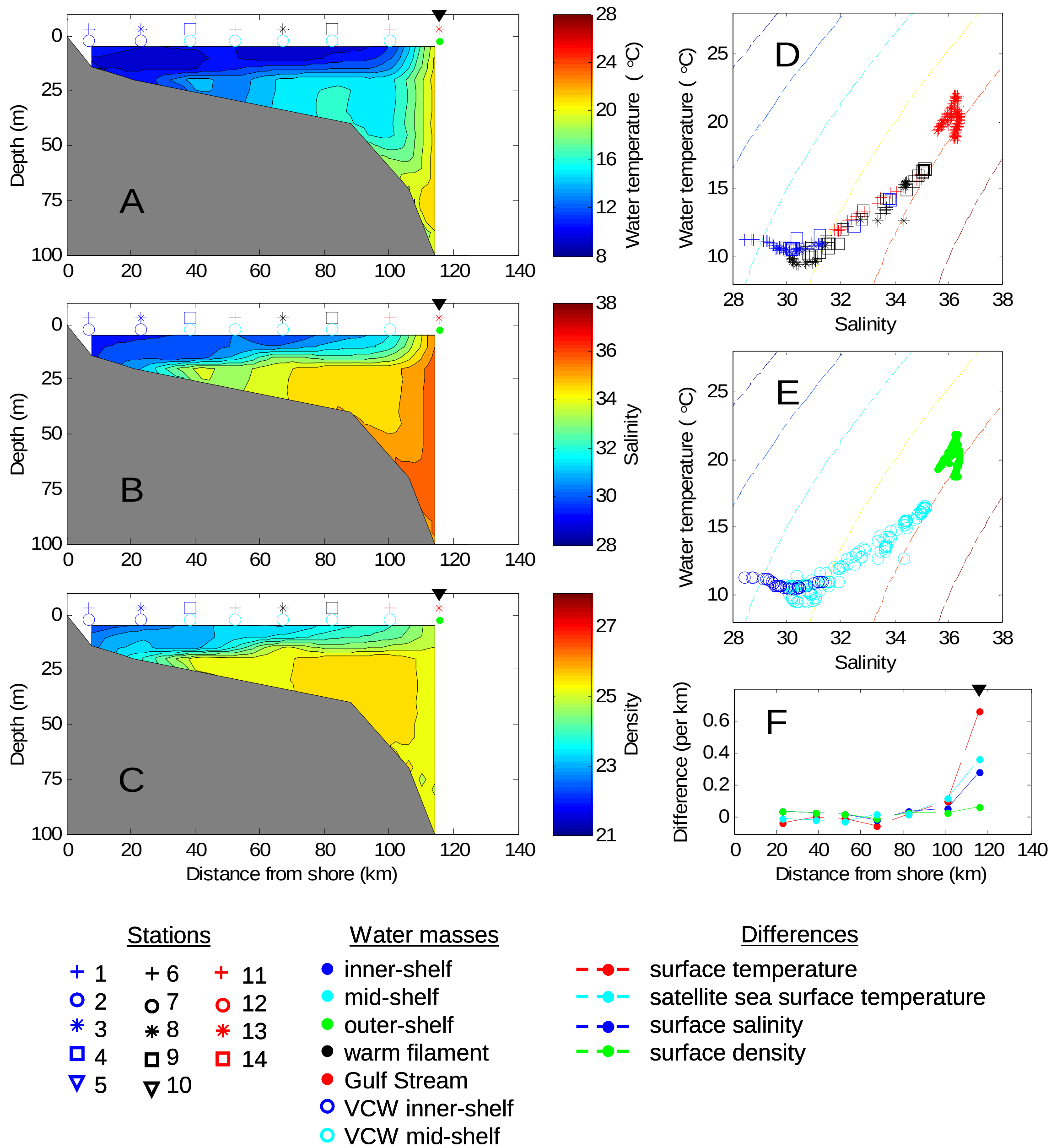

Figure A21. Hydrographic data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2) sampled 25-26 February 1998. Cross-shelf profiles of water temperature (A, °C), salinity (B), density (C, σ_t, kg·m^{-3}), and average water column temperature, salinity, and density (D, lines of equal density at a pressure of 0 dbar) were used to define water masses (E) and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled and open circles (Water masses). Locations of fronts are shown with filled black triangles, and were detected by abrupt differences (Differences) in surface water temperature, satellite sea surface temperature, salinity, or density over a short distance (F).

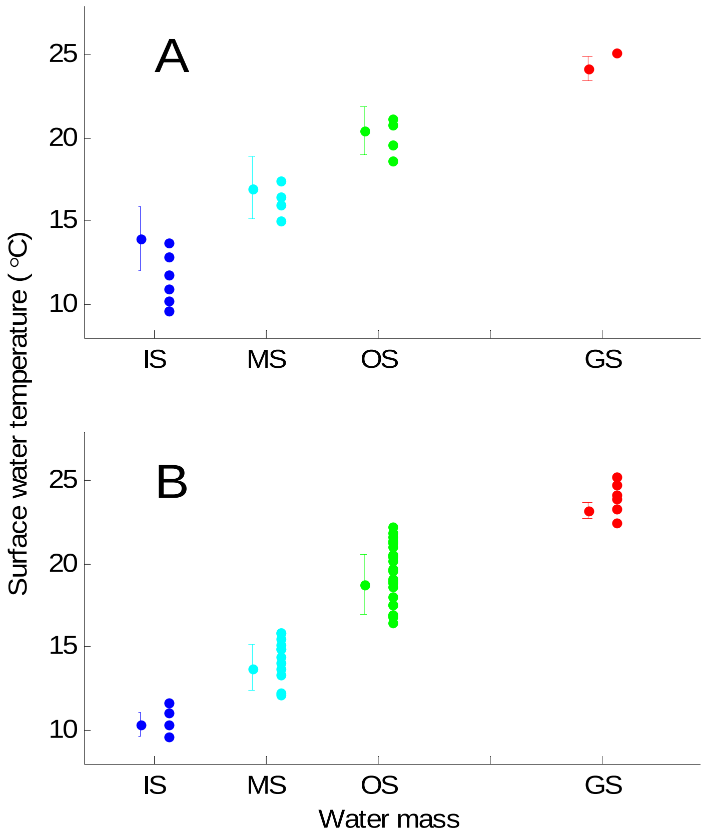

Figure A22. Mean (standard deviation) surface water temperature (^{o}C) from CTD cast and satellite sea surface temperature used to define water masses for transects with out CTD casts for December (A) and January – February (B). IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, and GS = Gulf Stream.

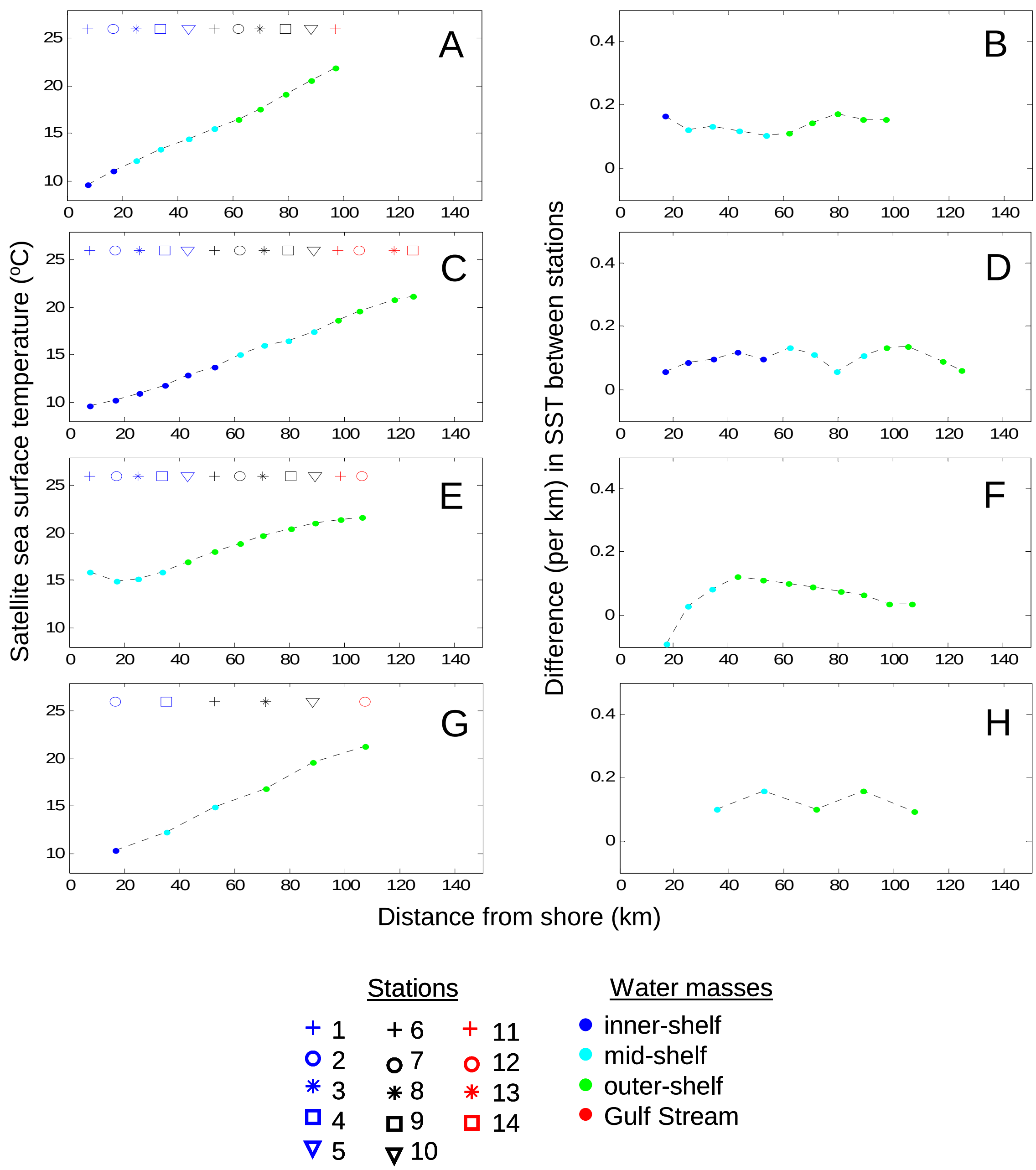

Figure A23. Satellite sea surface temperature (SST, °C) data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Transects shown are for 18 January 1994 (A, B), 6-7 December 1994 (C,D), 7 February 1995 (E, F), and 15-16 February 1996 (G, H). SST were used to define water masses and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled circles (Water masses; A, C, E, G). Locations of fronts were detected by abrupt differences in SST between stations (B, D, F, H).

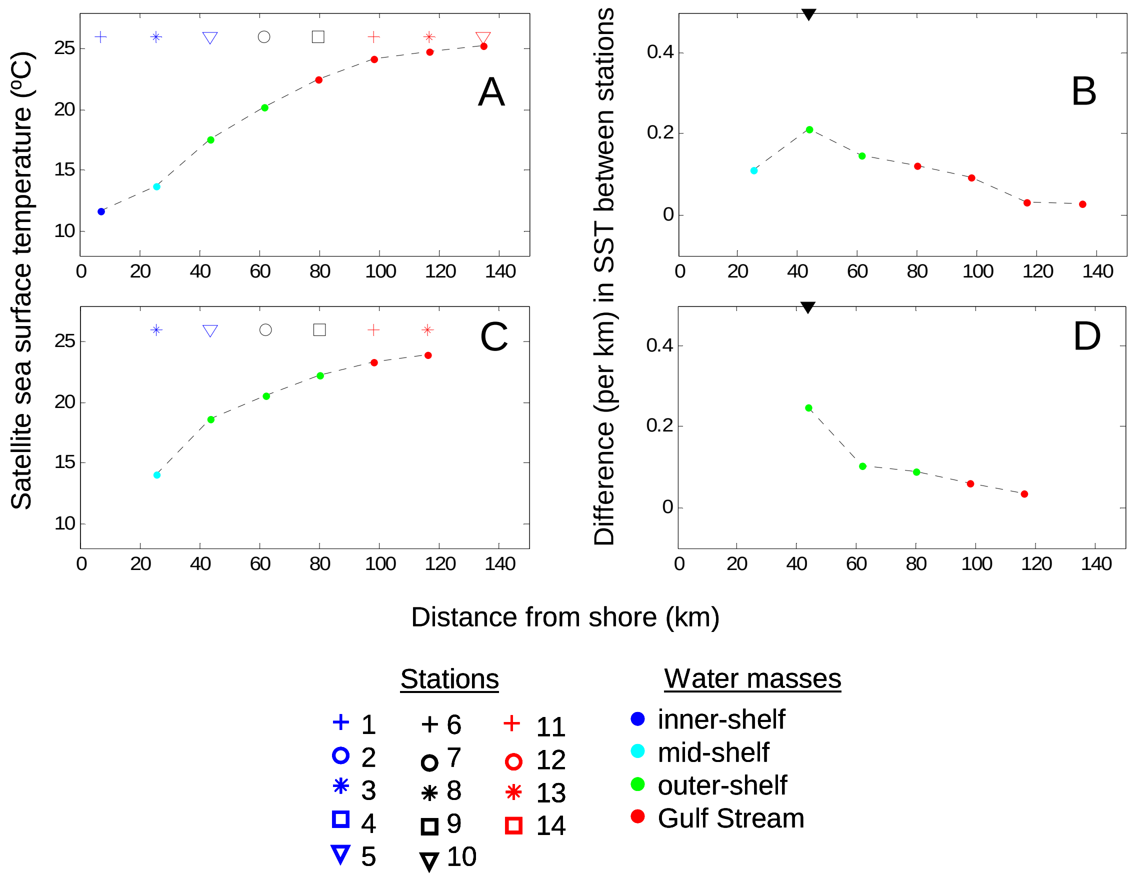

Figure A24. Satellite sea surface temperature (SST, °C) data from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Transects shown are for 18-19 January 1999 (A, B) and 28-29 January 1999 (C,D). SST were used to define water masses and locate fronts. Individual stations are shown with several types of symbols (Stations) and water masses are represented by filled circles (Water masses; A, C). Locations of fronts were detected by abrupt differences in SST between stations (B, D) and are shown with filled black triangles.

1.6b Appendix B: Larval fish data

Larval fish were sampled along a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Sampling was conducted on 27 cruises during December, January, and February from 1991 to 1999 (Table 1). Standard sampling techniques were used to collect ichthyoplankton using a 60 cm bongo net fitted with two 333 μm mesh nets. Oblique tows, which sampled the water column from the surface to within 1 m of the bottom or 200 m (which ever was shallower), were conducted. Ichthyoplankton samples were processed and larval fish abundances were standardized and abundances of three size classes (small, medium, and large) calculated for each taxa (see Methods section).

Concurrent hydrographic data from both a conductivity, temperature, and depth (CTD) probe and sea surface temperature (SST) data were used to determine water masses from each station and locate boundaries (i.e., fronts) between water masses along each transect (see Methods section and Appendix A).

Average cross-shelf patterns in larval abundance and size were described for each taxa-size class in relation to water masses (Figs. B1 – B6). Two-way ANOVAs were used to analyze the dependent variables were larval abundance and BL (see Methods section). Standardized larval abundance was used to visualize cross-shelf patterns for each taxa-size class.

Two analyses were used to determine whether larval distribution patterns change in the presence of fronts (see Methods section). Transects with a coastal front or Gulf Stream front were examined separately to determine whether peak abundance occurred at fronts (Table B1). Green's coefficient of dispersion was also used to determine if taxa-size classes were spatial aggregated when the coastal front was present (n = 16) versus absent (n = 11) and Gulf Stream front was present (n = 6) versus absent (n = 21) (Table B2).

Table B1. Location of peak abundance of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). Chi-square analysis was used to determine whether peak abundance for each taxa and size class of larvae occurred at fronts or not at fronts (*** = $p \leq 0.025$, ** = $p \leq 0.05$, * = $p \leq 0.10$).

		small larvae		medium larvae		large larvae	
Taxa	Front	at front	not at front	at front	not at front	at front	not at front
Atlantic menhaden	coastal	3	13 ***	6	10	10	6
	Gulf Stream	2	4	2	4	1	5
round herring	coastal	0	12 ***	0	15 ***	1	10 ***
	Gulf Stream	2	3	2	4	1	5
spot	coastal	0	15 ***	1	13 ***	1	8 ***
	Gulf Stream	4	2	1	4	0	5 **
Atlantic croaker	coastal	0	10 ***	2	12 ***	5	6
	Gulf Stream	1	4	1	5	0	4 *
summer flounder	coastal	2	8 *	0	12 ***	0	8 ***
	Gulf Stream	0	3 *	2	2	0	3 *
Paralichthys a / l	coastal	2	4	6	9	9	6
	Gulf Stream	1	1	2	3	0	5 *

Table B2. Mean (standard deviation) of Green's coefficient (GC) of three size classes for six taxa collected during 27 cruises (Table 1) from a cross-shelf transect bisecting Onslow Bay, North Carolina (Fig. 2). A one-way ANOVA was used to determine if GC differed whether or not the coastal front or Gulf Stream front was present (*** = $p \leq 0.001$, ** = $p \leq 0.025$, * = $p \leq 0.05$).

		small larvae		medium larvae		large larvae	
Taxa	Front	present	absent	present	absent	present	absent
Atlantic menhaden	coastal	0.58 (0.29)	0.60 (0.35)	0.35 (0.15)	0.35 (0.27)	0.57 (0.35)	0.51 (0.27)
	Gulf Stream	0.67 (0.26)	0.56 (0.32)	0.41 (0.12)	0.33 (0.22)	0.56 (0.39)	0.54 (0.30)
round herring	coastal	0.53 (0.32)	0.52 (0.29)	0.42 (0.25)	0.33 (0.21)	0.62 (0.33)	0.72 (0.29)
	Gulf Stream	0.54 (0.34)	0.52 (0.30)	0.30 (0.15)	0.41 (0.25)	0.74 (0.40)	0.62 (0.27)
spot	coastal	0.39 (0.22)	0.43 (0.26)	0.42 (0.21)	0.41 (0.21)	0.43 (0.30)	0.54 (0.29)
	Gulf Stream	0.42 (0.30)	0.40 (0.22)	0.42 (0.34)	0.42 (0.17)	0.53 (0.33)	0.47 (0.29)
Atlantic croaker	coastal	0.61 (0.36)	0.50 (0.36)	0.51 (0.29)	0.54 (0.34)	0.45 (0.32)	0.71 (0.32)
	Gulf Stream	0.70 (0.40)	0.51 (0.32)	0.62 (0.33)	0.48 (0.29)	0.22 (0.13)	0.65 (0.32) *
summer flounder	coastal	0.61 (0.34)	0.39 (0.28)	0.37 (0.32)	0.40 (0.27)	0.50 (0.40)	0.64 (0.35)
	Gulf Stream	0.57 (0.43)	0.50 (0.32)	0.46 (0.42)	0.37 (0.28)	0.51 (0.43)	0.57 (0.38)
Paralichthys a / l	coastal	0.44 (0.32)	0.45 (0.39)	0.48 (0.35)	0.54 (0.40)	0.49 (0.37)	0.49 (0.37)
	Gulf Stream	0.41 (0.06)	0.45 (0.38)	0.58 (0.39)	0.49 (0.36)	0.63 (0.41)	0.45 (0.35)

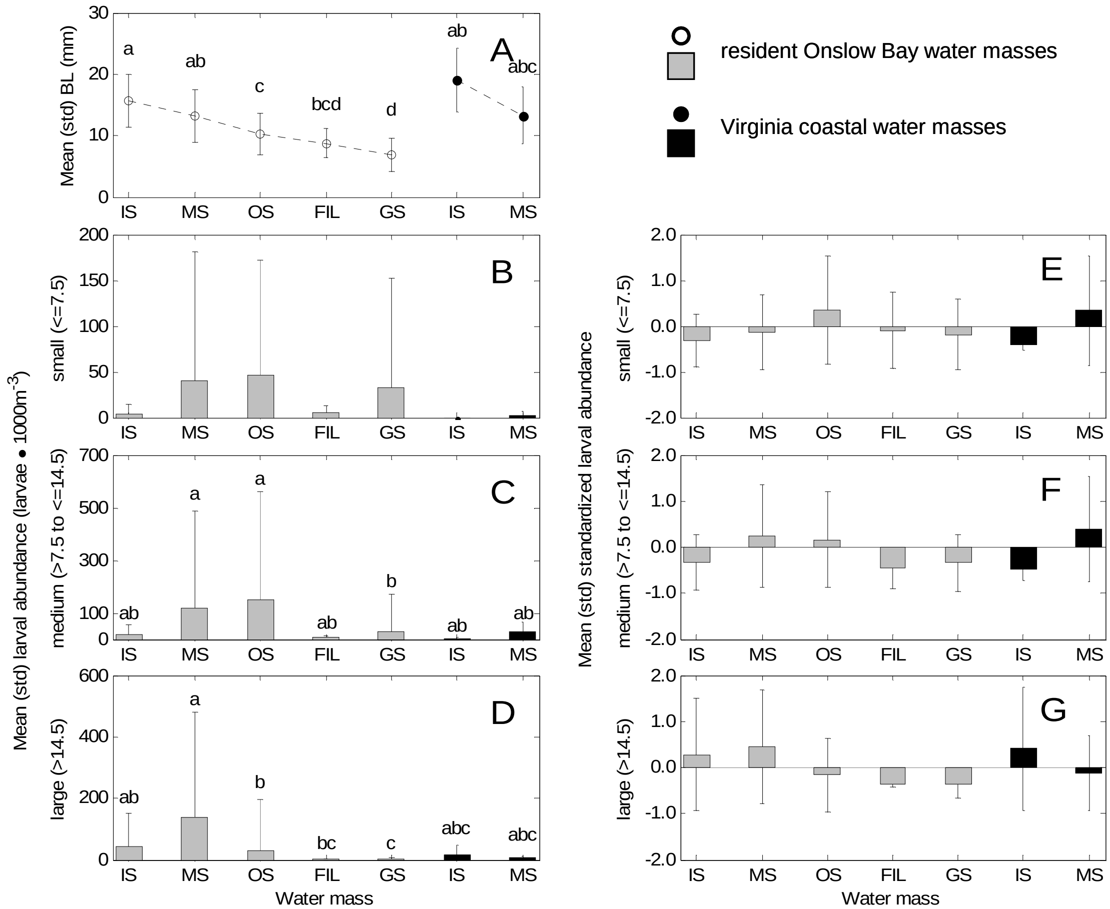

Figure B1. Mean (standard deviation) body length (A, mm) and abundance of small (B), medium (C), and large (D) Atlantic menhaden (*Brevoortia tyrannus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

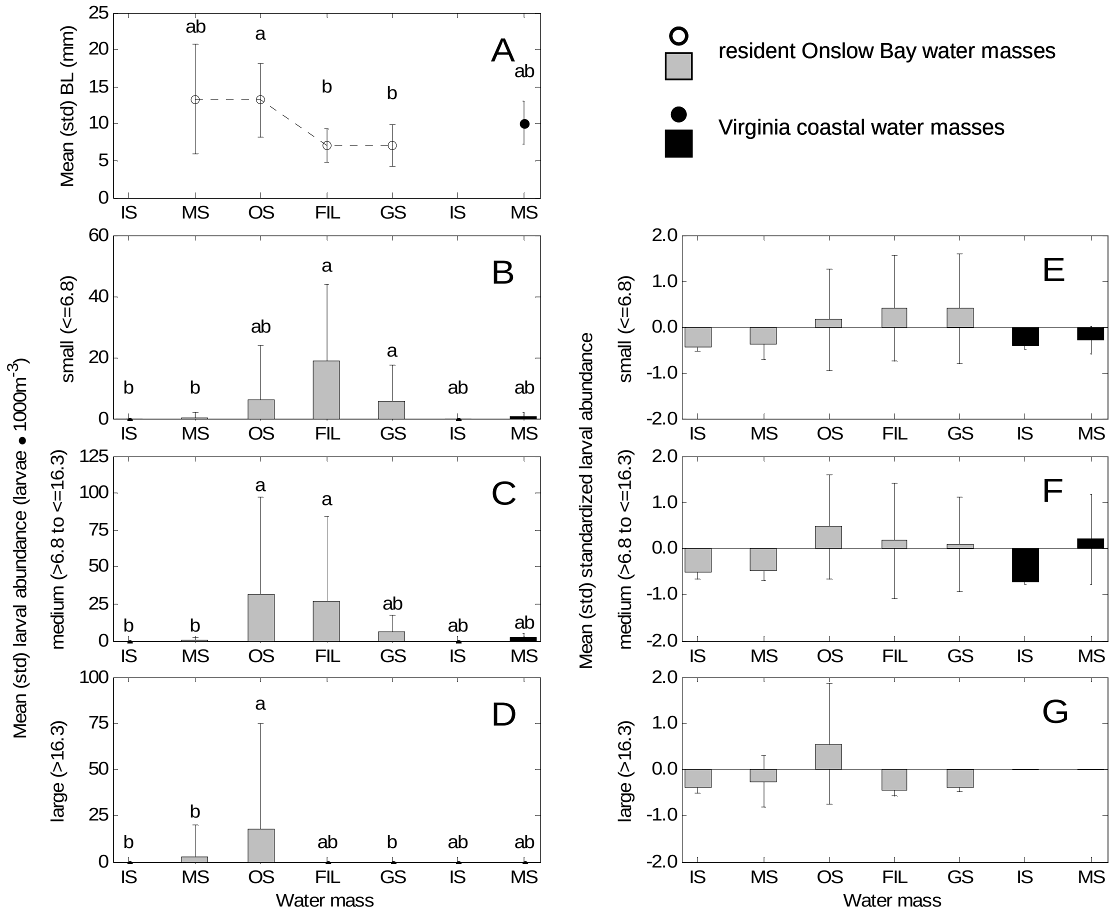

Figure B2. Mean (standard deviation) body length (A, mm) and abundance of small (B), medium (C), and large (D) round herring (*Etrumeus teres*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

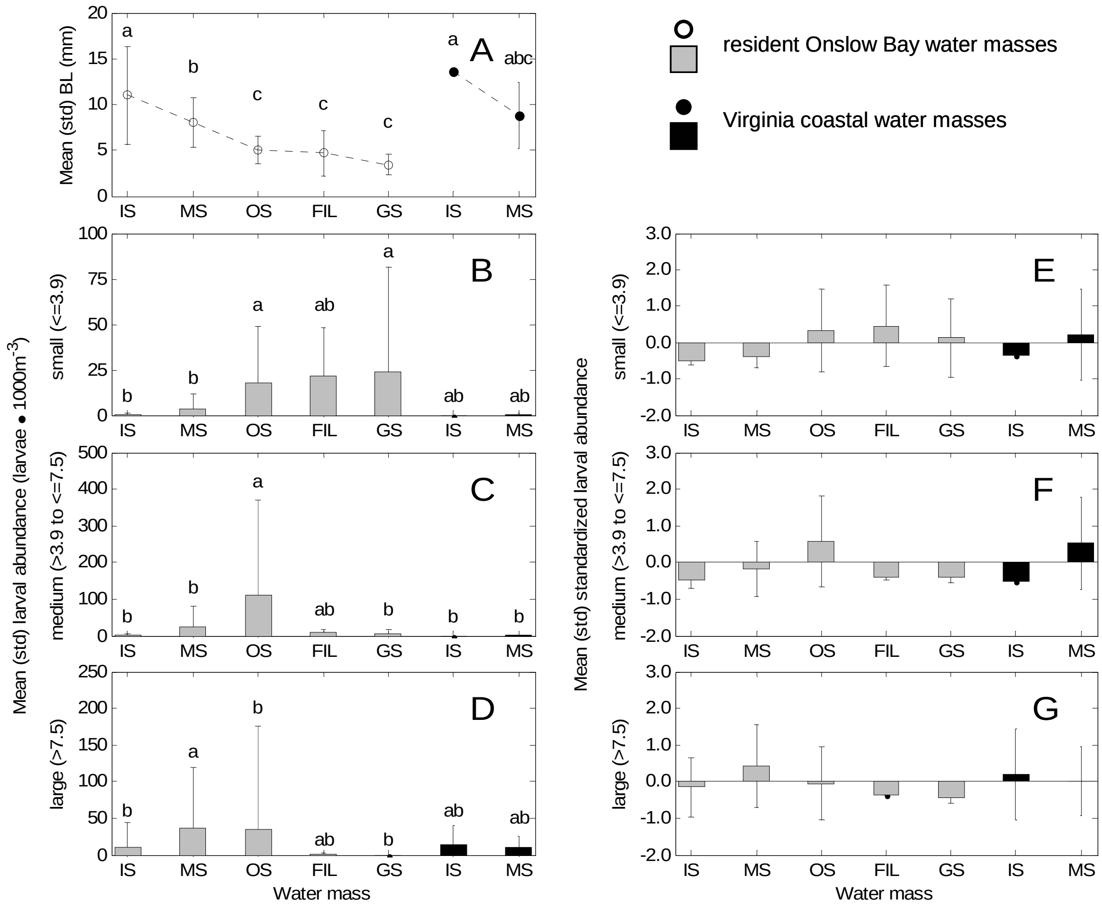

Figure B3. Mean (standard deviation) body length (A, mm) and abundance of small (B), medium (C), and large (D) spot (*Leiostomus xanthurus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

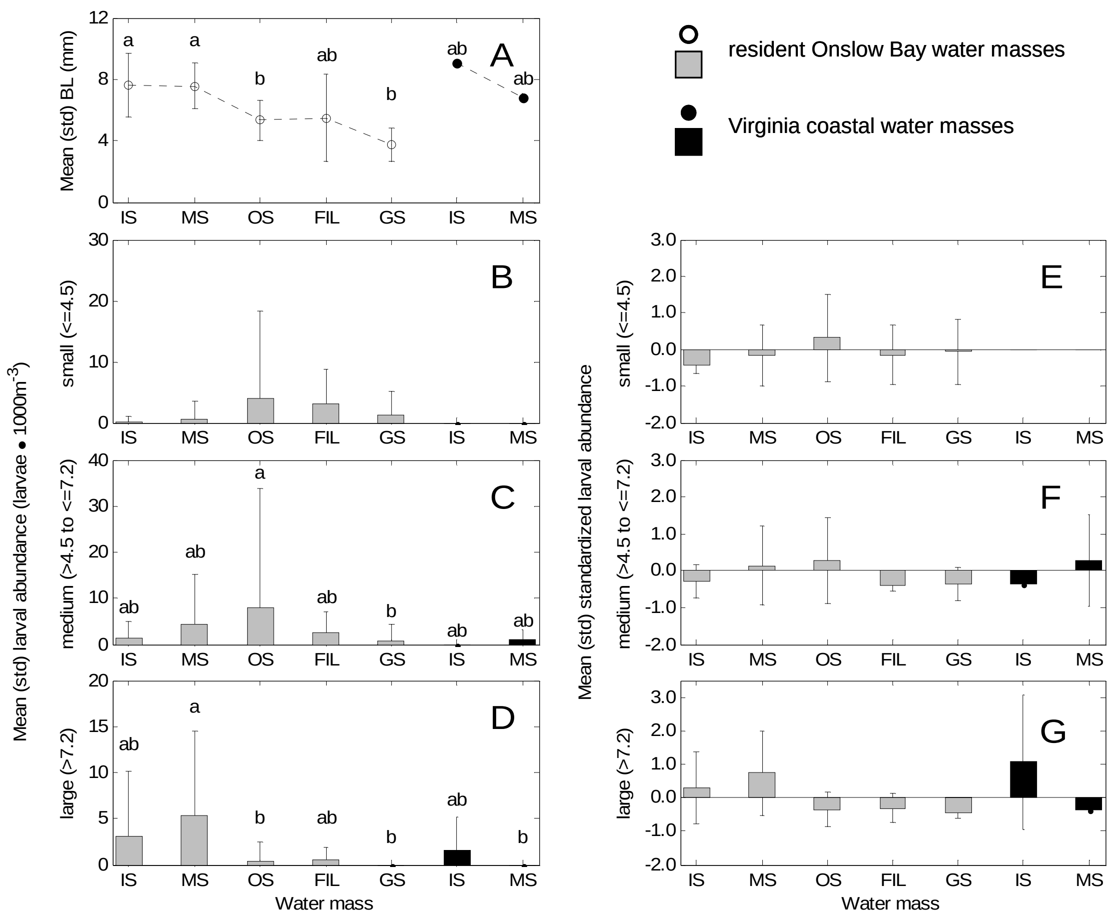

Figure B4. Mean (standard deviation) body length (A, mm) and abundance of small (B), medium (C), and large (D) Atlantic croaker (*Micropogonias undulatus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

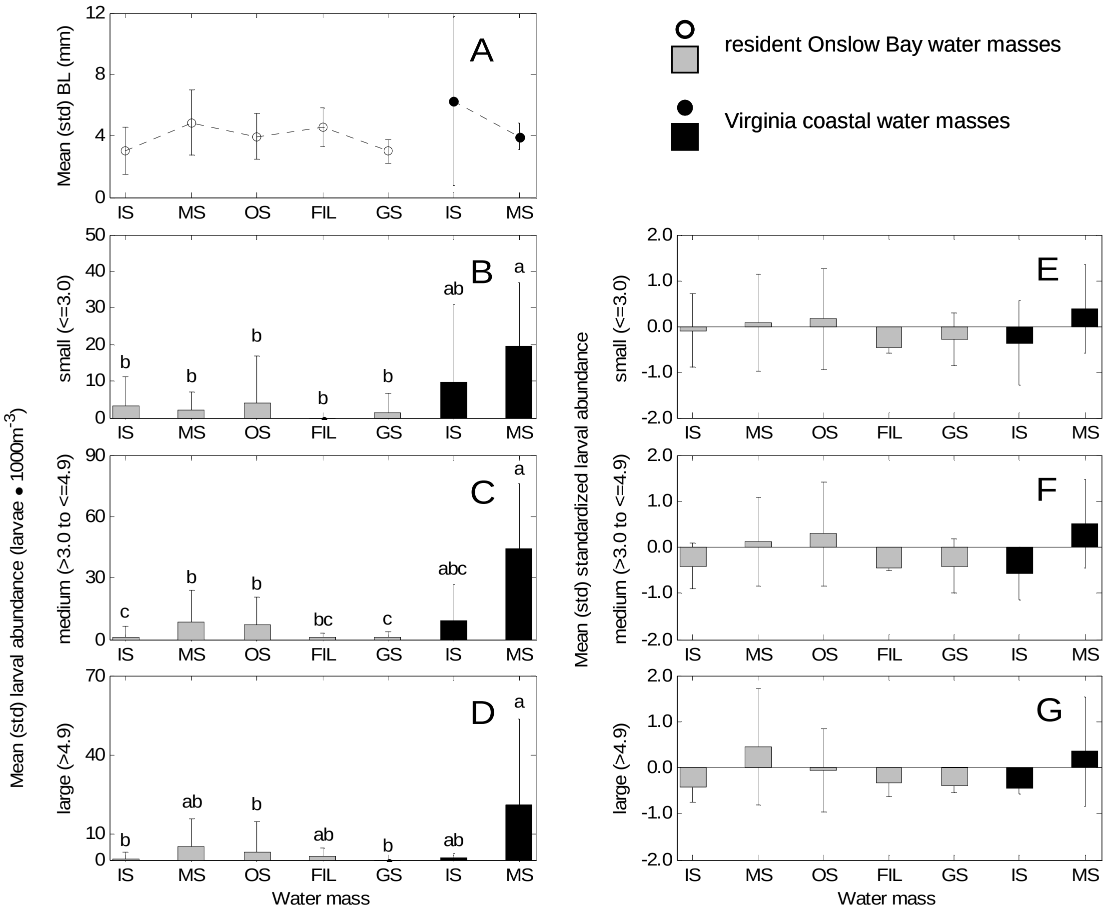

Figure B5. Mean (standard deviation) body length (A, mm) and abundance of small (B), medium (C), and large (D) summer flounder (*Paralichthys dentatus*) larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.

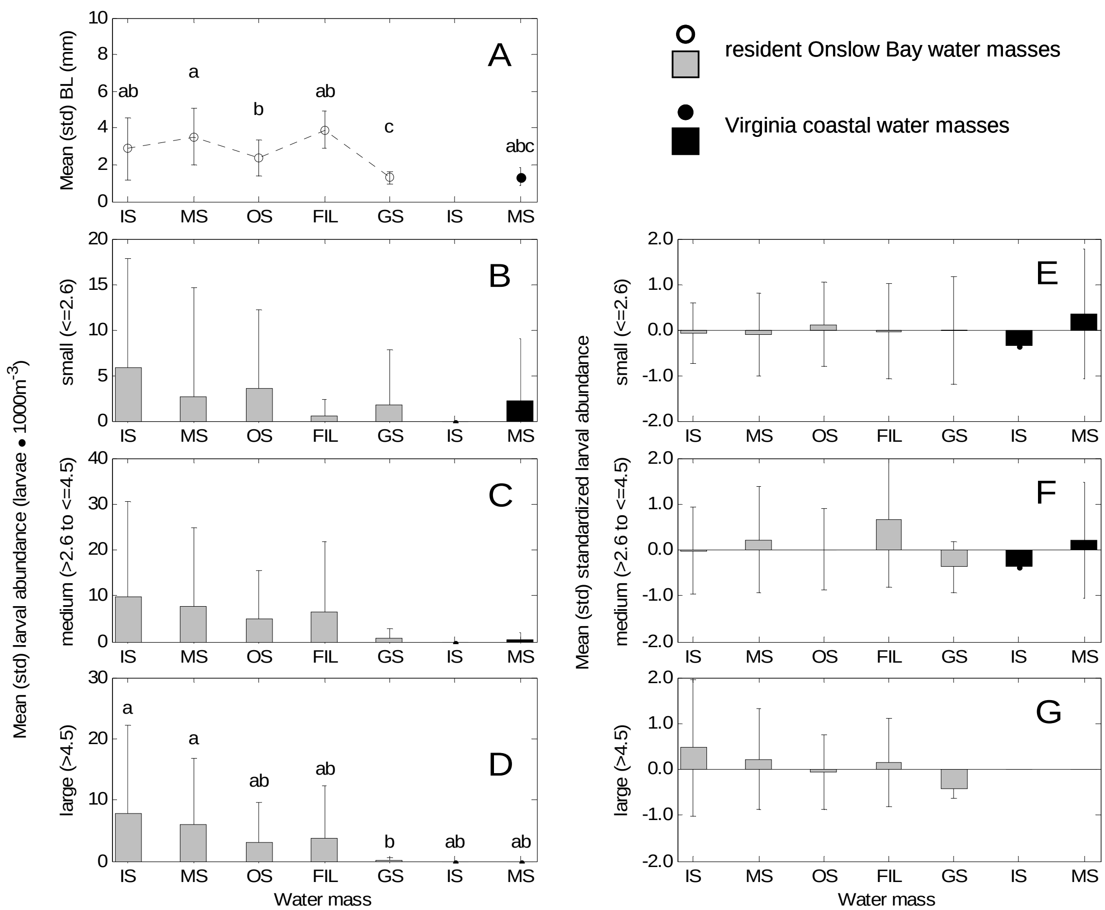

Figure B6. Mean (standard deviation) body length (A, mm) and abundance of small (B), medium (C), and large (D) *Paralichthys albigutta / lethostigma* larval collected on 27 occupations of a cross-shelf bisecting Onslow Bay, North Carolina. Differences among water masses of mean body length and $\log_{10}$ transformed (larval abundance + 1) were detected a *posteriori* using Scheffé's S procedure ($p \leq 0.05$), and are indicated by lower case letters. Larval abundance was also standardized to a mean of zero (standard deviation = 1) for each of the 27 transects, and mean (standard deviation) for small (E), medium (F), and large (G) larvae are shown. IS = inner-shelf, MS = mid-shelf, OS = outer-shelf, FIL = warm filament, and GS = Gulf Stream.