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WATER CIRCULATION PATTERNS DETECTED IN AVHRR-SST IMAGERY
IN RELATION TO
LARVAL MENHADEN ABUNDANCES IN THE SOUTH ATLANTIC BIGHT
BY
HEIDI M. FRANKLIN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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OF

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UNIVERSITY OF RHODE ISLAND

1996

ABSTRACT

Sea surface temperature (SST) imagery from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-9 and NOAA-11 satellites was used to observe surface circulation patterns in shelf waters off the coast of North Carolina. I hypothesized that interannual variation in the frequency and spatial extent of Gulf Stream induced onshore pulses of warm water are a cause of inter-annually varying larval fish abundances arriving at the mouths of North Carolina estuaries. The Atlantic menhaden, *Brevoortia tyrannus*, is an estuarine-dependent species which spawns offshore in 18-22°C water over a protracted period from November to April. A major menhaden spawning area is found along the shoreward Gulf Stream edge in the South Atlantic Bight. The developing larvae must travel approximately 100-150km to coastal inlets where they enter estuarine nurseries. A probable mechanism facilitating this migration is the onshore forcing of warm water masses due to Gulf Stream fluctuations. Using SST imagery, I tracked the shoreward progression of 18°C-22°C water as a potential location of menhaden larvae over the spawning season. The spatial location of this 18°C water is followed over the November - April spawning period to detect frequency and arrival of these warm water "pulses." Based on the inter-annual variability observed in a larval menhaden data set, I focused on the cross-shelf circulation of the following four spawning periods: two periods coinciding with times of relatively very high larval abundances (Nov.-Mar. 1987-88 and 1985-86), and two with very low larval abundances (Nov.-April, 1990-91, and 1991-1992).

Cross-shelf circulation analysis revealed that periods of maximum spawning were associated with large magnitude, shoreward progressing, 18°C water pulses. Although the results showed that the frequency of pulses over the protracted spawning period did not explain the interannual variability, there was a clear association between onshore pulse movement and maximum spawning periods supporting the theory that these pulses

may be a significant larval transport vehicle. This association was most notably evident from an event during December 1987, part of the highest larval abundance season. This particular event may have governed the relatively high number of larvae to reach the inlet in the spring of 1988. Thus, larger magnitude and longer duration pulses may aid in larval transport and estuarine recruitment. Rates derived from SST gradients over time coincided with the range of the transport rates estimated from larval ages and the distance from offshore spawning grounds to Beaufort Inlet.

The association between maximum spawning periods and large shoreward anomalies may not definitively explain the interannual variability in larval abundances but it does describe a possible mechanism facilitating larval transport for menhaden in the South Atlantic Bight. Tracking circulation via AVHRR-SST variability may provide a useful tool in the research and management of fisheries.

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1. INTRODUCTION

Sea surface temperature (SST) imagery from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-9 and NOAA-11 satellites was used to observe surface circulation patterns in shelf waters off the coast of North Carolina and thus determine a relationship, if any, between circulation and interannual variation in larval fish abundances. I hypothesized that interannual variation in the frequency and spatial extent of Gulf Stream induced onshore pulses of warm water are a cause of inter-annually varying larval fish abundances arriving at the mouths of North Carolina estuaries (Figure 1.). The representative fish species, *Brevoortia tyrannus*, or the Atlantic menhaden, is an estuarine-dependent species which spawns in 18-22°C waters offshore along the outer-continental shelf off North Carolina (Govoni, 1993). The developing larvae travel approximately 100-150km to coastal inlets where they enter estuarine nurseries. The trip duration from spawning ground to estuary is estimated between 30 and 90 days. A probable mechanism facilitating this migration is the onshore forcing of warm water masses due to Gulf Stream fluctuations. Analysis of SST imagery uncovered the frequency and arrival location of these warm water "pulses." This cross-shelf circulation was used to provide an explanation for a portion of the inter-annual variability of the larval menhaden abundances collected at Beaufort Inlet, North Carolina (Figure 2.). This research probed the following hypotheses:

- i. Years of highest larval abundances are associated with the years when warm water masses of Gulf Stream origin are more frequent and/or move closest to shore.
- ii. Translation of SST gradients to water mass transport rates using a time series of SST satellite images are very similar to the larval transport rates (from spawning ground to estuarine location) estimated in the field by larval collection and aging (using otolith analysis).

Menhaden Characteristics

Atlantic menhaden's range spans the eastern coast of North America from the Gulf of St. Lawrence to northern Florida (Gray, 1992). The schooling, plankton-feeding Atlantic menhaden undertake extensive seasonal migrations, moving north during the spring and south during the fall (Dryfoos et al., 1973; Durbin and Durbin, 1975).

This commercially valuable species represents 25-40% of the combined yearly catch of the menhaden species from the Gulf of Mexico and the Atlantic coast (Rogers and Van Den Avyle, 1983). Ninety-eight percent of the Atlantic menhaden catch is sold in the form of fish meal for fertilizer, oil, and cosmetics production (Rogers and Van Den Avyle, 1983).

Early life stages (egg, larval and juvenile) are critical in determining the eventual recruitment of a species (Lasker, 1981) and thus, the larval transport stage is a significant process affecting recruitment success. Passive Atlantic menhaden larvae are thought to depend on shoreward advection to transport them to coastal estuaries from the spawning area (Nelson et al. 1977, Warlen and Burke, 1990). The western boundary of the Gulf Stream, approximately 100-150km south of Cape Hatteras, has been described as a major spawning ground for Atlantic menhaden (Higham and Nicholson, 1964). Menhaden continuously spawn over a 5-6 month period from late fall to early spring (Warlen, 1994; Checkley et al., 1988; Kendall and Reintjes, 1975) in 18-22°C water (Govoni, 1993). This protracted spawning period has been suggested as a strategy to ensure reproduction during the most desirable periods for survival (Warlen, 1994). The eggs are pelagic and hatch after two days (Rogers and Van Den Avyle, 1983). Atlantic menhaden larvae are generally found in the upper portion of the water column with larvae being 1.5 times more abundant in the 0-10m depth zone than the 10-30m depth range (Checkley et al., 1988). The menhaden are able to adjust their vertical position in the water by inflating and deflating the gas-filled swim bladders. The menhaden acquire air from the surface and may use the filled swim bladder to conserve energy (Hoss et al., 1989). Hoss et al. (1989) also suggest that vertical migrations may aid in larval transport if the larvae

increase their swim bladder's volume to coincide with shoreward water mass movement. Miller (1988) discussed the importance of vertical migrations with tidal fluctuations to transport larvae through coastal inlets and also to aid in maintaining their position once they have arrived in the estuarine nurseries.

Larval Transport

How do the larvae reach their estuarine nurseries from the outer shelf spawning location? It has been hypothesized that species such as the Atlantic menhaden have evolved to spawn shoreward of a warm boundary current such as the Gulf Stream at times when transport to the coast is favored by climatological conditions such as storm-induced upwelling (Checkley et al, 1988). Nelson et al.(1977) concluded that Ekman transport plays a large role in menhaden larval transport in the SAB. These Ekman transport calculations and conclusions were disputed by others who emphasized the role of other factors such as upwelling caused by Gulf Stream instabilities, short-term wind reversals, and density-driven and thermohaline currents (Miller et al., 1984; Yoder et al., 1983). Warlen and Burke (1990) described the protracted spawning period of fall/winter spawning fishes as a mechanism to ensure recruitment success against extreme environmental events. They estimated a 30 - 90 day interval was necessary for the larvae to move from the spawning location to the estuarine nurseries. Warlen and Burke (1990) also suggested peak immigration of larvae into the estuaries coincided with rising water temperatures, a proliferation of plankton, and low numbers of predators and competitors.

South Atlantic Bight Circulation

The South Atlantic Bight continental shelf (Figure 1.) can be divided geographically into three depth zones: the inner-, mid-, and outer-shelf regions. The inner shelf spans the region from the shore to the 20-m isobath. The circulation in this area is influenced primarily by river input, tidal mixing, and wind action (Menzel et al., 1993). The effects of the Gulf Stream in the inner-shelf region have not been thoroughly investigated, although subsurface intrusions caused by Gulf Stream instabilities have

been found to reach inshore of the 20-m isobath in Onslow and other North Carolina bays (Blanton & Pietrefesa 1978).

The use of satellite imagery during the winter period in the SAB region is an extremely useful tool to study the surface circulation as the relatively warm Gulf Stream water and its fluctuations are highly visible in contrast to the cooler inner-shelf waters (see Figure 3. for a four image time series). The Gulf Stream dominates circulation on outer-shelf (region from 40-m to 60-m isobath) and with wind, influences circulation on the mid-shelf (region from the 20-m to 40-m isobath). In the South Atlantic Bight study area (south of Cape Lookout in Onslow Bay), the 400-m isobath represents the outer-shelf/Gulf Stream boundary and the 20-m isobath, the inner/mid-shelf boundary (Figure 3.). Gulf Stream processes such as meanders and subsequent shingles (surface structures consisting of warm bands of water extruded from the Gulf Stream front during a meander's most shoreward phase) and eddies, influence outer and mid-shelf circulation on an 'event' time scale, e.g. at a frequency ranging from days to weeks (Brooks and Bane, 1981). Eddies frequent this area at a rate of approximately one per week with a duration of 1-3 weeks. The Gulf Stream dominates circulation along the outer shelf of Onslow Bay which are important spawning grounds for Atlantic menhaden. Warm pulses of water oscillate in and out of Onslow Bay across the continental shelf. These warm water mass movements are well correlated with Gulf Stream instabilities (using the 400-m isobath as a location indicative of the Gulf Stream. location) (Stegmann and Yoder, 1996).

Larval Menhaden Research

Numerous collections of Atlantic menhaden have larvae revealed geographic location and related developmental stages of menhaden early life characteristics (Reintjes, 1961; Higham and Nicholson, 1964; and Lewis and Mann, 1971). Lewis and Mann(1971) gathered menhaden larvae at two North Carolina inlet locations (Beaufort and Bogue) over a two year period. Larvae entered the estuaries between November and

April with the majority collected from February to April. Similar trends in abundance occurred during the same year at the two different inlets. Recent research (Warlen and Burke, 1990; Warlen, 1994) has confirmed the continuation of trends uncovered by Lewis and Wilkens (1971).

The menhaden larval abundance data set generated by Warlen(1994) from collections at Pivers Island, North Carolina (see Figure 2.) set the foundation necessary to carry out the current study. Warlen collected larvae on a weekly basis just inside of Beaufort Inlet over the November-April estuary recruitment period starting in 1985/1986 and continuing over seven consecutive years. He found that 86% of the larvae arrived in the estuary between February and April. By aging the larvae through otolith analysis, Warlen determined the approximate birth week of the larvae. Of the larvae that reached Warlen's nets, it was determined that 76% were spawned in December or January.

This study focuses on the inter-annual variability of larval abundance of four spawning periods from Warlen's collection data (the two highest abundance seasons and the two lowest abundance seasons). The 1987-1988 spawning season possessed the highest larval abundances, reaching over 570 larvae/100m³ during early April. The next highest abundances were collected in 1985-1986 (over 200 larvae/100m³) in early March. The lowest abundance periods were 1990-1991 and 1991-1992 with peaks of less than 60 larvae/100m³ for both spawning seasons. Although many factors influence the survival of larval fish during the journey from spawning ground to coastal inlet (i.e. food availability, predation, storm events, etc.), this study focused exclusively on the possible role of ocean circulation and advection as a facilitating mechanism in aiding larvae to reach estuarine nurseries.

2. METHODS

2.1 SST AVHRR DESCRIPTION

The sea surface temperature data for the study period in question (November-April of 1985-1986, 1987-1988, 1990-91, and 1991-92) were obtained via the Advanced Very High Resolution Radiometer (AVHRR) flown on NOAA polar-orbiting satellites. The majority of images analyzed were retrieved via the AVHRR sensors on NOAA-9 and NOAA-11 satellites (images with the prefix 'I' and 'K', respectively). This multi-channel infra-red sensor detects thermal radiation from the earth's surface in the 3.5 - 4.0 μ m and 10.0 - 12.0 μ m wavelengths (Njoku and Brown, 1993). Measurements are made at these infrared and microwave wavelengths because the least atmospheric attenuation occurs within these wavelength regions (Njoku and Brown, 1993). Each satellite passes over the South Atlantic Bight approximately two times per day generating one night and one day image. Researchers at the University of Miami process the raw SST satellite data with a linear algorithm for favorable atmospheric and surface conditions. The algorithm equation is as follows:

$$T_s = a_0 + \sum_{i=1}^N a_i T_i$$

where T_s is the sea surface temperature, N is the number of channels used in the infrared retrieval, T_i are the observed radiometric brightness temperatures at wavelength λ_i (channel i), and a_i are coefficients derived by using independent *in situ* SST observations (Njoku and Brown, 1993). The images are retrieved over a computer network (Internet) and archived at GSO. Imagery resolution is approximately 1km x 1km. The images are mapped to a Mercator projection (meridians and parallels of latitude appear as lines crossing at right angles for entire globe so that areas appear greater the further away from the equator).

2.2 IMAGE PROCESSING

Images for the 4 spawning periods (named previously) from October 31 to April 15 were remapped to the study area's geographic location (32.5-36.5N and 74.5-79.5W) with the University of Miami DSP image processing software package on URI Graduate

School of Oceanography's VAX/VMS system. The images were scrutinized for cloud cover and the unfavorable images were removed from the time-series. Then, the images were navigated manually with University of Miami's DSP software to match the southeastern U.S. coastline so that images were standardized to the geographic projection (Mercator).

During image processing, I formed two groups of images for each of the four spawning seasons' time periods. One group consisted of all images with, at least, the 18°C location clearly distinguishable on the Onslow Bay transects and, thus, these images may contain some clouds along the entirety of the transects (group referred to below as 'total'). The second smaller collection contains images that are completely cloud free along the entirety of all transects (referred to below as 'cloud-free'). This smaller group was created for the purposes of conducting correlations and data interpolation. After eliminating imagery due to cloud cover, the following number of images were compiled for season: 1985/1986 - 102 total and 59 cloud-free; 1987/1988 - 106 total and 64 cloud-free; 1990/1991 - 93 total and 55 cloud-free; and 1991/1992 - 157 total and 49 cloud-free.

2.3 SST IMAGE ANALYSIS

2.3.1 Data Extraction

Following the methodology of Stegmann and Yoder(1996), a cross-continental - shelf, 90km long, transect, 'A', starting at the inner-shelf/mid-shelf boundary and ending at approximately the landward edge of the Gulf Stream, was marked on the images. See Figure 3. for transect locations. A total of six transects were marked on images, the five new transects, 'B' - 'F', were located south of the initial transect in Stegmann and Yoder(1996). All transects started at the 20-m isobath (point of reference for all data description) and ended at the 400-m isobath. The latitudinal and longitudinal end points and the transect distances of the six cross-shelf transects are listed in Appendix A. Next,

sea surface temperature(SST) was extracted along the transect and analyzed over the time series with IDL (Interactive Data Language) and MATLAB software.

2.3.2 Data Interpolation

To observe SST variability over the time series, the 'cloud-free' SST data were linearly interpolated. As the satellites make passes over the study area twice daily, two clear images may be available for one day. Thus, the SSTs were interpolated to 1/2 day intervals. 185 days were covered in the time series running from November - April (Year Day 300 - 365 and then Year Day 1- 120 of the following year), thus the half day time index had 370 units. The MATLAB routine, 'interp2', was used to linearly interpolate data in the vacant gaps in the six month time period (MATLAB, 1992). Then, to visualize the SST time series along transect A, I used a MATLAB routine called 'pcolor' which assigned a number of colors to a range of values and then plotted these colors as a 2-D array (MATLAB, 1992). The 'pcolor' color palette was set to the standard SST color palette where reds and oranges are the highest SSTs and blues and purples are the lowest SSTs. The color bar for these plots was generated using a MATLAB routine called 'colorbar.m' from MATLAB User's Library.

2.3.3 Tracking of 18°C Isotherm

The 18°C isotherm was tracked over the spawning season as a proxy for the potential location of menhaden larvae shoreward progression. The image time series shown in Figure 3. illustrates an example of this pulsing of warm water shoreward from Dec. 23, 1987 to Dec. 30, 1987 and then receding offshore Dec. 30, 1987 to Jan. 6, 1988 and then Jan. 12, 1988. The corresponding SST data were extracted for all six transects and then the 18°C temperature was located and recorded.

2.3.4 Index Development

The extracted SST data and the subsequent 18°C isotherm locations were analyzed in order to validate or reject *Hypothesis i*. An index was developed to quantify the pulses of warm water fluctuating between the Gulf Stream and the 20-m isobath in

Onslow Bay. The index was built with three steps. The first step consisted of finding the mean seasonal trend in each time period. The MATLAB routine, 'polyfit' (MATLAB, 1992), was used to fit a curve to the 18°C isotherm location time series for three transects (A, C, & F) for each of the four spawning seasons to generate a mean seasonal trend. Second, third and fourth degree polynomial curves were fit and the third degree polynomial fit was chosen as the proper curve fit for the index (see *Results 3.5.2*).

The second step involved removing the seasonal trend to look strictly at the isotherm variations. This step was accomplished simply by subtracting the actual 18°C isotherm locations from the average curve fit for all four years. These deviations/variations of the 18°C isotherm from a mean seasonal trend separated the data into negative and positive values. The positive values represented offshore movement and the negative values represented onshore movement. The third step was the generation of histograms to compile the magnitude and frequencies of the oscillations of the 18°C isotherm.

With these three steps, the 18°C isotherm location data was in a format to set the guidelines of the index, i.e. to determine anomalously high negative or positive values and anomalously high or low variation frequencies. The timing of specific anomalies was examined in relation to larval menhaden spawning periods (Warlen, 1994).

2.4 TRANSPORT RATES

To confirm the feasibility of the water "pulses" transporting the larvae, surface transport rates were computed from the 18°C isotherm locations. Rates were estimated between two images from the distance the isotherm moved divided by the time interval elapsed between the two images. Mean values were calculated from these rates. These rates were compared to a larval transport rate estimated from the larval ages and approximated distance traveled by the larvae from spawning ground to estuary inlet (Warlen, 1994).

2.5 LARVAL FISH DATA

Warlen's larval menhaden data set (Warlen, 1994) created the impetus and foundation for this study. The larval menhaden data set consisted of seven consecutive years of larval collections starting in 1985/1986 over a 5-1/2 month period from mid-November to the end of April for each year. Collections were made weekly at a station adjacent to Pivers Island located just inside Beaufort Inlet (Figure 1.) to record the number of larval menhaden recruited to the Newport River estuary from ocean waters. Figure 2. exhibits seven years of larval collections by weekly mean density. For the 1985/1986 spawning season, larvae were sampled with a 60-cm bongo frame with paired 505- μ m mesh nets and flow meters towed from a 6.7m boat. For 1986/1987 periods and onward, a 1x2-m neuston net frame with a 945- μ m mesh net was used to capture larvae just under the surface from a bridge platform in the center of the channel next to Pivers Island (Warlen, 1994). All tows were conducted at night just after mid-flood tide to reduce net avoidance (Warlen, 1994). Larvae were aged by otolith analysis and the subsequent spawning dates were back-calculated from the age data (Figure 4.). This larval data set was used as a criterion to establish the key time periods when circulation would have most affected larval survival.

3. RESULTS

The results are presented as follows: i.) Larval Fish Data, ii.) Transect SST Time Series, iii.) 18C Isotherm Movement, iv.) Index Development for inter-annual comparisons, and v.) Transport Rates.

3.1 LARVAL MENHADEN DATA

The two primary pieces of data retrieved from the larval Atlantic menhaden collection set (Warlen, 1994) were the weekly larval abundances recorded at Pivers Island, NC (Figure 2.) and the back-calculated spawning dates (birth weeks) of the collected larvae (Figure 4.). The larval abundances showed extreme interannual and

'within spawning period' variability. The larval collections varied by an order of magnitude. A summary of larval menhaden collection and spawning data was compiled from Warlen (1994) in order to focus on the most critical periods within each spawning season used in this study (Table 1.). Since the travel time from spawning ground to inlet differed for each larva, it was necessary to look at both the maximum collection time *and* the spawning dates. The spawning dates were back-calculated from larval ages estimated via otolith analysis. The week of maximum spawning and a range of weeks when 85% of the total collected larvae spawned, are noted for comparison with circulation/temperature variability.

The spawning range when 85% of the larvae were collected varied between the four spawning periods. This '85%' spawning period was less than two months for 1985/86 (31 days), 1987/88 (51 days), and 1990/91 (41 days). For the 1991/92 period (a low abundance year), the spawning time period of 85% of larvae collected was 67 days. The '85%' back-calculated spawning periods (85% of the larvae collected) occurred in December for periods 1987/1988 and 1991/1992; and in January for periods 1985/1986 and 1991/1992 (see Table 1.). With regard to the larval collections, the time ranges of the largest collections were less than one month for all four periods.

3.2 IMAGE TIME SERIES

3.2.1 Time Period Focus

I analyzed the inter-annual circulation variability as evidenced in SST imagery of four November through April time periods corresponding to Atlantic menhaden spawning periods. Warlen (1994) showed large inter-annual variability in menhaden larval abundances with: Nov. 1987 - April 1988 and Nov. 1991 - April 1992, the highest and lowest abundance seasons, respectively, of the seven consecutive years studied. Second highest and second lowest time periods, were November 1985 - April 1986 and November 1990 - April 1991, respectively. In brief, the two spawning seasons in the mid

to late 1980's had high larval abundance, whereas the two spawning seasons in the early 1990's had low larval abundance. Hereafter, I refer to these periods only by the year groups, i.e. 1985/1986, 1987/1988, 1990/1991, and 1991/1992.

Short duration image time series (on a scale of days to weeks) allowed observation of specific pulse events, i.e. warm water oscillating in and out of Onslow Bay. An example of the images used for the time series analysis is exhibited in Figure 3., and this figure also shows the cross-shelf transects over which SST was extracted to quantitatively measure the movement of warm waters of Gulf Stream origin. Of topographical importance, the shallow inner-shelf (20m isobath to shore) protrudes seaward considerably at the junctures of the bays at Cape Fear, Cape Lookout, and Cape Hatteras.

Gaps of data in the time series existed mostly due to cloud cover. Figure 3. shows the presence of clouds mostly offshore. Clouds were characterized by a range of colors and shapes which had to be distinguished, and discounted as SST. An example of cloud cover is exhibited in the Jan. 12, 1988 image from Figure 3. Clouds (purple, in this case) are shown covering all ocean area seaward of the mid-continental shelf.

3.3 TEMPERATURE VARIABILITY

3.3.1 Temporal Variability

During the menhaden spawning period (November-April), seasonal cooling and heating generally affected inner shelf water as follows: SSTs of 22 - 26°C in November decreased to 10-14°C by mid-January and then warmed to 16°C by April. There were some notable exceptions to the general pattern. During the 1985/86 spawning period, inshore cooling occurred more slowly compared with the other three time periods (Figures 5. - 8.). The 18°C water (represented by green range in Figures 5.-8.) occurred at the 20-m isobath on Dec. 15, 1985 before which time the isotherm was inshore of the 20-m isobath. This first appearance of the 18°C isotherm in 1985 was two to four weeks later than in the three other spawning periods (Figures 5. -8.). For both the 1987/1988

and 1990/1991 period, the inshore water (at the 20-m isobath) had cooled to 18°C by Nov. 15. During December 1985, SSTs along the 20-m isobath cooled rapidly (by 10°C) whereas the remaining three spawning periods showed a more gradual decrease in SST at the 20-m isobath location: for 1987/88 SSTs underwent this 10°C decrease from early Nov. to mid-late Jan. (~2-1/2 months); for 1990/1991 (Fig. 7.), mid-Nov. to mid-late Jan. (~ 2 months); and for 1991/1992 (Fig. 8.), the gradient occurred from early November to late December, about 2 months, also. Two of the spawning seasons had unusually cool temperatures. SSTs of 10 - 12°C persisted from January to late March for 1987/1988 and SSTs of 10 - 13°C occurred from mid-December through the end of April for 1991/1992. The 1985/1986 and 1990/1991 periods exhibited cooler waters residing inshore at the 20-m isobath for shorter time periods. The 1985/1986 period showed cool water (10-13°C) from late December until mid-February then inshore waters warmed to 15°C. During March 1986, inner shelf waters were unusually warm (~18°C) for a few days.

Due to the presence of the Gulf Stream, SST on the outer shelf and seaward fluctuated within a much smaller range than nearshore waters throughout the year (Table 2.). From November to April for all four years, SSTs at the seaward edge of Transect A (400-m isobath) ranged from 26 -24°C in November to 18-22°C in late February (maximum range of 8°C). The two low larval abundance years, 1990/91 and 1991/92, showed late January cooling at 'kilometer 90' of transect A (400-m isobath), reaching lows of ~19°C. The cooler water at the seaward end of the transect in both of these low abundance years was present until the beginning of April. The 1990/1991 400-m isobath (or 'km 90' of the transect location index) SSTs covered the spectrum of this range decreasing to 18°C on two separate occasions, Feb. 17, 1991 and March 10, 1991, whereas during the 1985/1986 and 1987/1988 periods, the minimum temperatures at the 400-m isobath were 20.0 and 20.5°C, respectively. The coolest temperatures during the 1985/86 period occurred in February while during 1987/88, offshore cool water was present primarily in March.

Figures 5. - 8. show the 'event time scale' temperature fluctuations at each location as noted by Stegmann & Yoder (1996) in their 1981-1986 time series. These fluctuations at each location appeared to be translated from 'km 90' towards shore and were most likely caused by Gulf Stream forcing in the form of meanders (Stegmann and Yoder, 1996). By observing the trends at four fixed locations, 1) one location at the 20-m isobath (shoreward edge of cross-shelf transect), 2) one at the 400-m isobath (seaward edge of transect), and 3) two locations between these end points, the effects of seasonal cooling of waters, inshore vs. offshore, are illustrated (Table 2.). For the November to April period during 1985/1986, 'km 90' sea surface temperature only fluctuated between 21 - 25°C. In contrast, SSTs were much colder at inshore transect locations due to seasonal cooling, most notably at 'km 1' where SST ranged from 10°C to ~21°C.

3.4 MOVEMENT OF '18°C' ISOTHERM

The location of the 18°C isotherm along all six transects and for each of the four spawning seasons followed a general offshore then onshore movement over the spawning period. The mean location of the 18°C isotherm for the six transects summarizes this general seasonal trend (Figure 9.). The offshore movement of the 18°C isotherm coincided with the seasonal cooling occurring during December and January. The end of the time series (April) exhibited a general shoreward movement of the 18°C isotherm coincident with spring warming. The standard deviations were considerable for many of the 18°C isotherm locations (Figure 9.). The smallest maximum standard deviation of the four periods was 16km during 1991/1992. The 1990/1991 period showed the largest maximum standard deviation of 33km between transects A-F. During all four periods, the general seasonal movement of the 18°C isotherm was consistently disturbed by short-term event oscillations on the scale of days to weeks.

3.4.1 1985-1986 18°C isotherm location

For the entire 1985/86 spawning period, the location of 18°C isotherm fluctuated from just shoreward of the 20-m isobath to approximately 80km seaward of the 20-m isobath. The six transect mean of the 1985/1986 18°C isotherm location (Figure 9.) exhibits the trend of seasonal cooling then warming as the isotherm moved offshore during winter months and onshore during late spring months. Figure 10. and 11. show the distance seaward of the 18°C front from the 20-m isobath for transects A, C, F and B, D, E, respectively. The 18°C isotherm remained closest to shore for November and December (within 0-40km seaward of the 20-m isobath) for transects A-F. With the exception of transect A, all the transects clearly exhibited a seasonal winter offshore movement of the 18°C water, particularly from early December to early March (Figure 10. and 11.). Transect A showed a sharp offshore movement of 18°C water in December and then slight mean offshore movement from December's end through March. After March, the 18°C isotherm clearly moved onshore continuing through April as evidenced by the six transects. The mean 18°C isotherm of the six transects exhibited seasonal cooling (December 10, 1985 - March 25, 1986) and then warming (starting March 25, 1986). This seasonal offshore and then onshore isotherm movement was consistently interrupted over the spawning period by short-term fluctuations on the scale of three to four days up to two weeks.

Short-term oscillations occurred frequently during 1985/1986, the period with second highest larval abundances collected from Warlen's seven year data set. These 'pulses' of warm water along Transect A-F were separated into events as indicated by the five areas enclosed in boxes (Fig. 10. and 11.). The boxes were used for ease of focusing on and describing movement of the 18°C isotherm. These pulse events outlined shoreward movement of warm water potentially moving larvae to the inner shelf. Events '1' and '2' occurred during the maximal back-calculated spawning period from Warlen (1994). On Dec. 9, 1985, the 18°C isotherm was found nearly 40km from the 20-m isobath. Within three days, it moved inshore to the 20-m isobath location, and then

offshore 56 km from the 20-m isobath. At this point, the 18°C isotherm pulsed shoreward again approximately 10 -15 km as shown in box '1' for all six transects(Figures 10. and 11.) Transect F, the transect furthest south, exhibited shoreward movement just prior to the box '1' period. This prior pulse may have propagated northward due to the alongshore flow of the Gulf Stream and thus developed into the shoreward movement shown in box '1' for transects A-E.

The pulse encompassed by box '2' was evident in all transects, although the 18°C isotherm did not stay as close to the 20-m isobath for as long of a period along transect F as for the other transects. The '2' event moved warm water within 15km of the 20-m isobath but then the 18°C isotherm moved offshore to its most seaward point thus far. Event '3' was the most difficult pulse to interpret, as each transect showed a different pattern. Inspection of the SST images showed that the cause for these differences was the extreme irregularities and roughness of the 18°C front. During event '4', the 18°C isotherm underwent a 25-30 km shoreward excursion, except along transect A where it moved only 10 -15 km. The isotherm event enclosed in box '5' experienced erratic movements especially for locations along transects A-D. After the box '5' event, the 18°C isotherm continued to move steadily closer to the 20-m isobath, owing to seasonal warming.

3.4.2 1987-1988 18°C isotherm location

The movement of the 1987/1988 18°C isotherm followed the same seasonal offshore then onshore trend as the 1985/86 period for the entire November to April time series (Figure 9.). The 18°C isotherm was at the 20-m isobath in mid-November and proceeded to move offshore until March where it 'plateaued' for the month. Viewing individual transects (Figures 12. and 13.), this leveling out of isotherm movement occurred in all transects except Transect F. The most southern transect, F, showed a steady onshore movement of the isotherm until March 12, 1988 at which time the

isotherm moved offshore. By early April, the 18°C isotherm rapidly moved back towards shore intersecting the 20-m isobath along Transect A and, within 10km of the 20-m isobath for transects B-F by mid-April. All transects showed 'end-of-spawning-period' offshore movement of the 18°C isotherm.

Four time periods showed considerable oscillations during the 1987-1988 November to April spawning period. These four events are enclosed in boxes labeled '6'- '9' (Figures 12. and 13.) for the six transects. One of the largest excursions of the 18°C isotherm observed in this study is evident in box '6' for transect A through C. The 18°C isotherm moved 70km from the 20-m isobath on Dec. 17, to nearly the 20-m isobath on Dec. 30, 1987, a total distance of approximately 60 km shoreward in a 13-day period (Figure 12.). The transect C box '6' event also underwent a shoreward excursion although it covered about half the distance of transect A and B. After this close encounter with the 20-m isobath, the 18°C isotherm moved offshore approximately 50km in a 25-day period along transects A, B, and C. However, the more southern transects (D, E, and F), exhibited only relatively small offshore movement during the 35-day period enclosed by box '6'. Note that event '6' encompassed the period of maximum spawning for this 1987/1988 period (Table 1).

The patterns during the period highlighted by box '7' differed among transects. Transect A box '7' event was the only transect that experienced only very slight movement (oscillated within a 10km distance). Transects B, C, and D all showed a shoreward pulse at the start of the box '7' event which then moved offshore. The 18°C isotherm moved shoreward just before box '7' along transect F and only slightly into box '7' along transect E. The lag in shoreward excursions from 'southerly' to 'northerly'-displayed' transects was consistent with the presence of alongshore northwestward propagation of Gulf Stream meanders.

On Feb. 22, 1988, the start of the box '8' event, the position of the 18°C isotherm remained constant for about 4 days. From observation of the satellite images during the

box '8' event, relatively small movement occurred along the 18°C front. Two warm water protuberances separated by a cold water filament were apparent over a thirteen day period. Warm water pulsed shoreward as evidenced by the 18°C isotherm along transect F, dipping within 5 km of the 20-m isobath. The cold filament settled along transect D from the 20-m isobath to approximately 40km from the 20-m isobath and over the next few days, moved to transect C and then was pushed back again to transect D. The cold filament activities affected the 18°C location along transect B, C, and D as evident in box '8'. Transect B was on the edge of the filament thus its fluctuations appeared to be 18°C movement but it was the intrusion of the cold water that caused the apparent erratic movement.

The end of the 1987/88 spawning period brought the 18°C isotherm close to the 20-m isobath along all transects due to a combination of warm water of Gulf Stream origin being pushed shoreward as well as seasonal warming of the inshore waters (event enclosed by box '9', Figure 12. and 13). Since two large gaps of data, a 16-day and 11-day gap, existed in the '9' event, it was difficult to determine which process may have caused the 18°C isotherm to be located 50-km from the 20-m isobath from April 30 through May 1, 1988.

Note that Transect F time series was shorter (by approximately 20 days) than the other five transects due to warm inshore waters at the beginning of the spawning period in the vicinity of Transect F (the 18°C isotherm significantly inshore of the 20-m isobath).

The maximal back-calculated menhaden spawning occurred during the week of Dec. 14, 1987 for the 1987/88 spawning period (Table 1). This 'birthweek' was responsible for 25% of the larvae collected over the spawning season (Warlen, 1994). The spawning range of 85% of the larvae collected ran from Dec. 1, 1987 through January 20, 1988. Events '6' and the start of '7' fell within this '85%' range. Unfortunately, an eight-day gap in imagery existed between Jan. 14 and Jan. 23, 1988

occurring within maximal spawning time. Besides the week of Dec. 14, 1987, the 1987/1988 period experienced an important second larval spawning peak in the weeks of Jan. 10 and 20, 1988. These two smaller peak 'birthweeks' contributed 10% each to the total number of larvae collected. The second spawning peak coincided with the box '7' event and thus increased the event's potential as a significant mass transport vehicle.

3.4.3 1990-1991 18°C isotherm location

Onslow Bay experienced the same overall seasonal cooling then warming during the November to April time series, as did the previously discussed two spawning periods. This pattern was evident in the 18°C isotherm location mean for the six transects (see Figure 9.). During November 1990, the isotherm resided close to the 20-m isobath and steadily moved offshore beginning in December and continuing through March. Nearing March's end and throughout April 1991, the 18°C progressed shoreward as shelf waters warmed. Transects A-F 18°C isotherm dynamics showed that the general seasonal trend did not alone, accurately describe the isotherm advection. The Onslow Bay circulation, as in the previous two periods, was periodically altered by Gulf Stream disturbances.

During November of the 1990/1991 spawning period, the 18°C isotherm hovered near the 20-m isobath along the six transects (box '10', Fig. 14. and 15.). For transect F, the 18°C isotherm location was shoreward of the 20-m isobath for the first 25 days of the time series (Nov. 15 - Dec. 9, 1990). The 18°C location for transect D also reached the 20-m isobath on Dec. 20 and for transect E, the 18°C isotherm comes within 5km of the 20-m isobath in early Jan. The 18°C isotherm location moved offshore to a distance of 72 km from the 20-m isobath on Jan. 14, 1991 along transect A, distinguished by boxed event '11' (Figure 14. and 15.). The isotherm pulsed shoreward along all transects within box '11'. All transects, particularly B and C, exhibited steady offshore movement after the shoreward push, as much as 60km from the 20-m isobath along transect B.

Another onshore excursion of importance was the box '12' event found along transect B, reaching 11.3km from the 20-m isobath. The 18°C isotherm along transect C

took a similar leap shoreward reaching 19.2km from the 20-m isobath on Feb. 12, 1991. The imagery showed the onshore pulse concentrated along transects B and C. The southern edge of the pulse ran along transect D. By the Feb. 17, the 18°C water receded seaward as a cold water finger protruded along the Cape Lookout Shoals.

During the period enclosed by box '13', the 18°C isotherm moved shoreward along transects A and B, while it displayed mostly offshore motion along the other transects. Transects D, E, and F exhibited a seaward 'spike' which occurred over a five-day period. The imagery displayed a cold filament extending from the inner shelf seaward along transect F and also impacting the 18°C isotherm location along D and E. Transects C, D, E, and F showed erratic behavior at the end of the spawning period, encapsulated by box '14' on Figures 14. and 15. The 18°C isotherm of the more northward transects, A and B, stayed within 20km of the 20-m isobath and lacked an erratic rough front.

The 1990-1991 spawning period was relatively low in larval abundance(Fig. 2. and 4., and Table 1.). Spawning during the week of Jan. 17, 1991 produced 42% of the larvae collected during Nov., 1990 to April 1991. The boxed event '11' coincided with the production of the maximum 'birthweek' cohort. The range of spawning for 85% of larvae collected encompassed about 40 days, Jan. 10 to Feb. 20, 1991.

3.4.4 1991-1992 18°C isotherm location

The low-frequency movement of the 18°C isotherm followed the general seasonal cooling then warming trend although during the majority of the November - April 1991/1992 season, the 18°C stayed further offshore in comparison to the three other spawning periods discussed. This trend was evidenced by the six transect mean (Fig. 9.) and the cooler temperatures exhibited in interpolated transect A SSTs (Fig. 8.).

Five periods showed notable shoreward movement of the 18°C isotherm for the 1991/1992 season. During the first period (box '15', Figs. 16. and 17.), the 18°C isotherm was close to the 20-m isobath along transects A-E, while along F, it was shoreward of

the 20-m isobath until Dec. 4, 1991. The 18°C isotherm made a 20-km excursion along Transects A-D from Dec. 25, 1991 to Jan. 6, 1992 (Figure 16. and 17.). During the period enclosed by box '16', major shoreward movement occurred along transects A-E, up to a 35 km distance over a 14 day period. Following a six day gap in imagery, the 18°C isotherm was located 82km from the 20-m isobath on Jan. 31, 1992, shown at the beginning of box '17'. The period represented by '17' contained onshore pulses along all transects, with large onshore pulse activity occurring along transects C through F. One prominent feature evident in the box '17' AVHRR images was a 'tongue' of 5 - 7°C water which moved southward around Cape Hatteras. The fourth period of the shoreward position of the 18°C isotherm occurred from about Mar. 9 - Mar. 24, exhibited by box '18'. This cold water tongue was also visible south of Cape Hatteras in the '18' event imagery although it had receded northward. This cold water intrusion from north of Cape Hatteras appeared to have slowed northward propagating water along the seaward/offshore portion of the transect by creating a flow barrier. The last notable onshore movement enclosed by box '19' occurred at the end of the 1991/1992 time series. The 18°C isotherm moved up to 75 km shoreward along the transects to arrive at its closest position to the 20-m isobath since mid-November.

3.4.5 Spatial Variability

At times, movement of the 18°C isotherm varied along different transects. To address this spatial variability, correlation coefficients were calculated to establish and estimate an association between transects for each spawning season (Sokal and Rohlf, 1969). The MATLAB routine 'corrcoef' was used which produced a matrix of correlation coefficients where each correlation coefficient was the zero-th lag of the covariance function (MATLAB, 1992).

The similarity (correlation) between transects decreased with distance for the six transects for all four periods (Figures 18.- 21.). Adjacent transects were well correlated

($r > 0.76$ for 85/86; $r > 0.63$ for 87/88; $r > 0.72$ for 90/91; and $r > 0.81$ for 91/92). The correlations between transect A and F displayed the lowest correlation ($r = 0.41$) for 1985/1986; B and F ($r = 0.21$) for 1987/1988; B and F ($r = 0.19$) for 1990/1991 also; and A and C ($r = 0.71$) for 1991/1992. The 1991/1992 period was relatively well correlated throughout all the transects. The 1985/1986 period correlations also showed that the six transects were fairly well correlated with each other. Decreasing correlation with distance is consistent with the effects of northerly (or southerly) propagating Gulf Stream or other thermal features, since correlations were only for the zero-th time lag.

3.5 Quantification of High Frequency Variability: INDEX DEVELOPMENT

3.5.1 Rationale for Index

Hypotheses i. is "Years of highest larval abundances are associated with the years when warm water masses are more frequent and/or move closest to shore." A descriptive index was developed to analyze inter-annual circulation variability, specifically focusing on three items: 1) location of pulses relative to the 20-m isobath, 2) frequency of oscillations in Onslow Bay, and 3) timing of the oscillations relative to peak menhaden spawning and delivery of larvae to coastal collection area. The index was built using four steps: 1) a curve was fit to the 18°C isotherm location time series for three transects, A, C, and F, for each of the four spawning seasons to generate a mean seasonal trend, 2) the seasonal trend was removed to look strictly at the isotherm variations, 3) histograms were generated to compile the magnitude and frequencies of the oscillations of the isotherm, and 4) the timing of anomalies were examined in relation to Warlen's (1994) larval menhaden data during heavy spawning. The following sections describe the development process and the results at each stage.

3.5.2 Curve fitting

Polynomial curve fitting was used to obtain the mean seasonal trend for transects A, C, and F. Curves were fit to separate transects, owing to the previously described

large standard deviation of the six-transect mean and the spatial inter-transect correlation results. Due to the high correlation between adjacent transects for the 18°C isotherm location, the focus was shifted to three of the six transects (A, C, and F) for the inter-annual comparisons. Curves were fit using the second, third, and fourth degree polynomials. The second degree fit was too coarse, particularly at the beginning and end of the spawning season missing a sizable portion of the trend in the actual data. The fourth degree curve fit tracked the deviations in the actual data too closely so that the mean seasonal (curve fit) trend also included high frequency changes. Since the high frequency changes were on a scale of days to weeks versus a seasonal scale of months, the fourth degree fit was not used in the interannual comparison. The third degree curve fit was used as it illustrated the best approximation of the mean seasonal trend for the 18°C isotherm location.

Comparison of the curve fits of each spawning season for transects A, C, and F showed that the mean seasonal trends varied between 12 and 35km from each other. (Figure 22.). The third degree curve fits for each time period were averaged for the three transects: A, C, and F. The mean curve fit for the four periods was derived by calculating the mean of the four mean 18°C isotherm locations derived by the polynomial curve fit. This mean calculation was performed for transect A, transect C, and transect F, all separately. Then, the three 4-year mean curve fits were superimposed on the 18°C isotherm plots for transects A, C, and F (Figures 10., 12., 14., and 16.) to observe the 18°C isotherm shoreward anomalies.

3.5.3 Deviations from the Mean Trend

In order to look at the placement of the 18°C isotherm with respect to seasonal changes, the isotherm variations from the curve fit were analyzed to compare anomalies within and between the spawning periods with particular focus on shoreward water movement. Positive numbers represented offshore movement of the 18°C isotherm and negative values represented shoreward or onshore movement.

Histograms (Figs. 23. -26.) were used to compile the magnitudes and frequencies of the negative deviations, as they represented onshore movement of warm water. Table 3. summarizes the means and standard deviations of pulse magnitudes. Each histogram consisted of ten bins centered on deviations 5km apart (-45, -40, -35,...,-10, -5, 0 km). The number of anomalies in each of the four spawning seasons reflected, in part, the number of SST images available for each year. Thus, I also indicated the relative frequency of the onshore anomalies in the position of the 18°C isotherm by including the percentage of total images represented by onshore anomalies.

Results showed that the 1985/1986 spawning period underwent somewhat frequent onshore movement and had a mean shoreward excursion magnitude similar to 1987/1988 and smaller in magnitude than 1990/1991(Fig. 23. and Table 3.). Transect A exhibited thirty negative anomalies representing shoreward movement (38.0% of the 18°C isotherm locations were shoreward of the mean trend); transect C and F showed 37 and 50 anomalies with 41.1% and 53.8% of the total 18°C isotherm locations, respectively. For the 1985/1986 period, movement along transect A showed the largest onshore anomaly magnitudes of the three transects with seven anomalies in the -25 km bin.

The 1987/1988 period had more onshore anomalies than 1985/1986 with two very large anomalies: the '-40km' bin and the '-35km' bin (Figure 24.). Both of these large anomalies occurred along transect F. Movement of the 18°C along transect A also showed two relatively large anomalies in the '-30km' bin. The percentages of onshore anomalies for transect A, C, and F for 1987/1988 were 59.7, 64.5, and 74.6% respectively. The percentage of shoreward locations along transect F represented the highest percentage for this transect of the four periods.

The 1990/1991 spawning season, a relatively low larval abundance season, displayed more negative anomalies (Table 3.) and larger shoreward percentages for transect A and C than 1987's A and C, although the magnitudes were in the same range. The histogram shown in Figure 25. illustrates the negative anomalies from the seasonal

mean for 1990/1991 spawning period. The percentages of shoreward locations in the 18°C isotherm data were 81.2%, 70.6% and 69.8% for transects A, C, and F, respectively. The percentages for transect A and C represented the highest percentages for these two transects of the four periods. 1990/1991's transect F showed slightly less onshore locations and no large magnitude anomalies compared to 1987/1988.

The 18°C isotherm of 1991/1992 period was located further offshore throughout most of the spawning season than the previous three periods, thus there were substantially less negative/onshore anomalies and smaller magnitudes for this period versus the other periods (Figure 26.). The percentages of the shoreward 18°C locations were also significantly lower than the previous three spawning seasons at: 20.7%, 33.7% and 25.0% for transects A, C, and F, respectively.

3.5.4 Temporal Pulse Estimation

The number of negative or onshore anomalies of the 18°C isotherm was based on the number of 18°C locations available, which was influenced by the images available per year. This discrepancy needed to be accounted for in order to make an interannual comparison. To account for this potential bias, a 1-km by 1-day grid was placed on plots of the 18°C isotherm anomalies. For each of the four periods, the abundance of onshore pulses was quantified by determining the number of grid boxes covered by onshore anomalies. Three rules were applied to this process: 1) any shoreward location under 5km was not included in the estimation, 3) a linear trend was assumed between data points, and 3) if a gap of data existed longer than 12 days, these days were not included in the estimation. Table 4. summarizes the data after grid analysis.

The same general trends shown in the histograms (Fig. 23.- 24. and Table 3.) resulted from the grid analysis exercise (Table 4.) with 1990/1991 and 1987/1988 having the largest pulse magnitudes and 1991/1992 having the lowest magnitudes. Although, grid analysis results (Table 4.) exhibited higher magnitude means for most cases than depicted by the onshore movement with interpolation (Table 3.). The varied behavior

between transects was also apparent by the different number of pulses along each transect within the same period (Table 4.), e.g. the 1987/1988 period had the most pulses along transect A (10 pulses) and then transect C with 8 pulses, and lastly transect F with 7 pulses. The 1985/1986 period showed the opposite trend with the most pulses along transect F and the least number of pulses along A.

The count (n) represented the number of estimated days that the 18°C was shoreward of the mean seasonal trend. This number divided by the number of days in the time series (165 days for A and C, 145 days for transect F) approximated the percentage of the spawning season that warm water was in an onshore position (Table 4. (% of days)). The transect F time period was shorter due to absence of the 18°C isotherm along this transect in the first 20 days of the time series. The following percentage ranges of days of shoreward 18°C locations resulted: 8% (1991/92) - 45%(1990/91) for transect A; 17%(1991/1992) - 40%(1987/88) for transect C; and 10%(1991-1992) - 38%(1987-1988) for transect F.

To determine if results depicted in Table 4. were statistically significant the data were grouped in four sets: 1) transect A, 2) transect C, 3) transect F, and 4) transects A, C, and F, and compared using one-way ANOVA (Table 5.). There was no significant difference between 1985/1986 and 1987/1988, the two high larval abundance periods, nor between 1987/88 and 1990/1991 for the 4 sets. The comparisons between 1991/1992 with the three other periods for the 4 sets determined that 1991/1992 was significantly lower than the other time periods. The 1990/1991 period was also significantly higher than the 1985/86 for the 3-transect group only.

3.5.5 Timing of Pulses during Peak Spawning

Warlen (1994) stated: "In every spawning season, there was a dominant birth week mode that contributed from 25 to 43% of the total estuarine recruits." Although there was a protracted spawning period for menhaden, one shorter period of spawning (on

the order of days) contributed a large percentage of the estuarine juvenile population at Beaufort Inlet. Thus, it was essential to observe 18°C isotherm events during this 'dominant birthweek' and surrounding weeks. From the histograms, the largest anomalies fell within the range of 20 to 40km shoreward (negative) movement from the seasonal trend. It was necessary to find associations between the maximum spawning periods and these large shoreward anomalies. The following four sections discuss the relationship between maximum spawning periods and synchronous advective anomalies.

3.5.5.1 1985-1986 '85%' Spawning Period

The week surrounding January 10, 1986 was the time of maximal back-calculated spawning with 44% of all larvae/recruits collected from this birth week. The range of the 85% of the collected larvae's spawning times occurred from approximately Dec. 20, 1985 to Jan. 20, 1986. Maximum spawning occurred during the period influenced by events '1' and '2' (Fig. 10. and 11.) with maximum spawning week of Jan. 10, 1986 coinciding with the shoreward pulse evident in all transects during event '2'.

The 18°C isotherm showed onshore movement during event '1'. The AVHRR imagery from Dec. 27, 1985 revealed a filament of warm water 'shingling' off of the warmer Gulf Stream water. The filament started just south of Cape Lookout near the 20-m isobath and stretched southwest across the mid-shelf intersecting transects A and B. By Dec. 29, 1985, the outline of the shingle was still visible but appeared as though the warmer temperatures of the Gulf Stream had cooled due to the effect of the cooler inshore waters. The largest magnitude of the negative deviations/onshore movement during event '1' was 10.7km shoreward of the mean seasonal trend along transect A occurring on January 9, 1986, which was during the week of maximum spawning. For transects C and F, the largest anomalies during event '1' were 10.4km on January 3, 1986 for C and 16.2km on January 12, 1986 for F. Also, just before event '1', five large onshore anomalies (22.5 - 24.5km magnitudes) existed from December 11, - December 14, 1985. The grid analysis estimated this pulse as having a 7day duration and 7 - 24km magnitudes

along transect A, and of similar duration and magnitude along transect C. The 18°C isotherm along transect F displayed onshore activity with a lesser duration and magnitude (4 days and 6 - 15km magnitudes).

During event '2' (Fig. 10. and 11.), the 18°C isotherm moved onshore within 25km of the 20-m isobath for all transects. This shoreward movement was represented by negative anomalies (Fig. 23) of magnitude 17.9km on Jan. 20, 1986 for transect A (grid results estimated 7 day duration and 6 -16km magnitudes); five relatively large shoreward anomalies of 11.2 to 20.2km magnitudes during Jan. 20 - 22, 1986 along transect C (grid analysis: 10day duration and 6 - 20km magnitude); and three shoreward anomalies of 10.7 to 18.2km from Jan. 16 - Jan. 20, 1986 along transect F (grid results: 7 - 18km magnitudes for 6 days). Both events '1' and '2' exhibited isotherm locations shoreward of the 4-year mean trends for transects A, C, and F as evident in the negative/onshore anomalies.

3.5.5.2 1987-1988 '85%' Spawning Period

The 18°C isotherm underwent two important events during the 85% spawning range. Event '6' and the start of event '7', (Fig 12. and 13.), fell within the period from Dec. 1, 1987 to January 20, 1988 representing the 85% spawning range. A portion of event '6' is shown in the image time series in Fig. 4.. The significant shoreward excursion shown along transects A, B, and C in event '6' may have been a key factor in explaining the high abundances collected. The onshore pulse apparent on Dec. 30, 1987 -18°C, when water came within 10 km of the 20-m isobath, was over 25km shoreward of the 4-year mean seasonal trend for the curve fitted transects, A and C. The magnitude of the onshore anomalies ranged from 29.5km on Dec. 29, 1987 to 10.7km on Jan. 11, 1988 along transect A. Five onshore anomalies occurred along transect A with magnitudes greater than 10km, two of which were in the range of 29 km. For transect C, the largest magnitude onshore anomaly during event '6' was 17.1km on Jan. 5, 1988. The grid

analysis results showed that this shoreward pulse lasted for 20 days with magnitudes of 6 - 29km along transect A. For transect C, the pulse lasted 8 days with magnitudes of 15 - 18km. Transect F did not display any negative anomalies during this period but the 18°C isotherm along transect F was in the vicinity of the 20-m isobath as was the 4-year mean trend.

Event '7' coincided with a second smaller peak in spawning. The six transects displayed an onshore excursion during '7', particularly considerable along transects B, C, and D. The 18°C isotherm was shoreward of the 4-year mean trend for transects C and F for event '7'. Grid results showed this shoreward pulse lasting 9 days along transect C with magnitudes of 5 - 20 km; and, for transect F, lasting 12 days with magnitudes of 7 - 18km. The isotherm for transect A was either just shoreward of or coincident with the 4-year mean trend for the duration of event '7'.

3.5.5.3 1990-1991 '85%' Spawning Period

Events '11' and '12' occurred during the '85%' spawning range of the low abundance period of 1990/1991 (Figures 14. and 15.). Along transect A, a large pulse began its shoreward advance on January 13, 1991 and reached its most nearshore location on Jan. 28, 1991 during boxed event '11'. The negative/shoreward anomalies associated with this movement were 17.8 and 20.8km magnitude pulses on Jan. 26 and 27, 1991. The coinciding grid results estimated the shoreward pulse lasting for 15 days with magnitudes ranging from 5 - 20km. Some onshore movement was visible along all six transects particularly A, B, E, and F. Along transect F during event '11', the 18°C isotherm came within 10km of the 20-m isobath. The shoreward anomalies from the 4-year seasonal trend along transect F associated with this movement were 23.8 and 24.7km in magnitude both occurring on Jan. 17, 1991 (day and night images); corresponding grid results estimated a 17-day shoreward pulse with magnitudes of 8 - 24km. Also, this

pulse was located shoreward of the 4-year mean trend evidenced by three onshore anomaly magnitudes: 9.0, 9.2, and 10.0km for transect C; grid results showed the pulse along transect C lasting 4 days with magnitudes of 8 - 10km. This shoreward excursion was synchronized with the maximum back-calculated spawning during the week of January 17, 1991. This 'birthweek' contributed 42% of the total estuarine recruits captured.

After the maximum spawning week of Jan. 17, 1991, spawning during the next four week period through late February contributed ~39% of the total larvae captured. This four-week spawning period was coincident with the shoreward excursion found in event '12'. This onshore pulse was concentrated along three transects: A, B, and C, with the 18°C isotherm advancing to 15km from the 20-m isobath. The inner shelf excursion in event '12' was shoreward of the 4-year mean trend along transects A and C: largest magnitude anomalies were 28.0km on Feb. 10 and 14, 1991 for A and 30.8km on Feb. 12, 1991 for C. During event '12', the 18°C isotherm experienced three relatively large anomaly magnitudes (28.0, 18.7, and 28.0km) along transect A and three large anomaly magnitudes (24.0, 28.3, and 30.8km) along transect C. The grid results estimated this shoreward pulse continuing for 8 days along transect A and 5 days along transect C.

3.5.5.4 1991-1992 '85%' Spawning Period

The majority of 1991-1992 spawning took place during the 67-day period from Nov. 25, 1991 to Jan. 31, 1992 as 85% of the total collected larvae were spawned during this time. The week of December 10, 1991 was defined as the largest birthweek contributing 32% of the larvae collected during this Sept.-April spawning season (Warlen, 1994). The 18°C isotherm events in box '15' and '16' (Fig. 16. and 17.) fell within this critical spawning period.

The event '15' 18°C position stayed close to the 20-m isobath making the distance shorter that the larvae would have had to travel to the estuarine nurseries. Observing the 18°C isotherm motion, one excursion was of note during event '15' (Fig. 16. and 17.). On

Dec. 11, 1991, the 18°C isotherm was 53km from the 20-m isobath along Transect A. On Dec. 12, the isotherm was located at 11km from the 20-m isobath, having moved 42km towards shore from the previous day. This pulse may have been of particular importance as the highest percent of recruits occurred from the back-calculated spawning week of December 10, 1991. There was a shoreward advance of the 18°C isotherm apparent on Transects B, D, and E for Dec. 11-12 time period. The 18°C isotherm did not move shoreward during Dec. 11-12 along Transects C and F but, it did remain within 20km of the 20-m isobath from Dec. 7 to 14, 1991. Although there was onshore movement during event '15', the only onshore anomaly that registered above a 5km magnitude along transects A, C, and F was a 12.4km magnitude pulse along transect A on Dec. 12, 1991.

The 18°C isotherm pulsed shoreward during event '16' along transects A-D. The pulse evident in box '16' occurred in latter part of December lagging 1-2 weeks after the maximum spawning week but still within the '85%' spawning range for the season. Although a considerable advance towards shore was evident along transects A-D during event '16', grid results showed that the 18°C isotherm shoreward anomaly magnitudes were never more than 10km and lasted for no more than 2 days.

Relatively large magnitude shoreward anomalies (15 - 40km) may have been essential to shoreward transport of larvae. Summarizing the shoreward anomaly results, the number of relatively large shoreward anomalies per maximum spawning period and per protracted spawning season (entire time series) are as follows: for 1985/1986, 19 of the 41 large shoreward anomalies (15 - 40km bins) occurred during maximum spawning period; for 1987/1988 10 of the 53 large anomalies occurred during maximum spawning; for 1990/1991, 15 of the 55 large anomalies took place during maximum spawning; and, for 1991/1992, 1 of the 13 large anomalies occurred during maximum spawning. Of note, ten of the 19 large anomalies from 1985/1986 period were in the smallest bin, the '15km' bin.

Table 6. summarizes the maximum birthweek warm water pulse activity for the four spawning periods. This summary shows that there was substantial shoreward pulse activity in all periods except that of the 1991/1992 spawning period, a low abundance period.

3.6 TRANSPORT RATE RESULTS

In order to check the feasibility of larvae being transported by the onshore pulses, transport rates were calculated based on the locations of the 18°C isotherm along the six transects. Each 18°C isotherm distance from the 20-m isobath was subtracted from the next consecutive 18°C isotherm distance and divided by the number of days in between each image. Two groups of rates were formed: 1) negative transport rates representing shoreward advection, and 2) positive transport rates representing seaward movement. The mean was also calculated. Table 7. reports the maximum, minimum, and mean of the shoreward and seaward rates, and the net transport rates for each transect for each of the four periods. The 1985/1986 period had the mean highest shoreward, seaward, and net rates. The high mean rates in 1985/1986 and 1987/1988 were influenced by the fact that 1985/1986 and 1987/88 both had extremely high outliers in their rates shown by the maximum shoreward and seaward rates. The 1990/1991 period had the lowest mean shoreward rates. Transport rates were also calculated for just the maximum birthweek and following week. Table 8. displays these rate results.

Since the larval journey from spawning ground to inlet/estuary was estimated to take approximately 30-90 days and the estimated distance they needed travel was ~125 - 200km, the rates of larval transport fall between 1.4 km/day and 6.7 km/day. The mean transport rates calculated from the 18°C isotherm locations were higher than the estimated rates and ranged from 5.4 km/day to 15.3 km/day (6.3 to 17.7 cm/sec).

4. DISCUSSION

4.1 OVERVIEW

The early portion of fishes' life history is considered to be a critical period in that survival rate greatly affects recruitment and ultimately fisheries stock. Larval fish mortality rates have been estimated as high as 5-10% per day during the early larval stages (Rothschild, 1986). Hjort (1914) hypothesized that availability of food during the larval period determined the resultant class size. Lasker (1981) elaborated on this idea with his stable ocean theory which suggested that the less turbulent the ocean environment was, the better the larvae's opportunity to feed and thus contributing to higher survival and a stronger year class. Many recent studies focused on the larval stage and mechanisms that influence survival such as starvation, predation (Lillelund and Lasker, 1971), storms (Maillet and Checkley, 1991), wind (Johnson et al., 1984; Norcross and Bodulus, 1992) and circulation patterns (Cowen et al., 1993; Parrish et al., 1981; Nelson et al. 1977). It seems that no one factor can be held accountable for the variability in estuarine recruitment, instead myriad factors combine to influence the larval growth and survival, and year class strength. An added complexity to the life history process is the elusive connection between collected larval abundances and recruitment to the adult population (Morse, 1989). In this study, I focused on one component of the whole which affects the larval stage, namely larval transport via circulation.

Hydrodynamic fronts are associated with aggregation of fish larvae (Wolanski and Hamner, 1988; Nakata, 1989) and their subsequent transport to nursery areas (Checkley, et al., 1988). In particular, western boundary currents, such as the Gulf Stream, play a significant part in transporting larvae and defining larval distribution spatially and temporally (Atkinson and Targett, 1983; Nakata, 1989.). A portion of the Gulf Stream/Florida Current follows the southeastern coast of the U.S. coursing along the shelf/slope boundary from Florida to Cape Hatteras at which point the Stream veers northeastward into the Atlantic. This area of the Gulf Stream is characterized by an extremely dynamic front with major effects on shelf water due to its proximity to the shelf break. The dynamics and energy exchanges are borne out in instabilities causing

meandering of the front which facilitates exchanges of shelf and Gulf Stream waters and provides relatively warm water to the outer shelf. These meanders lead to shingles (Von Arx et al., 1955), filaments, and eddies (Brooks and Bane, 1981; Bane et al., 1981; and Glenn and Ebbesmeyer, 1994a and 1994b). A number of estuarine-dependent fish species (Atlantic menhaden, spot, Atlantic croaker, bluefish) are known to spawn offshore along the continental shelf/slope break at the western edge of the Gulf Stream (Warlen and Burke, 1990; Warlen and Chester, 1985; Weinstein, 1979). Atlantic menhaden and some other species must reach southeastern estuaries, if they are to survive beyond the larval stage. Onshore flow induced by lateral movement of the Gulf Stream front may be a vehicle facilitating larval movement towards shore on the western side of the Gulf Stream.

This study focused on the Gulf Stream induced circulation patterns in Onslow Bay, NC, and their relation to Atlantic menhaden larval abundances and their subsequent spawning dates. Larvae must journey shoreward across the shelf to reach their estuarine destinations. Stegmann and Yoder (1996) concentrated on the cross-shelf water movement by tracking sea surface temperature (SST) variability along a cross continental shelf transect. They concluded from their six year time series (1981-1986) that cross-shelf oscillations, termed 'pulses', in Onslow Bay occurred regularly as short-term events (onshore displacement every 3-5 days) and were governed primarily by Gulf Stream dynamics. The present study extended their time series, following the same methodology, for four more spawning periods and five additional transects.

4.2. SST INTERANNUAL VARIABILITY

This study evaluated two processes: seasonal cooling/warming and 'event' fluctuations, related to the location and movement of larval fish. The particular cooling trends for each season are important to the location of the spawning fish, i.e. the farther offshore the warm 18-22°C water, the farther offshore the adult fish spawn and thus the longer distance the larvae have to travel to estuarine nurseries. The pulses of warm water

on 'event' time scales, may have supplied the transport vehicle for offshore spawned fish to reach coastal nursery areas.

By using six cross shelf transects, a lagrangian view of water mass movement was attempted. Multiple transects allowed us to observe the existing alongshore movement as well as cross-shelf movement.

Seasonal changes in water temperature may have affected spawning location and larval survival (Lewis, 1965), and seasonal changes in SST differed among the four spawning seasons. During December 1985, the warmer water nearer shore may have allowed for spawning to take place closer to shore. If so, the menhaden larvae had less distance to travel, possibly contributing to the relatively higher number of larvae captured at the inlet (Govoni, 1993; Warlen, 1994). The 1990/1991 spawning period, with its relatively low abundances, experienced warm SSTs (18 -23°C) in November and early December, and relatively cool SSTs (10-13°C) during late January through late March. Since the 1990/1991 spawning period was characterized by frequent and sizable warm water movement towards shore, it lends evidence contrary to my *Hypothesis i*.

Contrary to the 1990/1991 period, the second low abundance period, 1991/1992, cross-shelf SST variability/circulation appeared to support *Hypothesis i*. Shoreward pulses were not of sizable magnitude or frequency relative to the other spawning periods. The 1991/1992 spawning period showed steady inshore cooling from Nov. 1, 1991 through Feb. 10, 1992, at which point the inshore waters remained cool for the remainder of the spawning season. Peak spawning occurring in early December at which time 18-22°C waters were approximately 30-40km from the 20-m isobath. This location of warm water was the closest that the warm water came to the 20-m isobath for the remainder of the spawning season. The larvae may have had the greatest chance of survival at this time due to the proximity of the warm spawning waters to the coast.

The frequency and magnitude of onshore pulses of the 18°C isotherm showed significant differences between the 1987/1988 period and the 1991/1992 period, and

between the 1990/1991 period and the 1991/1992 period. The 1991/1992 period displayed relatively little shoreward movement both in regards to frequency and magnitude. The results from the grid analysis showed 1991/1992 with the lowest number of pulses, the lowest mean of magnitude of pulses and the lowest percentage of days that the 18°C isotherm anomalies were shoreward of the 4-period seasonal mean trend. In contrast, the 1990/91 and 1987/1988 spawning seasons had large magnitude pulses toward shore and with greater frequency than the other two periods. During the relatively high larval abundance period of 1985/1986, onshore pulse activity was greater than that of the 1991/1992 period and lesser than that of the 1987/1988 and the 1991/1992 periods.

4.3 MAXIMUM SPAWNING PERIOD

Warlen (1994) described an important birthweek for each spawning period which contributed a significant portion to the larvae collected at the inlet. In each spawning period, a coincident onshore pulse occurred with this peak birthweek. During the 1985/86 period, cross-shelf circulation displayed relatively large magnitude shoreward anomalies, 11 - 20km shoreward of the mean seasonal trend lasting 6 - 10 days along transect A, C, and F. During the maximum birthweek of the 1987/1988 spawning period, sizable onshore anomalies of up to 29km in magnitude occurred along transects A, B, and C. This pulse (event '6') lasted approximately 20 days. Relative to its farthest offshore location during this event, the 18°C isotherm moved approximately 70km along transect A. This is one of the most rapid onshore movements observed during my study.

The low abundance period of 1990/1991 experienced sizable onshore anomalies of 24km shoreward of the 4-year seasonal mean trend although the duration was not as long as for the 1987/1988 event discussed above. Also, the sizable shoreward anomalies were along Transect F, the most southern transect and the farthest from Beaufort Inlet. The 1991/1992 period, another relatively low abundance spawning season, exhibited only small magnitude pulses with short durations.

4.4 OTHER CIRCULATION PROCESSES

Although cross-shelf circulation in the form of warm water pulse oscillation was the main focus of this study, other circulation and climatological processes may affect these oscillations and larval transport. These processes include cold water intrusions from north of Cape Hatteras, frontal eddy propagation, Gulf Stream induced upwelling, Gulf Stream bimodality, and wind dynamics. The cold tongue intrusions from north of Cape Hatteras may affect circulation processes and thus larval distributions/transport in Raleigh and Onslow Bays (Gray and Cerame-Vivas, 1963; Stegmann and Yoder, 1996). Evidence of these cold water intrusions were seen in SST imagery for the present study's time series although their physical effect on Onslow Bay circulation was unclear. Upwelling cold domes of North Atlantic Central Water (Gulf Stream Water) in frontal eddy centers have been found to displace large volumes of shelf water and enhance shelf primary productivity (Blanton, et al. 1981; Oey et al., 1987; Lee et al., 1991) and govern fish distribution (Atkinson and Targett, 1983). Also, Brooks and Bane (1981) described frontal eddy counter currents of up to 50cm/s traveling southwestward in the South Atlantic Bight opposing the Gulf Stream downstream propagation speeds of 40km/day. These countercurrents may displace larvae and thus alter estuarine recruitment. Bane and Dewar (1988) described two modes of the Carolina Bays portion of the Gulf Stream downstream of the Charleston Bump and south of Cape Hatteras: a weakly deflected state and a strongly deflected state. Fall and winter are periods when the strongly deflected mode preferentially occurs (Bane and Dewar, 1988). This strongly deflected state is characterized by the Stream sharply turning seaward of the Bump and thus the Gulf Stream's western edge SSTs occur seaward of the 600-m isobath by up to several tens of kilometers along the continental slope. This seaward displacement of the Gulf Stream most likely affects spawning behavior and location and subsequently larval transport and survival.

Wind effects on circulation in the South Atlantic Bight have been studied extensively (Stegmann and Yoder, 1996; McClain et al., 1984; Lee and Atkinson, 1983; Yoder, 1983; Brooks and Bane, 1981; Nelson et al., 1977). Brooks and Bane(1981) found that currents associated with the upper continental slope (200-400m isobaths) of Onslow Bay were not correlated with nearby wind stress or sea level fluctuations. Stegmann and Yoder(1996) found in their 1981 - 1986 time series in Onslow Bay that the influence of wind and air temperature played a lesser role in SAB circulation than that of the Gulf Stream. They also found that the wind and air impact was greater on the inner shelf as opposed to the outer shelf. The present study followed the postulation that Gulf Stream dynamics primarily governed Onslow Bay circulation along the mid and outer shelf.

4.5 TRANSPORT

The calculated transport rates showed that larval transport through shoreward transport by warm water pulses was feasible when compared to the larval ages and distance traveled from Warlen (1994). The calculated net rates (Tables 7. and 8.) displayed net shoreward for all transects in 1987/1988 for both the entire spawning period and the maximum birthweek period whereas the 1990/1991 spawning period showed net seaward rates for the entire spawning period for transects A, C, and F. For the maximum birthweek period during the 1990/1991 period, the net rates were relatively low shoreward transport for transects A and F, and low seaward transport for transect C.

The along transect (cross-shelf) rates may have been biased by alongshore transport due to the Gulf Stream. Tidal signals in the inner shelf areas may also have influenced transport rates calculated from isotherm locations near the 20-m isobath. The calculated transport estimates compared reasonably with other studies (Stegmann and Yoder, 1996, and references cited therein). Other factors which may have affected transport rate discrepancies are the varying speeds of the larvae during their transport. The larval speed may be affected by the growth and development of the larvae

themselves and by the different water masses they encounter (outer shelf vs. inner shelf). Also, Govoni(1993) and Warlen(1994) suggested that larvae may gather at the inlet entrance and wait for certain cues such as temperature, salinity, pH, and turbidity (Miller, 1988) to enter the estuary by tidal transport or nonlocal forcing at the estuary mouths (Pietrafesa and Janowitz, 1988).

4.6 ECOLOGICAL SIGNIFICANCE

The use of AVHRR satellite imagery to investigate temperature variability has made a significant contribution to the knowledge of circulation patterns. AVHRR data as a proxy for circulation patterns is particularly applicable and valuable in areas where a clear distinction between water masses is easily distinguishable by temperature gradients. The conditions during the fall, winter, and spring months in the South Atlantic Bight are conducive to satellite imagery applications because of the warm Gulf Stream and the cool inner shelf waters. As this study and many others have shown, Gulf Stream meanders and subsequent developments are clearly visible in stark contrast to shelf waters. Satellite imagery data possess the unique feature of large-scale coverage and numerous samplings (2 passes per day over most areas) allowing a broad scale picture and long time series (Cornillon et al., 1987). Many applications of satellite imagery exist and have been utilized in much research (Abbot and Chelton, 1991; Denman and Abbott, 1988; Fu et al., 1990). Any ecological system governed by circulation on a 100s of kilometer scale is amenable to satellite imagery as a research tool. Application examples include the prediction of oil spills, red tide dynamics and expatriation of biological units (Tester, 1991), and migratory patterns and distributions of fish and cetaceans. The present study applied SST satellite imagery to explain variability in larval fish abundances which in the future may aid in menhaden and related fisheries research and management strategies.

5. CONCLUSIONS

The original question asked at the beginning of this study was "is there a relationship between inter-annual differences in larval abundances/spawning dates and

the inter-annual variability in the cross-shelf warm water mass movement?" A number of calculations were completed to determine the relationship between two sets of data: larval fish abundances and AVHRR satellite imagery. The relationship between cross-shelf temperature/circulation variability and larval abundances/spawning times over the protracted spawning period was not a simple correlation. The results did not support *Hypothesis i*. It was evident that the frequency of pulses over the protracted spawning period (November through April) did not explain the interannual variability. However, there was a clear association with onshore pulse movement and maximum spawning periods supporting the postulation that these pulses may be a significant larval transport vehicle. This association was most notably apparent during the December 1987 event '6', a shoreward pulse of large magnitude and long duration which coincided with the maximum spawning period defined by the largest birthweek cohort contribution to the larval collections (Warlen, 1994).

Rates derived from SST gradients over time coincided with the range of the transport rates estimated from larval ages and the distance from offshore spawning grounds to Beaufort Inlet (and also with previous research) supporting *Hypothesis ii*.

The connection between AVHRR imagery and larvae recruited to a coastal estuary may have been complicated by several factors. Predation by fish and gelatinous zooplankton (Purcell, 1992), food availability and starvation, storm-induced turbulence within the water column (Checkley et al. 1988), entrainment in the northeastward propagating Gulf Stream (Stegmann and Yoder, 1996), and inter-annual spawning variability (adult year class differences) are among some of the possible major influences on larval recruitment to estuarine nurseries. Although any number of these factors may hinder or enhance the success of larval recruitment to coastal estuaries, this study showed that the interannual variability of menhaden larval recruitment to North Carolina estuaries may be related to onshore pulses of warm water during the week following maximum spawning. This association may not definitively explain the interannual variability in

larval abundances but it does describe a possible mechanism for rapid larval transport toward shore.

REFERENCES SITED

- Abbott M.R. and D.B. Chelton. 1991. Advances in passive remote sensing of the ocean. *Reviews of Geophysics, Supplement* April 1991, 571-589.
- Atkinson, L.P. and T.E. Targett. 1983. Upwelling along the 60-m isobath from Cape Canaveral to Cape Hatteras and its relationship to fish distribution. *Deep Sea Research* **30**(2A), 221-226.
- Bane, J.M., Jr., D.A. Brooks, and K.R. Lorenson. 1981. Synoptic observations of the three-dimensional structure and propagation of Gulf Stream meanders along the Carolina continental margin. *Journal of Geophysical Research* **86**(C7), 6411-6425.
- Bane, J.M., Jr., and W.K. Dewar. 1988. Gulf Stream bimodality and variability downstream of the Charleston Bump. *Journal of Geophysical Research* **93**(C6), 6695-6710.
- Blanton, J.O., L.P. Atkinson, L.J. Pietrafesa, and T.N. Lee. 1981. The intrusion of Gulf Stream water across the continental shelf due to topographically-induced upwelling. *Deep Sea Research* **28A**(4), 394-405.
- Blanton, J.O. and L.J. Pietrafesa. 1978. Flushing of the continental shelf south of Cape Hatteras by the Gulf Stream. *Geophysical Research Letters* **5**, 495-498.
- Brooks, D. A. and J.M. Bane, Jr. 1981. Gulf Stream fluctuations and meanders over the Onslow Bay upper continental slope. *Journal of Physical Oceanography* **11**, 247-256.
- Cornillon, P., C. Gilman, L. Stramma, O. Brown, R. Evans, and J. Brown. 1987. Processing and analysis of large volumes of satellite-derived thermal infrared data. *Journal of Geophysical Research* **92**(C12), 12,993-13,002.
- 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**(2), 567-587.
- Checkley, D.M., Jr., S. Raman, G.L. Maillet, and K.M. Mason. 1988. Winter storm effects on the spawning and larval drift of a pelagic fish. *Nature* **335**, 346-348.
- Denman, K.L. and M. R. Abbott. 1988. Time evolution of surface chlorophyll patterns from cross-spectrum analysis of satellite color images. *Journal of Geophysical Research* **93** (C6), 6789-6798.

- Dryfoos, R.L., R.P. Cheek, and R.L. Kroger. 1973. Preliminary analyses of Atlantic menhaden, *Brevoortia tyrannus*, migrations, population structure, survival and exploitation rates, and availability as indicated from tag returns. *Fishery Bulletin* **71**, 719-734.
- Durbin, A.G. and E.G. Durbin. 1975. Grazing rates of the Atlantic menhaden *Brevoortia tyrannus* as a function of particle size and concentration. *Marine Biology* **33**, 265-277.
- Fu, L., W. T. Liu, and M.R. Abbott. 1990. Satellite Remote Sensing of the Ocean. in The Sea: Ocean Engineering Science Vol. 9, John Wiley & Sons, Inc. 1193-1236.
- Glenn, S.M. and C.C. Ebbesmeyer. 1994. The structure and propagation of a Gulf Stream frontal eddy along the North Carolina shelf break. *Journal of Geophysical Research* **99**(C3), 5029-5046.
- Glenn, S.M. and C.C. Ebbesmeyer. 1994. Observations of Gulf Stream frontal eddies in the vicinity of Cape Hatteras. *Journal of Geophysical Research* **99**(C3), 5047-5055.
- 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**(2), 538-566.
- Gray, C.L. 1992. Atlantic menhaden species profile, Current Report, the Narragansett Bay Project. NBP-92-84. R.I. Dept. of Environmental Management.
- Gray, I.E. and M.J. Cerame-Vivas. 1963. The circulation of surface waters in Raleigh Bay, North Carolina. *Limnology and Oceanography* **8**, 330-337.
- Hjort, J. 1914. Fluctuations in the great fisheries of Northern Europe viewed in the light of biological research. *Rapp. P. -v. Reun. Cons. Perm. int. Explor. Mer* **20**, 1-228.
- Hoss, D.E., D.M. Checkley, Jr., and L.R. Settle, 1989. Diurnal buoyancy changes in larval Atlantic menhaden (*Brevoortia tyrannus*). *Rapp. R.-v. Reun. Cons. int. Explor. Mer*, 191:105-111.
- Higham, J.R. and W.R. Nicholson. 1964. Sexual maturation and spawning of Atlantic menhaden. *U.S. FWS Fish. Serv. Bull.* **63**(2):255-271.
- Johnson, D.R., B.S. Hester, and J.R. McConaughy. 1984. Studies of a wind mechanism influencing the recruitment of blue crabs in the Middle Atlantic Bight. *Continental Shelf Research* **3**(4), 425-437.

- June, F.C. and F.T. Carlson. 1971. Food of young Atlantic menhaden, *Brevoortia tyrannus*, in relation to metamorphosis. *Fishery Bulletin* **68**(3), 493-511.
- Kendall, A.W., Jr. and J.W. Reintjes. 1975. Geographic and hydrographic distribution of Atlantic menhaden eggs and larvae along the middle Atlantic coast from RV *Dolphin* cruises, 1965-66. *Fishery Bulletin* **73**, 317-332.
- Lasker, R. 1981. The role of a stable ocean in larval fish survival and subsequent recruitment. pp. 80-87 in R. Lasker, ed. *Marine Fish Larvae*. Washington Sea Grant Program, University of Washington Press, Seattle.
- 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**(C12), 22,191-22,205.
- Lee, T.N., and L.P. Atkinson. 1983. Low-frequency current and temperature variability from Gulf Stream frontal eddies and atmospheric forcing along the southeast U.S. outer continental shelf. *Journal of Geophysical Research* **88**(C8), 4541-4567.
- Lewis, R.M. 1965. The effect of minimum temperature on the survival of larval Atlantic menhaden, *Brevoortia tyrannus*. *Transactions of American Fisheries Society* **94**, 409-412.
- Lewis, R.M. and W.C. Mann. 1971. Occurrence and abundance of larval Atlantic menhaden, *Brevoortia tyrannus*, at two North Carolina inlets with notes on associated species. *Transactions of American Fisheries Society* **2**, 296-301.
- Lewis, R.M. and E.P. Wilkens. 1971. Abundance of Atlantic menhaden larvae and associated species during a diel collection at Beaufort, North Carolina. *Chesapeake Science* **12**, 185-187.
- Lillelund, K. and R. Lasker. 1971. Laboratory studies of predation by marine copepods on fish larvae. *Fishery Bulletin* **69**, 655-667.
- Menzel, D.W., ed. 1993. Ocean Processes: U.S. Southeast Continental Shelf: A summary of research conducted in the South Atlantic Bight under the auspices of the U.S. Department of Energy. U.S. Dept. of Energy, DOE/OSTI--11674(DE93010744).
- Maillet, G.L. and D.M. Checkley, Jr. 1991. Storm-related variation in the growth rate of otoliths of larval Atlantic menhaden *Brevoortia tyrannus*: a time series analysis of biological and physical variables and implications for larva growth and mortality. *Marine Ecology Progress Series* **79**, 1-16.

- MATLAB, 1992. MATLAB (High Performance Numeric Computation and Visualization Software) Reference Guide. The Math Works, Inc. Natick, MA. p548.
- Miller, J.M. 1988. Physical processes and the mechanisms of coastal migrations of immature marine fishes. *American Fisheries Society Symposium* **3**, 68-76.
- Miller, J.M., J.P. Reed and L.P. Pietrafesa. 1982. Patterns, mechanisms and approaches to the study of migrations of estuarine-dependent fish larvae and juveniles. pp. 209-225 in J.D. McCleave, G.P. Arnold, J.J. Dodson and W.H. Neill, eds. Mechanisms of migration in fishes. Plenum, N.Y.
- Morse, W.W. 1989. Catchability, growth and mortality of larval fishes. *Fishery Bulletin, U.S.* **87**, 417-446.
- Nakata, H. 1989. Transport and distribution of fish eggs and larvae in the vicinity of coastal fronts. *Rapp. P.-v. Reun. Cons. int. Explor. Mer.* **191**, 153-159.
- Nelson, W., M., C. Ingham, and W.E. Schaaf. 1977. Larval transport and year-class strength of Atlantic menhaden, *Brevoortia tyrannus*. *Fishery Bulletin U.S.* **83**, 151-170.
- Njoku, E.G. and O. B. Brown. 1993. Sea surface temperature. pp. 237-249 in R.L. Gurney, J.L. Foster, and C.L. Parkinson, eds. Atlas of satellite observation related to global change. Cambridge University Press, London, Great Britain.
- Norcross, B.L. and D.A. Bodolus. 1992. Hypothetical northern spawning limit and larval transport of spot. in Hoyt, R.D. (ed.), Larval fish recruitment and research in the Americas. NOAA Technical Report NMFS **95**: p 77-88.
- Oey, L.-Y., L.P. Atkinson, 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.
- Parrish, R.H., C.S. Nelson, and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California Current. *Biological Oceanography* **1**(2), 175-203.
- Pietrafesa, L.J. and G.S. Janowitz. 1988. Physical oceanographic processes affecting larval transport around and through North Carolina inlets. *American Fisheries Society Symposium* **3**, 34-50.
- Purcell, J.E. 1992. Effects of predation by the scyphomedusan *Chrysaora quinquecirrha* on zooplankton populations in Chesapeake Bay, USA. *Marine Ecology Progress Series* **87**, 65-76.

- Reintjes, J.W. 1961. Menhaden eggs and larvae from M/V Theodore N. Gill cruises, South Atlantic coast of the United States, 1953 - 1954. U.S. FWS Special Scientific Report. Fisheries No. 393. Washington, D.C. Sept., 1961.
- Rogers, G.S. and M.J. Van Den Avyle. 1983. Species Profiles: Life histories and environmental requirements of coastal fishes and invertebrates (So. Atlantic), Atlantic menhaden. FWS/OBS-82/11.11, Georgia Cooperative Fishery Research Unit, Univ. of Georgia, Athens, GA.
- Rothschild, B. 1986. Dynamics of marine fish populations. Harvard University Press, Boston. p 277.
- Sokal, R.R. and F.J. Rohlf. 1969. Biometry. W.H. Freeman and Co., San Francisco.
- 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. Accepted by *Continental Shelf Research*, 2 Nov., 1994.
- Tester, P. et al. 1991. An expatriate red tide bloom: transport, distribution and persistence. *Limnology and Oceanography* **36**(5), 1053-1061.
- Vaughan, D.S. and J.W. Smith. 1988. Stock assessment of the Atlantic menhaden, *Brevoortia tyrannus*, fishery. NOAA Technical Report NMFS 63, 18p.
- Von Arx, W.S., D. Bumpus, and W.S. Richardson. 1955. On the fine structure of the Gulf Stream front. *Journal of Geophysical Research* **64**(1), 33-40.
- 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. 1994. Spawning time and recruitment dynamics of larval Atlantic menhaden, *Brevoortia tyrannus*, into a North Carolina estuary. *Fishery Bulletin* **92**, 420-433
- Warlen, S.M. and J.S. Burke. 1990. Immigration of larvae of fall/winter spawning marine fishes into a North Carolina estuary. *Estuaries* **13**(4), 453-461.
- Warlen S.M. and A.L. Chester. 1985. Age, growth, and distribution of larval spot, *Leiostomus xanthurus*, off North Carolina. *Fishery Bulletin* **83**(4), 587-599.
- Weinstein, M.P. 1979. Shallow marsh habitats as primary nurseries for fishes and shellfish, Cape Fear River, North Carolina. *Fishery Bulletin* **2**, 339-357.

- Wolanski, E. and W.H. Hamner. 1988. Topographically controlled fronts in the ocean and their biological influence. *Science* **241**, 177-181.
- Yoder, J.A. 1983. Statistical analysis of the distribution of fish eggs and larvae on the southeastern U.S. continental shelf with comments on oceanographic processes that may affect larval survival. *Estuarine, Coastal and Shelf Science* **17**, 637-650.

FIGURE LEGENDS

Figure 1. Map of the South Atlantic Bight. Note Beaufort Inlet adjacent to Cape Lookout and Onslow Bay.

Figure 2. Seven year larval abundance data set collected near Beaufort Inlet from Warlen (1994). "Weekly mean density (larvae/100m³) of Atlantic menhaden, *Brevoortia tyrannus*, larvae in collections at Pivers Island, North Carolina, in the lower Newport River estuary during seven consecutive estuarine recruitment years."

Figure 3. Time series of four images from Dec. 1987 - Jan. 1988. The 20-m isobath and 400-m isobath are displayed. Transects A-F are marked on the image, the most northward transect being 'A' and the most southern transect being 'F'. The black pixels represent the location of the 18°C front. This front exhibits the oscillation of warm water towards shore and offshore in Onslow Bay over the series of images. On Dec. 23, 1987, the front was located about mid-way through the most northward transect (transect A). On Dec. 30, 1987, the front has moved inshore close to the 20-m isobath. The Jan. 6 and 12, 1988 images show the front has moved offshore.

Figure 4. Spawning times for the larvae collected from Warlen (1994). "Birthdate frequency distributions calculated from the relative abundances of larval Atlantic menhaden, *Brevoortia tyrannus*, collected in the lower estuary at Pivers Island, North Carolina, in each of seven recruitment years. In each distribution, the vertical line is the median value and the box represents the second and third quartile intervals (central 50%). Lines beyond the boxes represent the range of data."

Figure 5. Transect A SST Data with Interpolation for 1985-1986 time series. The color palette used is synonymous with the AVHRR-SST standard palette: purples and blues represent cold temperatures (~10 - 14°C) and reds and oranges represent warm temps (~23 - 26°C). The x-axis is days starting from November 1st and running through April. The y-axis is the transect index location in kilometers where y=0 is the 20-m isobath and as transect index increases the distance offshore increases. The 90km point is the 400-m isobath and the approximate western edge of the Gulf Stream. The asterisks represent days when SST was available, the rest of SSTs are linearly interpolated.

Figure 6. Same as Figure 5. for 1987-1988 SST time series.

Figure 7. Same as Figure 5. for 1990-1991 SST time series.

Figure 8. Same as Figure 5. for 1991-1992 SST time series.

Figure 9. Mean (and standard deviation) location of the 18°C isotherm along the six transects for the four study periods: 1985/1986, 1987/1988, 1990/1991, and 1991/1992.

Figure 10. Transects A, C, and F 18°C isotherm location for spawning period 1985-1986. The circles represent points of 18°C SST extracted from satellite AVHRR images. The mean seasonal trend generated by a third degree polynomial curve fit is represented by the curved solid line.

Figure 11. Transects B, D, and E 18°C isotherm location for spawning period 1985-1986. The circles represent points of 18°C SST extracted from satellite AVHRR images.

Figure 12. Transects A, C, and F 18°C isotherm location for spawning period 1987-1988. The circles represent points of 18°C SST extracted from satellite AVHRR images. The mean seasonal trend generated by a third degree polynomial curve fit is represented by the curved solid line.

Figure 13. Transects B, D, and E 18°C isotherm location for spawning period 1987-1988. The circles represent points of 18°C SST extracted from satellite AVHRR images.

Figure 14. Transects A, C, and F 18°C isotherm location for spawning period 1990-1991. The circles represent points of 18°C SST extracted from satellite AVHRR images. The mean seasonal trend generated by a third degree polynomial curve fit is represented by the curved solid line.

Figure 15. Transects B, D, and E 18°C isotherm location for spawning period 1990-1991. The circles represent points of 18°C SST extracted from satellite AVHRR images.

Figure 16. Transects A, C, and F 18°C isotherm location for spawning period 1991-1992. The circles represent points of 18°C SST extracted from satellite AVHRR images. The mean seasonal trend generated by a third degree polynomial curve fit is represented by the curved solid line.

Figure 17. Transects B, D, and E 18°C isotherm location for spawning period 1991-1992. The circles represent points of 18°C SST extracted from satellite AVHRR images.

Figure 18. 1985/1986 transect spatial correlations. The six panels show separate plots for transects A-F and the correlation with each of the five remaining transects. The x-axis represents the six transects and the y-axis represents the corresponding correlation coefficients. Number of values correlated for each transect is 66 (n=66).

Figure 19. 1987/1988 transect spatial correlations. The six panels show separate plots for transects A-F and the correlation with each of the five remaining transects. The x-axis represents the six transects and the y-axis represents the corresponding correlation coefficients. Number of values correlated for each transect is 57 (n=57).

Figure 20. 1990/1991 transect spatial correlations. The six panels show separate plots for transects A-F and the correlation with each of the five remaining transects. The x-axis represents the six transects and the y-axis represents the corresponding correlation coefficients. Number of values correlated for each transect is 49 (n=49).

Figure 21. 1991/1992 transect spatial correlations. The six panels show separate plots for transects A-F and the correlation with each of the five remaining transects. The x-axis represents the six transects and the y-axis represents the corresponding correlation coefficients. Number of values correlated for each transect is 68, (n=68).

Figure 22. Transect A, C, and F third degree polynomial curve fits for the four study periods. The solid line represents the third degree polynomial curve fitted to the 1985/1986 period 18°C isotherm locations; the dashed line represents the

1987/1988 period; the dash-dot line represents the 1990/1991 period; and the dotted line represents the 1991/1992 period.

Figure 23. 1985-1986 histogram of negative variation frequencies. Ten bins of 5km each range from (-45) to (0). The x-axis represents the magnitude of the shoreward pulses in kilometers. The y-axis represent the number of occurrences.

Figure 24. 1987-1988 histogram of negative variation frequencies. Ten bins of 5km each range from (-45) to (0). The x-axis represents the magnitude of the shoreward pulses in kilometers. The y-axis represent the number of occurrences.

Figure 25. 1990-1991 histogram of variation frequencies. Ten bins of 5km each range from (-45) to (0). The x-axis represents the magnitude of the shoreward pulses in kilometers. The y-axis represent the number of occurrences.

Figure 26. 1991-1992 histogram of variation frequencies. Ten bins of 5km each range from (-45) to (0). The x-axis represents the magnitude of the shoreward pulses in kilometers. The y-axis represent the number of occurrences.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.
TRANSECT A

Figure 11.

Figure 12.

TRANSECT A

TRANSECT C

TRANSECT F

Figure 13.

Figure 14.

Figure 15.

Figure 16.

Figure 17.

Figure 18.

Figure 19.

CORRELATED TRANSECT

Figure 20.

Figure 21.

Figure 22.
TRANSECT A

TRANSECT C

TRANSECT F

Figure 23.

Figure 24.

Figure 25.

Figure 26.

Table. 1. Menhaden Larval Collection Data for Four Spawning Periods from Warlen(1994). Time of Maximum Back-Calculated Spawning also refers to the maximum birthweek.

<i>Spawning Period (Nov-April)</i> <i>[Relative Abundances]</i>	<i>Time of Maximum Larval Collection (week of)</i>	<i>Time Range of Largest Collections</i>	<i>Time of Maximum Back-Calculated Spawning (week of) [% of recruits]</i>	<i>Range of Back-Calculated Spawning (approximately 85% of recruits)</i>
1985-1986 [HIGH]	March 3	March 1 - April 1	January 10 [44%]	December 20 - January 20
1987-1988 [HIGH]	April 5	March 25 - April 15	December 14 [25%]	December 1 - January 20
1990-1991 [LOW]	April 11	March 25 - April 10	January 17 [42%]	January 10 - February 20
1991-1992 [LOW]	March 10	March 1 - March 20	December 10 [32%]	November 25 - January 31

**Data approximated from larval menhaden collections near Beaufort Inlet, NC from Warlen, 1994.

Table 2. Transect A Temperature Variability Ranges.
SST Ranges during the November to April Spawning Period at Four
Transect Locations.

Transect "A" Location	1985/1986 (°C)	1987/1988	1990/1991	1991/1992
kilometer 1	23-10 Δ13	20-11 Δ9	22-11 Δ11	21 -10 Δ11
kilometer 20	24-13 Δ11	24-13 Δ11	25-15 Δ10	22 -13 Δ9
kilometer 60	24-16 Δ8	26-17 Δ9	27-15 Δ12	24-15 Δ9
kilometer 90	26-21 Δ5	27-20 Δ7	27-20 Δ7	26-18 Δ8

Table 3. Means and Standard Deviations of Onshore Movement (Negative Variations from the Mean Curve fit).

TRANSECT	A		C		F	
	mean & count	stand dev	mean & count	stand dev	mean & count	stand dev
1985/1986	-10.83 30	8.66	-10.55 37	6.07	-9.07 50	6.72
1987/1988	-10.17 46	8.33	-9.95 49	6.28	-11.66 50	8.65
1990/1991	-12.10 56	8.54	-11.73 48	7.80	-9.58 37	6.56
1991/1992	-6.77 19	7.11	-7.71 29	5.29	-8.31 18	6.92
ALL YEARS:	-10.59 151	8.42	-10.21 163	6.65	-9.94 155	7.42

Table 4. Grid analysis results.

TRANSECT A	approximate # of onshore pulses	mean of magnitude	standard deviation of magnitude	count and (% of days)
1985/1986	7	11.7	5.1	43 (29%)
1987/1988	10	13.0	7.0	64 (39%)
1990/1991	10	13.6	5.3	74 (45%)
1991/1992	8	9.9	6.3	13 (8%)

TRANSECT C	approximate # of onshore pulses	mean of magnitude	standard deviation of magnitude	count and (% of days)
1985/1986	8	10.3	3.8	35 (27%)
1987/1988	8	10.6	4.9	66 (40%)
1990/1991	8	12.0	5.1	59 (36%)
1991/1992	6	8.1	2.8	28 (17%)

TRANSECT F	approximate # of onshore pulses	mean of magnitude	standard deviation of magnitude	count and (% of days)
1985/1986	9	11.3	4.7	37 (26%)
1987/1988	7	13.2	8.5	56 (38%)
1990/1991	8	12.1	6.1	55 (37%)
1991/1992	5	8.4	3.7	14 (10%)

Table 5.

TRANSECTS A, C, and F

Fisher PLSD Pairwise Multiple Comparison, $\alpha = 0.05$
 Years with the same letter are not significantly different.

Year	Count (n)	Mean	SD	Year Comparisons
1985/1986	113	1.009	.177	A
1987/1988	136	1.038	.238	A,B
1990/1991	128	1.066	.206	B
1991/1992	55	.896	.177	

One-way ANOVA, $f = 9.226$, $DF = 3$, $P < 0.0001$

TRANSECT A: Fisher PLSD Pairwise Multiple Comparison, $\alpha = 0.10$

Years with the same letter are not significantly different

Year	Count (n)	Mean	SD	Year Comparisons
1985/1986	43	1.030	.177	A,B
1987/1988	64	1.045	.254	A
1990/1991	74	1.096	.193	A
1991/1992	13	.927	.246	B

One-way ANOVA, $f = 2.677$, $DF = 3$, $P = .0484$

TRANSECT C: Fisher PLSD Pairwise Multiple Comparison, $\alpha = 0.10$

Years with the same letter are not significantly different

Year	Count (n)	Mean	SD	Year Comparisons
1985/1986	35	.986	.163	A,B
1987/1988	66	.980	.194	A,C
1990/1991	60	1.032	.192	B,C
1991/1992	27	.892	.141	

One-way ANOVA, $f = 3.73$, $DF = 3$, $P = .0123$

Table 6. MAXIMUM BIRTHWEEK PULSE ACTIVITY

The warm water pulse activity of the four spawning periods along transects A, C, and F for the week of the maximum birthweek and the week following the maximum birthweek. The pulse # refers to the pulses defined by the grid analysis (results are in Table 4.). The pulses were numbered by the sequence in which they occurred starting with the number one for each of the four periods (i.e. #A2 is the second shoreward pulse over 5km in magnitude along transect A). The count (% of days) refers to the percentage of the days during the two week period of maximum birth week and week following maximum birthweek.

<i>YEAR</i>	<i>Transect</i>	<i>PULSE</i>	<i>DURATION</i>	<i>MAGNITUDE</i>	<i>COUNT (% OF DAYS)</i>
<i>1985/ 1986</i>	<i>A</i>	end of #A2 #A3	1 day 5 day	10 km 8-18 km	6 (42%)
	<i>C</i>	end of #C2 start of #C3	1 day 2 day	6 km 6-9 km	3 (21%)
	<i>F</i>	#F4 #F5	3 day 4 day	5-16 km 7-17 km	7 (50%)
<i>1987/ 1988</i>	<i>A</i>	#A2 start of #A3	1 day 5 day	5 km 6-18 km	6 (42%)
	<i>C</i>	start of #C3	3 day	16-17 km	3 (21%)
	<i>F</i>	#F1 start of #F2	1 day 3 day	8 km 7-8 km	4 (29%)
<i>1990/ 1991</i>	<i>A</i>	end of #A4 start of #A5	3 day 3 day	5-13 km 7-27 km	6 (42%)
	<i>C</i>	start of #C4	1 day	12km	1 (7%)
	<i>F</i>	end of #F3 #F4	6 day 2 day	13-8 km 5 km	8 (57%)
<i>1991/ 1992</i>	<i>A</i>	#A2 #A3	1 day 1 day	11 km 8 km	2 (14%)
	<i>C</i>	none			
	<i>F</i>	none			

Table 7. Transport Rates in km/day for the entire spawning season for the four time periods. The negative numbers represent shoreward movement and the positive numbers represent offshore movement.

Rates: km/day		S h o r e w a r d r a t e s			S e a w a r d r a t e s			Net rate
		Mean	Max	Min	Mean	Max	Min	
1985/ 1986	A	-15.3	-121.1	-0.28	11.5	101.0	0.20	-254
	C	-13.0	-67.2	-0.38	10.1	96.3	0.12	-73.6
	F	-12.7	-89.1	-0.11	10.5	73.3	0.43	-144
	mean	-13.7			10.7			
1987/ 1988	A	-11.2	-99.6	-0.18	7.7	35.8	0.04	-162
	C	-9.2	-41.1	-0.29	10.6	54.5	0.25	-8.58
	F	-9.6	-51.7	-0.03	10.0	53.6	0.24	-83.5
	mean	-10.0			9.4			
1990/ 1991	A	-6.5	-28.7	-0.75	7.1	25.2	0.10	79.5
	C	-6.3	-40.3	-0.27	10.0	67.8	0.12	81.7
	F	-5.4	-18.3	-0.21	8.7	34.3	0.71	62.1
	mean	-6.1			8.6			
1991/ 1992	A	-9.7	-42.3	-0.66	7.6	34.8	0.21	-77.4
	C	-7.8	-29.1	-0.23	7.6	26.4	0.12	-6.18
	F	-6.4	-19.1	-0.64	8.0	41.8	0.15	61.4
	mean	-8.0			7.8			

Table 8. Transport Rates in km/day for the maximum birthweek and the following week for the four time periods. The negative numbers represent shoreward movement and the positive numbers represent seaward movement.

Rates: km/day		Shore ward rates			Sea ward rates			Net rate
		Mean	Max	Min	Mean	Max	Min	
1985/ 1986	A	-12.25	-37.32	-1.06	4.09	10.61	0.20	-36.7
	C	-17.02	-44.26	-0.76	2.82	5.70	0.12	-76.7
	F	-7.17	-21.23	-0.79	14.75	75.38	0.58	67.8
1987/ 1988	A	-26.30	-99.68	-0.63	9.55	24.90	0.60	-136
	C	-17.01	-41.08	-1.27	3.96	10.22	0.48	-36.3
	F	-17.59	-51.7	-0.18	3.17	7.09	0.50	-71.1
1990/ 1991	A	-7.63	-11.99	-1.16	4.13	10.40	2.18	-5.71
	C	-5.63	-14.96	-0.91	2.58	5.16	0.12	1.174
	F	-4.13	-7.38	-0.49	4.07	12.85	1.01	-0.3
1991/ 1992	A	-11.63	-25.3	-1.77	6.36	16.2	0.90	-8.76
	C	-7.00	-13.2	-1.18	6.26	10.64	0.73	1.11
	F	-4.23	-5.58	-0.64	3.75	13.31	1.35	-2.85

APPENDIX A

LATITUDES AND LONGITUDES OF TRANSECT END POINTS

TRANSECT	20-m ISOBATH END POINT (shoreward end)		400-m ISOBATH END POINT (seaward end)	
	LATITUDE	LONGITUDE	LATITUDE	LONGITUDE
A				
B	34.46	-77.05	33.84	-76.45
C	34.38	-77.18	33.74	-76.55
D	34.34	-77.28	33.73	-76.67
E	34.29	-77.35	33.69	-76.76
F	34.19	-77.45	33.53	-76.81

BIBLIOGRAPHY

- Abbott M.R. and D.B. Chelton. 1991. Advances in passive remote sensing of the ocean. *Reviews of Geophysics, Supplement* April 1991, 571-589.
- Allen D.M. and D. L. Barker. 1990. Interannual variations in larval fish recruitment to estuarine epibenthic habitats. *Marine Ecology Progress Series* **63**, 113-125.
- Atkinson, L.P. and T.E. Targett. 1983. Upwelling along the 60-m isobath from Cape Canaveral to Cape Hatteras and its relationship to fish distribution. *Deep Sea Research* **30**(2A), 221-226.
- Boehlert, G.W. and B.C. Mundy. 1988. Roles of behavioral and physical factors in larval and juvenile fish recruitment to estuarine nursery areas. *American Fisheries Society Symposium* **3**, 51-67.
- Bane, J.M., Jr., D.A. Brooks, and K.R. Lorenson. 1981. Synoptic observations of the three-dimensional structure and propagation of Gulf Stream meanders along the Carolina continental margin. *Journal of Geophysical Research* **86**(C7), 6411-6425.
- Bane, J.M., Jr., and W.K. Dewar. 1988. Gulf Stream bimodality and variability downstream of the Charleston Bump. *Journal of Geophysical Research* **93**(C6), 6695-6710.
- Blanton, J.O., L.P. Atkinson, L.J. Pietrafesa, and T.N. Lee. 1981. The intrusion of Gulf Stream water across the continental shelf due to topographically-induced upwelling. *Deep Sea Research* **28A**(4), 394-405.
- Blanton, J.O. and L.J. Pietrafesa. 1978. Flushing of the continental shelf south of Cape Hatteras by the Gulf Stream. *Geophysical Research Letters* **5**, 495-498.
- Brooks, D. A. and J.M. Bane, Jr. 1981. Gulf Stream fluctuations and meanders over the Onslow Bay upper continental slope. *Journal of Physical Oceanography* **11**, 247-256.
- Cornillon, P., C. Gilman, L. Stramma, O. Brown, R. Evans, and J. Brown. 1987. Processing and analysis of large volumes of satellite-derived thermal infrared data. *Journal of Geophysical Research* **92**(C12), 12,993-13,002.
- 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**(2), 567-587.

- Checkley, D.M., Jr., S. Raman, G.L. Maillet, and K.M. Mason. 1988. Winter storm effects on the spawning and larval drift of a pelagic fish. *Nature* **335**, 346-348.
- Denman, K.L. and M. R. Abbott. 1988. Time evolution of surface chlorophyll patterns from cross-spectrum analysis of satellite color images. *Journal of Geophysical Research* **93** (C6), 6789-6798.
- Dryfoos, R.L., R.P. Cheek, and R.L. Kroger. 1973. Preliminary analyses of Atlantic menhaden, *Brevoortia tyrannus*, migrations, population structure, survival and exploitation rates, and availability as indicated from tag returns. *Fishery Bulletin* **71**, 719-734.
- Durbin, A.G. and E.G. Durbin. 1975. Grazing rates of the Atlantic menhaden *Brevoortia tyrannus* as a function of particle size and concentration. *Marine Biology* **33**, 265-277.
- Emery, W.J., A.C. Thomas, and M.J. Collins. 1987. An objective method for computing advective surface velocities from sequential infrared satellite images. *Journal of Geophysical Research* **91**, 12,865-12,878.
- Flores-Coto, C. and S. M. Warlen. 1993. Spawning time, growth, and recruitment of larval spot *Leiostomus xanthurus* into a North Carolina estuary. *Fishery Bulletin* **91**(1), 8-22.
- Fore, P.L. and K.N. Baxter. 1972. Diel fluctuations in the catch of larval Gulf menhaden, *Brevoortia patronus*, at Galveston Entrance, Texas. *Transactions of American Fisheries Society* **101**, 729-732.
- Fu, L., W. T. Liu, and M.R. Abbott. 1990. Satellite Remote Sensing of the Ocean. in *The Sea: Ocean Engineering Science* Vol. 9, John Wiley & Sons, Inc. 1193-1236.
- Glenn, S.M. and C.C. Ebbesmeyer. 1994. The structure and propagation of a Gulf Stream frontal eddy along the North Carolina shelf break. *Journal of Geophysical Research* **99**(C3), 5029-5046.
- Glenn, S.M. and C.C. Ebbesmeyer. 1994. Observations of Gulf Stream frontal eddies in the vicinity of Cape Hatteras. *Journal of Geophysical Research* **99**(C3), 5047-5055.
- 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**(2), 538-566.
- Gray, C.L. 1992. Atlantic menhaden species profile, Current Report, the Narragansett Bay Project. NBP-92-84. R.I. Dept. of Environmental Management.

- Gray, I.E. and M.J. Cerame-Vivas. 1963. The circulation of surface waters in Raleigh Bay, North Carolina. *Limnology and Oceanography* **8**, 330-337.
- Hettler, W.F. 1981. Spawning and rearing Atlantic menhaden. *Prog. Fish-Cult.* **43**(2), 80-84.
- Hettler, W.F. and A.J. Chester. 1990. Temporal distribution of ichthyoplankton near Beaufort Inlet, North Carolina. *Marine Ecology Progress Series* **68**, 157-168.
- Hjort, J. 1914. Fluctuations in the great fisheries of Northern Europe viewed in the light of biological research. *Rapp. P. -v. Reun. Cons. Perm. int. Explor. Mer* **20**, 1-228.
- Hoss, D.E., D.M. Checkley, Jr., and L.R. Settle, 1989. Diurnal buoyancy changes in larval Atlantic menhaden (*Brevoortia tyrannus*). *Rapp. R.-v. Reun. Cons. int. Explor. Mer*, 191:105-111.
- Higham, J.R. and W.R. Nicholson. 1964. Sexual maturation and spawning of Atlantic menhaden. *U.S. FWS Fish. Serv. Bull.* **63**(2):255-271.
- Johnson, D.R., B.S. Hester, and J.R. McConaughy. 1984. Studies of a wind mechanism influencing the recruitment of blue crabs in the Middle Atlantic Bight. *Continental Shelf Research* **3**(4), 425-437.
- June, F.C. and F.T. Carlson. 1971. Food of young Atlantic menhaden, *Brevoortia tyrannus*, in relation to metamorphosis. *Fishery Bulletin* **68**(3), 493-511.
- Katz, C.H., J.S. Cobb, and M. Spaulding. 1994. Larval behavior, hydrodynamic transport, and potential offshore-to-inshore recruitment in the American lobster *Homarus americanus*. *Marine Ecology Progress Series* **103**, 265-273.
- Kendall, A.W., Jr. and J.W. Reintjes. 1975. Geographic and hydrographic distribution of Atlantic menhaden eggs and larvae along the middle Atlantic coast from RV *Dolphin* cruises, 1965-66. *Fishery Bulletin* **73**, 317-332.
- Lasker, R. 1981. The role of a stable ocean in larval fish survival and subsequent recruitment. pp. 80-87 in R. Lasker, ed. Marine Fish Larvae. Washington Sea Grant Program, University of Washington Press, Seattle.
- 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**(C12), 22,191-22,205.

- Lee, T.N., and L.P. Atkinson. 1983. Low-frequency current and temperature variability from Gulf Stream frontal eddies and atmospheric forcing along the southeast U.S. outer continental shelf. *Journal of Geophysical Research* **88**(C8), 4541-4567.
- Legeckis, R. 1975. Application of synchronous meteorological satellite data to the study of time dependent sea surface temperature changes along the boundary of the Gulf Stream. *Geophysical Research Letters* **2** (10), 435-438.
- Lewis, R.M. 1965. The effect of minimum temperature on the survival of larval Atlantic menhaden, *Brevoortia tyrannus*. *Transactions of American Fisheries Society* **94**, 409-412.
- Lewis, R.M., D.W. Ahrenholz, and S.P. Epperly. 1987. Fecundity of Atlantic menhaden, *Brevoortia tyrannus*. *Estuaries* **10**, 347-350.
- Lewis, R.M. and W.C. Mann. 1971. Occurrence and abundance of larval Atlantic menhaden, *Brevoortia tyrannus*, at two North Carolina inlets with notes on associated species. *Transactions of American Fisheries Society* **2**, 296-301.
- Lewis, R.M. and E.P. Wilkens. 1971. Abundance of Atlantic menhaden larvae and associated species during a diel collection at Beaufort, North Carolina. *Chesapeake Science* **12**, 185-187.
- Lillelund, K. and R. Lasker. 1971. Laboratory studies of predation by marine copepods on fish larvae. *Fishery Bulletin* **69**, 655-667.
- Menzel, D.W., ed. 1993. Ocean Processes: U.S. Southeast Continental Shelf: A summary of research conducted in the South Atlantic Bight under the auspices of the U.S. Department of Energy. U.S. Dept. of Energy, DOE/OSTI--11674(DE93010744).
- MATLAB, 1992. MATLAB (High Performance Numeric Computation and Visualization Software) Reference Guide. The Math Works, Inc. Natick, MA. p548.
- Maillet, G.L. and D.M. Checkley, Jr. 1991. Storm-related variation in the growth rate of otoliths of larval Atlantic menhaden *Brevoortia tyrannus*: a time series analysis of biological and physical variables and implications for larva growth and mortality. *Marine Ecology Progress Series* **79**, 1-16.
- Miller, J.M. 1988. Physical processes and the mechanisms of coastal migrations of immature marine fishes. *American Fisheries Society Symposium* **3**, 68-76.

- Miller, J.M., J.P. Reed and L.P. Pietrafesa. 1982. Patterns, mechanisms and approaches to the study of migrations of estuarine-dependent fish larvae and juveniles. pp. 209-225 in J.D. McCleave, G.P. Arnold, J.J. Dodson and W.H. Neill, eds. Mechanisms of migration in fishes. Plenum, N.Y.
- Morse, W.W. 1989. Catchability, growth and mortality of larval fishes. *Fishery Bulletin, U.S.* **87**, 417-446.
- Nakata, H. 1989. Transport and distribution of fish eggs and larvae in the vicinity of coastal fronts. *Rapp. P.-v. Reun. Cons. int. Explor. Mer.* **191**, 153-159.
- Nelson, W., M., C. Ingham, and W.E. Schaaf. 1977. Larval transport and year-class strength of Atlantic menhaden, *Brevoortia tyrannus*. *Fishery Bulletin U.S.* **83**, 151-170.
- Njoku, E.G. and O. B. Brown. 1993. Sea surface temperature. pp. 237-249 in R.L. Gurney, J.L. Foster, and C.L. Parkinson, eds. Atlas of satellite observation related to global change. Cambridge University Press, London, Great Britain.
- Norcross, B.L. and D.A. Bodolus. 1992. Hypothetical northern spawning limit and larval transport of spot. In Hoyt, R.D. (ed.), Larval fish recruitment and research in the Americas. NOAA Technical Report NMFS **95**: p 77-88.
- Oey, L.-Y., L.P. Atkinson, 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.
- Parrish, R.H., C.S. Nelson, and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California Current. *Biological Oceanography* **1**(2), 175-203.
- Pietrafesa, L.J. and G.S. Janowitz. 1988. Physical oceanographic processes affecting larval transport around and through North Carolina inlets. American Fisheries Society Symposium **3**, 34-50.
- Purcell, J.E. 1992. Effects of predation by the schyphomedusan *Chrysaora quinquecirrha* on zooplankton populations in Chesapeake Bay, USA. *Marine Ecology Progress Series* **87**, 65-76.
- Reintjes, J.W. 1961. Menhaden eggs and larvae from M/V Theodore N. Gill cruises, South Atlantic coast of the United States, 1953 - 1954. U.S. FWS Special Scientific Report. Fisheries No. 393. Washington, D.C. Sept., 1961.
- Rogers, G.S. and M.J. Van Den Avyle. 1983. Species Profiles: Life histories and environmental requirements of coastal fishes and invertebrates (So. Atlantic),

- Atlantic menhaden. FWS/OBS-82/11.11, Georgia Cooperative Fishery Research Unit, Univ. of Georgia, Athens, GA.
- Rothschild, B. 1986. Dynamics of marine fish populations. Harvard University Press, Boston. p 277.
- Roughgarden, J., S. Gaines, and H. Possingham. 1988. Recruitment dynamics in complex life cycles. *Science*, 241, 1460-1466.
- Schwing, F.B., B. Kjerfve and J.E. Sneed. 1983. Nearshore coastal currents on the South Carolina continental shelf. *Journal of Geophysical Research*, **88** (C8), 4179-4729.
- Smith, J.W., W.R. Nicholson, D.S. Vaughan, D.L. Dudley, and E.A. Hall. 1987. Atlantic menhaden, *Brevoortia tyrannus*, purse seine fishery, 1972-1984, with a brief discussion of age and size composition of the landings. NOAA Technical Report NMFS 59, 23p.
- Sokal, R.R. and F.J. Rohlf. 1969. Biometry. W.H. Freeman and Co., San Francisco.
- 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. Accepted by *Continental Shelf Research*, 2 Nov., 1994.
- Tester, P. et al. 1991. An expatriate red tide bloom: transport, distribution and persistence. *Limnology and Oceanography* **36**(5), 1053-1061.
- Vaughan, D.S. and J.W. Smith. 1988. Stock assessment of the Atlantic menhaden, *Brevoortia tyrannus*, fishery. NOAA Technical Report NMFS 63, 18p.
- Von Arx, W.S., D. Bumpus, and W.S. Richardson. 1955. On the fine structure of the Gulf Stream front. *Journal of Geophysical Research* **64**(1), 33-40.
- 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. 1994. Spawning time and recruitment dynamics of larval Atlantic menhaden, *Brevoortia tyrannus*, into a North Carolina estuary. *Fishery Bulletin* **92**, 420-433
- Warlen, S.M. and J.S. Burke. 1990. Immigration of larvae of fall/winter spawning marine fishes into a North Carolina estuary. *Estuaries* **13**(4), 453-461.
- Warlen S.M. and A.L. Chester. 1985. Age, growth, and distribution of larval spot, *Leiostomus xanthurus*, off North Carolina. *Fishery Bulletin* **83**(4), 587-599.

- Weinstein, M.P. 1979. Shallow marsh habitats as primary nurseries for fishes and shellfish , Cape Fear River, North Carolina. *Fishery Bulletin* **2**, 339-357.
- Wolanski, E. and W.H. Hamner. 1988. Topographically controlled fronts in the ocean and their biological influence. *Science* **241**, 177-181.
- Yoder, J.A. 1983. Statistical analysis of the distribution of fish eggs and larvae on the southeastern U.S. continental shelf with comments on oceanographic processes that may affect larval survival. *Estuarine, Coastal and Shelf Science* **17**, 637-650.