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Oregon Inlet: Hydrodynamics, Volumetric Flux and
Implications for Larval Fish Transport

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Abstract

The temporal response of Oregon Inlet currents to atmospheric forcing and sea level fluctuations is analyzed using time and frequency domain analysis. Temporally persistent and spatially extensive ebb and flood events are identified using data sets from both within and outside of Oregon Inlet. Prism estimates are made to generate a time series of volumetric flux of water transported through the inlet. Water masses flooding into the Pamlico Sound via Oregon Inlet are identified in temperature (T) and salinity (S) space to determine their source of origin. Correlations are examined between the atmospheric wind field, the main axial slope of the inlet's water level, inlet flow and T, S properties. Synoptic scale atmospheric wind events are found to dramatically and directly affect the transport of water towards (away from) the inlet on the ocean side, in concert with the contemporaneous transport away from (towards) the inlet on the estuary side, and a subsequent flooding into (out of) the estuary via Oregon Inlet. Thus, while astronomical tidal flooding and ebbing events are shown to be one-sided as coastal waters either set-up or set-down, synoptic scale wind events are shown to be manifested as a two-sided in-phase response set-up and set-down inside and outside the inlet, and thus are extremely effective in driving currents through the inlet. These subinertial frequency flood events are believed to be essential for both the recruitment and subsequent retention of estuarine dependent larval fish from the coastal ocean into Pamlico Sound. Year class strength of these finfish may be determined annually by the relative strength and timing of these climatological wind events.

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1. INTRODUCTION

Oregon Inlet is believed to be a principal conduit for commercially important estuarine dependent finfish larvae which are spawned on the continental shelf and passively enter the Albemarle-Pamlico estuary from January - March (Miller et al., 1984). This study investigates the relationship between subtidal frequency currents and synoptic scale storms which are related to this entry.

LARVAL FISH MIGRATION

Miller et al. (1984) have shown that North Carolina (NC) inlets serve as transport routes for such commercially important fish larvae as menhaden, spot, croaker and both summer and southern flounder. These authors reported that while the above five species represent only 10% of the types of fish found in North Carolina's Albemarle-Pamlico Sound system, these five species constitute 90% of the total fish biomass. According to Miller et al. (1984), the adult finfish spawn their larvae on the NC coast during the winter months from November through February, and these fish larvae, about 5 to 20 mm long, swim energetically from 1 to 2 body lengths per second in short bursts and then rest. In NC coastal waters, wind-driven surface currents are approximately 3% of the wind vector magnitude, which on average, during the period November-February, is about 6 m/s and directed to the south (Weisberg and Pietrafesa, 1983). So, the associated surface currents are approximately 18 cm/s and directed towards the coast. In the interior of the water column between the surface and bottom frictional boundary layers, following Pietrafesa (1990), we estimate the wind-induced, barotropic-geostrophic pressure gradient forced currents to be about 11 cm/sec on average down the coast. Thus, the natural positioning of larvae in the water column, via self buoyancy, and the water's motion become the determining factors relevant to their transport. Consequently, differences in vertical larval distribution and seasonal changes in the

environment should affect migration mechanisms by altering the transport of young fish.

Miller et al. (1984) compared seasonal winds and drift currents to determine favorable transport paths from the Gulf Stream front to the barrier islands. Once the larvae reach the littoral zone, longshore currents and associated breaking waves should facilitate their movement toward the inlets. The fry should aggregate near the inlet plume front as a result of stimuli such as olfactory cues and high turbidity (Miller et al., 1984). Then, flood tides and subtidal frequency flood currents could jet oceanic water laden with young fish into the Pamlico Sound estuary via Oregon Inlet in the related pulses.

OREGON INLET: SETTING AND PHYSICAL PROCESSES

Oregon Inlet is a dynamic feature located in the barrier island chain of North Carolina about 63 km north of Cape Hatteras, and connects the northern end of Pamlico Sound to the Mid Atlantic Bight region of the Atlantic Ocean (Figure 1). Oregon Inlet is believed to be an especially important passage for larval fish recruitment. It is one of only four major routes connecting the ocean to the sound on the coastline between Cape Henry, VA, and Beaufort Inlet, NC, a distance of 402 km (Figure 1). The inlet is approximately 2.4 km along its' axis and 1 km wide and is situated between Bodie Island to the north and the Pea Island National Wildlife Refuge to the south. The 3.9 km long Herbert C. Bonner Bridge spans the inlet's two main channels and connects the two barrier islands (Figure 2). The primary navigation channel, Oregon Inlet Channel, extends 4.8 km and is aligned northeastward in the inlet proper and then turns northwestward to Old House Channel, into Pamlico Sound (Figure 2). Davis Channel, a secondary route just west of Pea Island, runs to the southwest for 4 km and is especially susceptible to shoaling. Energetic currents and fluctuations in water level are often attributed to

the semidiurnal diurnal and diurnal astronomical tides. However, it is also known that dramatic changes in the inlet's morphology usually accompany severe atmospheric storms, typically wintertime "Atlantic Lows" or summertime hurricanes. Recently, Cione et al. (1993) showed that each month during the period November-March, there are 4 or 5 extratropical cyclones which occur per month in the vicinity of Cape Hatteras, with each event lasting 1 to 4 days. The cumulative effects of these storms are evident in Figures 3a, b, c which show the relative shape and locations in the Inlet's distal bar to the north on the south end of the Bodie Island and Pea Island to the south from aerial photographs taken during April, 1988 (Fig. 3b) and December, 1990 (Fig. 3c).

Past investigators (Department of the Army, 1949; US Army Corps of Engineers, 1968; US Army Corps of Engineers, 1970; Singer and Knowles, 1975; Giese et al., 1985; Pietrafesa et al., 1986a, and Inman and Dolan, 1989) have analyzed tidal currents in and around the Pamlico Sound inlets which vary semidiurnally and diurnally in phase with the Principal lunar, M_2 , Luni solar-diurnal, K_1 , and Principal solar, P_1 , constituents of the astronomical tide producing force (Pietrafesa et al., 1985). Inman and Dolan (1989) report spring tidal ranges at Cape Hatteras of 1.3 m and 1 m along other areas of the Outer Banks. Oregon Inlet, a microtidal passage, has an M_2 tidal range typically between 60 cm and 73 cm at the inlet mouth (Pietrafesa and Janowitz 1988). The tidal range damps from the barrier inlets toward land from approximately 61 cm to 15 cm (NOAA, 1988). The 1988 Tide Tables (NOAA 1988) report an amplitude of 12 cm for Old House Channel. The drop in mean tidal range along Oregon Inlet Channel to Old House Channel is approximately 3 cm/km and is similar to the Pietrafesa et al. (1986a) finding of 3.75 cm/km for tidal range damping inward from Ocracoke Inlet. Sheltered areas have even lower tidal ranges. For example, the 1988 Tide Tables (NOAA, 1988) predict a mean semidiurnal range of

tidal elevations of 9.1 cm at the Oregon Inlet Marina which is approximately 3.2 km north from the Oregon Inlet Channel mouth.

The magnitude of ebb and flood currents are influenced by astronomic and pressure gradient forces. As the ocean tide propagates towards (away from) a barrier island inlet, at a phase propagation rate of about 7 m/s (Redfield, 1958), a downhill (an uphill) tilt of the water surface during high (low) tide is created along the inlet axis and the water responds by jetting through the constriction into (out of) the sound. During the past six decades, various observations of ebb and flood flows ranged from 65 to 116 cm/sec with averages of 90 cm/sec. Jet amplitudes were dependent on changes in cross sectional area and the ability of pressure gradients to form at the inlet.

Since fish larvae have distinctive buoyancy ranges (Miller et al., 1984), they must be associated with water masses of certain densities, so it is important to rectify inlet water types with corresponding water masses. Surface water temperatures within the sound closely follow air temperature. However, the relationship between air and sound surface temperatures is neither one to one (Pietrafesa et al., 1986a) nor immediate, with Roelofs and Bumpus (1953) reporting a one day lag between air and surface water temperature fluctuations. Based on 10 years of 3-hourly, National Weather Service coastal meteorological observations, average air temperatures in the Cape Hatteras region of North Carolina are found to be 3°C during winter to 24°C in summer. Consequently, the temperate coastal climate fosters water masses with distinctive temperature signatures. Water temperatures based on monthly samples taken within Oregon Inlet are reported to range from 4°C in January (Williams et al. 1973) to 28°C in July (Schwartz and Chestnut, 1973), though our study shows larger extremes in T. Lateral thermal variations in the sounds rarely exceed 1 or 2°C (Giese et al., 1985). Vertical stratification is slight due to effective mixing by the wind. The frequency of water temperature fluctuations

measured at depths greater than 1 m match surface water values but have smaller amplitudes (Pietrafesa et al., 1986a). During winter, shallow sound waters tend to be cooler than the deeper offshore waters which are warmed by the Gulf Stream. Offshore surface water at Diamond Shoals averages 11° C in January and cools to around 8° C in February. April surface water temperatures reach about 17°C. By July, in the Diamond Shoals region, surface water temperatures reach 28°C. Thus, ocean waters passing through Oregon Inlet have temperature signatures derived from the effects of seasonal averages superimposed on the ambient water mass.

Water in the Carolina Capes (CCW) region to the south of Cape Hatteras, NC is more saline than Mid Atlantic Bight coastal water (MABW) to the north of Hatteras. CCW results from a mixture of freshwater runoff and Gulf Stream frontal waters derived from proximity to the highly saline Gulf Stream between Cape Fear and Cape Hatteras. MABW results from discharged fresh waters of Chesapeake Bay, VA, Delaware Bay, DE, and more northerly coastal waters. The NC coast north of Cape Fear and south of Cape Hatteras has relatively little estuarine discharge. While Oregon Inlet is geographically located in the MAB region, Gulf Stream-derived water has been known to reach the inlet (Singer and Knowles, 1975, and Pietrafesa and Janowitz, 1988). Figure 4 illustrates these temperature and salinity relationships (adopted from Pietrafesa et al., 1985) in which the shaded areas denote wintertime T-S relations and the non-shaded areas Spring, Summer and Fall values. These T-S distributions are important as water mass identifiers that facilitate the tracking of various fish species.

Water elevation variations within Pamlico Sound are found by Pietrafesa and Janowitz (1988) to be due primarily to mechanical wind forcing with water being driven to the southwest by south to southwestward winds and to the northeast by north to northeastward winds. Wind mixing in these shallow waters generally causes vertical salinity variation to be negligible at most places though Pietrafesa et

al. (1986a) showed differences of 5 psu over 2-meter depths along the western shore of the Pamlico Sound.

The marine atmosphere of the Cape Hatteras region is known for energetic winds that cause flooding or inlet closure. Weisberg and Pietrafesa (1983) found that the period of synoptic variability is on the order of two days to two weeks with sea/land breezes occurring over a 24-hour period. They found that the onset of winter is marked by the Icelandic Low pressure system. The average winter wind stress vector is directed toward the south. Strong wintertime winds are attributed to cyclones which tend to form in the region of the Carolina Capes from November to April. These events then move northward, reaching maximum intensification offshore of Cape Hatteras according to Cione et al. (1993) who described the Carolina coast as the principal cyclogenetic area for the western North Atlantic.

Most of the storms affecting the Outer Banks occur during the months November through April (Cione et al., 1993) with the most intense in January followed by December and February. Such weather events dominate water properties and currents in the Pamlico. For example, Pietrafesa and Janowitz (1988) have shown that variations in water level follow within three hours of the onset of winds blowing over the Pamlico Sound. In the coastal ocean, surface Ekman drift is mechanically driven, towards (away from) the coast, by synoptic scale winds from the northern (southern) quadrant, which tend to push ocean water against (away from) the seaward side of the Hatteras and Bodie barrier islands within 8 hours of the onset of the winds (Chao and Pietrafesa, 1980). The typical sequence or time series of winds which occur during the passage of an Atlantic Low is shown in Figure 5. Winds due to cyclones passing to the east of the barrier islands bordering Pamlico Sound, are first towards the southwest, then towards south and finally southeastward. As part of this study, we will consider the effects that such synoptic

scale wind forced events have on enhancing the volumetric influx of coastal waters, into Pamlico Sound via Oregon Inlet.

The experimental investigation section will describe physical measurements that were taken in concert with a larval finfish sampling program. The results section describes our scheme for determining volumetric flux. The summary and conclusions section ties atmospheric forcing to subtidal frequency jetting, a possible mechanism for moving fish larvae into Pamlico Sound.

2. EXPERIMENTAL INVESTIGATION

Four Interocean S4 current meters, three Aanderaa water level recorders and one Aanderaa weather station were deployed from April 1988 to July 1990 in the Albemarle Pamlico estuarine complex. Complementary meteorological data at Cape Hatteras were obtained from the National Climatic Data Center. A map of instrument locations is provided in Figure 2. S4 current meters were used to measure speed, direction, conductivity, temperature and pressure with a 30-minute sampling interval. The Aanderaa weather station was deployed on a tower 10 meters above mean sea level and collected hourly wind speed and direction data. Two current meters were affixed to pilings on the Bonner Bridge near the main channel while the other two meters were moored at Davis Channel. Current data were 3-hour low-pass filtered to remove high frequency motions and then subsampled hourly. This process eliminates noise, surface gravity wave and turbulence effects. Data were also 40-hour low-pass filtered to highlight subtidal (synoptic) frequency phenomena. The 40-hour low-pass filter removes semidiurnal and diurnal tidal, inertial, and diurnal land and sea breeze effects. Spectral analyses were performed on 3-hour low-passed data and reconstructed to be hourly. This filtering process is completely described by Pietrafesa et al. (1978).

East-West/North-South scatter diagrams of currents in the Oregon Inlet main channel, as well as Davis Channel (both shown schematically in Figure 2) are presented in Figure 6. The reversing currents align sharply with the major axis of the channels with flooding events showing less scatter than ebbing events. Dominant along channel currents on the order of 100 cm/s are typical of both channels. Low energy cross channel currents can be ignored. Based on the u, v scatterplots, current velocity components were rotated so that positive values represent the ebb or outflow and negative velocities represent flood or inflow events within both Oregon Inlet Channels. Principal component rotation minimized cross-channel flow and emphasized flow along the hydraulic axis.

3. RESULTS

The fluctuations of water pressure (i.e., relative sea level) in Oregon Inlet has a significant tidal signal, which is predominantly semidiurnal as evidenced in Figures 7a, b. In Figure 7a, we see a strong semidiurnal tide superimposed on a diurnal tide which is further modulated by subtidal frequency motions. In Figure 7b, the relative energies of the motions as a function of frequency show that tidal and longer period motions are both robust.

Figure 8a-c shows a detailed mid-depth velocity record from Davis Channel at 3 m below the surface from 28 March - 02 May, 1989. The original record is presented in its total (a), tidal (b), and subtidal (c) frequency parts. Mean channel flow of 20 cm/s indicates an outwards flow dominance. The tidal flow has an amplitude of approximately 60 cm/s. The subtidal frequency part contains velocity fluctuations with dominant time scales of 2 to 5 days in agreement with the energy spectrum shown in Figure 7b. Note that the inward or flooding event from 11 to 13 April (Julian 101 to 103) consisted of an average current of about 30 cm/s. The three subtidal or low frequency forced floods are described later in the text as Events 7, 8

and 10. Low frequency currents, despite their smaller amplitude relative to the M_2 tide, may be responsible for a significant portion of the total mass transport into or out of the sound system since, unlike tidal currents, the low frequency currents are non-reversing over a tidal cycle and may persist for several (1-5) day periods. Using a simple progressive vector concept, ($\int \bar{v} dt = x$), where $\bar{v}$ is axial velocity, t is time and x is distance, then this two day flood event would displace a particle 51 km. However, currents change drastically as they enter deeper, shallower and constricted portions of the estuary, so the progressive vector concept is not completely physically plausible.

Manning's equation for uniform-flow in open channels was used to derive an average velocity with respect to current meter depth and location. This systematic procedure is used to modify observed velocities in an effort to gain a representative value of velocity through the entire cross-section. Jarrett (1976) proposed that the average velocity through an entire cross section be computed as $V_a = V_m (R/D)^{2/3}$, where: V_a is the average velocity over the entire cross section; V_m is the measured averaged velocity from the vertical section; D is the current meter depth; H is the mean low water depth; and R is the hydraulic radius equal to the cross-sectional area divided by the wetted perimeter, or equivalently the depth H , since the inlet depth is much much less than the inlet width. Thus, inlet velocity is directly related to the hydraulic radius.

The tidal prism is the volume of water passing through an inlet over a complete tidal cycle. Here prisms are computed in a manner which retains all current events and thus represent the total volumetric flux. Each 1-hour average, 3-hour low-pass filtered velocity was multiplied by the concurrent area to estimate the associated transport value, $q = V_a A$. Cumulative volumes are estimated by numerically integrating transport, that is $Vol(t) = \int_0^t q(t') dt' [m^3]$. Prism values

are volumes obtained by estimating the volume over a complete inflow or outflow event.

Figure 10 depicts 12 representative subtidal frequency inflow or flood-type and outflow or ebb-type events at the Oregon Inlet Channel from 19 April (Julian date 110) through 7 August 1988 (Julian date 220). Factors other than the semidiurnal tide are included in prism calculations by summing until a sign change has been reached in the current meter record (i.e., a reversal is reached). The average prism for Oregon Inlet from Bonner bridge surface measurements during 1988 and 1989 is $1.1 \times 10^8 \text{ m}^3$. Inflow and outflow events lasting longer than a day, i.e. extended ebb and flood events, during the 1988-89 experiments ranged from 1 to 8 days and had total volumes ranging from $1.2 \times 10^8 \text{ m}^3$ to $5.0 \times 10^8 \text{ m}^3$ of water. The Delta Prism curve highlights peak ebb and flood volumetric influx. During prolonged storms the volume exchange could be on the order of billions of m^3 .

Over the study period, migrating fish experience temperature and salinity changes even within recruitment favorable water masses. Water surface temperatures at Oregon Inlet ranged from 8°C in March (1989) to 32.0°C in August (1988); 4°C higher than the high reported by Schwartz and Chestnut (1973). It should be noted that previous studies generally consisted of monthly, single station sampling while our study invoked the collection of continuous time series. An example of 40-hour low-pass filtered T and S is presented in Figure 10 with cross-correlations between the two time series shown in Figure 11.

From the evidence presented in Figure 7-10, it appears that synoptic scale atmospheric events, characterized by wind events lasting more than 40 hours, are an important driving force of Oregon Inlet currents. The wind stress, τ , is determined as $\tau = \rho C_d \bar{U} |\bar{U}|$, where $\bar{U}$ is the wind vector at 10m height, ρ is air density $1.23 \times 10^{-3} \text{ g/cm}^3$, and the drag coefficient C_d is taken as 1.5×10^{-3} (Pond, 1975).

The Oregon Inlet jetting mechanism related to synoptic scale extratropical cyclone atmospheric wind events, unlike that due to the astronomical tides, is two sided and thus is effectively double in effect. While coastal surface waters will flow to the right of the southward winds, piling up against the coast (Pietrafesa, 1989) and thus rise on the offshore side of the inlet. It has been determined that open ocean sea level from Chesapeake Bay to Cape Hatteras rises within 8 hours in concert with southward and southwestward winds (Wang and Elliot, 1978; Chao and Pietrafesa, 1980; Pietrafesa and Janowitz, 1988).

Within Pamlico Sound, southward and southwestward winds cause water level to fall in the northern end, specifically on the inside of Oregon Inlet, while northeastward winds cause sea level to rise at this end of the sound (Pietrafesa and Janowitz, 1988). Both water level adjustments to the wind occur within 3 hours of the onset of these winds. Consequently, given the orientation and structure of this lagoon-ocean system (as shown in Figures 1 and 2) and that of Pamlico Sound seen in Figure 1), coupled with the alignment of Oregon Inlet, an ideal topographic triad is established for maximum hydrodynamic flooding (or ebbing) due to atmospheric wind events. So a wind-induced convergence (divergence) of water on one side of the inlet is typically accompanied by a wind-induced divergence (convergence) on the opposite side. Clearly 80-85% of the variability of the currents in Oregon Inlet, with periods greater than a day, can be ascribed to this process (Figure 13c).

Time series of water level measured during 1988, outside and inside the Oregon Inlet Channel (cf Figure 15), confirm the trend that northward winds force a sea level rise while southward winds induce a decline in water levels inside the inlet. This effects the tilt in the water level depicted in Figure 16.

The causal relation between alongshore wind (τ_y) and coastal sea level (η), which is direct, is shown in Figure 13a. The direct causal relation between the water level difference ($\Delta\eta$) (outside minus inside) relation along the axis of Oregon Inlet

and axial flow (v) is shown in 13b. The indirect relationship between alongshore wind component and inlet axial flow is presented in Figure 13c. All four parameters, τ_y , v , η outside and $\Delta\eta$ (outside - inside) show strong correlation at synoptic time scales. The phase and transfer function convention (not shown) is that for a southward wind, currents flood through the inlet, and for a northward wind, flow is outward. The magnitude squared coherence of water height differences between that outside of the inlet and that inside Oregon Inlet versus channel flow show remarkably high coherency at the semidiurnal period and periods greater than two days (Figure 13b). Negative phase (not shown) suggests that sea level pressure gradients lead channel flow so the suggestion is that when the water level is tilted downwards (upwards) inwards (out of) the inlet, water floods into (drains out of) the sound via the inlet. Figure 13c shows the coherency between Oregon Inlet Channel flow and longshore wind component with extremely high coherency at periods greater than 1 day.

During the June-July, 1988 period there were six distinct periods when winds persisted from the northeast (Figure 14). Coincident with these winds were residual flood currents in Oregon Inlet Channel (events F1-6). In fact, over the entire period of the experiment, this is found to be the general condition, regardless of season. We note that flood events always bring higher salinity or shelf water into the sound. Alternatively, residual ebb events, characterized by low salinity water, are associated with winds from the south (Figure 14). Water flowing out of Oregon Inlet into the coastal ocean during spring, 1989 had temperatures as low as 12° C with salinity around 16 psu while flood water resembling Mid Atlantic Bight Water, VCW, measured 8° C with a salinity signature in excess of 32 psu.

Current measurements indicated that over a 240-day period, the inlet was clearly outflux or ebb dominated, yet showed many strong influx or flood events. These influx events were all caused by the pressure gradient created from southward

winds. Analysis of sea level differences versus temperature fluctuation was very strongly coherent at synoptic time scales; (Figure 17a) even more so than that shown by S or T vs η , alone (Figure 12). Transfer function amplitude over the synoptic time scale range gave a value of 1.0° C per decimeter of water level difference. Sea level differences versus salinity time series during the same periods were coherent and had a transfer function amplitude of 1.6 psu per decimeter of water level difference (Figure 17b). Cross spectrum analysis demonstrates a clear dependence between the pressure gradient force and the movement of identifiable water types through Oregon Inlet.

Table 1 identifies 10 individual flooding events using T, S time series which were characterized as Mid Atlantic Bight Water entering Pamlico Sound through Oregon Inlet. Five events featuring Carolina Capes and Gulf Stream Water intrusions are also identified. Over the 240-day observational period, Mid Atlantic Bight Water encroached through the inlet over a several-day period more frequently than either Carolina Capes or Gulf Stream Water, which is not surprising since Oregon Inlet is located in the Mid Atlantic Bight. The actual flooding events are shown by the current vectors in Figure 18.

4. SUMMARY AND CONCLUSIONS

Astronomical tides and the atmospheric wind are both shown to be effective in the non-local forcing of water through the chain of barrier islands flanking the Albemarle-Pamlico coastal lagoonal estuarine system. Semidiurnal and diurnal tidal currents, which are controlled by the convergence or divergence of water at the mouths of the barrier island inlets, force water into and out of the sounds with a maximum distance of 2.5 km in either direction. Additionally, atmospheric winds set waters up and down on both sides of these inlets and drive an inlet jetting process which moves water into and out of the sound over periods longer than a

day and some 5 to 50 kms into the Sound. The situation at Oregon Inlet is such that when water converges on one side it diverges from the opposite side so that, as a function of wind magnitude and persistence, the pressure gradient force can be of order 50 to 200 percent greater than that associated with the tide alone.

Jetting occurs regularly at the inlets in synchronization with synoptic scale atmospheric winds. This process has the important effect of facilitating the annual winter migration of infant fish from the Gulf Stream front and from Virginia spawning areas to North Carolina estuaries. Oregon Inlet is the Albemarle-Pamlico estuarine complex's northern-most source for MABW, CCW and GSW. Ocean water masses, which enter the estuary, mix with fresh water to produce conditions favorable for the reproduction and growth of commercially important finfish and shellfish (Miller et al., 1984).

Tidal currents and sub inertial frequency jetting processes scour and transport sand towards as well as away from the inlet opening. Changes in volumetric flux by sedimentation and dredging will affect the cross-sectional flow area and consequently the ability of currents to transport fish larvae into their estuarine nurseries. Alteration of a particular barrier island inlet will modify the flow characteristics of neighboring inlets as the Albemarle-Pamlico estuarine system strives to maintain its outflow or flushing requirement and also will impact on sedimentation rates and the estuarine retention of drifting plants and animals. Natural changes and human meddling can alter the present migration routes for fish inhabiting the coastal ocean. The cause of the extended flood events which carry fish into the Albemarle-Pamlico estuarine system is a synoptic scale phenomena. Therefore, small scale changes at the inlet should have a negligible effect on the inlet jetting process. The danger seems to be that structures extending past the surf zone (littoral drift) will create a barrier that will disrupt immature fish

pathways from the open coast to the inlet channel. If the larvae fail to travel around the tip of an updrift jetty, they will not complete their migratory cycle.

The natural processes of migration results in the retention of immature fish within the Albemarle-Pamlico estuarine system and, therefore, is of value to commercial and recreational fishermen. The amount of North Carolina fish larvae that will eventually comprise a year group is directly influenced by a coupled meteorological and coastal circulation system. In order for winter-spawned estuarine-dependent fish species to reach a marketable size, they must successfully move from the shelf break through a barrier island inlet and into their nursery area.

Table 1. Water type intrusions into Albemarle-Pamlico Complex. Temperature and salinity measurements were obtained from S4 current meters and thermistor gages attached to water level recorders.

Flood Event No.	Start Date mo-day-yr (Julian)	No. of Days	Temperature Range (°C)	Salinity Range (psu)	Source of Water
1	4-25-88 (116)	2	11.2 - 13.8	30.6 - 31.7	MABW
2	5-07-88 (128)	1.5	12.6 - 13.9	30.6 - 31.9	MABW
3	5-26-88 (147)	3	23.3 - 17.8	31.1 - 32.2	MABW
4	6-24-88 (176)	2	17.7 - 25.3	30.1 - 35.5	MABW CCW
5	6-27-88 (179)	1	18.9 - 21.9	32.6 - 35.5	CCW
6	7-01-88 (183)	7	21.5 - 25.5	30.5 - 35.5	CCW
7	4-11-89 (101)	2.5	8.0 - 9.7	30.5 - 32.5	MABW
8	4-20-89 (110)	2.5	9.9 - 13.5	30.8 - 35.0	MABW CCW
9	4-23-89 (113)	1	12.0 - 13.7	30.5 - 32.0	MABW
10	4-28-89 (118)	1	13.8 - 16.3	31.2 - 33.1	MABW
11	6-11-89 (162)	1.5	18.2 - 24.5	33.0 - 36.0	MABW CCW GCW
12	6-30-89 (181)	2	23.0 - 24.0	31.0 - 32.0	MABW

Mature fish spawn and larvae drift toward the inlets where they become entrained into the lagoonal circulation system described by Pietrafesa et al. (1986a), which eventually carries postlarvae fish toward the western edge of the Pamlico Sound. The fish (Pietrafesa et al., 1986b) then inhabit the primary nurseries which allows for growth to adulthood. This process affects the movement of certain predatory fish and is of major economic importance to the fishing industry of North Carolina.

During this investigation, there were frequent observations of energetic flooding events which lasted several days in duration and which brought significant volumes of ocean water into the Albemarle-Pamlico estuarine system. These events occur year round but are especially energetic during the period October - April, a period which encompasses the December - April period of the shoreward migration of offshore spawned estuarine dependent finfish larvae as well as November - April, the principal season of atmospheric cyclogenesis on the NC coast (Cione et al., 1993). In each subtidal frequency flood case, observed winds from the north and northeast were found to facilitate inlet jetting which is capable of carrying fish larvae into the sounds. Fish larvae riding the jets at the beginning of an extended flood would have the highest probability of retention within the sound.

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6. REFERENCES

- Chao, S.-Y. and L.J. Pietrafesa, 1980. The Subtidal Response of Sea Level to Atmospheric Forcing in the Carolina Capes. *Journal of Physical Oceanography*, vol. 10(8):1246-1255.
- Cione, J.J., S. Raman and L.J. Pietrafesa, 1993. The Effect of Gulf Stream-induced Baroclinicity on U.S. East Coast Winter Cyclones. *Monthly Weather Review*, vol. 121. 121:421-430.
- Department of the Army, 1949. Examinations of Rivers and Harbors, 3, 256-379, 81st Congress, 1st Session.
- Ekman, V.W., 1905. Arkiv. Matem. Astr. Fysik., Stockholm 2(11):1-52.
- Giese, G.L., H.B. Wilder and G.G. Parker, Jr., 1985. Hydrology of major estuaries and sounds of North Carolina, U.S. Geological Survey Water-Supply Paper, 2221, 108 pp., U.S. Geological Survey, Alexandria, VA.
- Inman, D.L. and R. Dolan, 1989. The Outer Banks of North Carolina: budget of sediment and inlet dynamics along a migrating barrier system, *J. of Coastal Res.*, 5: 193-237.
- Jarrett, J.T., 1976. Tidal prism - inlet area relationships, GITI Rep. No. 3, U.S. Army Coastal Engineering Research Center, Fort Belvoir, VA and U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Miller, J.M., J.P. Reed and L.J. Pietrafesa, 1984. Patterns, mechanisms and approaches to the study of estuarine dependent fish larvae and juveniles, in *Mechanisms of Migration in Fishes*, edited by J.D. McCleave, G.P. Arnold, J.J. Dodson, and W.H. Neill, pp. 209-225, Plenum, New York.
- NOAA, 1988. Tide Tables, high and low water predictions: east coast of North America and South America including Greenland, U.S. Dept. of Commerce, Rockville, MD.

- Pietrafesa, L.J., 1989. The Gulf Stream and Wind Events on the Carolina Capes Shelf. NOAA-National Undersea Research Program, Rep. 89-2, R.Y. George and A.W. Hulbert, eds, p. 89-129.
- Pietrafesa, L.J., 1990. Upwelling processes associated with Western Boundary Currents. Phosphate deposits of the world, Volume 3, Neogene to modern phosphorites Chapter 1:3-26. W.C. Burnett and S.R. Riggs, eds. Cambridge Univ. Press.
- Pietrafesa, L.J. and G.S. Janowitz, 1988. Physical oceanographic processes affecting larval transport around and through North Carolina inlets, in Larval Fish and Shellfish Transport through Inlets, edited by M.P. Weinstein, pp. 34-50, American Fisheries Society Symposium 3, Bethesda, MD.
- Pietrafesa, L.J., J.M. Morrison, M.P. McCann, J.H. Churchill, E. Böhm and R.W. Houghton, 1994. Water mass linkages between the Middle and South Atlantic Bights. DEEP-SEA RESEARCH, PART II: SEEP II, 41 (2/3): 365-389.
- Pietrafesa, L.J., G.S. Janowitz, S.Y. Chao, R.H. Weisberg, F. Askari and E. Noble, 1986a. The physical oceanography of Pamlico Sound, Publication 86-5, University of North Carolina Sea Grant College Program, Raleigh, NC.
- Pietrafesa, L.J., G.S. Janowitz, J.M. Miller, E.B. Noble, S.W. Ross and S.P. Epperly, 1986b. Abiotic factors influencing the spatial and temporal variation of juvenile fish in Pamlico Sound, North Carolina, in Estuarine Variability, edited by D. A. Wolfe, pp. 341- 353, Academic Press, New York.
- Pietrafesa, L.J., G.S. Janowitz and P. Wittman, 1985. Physical Oceanographic Processes in the Carolina Capes, In: L.P. Atkinson, D.W. Menzel and K.A. Bush (eds.). *Oceanography of the Southeastern U.S. Continental Shelf*, Coastal and Estuarine Sciences, 2, 23-32.

- Pietrafesa, L. J., R. D'Amato, C. Gabriel and R.J. Sawyer, 1978. Continental margin atmospheric climatology and sea level, Raleigh Rep. No. UNC-SG-78-09, 189 pp., University of North Carolina Sea Grant College Program, Raleigh, NC.
- Pond, S., 1975 . The exchanges of momentum, heat and moisture at the ocean-atmosphere interface. *Numerical Models of Ocean Circulation*, National Academy of Sciences, Washington, DC, pp. 26-38.
- Redfield, A.C., 1958. The influence of the continental shelf on the tides of the Atlantic coast of the United States. *J. of Marine Res.*, 17, 432-438.
- Roelofs, E.W. and A.W. Bumpus, 1953. The hydrography of Pamlico Sound, *Bulletin Marine Science Gulf and Caribbean*, 3,181- 205.
- Schwartz, F.J. and A.F. Chestnut, 1973. Hydrographic atlas of North Carolina estuarine and sound waters, Sea Grant Pub. No. UNC-SG-73-12, University of North Carolina, Chapel Hill, NC.
- Singer, J.J. and C.E. Knowles, 1975. Hydrology and circulation patterns in the vicinity of Oregon Inlet and Roanoke Island, North Carolina, Pub. 75-15, University of North Carolina Sea Grant College Program, Raleigh, NC.
- US Army Corps of Engineers, 1970. Report of the Board of Engineers for rivers and harbors, Manteo (Shallowbag) Bay, North Carolina, House Document No. 91-3039, N.C. 1st Congress, 2nd Session.
- US Army Corps of Engineers, 1968. Review report, Manteo (Shallowbag) Bay, NC, Wilmington, NC.
- Wang, D.-P. and A.J. Elliot, 1978. Non-tidal variability in the Chesapeake Bay and the Potomac River: Evidence for non-local forcing. *Journal of Physical Oceanography*, vol. 8:225-232.
- Weisberg, R.H. and L.J. Pietrafesa, 1982. Surface Wind Field Analysis in the South Atlantic Bight. Technical Report No. 82-5, Department of Marine, Earth and

Atmospheric Sciences, North Carolina State University, Raleigh, NC, May 19,
p. 52.

Weisberg, R.H. and L.J. Pietrafesa, 1983. Kinematics and Correlation of the Surface
Wind Field in the South Atlantic Bight. *Journal of Geophysical Research*, vol.
88(C8):4593-4610.

Williams, A. B., G. S. Posner, W. J. Woods and E. E. Deubler, Jr., 1973. A
hydrographic atlas of larger North Carolina sounds, Sea Grant Pub. No. UNC-
SG-73-02, University of North Carolina, Chapel Hill, NC.

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