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Daily variation in ingress of fall-spawned larval fishes into Delaware Bay in relation to alongshore and along-estuary wind components

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ABSTRACT

Identifying factors that affect ingress of larval fishes from offshore spawning areas into estuarine nurseries is important to improve understanding of variability in recruitment of many coastal marine species. This study investigated the ingress of larval Atlantic croaker (*Micropogonias undulatus*), Atlantic menhaden (*Brevoortia tyrannus*), and summer flounder (*Paralichthys dentatus*) at Roosevelt Inlet, near the mouth of Delaware Bay, USA in relation to short-term wind events. Nightly abundances, from November 15 to December 15, 2010, were analyzed with alongshore and along-estuary wind components (direction and speed) using cross-correlation analysis to determine if winds affect larval ingress. Ingress of Atlantic croaker and summer flounder correlated with along-estuary winds, whereas Atlantic menhaden showed no significant correlations with either alongshore or along-estuary winds. Although along-estuary winds during this period were predominantly down-estuary, Atlantic croaker ingress was correlated with positive along-estuary winds (blowing up-estuary), with a three-day lag; and a particularly large ingress peak occurred following the largest up-estuary wind peak. Ingress of summer flounder was correlated with negative along-estuary winds (blowing down-estuary), with a two-day lag. These results suggest that species-specific vertical position in the water column influenced ingress into Delaware Bay. The lag results also suggest that ingressing Atlantic croaker and summer flounder may have a pooling stage outside the mouth of Delaware Bay.

1. Introduction

Estuaries serve as nursery habitats for the larval and juvenile stages of many ecologically and economically important marine fishes that spawn offshore (Boehlert and Mundy, 1988; Bilkovic and Roggero, 2008). Recruitment to adult populations is thus largely dependent on processes operating during the larval and early juvenile stages (Crecco and Savoy, 1984; Rothschild, 1986; Sogard, 1994; Peterson, 2003). Research along the east coast of the United States has examined mechanisms that control larval transport across the continental shelf and into estuarine systems (e.g. Joyeux, 1998; Hare et al., 2005; Schaffler et al., 2009), in addition to subsequent retention within these systems (e.g. North and Houde, 2006).

Although several mechanisms of larval transport have been described, understanding how they interact across spatial and temporal scales, as well as how they vary among species, ontogenetic stages, and even estuary types remains a challenge. A current paradigm holds that larval ingress occurs in three stages: transport of larvae across the continental shelf to nearshore areas, movement from nearshore areas to pooling near estuary mouths, and subsequent ingress of larvae from these pools into the estuary (Boehlert and Mundy, 1988; Schaffler et al., 2009). Because eggs and young larvae are planktonic, initial transport is largely due to physical forcing such as wind-driven Ekman transport and gyre circulation (Hettler and Hare, 1998; Epifanio and Garvine, 2001) that can vary seasonally, and by large-scale climatic cycles such as the North Atlantic Oscillation (Hare and Able, 2007). Transport across the shelf culminates as larvae arrive at nearshore areas and estuary mouths (Nelson et al., 1977; Boehlert and Mundy, 1988; Hettler and Hare, 1998; Schaffler et al., 2009). At this stage, a new suite of factors directs larval ingress into estuaries. It has been shown that sinking to the bottom to take advantage of residual bottom inflow can be important for some demersal species, including Atlantic croaker *Micropogonias undulatus* (Schultz et al., 2003; Hare et al., 2005). Larvae may also utilize various active behaviors such as

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selective tidal stream transport (STST) to promote up-estuary transport. In this process, larvae migrate up in the water column on flood tides and down during subsequent ebb tides, resulting in a net up-estuary displacement (Epifanio, 1988; Rowe and Epifanio, 1994; Hare et al., 2005). Larvae are also subject to local physical processes determined by bathymetry and morphology of the specific estuary mouth (Norcross, 1991; Schaffler et al., 2009) as well as event-scale processes near the inlet or estuary mouth (Hare et al., 2005).

Delaware Bay is the second largest estuary on the east coast of the United States (Sharp et al., 1982; Bryant and Pennock, 1988), and the bay and its tributaries provide nursery habitat for several ecologically and economically important offshore spawners that ingress as larvae or early juveniles during fall and winter months. These species include Atlantic croaker *Micropogonias undulatus*, Atlantic menhaden *Brevoortia tyrannus*, and summer flounder *Paralichthys dentatus* (Rhode, 2008), and the mechanisms that control the ingress of their larvae into Delaware Bay have not been extensively studied. Atlantic croaker spawn on the continental shelf during late summer and early fall and larvae ingress into the estuaries of the Mid-Atlantic Bight during the fall and winter, starting in September (Norcross, 1991; Witting et al., 1999; Hare and Able, 2007; Rhode, 2008). Atlantic menhaden spawn during a yearly north to south migration (Ahrenholz, 1991; Govoni, 1993; Stegmann et al., 1999; Hare et al., 1999) and these larvae occur in the Mid-Atlantic Bight region from October into February (Warlen et al., 2002; Rhode, 2008). Menhaden larvae are often abundant again in early spring (Rhode, 2008; Love et al., 2009), although this cohort originates from spawning south of Cape Hatteras (Warlen et al., 2002). Summer flounder in the Mid-Atlantic Bight spawn during migration to deeper waters on the continental shelf for the winter and larvae arrive in estuaries from October to May (Rogers and Van Den Avyle, 1983; Able et al., 1990; Malloy and Targett, 1991; Rhode, 2008).

Research on the larval fish assemblage in Delaware Bay is limited to that of Rhode (2008), which sampled ichthyoplankton weekly at the mouth of Delaware Bay during 2006 and 2007 to determine species composition, abundance, and seasonality. This study found Atlantic croaker, Atlantic menhaden, and summer flounder larvae to be among the eight most abundant species, and weekly variability in larval concentration to be considerable. However, physical forces acting on larvae have been shown to cause substantial variation in larval fish and invertebrate concentrations on sub-weekly, even daily scales within estuaries (Jones and Epifanio, 1995; Hettler et al., 1997). Short-term wind events, for example, can significantly alter flux of water into an estuary on the order of just a few days (Pietrafessa and Janowitz, 1988; Liu, 1992; Churchill et al., 1999). North and Houde (2004) illustrated that wind events as short as 12–24 h significantly altered transport of bay anchovy (*Anchoa mitchilli*) within Chesapeake Bay. Therefore, high-resolution (e.g. daily) ichthyoplankton sampling is necessary to reveal relationships between short-term wind events and larval ingress. Such high temporal-resolution sampling has yet to be done and critically analyzed for Delaware Bay.

The objective of this study was to determine whether daily wind patterns significantly affect larval fish ingress to Delaware Bay, through analysis of daily abundance fluctuations of selected species at the near the entrance of Delaware Bay. We sampled nightly for one month from mid-November through mid-December, when three species, Atlantic menhaden, Atlantic croaker, and summer flounder, were likely to be present (Rhode, 2008). We evaluated the data to determine if there were significant relationships and time lags between the daily wind components (speed and direction) and larval ingress for each species using time-series analysis techniques.

2. Materials and methods

2.1. Study site

Delaware Bay (Fig. 1) is a well-mixed coastal plain estuary in the mid-Atlantic region of the USA (Janzen and Wong, 2002). The estuary has a longitudinal axis of 160° from true north (°T), while the mouth of the estuary is oriented 190 °T. The estuary is 213 km long extending from Trenton, NJ to Cape May, NJ along the north and Cape Henlopen, DE along the south (Janzen and Wong, 2002). The Delaware River is the major source of freshwater input to the bay and accounts for 58% of the mean annual discharge (Lebo and Sharp, 1993). Mean depth of the bay is 8 m (Garvine, 1991). The lower 100 km of the bay accounts for 90% of the surface area and has a mean depth of 10 m. The mouth of the estuary is 18 km wide, extends to 45 km just inside the mouth, and decreases in width with distance up-estuary. The bay has a single deep channel that is 45 m in depth, runs along the longitudinal axis of the bay and extends onto the continental shelf (Janzen and Wong, 2002).

The southwestern portion of the bay mouth exhibits conventional two-layer gravitational circulation pattern due to the close proximity of the deep channel, which experiences regular periods of bottom layer inflow (Wong, 1996). The northeastern portion of the bay mouth is much shallower and lacks consistent periods of bottom layer inflow. Episodic wind events have the ability to modulate this typical, sub-tidal flow pattern. Localized, negative along-estuary winds enhance surface water flow out of the estuary,

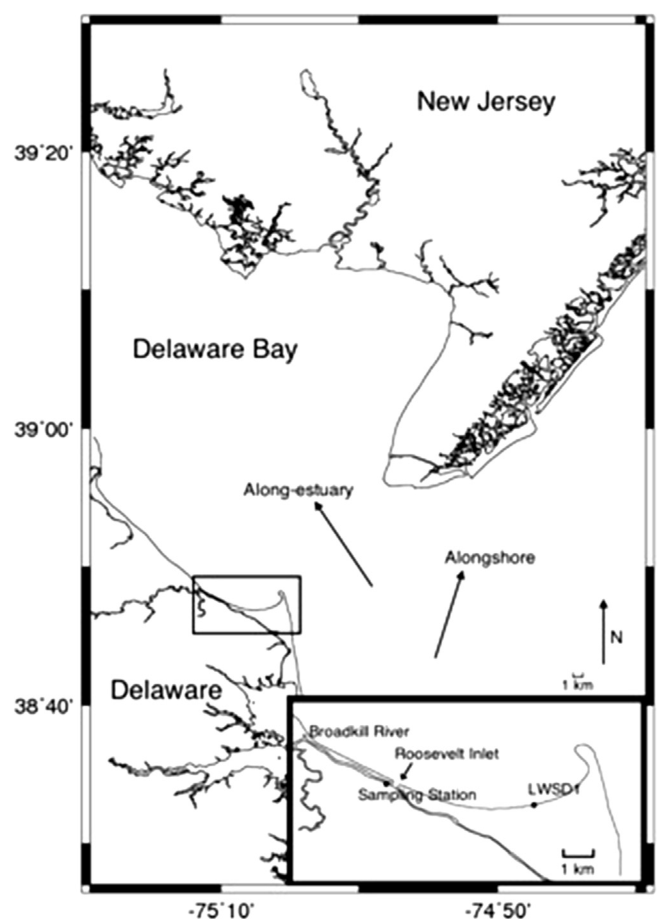

Fig. 1. Mouth of Delaware Bay (USA). Inset shows the sampling station inside Roosevelt Inlet and NOAA weather station LWSD1 (from which wind direction, speed, and water temperature were obtained). Arrows indicate approximate orientation of the alongshore and along-estuary wind components; they point in the positive direction.