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The relationship between coastal *Mysis diluviana* abundance and spring thermal bar dynamics

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ABSTRACT

We studied the density and age structure of *Mysis diluviana* in Lake Michigan with respect to spatial structure relating to spring thermal bar dynamics. The thermal bar is a zone of sinking 4 °C water that separates warmer inshore water from colder offshore water. The thermal bar migrates offshore as inshore water warms. The density of *Mysis* did not differ statistically between inshore (about 6 °C, as shallow as 17 m bottom depth) and offshore of the spring thermal bar, but the percentage of *Mysis* that were juveniles (<10 mm length) was significantly higher inshore ($P = 0.011$). Our data suggested that inshore *Mysis* may have an advantage in growth, but an impact on the entire population is unlikely. This study has important implications for both the predators and competitors of *Mysis*. First, the thermal bar period may be the most extended time that *M. diluviana* and the invasive *Hemimysis anomala* overlap spatially. Second, at the only well-studied Great Lakes lake trout nursery, a Lake Superior shallow reef, juvenile *Mysis* are important prey for lake trout fry (*Salvelinus namaycush*) which emerge and begin feeding in spring. Our study shows that *Mysis* are often abundant in coastal Lake Michigan water during the period when the lake begins to warm. Hence, lake trout restoration efforts for coastal spawning areas of the other Great Lakes may have potential *Mysis*-based nursery grounds essentially "on site," at or adjacent to spawning reefs.

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Introduction

Mysis diluviana (henceforth *Mysis*) is an important food source for a diverse range of Great Lakes fishes and its importance may have increased following the decline of *Diporeia* spp. in the four Great Lakes invaded by dreissenid mussels (Hondorp et al., 2005; Pothoven and Madenjian, 2008). *Mysis* generally reside at depths greater than 100 m in the daytime in the Great Lakes, partially due to their preference for low light levels, and at night they ascend to depths determined in part by light intensity, but modified by other factors (Boscarino et al., 2007, 2009). However, during summer upwelling events, *Mysis* can be as shallow as 7 m bottom depth; they are in the water column at night but during the day they are always under rocks (JJ scuba obs. 1978 to present).

There has been little Great Lakes coastal (<20 m) sampling for *Mysis* during spring. The shallowest reported occurrence in Lake Michigan was by Reynolds and DeGraeve (1972) who sampled via bottom sled from 9 to 130 m during daytime. They found no *Mysis* shallower than 20 m during April and May but *Mysis* could occur shallower during winter and upwelling events in summer. In Lake Ontario, *Mysis* was collected at night in depths less than 10 m during the end of May (Johannsson, 1995).

Spring warming in the deep Great Lakes occurs from the coast towards the center with the thermal bar being a physical structure. The thermal bar is marked by 4 °C water that sinks about 9.5–20.7 cm/day (Moll et al., 1993). The sinking water creates a front that separates warmer inshore water from cooler offshore water (Stoermer, 1968) and gradually, but erratically, moves offshore (Mortimer, 1988). Chlorophyll is more concentrated inshore of the thermal bar than offshore (Mortimer, 1988; Moll et al., 1993; Consi et al., 2009); hence, inshore water is believed to benefit coastal zooplankton (Brandt, 1993). *Mysis* feed on larger phytoplankton and zooplankton (Bowers and Grossnickle, 1978; Nero and Sprules, 1986; Nordin et al., 2008) so an increase in either phyto- or zooplankton should be a benefit.

We report on the relative density and age composition (as expressed as percent juvenile) of *Mysis* juveniles inshore vs. offshore of the thermal bar for three successive spring warm-ups.

Methods

Our sampling targeted larval fish distribution and *Mysis* was an unexpected, but substantial bycatch. We sampled *Mysis* on night cruises during the thermal bar period in spring from 2007 to 2009 in western Lake Michigan near Milwaukee, WI from the University of Wisconsin-Milwaukee's R/V Neeskay. Sampling was conducted along an inshore to offshore transect (approximately 43°05′, 87°50′-

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43°05′, 87°42′) that crossed the thermal bar. Because the thermal bar is a mobile physical structure, the initial location of tows was determined with respect to near the center of the 4 °C temperature band. Sampling was limited to two stations per night because several hours were needed to complete each station; also there were long travel times between stations, and the period of darkness was as short as 6 h by late May. The thermal bar was located via a continuously recording calibrated sonde (YSI model 6600ZDS-M) which rested in a PVC pipe with continuous fresh water flow pumped from about 2 m below the surface. The offshore tows were about 2–3 km offshore of the thermal bar, in water less than 4 °C and the inshore tows were initiated at a location of near 6 °C. As the thermal bar moved offshore, the sampling locations also moved offshore.

At each station, a 1.4 × 1.4 m opening rectangular Tucker trawl with 500 μm mesh net was deployed. Sampling was conducted at night, at least 1 h after sunset and at least 90 min before sunrise with the ship's lights off. Towing speed was 2 knots. Tow depth was stepped, beginning at 10 m (± about 1 m) deep, every 3 min the trawl rose, in steps, approximately 1 m by pulling in on the winch cable. The maximum tow depth was determined by previous work on larval fishes (Nash and Geffen, 1991). Tow direction was into the wind and waves to maximize control of the vessel and trawl depth. Depth was recorded by a Reefnet SensusPro depth logger. Flow data from a General Oceanics calibrated flowmeter attached to the center of the Tucker Trawl mouth was used to estimate the volume of water sampled (following Nash and Geffen, 1991). Samples were stored in 95% ethanol immediately after capture. In the laboratory, all *Mysis* were counted. About 50 *Mysis* (when available) were randomly selected from each sample for measurement to the nearest 0.1 mm (tip of the rostrum to end of telson). These measurements showed a bimodal length distribution with the minimum between modes at about 10 mm. Consequently each individual from all samples was categorized as “juvenile,” using <10 mm as an operational definition, and >10 mm as “large.” Mean density was calculated for each tow.

Vertical temperature structure and surface fluorescence were continuously recorded at three buoyed stations (Fig. 1) via a near surface sonde (YSI model 6600ZDS-M) and thermister strings (Consi et al., 2009). The buoys were anchored at 20 m, 40 m, and 60 m (2.2 km, 6.0 km, and 12.0 km from shore respectively and within a few km of our sampling transect; see Consi et al. for details). Buoys were deployed over a period of about three weeks, with the shallowest buoy deployed first and the deepest buoy deployed last.

The densities of *Mysis* were compared between inshore and offshore using paired t-tests with date being the replicate. The percent juvenile was compared using an analysis of covariance (ANCOVA) with sampling location (inshore vs. offshore of the thermal bar) and year as group variables and date since April 15 (arbitrary starting date) as a covariate. A two-sample *t*-test was used for comparison of the length of juveniles between inshore and offshore samples.

Results

Temperature profiles from buoys show the passage of the thermal bar and the onset of stratification progressing from shallow to deeper water (Fig. 1). First onset of the thermal bar occurred on 20 April, 29 April (briefly), and 9 May 2009 (briefly) for the 20, 40 and 60 meter stations respectively. Consi et al. (2009) reported that chlorophyll was more concentrated inshore of the thermal bar than offshore. The dynamic nature of the thermal bar and the fluctuation in its position is illustrated in Fig. 1. For example, within the period of 5–9 May the thermal bar was offshore of the 40 m buoy and there was a brief period in which there was a thermocline (Fig. 1). The thermal bar, or wedge, even migrated briefly past the 60 m buoy around 9 May. The surface chlorophyll concentration at the 40 m buoy increased during the time interval of 5–9 May as the water warmed to about 8 °C (Fig. 2). Mixing due to a wind event then weakened the thermocline and diluted the surface chlorophyll.

Reynolds and DeGraeve (1972) used 11 mm as the cutoff to separate juvenile and adult *Mysis*. Our measurements showed a bimodal length distribution with the gap at about 10 mm; consequently, we used 10 mm as our criterion to separate “juvenile” and “large” (Fig. 3).

We collected *Mysis* in 6 °C surface water as shallow as 17 m bottom depth and consistently over 20–25 m bottom depth (Fig. 4). Data from two nights with a full moon were excluded due to the low numbers of *Mysis* at both inshore and offshore stations. Mean density of *Mysis* inshore was 0.150/m^3, while offshore was 0.313/m^3 (Fig. 4) but there was no consistent pattern regarding whether *Mysis* densities were denser offshore vs. inshore (paired $t_9 = 1.37$, $P = 0.205$). However, when we excluded juveniles from the counts there were significantly higher densities of *Mysis* at the offshore stations (paired $t_9 = 3.3$, $P = 0.011$).

The overall size distribution (Fig. 4) showed a tendency for juvenile *Mysis* to be at the shallow stations. This was confirmed by the statistical analyses; the percent of the sample that was juveniles was greater for inshore vs. offshore stations (Fig. 5; $F_{1,13} = 8.7$, $P = 0.011$). Neither the year effect nor the time covariate (days since April 15) effect was statistically significant ($F_{2,13} = 1.9$, $P = 0.19$ and $F_{1,13} = 2.1$, $P = 0.17$ respectively).

Further examination of the length distribution using only the juvenile size class suggests that those from the shallow stations are slightly larger than those from the deeper station (Fig. 4). A statistical analysis considering all factors was highly unbalanced because there were frequently low numbers of juvenile *Mysis* at the offshore stations so the number of replicate dates is small. However, when we pooled all dates to compare lengths for inshore vs. offshore juvenile *Mysis*, juvenile *Mysis* were statistically larger than those collected offshore. (inshore: 7.1 mm ($s = 1.64$) vs. offshore: 6.4 mm ($s = 2.04$); $t_{175} = 2.35$, $P = 0.020$).

Discussion

Our results justify more intensive study of *Mysis* in regards to thermal bar dynamics. A particularly interesting time is during thermal bar development, when temperature structure is mostly horizontal rather than the better studied vertical structure of summer. We propose that *Mysis* interactions with these physical structures and benthic organisms will likely parallel that of euphausids, which are marine analogs to *Mysis*. Genin et al. (1988) found predation by bottom-associated fishes on vertically migrating euphausids advected into shallow water with consequent intensification of euphausid patchiness. The ability to ascertain parallel dynamics for the Great Lakes will require better bathymetry maps and a better understanding of coastal hydrodynamics. Our work shows that *Mysis* can occur shallow enough for diverse dynamics analogous to those described by Genin et al. (1988).

Prior to our study the shallowest depth that *Mysis* had been collected in spring (April–May) for Lake Michigan was at 37 m (none at 27 m) (Reynolds and DeGraeve, 1972); we consistently collected *Mysis* 12–15 m, and at other depths shallower than 37 m. Johannsson (1995) found *Mysis* at shallow depths comparable to ours in Lake Ontario. Johansson did not report temperatures, so we do not know what water mass they were in. However, her sampling occurred in the last week of May. So if warming was comparable to our Lake Michigan work the spring thermal bar period was over.

We suggest that *Mysis* were advected prior to thermal bar initiation into shallow water by strong winter/early spring currents when the lake has negligible thermal structure. Reynolds and DeGraeve (1972) found *Mysis* in December and January at a depth of 27 m (but none at 18 m). They found *Mysis* as shallow as 18 m during summer upwelling events, presumably advected along with the hypolimneic water. In Lake