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Onshore Transport of Elopomorph Leptocephali and Glass Eels (Pisces: Osteichthyes) in the Florida Keys

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The influx of elopomorph leptocephali and glass eels to Florida Bay was monitored on 160 nights from January through December 1993. Metamorphic leptocephali and glass eels were both captured in channel nets moored in Channel Five near Long Key, FL. Eighty-eight percent of the 2,811 leptocephali collected were speckled worm eels (*Myrophis punctatus*, n = 2,486). The remaining 12% of leptocephali consisted of nine species, including key worm eels (*Ahlia egmontis*, n = 153), shrimp eels (*Ophichthus gomesi*, n = 69), and moray eels (*Gymnothorax* spp., n = 33). The glass eels collected were *Myrophis punctatus* (n = 230) and *Ahlia egmontis* (n = 34). Recruitment of leptocephali and glass eels into Florida Bay was seasonal. *Myrophis punctatus* leptocephali recruited into Florida Bay during fall and winter and were most abundant during November–January. Peak periods of recruitment were associated with nighttime moonless flood tides, strong onshore winds, and easterly (along-shelf) winds. *Ahlia egmontis* leptocephali recruited during January–April. *Ophichthus gomesi* was the only species with major recruitment during the summer and fall (July–November). All of the glass eels were captured from January to April.

The elopomorph fishes of the Florida Keys and Florida Bay include several economically and ecologically important species of the Albulidae (bonefishes), Megalopidae (tarpons), Ophichthidae (snake eels), and Muraenidae (moray eels). Bonefish and tarpon are highly sought after sportfish, whereas many of the eels are secretive, nocturnal scavengers and predators living in reefs, grass flats, and sand flats (Böhlke and Chaplin, 1993). Premetamorphic leptocephalus larvae of elopomorph fishes are abundant in clear, warm, offshore waters worldwide (Smith, 1989), and they are an important component of the Caribbean ichthyoplankton (Shenker et al., 1993; Thorrold et al., 1994a, 1994b, 1994c; Mojica et al., 1995). After the pelagic larval phase, many elopomorph species recruit to estuarine or inshore habitats as metamorphic leptocephali. While entering their juvenile habitats, these leptocephali metamorphose into glass eels, which have a thicker, longer body than leptocephali but are still completely transparent and lack juvenile pigmentation (Leiby, 1989).

The temporal and spatial patterns of the settlement of numerous reef taxa (e.g., Haemulidae, Labridae, Pomacentridae) have been examined by researchers studying recruitment in tropical environments. Recruitment of these taxa has typically been measured by visual censuses of newly settled juveniles (e.g., Victor, 1986; Doherty, 1987; Richards and Lindeman, 1987; Shapiro, 1987; Robertson, 1988). The cryptic elopomorph larvae and fast-swimming and schooling juveniles are not amenable to such visual census techniques, but they have been successfully sampled with channel nets in the Bahamas and the south Pacific (Dufour and Gazlin, 1993; Shenker et al., 1993; Mojica et al., 1995).

Recruitment of larval fishes and invertebrates is influenced by oceanographic and meterological parameters (Richards and Lindeman, 1987; Checkley et al., 1988; Shanks, 1988; Farrell et al., 1991; Lee et al., 1992; Thorrold et al., 1994b). Pfeiler (1984) captured *Albula* sp. leptocephali in small channels leading to lagoons in the Gulf of California and found that larvae recruit during December–April. In the Bahamas, leptocephali of *Albula vulpes* and the eel families Congridae, Ophicthidae, and Moringuidae recruited during the winter and early summer, principally during the new moon (Drass, 1992; Shenker et al., 1993; Thorrold et al., 1994a, 1994b, 1994c; Mojica et al., 1995). Recruitment pulses were often associated with periods of onshore winds, but no association with alongshore or cross-shelf currents was found. Additionally, larval transport principally occurred at night in the top meter of the water column. The objective of our study was to quantify the transport of leptocephali into Florida Bay through a channel in the Florida Keys and to characterize the environmental conditions associated with major periods of larval transport.

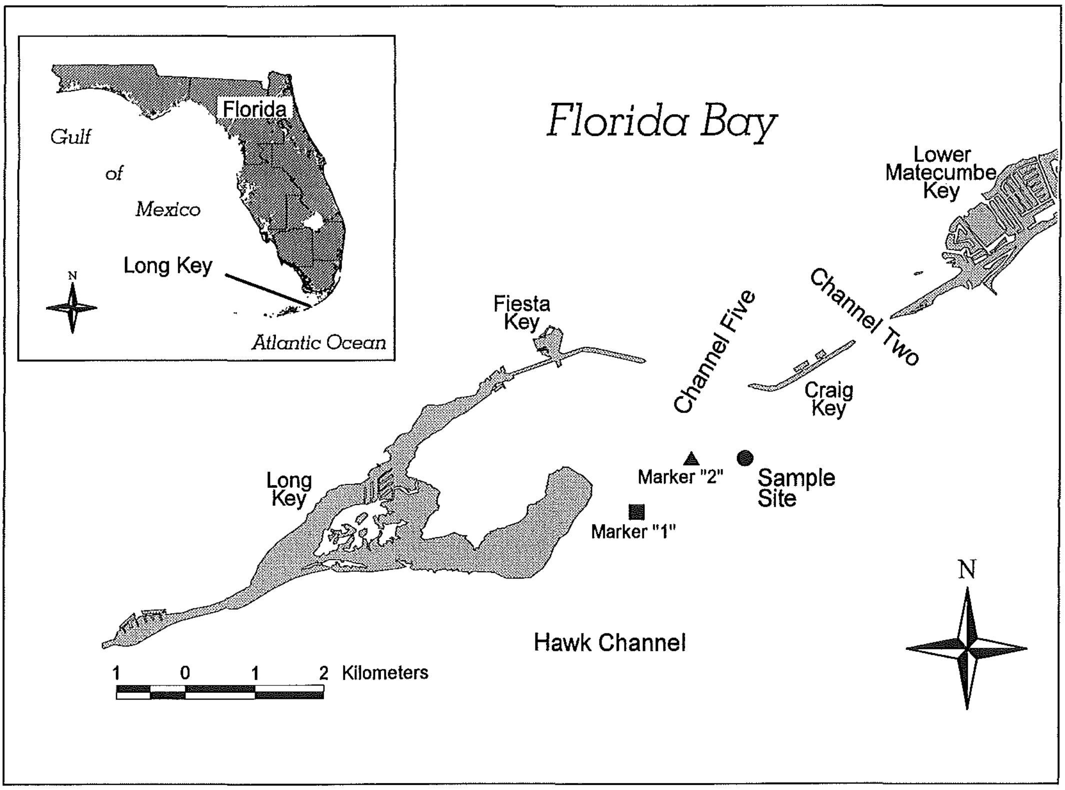

Fig. 1. Location of the sampling site in Channel Five of the middle Florida Keys.

Materials and Methods

Study site.—Samples were collected in Channel Five between Craig Key and Long Key in the middle Florida Keys (24°49.6′N, 80°46.2′W; Fig. 1). The site was over a hard-bottom area approximately 3 m deep and was approximately 9 km from the deep-pelagic habitat beyond the reef tract. Channel Five is a relatively large channel (0.5 km wide) connecting the Atlantic Ocean to Florida Bay. Like other channels examined in the Keys, it has a long-term net flow from Florida Bay to the Florida Straits (Smith, 1994).

Plankton collections.—Samples were collected on 160 nights from January to December 1993. Because Shenker et al. (1993) found that the recruitment of leptocephali in the Bahamas was greatest during the new moon, samples were collected three to five nights before and after the new moon of each month. Additional samples were collected on two or three nights each week during the rest of each month.

Larvae were collected with two moored plankton nets set approximately 100 m apart. Each net was constructed with 1-mm mesh. Nets had an opening 2 m wide and 1 m deep and were 3 m long. Because Channel Five is only 3 m deep, the nets were suspended at the surface. Nets were deployed around 1700 hr and retrieved around 0800 hr the next day. The nets rotated freely with the current and sampled both the flood and ebb tides, thus collecting leptocephali moving in both directions through the channel each night.

After they were collected, the samples were sorted to remove large pieces of seagrass and algae and preserved in a 10% formalin and seawater solution. Samples were later rinsed in water and stored in 70% ethanol. All leptocephali were then identified, counted, and measured to the nearest millimeter (standard length).

After sorting the samples from the first 5 mo, we compared the total nightly catches of leptocephali from the two nets. We found no significant difference in the number of *Myrophis punctatus* collected each night from the two nets (t-test, df = 146, t = −0.0628, $P >$ 0.05) or in the total nightly catches of all leptocephali from the two nets (t-test, df = 148, t = −0.121, $P >$ 0.05). Subsequent sampling was

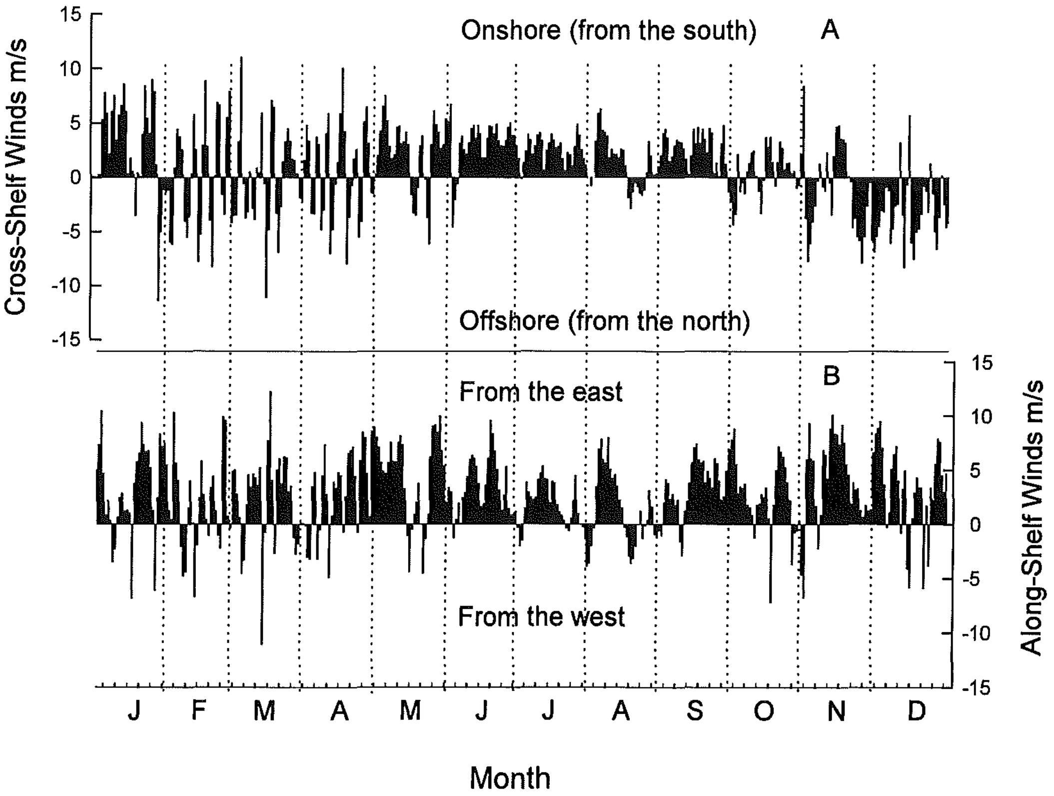

Fig. 2. Winds (m/sec) near Channel Five of the middle Florida Keys from January to December 1993. Cross-shelf winds (A) are categorized as winds moving onshore from the south (positive) and offshore from the north (negative). Alongshelf winds (B) are categorized as winds from the east (positive) and from the west (negative).

continued with only one net. All analyses of temporal patterns and environmental associations of leptocephali are based on data from this single net. Glass eels recruited only during the period when both nets were fished (January–March); therefore data from both nets are included for these analyses.

Environmental data.—Environmental data were obtained from the SEAKEYS environmental monitoring project (D. Forcucci, NOAA/AOML/OCD, pers. comm.). A meteorological station on the Molasses Reef light station, approximately 45 km northeast of the sampling site, collected average hourly wind velocity and direction, surface sea temperature, and salinity. Hourly measurements of current velocities in Hawk Channel, which is oriented parallel to the Keys, were made with a General Oceanics Mark II current meter moored inside the reef tract immediately south of Channel Five (Fig. 1) at middepth over a bottom depth of 7 m (N. Smith, P. Pitts, Harbor Branch Oceanographic Institute, pers. comm.). Data on only winter (January–February and November–December) currents were collected and analyzed.

Data analysis.—Time series of nightly catch rates (number of leptocephali/night) were plotted for each taxon to reveal seasonal patterns of recruitment. G-tests (Sokal and Rohlf, 1981) were used to relate differences in abundances of *M. punctatus* larvae with the speed and direction of the winds, the nightly duration of dark (moonless) flood tide, and Hawk Channel current data. Each comparison was done separately. All G-tests were performed by dividing each environmental parameter into different categories and comparing the proportion of nights in each category (expected) with the proportion of larvae captured during each type of night (observed). All meteorological measurements were converted into 24-hr averages (from 1200 hr to 1200 hr) to reveal conditions that could have affected nightly episodes of recruitment. Winds were divided into

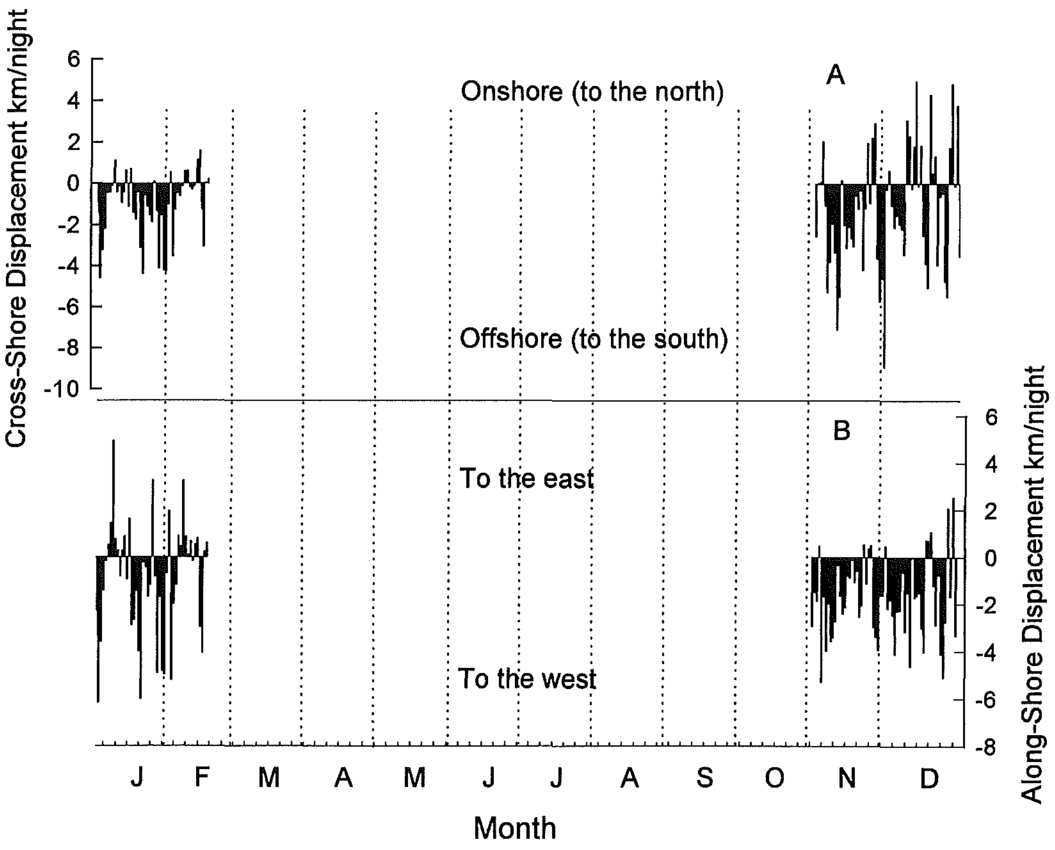

Fig. 3. Average nightly water displacement outside Channel Five of the middle Florida Keys from January to December 1993. Cross-shore displacement (A) is categorized as flow moving onshore to the north (positive) and offshore to the south (negative). Alongshore displacement (B) is categorized as flow moving to the east (positive) and to the west (negative). Data about currents were collected only in winter.

four categories by velocity and direction. The cross-shelf components of the wind were grouped into onshore (0–4 m/sec and >4 m/sec) and offshore (0–4 m/sec and >4 m/sec). The alongshelf components of the wind from the east and west were grouped into the same velocity categories as cross-shelf winds. Hours of dark flood (HDF) tide were the number of hours of incoming tide that occurred between sunset and sunrise and before moonrise or after moonset. The variable HDF was divided into 0–2 hr, 2.1–4 hr, and 4.1–6 hr. Although HDF was greatest on the night of the new moon, substantial levels of HDF occurred even on nights with bright half-moon phases. Currents in Hawk Channel were divided into onshore–offshore and east–west components. Net flow during each sampling period was calculated by summing the average hourly current speeds from 1800 hr to 0600 hr. The rate was assumed to be constant for the entire hour. The results of these calculations are expressed as a net displacement (km/night) of water through the sampling area. A G-test was used to compare the number of fish caught with the onshore–offshore and east–west components of displacement.

RESULTS

Environmental data.—Weather during the 12-mo sampling period was dominated by two seasonal wind patterns (Fig. 2). From January through May and the following October–December, the region experienced the episodic passage of cold fronts. As fronts approached the Keys, winds blew from the south toward Florida Bay (onshore). As fronts passed over the study area, winds blew strongly (>7m/sec) from the north (offshore). Because of the east–west orientation of the middle Florida Keys, northerly winds resulted in a net offshore water flow. Summer was characterized by breezes from the southeast, and winds had a

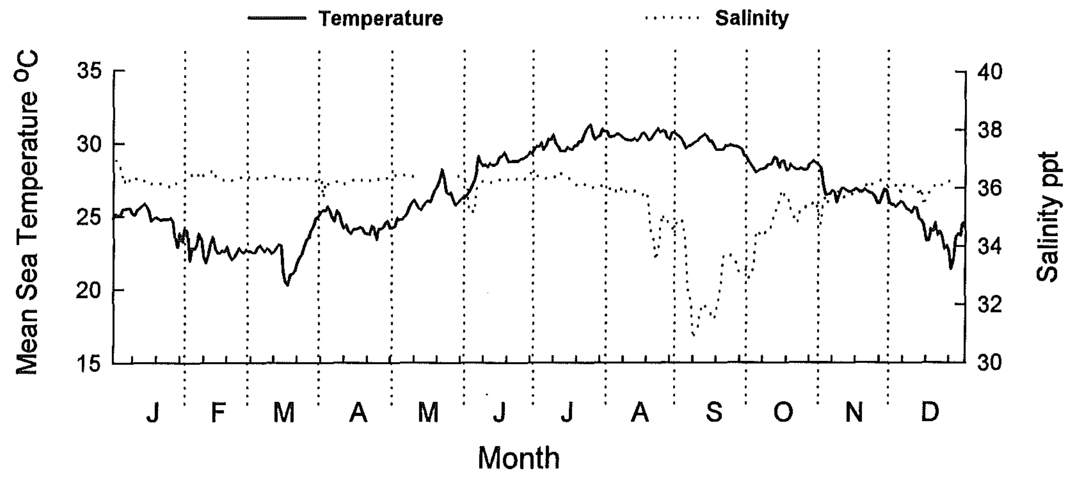

Fig. 4. Daily mean sea temperature (C) and salinity (ppt) near Channel Five of the middle Florida Keys from January to December 1993.

more consistent onshore component than during winter. Net currents during winter in Hawk Channel flowed south (offshore) toward the Atlantic Ocean on 86% of the nights analyzed and typically had a western alongshelf component of motion (Fig. 3).

Average daily water temperatures ranged from a high of 31.2 C in July to a low of 20.3 C in March. Average daily salinities usually ranged between 35.0 ppt and 37.0 ppt during all months except late August and September, when salinities as low as 30.8 ppt were recorded (Fig. 4). Low salinities in August and September were probably caused by the extensive summer flooding of the Mississippi River during 1993 (D. Forcucci, NOAA/AOML/OCD, pers. comm.).

TABLE 1. Leptocephali and glass eels collected in Channel Five of the middle Florida Keys. Net 1 was fished on 82 nights from January to May 1993, and net 2 was fished on 82 nights from January to May 1993, and net 2 was fished on 160 nights from January to December 1993.

Species	Net 1	Net 2
Leptocephalus larvae		
Myrophis punctatus	766	1,720
Ahlia egmontis	69	84
Ophichthus gomesi	0	69
Elops saurus	0	15
Elops sp.	14	16
Gymnothorax spp.	10	23
Rynchoconger flavis	4	8
Megalops atlanticus	0	5
Albula vulpes	5	1
Myrophis platyrhynchus	0	2
Net 1 and net 2 total	2,811	
Glass eels		
Myrophis punctatus	146	84
Ahlia egmontis	18	16
Net 1 and Net 2 Total	264	
Total Elopmorpha larvae	3,075	

Leptocephalus abundance.—Elopomorph fishes made up 9% of the 34,686 larval fishes collected in Channel Five. We caught 2,811 leptocephali representing 10 taxa (Table 1). Net 2, which was fished the entire 12 mo, caught 69% of these leptocephali. We collected 264 ophichthid glass eels, 230 *M. punctatus,* and 34 *Ahlia egmontis* in both nets combined.

The majority of elopomorph recruitment occurred during the winter and spring. The speckled worm eel, *M. punctatus* (Ophichthidae), was the most abundant species collected and made up 89% of all leptocephali collected in net 2. These leptocephali recruited during winter (Fig. 5), and the greatest catches (>150 larvae/night) were made in December and January. *Myrophis punctatus* glass eels (n = 230) were also numerous, with peak abundance in March (Fig. 6). Another ophichthid, the key worm eel (*A. egmontis*), was the second most abundant species collected (Table 1). Leptocephali of this species recruited from November to May (Fig. 5), and glass eels were most abundant in April (Fig. 6).

Winter recruitment was also observed for ladyfish (*Elops* spp.), which were present in small numbers (n = 31) from November to May (Table 1). *Elops* larvae included two species, *Elops*

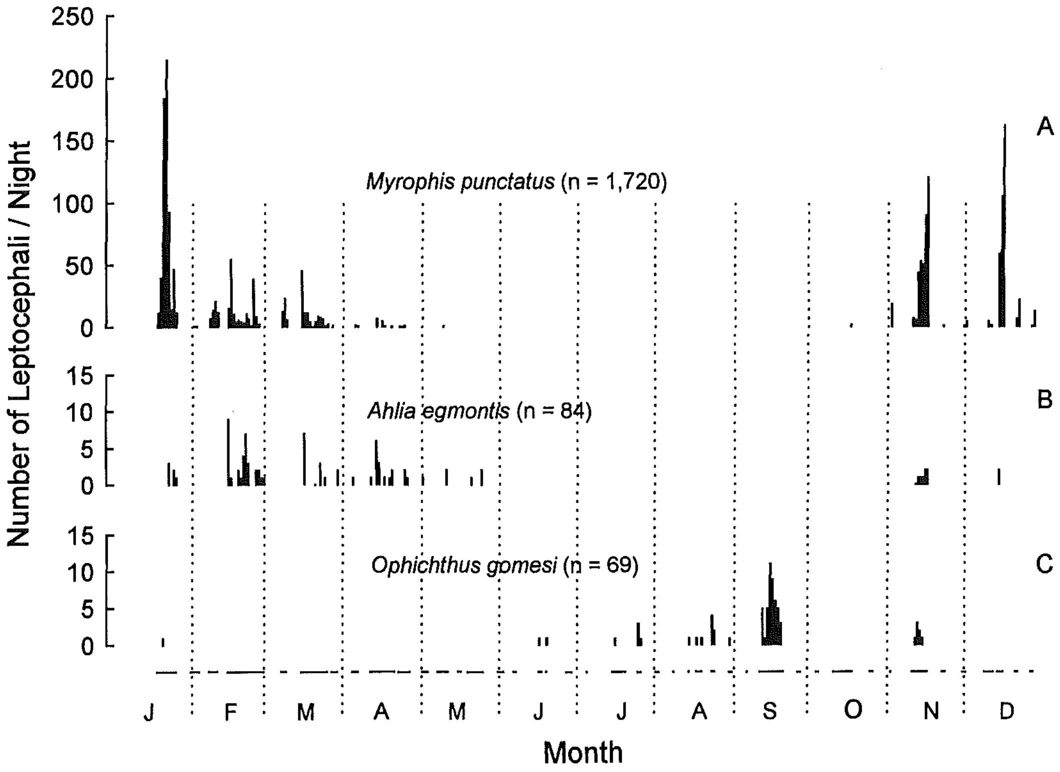

Fig. 5. Leptocephali catch rates of (A) *Myrophis punctatus,* (B) *Ahlia egmontis,* and (C) *Ophichthus gomesi* in Channel Five of the middle Florida Keys. The broken line on the x-axis depicts the nights sampled from January through December 1993. Leptocephali catch rates are for net 2 only.

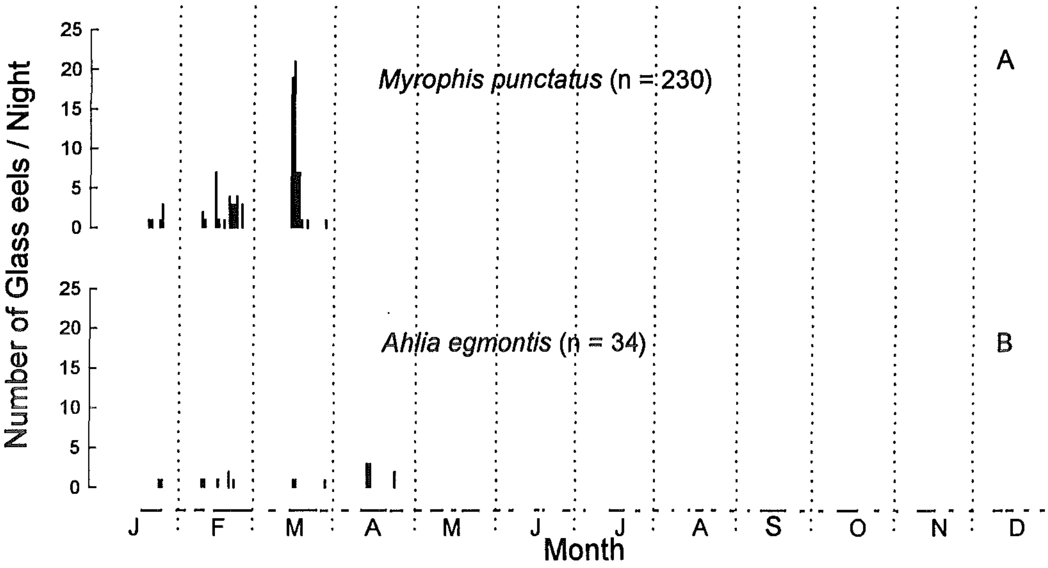

Fig. 6. Seasonal abundance of glass eels (A) *Myrophis punctatus* and (B) *Ahlia egmontis.* The broken line on the x-axis depicts the nights sampled from January through December 1993 in Channel Five of the middle Florida Keys. Glass eel catch rates are for both nets 1 and 2.

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saurus (November–December, n = 15) and an undescribed *Elops* species (November–March, n = 16) (Smith, 1989). Recruitment of *Elops* larvae was sporadic, and no more than four larvae were collected per night.

Only 23 moray eel (*Gymnothorax* spp.) leptocephalus larvae were captured during the winter (Table 1). These *Gymnothorax* leptocephali are in the *Gymnothorax ocellatus* complex but cannot yet be identified to species (Smith, 1989). The complex is made up of *G. ocellatus, G. saxicola,* and *G. nigromarginatus.*

Several elopomorph species recruited into Florida Bay during the summer. The shrimp eel (*Ophichthus gomesi,* Ophichthidae) recruited from June to November (n = 69) and was most abundant during September (Fig. 5). A few tarpon (*Megalops atlanticus,* n = 5) and a bonefish (*A. vulpes,* n = 1) were also collected during the summer.

Recruitment of M. punctatus leptocephali.—Metamorphic *M. punctatus* leptocephali were the only larvae collected in sufficient numbers for us to statistically analyze the recruitment patterns and associations with environmental parameters. The number of larvae that moved through the channel had a significant positive association with the number of hours of dark (moonless) flood tide (G-test, $P < 0.001$; Table 2; Fig. 7).

Large pulses of larvae were also associated with strong onshore winds (>4m/sec) (G-test, $P < 0.001$; Table 2; Fig. 7). These strong onshore winds occurred on 25.7% of the nights sampled, and 52.0% of the *M. punctatus* were collected on these nights (Table 2). Strong alongshore winds from the east, net offshore current flow, and reversals in the usual alongshore current flow also showed positive associations with the influx of larvae (G-test, $P < 0.001$; Table 2). The reversals in alongshore current flow (flowing to the east) in Hawk Channel occurred on only 10.6% of the sampling nights, but 22.0% of the catch of *M. punctatus* (Table 2) was collected on those nights.

TABLE 2. The relationship between environmental parameters and the number of *Myrophis punctatus* leptocephali collected. The percentage of nights sampled is the expected percentage of larvae to be collected. The percentage of *M. punctatus* collected is the observed percentage of larvae collected.

	% Nights sampled	% *M. punctatus* collected
Hours of dark flood tide		
0–2	34.3	14.8
2–4	28.6	30.4
4–6[a]	37.1	54.8
Across-shelf winds		
From the south >4 m/sec[a]	25.7	52.2
From the south 0–4 m/sec	28.6	24.1
From the north >4 m/sec	20.0	18.1
From the north 0–4 m/sec	25.7	5.6
Alongshelf winds		
From the east >4 m/sec[a]	50.0	65.4
From the east 0–4 m/sec	31.4	21.3
From the west >4 m/sec	7.2	10.8
From the west 0–4 m/sec	11.4	2.5
Across-shore displacement		
To the north	36.6	18.2
To the south[a]	63.4	81.8
Along-shore displacement		
To the east[a]	10.6	22.0
To the west	89.4	78.0

[a] Denotes which category is significantly associated with high catch rates.

DISCUSSION

Leptocephalus larvae were an abundant component of the ichthyoplankton moving through Channel Five in the Florida Keys. Most of the leptocephalus larvae we collected in our study area were ophichthid eels, whereas a more diverse assemblage of leptocephali were collected in Bahamian collections (Drass, 1992; Mojica et al., 1995). Although *M. punctatus* was abundant in the Bahamas, additional species, including congrid eels and *Albula* larvae, were also abundant (Drass, 1992; Mojica et al. 1995). These species have been reported from the pelagic habitat off Florida (Smith, 1989), and their absence from our collections as leptocephali suggests that they may settle on the bottom in deep water or find suitable juvenile habitat in the 9 km between the offshore edge of the reef tract and Channel Five. The region between the reef tract and Channel Five is characterized by expansive seagrass flats (*Thalassia testudinum*), sand flats, patch reefs, and large reef structures where leptocephali could settle. In the Bahamian studies, however, larvae were collected after moving across only a very narrow shelf (1 km), so they had little opportunity for settlement.

Most of the leptocephali collected in Channel Five were species that use Florida Bay as juvenile or adult habitat. The soft substrate of Florida Bay provides ideal habitat for the burrowing ophichthid eels that made up 97% of the leptocephali caught. Surprisingly few bone-

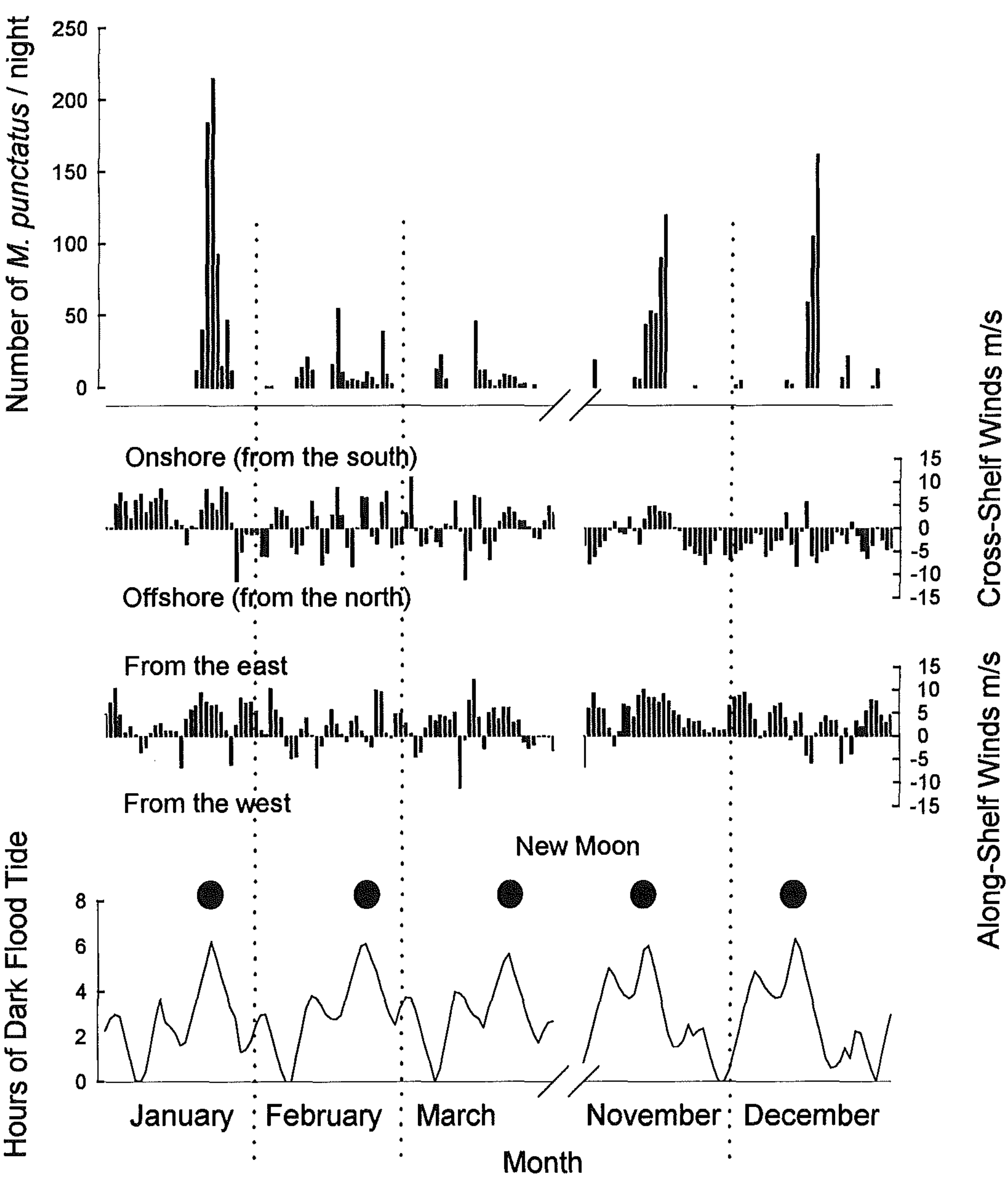

Fig. 7. Winter catch rates of *Myrophis punctatus* and significantly associated environmental parameters: cross-shelf and alongshelf winds and hours of dark flood tide.

fish (n = 6) and tarpon (n = 5) were collected despite large adult populations in the waters of the Florida Keys and Florida Bay. The scarcity of bonefish and tarpon in our collections suggests either that larvae enter the bay from other areas or that these species do not use Florida Bay as a primary nursery area. It is also possible that recruitment of these species through Channel Five is episodic and occurred on nights that were not sampled.

Recruitment of *M. punctatus* appeared to be associated with periods of dark flood tide, principally around the new moon. This pattern of influx was similar to the recruitment patterns reported for other fish species (Shenker et al., 1993; Thorrold et al., 1994b, 1994c; Mojica et al., 1995). Shenker et al. (1993) found that larvae of many fishes, including leptocephali, recruited on nights with 4–6 hr of dark flood tide, regardless of lunar phase. Larval influx during darkness could be mediated by larval behavior, with recruitment occurring during times of low light to minimize predation while settling (Shenker et al., 1993).

Recruitment pulses associated with the new moon could also occur for other reasons. The time of recruitment may reflect a cyclical spawning pattern, followed by a fixed larval duration that controls the time of recruitment. Spawning in many species (e.g., bicolor damselfish [*Stegastes partitus*], and tarpon [*M. atlanticus*]) is associated with lunar phase (Robertson et al., 1988; Crabtree, 1995), and this could result in pulses of larvae corresponding to particular spawning events. We could not evaluate the role of spawning rhythms on the recruitment of the eel species we captured because their reproductive biology is too poorly known.

The influx of *M. punctatus* in Channel Five was greatest during periods when strong onshore winds coincided with the new moon. The combination of winds and moon phase possibly increased the water flowing through the channel and bolstered larval catches. Alongshelf winds from the southeast also contributed to transport of *M. punctatus.* These alongshelf winds, blowing with the normal current flow of Hawk Channel, result in onshore Ekman drift of the surface layer and could drive larvae in surface waters of Hawk Channel toward Florida Bay. Lee et al. (1992) examined the mechanisms for transport of fish (Lutjanidae, Serranidae) and crustacean (Scyllaridae) larvae in the Florida Keys and found patterns similar to those described in our study.

An influx of larvae was also associated with reversals in the alongshore current flow. Larvae moving onshore on these nights may have been concentrated along the 8-km shoreline of Long Key prior to their movement through Channel Five—the first available inlet. Conversely, normal flow toward the west would have permitted larval entry through the many closely spaced inlets upcurrent from Channel Five. Another possible explanation is that the larval densities on these nights were bolstered because of lunar phase or some other environmental condition correlated with increased catches.

The vertical distribution of larvae in the 3-m-deep Channel Five was not studied; the abundance of leptocephali and other larvae in the upper 1 m of the water column suggests that larvae use the surface layer for cross-shelf transport toward nursery areas in Florida Bay. Shenker et al. (1993) and Thorrold et al. (1994a, 1994b, 1994c) found larval densities to be greatest near the surface when they used moored channel nets to examine the patterns of abundance of settlement-stage Nassau groupers and other larvae, including leptocephali, passing through channels in the Bahamas. Dufour and Gazlin (1993) used moored plankton nets to sample ichthyoplankton in French Polynesia and also found larval densities to be greatest near the surface.

The number of leptocephali collected in the present study suggests that large numbers of adult eels may exist in Keys waters. These cryptic predators are poorly understood but may have a significant effect on the survival of newly recruited fishes and on the trophic structure of Keys ichthyoplankton assemblages.

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