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ABSTRACT

To examine the role of cyclic environmental parameters and stochastic hydrodynamic events on the delivery of fish larvae to shallow coral reefs along a major western boundary current, a series of light traps was deployed over shallow coral reefs along the upper Florida Keys every other night for six months from May-October of 2002 and 2003. Wind speed, current velocity, and water temperature were measured concurrently. In total, 27,649 larval fishes from 55 families, encompassing pelagic, mesopelagic, seagrass and reef species, were collected during the two year time series. Besides small silvery fishes in the families *Clupeidae, Engraulidae,* and *Atherinidae*, the collections were dominated by the families *Pomacentridae, Chaenopsidae, Tripterygiidae*, *Gerreidae, Labrisomidae, Opistognathidae, Scaridae, Labridae, Scorpaenidae, Lutjanidae, Monocanthidae,* and *Sphyraenidae*. The temporal nature of larval delivery in the study area appears both cyclic and episodic. Physical data indicated that 2 - 3 mesoscale eddies associated with the Tortugas Gyre passed through the study area each year, each with a residence time of several days. Such eddies caused a weakening or reversal of the mean northeast flow. The relative influence of these mesoscale features was taxon specific. Results from this study will improve our understanding of the dynamics of larval fish supply and how it is affected by physical environmental factors.

KEY WORDS: Larval fish, recruitment, Florida Keys

Patrones y procesos de la oferta de larvas de peces en los arrecifes de los cayos superiores de la Florida

Para examinar el papel de parámetros medioambientales cíclicos y de eventos hidrodinámicos estocásticos en la distribución de larvas de peces en arrecifes coralinos someros en cercanías a una corriente importante, se instalaron una serie de trampas de luz a lo largo de los cayos superiores de la Florida cada noche de por medio por un período de seis meses, de mayo a octubre del 2002 y del 2003. Al mismo tiempo se midieron la velocidad del viento y la temperatura. Durante el período de muestreo se recogieron un total de 27 649 larvas de peces pertenecientes a 55 familias, representando especies pelágicas, mesopelágicas, de pastos marinos, y arrecifales. Además de sardinas de las familias *Clupeideae, Engraulidae*, y *Atherinidae*, las colecciones estuvieron dominadas por las familias *Pomacentridae, Chaenopsidae*,

Tripterygiidae, *Gerreidae, Labrisomidae, Opistognathidae, Scaridae, Labridae, Scorpaenidae, Lutjanidae, Monocanthidae, y Sphyraenidae*. El carácter temporal de la entrega de larvas en el área de estudio parece ser tanto cíclica como episódica. La información física indica que entre 2–3 eddies asociados con el 'Tortugas Gyre' pasan por el área de estudio anualmente, y se quedan en la zona por varios días. Estos eddies ocasionaron una disminución, o una inversión de la corriente de flujo del noreste. Se encontró que la influencia relativa de estos parámetros de mesoescala fue específica para cada taxa. Se espera que los resultados de este estudio mejoren nuestro entendimiento de la dinámica que controla la oferta de larvas de peces de arrecife y cómo está afectada por los parámetros medioambientales.

PALABRAS CLAVES: Peces en arrecifes coralinos, larvas, cayos superiores de la Florida

INTRODUCTION

The coral reefs of the Florida Keys are located on the western edge of the Florida Current (FC), a major western boundary current with predominantly northeasterly flow. Replenishment processes to the fish populations on these reefs are important due to high natural mortality and recreational fishing pressure. Although the supply of settlement stage fish larvae is a prerequisite of replenishment, very little is known about temporal patterns of larval supply.

The supply of larvae to coral reefs is variable over time and strongly influenced by the physical environment. Cyclic processes such as lunar phase and tidal amplitude may act as cues for settlement while less predictable hydrodynamic variability may affect the delivery of larvae to suitable habitat (Dufour 1991, Thorrold et al. 1994, Sponaugle and Cowen 1996).

Although the FC flows consistently to the northeast, there is considerable variability in flow along its northwestern front where the coral reefs of the Florida Keys are situated. Mesoscale (> 50 km) recirculation features (Tortugas eddies), originating as meanders of the eastern leg of the Loop Current, propagate along this front causing a weakening or reversal of the northeast flow along the shelf. It has been hypothesized that these features enhance delivery of fish larvae to the Florida Keys (Lee and Williams 1999). These eddies are considerably elongated and sheared apart by the time they reach the eastern Straits of Florida and the reefs of the upper Florida Keys. Smaller, faster moving, submesoscale (< 50 km) frontal eddies cause similar current reversals on shorter time scales.

The focus of this study was to measure the effect of cyclic environmental processes and episodic current reversals associated with the Tortugas gyre on the temporal patterns of larval fish supply to the reefs of the upper Florida Keys. The null hypothesis was that larval fish supply to the reefs of the upper Florida Keys is temporally random.

MATERIALS AND METHODS

Light traps modified from Sponaugle and Cowen (1996) were used to measure the temporal pattern of larval fish supply. The design consisted of a cylinder of Nitex netting with three funnel-shaped openings surrounding a submersible fluorescent light. Weather permitting, three replicate traps were deployed on French Reef, Key Largo every other night for two six-month periods (May-October, 2002 and 2003). Traps were attached to Florida Keys National Marine Sanctuary mooring buoys at sunset and retrieved at dawn. Samples were preserved in 95% ethanol for later sorting. Fish larvae were removed and identified to the lowest taxonomic level possible.

Wind and tide data were obtained from the NOAA C-MAN Molasses Reef tower located approximately two km southwest of the study site. Current flow was monitored by two acoustic Doppler current meters fixed to subsurface mooring at 21 and 4 meters depth approximately 4 km northeast of the study site (T. Lee, RSMAS, University of Miami). Prior to analysis, the raw current meter data were broken into V-alongshore and U-cross-shelf components, rotated to standard oceanographic convention, filtered with a low pass 40 hour filter to remove high frequency variability, and regressed against wind data to remove wind induced water flow. Ocean color satellite imagery was provided by the Institute for Marine Remote Sensing at the University of South Florida.

In order to examine possible cycling in the biological data, larvae of all fish taxa (excluding silvery bait fishes of the families *Clupeidae, Atherinidae*, and *Engraulidae*) were grouped together and the mean number of fish larvae per trap per night sampled was calculated. The Autocorrelation Function (ACF), was applied to these data to determine the lag at which the data cycled in time. The entire twelve month time series was then collapsed into a single 30 day lunar cycle with day 1 corresponding to the new moon and day 15 corresponding to the full moon. Raleigh circular statistics were then used to determine if separate taxa were randomly distributed over the lunar cycle. If this test indicated that a taxon was non-randomly distributed over the lunar cycle, the mean day about which the data were centered was calculated. Only taxa in which more than 100 individuals were caught were analyzed in this manner. These were *Stegastes partitus (Pomacentridae), Pomacentridae* (excluding *S. partitus*), *Chaenopsidae*, *Tripterygiidae*, *Gerreidae, Labrisomidae, Opistognathidae, Sparisoma spp. (Scaridae), Labridae, Scorpaenidae, Lutjanidae, Monocanthidae,* and *Sphyraenidae.* Because these thirteen taxa comprised almost three quarters of the total number of fish larvae captured (excluding silvery bait fishes), they were considered to be representative of the entire data set. Bray-Curtis cluster analyses were also carried out with these twelve taxa. Data were separated by year and transformed into proportions of the total number of each taxon caught in order to prevent clustering due to overall abundance. Any cycling was then removed from the data set by fitting a sin wave (corresponding to phase of the moon) to the data and obtaining the residuals. The residuals reflected episodic variability that could then be compared to episodic physical features such as passage of mesoscale eddies.

Current meter data as well as ocean color satellite imagery were carefully reviewed to determine periods when mesoscale eddies passed by the study site.

These periods were then compared with the biological data to examine the effects of mesoscale eddies on the supply of fish larvae to the study site.

RESULTS AND DISCUSSION

In total, 154 nights were sampled over the two six-month periods. 496 samples were collected on French Reef yielding 7,791 larval fishes from 55 different families (silvery bait fishes excluded).

The ACF revealed that larval supply of all fish taxa collected was cycling at a lag of approximately 30 days and in synchrony with the lunar/tidal amplitude cycle. Raleigh tests determined that all taxa combined as well as the twelve most abundant taxa separately were non-randomly distributed over the lunar cycle at the $\alpha = .05$ level. All fish combined were centered on a mean lunar day of 27.1 and the mean lunar days about which separate taxa were centered ranged from 24.1 and 1.1, between the third quarter and new moons. The multi-species cyclic nature of these data suggests that the lunar/tidal amplitude cycle is a common cue for a majority of fish larvae captured in the traps. The number of dark hours (hours when the moon is visible over the horizon), as well as the percentage of the moon illuminated, are decreasing during this period and reach a minimum at the new moon. Inversely, the tidal amplitude is increasing to a peak at the new moon during this time. The tidal amplitude and lunar cycle are in phase in the study area and teasing apart the influence of these two cycles is difficult. Because of the large range of mean lunar days for separate taxa, it is likely that both cycles are important and the degree to which each influences larval supply varies among different families.

Examination of current meter data as well as ocean color imagery revealed that three mesoscale eddies passed by the study site during each six month sampling period. Comparison of the residuals (lunar/tidal amplitude cycling removed) of all fish larvae combined and periods where mesoscale eddies passed by revealed that the eddies increased variability in the data when present or up to a week after their passage. The first eddy in 2002 and the first two in 2003 enhanced larval supply to the study site. The remaining three eddies appeared to disrupt larval supply. Whether eddy passage increased or decreased larval supply may depend on when during the lunar cycle eddies were present. Full moon periods consistently had very low larval supply whether or not an eddy passed. Larval supply increased when eddies were present during the period encompassing the third quarter and new moons.

Cluster analyses indicated that the where the influence of the mesoscale eddies was positive, it was also taxon-specific. Because all twelve of the most abundant taxa shared a similar cyclic pattern, the cluster analysis created groups largely due to episodic variability in the data. Three different groups of larvae clustered according to their presence during the three eddies that enhanced larval supply. There was no obvious clustering related to reproductive strategy. The fact that different families were affected differentially by each eddy may simply reflect differential presence in nearshore waters during the eddy's propagation along the reefs.

In conclusion, the supply of fish larvae to the reefs of the upper Florida Keys follows a predictable cyclic temporal pattern which is closely linked to

variation in the lunar/tidal amplitude cycles. However, this cycle may be either disrupted or enhanced by the episodic passage of mesoscale frontal eddies.

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