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Gag grouper larvae pathways on the West Florida Shelf

Robert H. Weisberg *, Lianyuan Zheng, Ernst Peebles

College of Marine Science, University of South Florida, St. Petersburg, FL 33701, United States

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ABSTRACT

A numerical circulation model, quantitatively assessed against in situ observations, is used to describe the circulation on the West Florida Continental Shelf during spring 2007 when pre-settlement gag (*Mycteroperca microlepis*) were present in the surf zone near Tampa Bay, Florida. The pre-settlement fish were found to be isotopically distinct from settled juveniles in the area, which is consistent with recent arrival at near shore nursery habitats from offshore spawning grounds. Simulated particle trajectories are employed to test hypotheses relating to either a surface or a near-bottom route of across-shelf transport. The surface-route hypothesis is rejected, whereas the bottom-route hypothesis is found to be consistent with the location of pre-settlement fish and their co-occurrence with macroalgae of offshore, hard-bottom origin. We conclude that gag larvae are transported to the near shore via the bottom Ekman layer and that such transport is facilitated by remote forcing associated with Gulf of Mexico Loop Current interactions with the shelf slope near the Dry Tortugas. Being that such remote forcing occurs inter-annually and not always in phase with the preferred spawning months (late winter through early spring), gag recruitment success should similarly vary with year and location.

1. Introduction

1.1. Motivation

Gag (*Mycteroperca microlepis*) support important recreational and commercial fisheries in the low-latitude continental shelf waters of the Western Atlantic, where they are known to spawn offshore and to settle near shore, at which time they develop heavy pigmentation to facilitate cryptic behavior within seagrass meadows and other structured, post-settlement habitats (Keener et al., 1988; Levin and Hay, 2003; Casey et al., 2007).

According to Fitzhugh et al. (2005) and papers cited therein, gag in the eastern Gulf of Mexico belong to a single population (see also Jue, 2006) that spawns from late winter to early spring at hard-bottom habitats between about the 50 m isobath and the shelf break. Early stage *Mycteroperca* larvae have been collected from surface waters near the shelf break (Marancik et al., 2012), and heavily pigmented (settled) juveniles are abundant enough within shallow, polyhaline near shore waters to be surveyed routinely (Casey et al., 2007; Switzer et al., 2012). Otoliths indicate that the time between spawning and settlement varies from roughly 30–50 days, and juvenile densities (juveniles caught per area sampled) tend to be the highest along the coast from Tampa Bay to Charlotte Harbor, as compared with locations farther north and south, although there is substantial inter-annual and geographic variability in juvenile density (Fitzhugh et al., 2005; Switzer et al., 2012).

It has been speculated that larval movement to near shore settlement habitat occurs in surface waters (e.g., Heppell et al., 2006; Adamski et al., 2012). However, Fitzhugh et al. (2005) found that the temporal and geographic trends in the mean fertilization and settlement dates of juvenile gag do not agree with seasonal changes in wind-driven surface currents, and thus suggested further evaluation of across-shelf transport modes using a three-dimensional circulation model.

1.2. Local and deep ocean influences on WFS circulation and upwelling

The circulation on the West Florida Continental Shelf (WFS) is known to be upwelling-favorable on long-term average (Weisberg et al., 2009), and the seasonal variations about the long-term average tend to be upwelling-favorable in fall to spring months and downwelling-favorable in summer months (Liu and Weisberg, 2012). Thus, during the interval when gag larvae tend to be en route to the near shore, the surface currents tend to have an offshore-directed component, whereas the near-bottom currents tend to have an onshore-directed component, which is consistent with the lack of evidence for a surface transport route as noted by Fitzhugh et al. (2005). In addition to the effects of local wind on driving these long-term and seasonal means, interactions between the adjacent Gulf of Mexico Loop Current and the shelf slope may also impact larval transport.

* Corresponding author.

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The Loop Current, a circulation feature of the deep ocean, does not directly override the WFS. Instead, it may indirectly perturb the WFS circulation through its shelf–slope interactions (e.g., Hetland et al., 1999). Two highly anomalous upwelling years, 1998 and 2010, provide cases in point (Weisberg and He, 2003; Weisberg et al., 2014a, 2014b). The Loop Current in both of these years contacted the shelf slope in the vicinity of the Dry Tortugas in the south. The significance of this derives from the Dry Tortugas being the western terminus of the Florida Keys chain, such that shallow WFS isobaths must wrap around the Dry Tortugas. According to continental shelf wave dynamics (e.g., Gill, 1982), pressure perturbations, when contacting sloping bottom topography, tend to propagate with the shallower isobaths to the right, or from south to north along the WFS. This can result in an across-shelf pressure gradient force and an associated along-shelf (southward directed) geostrophic current extending across the entire WFS when the Loop Current imposes a high pressure perturbation near the Dry Tortugas. A southward directed geostrophic current, in turn, must rotate to the left across the bottom Ekman layer, resulting in a shoreward directed (upwelling-favorable) velocity component near the bottom. The effects of these physical processes were readily observed in 1998 and 2010 as anomalously cold water found near shore in both of these years. Accompanying such cold water of deep ocean origin were elevated inorganic nutrient levels (e.g., see Weisberg and He (2003) and Walsh et al. (2003) for a description of the 1998 event), and an attendant consequence in 2010 was the absence of a *Karenia brevis* red tide bloom in that year (Weisberg et al., 2014a).

Whereas 1998 and 2010 exhibited anomalously intense and prolonged upwelling by such deep-ocean interactions, other years express shorter duration events that may also impact the across-shelf transport of material properties, including fish and invertebrate larvae. An example of one such year is 2007, when Loop Current interactions impacted the WFS circulation from the end of March through the middle of May, accentuating the upwelling circulation over that time interval. It was in 2007 that pre-settlement gag were present in the surf zone at Mullet Key located just north of the Tampa Bay mouth (Fig. 1).

1.3. Initial observation of pre-settlement recruitment

On 8-May-2005, 14 specimens of 15–19 mm standard length (SL) pre-settlement gag (translucent, lacking juvenile pigmentation) were dip-netted as they occupied drifting macroalgae in the surf zone of Mullet Key (Fig. 2), 2.1 km north of the principal entrance to Tampa Bay, Florida (Egmont Channel) and 2.7 km south of a secondary entrance (Bunces Pass). The specimens were collected from within clumps of drift algae that occurred over sandy substrate during a mid-morning flood tide under calm wind and surf conditions. Five fish were found in one clump of drifting *Codium isthmocladum* that was 15–20 cm in diameter, whereas most clumps of drifting *Gracilaria varrucosa* contained no fish. The relative catch rate among algal types was *Codium* $\gg$*Acanthophora spicifera* > *Gracilaria*, even though *Gracilaria* was the most abundant macroalga present. During spring 2007, shoreward-moving drift algae were again noted to be abundant at the 2005 Mullet Key site, so a second collection effort was carried out with the objective of isolating a recruitment event date that could be linked to physical oceanographic processes.

1.4. Overview

Given the background information and the documentation of a pulse of pre-settlement gag approaching landfall on a specific date (23–24-May-2007, as described herein), we address the issue of larval gag transport from offshore to near shore. We describe the circulation on the WFS over the first half of 2007 using a primitive equation, three-dimensional and density-dependent numerical circulation model simulation gauged against in situ observations. We then show results from particle trajectory simulations conducted both near the surface and near the bottom, rejecting the hypothesis (as did Fitzhugh et al., 2005) of a surface transport route, and demonstrating the compatibility between the observations of pre-settlement gag in the surf zone and what we advance as a near-bottom transport hypothesis. By expanding upon the pre-settlement gag observations in 2007 (and also in 2005), we offer isotopic and behavioral observations that support our hypothesis that gag larvae are transported from the offshore spawning regions to the near shore settlement region via the bottom Ekman layer.

2. Materials and methods

2.1. Detecting a recruitment event date

Following the 2005 event, substantial springtime accumulations of drift algae at Mullet Key were not observed again until 3-April-2007. As in 2005, the algal clumps were observed to be primarily moving shoreward near the bottom, rather than being suspended in the water column, and were accreting to wrack lines in the shallows at the beach. Starting 3-April, drift algae were sampled by dip-net from the beach and from a boat that traveled along the beach at the 2–3 m isobath. Once the first pre-settlement gag was encountered, inter-sampling intervals were shortened from 7–10 days to 1–3 days to improve temporal isolation of the recruitment event. The recruitment event was then resolved by six consecutive collections that spanned a combined 8 days. After the recruitment event subsided, the inter-sampling interval was returned to 7–10 days, producing a total of 15 collection efforts conducted between 0900 and 1230 EDT and ending on 12-June-2007.

Daily effort was represented as man-hours spent collecting and manually searching through drift algae, with catch represented as total individuals collected hr^{-1}. Daily effort ranged 1–2 h, averaging 1.7 h. Collected specimens were either preserved in 50% isopropanol or were kept alive for subsequent behavioral observation and isotopic analysis. Upon return to the lab, preserved specimens were measured to the nearest 0.1 mm using an ocular micrometer (standard length, SL), weighed to the nearest 0.01 g using a calibrated electronic balance, and were examined to obtain diagnostic anal-fin meristics. Identifications followed Johnson and Keener (1984), Keener et al. (1988), and Richards (2006).

2.2. Determination of fish origin – stable isotopes

Trunk sections (i.e., non-organ tissue) from four pre-settlement specimens (17.7–25.1 mm SL) collected 22–24-May-2007 were analyzed for bulk $\delta^{13}C$ and $\delta^{15}N$, and these values were compared to isotope values from muscle tissue of 52 larger gag (121–981 mm SL) collected from Mullet Key (trawl), nearby Egmont Key (trawl), and offshore waters west of these areas (long line deployments at 18–110 m depth). The four pre-settlement specimens and 38 of the 52 larger gag samples were analyzed at the University of South Florida. These were dried at 50 °C and then powdered. Carbon and nitrogen samples (> 70 μg organic N) were loaded into tin boats and combusted at 1050 °C using a Carlo Erba 2500 Series I elemental analyzer. The isotopic ratios of the combustion products, CO_2 and N_2 gases, were measured sequentially using a continuous-flow inlet system on a Finnigan Mat Delta Plus XL stable-isotope mass spectrometer. Carbon (^{13}C:^{12}C) and nitrogen (^{15}N:^{14}N) isotope values are reported in conventional per-mil notation (‰)