Reef Fish in the Northern Gulf of Mexico and Decadal Circulation Patterns

Peces de Arrecife en el Norte del Golfo de México y los Patrones de Circulación Decenal

Poissons de Récif dans le Nord du Golfe du Mexique et les Régimes de Circulation Décennale

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ABSTRACT

In the northwest Gulf of Mexico, large energetic eddies spin off the intruding Loop Current and migrate westward along the continental slope region, causing sporadic exchanges of water between the nutrient rich shelf and the more oligotrophic deep basin. These exchanges enrich surface waters over the deep basin, enhancing the spawning grounds of Bluefin Tuna (*Thunnus thynnus*) and other important big game fish, but may be deleterious for retention of reef fish which spawn and settle as juveniles on the shelf. Many reef fish are broadcast spawners with eggs and larvae susceptible to entrainment in this large-scale, water exchange process. Subsequent dispersal over the deep basin reduces potential larval settlement success for species that have shallow water habitat requirements for post-larval stages, and ultimately may influence recruitment and population abundance. In this study we examine the effect on egg/larval dispersal from the Flower Gardens National Marine Sanctuaries (FGNMS), located toward the outer shelf in an area commonly impacted by the spin-off eddies. During the heavy spawning season (summer) between 2003 and 2014, eddy energy over the upper slope decreased substantially with concomitant egg/larvae retention on the continental shelf and weaker loss to the deep basin. Although retention for settlement in favorable FGNMS habitat (i.e. larvae contributed by local spawners) was increased, ability to broadcast larvae over broad areas was decreased and larval dispersal from dense (western Gulf of Mexico) to depauperate (eastern Gulf of Mexico) red snapper populations was diminished.

KEY WORDS: Larval dispersal, eddy energy, red snapper, National Marine Sanctuary, Gulf of Mexico

INTRODUCTION

The most dominant circulation features in the Gulf of Mexico (GOM) are the Loop Current (LC) and its large, energetic spin-off eddies (Leipper 1970, Elliott 1982, Vukovich 2007). The LC is a limb of the western boundary current in the North Atlantic. It intrudes northward into the GOM through the Yucatan Channel at core flow speeds in excess of 2 m/s before turning southward and exiting into the Straits of Florida. After a strong extension northward, the dynamically unstable LC at times turns back onto itself with the head breaking off into a spin-off eddy (Figure 1). After detachment, this eddy migrates west under the influence of the earth's rotation as it disintegrates, shedding smaller cyclonic and anticyclonic eddies around its periphery. If the westward migration path is at higher latitudes where it is bounded by the continental slope, interactions with shelf waters can occur (Ohlmann et al. 2001, Hanisko and Lyczkowski-Shultz 2003) with planktonic larvae pulled from the shelf region where they normally settle, into deep basin waters, which is likely to result in lower settlement success. This in turn would lead to a reduction in recruitment to the population.

The Flower Gardens National Marine Sanctuary (FGNMS; Figure 1) is composed of three ancient salt domes along the outer shelf where they are vulnerable to water exchanges with the deep basin. These domes consist of Stetson Bank, West Flower Gardens and East Flower Gardens. These banks rise to within ~17 m of the surface and support the northernmost living coral in the Gulf of Mexico as well as large aggregations of reef fish. Larval dispersal from the FGNMS has been previously examined and the large impact of LC eddies on dispersal has been noted (Lugo-Fernandez 1998; Ohlmann et al. 2001, Hanisko and Lyczkowski-Shultz 2003, Teague et al. 2013). Furthermore, using satellite altimetry and larval surveys, Lindo-Atichati et al. (2012) observed a tendency for the LC to vary in its interannual penetration northward, which can affect the latitude of the westward eddy migration path and eddy interactions with the shelf on a multi-year scale. In addition, they found that higher abundances of pelagic larvae were associated with the LC and its mesoscale features, demonstrating the potential for larvae to be incorporated and retained in these features.

In this study, we use currents from a data assimilative ocean model to track interannual larval dispersal from the FGNMS in relation to kinetic energy on the continental slope from the spin-off eddies. Satellite altimetry data assimilation has been an important part of improvements in operational models (e.g., Kantha and Clayson 2000) which describe ocean events in near real-time; satellite altimetry data assimilation phase-locks model runs to real ocean events, such as spin-off eddies, in space and time. This is especially necessary in describing the LC since it is considered to be dynamically unstable (Hurlbert and Thompson 1980) and eddy spin-off is not readily amenable to predictive modeling where timing with respect to seasonal spawn is important.

METHODS

Lagrangian Larvae Tracking

Archived currents from the HYbrid Coordinate Ocean Model (HYCOM; Bleck 2002) with 1/25° longitude/latitude grid spacing were used for both larval dispersal and eddy energy determination. HYCOM model runs from 2003 - 2014 provided a decadal scale to investigate climate variations on the process of dispersal by offshore eddies. Red snapper (*Lutjanus campechanus*) life history was used as a model for reef fish in the northern Gulf since they are abundant in the FGNMS and are of high economic value for GOM fisheries. Larvae are theoretically spawned in the model every six days from June through August (primary red snapper spawning season) and the associated parcels of water tracked for 30 days (red snapper planktonic larval duration: PLD). At the end of the PLD, larvae are ready to settle. If they are in water deeper than 400 m at this time, they are considered lost to the source area and to the general population even though a few could end in suitable habitat elsewhere in the Gulf (e.g., Hare et al. 2002, Johnson et al. 2012).

The parcel tracking algorithm provides a means to account for sub-grid scale turbulence (Dutkiewicz et al. 1993; Johnson et al. 2012). For each spawn, 10 parcels were launched. Nine parcels were tracked using the HYCOM current but at each step a small random displacement was added; one parcel was tracked without the turbulent addition. A number of different turbulence amplitudes and random displacement forms were tested with little difference on the observed parcel track. In consideration of these tests, we chose a simple form:

$$\delta u = 0.1 * S * P_u$$

where δu is a turbulent addition to the current component, S is the speed of the current and P_u is a standard normal random variable.

The cumulative effect of active vertical migration on red snapper larval dispersal is unclear. At-sea studies of vertical migration (Huebert et al. 2011) indicated that ontogenic sinking to greater depth, i.e., gradually moving deeper with growth and development, may be more likely than daily vertical migrations for Lutjanidae such as red snapper. In addition, the Lutjanidae larvae appeared to be concentrated in the upper 25 m of the water column but were distributed throughout this layer. In this study, we model a simple case in which currents are averaged, and larvae are distributed uniformly over the upper 30 m of the water column.

Eddy Energy

It is well understood that eddies interact with the continental shelf across the upper continental slope and shelf break; the mechanism by which this complex interaction takes place can be mathematically described (Ohlmann et al. 2001). In this study we simplified the problem by estimating the turbulent kinetic energy (TKE) available for interactions to occur. This allowed a simple criteria to compare with larvae lost from natal areas and avoids the difficulty of trying to determine coincidental larval availability and eddy interaction placement. HYCOM currents averaged over the upper 30 m (same as in larva tracking) were separated into mean and fluctuating components:

East component: $U = \bar{U} + U'$

North component: $V = \bar{V} + V'$

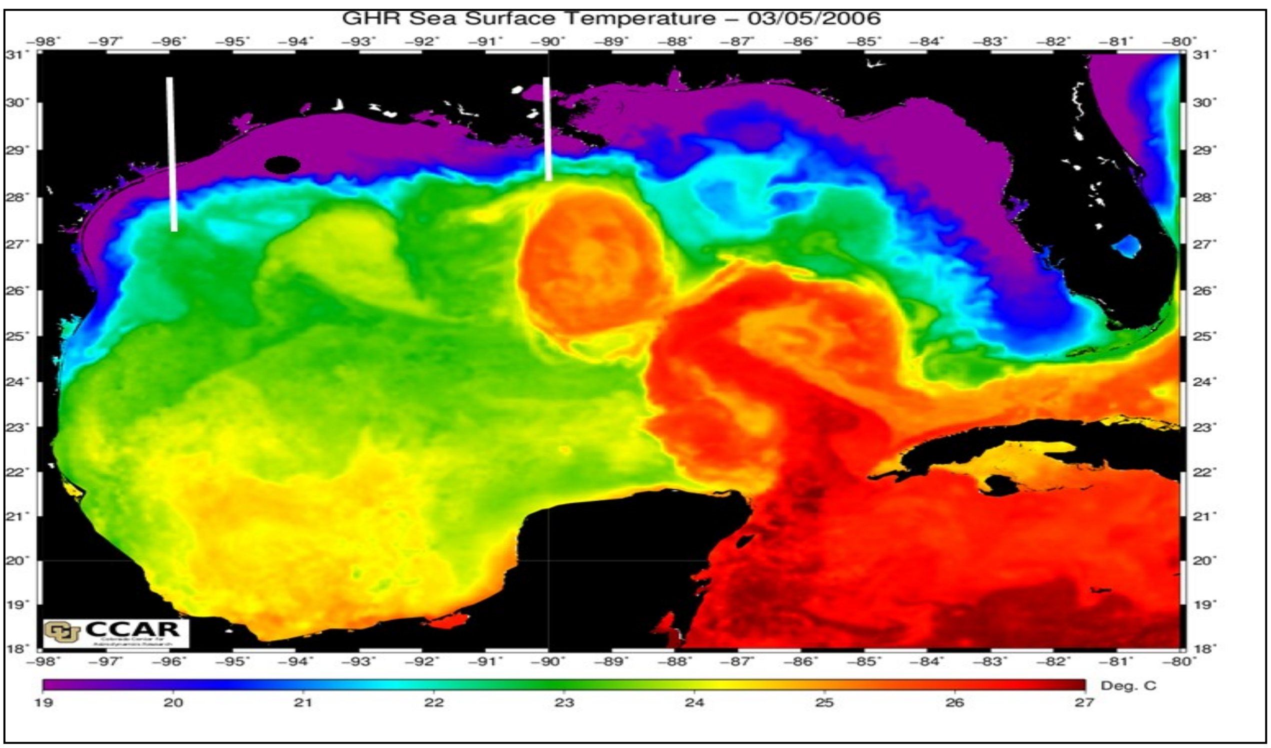

Figure 1. Thermal imagery of Loop Current with Spin-off eddy detaching. The solid white lines show boundaries of area of interest. Black dot shows FGNMS.

Where:

$$\bar{U} = \frac{1}{T}\int_0^T U dt$$

TKE $$= \frac{\rho}{2}\sum(U'^2 + V'^2 \quad \Delta x \Delta y \Delta z$$

ρ is water density and $\Delta x \Delta y \Delta z$ is area.

In practice, TKE is computed at each model grid point and both water density and area along with the factor of 2 are dropped as non-varying components. To compare with larvae lost to the deep basin by eddy interactions, TKE is summed over all grid points lying between the meridional boundaries in Figure 1 and between the 400 m and 1000 m isobaths of the upper continental slope. Due to satellite orbital variations over strong along-track geoidal changes (continental slope) and to tidal amplitudes over the shelf, altimetry is only accepted as valid for data assimilation (Ko and Wang 2014) in depths exceeding 400 m. In tests, we found little difference in larvae loss with the commonly accepted shelf break of 200 m depth for larval loss to the deep basin, and the 400 m criteria for altimetry. We used the 400 m isobath for both.

It should be noted that larval dispersal is calculated over the primary red snapper spawning season from June-August. TKE is also computed over the same summer time frame. This is important in that it avoids substantial TKE that would otherwise be included as a result of change-of-season wind stress and aids in focus on the large eddy contribution.

Florida Current Transport

The LC enters the GOM through the Yucatan Channel and exits through the Straits of Florida. By simple mass balance it is readily assumed that there is a long-term correspondence between the LC and the Florida Current (FC). FC transport has been measured since 1982 (Larsen 1992) by using the inductive voltage in a submarine cable running between Florida (Miami) and the Bahamas. In 2003, the cable was moved, but good quality signals have since been obtained and the measurements considered valid (see Acknowledgements). Here we are using FC transport measurements as a means of identifying decadal variations in strength of LC transport.

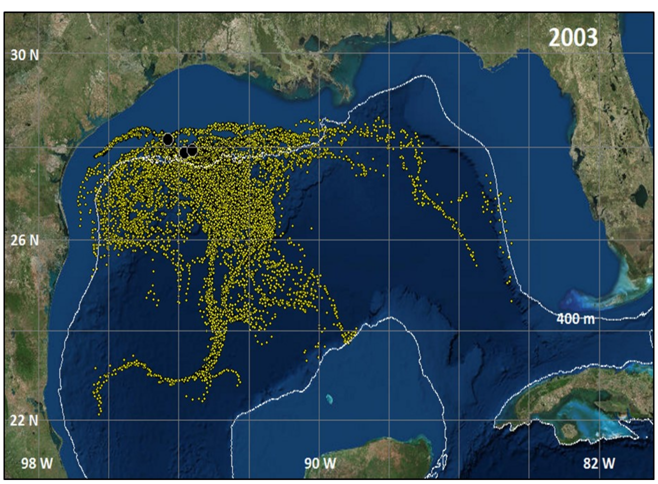

Figure 2. Larvae dispersal from FGNMS sites in 2003. Yellow dots are daily positions for the 30 day PLD. Individual larva outside the 400 m isobath (shown) at the end of the PLD are considered lost.

RESULTS

The highest offshore dispersal from the FGNMS occurred in 2003 (Figure 2). Dispersal offshore extended to the Campeche Banks in the south, to the southwest Florida shelf in the east and to the Texas/Mexico border (~ 26ºN) in the west. It should also be noted that dispersal of larvae shoreward to suitable habitat for juvenile red snapper (Gallaway et al 1999, Rooker et al. 2004, Gallaway et al 2011) was weak.

Comparing the dispersal of 2003 with TKE available for interactions between the continental shelf and the deep basin suggests that TKE is a simple approach to predict the impact of LC eddies on recruitment and, consequently, to better understand fluctuations in abundance of red snapper populations. The largest TKE was located along the east side of Campeche Bank and the far southwestern Florida shelf where direct interactions with the loop current were taking place. TKE during the summer of 2003 (Figure 3 left panel) was also high along the upper slope in the northwestern GOM where eddy interactions commonly take place. This matches the high larval dispersal that was calculated from the model in 2003. In contrast the TKE of 2013 in the same area (Figure 3 right panel) was considerably weaker, suggesting weak interaction with larvae from the FGNMS.

Figure 4 summarizes the core findings of this study showing:

i) Larvae dispersed in the model but ending their PLD in the deep basin,
ii) TKE available over the upper continental slope, and
iii) Current transport associated with strength of the LC.

At each of the three spawning locations, 160 model larvae were launched over the three month spawning season for a total of 480 each year. The number lost to the deep basin as a percentage of 480 total launched is plotted for each year between 2003 and 2014. In 2003, the percent of larvae lost to the deep basin (> 400 m) exceeded 75%, a remarkable percentage of the total summer model spawn. After 2003, the trend was downward, with the lowest point reached in 2012 (~15% lost). TKE over the upper slope during the same time frame also showed a downward slope, with ~ 50% reduction in available energy between 2003 and 2014. In the meantime, the FC transport was reduced by about 10%. This suggests that inflow in the GOM and northward penetration of the LC (Bulgakov and Meulenert-Pena 2003, Alvera-Azcárate et al. 2009) was also reduced, resulting in spin-off eddies that took a more southern pathway toward the western boundary of the GOM, in decreased interactions with the shelf and in decreased larval dispersal offshore.

DISCUSSION

Using the HYCOM model currents, larvae were tracked from three FGNMS spawning areas in the north-western GOM for an 11-year period. Although larval dispersal from the FGNMS has been studied and the effect of LC spin-off eddy interactions with shelf waters and its load of shelf spawned larvae has been duly noted, this study focused on the decadal scale variations in larvae loss to the deep basin resulting from these eddies. Life history of red snapper, with a primary summer spawning season and a PLD of 30 days, can be used as a surrogate for many reef fish. Loss to the deep basin was defined as the percent of larvae spawned at the FGNMS sites from June - August and ending the 30 day PLD in water depths greater than 400 m. This LC spin-off eddy effect could be responsible for episodic reductions in recruitment with subsequent decrease in the abundance of these reef fish populations.

In this study, we found a significant decadal scale downward trend in both dispersal and loss of red snapper larvae to the deep basin and in TKE related to spin-off eddy interactions with waters on the northern shelf. Although the trend favored retention of larvae in source habitats, dispersal to other suitable habitats in the GOM was diminished. Johnson et al. 2009 found that it was difficult for red snapper larvae in the high spawning areas of the western GOM to be transported in shelf currents to the more depauperate populated eastern GOM due to topographic features. This study indicated that, while it is possible for the big eddies to move larvae to the eastern GOM, the numbers are fairly low.

TKE is defined using departure from the mean current. Since we are interested in the impact of large eddies on the shelf, elimination of seasonal wind transitions can be important. The GOM has been defined as having two seasons (Cho et al. 1998): summer and non-summer. Our choice of the summer season as the averaging time scale reflected not only the primary red snapper spawning season, but also eliminated strong spring and fall wind transitions and their contributions to TKE.

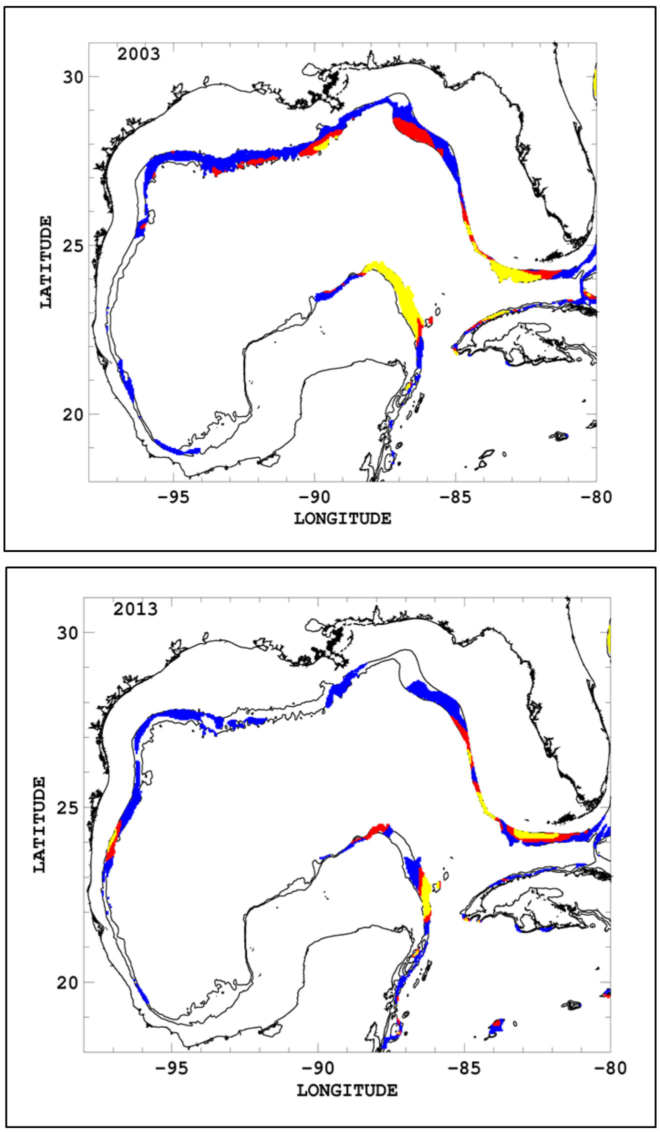

Figure 3. TKE between 400 m and 1000 m isobaths for 2003 (left) and 2013 (right).
Blue: $0.025\ m^2/s^2 \leq TKE < 0.050\ m^2/s^2$
Red: $0.050\ m^2/s^2 \leq TKE < 0.075\ m^2/s^2$
Yellow: $0.075\ m^2/s^2 \leq TKE$

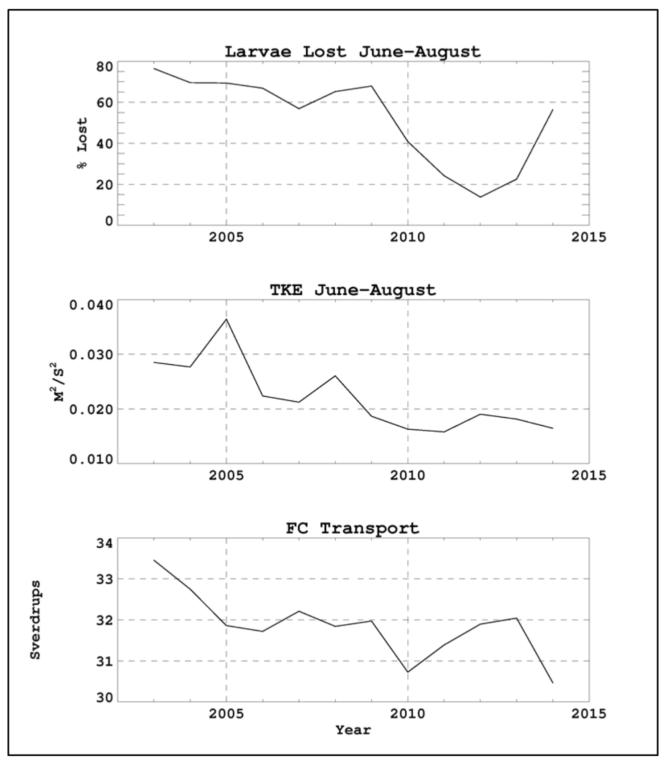

Figure 4. Upper: Annual % of larvae lost from FGNMS (ended PLD > 400 m depth).

Middle: Turbulent Kinetic Energy anomaly (Jun-Aug departure) over the upper continental slope

Lower: Annual Florida Current Transport from cable measurements.

Significant multidecadal changes in the GOM ecosystem have been noted (Karnauskas et al. 2015, Sanchez-Rubio 2011) and related to the Atlantic Multidecadal Oscillation (AMO) index, a measure of north Atlantic sea surface temperature. The AMO was further related to the Atlantic Meridional Overturning Circulation (AMOC; Liu et al. 2012), a limb of the global ocean conveyor belt, and its effects on inflow into the GOM noted. In this context, then, it is recognized that the AMO reached a broad peak in the time frame 1998 - 2010 and appears to be diminishing. Thus the decadal scale changes in larval dispersal to the deep basin and TKE over the continental slope as noted here, may be part of a multidecadal oscillation.

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