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Key Points:

- West Florida shelf water properties are strongly influenced by upwelling of deeper ocean water across the shelf break
- Protracted upwelling of deeper ocean water occurs interannually through boundary current interactions
- Such upwelling origins are the upper slope, generally above 150 m depth, although water renewal may be from depths down to around 300 m

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West Florida shelf upwelling: Origins and pathways

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Abstract Often described as oligotrophic, the west Florida continental shelf supports abundant fisheries, experiences blooms of the harmful alga, *Karenia brevis*, and exhibits subsurface chlorophyll maxima evident in shipboard and glider surveys. Renewal of inorganic nutrients by the upwelling of deeper ocean water onto the shelf may account for this, but what are the origins and pathways by which such new water may broach the shelf break and advance toward the shoreline? We address these questions via numerical model simulations of pseudo-Lagrangian, isopycnic water parcel trajectories. Focus is on 2010, when the west Florida shelf was subjected to an anomalously protracted period of upwelling caused by Gulf of Mexico Loop Current interactions with the shelf slope. Origins and pathways are determined by integrating trajectories over successive 45 day intervals, beginning from different locations along the shelf break and at various locations and depths along the shelf slope. Waters upwelling across the shelf break are found to originate from relatively shallow depths along the shelf slope. Even for the anomalous 2010 year, much of this upwelling occurs from about 150 m and above, although waters may broach the shelf break from 300 m depth, particularly in the Florida Panhandle. Such interannual renewal of west Florida shelf waters appears to have profound effects on west Florida shelf ecology.

1. Introduction

The West Florida Continental Shelf (WFS) is generally described as being oligotrophic [e.g., *Steidinger*, 1975; *Heil et al*., 2001; *Vargo et al*., 2008; *Dixon et al*., 2014]. Yet, it supports robust commercial and recreational fisheries [*NOAA-NMFS*, 2014], and it experiences interannual blooms of the harmful alga, *Karenia brevis* [e.g., *Heil et al*., 2014]. The hypothesis on the sequential development of a *K. brevis* bloom by *Walsh et al*. [2006] provides a nutrient-driven, primary productivity perspective under oligotrophic conditions, lending itself to the possibility that the development of a *K. brevis* bloom may be shut down by too much nutrient injection. Such appears to have been the case in 1998, a year of anomalous upwelling [*Weisberg and He*, 2003] when only a nominal *K. brevis* bloom occurred [*Walsh et al*., 2003]. Further evidence is provided by the anomalous upwelling conditions of 2010 when no *K. brevis* bloom was observed, which led *Weisberg et al*. [2014a] to conclude that the circulation physics and the organism biology each provide necessary conditions for bloom development, with neither alone being a sufficient condition. This conclusion found further support in a comparative study between the *K. brevis* blooms of 2012 and 2013 by *Weisberg et al*. [2016a].

Together with relatively low river inputs, oligotrophic conditions follow from the WFS being wide and gently sloping. Along with freshets, elevating nutrients in the vicinity of the nearshore, interannual injections of new inorganic nutrients are by anomalous upwelling conditions bringing water of deeper ocean origin across the shelf break. From historical eastern Gulf of Mexico temperature-nutrient relationships, it is known that inorganic nutrients begin to increase monotonically with depth for temperatures less than about 19°C [e.g. *Weisberg and He*, 2003] and this accounts for the relatively high nutrients observed on the WFS during the anomalous upwelling conditions of 1998 [*Walsh et al*., 2003]. Given that oligotrophic conditions may be overcome interannually by anomalous upwelling, questions remain pertaining to the origins and pathways of the nutrient-rich water when found on the WFS. This paper provides such a perspective by focusing on 2010, a year of anomalously strong and protracted upwelling.

2. The Anomalous WFS Circulation of 2010

2.1. Origin of the Anomalous Upwelling

The WFS coastal ocean circulation is driven by a combination of local (winds, rivers, surface buoyancy fluxes) and deep-ocean (Loop Current and eddy interactions with the shelf slope and tides) influences [e.g., *He and*

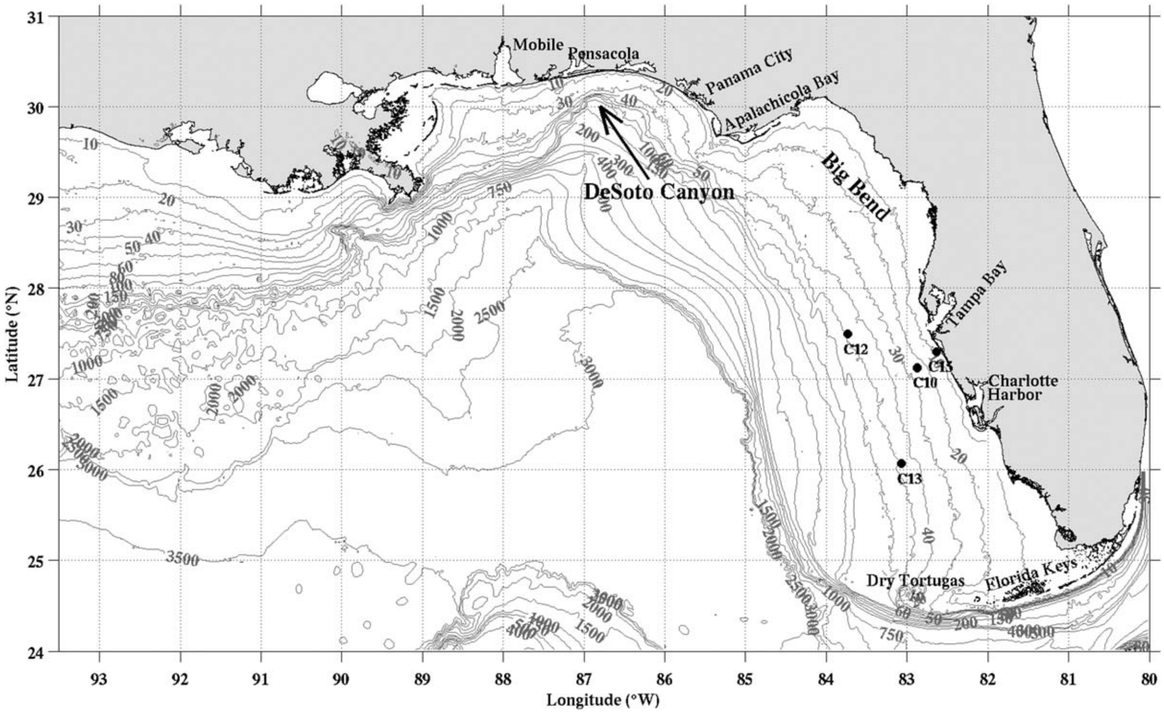

Figure 1. Isobath distributions for the northeast Gulf of Mexico, and the locations of moorings used for the observation and model simulation comparisons in Figure 3.

Weisberg, 2003; *Weisberg and He*, 2003; *Fan et al*., 2004]. How these manifested in 2010 is described by *Liu et al*. [2011a, 2016] and *Weisberg et al*. [2014a, 2016b]. In essence, after shedding an eddy in May 2010, the Loop Current retreated southward and contacted the shelf slope near the Dry Tortugas, a group of islets located at the southwest corner of the WFS (Figure 1). When this occurred, a relatively high pressure perturbation propagated northward, along the isobath contours with shallow water to the right (i.e., counterclockwise in the northern hemisphere, consistent with continental shelf wave dynamics) [e.g., *Gill*, 1982]. Unique about the Dry Tortugas is that, as the western terminus of the Florida Keys chain, isobaths shallower than around 25 m must wrap around the Dry Tortugas. Thus, and as first suggested by *Hetland et al*. [1999], by coming into contact with the shelf slope there, the Loop Current may impose a pressure gradient force across the entire width of the WFS, versus only over a distance equal to an internal Rossby radius of deformation [e.g., *Chapman and Brink*, 1987; *Kelly and Chapman*, 1988] if the contact occurs elsewhere [*He and Weisberg*, 2003; *Oey and Zhang*, 2004]. Thus the entire WFS in 2010 was set into an upwelling circulation state, with a geostrophic flow to the south and with the associated left hand turning across the bottom Ekman layer carrying upwelled fluid from the shelf break toward the coastline. This general state of upwelling then persisted throughout 2010 because the Loop Current remained contracted to the south and in contact with the shelf slope near the Dry Tortugas [e.g., *Liu et al*., 2011a; *Weisberg et al*., 2014a, 2016b].

2.2. Numerical Model Simulated Coastal Ocean Circulation

To account for both local and deep-ocean forcing, we nest the Finite Volume Coastal Ocean Model (FVCOM) [*Chen et al*., 2003] in the Hybrid Coordinate Ocean Model (HYCOM) [*Chassignet et al*., 2009] with eight tidal constituents added along the open boundary. A full description of this West Florida Coastal Ocean Model (WFCOM) construct, including a quantitative gauging of the model performance against in situ observations for calendar year 2007, is provided by *Zheng and Weisberg* [2012]. Modified from the original, WFCOM now nests into the Gulf of Mexico HYCOM and extends west of the Mississippi River Delta to include actual river inflows, versus climatology [*Weisberg et al*., 2014b]. For 2010 the Gulf of Mexico HYCOM excluded tides in its version 30.1 that we employed. Recent applications with quantitative comparisons between water column observations of velocity and temperature and model simulations for the entirety of 2010 are given by *Weisberg et al*. [2014a,2014b]) where it is shown (using glider transects and velocity time series from moored acoustic Doppler current profilers) that the effects of upwelling on water properties extended across the

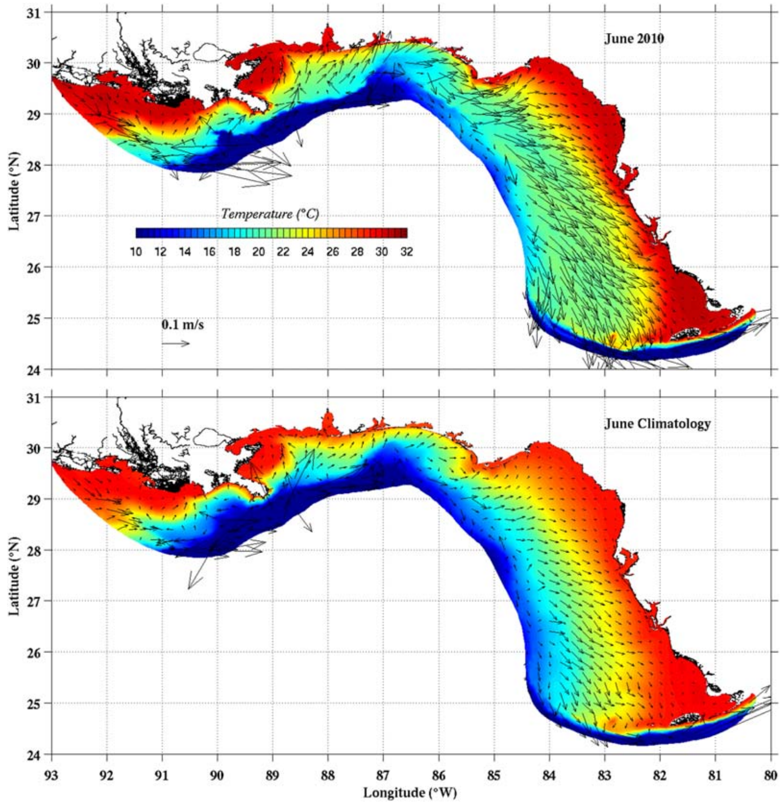

Figure 2. A comparison between the monthly averaged, near bottom horizontal velocity superimposed on potential temperature for the June 2010 WFCOM simulation and for the June climatology averaged over WFCOM simulations for 2004–2015.

entire shelf and that the near bottom circulation was upwelling oriented. The WFCOM simulations are further tested using 2010 satellite-tracked surface drifter observations in *Liu and Weisberg* [2011], where the WFCOM performance on the shelf is found to exceed that of other models [*Liu et al*., 2014]. These model veracity demonstrations justify the use of the WFCOM simulations for describing the WFS circulation in 2010.

The WFCOM simulations (and discussions in the works previously cited) show that the Loop Current interactions with the shelf slope initiated the protracted upwelling state on 18 May 2010 and that an upwelling circulation then generally persisted throughout the year. Shown in Figure 2 are near bottom (lowest sigma layer) horizontal velocity vectors superimposed on potential temperature both as averages over the month of June 2010 and climatological averages for June computed from the WFCOM simulations: 2004–2015. The inner shelf near bottom temperatures are colder and the upwelling circulation is more intense in June 2010 than in the climatological averages Time series comparisons between the WFCOM simulation and bottom temperatures observed by moored instrumentation also show that the WFCOM simulation accounts reasonably well for the near bottom temperature throughout 2010 (Figure 3).

How the near bottom velocity and temperature fields relate to depth is evident from the isobath geometry (Figure 1). DeSoto Canyon is the region just south of Pensacola, FL. To the west of the canyon the shelf slope is quite steep, whereas to the east of the canyon it is less so. The demarcation isobath for these slope changes on the two sides of the canyon is roughly 200 m (Figure 1).

The shelf break for most of the WFS tends to be at about the 70 m isobath, shoaling to about the 60 m isobath in the Florida Big Bend region and then to the 40 m isobath offshore of Pensacola, FL on the Florida Panhandle. With the Loop Current or its eddies potentially coming in closer proximity to the coast and contacting shallower isobaths in the northern region, it follows that deep ocean influences may directly impact the region in the north and to the west of the canyon. Being that the WFS is wider and with a deeper shelf break, deep-ocean boundary current influences there may affect the nearshore region less than in the

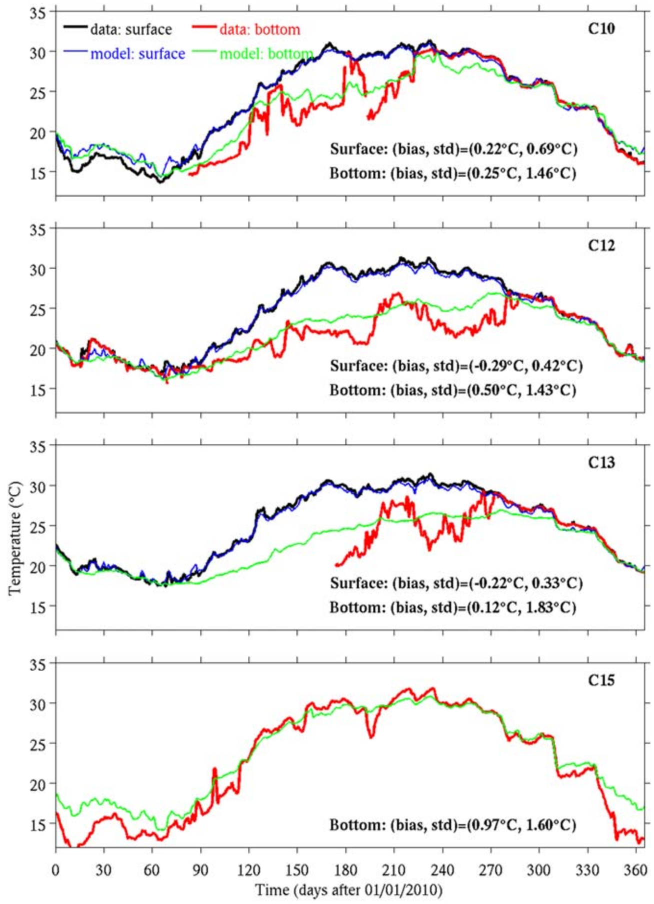

Figure 3. Comparisons for 2010 between year-long temperature time series observed with moored instrumentation and simulated by WFCOM, both near the surface and the bottom. (top–bottom) C10, C12, C13, and C15 (Figure 1) are located on the 25 m isobath offshore of Sarasota, the 50 m isobath offshore of Tampa Bay and Charlotte Harbor, and the 10 m isobaths off shore of Sarasota, FL, respectively.

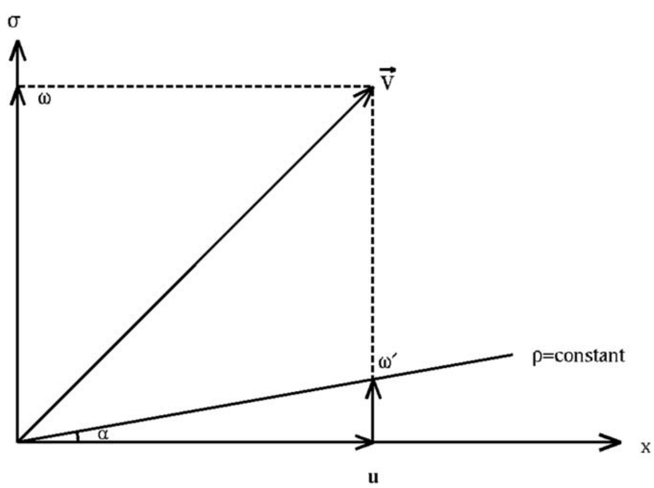

Figure 4. A two-dimensional representation of the velocity transformation in the sigma coordinate system computational plane (x, σ) restricting the particle trajectories to be isopycnic. The velocity vector (u, ω) transforms to (u, ω'), where $w' = u\tan\alpha$, α being the angle between the sigma and the isopycnal surfaces.

north. Nonetheless, with the 60–70 m isobath depth window being quite broad to the west of the Dry Tortugas and with shallower isobaths close to the Dry Tortugas, boundary current influences there are expected to have profound effect upon the WFS circulation. These geometrical arguments are consistent with what we see in Figure 2.

3. Methods

Employed is pseudo-Lagrangian particle tracking. The qualifier, pseudo, recognizes that fluid parcels, within nonisentropic flow fields, will change their properties en route. Thus only under conservative forcing (or in a homogeneous medium) is it physically sensible to estimate displacement by simply integrating the velocity vector without imposing some additional constraints. For instance, if there is reason to believe that particles are not fluid elements and may be constrained by buoyancy or behavior to stay either at the surface, or near the bottom, then fixing a level or a sigma layer may be a reasonable approach. Such argument may also apply to other behaviors, or to changes in buoyancy or drag due to particle-size variations as oil or other substances are consumed by bacteria. Three examples of such techniques applied to the Deepwater Horizon oil spill are given by *Liu et al*. [2011b], *North et al*. [2011], and *Lindo-Atichati et al*. [2016]. For the present case, we are interested in the fluid parcels themselves. Noting that it is unrealistic for such parcels to cross surfaces of constant density (material surfaces) without those surfaces themselves changing through mixing, we opted for isopycnic tracking, whereby we save the ambient density and velocity fields averaged hourly, as calculated using complete conservation equations at the model internal time step, and we then perform trajectory analyses offline by adjusting the vertical component of the velocity vector so that the

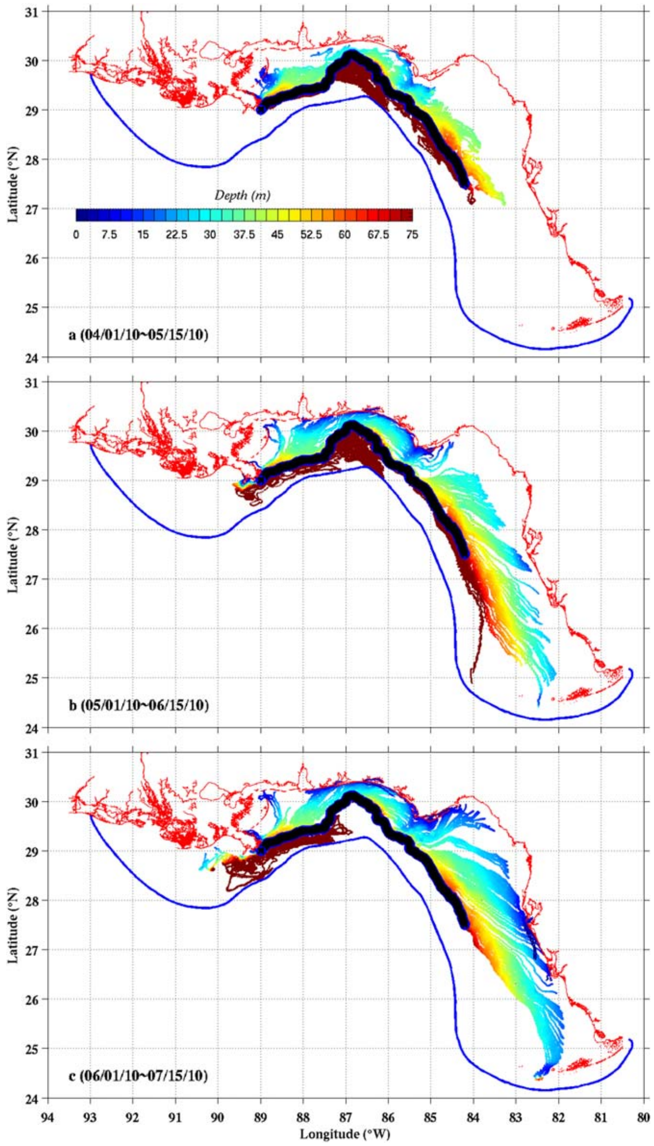

Figure 5. WFCOM simulated isopycnal water parcel trajectories, originating from the lowest sigma layer at 1 km intervals along the 75 m isobath and spanning (from top to bottom): (a) 1 April 2010 to 15 May 2010, (b) 1 May 2010 to 15 June 2010, and (c) 1 June 2010 to 15 July 2010.

velocity vector (adjusted for tracking) is parallel to the isopycnal at each (offline) hourly time step location.

For the sigma coordinate, WFCOM, the isopycnic velocity vector is illustrated in Figure 4 (in the computational plane (x, σ) and in two dimensions for simplicity), and the adjusted vertical velocity component in the computational plane, ω', is calculated from $\omega' = (u^2+v^2)^{1/2}(\tan\alpha)$, where u, v, ω are the velocity components along the x, y, and σ directions, ω' is the adjusted vertical velocity component in the σ coordinate space and α is the angle between the sigma and isopycnal surfaces. The procedure used at each (offline hourly) time step is as follows. We first locate the grid element in which the particle resides and determine the depth and density at the particle location within that grid element. Next, at each of the three nodes (vertices) of the triangular grid element, we determine the depth that has the same density as at the particle location. Based on the differences between the depths at each vertex and the horizontal distances from the particle, we obtain the angles between the sigma coordinate surface and isopycnal surface, and we average these three estimates to get the angle α between the sigma and isopycnal surfaces at that particle position. By doing this offline, using saved, hourly-mean, three-dimensional velocity components, u, v, and ω, depths and densities, we allow the actual model run to employ full conservation laws while also estimating isopycnic particle trajectories. We further note that as the density gradient approaches zero (or for a homogeneous fluid) the angle between the isopycnal surface and the velocity vector approaches zero, and hence the adjusted vertical velocity component ω' approaches the actual vertical velocity component ω.

Given the hourly isopycnic velocity vectors, the space/time evolution of the pseudo-Lagrangian water parcel trajectories are then determined via a fourth-order Runge-Kutta method. We note that this approach allows for isopycnal surface displacement in the online calculation, either by an across-isobath component of velocity or turbulent mixing, but not so in the offline calculation. This approach (for a sigma coordinate model) may be thought of as an analog of the isopycnic coordinate model (HYCOM) technique applied by *Halliwell et al.* [2003], who considered Atlantic Ocean, upper limb, across-equator and intergyre fluid parcel pathways.

For the purposes of our paper, which is concerned with deep ocean influences on the coastal ocean via upwelling across the shelf break, we consider water parcels with origins at the 75 m isobath and deeper. Specifically, we track pseudo-Lagrangian water parcel trajectories from the 75, 100, 150, 200, 250, and 300 m isobaths, approximating the shelf break and the upper portion of the shelf slope. The model geometry, the WFS geometry and previous experience [*Weisberg et al.*, 2014c] are such that water parcels under anomalous upwelling conditions may transit the shelf in about 45 days; hence, we choose this to be the integration time interval.

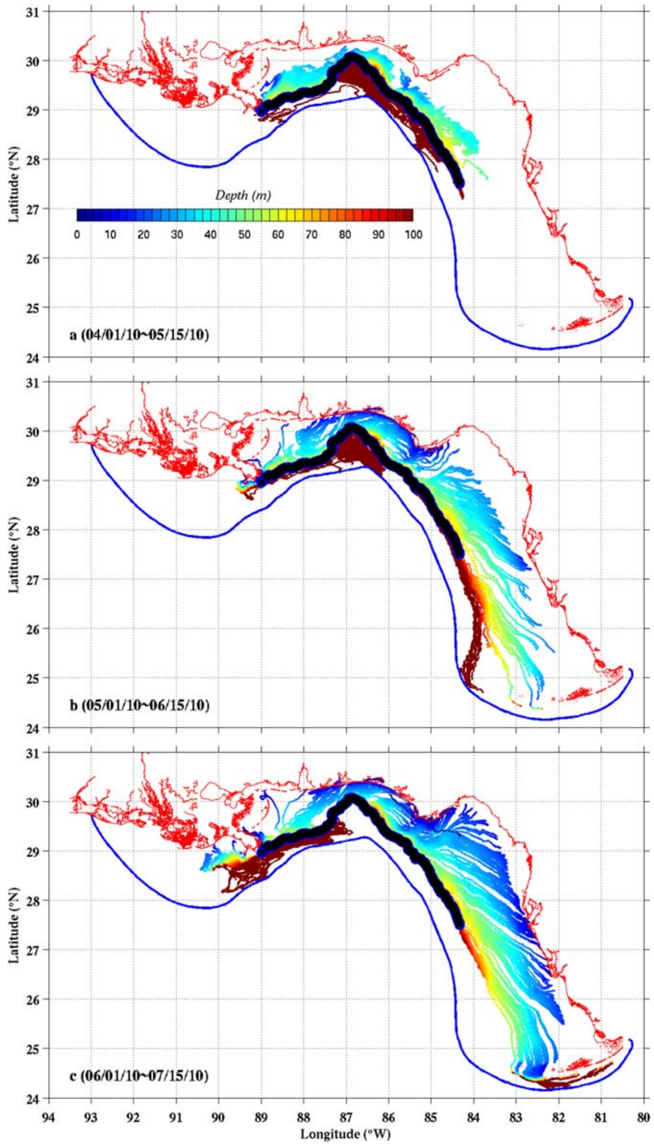

Figure 6. WFCOM simulated isopycnal water parcel trajectories, originating from the lowest sigma layer at 1 km intervals along the 100 m isobath and spanning (from top to bottom): (a) 1 April 2010 to 15 May 2010, (b) 1 May 2010 to 15 June 2010, and (c) 1 June 2010 to 15 July 2010.

4. Results

Given the 2010 protracted upwelling onset in mid-May, we chose three 45 day intervals to illustrate the pseudo-Lagrangian trajectories. The first of these begins on 1 April 2010 to consider a time interval prior to the protracted upwelling onset; the second begins on 1 May 2010 including persistent upwelling over a portion of the interval; and the third begins on 1 June 2010 with persistent upwelling over the entire interval. Anomalous upwelling continued throughout the year, but these three intervals are adequate to demonstrate the results of concern to this paper.

Water parcel trajectories originating within the lowest sigma layer at 1 km intervals along the 75 m isobath, or approximately along the shelf break (a little deeper than the shelf break in the DeSoto Canyon vicinity), are shown in Figure 5. Most of the trajectories in the top plot (beginning on 1 April 2010) ended in shallower water, but only a few of them came to the vicinity of the shoreline. In general, they stayed within the lower two thirds of the water column between the shelf break and the shoreline. For the points to the west of DeSoto Canyon, the trajectories were initially toward the east and up, but they then reversed to the west. In other words, no clear patterns are evinced by the trajectory simulation during this 1 April 2010 to 15 May 2010, preprotracted Loop Current induced upwelling interval.

Trajectories beginning a month later on 1 May 2010 (Figure 5, middle) were decidedly different. Whereas the initial pathways were nondescript, with the onset of upwelling most of these headed shoreward and to shallower depths, following pathways consistent with proximity to the bottom Ekman layer. Some of those originating in the northern part of the domain paralleled the beach in very close proximity and a few transited the barrier island inlets to enter the estuaries behind the barrier islands (WFCOM has sufficient resolution nearshore to include major inlets). Exceptions to shoreward transport were some of the particles that originated to the west of DeSoto Canyon and stayed in deeper water.

Trajectories under upwelling conditions spanning the entire 45 day interval 1 June 2010 to 15 July 2010 (Figure 5, lower) are even more pronounced. Here we see water parcels reaching the shoreline between

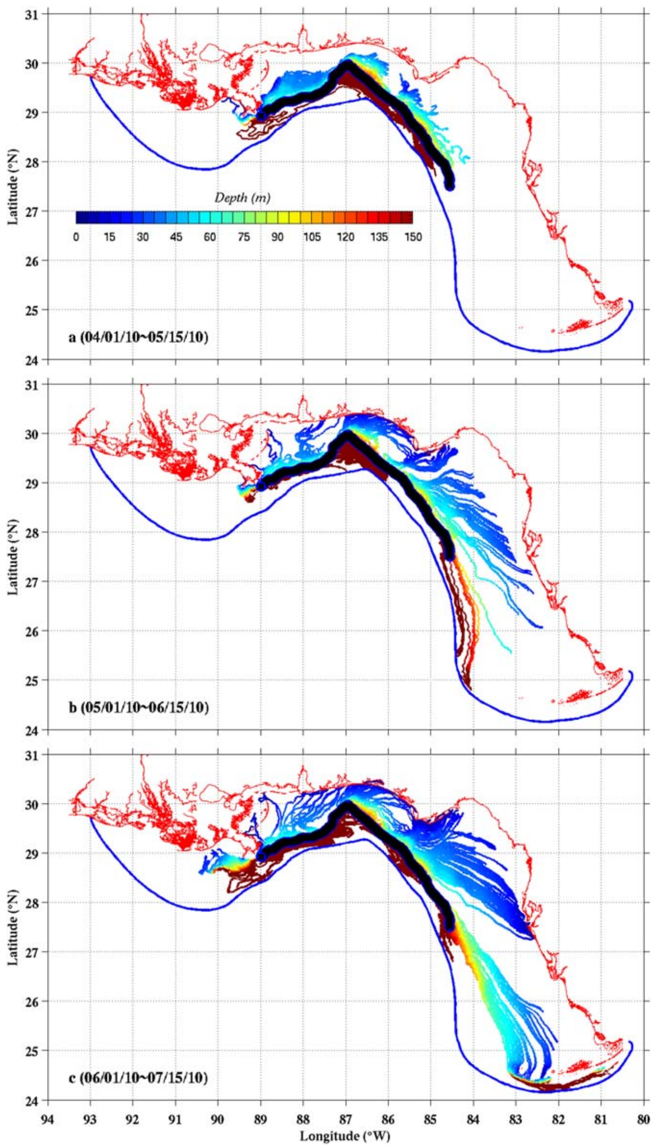

Figure 7. WFCOM simulated isopycnal water parcel trajectories, originating from the lowest sigma layer at 1 km intervals along the 150 m isobath and spanning (from top to bottom): (a) 1 April 2010 to 15 May 2010, (b) 1 May 2010 to 15 June 2010, and (c) 1 June 2010 to 15 July 2010.

Tampa Bay and Charlotte Harbor, along the Apalachicola Bay barrier islands and along the Florida Panhandle. The pathways are again within the vicinity of the bottom Ekman layer, and they are consistent with the distributions of bottom temperature shown in Figure 2. As in the middle plot, some of the trajectories include transits through barrier island inlets. In particular, note the parcels that transited into both Apalachicola Bay and Tampa Bay.

Consistent with Figure 2, these trajectories suggest that whereas nearshore waters within the region between Tampa Bay and Charlotte Harbor and in the Florida Panhandle (Apalachicola Bay to Pensacola, FL) are renewed during protracted upwelling circulations, those in the Florida Big Bend and in the Florida Bay regions are not so readily renewed.

Having established that water parcels from the shelf break region may transit across the shelf, what happens to parcels originating at deeper depths along the continental shelf slope? Results for the 100 m isobath are shown in Figure 6, using the same time intervals as in Figure 5. Nondescript distributions occurred for the period prior to upwelling (Figure 6, upper), with some of the trajectories heading farther offshore into deeper water in the vicinity of DeSoto Canyon. Similar distributions occurred for the next subsequent time intervals, with some subtle differences, as would be expected from different initiation points and times. For the period 1 June 2010 to 15 July 2010 many of the parcels from the DeSoto Canyon region arrived along the Florida Panhandle shoreline, and WFS parcels from south of 29°N all headed toward the west Florida shoreline, with the southernmost ones either rounding the Dry Tortugas or passing through cuts in the shoals between Key West and the Dry Tortugas before entering the Florida Current.

Continuing to deeper initiation depths, Figure 7 shows results for 150 m. Prior to the protracted period of upwelling (Figure 7, top) there were only a few transits of water parcels across the shelf break, particularly at and west of DeSoto Canyon. This changed after the onset of upwelling, upon which the results (Figure 7, middle) are similar to those at the shallower depths, with the exception that the trajectories are more diverse. In particular, the southernmost trajectories stayed within the shelf slope or along the shelf break. With upwelling occurring over the entire duration (Figure 7, bottom), the transit of parcels to the vicinity of Tampa Bay is pronounced. Parcels originating south of about 28.5°N either stayed on the shelf slope or followed the shelf break toward the Dry Tortugas, which they transited before entering the Florida Current.

The influence of water parcels from depths below 150 m in renewing the waters of the nearshore along Florida's west coast is diminished. Figure 8 shows parcels originating at depths of 200, 250, and 300 m for the tracking period 1 June 2010 to 15 July 2010. Whereas the nearshore waters of the Florida Panhandle show some renewal from all of these depths, particularly for those originating at or to the west of DeSoto Canyon, for the WFS only a few trajectories approached the nearshore from 200 m depth, and no trajectories approached the nearshore from deeper depths.

Similar findings, while not shown, continued throughout this 2010 year of anomalously protracted upwelling. Waters from the shelf break to 150 m depth along the shelf slope readily renewed the waters of the nearshore, as already shown. Waters down to 250 m depth also occasionally penetrated the WFS. In contrast, there were only a few occasions when waters of 300 m depth broached the shelf break and headed shoreward. These occurrences tended to be along the Florida Panhandle coast and originating from west of the DeSoto Canyon head

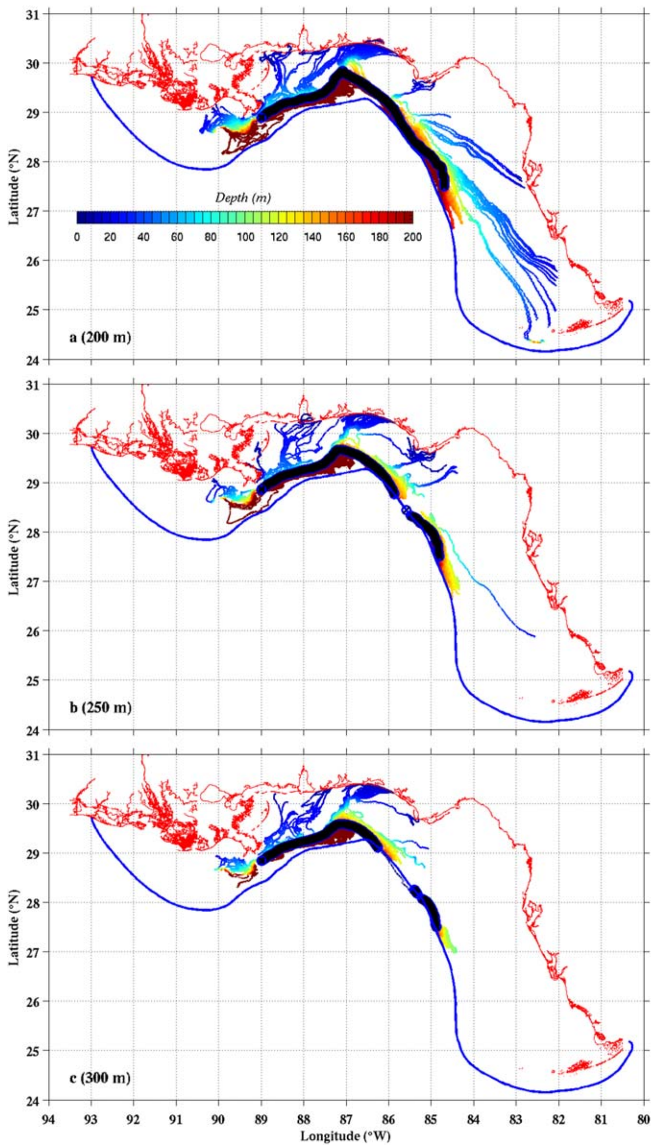

Figure 8. WFCOM simulated isopycnal water parcel trajectories, originating from the lowest sigma layer at 1 km intervals along the (a) 200 m, (b) 250 m, and (c) 300 m isobaths and spanning 1 June 2010 to 15 July 2010.

5. Discussion

The results of these pseudo-Lagrangian water parcel trajectory analyses conforms with much that has been learned about the functionality of the WFS circulation (reviews are provided by *Weisberg et al*. [2005, 2009], and recent applications are given by *Weisberg et al*. [2015]). While the shelf may be described as oligotrophic, it does, on occasion, experience water (and hence water property) renewal through deep ocean interaction events, as occurred in the 2010 year diagnosed herein. However, such water property renewal does not occur homogeneously, suggesting that regional differences may be ecologically important. For west Florida, two nearshore locales stand out as being renewed through such deep-ocean interaction events, versus two other locales that are not similarly renewed. The renewed regions are the Florida Panhandle and the region between the Tampa Bay and Charlotte Harbor estuaries; the less renewed regions are the Florida Big Bend and Florida Bay. We may therefore speculate that the nutrient sources for the first two are to some degree determined by upwelling of deeper ocean waters across the shelf break in response to deep ocean interactions with the shelf slope, whereas the nutrient sources for the other two are primarily by land drainage. These physical differences in water parcel origins and pathways, in addition to the advection of Mississippi River water, may help to explain the emergence of isoscapes evident in organism isotope analyses [e.g., *Radabaugh and Peebles*, 2014]. They may also begin to explain why certain regions are more conducive to supporting prolific shrimp and finfish habitats.

Even in an anomalously persistent upwelling year like 2010, the origins of waters renewing the WFS are primarily from above 150 m depth. Upwelling from very deep depth (below 300 m) does not appear to occur locally. Nonetheless, with temperature-nutrient relations showing monotonically increasing nutrients with decreasing temperature below about 19°C, as generally found along the WFS slope between 100 and 150 m depths [e.g., *Weisberg and He*, 2003; *He and Weisberg*, 2003], the upwelling of such upper shelf slope water fuels primary productivity [e.g., *Walsh et al*., 2003]. This is evident in shipboard or glider surveys that consistently show subsurface chlorophyll maxima extending from the deeper ocean onto the WFS [e.g., *Weisberg et al*., 2014a for a 2010 example].

These persistent, interannually occurring upwelling events offer explanation on how the otherwise oligotrophic WFS supports robust commercial and recreational fisheries and experiences blooms of the harmful alga, *K. brevis* interannually, versus annually. Complex biological processes, with many degrees of freedom, will be successful if the physics of the coastal ocean circulation provide environmental conditions that are conducive to success, and conversely.

Acknowledgments
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