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A WEST FLORIDA COASTAL OCEAN CIRCULATION MODEL

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ABSTRACT

Presented is a West Florida Coastal Ocean Model (WFCOM) that downscales from the deep-ocean, across the continental shelf and into the estuaries, plus four applications to environmental matters of societal concern: 1) harmful algal blooms, 2) transit of Deepwater Horizon hydrocarbons to the West Florida Shelf, 3) gag grouper recruitment and 4) how Deepwater Horizon oil arrived on north Florida beaches. Along with these hindcast simulation applications, WFCOM provides daily, automated nowcasts and forecasts that are publically available at http://ocgweb.marine.usf.edu. The WFCOM design follows from the coastal ocean circulation being driven by a combination of deep-ocean and local forcing and the need for increasing resolution at important regions of mass conveyance. As such, WFCOM simulations provide the offshore conditions that affect water properties within Tampa Bay and other west Florida estuaries, and hence may find use in forecasting when harmful substances may enter one of the west Florida estuaries in the event of a future oil spill. Other applications may include the communication of water properties and materials between the Big Bend Nature and Springs Coasts with the Tampa Bay, Charlotte Harbor and Florida Bay regions. Being that water properties and transport routes are full three dimensional, with near bottom currents being of particular importance throughout the west coast of Florida, WFCOM simulations are germane to anything pertaining to the ecosystems services of the west Florida coastal ocean.

INTRODUCTION

Ecosystems services, when applied to the coastal ocean, pertains to the total economic value derived therefrom, including living marine resources, their commercial and recreational exploitation, tourism and its intrinsic economic value through hotels, restaurants and services and the indigenous populations pursuit of enjoyment through what the aesthetics offered by the coastal ocean and its beaches. Moreover, given that Florida is a peninsula, it may be argued that no aspect of the Florida economy goes untouched by the adjacent ocean. Effective management of Florida's coastal ocean and related ecosystems services necessitates an understanding of how the complex coastal ocean system works. That need is the motivation of our coordinated coastal ocean observing and modeling activities on the West Florida Continental Shelf (WFS).

A Coastal Ocean Monitoring and Prediction System (COMPS) was initiated in 1997, and grew through complementary research efforts, including support from the Integrated Ocean Observing System Office presently housed within NOAA. Our COMPS and related activities coordinate observations with models of the coastal ocean circulation to describe and predict how water properties vary along the WFS and how this bears upon various ecological phenomena, either natural, or human-induced. Observations provide the starting point of scientific investigation, but by virtue of the coastal ocean's vastness, these observations are intrinsically sparse, requiring suitably constructed models to help fill observational gaps. But models, even perfect ones (if such could exist), require observations for initialization, boundary conditions and simply to determine if the model bears any resemblance to nature. Hence coastal ocean observations and models are best done in coordination, which is our adopted approach.

Here we report on a relatively recent numerical circulation model referred to as the West Florida Coastal Ocean Model (WFCOM) that downscales from the deep ocean, across the continental shelf and into the estuaries by nesting the Finite Volume Coastal Ocean

Model (FVCOM; e.g., Chen et al., 2003) into the Global Hybrid Coordinate Model (HYCOM; e.g., Chassignet et al., 2009), with the addition of eight principal tidal constituents. WFCOM was introduced by Zheng and Weisberg (2012), where a calendar year 2007 hindcast was used to demonstrate model simulation veracity gauged against available in situ data. Subsequent applications were made to K. brevis Harmful Algal Blooms (HABs) by Weisberg et al (2014a) and to the subsurface transport of Deepwater Horizon hydrocarbons to the WFS by Weisberg et al. (2015a). The WFCOM domain was then expanded westward beyond the Mississippi River Delta to include actual Mississippi River inflows, versus climatology, and this version was used to explain gag grouper recruitment on the WFS (Weisberg et al., 2014b). These four refereed WFCOM publications provide the model details, quantitative comparison with in situ data for establishing model simulation veracity and methods. Here we will summarize these applications and findings, and provide an introduction to publically available nowcasts and forecasts. One new application (Weisberg et al., 2015b; in review) provides an explanation on how Deepwater Horizon oil was transported to the north Florida beaches.

APPLICATIONS

WFCOM in its present configuration has horizontal resolution varying from that of the HYCOM in the nesting region to 150 m in the Tampa Bay and Charlotte Harbor estuaries. It is three-dimensional and density dependent, with 31 terrain following sigma layers in the vertical, and it also includes flooding and drying of adjacent land. Figure 1 shows the WFCOM domain and an example of the surface velocity field superimposed on surface salinity for June 19, 2010 when Deepwater Horizon surface oil was rapidly moving eastward. Such hindcast simulations are available from 2004 through the present time, and we also run daily, automated nowcasts and 3.5 day forecasts that are publically available at http://ocgweb.marine.usf.edu.

2.1 Circulation control of Karenia brevis HABs on the WFS

The 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 inter-annual 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. A comparative study between a robust bloom observed in 2012, versus a nearly null event in 2013 provides further evidence for this conclusion (Weisberg et al., 2016b).

Upwelling is required for an offshore originating *K. brevis* bloom (Steidinger, 1975) to manifest along the shoreline (Weisberg et al., 2009), but too much upwelling may result in the introduction of new inorganic nutrients of deeper ocean origin through upwelling across the shelf break. With new inorganic nutrients, the WFS may no longer be oligotrophic, thereby allowing faster growing diatoms to outcompete slower growing dinoflagellates, as shown in the companion papers by Weisberg et al. (2003) on the circulation and Walsh et al. (2003) on the phytoplankton biology for the anomalous conditions of 1998.

Anomalous upwelling through deep-ocean, shelf interactions occurs when the Gulf of Mexico Loop Current comes in prolonged contact with the shelf slope near the Dry Tortugas. The Dry Tortugas is important for two reasons. First, the dynamics of continental shelf waves are such that these waves propagate with shallow water on right in the northern hemisphere (e.g. Gill, 1982). Second, as the western terminus of the Florida Keys chain all isobaths shallower than 25 m must wrap around the Dry Tortugas. By combining these two attributes, it follows that a surface dynamic height high imposed near the Dry Tortugas will result in a pressure gradient force extending across the entire WFS, with an associated southward directed geostrophic current, as suggested by Hetland et al. (1999). The turning to the left of this southward geostrophic current by friction across the bottom Ekman layer results in an upwelling circulation bringing relatively cold, higher nutrient water toward the coast, as demonstrated by Weisberg et al. (2003).

The above scenario occurred from approximately May 20, 2010 through the end of the year when the Loop Current shed an eddy and retreated southward. This is demonstrated in Figure 2 through a series of biweekly snapshots of sea surface height (observed by satellite altimetry) and associated surface geostrophic currents. An example of the WFCOM simulations of both the near surface and near bottom currents superimposed on temperature for July 15, 2010 is shown in Figure 3, where we see the upwelling circulation and cold water in close proximity to the coast. That the WFCOM simulation bears resemblance to nature is demonstrated in Figures 4 and 5, the first of these showing observed water properties from an across shelf glider transect in July 2010 and the second showing a full year (2010) comparison between observed and modeled velocity vectors from one of the COMPS moorings (C10, situated on the 25 m isobath offshore from Sarasota, FL).

Thus we may explain the absence of a *K. brevis* HAB bloom on the WFS in 2010 by the injection of new, inorganic nutrients of deeper ocean origin, caused by anomalously strong and prolonged upwelling. The anomalous and prolonged upwelling was due to Loop Current interaction with the shelf slope near the Dry Tortugas. With the nutrient conditions of the WFS reset by the coastal ocean circulation, diatoms were favored over dinoflagellates, and no *K. brevis* bloom occurred in 2010.

2.2 The transit of Deepwater Horizon hydrocarbons to the WFS

Subsequent to the Deepwater Horizon oil spill was the emergence of anecdotal information regarding skin lesions and other abnormalities in commercial and recreations fish species. These reports, while primarily from the region where oil was prevalent at the surface, were not limited to that region. Reports from the WFS motivated a purposeful scientific study that found skin lesions in reef fish, along with chemical evidence of hydrocarbon exposure (Murawski et al., 2015). Whereas there were no reports of Deepwater Horizon oil on the surface to the east of Cape San Blas (and hence on the WFS), hydrocarbons of Deepwater Horizon origin may have made their way to the WFS sight unseen beneath the surface. This question was addressed by Weisberg et al. (2015a) using the WFCOM.

Surface oil was quite pronounced offshore of the north Florida coastline throughout most of June 2010. If we hypothesize that some of this oil became entrained in the water column via Langmuir circulation or by other means then it would follow that the persistent and prolonged upwelling circulation described in the previous section would have carried this subsurface oil to the WFS. To test this hypothesis we introduced a passive tracer in the WFCOM on June 19, 2010 where satellite imagery (Hu, personal communication, 2014) showed abundant surface oil. The tracer was positioned uniformly over the water column and its initial concentration was normalized so that we could determine the dilution as the tracer was advected and mixed by the evolving flow field. Figure 6 shows the initialization of the tracer and Figure 7 provides the near bottom concentrations on June 30, 2010 and September 30, 2010. The tracer rapidly covered the entire WFS domain following the upwelling induced flow field and eventually exited the WFS near the Dry Tortugas. Normalized concentration values were within 10% of the initial values along the coastline from Tampa Bay to Charlotte Harbor. By making certain assumptions on how much of the surface oil may have permeated the water column, Weisberg et al. (2014c) suggested that actual concentration levels may have been in the 10s of parts per billion, sufficient to have been detrimental to fish. The simulated tracer pattern also aligns reasonable well with where the Murawski et al. (2014) study found fish with skin lesions (Figure 8).

Whereas direct hydrocarbons in the water column evidence does not exist (no samples were taken), indirect evidence through fish lesions and liver chemistry support the inference that Deepwater Horizon hydrocarbons permeated the WFS sight unseen beneath the surface. This inference is consistent with the known aspects of the coastal ocean circulation from June 2010 when surface oil was off the north Florida beaches and subsequently.

2.3 Gag grouper recruitment

Gag are known to spawn in winter to early spring months near the shelf break, with subsequent juvenile settlement occurring some 30-50 days later along the shore (Fitzhugh et al., 2005). Unknown was the mechanism by which the larvae and juveniles transited the shelf from spawning to settlement. This was the topic addressed by Weisberg et al. (2014b). The starting point was a time series of juvenile settlement sampled in May, 2007 at Mullet Key (the southern end of Pinellas County, FL). Winter and spring 2007 showed very good agreement between our WFCOM simulations and observations of velocity made in situ using a WFS array or moorings. Similar to 2010, the Loop Current was in contact with the shelf slope in the vicinity of the Dry Tortugas, and this drove an upwelling circulation in April and May, 2007. We tested two hypotheses, the first being a surface route of transport, the other being a near bottom route. Particles were input to the model along different isobaths and at different times, and their trajectories were then calculated over 45 day intervals. None of the near surface particles made any progress toward the shore, whereas the near bottom particles did result in shore impacts. Examples of these results are provided in Figure 9 (surface) and Figure 10 (near bottom).

The WFCOM particle trajectory analyses were supplemented by both biochemical evidence and the co-location of juveniles on Mullet Key with macro-algae of deep water (mid-shelf to shelf), hard bottom origin. Three conclusions may be drawn. First, the mechanism for gag larvae and juvenile transport from spawning to settlement is the near bottom (Ekman layer) circulation under upwelling favorable conditions. Second, the preferred settlement locations, Tampa Bay to Charlotte Harbor and Apalachicola Bay and westward are consistent with the upwelling circulation necessary to transport the larvae and juveniles to the shore. Third, and as a corollary to the near bottom transport route, inter-annual variability in gag recruitment success is tied to the requirement that an upwelling circulation must last long enough and be in phase with spawning for there to be a successful recruitment.

2.4. How Deepwater Horizon oil arrived on north Florida beaches.

The northern Gulf of Mexico beaches, particularly from the Mississippi River Delta to the Florida Panhandle, were oiled during the Deepwater Horizon oil spill and most notably in June 2010. We (Weisberg et al., 2016, in review) used four different numerical circulation models to track particles at the surface in an attempt to account for the transport of surface oil from the deep ocean to the beaches. These models were the Gulf of Mexico HYCOM and the Global HYCOM, both run by the Naval Research Laboratory and the WFCOM nested into either the Gulf of Mexico HYCOM or the Global HYCOM. Surface particles were initialized on May 24, 2010 using satellite imagery (C. Hu, personal communication, 2014), and new particles were added at the well site on a three hourly basis through July 15, 2010 to mimic the continual input of oil. Tracking was done using a fourth order Runge-Kutta scheme relying on HYCOM fields when particles were positioned in HYCOM and WFCOM fields when particles were positioned in WFCOM. In addition to these ocean circulation fields, we also added wave effects via Stokes drift derived from the SWAN wave model (Zijlema, 2010).

The initial particle positions, as initialized on May 24, 2010, are shown in Figure 11. Particles were generally in deep water and quite distant from the northern Gulf (Mississippi to Florida) beaches at this time. Within two weeks, however, oil was sullying these beaches. Our results in closest agreement with observations were with the WFCOM nested in the Global HYCOM and including Stokes drift. These results, with and without Stokes drift, are shown in Figure 12. A limitation of the Gulf of Mexico HYCOM during this time interval was the appearance of an eddy that shifted many particles too far to the east and inconsistent with observations. A limitation of the Global HYCOM alone was its limited resolution. By nesting the WFCOM in the Global HYCOM we benefitted from the Global HYCOM deep ocean circulation being constrained through data assimilation and from the high resolution afforded by the WFCOM.

Our findings suggest that the ocean circulation brought the surface oil to the vicinity of the beach, and that the Stokes drift then deposited the oil on the beach. This combination of effects is physically sensible because the circulation tends to be parallel to the isobaths and to the beach upon approaching the shoreline, whereas the Stokes drift may be perpendicular to the beach. From these findings it follows that forecasting the beaching of oil requires: 1) adequate initialization of where the oil may be, 2) an accurate deep ocean model suitably constrained by data assimilation, 3) a high resolution coastal ocean model nested in the deep ocean model and inclusive of the barrier islands and estuaries and 4) a wave model.

SUMMARY AND CONCLUSIONS

We introduced a West Florida Coastal Ocean Model (WFCOM) that nests an unstructured grid finite volume model (FVCOM) into an operational data assimilative deep ocean model (either the Gulf of Mexico or the Global HYCOM). The utility of this approach to modeling the coastal ocean circulation was demonstrated using four hindcast simulation examples: 1) K. brevis HABs on the WFS, 2) Deepwater Horizon hydrocarbon transport in explanation of fish lesions on the WFS, 3) gag grouper recruitment and 4) how Deepwater Horizon oil reached the northern Gulf of Mexico beaches. The first three of these examples further demonstrates the multidisciplinary nature of coastal ocean ecology.

Three general conclusions follow. First, coastal ocean environmental stewardship requires a multidisciplinary approach, including observations coordinated with models. Observations alone are too sparse. Models without observations for initialization, boundary values, forcing functions and veracity testing are not very useful. Second, ecology is the sum of all processes necessary for an organism to make a living. As shown for HABs and fish recruitment, the physics of the circulation are as important as the biology of the organism. Third, adapting our science strategy to accommodate the multidisciplinary nature of coastal ocean ecology will provide improved understandings on complex ecological questions that are necessary for facilitating improved environmental stewardship in this coastal ocean region where society meets the sea.

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