A coordinated coastal ocean observing and modeling system for the West Florida Continental Shelf

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ABSTRACT

The evolution of harmful algal blooms, while dependent upon complex biological interactions, is equally dependent upon the ocean circulation since the circulation provides the basis for the biological interactions by uniting nutrients with light and distributing water properties. For the coastal ocean, the circulation and the resultant water properties, in turn, depend on interactions between both the continental shelf and the deep-ocean and the continental shelf and the estuaries since the deep-ocean and the estuaries are primary nutrient sources. Here we consider a coordinated program of observations and models for the West Florida Continental Shelf (WFS) intended to provide a supportive framework for K. brevis red-tide prediction as well as for other coastal ocean matters of societal concern. Predicated on lessons learned, the goal is to achieve a system complete enough to support data assimilative modeling and prediction. Examples of the observations and models are presented and application is made to aspects of the 2005 red-tide. From an observational perspective, no single set of measurements is adequate. Required are a broad mix of sensors and sensor delivery systems capable of describing the three-dimensional structure of the velocity and density fields. Similarly, models must be complete enough to include the relevant physical processes, and data assimilation provides the integrative framework for maximizing the joint utility of the observations and models. While we are still in the exploratory stages of development, the lessons learned and application examples may be useful to similar programs under development elsewhere. One scientific finding is that the key to understanding K. brevis red-tide on the WFS lies not at the surface, but at depth.

1. Introduction

We begin with the premise that the coastal ocean circulation physics provide a fundamental contribution to the ecology of harmful algal blooms (HAB). Specifically, with nutrient sources deriving from both the deep-ocean and the estuaries the
circulation is responsible for the advection of these nutrients onto the continental shelf and the subsequent distribution and concentration across the shelf. Moreover, with nutrients tending to concentrate near the bottom the circulation is responsible for uniting nutrients with the euphotic zone. Concentration of both nutrients and organisms along fronts and other features is also a function of the circulation. Thus a necessary ingredient to the study of red-tide ecology is a specification of the circulation.

By virtue of the Earth's rotation, and through the conservation of potential vorticity, the continental shelf circulation is greatly influenced by geometry. Located in the eastern Gulf of Mexico, much of the West Florida Continental Shelf (WFS) is broad, gently sloping and of width similar to that of the sub-aerial Florida landmass. Whereas the geometry offshore of Tampa Bay is relatively simple, significant along shelf variations occur between the Florida Keys and the Florida Panhandle. For instance, in the south, the Florida Keys provide a partial barrier to water motions, and in the north, the narrowing at the DeSoto Canyon allows deep-ocean water properties to extend very close to the coastline. The WFS is therefore geometrically complex, and its flow fields must be considered as being fully three-dimensional. These geometrical features, along with the circulation physics, result in instances of remote forcing wherein ecologically relevant observations made locally may be due to interactions occurring several hundred kilometers away (e.g., Weisberg and He, 2003; Walsh et al., 2003). Hence complete enough sets of observations and models are required to describe and understand the processes that govern K. brevis blooms within the context of the ecology of the WFS. Our focus here will be on the ocean circulation aspects of this. Vargo et al. (2008) provides an observational basis for nutrient distributions in relationship to K. brevis, and Walsh et al. (2006) discusses the biological aspects of K. brevis modeling. A review of previous observations and models of the WFS circulation is provided by Weisberg et al. (2005). Here we will draw upon some of these findings to provide lessons learned on the design of observing and modeling systems for studying the ecology of the WFS.

We begin by describing an observing system as it presently exists. Far from complete, this observing system at least provides a starting point for examining the circulation across a range of time scales and spatial domains. The observations consist of in situ data and data analysis products deriving from either satellite observations or operational model products combined with in situ data. These observations and products are necessary to both run and quantitatively gauge the performance of coastal ocean circulation models. For instance, models, even if perfect, derive their solutions from boundary and initial conditions so their solutions will be imperfect without perfect winds and heat fluxes to force and data to initialize them. Since models depend on parameterizations of unresolved processes, they are hardly perfect. In the same way that there are never enough observations to fully specify a complex system, models, without adequate observations for initialization, forcing, and, correction, are insufficient. Only through the coordination of observations with models, each complete enough, can we hope to describe and predict HABs in the coastal ocean.

Section 2 describes the in situ observations and the data analysis products. Section 3 discusses the models that are presently in use. Section 4 attempts to summarize previous lessons learned, and Section 5 makes application to the 2005 red-tide event. On the basis of these findings, coastal ocean observing system (COOS) design recommendations pertinent to HABs are presented in Section 6.

2. Observations and analysis products

The Coastal Ocean Monitoring and Prediction System (COMPS), under the auspice of the College of Marine Science, University of South Florida (CMS-USF), is a contributor toward an emergent Regional Coastal Ocean Observing System (RCOOS) for the south-eastern United States. COMPS consists of two elements. The first is a coastal element comprised primarily of tide gauges and surface meteorological sensors that add to the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) National Water Level Observing Network (NWLO) and National Weather Service (NWS) Coastal Marine Automated Network (CMAN) stations along the west coast of Florida. The second is a coastal ocean element comprised of: (1) buoys with acoustic Doppler current profilers (ADCP) for full water column currents, temperature (T) and salinity (S) sensors at a few (two to three) discrete depths, and surface meteorological sensors; (2) high frequency (HF)-radar for surface current mapping; (3) bottom-stationed ocean profilers (BSOP) for discrete profiles of T and S; and (4) various data analysis products. COMPS real-time data are available at http://comps.marine.usf.edu. Other analyses and related information are available at http://oceanweb.marine.usf.edu. Fig. 1 shows the COMPS array in relationship to the NOAA NOS and NWS national backbone observing stations that also includes buoys along with the NWLO and CMAN stations. Here we will be concerned primarily with the coastal ocean element of COMPS.

A total of six buoys with real-time telemetry are presently maintained, five with surface meteorological measurements in addition to in-water sensors. In addition to these surface moorings with telemetry four other (subsurface) moorings are maintained at locations for which data were previously not available. We are also testing subsurface wave sensors linked by acoustic modems to either a surface buoy or a fixed tower at two experimental near-shore sites. These near-shore stations may eventually become part of the telemetry suite. The rationale for choosing the buoy locations are to: (1) span dynamically distinctive regions of the coastal ocean and (2) provide spatial coverage for winds so that the coastal ocean wind fields used to force coastal ocean models may be improved. Fig. 2 provides an example of the buoy system in use. These buoys are mechanically robust in that they have withstood close encounters with hurricanes. As an example, buoy C17 was visited at close proximity by Hurricanes Katrina, Rita, and Wilma in 2005. While the meteorological sensors failed, the buoy survived and provided data on the water column currents, an example of which is given in Fig. 3.

The HF-radar component presently consists of three long range CODAR Ocean Sensors SeaSonde units located at Indian Rocks Beach in Pinellas Co., Venice Beach in Sarasota Co., and Naples Beach in Collier Co. Fig. 4 proves an example of the surface velocity field sampled by these radars. Operating at 4.55 MHz, a measurement goal was to extend offshore to the vicinity of the Loop Current (LC). The unit deployed in Venice is maintained by the Mote Marine Laboratory in collaboration with Rutgers University and USF.

To obtain profiles of T and S (and eventually other environmental variables) we designed the BSOP as an autonomous, unthethered, profiling float that tends to hold station by parking on the bottom in between profiles. Using two-way satellite communications we are able to track and receive BSOP data and adjust mission parameters. Intended to provide synoptic fields for the mapping of T, S and other variables (to the extent that enough units are deployed), the experimental design concept is to deploy these in conjunction with gliders. By combining the attributes of BSOP (synoptic sampling at high vertical resolution, but limited horizontal resolution) with those of gliders (high spatial resolution, but non-synoptic sampling), the intention is to provide three-dimensional maps of T, S and other data fields for description and assimilation into models. Fig. 5 is an example of BSOP T and S data collected in August 2005, prior to and with the passage Hurricane Katrina. Prior to Katrina the shelf was strongly stratified, with relatively warm, low salinity water atop cooler, saltier water near...
shore. Farther offshore, and away from the coastal fresh water source (Tampa Bay in this instance), the salinity values were higher. As Katrina translated westward across the WFS it first generated northerly winds followed by southerly winds in its wake. SST began to cool around August 25th by a net surface heat flux perturbation out of the ocean. With southerly, downwelling favorable winds then causing a shoreward advection of near-surface water, the deeper isotherms descended with time further decreasing the temperature stratification, and the relatively low salinity near-shore water was paved over by higher salinity offshore water reversing the salinity stratification. The end result of this Katrina response was a destratification of the water column, the evolution of which was documented by BSOP.

To the aforementioned in situ and HF-radar data are five different analysis products, each automated and available on the internet: (1) a blend of National Centers for Environmental Prediction (NCEP) reanalysis winds combined with in situ winds from buoy and coastal stations, (2) a daily, gridded, cloud-free sea surface temperature (SST) analysis that combines advanced very high resolution radiometer (AVHRR) SST from NOAA polar orbiting and geostationary satellites with microwave SST from the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) satellite (He et al., 2003), (3) a daily, gridded, cloud-free ocean color product that uses moderate resolution imaging spectroradiometer (MODIS) Aqua color data, (4) a daily Sea Surface Height (SSH) and surface geostrophic current analysis that combines SSH anomalies from the analysis of Collecte, Localisation, Satellites (CLS) with a mean field derived from the Hybrid Coordinate Ocean Model (HYCOM) (Alvera-Azcarate et al., 2008), and (5) a weekly, Lagrangian surface trajectory analysis by integrating these surface geostrophic currents in time and space. Fig. 6 provides an example of the Lagrangian trajectories superimposed on the cloud-free SST. Whereas the SST covers the entire southeastern United States in Fig. 6, the Lagrangian trajectory analysis includes only the region of the swift Loop Current–Florida Current–Gulf Stream (LC–FC–GS) system since elsewhere the omitted wind-driven currents are expected to be the dominant contributor, and the SSH analysis is not reliable on the shelf. Along with Fig. 6 domain, not shown is a second domain that covers the Caribbean Sea. Through a 1-week hindcast followed by a 1-week forecast (with currents held constant for the forecast), the co-evolution of the SST and the Lagrangian trajectories shows the distance over which particles released from certain locations may travel under the influence of the surface geostrophic currents. It also shows that SST within the LC–FC–GS is largely affected by advection.

The wind product was designed to improve numerical circulation model-derived currents by improving the wind field used to drive the model (He et al., 2004). Similarly the cloud-free SST product was designed so that we could correct the modeled SST by nudging it to an observed SST in view of errors in the surface heat flux (e.g., Barth et al., 2008). The other products are for descriptive and tracking purposes.
3. Models

Three types of models are presently in use. The first is a model that links the deep-ocean with the coastal ocean in order to address the mass, heat, and momentum fluxes across the shelf break. For this we are presently using an adaptation of the Regional Ocean Modeling System ROMS (Shchepetkin and McWilliams, 2005), nested in the 1/12th degree North Atlantic (now Global) HYCOM (Chassignet et al., 2003, 2007). Fig. 7 provides an example that shows the smooth transition from one model domain to the other, with the LC flowing in and out across the WFS regional model open boundary. The second is a model that links the coastal ocean with the estuaries. For this we are presently using the Finite Volume Coastal Ocean Model (FVCOM) (Chen et al., 2003). Fig. 8 provides an example. Here we see the movement of relatively fresh water emanating from the Tampa Bay and the Charlotte Harbor estuaries and the near-shore interactions that occur between these water sources. The third consists of higher resolution models of the estuaries themselves that include enough of the adjacent WFS to provide for tidal forcing and for the flux of materials into and out of the estuaries. FVCOM is also used for baroclinic estuary circulation simulations in Tampa Bay, Rookery Bay, and Naples Bay (Weisberg and Zheng, 2006a; Zheng and Weisberg, submitted for publication). Similarly, FVCOM is used for applications to coastal inundation by hurricane storm surge with density held constant and flooding and drying provisions enabled (Weisberg and Zheng, 2006b,c). Preceding these applications were studies using the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). All of these modeling studies, when combined with observations for the purpose of quantitative comparison, have led to lessons learned about the WFS shelf circulation that are relevant to the understanding of K. brevis red-tide.

4. Examples of science lessons learned

The first and perhaps the most important lesson learned on the WFS circulation (through coordinated observing and modeling) germane to K. brevis red-tide is that the inner shelf circulation is fully three-dimensional, even in very shallow water. Moreover the bottom Ekman layer provides the major conduit for the transport...
of biologically active materials to the near-shore. It follows that surface information alone is insufficient for the study of red-tide, and that our understanding of, and predictive capability for, *K. brevis* red-tide has been hampered by a paucity of subsurface information. This should not be a surprising given previous WFS red-tide studies such as Steidinger (1975), which discussed offshore origination and the possibility of a benthic resting stage as part of the *K. brevis* life history.

Discussions on across shelf transport mechanisms for the WFS must begin with a definition of the inner shelf. Li and Weisberg (1999a,b) describe this through the use of primitive equation, constant density (POM) model simulations under idealized upwelling and downwelling wind stress forcings. As shown in Fig. 9 (for upwelling wind stress), a wide shelf can be broken into distinctive regions, each defined through momentum balances. With respect to vertically integrated momentum balances, the inner shelf may be thought of the region between some offshore isobath (approximately 50 m in Fig. 9) and the shoreline. Seaward of that isobath, the along shelf momentum balance is in pure surface Ekman layer balance such that the Coriolis force (due to the along shelf flow) balances the wind stress, and the bottom stress is negligible. In contrast, near the shoreline the Coriolis force is negligible, and the bottom stress nearly balances the wind stress. Thus the inner shelf is the transition region between these two different states of along shelf momentum balance. The associated momentum balance in the across shelf direction is geostrophic (i.e., between the across shelf pressure gradient force and the Coriolis force due to the along shelf flow). Seaward of the inner shelf is a mid-shelf region where a countercurrent tends to exist due to the partial closure of the WFS by the Florida Keys in the south. Farther offshore is the shelf break, which provides a transition between the shelf and the deep-ocean. Deep-ocean processes are expected to penetrate onto the shelf over a distance equal to the Rossby radius of deformation, and this transition region is referred to as the outer shelf. If the shelf is wide enough, such that the inner and outer shelves do not overlap, then it is possible to distinguish between these regions of distinctly different dynamical balances. The Burger number (the square of the ratio of the baroclinic Rossby radius of deformation evaluated at the shelf break to the shelf width) provides a measure of this width. For small Burger number the inner shelf is isolated from the shelf break since the pressure variations imposed at the shelf break by the deep-ocean tend to be baroclinically compensated within a Rossby radius of deformation (e.g., Janowitz and Pietrafesa, 1980; Clarke and Brink, 1985). The WFS is sufficiently wide offshore of Tampa Bay for this to apply. In contrast, the inner shelf extends beyond the shelf break in the narrow, DeSoto Canyon region.

The response of the WFS to upwelling favorable wind stress was subsequently explored under realistic conditions using a combination of observations and models. Weisberg et al. (2000) provides an upwelling case study for which upwelling favorable winds switched on abruptly in May 1994 following an interval of weak winds. Coastal sea level dropped in response to an offshore directed flow in the surface Ekman layer, an alongshore geostrophic current ensued, along with an onshore directed flow in the bottom Ekman layer, and this all took place over the course
Fig. 5. An example of salinity (upper panel) and temperature (lower panel) collected by a BSOP deployed near the 50 m isobath in August 2005 coincident with the passage of Hurricane Katrina. Another BSOP (not shown) was positioned near the 25 m isobath.

Fig. 6. An example of Lagrangian trajectories derived from a geostrophic analysis of satellite derived SSH superimposed on a cloud-free SST analysis. Parcels of drifters are released at three locations: the Yucatan Strait, south of the Mississippi River delta, and the Florida Straits. These are tracked in hindcast for 1 week using varying surface velocity followed by a 1 week forecast with velocity held constant in time. The image shown is at the end of the forecast cycle.

Fig. 7. An example of the WFS ROMS model nested in the North Atlantic HYCOM. The WFS regional model is inside of the dashed line; the HYCOM is outside the dashed line.
of a pendulum day. This sequence of events demonstrated an
Ekman-geostrophic route to the establishment of the inner shelf
currents, and the net result was the appearance of relatively cold
water near the 25 m isobath just south of Tampa Bay. Subsequent
baroclinic model studies (Weisberg et al., 2001) showed that
stratification tends to displace the region of maximum upwelling
both shoreward and down-wind since stratification inhibits
vertical motion across the thermocline. These findings were later
confirmed though a combination of observations and model
simulations by He and Weisberg (2002, 2003), Weisberg and He
(2003) and Weisberg et al. (2004). As an example, Fig. 10 shows the
modeled near-bottom currents for an upwelling event on May 15th
1998. The bottom Ekman layer is the conduit for across shelf
transport in this figure, and satellite imagery (see Weisberg et al.,
2004) showed that the position of maximum upwelling was along
the beach between the Tampa Bay and Charlotte Harbor estuaries.
Cold water in this event literally upwelled at the beach because the
thermocline was strongly developed all the way to the shoreline.
The Ekman-geostrophic mechanism by which this occurred is
further illustrated in Fig. 11, which shows Lagrangian trajectories
for particles released in an FVCOM simulation of coastal upwelling.
The color coding corresponds to the model sigma layer (normal-
ized depth). Particles originating at the surface go offshore,
whereas particles originating near the bottom go onshore until
they are upwelled to the surface.

The second lesson learned is that along with the importance
of three-dimensionality is the need for long time series. Whereas the
emergent COOS emphasizes the importance of real-time data, a
point not disputed, it is the data that are most important, whether in
real-time or not. This is because continental shelf processes of
ecological importance (red-tide and other) occur over a variety of
time scales, including diurnal, synoptic weather, seasonal, and
interannual. The figures already discussed provide examples of
synoptic weather-induced (typical upwelling responses) and
interannual (anomalously prolonged upwelling responses in
1998) variations. Fig. 12 demonstrates the seasonal variations
though the monthly binning of multiyear data sets. It is only through
sustained and systematic observations that processes of WFS
ecological importance can be described, understood, and modeled.
In that sense the implementation of COOS is essential, but we must
be careful not let the COOS concept of interoperable, real-time data
get in the way of COOS operability; i.e., the data are needed now, not
many years from now after all of the interoperability and data
management considerations may be realized.

Not only does stratification alter the position of where water
may upwell to the surface; it also rectifies the responses to winds

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Fig. 8. An example of the FVCOM results linking the estuaries (Tampa Bay in the
north and Charlotte Harbor in the south) with the shelf. Shown are surface currents
superimposed on surface salinity.

Fig. 9. Vertically integrated momentum balance analysis for upwelling wind stress
under constant density conditions (from Li and Weisberg, 1999b). The upper panel
is the along shelf balance and the lower panel is the across shelf balance. The bold
dotted line denotes the pressure gradient term, the dash dotted line denotes the
Coriolis term, the bold dashed line denotes the wind stress term, the thin dashed
line denotes the bottom stress term, the bold solid line denotes the advection term,
and the thin solid line denotes the local acceleration term.

Fig. 10. Near-bottom currents modeled for an upwelling event on May 15th 1998.
The bottom Ekman layer is the conduit for across shelf transport in this simulation.
such that upwelling responses tend to be larger and to extend farther offshore than downwelling responses when driven by winds of similar magnitude. It does this through the modification of the bottom Ekman layer response because of the tendency for the thermal wind to increase the upwelling response relative to the downwelling response [Weisberg et al. (2001) provides an explanation and discussion relative to the findings of Trowbridge and Lentz (1991) and Garrett et al., 1993]. In analogy to wind-waves systematically transporting sediment to the beach, the regular occurrence of upwelling and downwelling sequences in response to synoptic scale weather can systematically transport materials of biological importance to the near-shore. Moreover, since stratification controls the vertical distribution of turbulence throughout the water column, stratification largely controls how the Ekman-geostrophic responses to wind stress evolve. Coastal ocean circulation models, therefore, require sufficient data on the internal $T$ and $S$ structures for initialization and for data assimilative updates. So along with the lesson that surface data alone are insufficient to describe and forecast the distributions of biota, the third lesson is that surface data alone are also insufficient to describe and forecast the physical processes upon which the biological processes depend.

5. Preliminary applications to the 2005 red-tide

On the basis of the physical oceanographic observations and models that were in place on the WFS at the time of the 2005 red-tide event, what can be said about the evolution of this event? Rather than attempt a full description and hindcast for which the data are

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**Fig. 11.** A Lagrangian particle simulation for fall 2001 using FVCOM. The color coding corresponds to sigma level (normalized depth varying here from 0 at the surface to $-1$ at the bottom). Particles were released at sigma levels $-0.1$, $-0.3$, $-0.5$, $-0.7$, and $-0.9$ at two locations along the 20 m isobath and then tracked for 40 days (the dots are separated by 5 days). The first 25 days was a period of prolonged, upwelling favorable wind forcing.

**Fig. 12.** Climatological monthly mean velocity vectors sampled at near surface, mid-depth, and near bottom levels superimposed on climatological monthly mean SST. The velocity vectors are averaged over the period, October 1998 to September 2001. The SST data are averaged over the period January 1998 to December 2002. [from Liu and Weisberg, 2005].

insufficient, we will instead address certain aspects of the evolution, as supported by the observations and models. The first question to ask is: are the physical models at all suited for the task? Given the exploratory nature of this application we will only partially address this concern. The basic answer is yes, in that a reasonable degree of fidelity exists between the model hindcasts, independent of data assimilation, and the observations. This is demonstrated through a comparison (Fig. 13) of currents observed and modeled at mooring location C10 (at the 25 m isobath offshore of Sarasota, FL). Shown are time series of daily-averaged velocity vectors for the first 240 days of 2005, sampled near the surface, at mid-depth, and near the bottom, along with the vector correlations (correlation coefficients, angular deviations, and regression coefficients) between the observed and modeled current pairs. The general model fidelity is good, with correlation coefficients of about 0.7, angular deviations within $13^\circ$, and regression coefficients between 0.6 and 0.9. The results of He et al. (2004) suggest that these can be improved by improving the surface wind forcing and (as discussed earlier) by assimilating internal $T$ and $S$ data to better constrain the stratification. For the present purposes let us see what we can account for on the basis of the circulation simulation.

Regardless of the origin of the bloom (perhaps by wintertime resuspension consistent with Steidinger, 1975) the first sightings of the 2005 red-tide event were made offshore of the Tampa Bay vicinity at a front jointly formed by $T$ and $S$. These sightings triggered sampling cruises for cell counts. Figs. 14 and 15 address the question of whether or not the model is capable of tracking the evolution of the $K. brevis$ cell counts, exclusive of the biology. In other words, given a set of initial conditions can we track the pathways of the $K. brevis$ cells, and if so what were these pathways? The first of these figures shows a set of Lagrangian trajectories for particles released near the bottom at three locations near the point of the initial sighting. The cell counts to the right on January 13th and February 18th are courtesy of K. Steidinger and J. Tustison (personal communication, 2006). In essence, the cell counts were observed to progress onshore and toward the southeast, and the

Fig. 13. A comparison of velocity vectors observed and modeled at mooring C10 (25 m isobath offshore of Sarasota, FL). Shown are daily-averaged velocity vectors for the first 240 days of 2005 sampled near the surface, at mid-depth, and near the bottom, along with the vector correlations (correlation coefficients, angular deviations, and regression coefficients) between the observed and modeled current pairs.
Lagrangian trajectories for particles originating near the bottom show the same progression. A repeat of this experiment is shown in Fig. 15, but this time with particles released near the surface. Instead of heading shoreward and to the southeast, these particles traveled farther offshore. This demonstrates that the \textit{K. brevis} cells progressed from their initial offshore sighting to the beach via transport in the bottom Ekman layer. Continued tracking in this manner throughout the winter (not shown) found similar success in describing the movement of this 2005 red-tide event, including its eventual entry into Tampa Bay in summer 2005. Since previous \textit{K. brevis} blooms have been observed to initiate offshore (e.g., Steidinger, 1975; Steidinger et al., 1998; Tester and Steidinger, 1997) this finding on the importance of the bottom Ekman layer in providing a conduit for transport to the near-shore appears to be of general importance.

An anomalous and very important ecological event accompanied the 2005 red-tide, that of a large-scale benthic die-off that occurred offshore of Tampa Bay and the Pinellas County waters northward. Sampling cruises attributed (C. Heil, personal communication, 2006) this to anoxic conditions of \textit{K. brevis} origin, sustained by anomalously stable stratification. While we will not attempt to address the biology and chemistry of this anoxic benthic die-off, we can address whether or not the model simulation can account for the anomalous stratification and from whence it originated. Our BSOP profiles (Fig. 5, courtesy of C. Lembke, personal communication, 2006) provided observations of the $T$ and $S$ stratification at that time, and for comparison the model simulated $T$ and $S$, sampled at the C10 buoy location (25 m isobath offshore of Sarasota), are shown in Fig. 16. From mid-July to the end of August we see relatively fresh, warm water overlaying relatively salty, cool water. So the stratification was of coastal origin. To assess from whence it came (the Tampa Bay or Charlotte Harbor estuaries) we performed a set of Lagrangian trajectory analyses with distributed particles originating in the vicinity of either

Fig. 14. Simulated particle trajectories for the case of particles released near the bottom (left) compared to \textit{K. brevis} cell count data (right). The color bar for the left hand panel signifies particle depth (m). The right hand panels are courtesy of Steidinger and Tustison (personal communication, 2006). Color coding signifies the age of the measurement. Darker shades designate prior observations so the gradient from dark to light is indicative of the bloom movement from January 13th (upper right panel) to February 18th (lower right panel).

Fig. 15. Same as Fig. 14 left hand panel, but for particles released near the surface. The color bar signifies depth (m).
facilitate a *K. brevis*-related benthic die-off had its origin with fresh water emanating from Tampa Bay, as contrasted with Charlotte Harbor.

These results, based on past and ongoing Coastal Ocean Observing System (COOS) activities for the WFS (the COMPS and SEACOOS Programs in particular), demonstrate the societal value of emergent RCOOS, complementing examples from elsewhere (such as applications to the harmful alga, *Alexandrium* in the Gulf of Maine, e.g., McGillicuddy et al., 2005). While this value extends well beyond the study of HABs, application to *K. brevis* red-tide requires the same attributes as any other societal-relevant coastal ocean application, rendering the findings herein of general COOS design applicability. Thus some scientific and pragmatic lessons learned with applicability to HABs and COOS are as follows.

6.1. Science lessons

The circulation, through its role in uniting nutrients with light and transporting (and concentrating) water properties, is a fundamental contributor to the shelf ecology. Moreover, the circulation, even in shallow water, is fully three-dimensional, and for a broad shelf like the WFS, the bottom Ekman layer is a primary conduit for the across shelf transport of biologically important materials. It follows for the WFS that a key to the understanding of *K. brevis* red-tide lies at depth. Second, measurements should not be arbitrarily placed. These are needed over dynamically distinct regions: the outer shelf (within a baroclinic Rossby radius of the shelf break), the inner shelf (the region where surface and bottom Ekman layers interact through divergence), the near-shore (the inner shelf portion directly impacted by estuaries), and the mid shelf (if the shelf is wide enough to distinguish the inner and outer parts). While platforms of opportunity are useful, their availability must be gauged against physics-based sampling requirements (under the lamppost may not be the best place to search for missing keys). Third, long time series are essential. While real-time data are useful, it must be recognized that data sufficient to characterize the environment are what is most important. A balance between real-time and delayed-mode data must be achieved since real-time is generally more difficult and expensive to implement. Fourth, since the response of the coastal ocean to external forcing is stratification-dependent, the acquisition of internal temperature and salinity data for assimilation into ocean circulation models is critical. As with nearly all variables, surface information alone is insufficient. Fifth, from quantitative comparisons between observations and models we know that local wind and heat flux forcing inadequacies are limitations to accurate model simulations. Improvements to ocean-atmosphere interaction data are therefore necessary for improving the veracity of coastal ocean model simulations. Sixth, along with such local forcing effects, interannual anomalies of ecological importance can also occur via deep-ocean interactions. Hence HABs and fisheries matters require knowledge on interactions occurring between both the shelf and the deep-ocean and the shelf and the estuaries. It follows that a systems-wide approach to the entire coastal ocean is necessary for sound ecological management.

6.2. Pragmatic lessons

Most importantly is the recognition that people are the limiting commodity, and this necessitates sustained funding. Second is the recognition that instruments and systems fail, and this necessitates adequate spares along with maintenance and calibration support. Logistical support is also limiting. Along with technical personnel support and spares is the need of ships to service platforms and instruments. Third, for the purpose of real-time data acquisition, bandwidth and power are also limiting. In view of this
care must be taken to define data requirements and to ensure that instrument placement is science-driven, not bandwidth and power-driven. All of the above establishes the need for economies of scale and well-thought-through collaborations. Fourth, a coastal ocean observing system also requires close coordination between observations and models. Models rely on observations and observations gain value through model integration so these activities are not separable. Products flow from both, and the most complete and reliable products will flow from observations and models that are combined through data assimilation. Fifth, not all groups have the same capabilities, logistically or otherwise, necessitating partitions of effort between federal, state, academic, and private sector participants.

6.3. System design recommendations

Of foremost concern is the fact that no single measurement system is adequate. Required are: moorings, HF-radar (and drifter complement), profilers/gliders, satellites, and ships supporting multidisciplinary suites of sensors. A diverse data set is also needed for both model verification and data assimilation since verification and assimilation are independent data functions. The system must be designed for full water column observations distributed over dynamically distinct regions, including the inner shelf and its embedded near-shore, the shelf break (outer shelf), the middle shelf (if the shelf is wide enough), and the shelf slope. Along with the usual variables, there is an obvious need is for K. brevis cell counts. Second, coastal ocean monitoring and coastal ocean science must be related. It is a mistake to discuss these separately because a system cannot be effectively monitored without scientific understanding. Third, observations and models must be coordinated. Coastal ocean state variable estimation by data assimilative models requires adequate wind and surface heat flux fields along with interior density fields. Hence arrays of buoys are required to support assimilative meso-scale atmosphere models, and adequate river flow rate data are needed to specify land drainage. For the interior T and S fields, three-dimensional mappings are needed through the use of profilers, gliders, and other means. Remote sensing (satellites and HF-radar), while important, is insufficient since these only provide surface fields. Fourth, with system maturation will come model-based observing systems sensitivity experiments. These will offer refinements to the above recommendations, but they will not supplant these recommendations. So while continued planning and testing is of obvious importance, it should be recognized that programs already in place require continued and expanded support to ensure that their investments will not lost in the planning process.

In summary, K. brevis red-tide is a complex, multidisciplinary, and fully three-dimensional problem. If a simple, single hypothesis were at work we would know it; we do not! Progress demands a complete enough set of observations (deriving from multiple sensors and sensor delivery systems) and models, with emphasis on the circulation since the circulation underpins the water property distributions. The prediction pathway will be through the merging of observations and models through data assimilation. A next step for the WFS is the direct coupling of physical and biological models building on the simple (but incomplete) advective arguments presented here. Such coupled models can then be used to test various hypotheses on K. brevis bloom initiation, maintenance, and demise. On a larger, national scale, excellent observing and modeling capabilities exist in many regions, and the regional association and regional coastal ocean observing system concept provides a framework for advancement. A small shift in emphasis from planning to more action toward sustaining and enhancing ongoing efforts will bring us a long way toward realizing the societal goals that are being espoused.

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