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Developing a Smart Semantic Web With Linked Data and Models for Near-Real-Time Monitoring of Red Tides in the Eastern Gulf of Mexico

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***Abstract*—In recent decades, the technology used to detect and quantify harmful algal blooms (commonly known as red tides) and characterize their physicochemical environment has improved considerably. A remaining challenge is effective delivery of the information generated from these advances in a user-friendly way to a diverse group of stakeholders. Based on existing infrastructure, we establish a Web-based system for near-real-time tracking of red tides caused by the toxic dinoflagellate *Karenia brevis*, which annually threatens human and environmental health in the eastern Gulf of Mexico. The system integrates different data products through a custom-made Web interface. Specifically, three types of data products are fused: 1) near-real-time ocean color imagery tailored for red tide monitoring; 2) *K. brevis* cell abundance determined by sample analysis; and 3) ocean currents from a nested and validated numerical model. These products are integrated and made available to users in Keyhole Markup Language (KML) format, which can be navigated, interpreted, and overlaid with other products in Google Earth. This integration provides users with the current status of red tide occurrence (e.g., location, severity, and spatial extent) while presenting a simple way to estimate bloom trajectory, thus delivering an effective method for near-real-time tracking of red tides.**

***Index Terms*—Cyberspace, data fusion, geographic information sciences, Google Earth (GE), harmful algal blooms (HABs), prediction, remote sensing.**

I. Introduction

A. Need for Near-Real-Time Monitoring

IN RECENT decades, the frequency, spatial extent, and economic effects of harmful algal blooms (HABs), commonly known as red tides, have increased worldwide [1]–[3]. In the eastern Gulf of Mexico, blooms of the toxic dinoflagellate *Karenia brevis* occur nearly annually, can extend over large areas (hundreds of square kilometers), and can persist as long as 23 months [4]. Blooms can result in fish kills and marine mammal mortalities [5]–[7], as well as human illnesses. Specifically, humans can experience respiratory irritation from inhaling aerosolized algal toxins or can contract Neurotoxic Shellfish Poisoning from the consumption of contaminated shellfish [8], [9]. The financial costs associated with such blooms in the fishery, public health, recreation, and tourism sectors are estimated to be $80 million per year [10]. Many of these costs are incurred along Florida's Gulf Coast. For example, during a moderate red tide season (2002–2003), Florida aquaculture and oyster industries lost an estimated $6 M as a result of shellfish bed closures intended to protect public health [11].

Local and regional stakeholders require near-real-time information on blooms, such as those caused by *K. brevis*, to mitigate their negative effects. In fact, the Gulf of Mexico Alliance's Governor's Action Plan suggested that researchers and managers "improve capabilities of Gulf-wide HAB monitoring networks to support HAB detection and tracking" [12]. With improved monitoring capabilities, coastal communities can prepare for blooms by enacting preparedness networks, coordinating messaging, and creating outreach documents. In Florida, near-real-time bloom tracking information is used by managers to direct event response activities (e.g., water sampling), public health officials to minimize health impacts, local visitor centers to reduce losses to the tourism industry, and the public to plan recreational activities. Thus, the utilization of tracking information before and during blooms enhances the efficiency and cost-effectiveness of monitoring programs and reduces the negative effects of HABs regionally. However, to enable effective communication of essential HAB monitoring data with a diverse group of stakeholders, data must be integrated and disseminated through simple, user-friendly, and decision support tools.

B. Current Infrastructure for Monitoring and Information Dissemination

1) Field Sampling: Since 1954, the Florida Fish and Wildlife Conservation Commission (FWC)'s Fish and Wildlife Research Institute has monitored marine and estuarine waters either routinely (i.e., weekly, twice-monthly, and monthly) or in response to observations of discolored water, respiratory irritation, or wildlife effects. A primary goal of this monitoring is to detect

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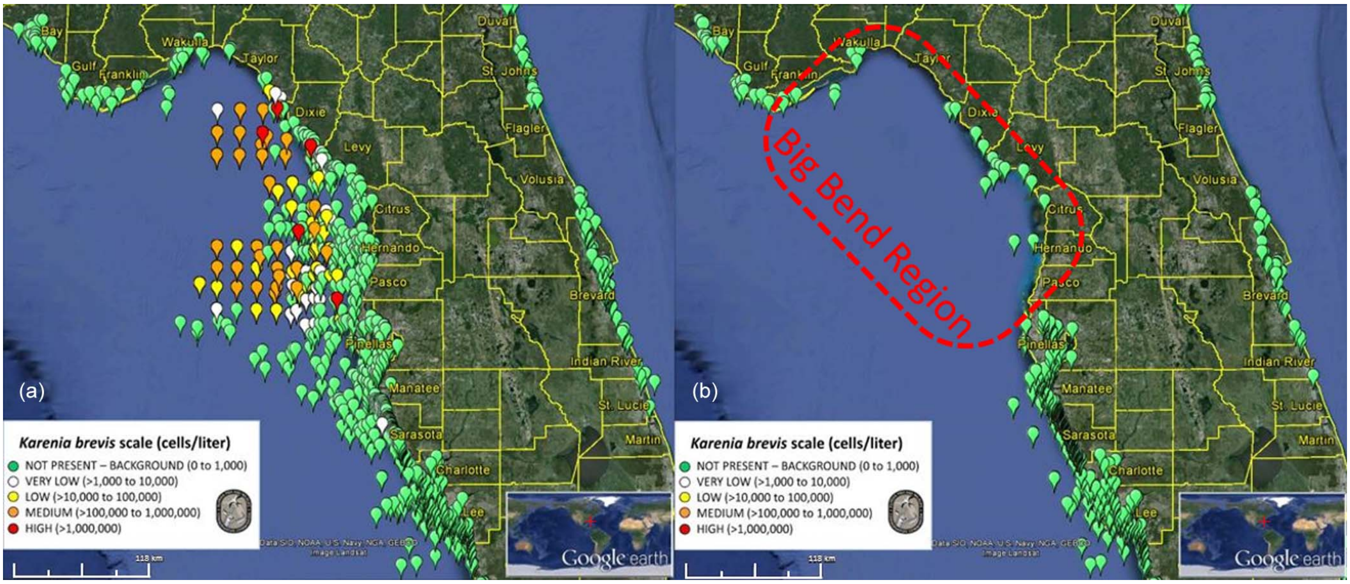

Fig. 1. Maps of west Florida showing sampling efforts and *Karenia brevis* cell abundance during representative (a) bloom (July to September 2014) and (b) nonbloom (March to May 2014) periods. Current status maps are posted on the state's website (MyFWC.com/RedTideStatus) weekly, and archived maps are available in a Flickr gallery (flickr.com/photos/myfwc). Florida's Big Bend region is outlined in red.

and quantify nuisance, harmful, and toxic blooms, including those caused by *K. brevis*. A network of approximately 190 state and county agencies, private research institutions, universities, and private volunteers work together to collect water samples, which are returned to the Fish and Wildlife Research Institute for analysis (for additional information on the monitoring infrastructure in Florida see Heil and Steidinger [13]). Based on historical bloom occurrences and trajectories and due to resource limitations (i.e., available vessels and funding), most sampling occurs in southwest Florida and is typically biased toward nearshore surface waters. However, during blooms, more extensive sampling occurs if state resources are appropriated (Fig. 1). HAB taxa including *K. brevis* are identified and enumerated from field-collected water samples via microscopy. Results are distributed to collaborators daily via individual reports and weekly to the public through a red tide status report posted to the FWC's website (MyFWC.com/RedTideStatus), social media (www.Facebook.com/FLHABs), and e-mail. Since 2013, the statewide red tide status page has averaged approximately 10 000 hits per month, with the greatest number of hits recorded during periods with blooms. In addition, FWC's weekly e-mail reports have been distributed to more than 430 000 individuals, approximately 99% to the public and less than 1% to other scientific organizations.

2) Satellite Remote Sensing: Satellite remote sensing is an effective tool for detecting water discoloration resulting from increases in *K. brevis* cell abundance (e.g., $> 10^4$ cells L^{-1}) and intracellular chlorophyll-a content (Chla, mg m^{-3}) during blooms of *K. brevis*. Moreover, bloom tracking is possible because of the satellites' synoptic and frequent measurements. Steidinger and Haddad [14] first used Chla estimated from the proof-of-concept ocean color satellite sensor Coastal Zone Color Scanner (CZCS, 1978–1986) to observe a major *K. brevis* bloom in 1979. Since then, several follow-on sensors have made near-operational observations possible. These sensors include the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, 1997–2010), the Moderate Resolution Imaging Spectroradiometer (MODIS, 2000–present on Terra and 2002–present on Aqua), and the Medium Resolution Imaging Spectrometer (MERIS, 2002–2012). Typically, a two-step approach is used to detect and characterize blooms. The first step is detection. Most detection algorithms are based on Chla or Chla anomaly [15]–[18] or on solar-stimulated fluorescence using the MODIS fluorescence line height (FLH) data product [19], [20] or its alternative [21]. The MODIS nFLH (FLH normalized to solar irradiance) provides a better measure of phytoplankton abundance [22] than satellite-derived Chla because the latter is based on blue-green reflectance ratios, which are sensitive to perturbations by colored dissolved organic matter (CDOM, a water constituent often found in coastal waters due to terrestrial runoff). Although nFLH is sensitive to perturbations by resuspended sediments [23], visual inspection of the enhanced red-green-blue (ERGB) image can differentiate sediment-rich from sediment-poor waters [20]. The MODIS standard data products are currently being generated and distributed through a Virtual Antenna System (VAS) daily in near real time by the Optical Oceanography Laboratory of the University of South Florida [24]. Through a Web interface, a user can search and browse a calendar for images of interest [Fig. 2(a)].

Once a bloom is detected by either the Chla or other MODIS products, the spectral shape in the blue-green wavelengths [25] or the backscattering efficiency [18], [26] is checked to determine whether the bloom is due to *K. brevis* or other nontoxic phytoplankton. Each method has its own advantages and disadvantages under different conditions, and recent evaluations suggested that the performance of these approaches is comparable [25], [27].

At present, federal and state agencies in the U.S. operationally use two of the aforementioned approaches to monitor *K. brevis* blooms in the Gulf of Mexico. Specifically, the National Oceanographic and Atmospheric Administration (NOAA) HAB Operational Forecast System combines

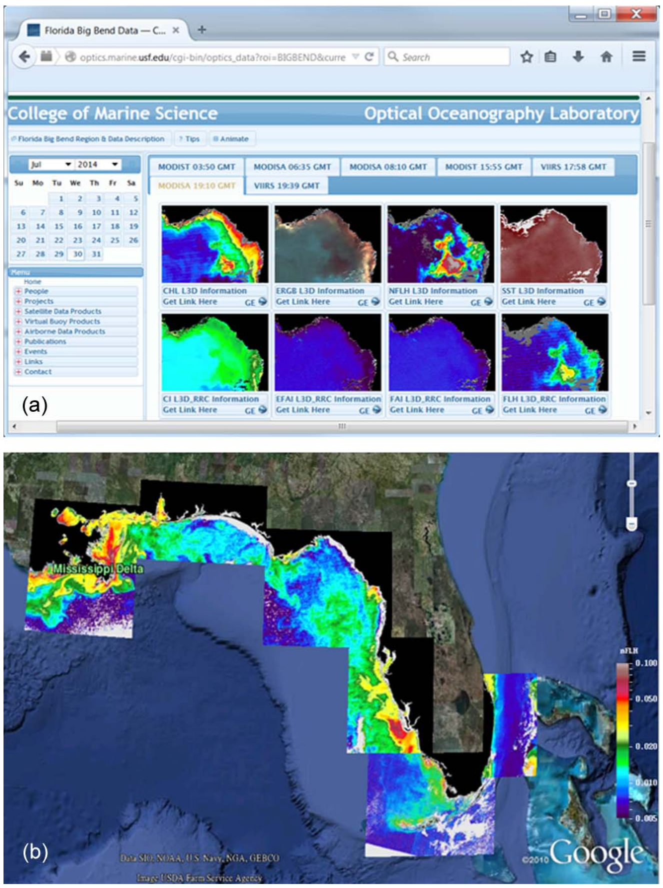

Fig. 2. (a) Examples of the VAS-produced satellite data products at optics.marine.usf.edu. The screenshot shows the various images captured by several satellite sensors on July 30, 2014, over Florida's Big Bend region. (b) For HAB monitoring, the eastern GOM is divided into several subregions to facilitate visualizing the medium-resolution (250 m–1 km) images.

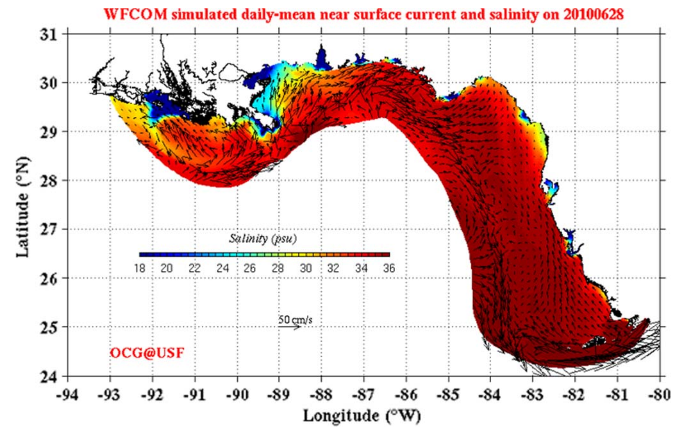

Fig. 3. Domain for the WFCOM nowcast-forecast model (surface velocity and salinity shown). Resolution for each is degraded for plotting purposes. Near-real-time and historical products are available at http://ocgweb.marine.usf.edu.

monitoring data collected by the FWC and other partners, meteorological and oceanographic data, and the Chla-anomaly and spectral curvature [16], [25] to forecast bloom movement and respiratory irritation for coastal regions of Florida and Texas. These forecasts are used to create bulletins (tidesandcurrents.noaa.gov/hab/) for general and scientific audiences. The FWC uses the MODIS nFLH data product [19] to inform sampling and produce integrative data products, including status maps (MyFWC.com/RedTideStatus), for its end users.

3) Numerical Models: The west Florida continental shelf (WFS) is located in eastern Gulf of Mexico and has a broad gentle slope. Circulation of the WFS is controlled by local (e.g., tides, river inputs, winds, and surface net heat fluxes) and remote (i.e., loop current) forcing, as well as interactions between the loop current, shelf, and estuaries [28], [29]. Numerical modeling of WFS dynamics requires inclusion of these different regions (i.e., deep gulf, shelf, and estuaries) and a high-resolution framework to resolve the narrow inlets connecting the estuaries and their adjacent coastal water regions. The West Florida Coastal Ocean Model (WFCOM) accounts for both local and deep-ocean forcing by nesting the Finite Volume Coastal Ocean Model (FVCOM, [30]) into the Hybrid Coordinate Ocean Model (HYCOM, [31]) and adding eight principal tidal constituents along the open boundary. A detailed description of the WFCOM construct, including a quantitative gauging of the model simulation performance against *in situ* observations for calendar year 2007, is provided by Zheng and Weisberg [29]. Currently, the surface wind and heat fluxes are interpolated from the NOAA's National Centers for Environmental Prediction Weather Research and Forecasting (WRF) NAM data (http://nomads.ncep.noaa.gov:9090/dods/nam/). The freshwater data are collected from the United States Geological Survey (USGS, waterdata.usgs.gov) to drive the model by either point or line sources, depending on the grid size and the width of rivers. Satellite-derived sea surface temperature (SST) is used to relax the modeled SST to correct the surface net heat fluxes. Model performance is quantified through the use of Tampa Bay Physical Oceanographic Real-Time System measurements (PORTS), sea level data collected at NOAA tidal gauges, and from West Florida Shelf velocity and other data collected from the University of South Florida's Coastal Ocean Monitoring and Prediction System (COMPS) buoys.

WFCOM was recently modified to extend to the west of the Mississippi River Delta (Fig. 3), to nest into the Gulf of Mexico HYCOM, and to include actual river inflows [32]. The model has a spatial resolution tapering to 150 m within the inlets, thus resolving the connections across the Florida Keys to the Florida Current and the interactions between the continental shelf and the estuaries. WFCOM is run daily with automated products (one day hindcast, one day nowcast, plus two and half day forecast) available at http://ocgweb.marine.usf.edu.

4) Objective: Integration, User-Friendly Information Delivery: Although field measurements, satellite remote sensing, and numerical modeling each individually generate specific data products relevant to HAB monitoring, these products are distributed in different formats from different sources and alone cannot individually provide a complete picture of bloom status or dynamics. For example, it is difficult to differentiate water masses from a single satellite image; field data provide validation of imagery. Furthermore, without satellite imagery, it is difficult to put *K. brevis* cell abundance data in context, even when the data are displayed directly on a map, as the points are often noncontiguous and few. An effective HAB monitoring system therefore requires integration of products from multiple

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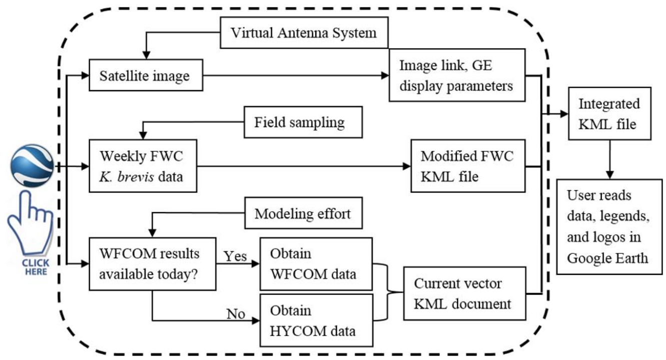

Fig. 4. Schematic flowchart showing various data layers and the steps to integrate them into Google Earth. A sample result is shown in Fig. 5.

disciplines [33], [34]. Hence, the objective of this effort is to integrate the aforementioned products through a common Web portal to facilitate interactive visualization and analysis for both researchers and the public in near real time.

II. Integration Methods

Integration is a multistep process (Fig. 4), described in detail in the following discussion. Google Earth (GE) provides the platform used to integrate data. Using Keyhole Markup Language (KML, an XML subset used to express visualization and geographic annotation), a KML file provides GE the information it needs to superimpose data products (Figs. 1 and 2), thereby offering management a tool beyond the capabilities of a normal Web browser. This integrated product is comprised of three components: satellite imagery, *K. brevis* cell abundance data, and current vector data.

Details on generation of satellite data products in near real time through the VAS are described in Hu *et al.* [24]. Briefly, low-level satellite data from MODIS and VIIRS are obtained from the NASA Goddard Space Flight Center through subscriptions to data from specific regions of interest (ROIs). The time-based job scheduler (termed "cron") is used to run programs written in-house that regularly check each ROI subscription for new satellite data. Once available, data are downloaded and processed using both NASA standard algorithms (through the software package SeaDAS) and other customized algorithms to generate products in near real time (with a ~4–8 hour delay from the satellite overpass). This job stream is managed by S4P software [35] with additional in-house programs. Satellite data are processed in near real time and then reprocessed four days later using updated ancillary data. For the integrated HAB product in the eastern GOM, six ROIs are defined [Fig. 2(b)].

FWC independently creates KML files that display map layers of *K. brevis* cell abundance data in GE (e.g., Fig. 1). To ensure that the most up-to-date information is made available, cron jobs attempt to download new FWC KML files on a daily basis. The KML files are typically created on each Friday, covering the calendar week. After being downloaded, the FWC KML files are renamed to be easily associated with a particular week of a year. If new data are found, older data are overwritten. While the *K. brevis* cell abundance data within these files are displayed in the integrated product, the FWC KML files are

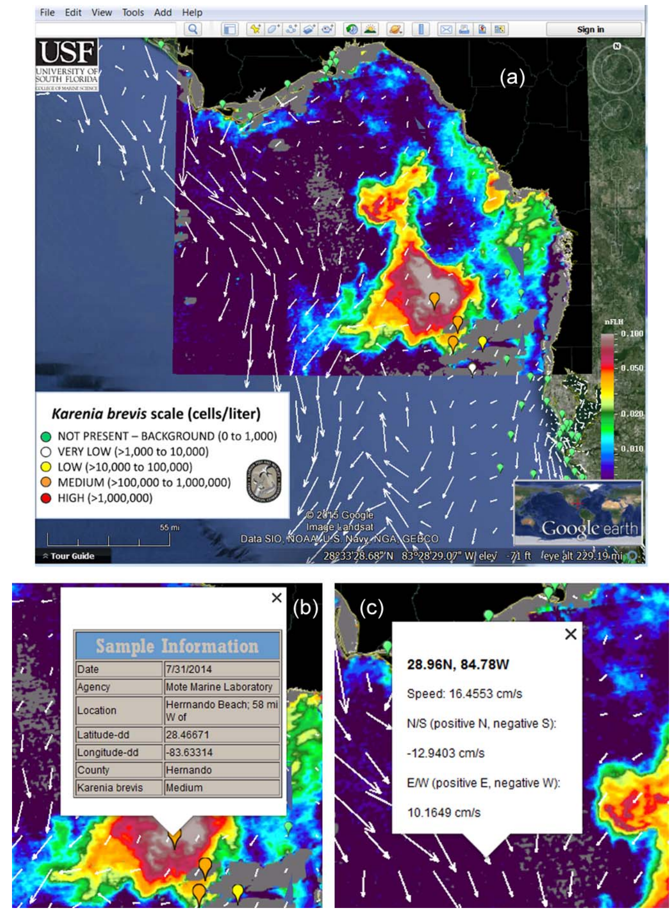

Fig. 5. Example of the integrated data product for the Florida's Big Bend region after a mouse click on the GE icon (Fig. 4). For illustration purposes, these are screenshots of mouse clicks on the various features. (a) Three types of data (satellite image, *K. brevis* cell counts, and surface currents) are brought into Google Earth through a simple mouse click. The background satellite image is MODIS nFLH on July 30, 2014; the current vectors are hindcast products for the same day; the cell count data are for that week. (b) Information on each cell count location is displayed in detail through a mouse click. (c) Information on surface currents (speed and direction) at each location (arrow) is also available through a mouse click.

modified for easier visualization with the other data sources. For example, the symbol sizes and colors are modified to make the cell abundance data more apparent when overlain on satellite images, and county boundaries are removed to reduce file size in the final product. Within GE, each *K. brevis* cell abundance record ("balloon"), when clicked, will display specifics on sample collection (date, location, and depth) as well as the numerical cell abundance [Fig. 5(b)].

On a daily basis, WFCOM makes forecast (2.5 days forward), nowcast (today), and hindcast (yesterday) data available on a webserver as ASCII files with four components: longitude, latitude, and the u- and v-vectors of ocean currents in cm s^{-1}. As with the FWC data, a cron job retrieves these files daily and begins processing the data into KML format. For each model result (i.e., geographic location), the current vector is transformed through trigonometric computations and written into a KML document as a "placemark." This "placemark" defines an arrow as well as associated instructions (on arrow size and position) for display in GE. Furthermore, when the arrow is clicked in the GE, a description of the arrow's starting

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location, the current speed, and the u- and v-components are revealed [Fig. 5(c)]. The transformed current vector KML document is stored in ZIP file format. As updated data become available, previous nowcast data are overwritten with hindcast data. Although WFCOM provides the best model results, lower resolution HYCOM current vectors are also available. While not included in the KML files created for the eastern GOM regions, HYCOM data are queried, downloaded, and formatted directly from the OpenDAP servers (https://hycom.org/) on a daily basis. This ensures redundancy in the case that WFCOM is delayed or unavailable, as the lower resolution HYCOM model results can be used as alternatives for data integration.

Finally, the last step in establishing an effective data integrated HAB monitoring system is to provide users a means to select images of interest and display them seamlessly in GE. As described in Hu *et al*. [24], once an ROI is selected (under "Satellite Data Products" on optics.marine.usf.edu), a program is called to write xhtml code that provides the user interface and displays visual thumbnails of the satellite data [Fig. 2(a)]. Several products are created for each satellite pass over each ROI, including those associated with red tide bloom detection: Chla, nFLH (for MODIS only), red-green-blue (RGB) composites, and enhanced RGB (ERGB) composites. Located underneath each thumbnail is a GE button that, when clicked, begins creation of a KML file in memory which is sent to the user (Fig. 4). This KML file contains the geolocation information (latitude and longitude bounds) of the specified satellite image, URL reference to the image file, URL reference to a corresponding color legend, and region-specific parameters for display in GE. Also integrated into this KML file are the modified FWC KML file (as a network link) and the corresponding current vector KML document.

Creating this integrated KML file on demand ensures that the most accurate satellite imagery available is combined with the most up-to-date *K. brevis* cell abundance data and current vectors. Since all of these products are updated automatically, the same GE button will thus produce a different integrated KML file as new data become available. As such, users are provided with a constantly updated tool with which to identify and monitor red tides in the eastern Gulf of Mexico.

III. Applications

The integrated system (Fig. 5) has been available online for users to obtain red-tide-related information since 2012. Note that the integrated product is brought to the user through one single mouse click on a GE button [shown in Fig. 2(a)]. The integrated map shows all three data layers: satellite image (in Fig. 5, this is a MODIS nFLH image from July 30, 2014), *K. brevis* cell abundance for the week encompassing the satellite image overpass (note that the *K. brevis* KML files are updated every Friday), and current vectors from WFCOM hindcast. Within GE, a user can choose to turn on/off each of the three data layers. Furthermore, a user can click on each cell count location or current vector location (arrow) to display the detailed information about the cell abundance data and the current speed and direction, as shown in Fig. 5(b) and (c), respectively.

This system has been used by FWC, the state agency responsible for HAB monitoring and management in Florida, to

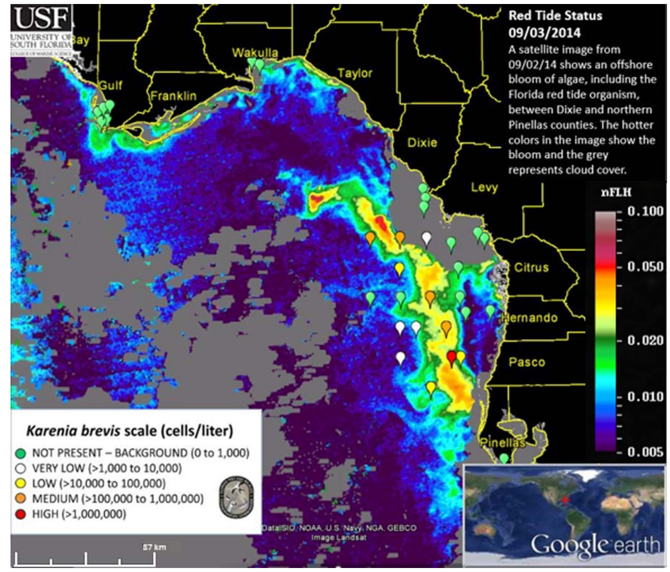

Fig. 6. Example of an FWC red tide bulletin based on the integrated monitoring system shown in Fig. 5(a). For clarity, the surface currents are removed, but interpretation of the image content is annotated by a human analyst. This type of bulletin is distributed routinely to various stakeholders.

trigger event response sampling, direct sampling efforts, and fill major data gaps. Importantly, the MODIS nFLH data product provides a spatial context for routine monitoring and event response. Once the satellite-detected features are confirmed with concurrent *K. brevis* abundance data, images can provide specific dimensions of surface blooms and fill major data gaps, particularly in offshore waters that are infrequently sampled. The current vectors overlaid on the image provide visualization on the potential transport of the surface bloom. This information is interpreted by a red tide analyst, with narratives annotated on the integrated map and subsequently disseminated to a variety of stakeholders (Fig. 6).

An example on how the system has been used is given in Hu *et al*. [36]. An offshore bloom near the Florida's Big Bend region (Fig. 1) was first captured in MODIS nFLH imagery in late June 2014, which (in combination with reported fish kills) triggered several targeted offshore surveys in July, August, and September. The adaptive cruise surveys not only collected bloom-relevant biophysical and optical data around the bloom (e.g., Fig. 6) but also provided validation of the MODIS observations and numerical circulation model. In turn, such integrated information was updated routinely (and in near real time whenever new data were available) and disseminated by FWC to various stakeholders (through an e-mail listserv) for decision making.

The examples shown in Figs. 5 and 6 are for illustration purposes only. In practice, the integration is made with all available image types (e.g., Chla, ERGB, and SST), user-specified date ranges for cell abundance data, and across all ROIs shown in Fig. 2(b). Once brought to GE, each image type can be turned on/off by a user; thus, information from different images can be visualized. To date, these products have provided an effective means to monitor the coastal environment. According to Web usage statistics, from 2013 to the present, GE products on optics.marine.usf.edu (which include the integrated GE

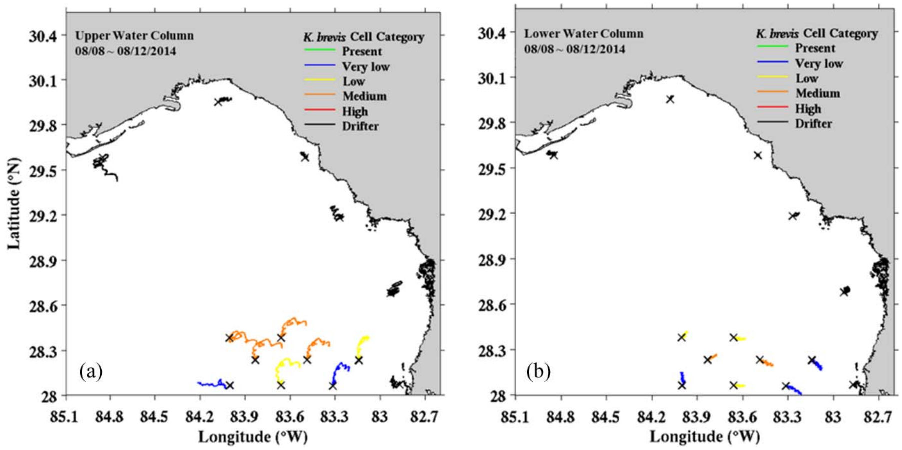

Fig. 7. (a) 3.5-day surface and (b) bottom trajectories of *K. brevis* generated by the WFCOM model. The initial concentrations were determined from water samples collected on 08/06–08/2014. Data products for and other regions in the eastern GOM are available in near real time at http://ocgweb.marine.usf.edu/hab_tracking/HAB_trajectories.html.

product) average approximately 28 000 hits and distribute over 8 GB of KML data on a monthly basis to users in academia, government, and private sectors.

Although field observations, satellite remote sensing, and numerical modeling individually provide critical information on HAB monitoring, none of them delivers a complete picture without others [13]. The Web-based integration of these components into a user-friendly format represents a milestone in HAB detection and tracking. In particular, the overlay of the surface current vectors and the ability to "read" the current speed and direction at any location provide a crude way to estimate the potential movement of the identified HABs, representing a short-term forecasting tool to trace surface movement of the HABs.

IV. Discussion

Although the integrated system has not been evaluated comprehensively (by all stakeholders) or by rigorous statistics, validation and accuracy assessment of the individual components have been available in the literature. The bloom detection by MODIS nFLH imagery has similar performance to other methods [27], with an overall accuracy of about 80% for bloom and nonbloom detections when bloom is defined as waters with *K. brevis* cell abundance of $> 50\,000$ cells L^{-1}. Accuracy may increase or decrease for individual events. For example, for the bloom event between July and September 2014 off the Big Bend region [36], the accuracy of differentiating bloom from nonbloom waters is nearly 100%, although pixelwise comparison showed an accuracy of ~90%. In other cases, the accuracy may be lower due to interferences of non-phytoplankton constituents to the MODIS nFLH signals.

The fidelity of the numerical model in nowcasting and hindcasting surface currents has also been evaluated [29], which showed excellent agreement between modeled and observed currents. For example, comparison between modeled and observed surface current speeds over six buoy stations over the west Florida shelf in 2010 (hourly data after 36-h low-pass filtering to remove tidal oscillations) showed root-mean-square uncertainties of 5 cm s^{-1} ($r = 0.52$, $N > 35\,000$) for a range of 0–45 cm s^{-1}.

While the field sampling component of this integrated system is limited in spatial and temporal coverage due to lack of infrastructure and financial resources, the other two components face several technical challenges. For satellite observations, there is still room for algorithm improvement to increase the detection accuracy, particularly in early bloom stages when cell concentrations are relatively low and water discoloration is not apparent (e.g., approaching 10 000 cells L^{-1}, the lower end of the "low" concentration defined by FWC. In a pure *K. brevis* population, this corresponds to about 0.1 mg m^{-3} Chla). In addition to the accuracy limitation, lack of observations due to frequent cloudcover is currently a major obstacle for daily distribution of satellite imagery in near real time. The use of multiple sensors may reduce cloudcover, yet VIIRS lacks a fluorescence band to detect blooms in CDOM-rich waters [36], thus demanding better algorithms to detect blooms using other visible and/or near-infrared bands.

Similarly, there are some limitations in the modeling component that require further improvement. Because the nested WFCOM relies on the GOM HYCOM to provide the open boundary conditions, the accuracy of the former also depends on the latter. An example is given in [29] when HYCOM did not provide correct location of the loop current near the Dry Tortugas in the second half of 2007, leading to large errors in the WFCOM simulations. Furthermore, WFCOM nowcasts and forecasts currently do not include precipitation/evaporation, which might lead to errors in estuaries or nearshore waters. Finally, the model relies heavily on wind, whose accuracy also plays a critical role in driving the model.

With improvements in detection through refined remote sensing algorithms and additional field observing techniques (e.g., gliders), we envision further development of the integrated products through improving the forecasting capacity. For example, currents in coastal oceans can change rapidly following winds, tides, and deep-ocean circulations. As such, bloom trajectories are better estimated by time-dependent currents, rather than hindcasted vectors. Development of such bloom trajectories has been implemented through the Collaboration for Prediction of Red Tides (CPR), a partnership between FWC and USF (Fig. 7). WFCOM simulations begin at 00:30 A.M. EST each day and finish at around 04:00 A.M. If new cell abundance data have been uploaded by FWC, the model prepares an input file for the tracking program. During this processing, the model selects recent *K. brevis* cell abundance data and subdivides them according to vertical position (upper or lower) in the water column. Particles are released in the WFCOM model based on the latitude, longitude, and depth of the cell abundance measurements, and their simulated movement is tracked to calculate the particle trajectories. Once finished, the surface and bottom trajectories are plotted [Fig. 7(a) and (b), respectively] and then automatically uploaded to the Web at http://ocgweb.marine.usf.edu/hab_tracking/HAB_trajectories.html. When data from the FWC are not available, fixed drifter stations at predetermined locations are used to fill the spatiotemporal gaps in data collection. The combination of real and artificial data provides a powerful tool for managers to forecast HAB trajectories. Therefore, our immediate next step in data integration will need to incorporate such a tool with the Google-Earth-based integration framework as described previously.

Furthermore, we recognize that monitoring of HABs requires coordinated efforts from many stakeholders, and there are several comprehensive Coastal Ocean Observing Systems (COOS) within the GOM with specific tasks of data integration. Such COOS include the Gulf of Mexico Coastal Ocean Observing System (GCOOS), the Southeast Coastal Ocean Observing Regional Association (SECOORA), and the Harmful Algal BloomS Observing System (HABSOS). However, these are designed to provide comprehensive access to a large suite of oceanographic data (e.g., SST, sea surface salinity (SSS), and sea surface height (SSH), among others) with an emphasis on historic data. The completeness of these systems is often compromised by the speed of data access and display. In contrast, the integrated products through Google Earth demonstrated here are specifically developed for stakeholders in HAB monitoring and response efforts. The simplicity of the data access and display enables an especially effective communication tool, which is therefore well suited for use by all stakeholders and in particular by members of the public.

V. CONCLUSION

Effective monitoring of *K. brevis* blooms in the Gulf of Mexico requires a coordinated and sustainable system for observations and forecast. While research efforts have led to progress in all aspects of bloom monitoring, including field measurements, satellite remote sensing, and numerical modeling, the work presented here represents one step further to integrate the data products from these efforts to a user-friendly format through a Web portal. In particular, the integrated Google Earth product is vital to making HAB data easily available and interpreted by a broad user base, as the data integration was designed with stakeholder needs in mind. The Web-based monitoring system has been serving the community through sharing integrated data products in near real time and is expected to improve in the near future as products are refined (through algorithm development) and as new forecasting data products are incorporated.

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