Harmful Algae 29 (2013) 22–30

Contents lists available at ScienceDirect

Harmful Algae

journal homepage: www.elsevier.com/locate/hal

Three-dimensional structure of a *Karenia brevis* bloom: Observations from gliders, satellites, and field measurements

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ARTICLE INFO

Article history:
Received 19 February 2013
Received in revised form 23 July 2013
Accepted 23 July 2013

Keywords:
FVCOM model
Glider
Harmful algal blooms (HABs)
Karenia brevis
Remote sensing
Upwelling

ABSTRACT

Autonomous underwater gliders with customized sensors were deployed in October 2011 on the central West Florida Shelf to measure a *Karenia brevis* bloom, which was captured in satellite imagery since late September 2011. Combined with *in situ* taxonomy data, satellite measurements, and numerical circulation models, the glider measurements provided information on the three-dimensional structure of the bloom. Temperature, salinity, fluorescence of colored dissolved organic matter (CDOM) and chlorophyll-a, particulate backscattering coefficient, and *K. brevis*-specific chlorophyll-a concentrations were measured by the gliders over >250 km from the surface to about 30-m water depth on the shallow shelf. At the time of sampling the bloom was characterized by uniform vertical structures, with relatively high chlorophyll-a and CDOM fluorescence, low temperature, and high salinity. Satellite data extracted along the glider tracks demonstrated coherent spatial variations as observed by the gliders. Further, the synoptic satellite observations revealed the bloom evolution during the 7 months between late September 2011 and mid April 2012, and showed the maximum bloom size of ~3000 km^2 around 23 November. The combined satellite and *in situ* data also confirmed that the ratio of satellite-derived fluorescence line height (FLH) to particulate backscattering coefficient at 547 nm ($b_{bp}(547)$) could be used as a better index than FLH alone to detect *K. brevis* blooms. Numerical circulation models further suggested that the bloom could have been initiated offshore and advected onshore *via* the bottom Ekman layer. The case study here demonstrates the unique value of an integrated coastal ocean observing system in studying harmful algal blooms (HABs).

1. Introduction

Karenia brevis (*K. brevis*) is a toxic dinoflagellate with both economic and ecological impacts (Kirkpatrick et al., 2004). It produces a suite of potent neurotoxins (brevetoxins) which can cause widespread deaths of fish, birds and marine mammals. Brevetoxins can accumulate in shellfish and cause Neurotoxic Shellfish Poisoning if ingested by humans. Aerosolized toxin can irritate human eyes and respiratory systems, affecting coastal residents and tourists.

Karenia brevis is responsible for most of the harmful algal blooms (HABs) in the Gulf of Mexico. *K. brevis* HABs occur near annually on the West Florida Shelf (WFS), usually during late summer and fall (Rounsefell and Nelson, 1966; Steidinger and Joyce, 1973; Anderson, 1995; Steidinger et al., 1998; Walsh and Steidinger, 2001; Walsh et al., 2006; Brand and Compton, 2007). A number of studies have addressed bloom dynamics and monitoring methods (Morton and Burklew, 1969; Williams and Ingle, 1972; Steidinger and Ingle, 1972; Steidinger and Joyce, 1973; Steidinger and Haddad, 1981; Anderson, 1995; Steidinger et al., 1998; Walsh and Steidinger, 2001; Stumpf et al., 2003; Hu et al., 2005, 2008; Walsh et al., 2003, 2006; Brand and Compton, 2007; Cannizzaro et al., 2008, 2009; Vargo, 2009; Weisberg and He, 2003; Weisberg et al., 2009; Carvalho et al., 2010; Lenes et al., 2012). Vargo (2009) provided a review on the environmental factors related to the distribution, growth, primary production, nutrient requirements and nutrient utilization, along with hypotheses

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http://dx.doi.org/10.1016/j.hal.2013.07.004

about the mechanism of initiation, growth, maintenance and demise of HABs on the WFS.

Timely detection of *Karenia brevis* blooms is important for ecological assessment and resource management. Conventional methods of shipboard observations and laboratory microscopic taxonomy are expensive and time consuming, thus limiting spatial and temporal coverage. This can be complemented by satellite observations once reliable algorithms are developed to detect and quantify the HABs. However, satellite measurements are limited to detection of blooms in surface waters under optimal conditions (*e.g.* minimal cloud cover and sun glint).

Over the past decade, the benefits of integrating autonomous underwater vehicles (AUVs) into ocean observing systems have become clear (Curtin and Bellingham, 2001; English and Carder, 2006; Fiorelli et al., 2006; Schofield et al., 2007; Boss et al., 2008; Weisberg et al., 2009). Gliders are lightweight and characterized by long duration deployments and low operation costs, allowing for measuring spatial time series and capturing intermittent, unpredicted, and short-lived episodic events (Glenn et al., 2008). For example, Perry et al. (2008) used optical data collected by gliders in the NW Atlantic to show that an apparent autumn bloom, as detected by satellite imagery, was actually a vertical redistribution of phytoplankton from the subsurface chlorophyll-a maximum. Fox et al. (2009) showed how the spring diatom bloom in the Strait of Georgia developed and evolved. Frajka-Williams et al. (2009) investigated the 2005 spring phytoplankton bloom in the Labrador Sea using a glider, and showed the unique value of glider measurements in studying physical–biological interactions. Asper et al. (2011) used gliders to observe the annual phytoplankton bloom in the Ross Sea. More recently, Xu et al. (2011) studied the seasonal variability of physical and optical properties in the Mid-Atlantic Bight using a combination of glider and satellite observations.

Nearly all previous observations of *Karenia brevis* blooms on the WFS have used *in situ* or satellite measurements, where the 3-dimensional (3-D) distributions of *K. brevis* blooms are largely unknown. Several studies have shown processes at depths (*e.g.* upwelling) using numerical models and vertical profiles at fixed locations (Walsh et al., 2003, 2006; Lenes et al., 2008, 2012; Weisberg and He, 2003; Weisberg et al., 2004, 2009, in press). The only proof-of-concept study using AUVs was conducted by Robbins et al. (2006), who deployed an AUV equipped with an optical phytoplankton discriminator (OPD, Kirkpatrick et al., 2000, 2003) to map the *K. brevis* bloom in 2005, track its movements, and examine the relationships between OPD data and temperature, salinity, chlorophyll-a, cell concentration, and ocean currents. However, the deployment lasted only for about 10 h with a total transverse distance of 14 km. To our knowledge, although subsurface chlorophyll-a maxima of some phytoplankton species such as diatoms are common (Smayda, 2002; Perry et al., 2008; Fox et al., 2009), continuous glider measurements of the 3-D structure of *K. brevis* blooms over large spatial and temporal scales on the WFS have not been recorded. Thus, the main objectives of this study were to measure, document, and describe the 3-D structure of a long-lasting *K. brevis* bloom on the WFS in fall 2011. We will first describe the 3-D structure of the bloom using *in situ*, satellite, and glider data. Then, the linkages between physical and optical properties will be explained. Finally, the unique role of using gliders to sample *K. brevis* blooms, as a component of an integrated observing system, will be discussed.

2. Data and methods

2.1. Glider deployment, data collection and processing

Two gliders were deployed to sample the *Karenia brevis* bloom during fall 2011. The Bass glider from University of South Florida was deployed on the central WFS from 12 October to 8 November 2011. The CTD measurements provided information on the ocean's physical state such as conductivity, temperature, and density. A customized Eco-Triplet (WET Labs Inc.) measured particulate backscattering coefficient of red light (685 nm, $b_{bp}(685)$) at 117° and fluorescence of chlorophyll-a and colored dissolved organic matter (CDOM). The sensors were calibrated before and after the field deployment. Further details of the glider payloads and deployment procedures can be found in English et al. (2009).

Two transects of the Bass glider between 22 and 29 October 2011 passed through the bloom region (Fig. 1). Data outliers were often found from the profiles of particulate backscattering and fluorescence of chlorophyll-a and CDOM due to instrument noise. The outliers were removed in the following way: the 95% confidence interval for every seven continuous data points (covering a depth interval of 1–1.5 m) was calculated, and the data point outside the 95% confidence interval was defined as an outlier and substituted with the median value of the remaining data points. Outliers in temperature and salinity data were also filtered in a similar manner. To compare with satellite data at 1-km resolution, the glider data were binned to a horizontal resolution of 1 km and vertical resolution of 1 m.

Another glider, equipped with the customized sensor package BreveBuster (Robbins et al., 2006; Kirkpatrick et al., 2008), was deployed by the Mote Marine Laboratory between 12 and 20 October 2011. The BreveBuster estimates the taxonomic composition of the phytoplankton community through the analysis of hyperspectral particle absorbance measurements. Water was pumped through a liquid waveguide capillary cell (LWCC). A tungsten/deuterium fiber-optic light source injected full spectrum visible light into the water path and a miniature fiber-optic spectrometer recorded the transmission spectrum. Spectral absorbance was calculated from the transmission spectrum, and the fourth-derivative spectrum of the absorbance was calculated for the sample. Multiple regression analysis found the best least-square fit of the multiple fourth-derivative spectra from a spectral library pre-defined from known uni-algal cultures. The resultant best-fit mix was binned into taxonomic classes providing the chlorophyll-a biomass attributable to each class. The BreveBuster passed those results to the laboratory during periodic data telemetry. The BreveBuster allowed determination of the phytoplankton community structure including *Karenia brevis* when *K. brevis* specific chlorophyll-a was >0.3 mg m^{-3} (corresponding to roughly 30,000–100,000 *K. brevis* cells L^{-1}). The BreveBuster glider also carried the same CTD sensor as on the Bass glider.

2.2. Satellite data collection and processing

MODIS/Aqua and MERIS data were obtained from NASA Goddard Space Flight Center and processed using calibration and algorithms in the SeaDAS software package (version 6.2). The data products included spectral normalized water-leaving radiance (nL_w, mW cm^{-2} μm^{-1} sr^{-1}), normalized fluorescence line height (FLH, mW cm^{-2} μm^{-1} sr^{-1}), and particulate backscattering coefficient at 547 nm ($b_{bp}(547)$, m^{-1}) derived from the spectral nL_w using the quasi-analytical algorithm (Lee et al., 2002). Following the approach of Hu et al. (2011), three products were used to differentiate *Karenia brevis* blooms from other features in this optically complex region. The enhanced Red-Green-Blue (ERGB) composite images, generated from the nL_w data at 547 nm (R), 488 nm (G), and 443 nm (B), were used to differentiate dark features (due to strong absorption by phytoplankton and/or CDOM) from bright features (due to sediment resuspension and/or shallow bottom reflection). FLH images were used to differentiate phytoplankton blooms from the dark