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VIIRS captures phytoplankton vertical migration in the NE Gulf of Mexico

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ABSTRACT

In summer 2014, a toxic *Karenia brevis* bloom (red tide) occurred in the NE Gulf of Mexico, during which vertical migration of *K. brevis* has been observed from glider measurements. The current study shows that satellite observations from the Visible Infrared Imaging Radiometer Suite (VIIRS) can capture changes in surface reflectance and chlorophyll concentration occurring within 2 h, which may be attributed this *K. brevis* vertical migration. The argument is supported by earlier glider measurements in the same bloom, by the dramatic changes in the VIIRS-derived surface chlorophyll, and by the consistency between the short-term reflectance changes and those reported earlier from field-measured *K. brevis* vertical migration. Estimates using the quasi-analytical algorithm also indicate significant increases in both total absorption coefficient and backscattering coefficient in two hours. The two observations in a day from a single polar-orbiting satellite sensor are thus shown to be able to infer phytoplankton vertical movement within a short timeframe, a phenomenon difficult to capture with other sensors as each sensor can provide at most one observation per day, and cross-sensor inconsistency may make interpretation of merged-sensor data difficult. These findings strongly support geostationary satellite missions to study short-term bloom dynamics.

1. Background

Karenia brevis, a toxic algae responsible for most harmful algal blooms (red tides) in the Gulf of Mexico (GOM), is known to migrate vertically with diel cycles to maximize its use of light and nutrients. This phenomenon has been observed and studied numerous times in laboratory cultures (Heil, 1986; McKay et al., 2006; Schaeffer et al., 2009; Levandowsky and Kaneta, 1987; Hand et al., 1965; Hunte, 1986; Kamykowski and Mccollum, 1986; Kamykowski et al., 1988, 1992) and from field measurements (Kerfoot et al., 2004; Schofield et al., 2006). Laboratory studies are, however, under controlled environments that may not represent realistic environmental conditions. Additionally, the limited field measurements of vertical migration only documented the behavior of *K. brevis* at one station, and thus are limited in both space and time. On the other hand, while satellite remote sensing provides synoptic and frequent measurements, most ocean color satellites can only observe the subtropical and tropical oceans at most once a day, making it impossible to observe such diurnal changes unless multiple satellites are combined. One possible exception may be the Visible Infrared Imaging Radiometer Suite (VIIRS, 2012 – present), as its wide swath (3060 km) occasionally allows for two observations during a day at a given location in subtropical oceans.

Between July – September 2014, a *K. brevis* bloom occurred in the NE GOM off Florida's Big Bend region, during which several studies documented the bloom size, intensity, and temporal evolution from field and remote sensing observations (Hu et al., 2015; Qi et al., 2015; Elhabashi et al., 2016). The bloom reached a maximum size of about 7000 km^2 by late July, with maximum *K. brevis* concentration of >1 million cells L^{-1}. Field measurements using a glider suggested vertical migration of *K. brevis* inside the bloom (Hu et al., 2016). At a speed of 0.5–1 m h^{-1}, *K. brevis* started to move upward from a depth of 8–10 m around sunrise, and started to move downward from a depth of ~2 m around sunset. Although *K. brevis* vertical migration was observed in the field at synoptic scale (~30 km) in several consecutive days, the glider measurement was still limited in both space and time due to its slow motion (e.g., about 400 m an hour).

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Therefore, the objective of this study is to test whether a combination of multiple satellite observations can reveal changes in optical properties of the surface waters in the bloom, from which vertical migration may be inferred. Once confirmed, the findings may be particularly useful for supporting future geo-stationary satellite missions that are designed to "stare" at selected ocean regions multiple times a day, for example from the GEO-CAPE mission recommended by the NRC's decadal survey (Fishman et al., 2012Salisbury et al., 2017).

2. Data and method

Level-2 data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard both Terra and Aqua satellites for the bloom period (July - September 2014) were downloaded from NASA Goddard Space Flight Center (http://oceancolor.gsfc.nasa.gov) on 19 April 2016 and mapped to an equidistant cylindrical projection at 1-km spatial resolution. These data contained the standard ocean data products, including spectral remote sensing reflectance (R_{rs}, sr^{-1}) in the visible bands, normalized fluorescence line height (nFLH, mW cm^{-2} μm^{-1} sr^{-1}), surface chlorophyll concentration (Chl, mg m^{-3}), and quality control flags (l2_flags, a 32-bit value for each pixel). Similarly, VIIRS Level-2 data were downloaded from NASA GSFC and also from NOAA STAR CoastWatch from MSL12 processing (ftp://ftp.star.nesdis.noaa.gov/pub/socd1/mecb/coastwatch/viirs/science/L2) about the same time as MODIS download (late April 2016) and mapped to the same equidistant cylindrical projection. The VIIRS data products are similar to those of MODIS, except that nFLH is not available from VIIRS due to its lack of a spectral band around 680 nm. In addition, the particulate backscattering coefficient at 486 nm (b_{bp}486, m^{-1}) and multispectral total absorption coefficients ($a_t(\lambda)$, m^{-1}) were derived from the latest version (version 6; http://www.ioccg.org/groups/Software_OCA/QAA_v6_2014209.pdf) of the Quasi-Analytical Algorithm (QAA) (Lee et al., 2002).

Because of the availability of VIIRS data products from both NASA and NOAA, they were first evaluated to determine which to use in this study. Indeed, although there are slight differences in the aerosol model look up tables (LUTs) and in the vicarious calibrations between the NASA L2GEN processing and NOAA MSL12 processing, the principles of deriving the Level-2 data products are identical, and their R_{rs} spectra in the green and red bands are very similar. Yet L2GEN R_{rs} spectra shapes in the blue wavelengths appeared to be slightly off for the study region at large viewing angles (not shown here), possibly due to residual errors of polarization correction. Therefore, in this study, VIIRS data from the MSL12 processing were used.

After applying the quality control flags to remove low-quality data, five products were examined: 1) the default blue-green band ratio Chl (OC3, Oreilly et al., 1998), which is available to the user community as a standard data product for both MODIS and VIIRS [note that although recent algorithm updates switched to the hybrid OCI algorithm (Hu et al., 2012), for coastal waters where Chl is >0.25 mg m^{-3} the default algorithm is still OC3]; 2) a new red-green band ratio Chl (RGCI, Le et al., 2013; Qi et al., 2015), which is only available from VIIRS because one of its spectral bands (662–682 nm) partially covers the spectral range of chlorophyll fluorescence; 3) R_{rs} in the visible bands. While the Chl images were used to examine spatial patterns of the bloom, R_{rs} spectra from representative locations outside and inside the bloom were extracted for further analysis and interpretation; 4) b_{bp}486, a measure of particulate concentration in the upper layer; and 5) $a_t(\lambda)$, a measure of absorption in the upper layer.

An ocean glider was deployed from 1 to 16 August 2014 to sample the *K. brevis* bloom and its surrounding environment. The details of the deployment and its measurements can be found in Hu et al. (2016), where glider data showed vertical migration of phytoplankton in several consecutive days. The upward migration appeared to start around sunrise at a depth of 8–10 m, while the downward migration appeared to start around sunset at a depth of ~2 m. The glider data were binned to image pixel size in Hu et al. (2016), but in this study the glider data were binned in time (every 30 min) and depth (every 1 m) in order to visualize temporal changes. Note that due to cloud cover and measurement logistics glider data were not collected on the same day as the VIIRS measurements examined below.

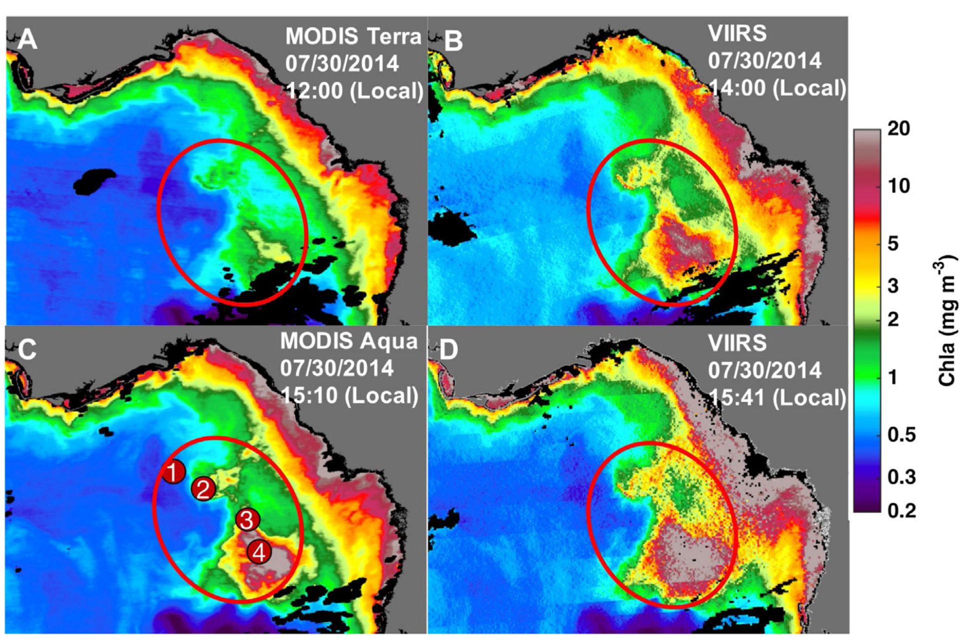

Fig. 1. MODIS and VIIRS OC3 Chl images on 30 July 2014 showing changes in Chl within 3 h 40 min, yet it is believed that some of these observed changes are due to algorithm artifacts and cross-sensor inconsistency. Therefore, they are presented here only to show the bloom's spatial pattern. Four locations (annotated as 1–4) outside and inside the bloom were selected to examine their R_{rs} spectral characteristics.