GOES Imager Shows Diurnal Changes of a *Trichodesmium erythraeum* Bloom on the West Florida Shelf

Chuanmin Hu and Lian Feng

**Abstract**—The advantages of geostationary observations of sediment plumes and phytoplankton blooms have been reported for coastal waters in the southern North Sea and west Pacific. So far, similar observations have not been possible for the Gulf of Mexico where blooms of *Trichodesmium erythraeum* often occur. Here, using data collected by the Geostationary Operational Environmental Satellite (GOES) Imager, we document diurnal changes of a *Trichodesmium* bloom first identified by the Moderate Resolution Imaging Spectroradiometer (MODIS). Despite the low-signal-to-noise ratio (∼46:1 for typical ocean radiance), the 550–750-nm band revealed clear patterns of *Trichodesmium* mats floating on the ocean surface and their temporal changes between 14:15 and 22:30 GMT on May 22, 2004. Normalization of the delineated bloom against the ocean background provided an effective atmospheric correction that enabled quantification of the changes in bloom size (i.e., area) and bloom intensity over the course of a day. The area coverage increased by about eightfold from midmorning (14–15 GMT) to reach its maximum around 18:30 GMT, whereas the mean intensity of the bloom area increased by ∼22% from midmorning to 17:30 GMT. In the afternoon, while the bloom area remained relatively stable on the water surface, bloom intensity sharply decreased. These temporal patterns may be caused by physical aggregation and/or vertical migration of the *Trichodesmium* cells, and they agree well with the diurnal changes of a harmful algal bloom of the dinoflagellate *Prorocentrum donghaiense* in the East China Sea observed by the Geostationary Ocean Color Imager.

**Index Terms**—Algal blooms, diurnal changes, geostationary, Geostationary Coastal and Air Pollution Events (GEO-CAPE), Geostationary Operational Environmental Satellite (GOES) Imager, Gulf of Mexico (GOM), oil spill, remote sensing, Spinning Enhanced Visible and Infrared Imager (SEVIRI), *Trichodesmium*.

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**I. INTRODUCTION**

**SATELLITE** remote sensing provides synoptic and frequent measurements of the ocean, and thus, it is ideal for studying large-scale changes in the ocean’s biological, optical, physical, and geochemical properties. Most previous studies have focused on seasonal or interannual changes, as the near-daily measurements are insufficient to document short-term (e.g., diurnal) changes. A recent study using the geostationary Spinning Enhanced Visible and Infrared Imager (SEVIRI) has demonstrated the ability to detect diurnal changes of sediment plumes in the southern North Sea [15]. The launch of the Geostationary Ocean Color Imager (GOCI) by the Korea Ocean Satellite Center in June 2010 represented a milestone in ocean color remote sensing [17]. With a 500-m nadir resolution, GOCI provides eight measurements a day over the Northeast Asian region from 9:30 A.M. to 4:30 P.M. Korea time. GOCI not only increases the number of cloud-free observations but also provides data critical to understanding short-term dynamics in the ocean environments. For example, preliminary studies show that GOCI data have the potential to study diurnal changes of suspended sediments, chlorophyll-a concentration (Chl), floating macroalgal patches, and harmful algal blooms (HABs) [2], [6], [12], [13], [19]. A recent review by Ruddick et al. [16] provides more details on the potentials and challenges of geostationary ocean color satellites.

While these pioneering studies using geostationary satellites show potentials for documenting short-term ocean changes, there is a lack of data to conduct similar studies of bloom dynamics for the Gulf of Mexico (GOM), a large semi-enclosed sea with world-renowned resources such as oil and corals. Although the U.S. NASA is planning the Geostationary Coastal and Air Pollution Events (GEO-CAPE, [3]) mission, the mission implementation will take several years and the satellite will not be launched until at least 2020. Thus, alternative methods must be sought out to study short-term changes of ocean’s properties.

A combination of the two Moderate Resolution Imaging Spectroradiometers (MODISs) on the Terra (morning pass) and Aqua (afternoon pass) satellites may occasionally show the progression of sediment plumes in the GOM within 2–3 h [1]. However, the orbital characteristics and the 2330-km swath make such observations opportunistic as there are at most two observations a day for the subtropical oceans. On the other hand, meteorological geostationary satellites such as the Geostationary Operational Environmental Satellite (GOES) series
have been operated by the U.S. NOAA since the 1970s. The GOES Imager is equipped with a broadband at 550–750 nm. Although this band was designed to map clouds and therefore has low-signal-to-noise ratio (SNR) over the cloud-free ocean surface (46:1 for a typical signal at solar zenith angle of 45°, with SNR roughly proportional to the square root of the input signal [10]), it may be possible to use this band to detect and track some bright features in the ocean. Such features include *Trichodesmium erythraeum* bloom mats, which show enhanced reflectance in the red and near-infrared (NIR) bands [9], [21]. Indeed, low SNR satellite instruments such as Advanced Very High Resolution Radiometer have been used in the past to map sediment plumes [20]. Thus, the primary objective of this letter is to test the feasibility of using GOES Imager data to observe the diurnal changes of *Trichodesmium* blooms in the GOM. MODIS-identified *Trichodesmium* blooms on the West Florida Shelf (WFS) off Charlotte Harbor were chosen to test such feasibility. The second objective of this letter is to document diurnal changes of the MODIS-identified *Trichodesmium* bloom. The bloom was identified with high floating algae index (FAI, [7]) values with *Trichodesmium*-specific spectral curvatures in the blue-green part of the MODIS reflectance spectra (see [9, Fig. 1]).

II. DATA AND METHODS

There are currently two GOES satellites at 135°W and 75°W, respectively, whose 550–750-nm broadband measures the Earth at approximately 1-km resolution every 3 h for the full-disk and every 15 min for the continental U.S. under three operational modes. The measurement covers a range of 1.6%–100% total reflectance (albedo) with radiometric uncertainties of ±5% at maximum scene radiance. GOES-12 Imager data were downloaded from NOAA Comprehensive Large Array-Data Stewardship System (CLASS) for all three operational modes. For the bloom case identified by MODIS (see Fig. 1), between 14:00 and 22:25 (GMT) of May 22, 2004, 49 granules covering the GOM were acquired, each taking approximately 10 min. Similarly, for another MODIS-identified bloom case on August 4, 2007, all available GOES data were downloaded. To compare ocean properties retrieved from multiple images at different solar angles, the total at-sensor radiance should be corrected for the atmospheric effects. However, there is only one 550–750-nm band, making traditional atmospheric correction difficult [4], [22]. Thus, a simple correction method was developed and applied to all granules. For all granules, a common region of interest (ROI) was delineated to encompass the bloom feature. Then, for each granule, the bloom feature was delineated with a carefully selected threshold, determined as the maximum signal from a background box close to the ROI. To avoid potential errors caused by image noise, a moving window of 3 × 3 pixels was used to delineate the bloom area. For each pixel within the ROI, if more than five of the nearest 3 × 3 pixels had signals greater than the threshold, the pixel was considered as a bloom pixel; otherwise, it was classified as a nonbloom pixel. To assure cross-image consistency, a two-step image normalization approach was used. First, each pixel value of the delineated bloom feature $I_{\text{raw}}$ was referenced against the nearest bloom-free pixels outside the ROI ($I_{\text{water}}$):

$$I_{\text{corrected}} = I_{\text{raw}} - I_{\text{water}}$$

Then, the corrected radiance value $I_{\text{corrected}}$ was normalized to the surface downwelling irradiance $E_d$

$$I_{\text{normalized}} = I_{\text{corrected}} / E_d = (I_{\text{raw}} - I_{\text{water}}) / E_d$$

where $E_d$, as a function of time, location, and atmospheric properties (i.e., surface pressure, ozone, water vapor, and aerosols), was estimated using a radiative transfer model [5]. Here, $I_{\text{normalized}}$ represents an image-independent index for cross-image comparison in the absence of an explicit atmospheric correction, as long as the bloom-free reference pixels remain stable during the course of a day. This is because, from radiative transfer theory, we have

$$I_{\text{raw}} = I_{\text{path}} + tL_{\text{raw}}$$

$$I_{\text{water}} = I_{\text{path}} + tL_{\text{water}}$$

$$I_{\text{normalized}} = t(L_{\text{raw}} - L_{\text{water}}) / E_d = tR_{\text{rs,raw}} - \text{constant}$$

where $t$ is the diffuse transmittance from the image pixel to the satellite (a constant during the day for geostationary satellites if the atmospheric does not change much), $L$ is the water-leaving radiance, and $R_{\text{rs}}$ is the remote-sensing reflectance. Clearly, $I_{\text{normalized}}$ used in this letter is equivalent to $R_{\text{rs}}$.

For each granule, the bloom feature was characterized by three parameters. The first was the number of pixels delineated as the bloom, representing the size (i.e., area) of the bloom. The second was the mean intensity of the bloom, calculated as the...
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III. RESULTS

Fig. 2(a)–(c) shows several grayscale images from the GOES Imager where the Trichodesmium bloom mats, corresponding to those shown in the MODIS image (see Fig. 1), appear as bright features. The changes in the size of the bloom mats can be visualized from these images. The image normalization method led to quantification of the bloom size (area coverage) and intensity as a function of time, which are shown in Fig. 2(d)–(f). To minimize the impact of noise and algorithm artifact, an hourly running mean was calculated to represent hourly changes. The time series clearly shows an increase in both area coverage and intensity from morning (14–16 GMT or 10–12 A.M. local time) to early afternoon (17–18 GMT or 1–2 p.m. local time), where the bloom area increased by eightfold [see Fig. 2(d)] and the mean bloom intensity increased by ∼22% [see Fig. 2(e)] from 14:30 to 18:30 GMT. When the ROI was considered as a whole, the mean intensity of all pixels within the ROI increased by ∼28% from 14:30 to 17:30 GMT. After 18 GMT, there was a slight variation in the bloom area [see Fig. 2(d)] but a sharp decrease in the bloom intensity [see Fig. 2(e) and (f)]. After 21:30 GMT, the bloom area appeared to have decreased, whereas the bloom intensity remained relatively stable.

An attempt was made to repeat the time-series analysis for other days when MODIS-detected blooms were found. Fig. 3 shows another case on August 4, 2007, when the MODIS-detected bloom [see Fig. 3(a)] was studied in detail using GOES observations [see Fig. 3(b)–(e)]. The images before 16:45 were contaminated by clouds and therefore discarded. Compared with the bloom case shown in Fig. 2, this bloom showed lower diurnal variation ranges in both size and intensity except after 22:00. Nevertheless, the two cases clearly demonstrated that even with only a single low-SNR band, the GOES arithmetic mean of $I_{normalized}$ for all pixels. Finally, the arithmetic mean of $I_{normalized}$ for all pixels within the common ROI was calculated as a parameter to represent both the bloom size and bloom intensity.
Imager may be used to study diurnal changes of _Trichodesmium_ bloom mats in the GOM.

**IV. Discussion**

**A. Causes of the Diurnal Changes**

Could the observed diurnal changes be due to sensor or algorithm artifacts? At large solar zenith angles in the early morning or late afternoon, the satellite signal is smaller than at solar noon, reducing the SNR (i.e., sensitivity) to detect small changes. Under typical radiance at a solar angle of 45°, SNR of GOES Imager was estimated to be 46:1 [10] and SNR is roughly proportional to the square root of the input signal. On May 22, 2004, solar zenith angle is 33.6° at 15 GMT, 6.7° at 17.5 GMT (solar noon), and 62.7° at 22 GMT. After taking account of the cosine effect, diurnal changes of the SNR are at most 20%–30%. Although changes in SNR can influence the sensor’s ability to detect small changes at any single pixel [10], such small changes in SNR are unlikely to affect the sensor’s ability to quantify the size or intensity of the bloom patch (many pixels) because most of the noise would be removed through averaging. The threshold used to classify bloom versus nonbloom pixels, on the other hand, does have a profound impact on the results. However, the normalization technique represents an effective atmospheric correction, making cross-image comparison possible. Indeed, results from adjacent observations (e.g., within 1 h) are close to each other (see Figs. 2 and 3), indicating the stability of the processing method. Thus, we believe that the observed changes are real changes in bloom characteristics.

For the May 22, 2004 bloom case, since a significant increase in bloom size occurred within several hours, it is unlikely that this can be explained by phytoplankton growth. Thus, there are two possible explanations for the changes. The first is physical aggregation, modulated by wind; indeed, data obtained from a nearby buoy showed relatively stable wind speed of < 5 ms\(^{-1}\) before 18 GMT [see Fig. 2(g)], after which wind speed decreased to about 3 ms\(^{-1}\). Therefore, it is possible that before 18 GMT, physical aggregation of _Trichodesmium_ cells could be a contributing factor to the observed increase in bloom size. On a relatively calm sea surface, _Trichodesmium_ cells mixed in the water column may aggregate on the surface to form mats [9]. However, this alone would not explain the entire time series, as the bloom area stopped increasing even after wind decreased to ∼ 3 ms\(^{-1}\). The second possible reason is phytoplankton vertical migration, which has been identified as a competitive strategy for phytoplankton growth [11]. In the GOM, _Karenia brevis_ (the harmful algae species responsible for most red tides) population increased in the upper 2 m of the water column [18] during the day with peak concentrations around late afternoon (∼ 20:00 GMT). Similarly, _Prorocentrum donghaiense_ cells in the East China Sea were found in surface waters around noon and in subsurface waters at night, with concentrations peaking around 14:30 local time [24]. The GOCI-based observations showed similar changing patterns in _Prorocentrum donghaiense_ bloom size [13]. The diurnal changing patterns of the _Trichodesmium_ bloom observed here are consistent with these previous observations of _Karenia brevis_ and _Prorocentrum donghaiense_ blooms, yet to our best knowledge, it is the first time that diurnal changes of a _Trichodesmium_ bloom have been reported. This is perhaps due to the difficulty in field sampling of _Trichodesmium_ as these phytoplankton cells form colonies and are very patchy. It is possible that both mechanisms (physical aggregation and vertical migration) contributed to the bloom changes observed in Fig. 2. _Trichodesmium_ in the GOM serves as a significant nitrogen source for _Karenia brevis_ [23]; thus, observations of _Trichodesmium_ diurnal changes from geostationary platforms may improve the understanding of nutrient cycling and the dynamics of _Karenia brevis_ red tides.

For the August 4, 2007 case (see Fig. 3), the changes in the morning could not be assessed due to cloud contaminations. In the afternoon, in contrast to the rapid changes shown in Fig. 2, both bloom size and bloom intensity remained relatively stable until 22:00 [see Fig. 3(c)–(e)]. This might be explained by the relatively high wind (∼ 5 ms\(^{-1}\)) after 18:00 when physical forcing (dissipation and mixing) could overwhelm biological forcing. The exact reason, however, is unclear unless a field measurement is conducted in response to similar bloom events in the future.

**B. Potential of GOES for Detection of Other Bright Features**

Could GOES Imager data be used to detect and track other bright features in the GOM, for example, oil spills? The Deepwater Horizon oil spill between April and July 2010 provided an opportunity to test this feasibility. Fig. 4(a) shows the oil slicks detected by MODIS on April 25, 2010 (18:55 GMT) showing surface oil slicks (delineated in red) from the Deepwater Horizon oil spill. (b) and (c) GOES images of the same oil slicks on the same day, outlined in the rectangular boxes. Note that due to the low SNR, only the thick oil slicks (see the left portion of the slicks in the MODIS image) show up in the GOES images.
this portion was close to the spill location and contained thick, possibly weathered oil. In contrast, the eastern portion of the MODIS-identified oil slicks is thinner. It was captured by MODIS because the sun glint enhanced the feature contrast, but it could not be captured by the glint-free low-SNR GOES imager. Clearly, the oil detection capacity of GOES Imager is limited to thick oil only. Furthermore, without a priori knowledge of the oil spill, it is hard to draw a solid conclusion that a certain bright feature is an oil slick. The same can be said for *Trichodesmium* bloom detection because a single band cannot differentiate phytoplankton functional groups spectrally. Clouds further complicate the capacity of the GOES Imager as clouds also appear as bright features. In the future, the use of the infrared bands may help differentiate clouds from the ocean surface features as clouds are typically colder, and the hyperspectral capacity of GEO-CAPE may differentiate *Trichodesmium* from other phytoplankton groups unambiguously (e.g., [14]). Nevertheless, the case study here demonstrates that, although the GOES Imager can only detect thick oil slicks, a combination of the polar-orbiting MODIS [or the most recent Visible Infrared Imager Radiometer Suite (VIIRS)] and geostationary GOES Imager may provide unprecedented information on *Trichodesmium* formation and evolution through time. Such a capacity may facilitate studies of bloom dynamics in the GOM before a well-designed GEO-CAPE is in space.

V. Conclusion

Unlike other geostationary sensors that are equipped with multiple spectral bands in the visible and NIR, the GOES Imager has only one broadband between 550 and 750 nm, making explicit atmospheric correction impossible. However, image normalization demonstrates that the low-SNR band is still capable of tracking diurnal changes of *Trichodesmium* blooms in the GOM when they form surface mats. Although its capacity in detecting other bright features such as oil spills is limited, the GOES Imager may provide supplemental information to enhance the polar-orbiting MODIS and VIIRS data when studying bloom dynamics.

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References


