Ocean Color Satellites Show Extensive Lines of Floating *Sargassum* in the Gulf of Mexico

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***Abstract*—We present satellite imagery that is interpreted as showing extensive lines of floating *Sargassum* in the western Gulf of Mexico in the summer of 2005. In spite of frequent reports of floating weed covering extended areas in different parts of the world's ocean, this appears to be the first observation of *Sargassum* from space. Satellite observations were made with the Medium Resolution Imaging Spectrometer (MERIS) on the Envisat satellite launched by the European Space Agency, and subsequently with the Moderate Resolution Imaging Spectroradiometer (MODIS) launched on both the Terra and Aqua satellites by the National Aeronautics and Space Administration. Both instruments cover wide swaths, providing near-daily images. Both have optical spectral bands in the range 670 to 750 nm, which detect the chlorophyll red-edge characteristic of land and marine vegetation, but only MERIS has a band at 709 nm, which was critical to the initial discovery. The combined satellite data from both sensors show the seasonal cycle of weed density in different areas of the Gulf. A wider ranging study is now needed to map its occurrence in other areas, including the Sargasso Sea (named for the weed, but not so far covered in our survey). The satellite observations suggest that *Sargassum* biomass is greater than previously estimated, and hence plays a more important part in oceanic productivity.**

***Index Terms*—Marine vegetation, Medium Resolution Imaging Spectrometer (MERIS), Moderate Resolution Imaging Spectroradiometer (MODIS), primary productivity, remote sensing, *Sargassum*, satellite imagery, satellite-mounted imaging sensors, water color.**

I. Introduction

THE AREA of the North Atlantic from 20 to 35 N and 30 to 70 W has been called the Sargasso Sea after the floating weed (*Sargassum natans* or *Sargassum fluitans*) commonly encountered there. Early reports of distribution and abundance of the alga in the Sargasso Sea were summarized by Winge [22], and further surveys including observations in the Gulf of Mexico were carried out by Parr [16]. Langmuir [13] used visual observations of *Sargassum* in his description of Langmuir circulation. This circulation results in surface convergence of floating algae and other material into lines oriented along the wind direction, with typical separations of 20 to 50 m [6]. The present ocean color satellite observations relate to larger area patterns where lines on the order of 100 to 1000 m wide and tens to hundreds of kilometers long are separated by tens of kilometers. Surface convergence on this larger scale is due to mesoscale, surface flow patterns. In several cases, the satellite chlorophyll images associated with the present observations showed evidence of the mesoscale features that result in these flows.

The authors are not aware of previous reports of floating *Sargassum* being recognized in satellite images. This lack of observations is surprising in view of the frequency and reported spatial scale of detections from ships (for example, Fig. 1). Attempts have been made in the past to estimate the total biomass of pelagic *Sargassum* from surface net tows, and satellite images should provide useful new data. Stoner [19] and Butler and Stoner [3] compared estimates made in the period 1933 to 1981 to examine evidence for a change in total biomass. More recently, the South Atlantic Fishery Management Council [18] has surveyed estimates of *Sargassum* biomass, so as to make recommendations for allowable harvest levels for the U.S. They stress the importance of floating *Sargassum* as an environment for fish and other marine organisms, including several threatened species of sea turtle. Total biomass estimates also are important for defining ocean productivity and carbon flux [15]. Press reports from the southern U.S. suggest that 2005 was an extremely "high *Sargassum*" year in the Gulf of Mexico with impacts on local fishing that were both positive (good fishing beneath weed patches) and negative (tangled gear and propellers).

The satellite images used here have spatial resolution down to 300 m [Medium Resolution Imaging Spectrometer (MERIS) full-resolution mode], with most images [MERIS reduced resolution (RR) and Moderate Resolution Imaging Spectroradiometer (MODIS) bands eight and above] having resolution of 1–3 km depending on distance from satellite nadir. *Sargassum* aggregations therefore have to be dense enough, over a large enough area, to affect the average color (visible surface reflectance) of pixels having this area. All photosynthetic vegetation is characterized by an abrupt change in reflectance (the chlorophyll "red edge") from low (< 0.1) in the visible, to high (> 0.4) at wavelengths longer than about 730 nm. This signature allows *Sargassum* to be detected in the presence of other confusing signals by sensors such as MERIS, MODIS, and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), that have the appropriate spectral capabilities. We are making use of a spectrum common to a very wide range of vegetation, with modification due to absorption by water, as discussed below. We do not make use of spectral differences between types of vegetation, which we expect to be relatively small,

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Fig. 1. *Sargassum* slick observed in the western Gulf of Mexico, on June 2, 2003 off Corpus Christi Texas at location "1" on Fig. 2(b) (27.5 °N, 96.9 °W). (Image courtesy of Tracy Villareal, University of Texas, Marine Science Institute.)

and certainly not the even smaller differences (if any) between species of *Sargassum*.

II. Satellite Image Data

MERIS was launched on the European Space Agency's (ESA) Envisat satellite in March 2002. A true-color MERIS image in RR mode (1.2 km) of the Gulf of Mexico on June 2, 2005 [Fig. 2(a)] shows strong sun glint on the eastern side, with scattered cloud over the western Gulf. The corresponding MERIS maximum chlorophyll index (MCI) image shows an extensive field of curvilinear surface slicks covering the western Gulf [Fig. 2(b)]. The MCI is computed from MERIS at-sensor data as the measured radiance at 709 nm, above a baseline radiance value at this wavelength interpolated linearly from at-sensor radiances measured at 681 and 754 nm. The MCI gives a measure of a peak in radiance, centered near 705 nm, whose presence indicates very high surface concentrations of chlorophyll a, either in phytoplankton or in some other form of floating vegetation [8]. These patterns in MCI images shown in Fig. 2(b) were first noticed in a global search for intense surface phytoplankton blooms, which included coastal areas of the Gulf of Mexico.

We identify the curvilinear slicks as the floating *Sargassum*, concentrated into narrow lines by the convergence and shear of the mesoscale current field. Several sharp fronts, defined by sudden changes in surface chlorophyll concentration as observed in satellite data (not shown here), coincide with lines of *Sargassum*. Ann Jochens and Douglas Biggs (personal communication), reported sightings of extensive weed lines during a cruise of the R/V Gyre, of Texas A&M University, in June 2005 in the western Gulf, especially on two transects, "2" on June 16, and "3" on June 22, plotted in Fig. 2(b). Fig. 2(b) shows *Sargassum* across these lines on June 2, and later images confirm the presence of *Sargassum* in these areas throughout the month of June.

Although the slicks were first noted on MERIS MCI images, only limited MERIS data were initially available. MODIS and SeaWiFS ocean color data are available in greater volume, since launch of these instruments in 1999 and 1997, respectively. Examples of MODIS and SeaWiFS images of the slicks for June 2, 2005 are also included in Fig. 2. SeaWiFS has the capability to tilt away from the sun, thereby avoiding the large areas of sunglint that affect MERIS and MODIS images. This is especially severe at these low latitudes, where the sun is nearly overhead at local noon in the summer. The MODIS image is also affected by residual striping. Its wider swath compared to MERIS allows more spatial coverage including more areas away from sunglint.

The fluorescence line height (FLH) MODIS product is useful to detect phytoplankton blooms in the presence of other optically important water constituents such as colored dissolved organic matter [11]. Here, the MODIS FLH image detects the *Sargassum* slicks as a lower signal than that from the surrounding water, due to the sensor design to detect the fluorescence signal using 676.7 nm as the peak, and 665.1 and 746.3 nm as

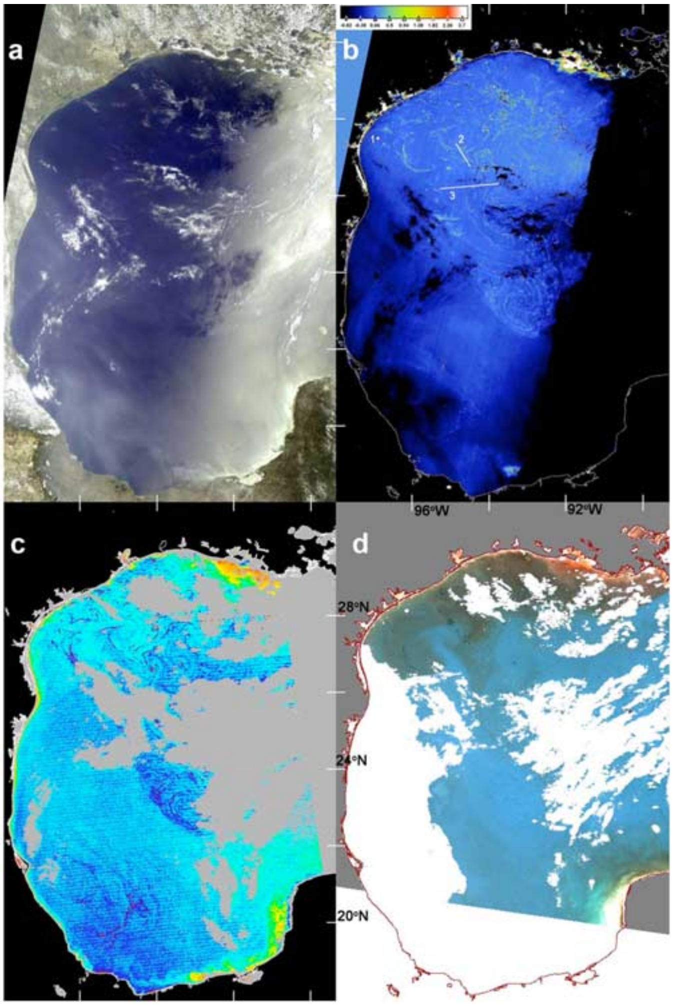

Fig. 2. Lines interpreted as *Sargassum* in the western Gulf of Mexico, observed with MERIS, MODIS, and SeaWiFS on June 2, 2005. (a) Shows a true-color image (MERIS RR) with high sunglint on the right side, making some of the slicks visible. (b) This panel (MERIS RR) shows the slicks as lines of high MCI with a dot (1) showing the position for Fig. 1, and lines (2) and (3) showing positions of ship transects, on which *Sargassum* was observed two to three weeks later by researchers from Texas A&M University. (c) This panel (MODIS) shows the slicks as lines of low FLH. (d) This panel (SeaWiFS, RGB image with atmospheric effects removed) shows some slicks as dark lines due to errors in the removal of atmospheric effects over the slicks. The atmospheric correction scheme was designed for water and not for floating vegetation on the surface.

the baseline. However, similar patterns are seen in both MERIS and MODIS images, and suggest well-developed slicks in the northwest of the Gulf, with a separate population of similar slicks in Mexican waters to the south. Both images show the well-delineated gyre, about 200 km in diameter, in the center of the western Gulf. The MERIS image (Figs. 2 and 3) shows a second gyre further north.

The slicks are also shown in the SeaWiFS enhanced red-green-blue (RGB) composite image [Fig. 2(d)]. The image was composed using surface reflectance data products (after the removal of atmospheric effects) at 555 nm (R), 490 nm (G), and 443 nm (B). The lines are darker than the surrounding waters despite the fact that they represent brighter vegetation (Fig. 1). This is due to the fact that the high near-infrared (IR) signal of the slicks causes an overestimate in the atmospheric effect, resulting in less than real computed surface reflectance. The chlorophyll data product of SeaWiFS also shows the slicks, but with much lower contrast, since underestimates of reflectance in two blue/green bands are partly cancelled in computing their ratio, which is used to empirically derive chlorophyll concentrations.

MODIS is equipped with two 250-m bands at 645 and 859 nm, respectively, which can be effectively used to detect small-scale features such as oil spills [10]. The *Sargassum* slicks are also detected by these medium-resolution images, but because of the lack of spectral resolution (only two bands in the red and near IR) and lack of an operational algorithm to process these medium-resolution data, their use is limited in this paper.

Spectral properties of the slicks can be deduced from MERIS, MODIS, and SeaWiFS data. Fig. 3 shows spectra and difference spectra computed from MERIS for pairs of points inside and outside the slicks at the points shown. Difference spectra show the added radiance due to the slicks, assuming that atmospheric and solar illumination conditions are the same over the slick and over nearby water. The difference spectra clearly show the "red edge" noted above, characteristic of land vegetation [9], [5]. The effect of water absorption on the reflectance spectrum observed from submerged vegetation was discussed by Gower *et al.* [7] in the context of observations by MERIS. The water absorption increases sharply from the red to the near IR, and therefore shifts the red edge so that the radiance increase occurs over the range 681–709 nm, rather than over the range 700–730 nm, as observed on land. The MERIS MCI radiance is increased by the "shifted red edge" radiance pattern. MODIS and SeaWiFS both lack a band near 709 nm, and SeaWiFS also lacks any fluorescence band near 680 nm. Presence of a red edge in the observed spectrum, with the radiance increase extending to wavelengths of 750 nm and longer, is indicative of dense mats of floating vegetation, or buoyant phytoplankton similar to those observed in cyanobacteria blooms in the Baltic [12]. We interpret radiance spectra with an isolated peak at 709 nm, such as those in Fig. 3 from coastal lagoons of Atchafalaya Bay and Laguna Madre, as showing phytoplankton cells floating in a layer close to, but below, the surface. In Atchafalaya Bay, the peak is the dominant feature of the radiance spectrum, indicating relatively low backscatter by inorganic material and high chlorophyll concentrations in near-surface phytoplankton on the order of 100 $\text{mg} \cdot \text{m}^{-3}$ [8].

Figs. 2 and 3 show slicks in the Gulf of Mexico, west of about 92 °W, affecting about 1% to 2% of the surface area of the Gulf at the 1.2-km resolution of the RR MERIS data. Comparison of RR images of the slicks, with the corresponding full-resolution (FR, 300 m) images, shows that the structure of the slicks is better defined in FR images (not shown here), but has the same turbulent pattern, so that the FR data do not improve the interpretation of the data. Even though some of the more intense lines are only a single-pixel wide at the FR, the averaging used to create the RR product increases the signal-to-noise ratio of the imagery and maintains contrast of the slicks with the surrounding water.

Sargassum coverage was computed for a 200 $\times$ 200 km area of open water in the northwest Gulf as shown in Fig. 3, using FR and RR images on May 23, 2005. Of 430 000 cloud-free FR pixels (300 $\times$ 300 m), 45 show an MCI signal greater than 5 $\text{mW}/(\text{m}^2 \cdot \text{nm} \cdot \text{sr})$ and 3500 show a signal greater than

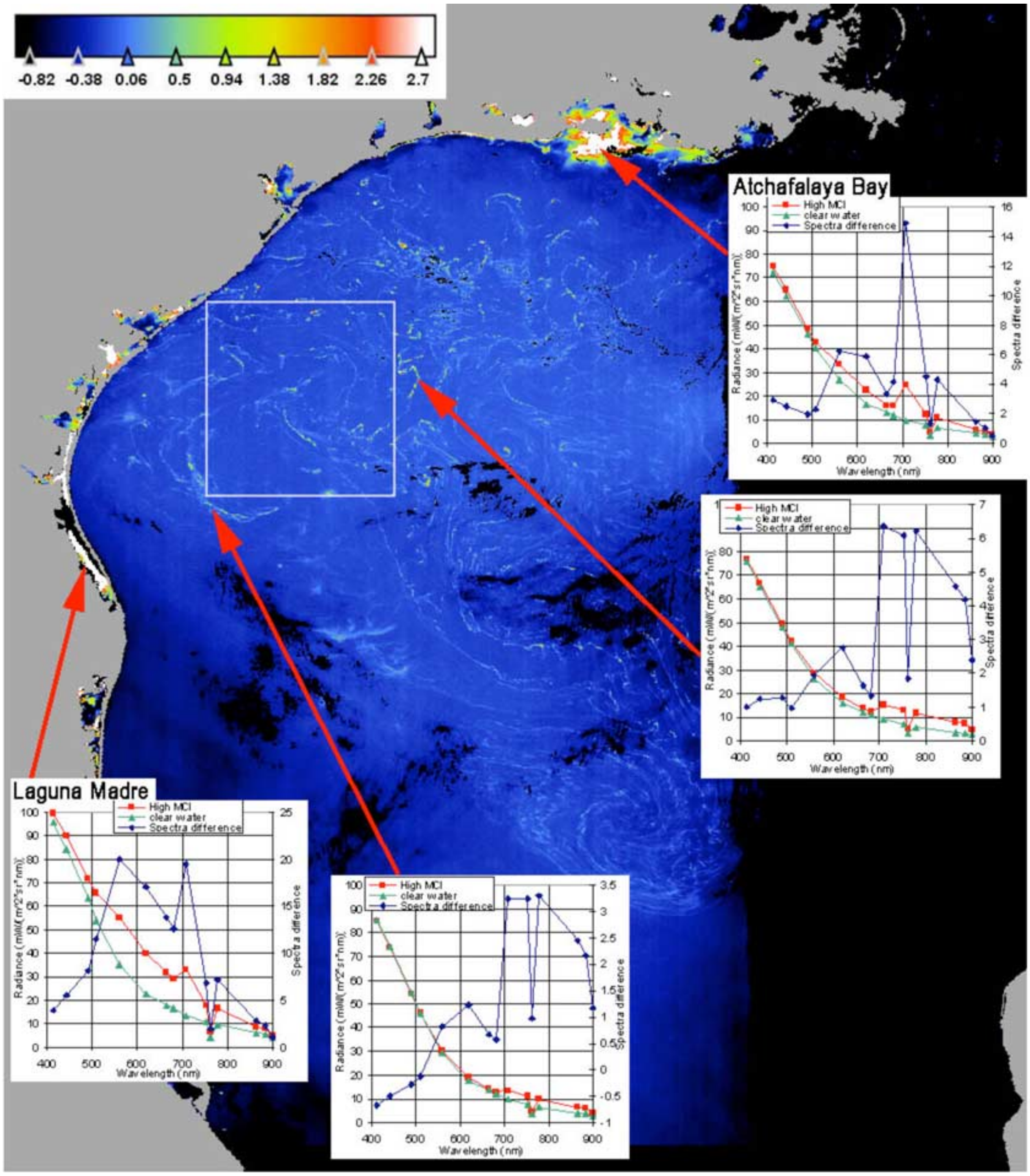

Fig. 3. Northern part of Fig. 2(b), showing spectra of radiance increases in *Sargassum* lines and coastal blooms compared to nearby "clear water" areas on June 2, 2005, and the area used to estimate weed coverage on May 23, 2005 (white square). Spectra for S*argassum* show the characteristic "red edge" of vegetation. Spectra of coastal blooms show the isolated peak near 705 nm, which can dominate the spectrum, as shown in Atchafalaya Bay.

$0.5\ \mathrm{mW}/(\mathrm{m}^2 \cdot \mathrm{nm} \cdot \mathrm{sr})$. We estimate that for the solar illumination conditions on that day, a $5\ \mathrm{mW}/(\mathrm{m}^2 \cdot \mathrm{nm} \cdot \mathrm{sr})$ MCI signal corresponds to about 16% coverage of the pixel by exposed biomass, based on measured radiances for full vegetation cover on adjacent land. Maximum observed MCI signal in the test area was $12.7\ \mathrm{mW}/(\mathrm{m}^2 \cdot \mathrm{nm} \cdot \mathrm{sr})$, corresponding to 40% coverage of the pixel by exposed biomass.

Computation from the histogram of the MCI values in the FR image gives an average coverage fraction for the whole area of 0.0006, equivalent to 1 in 1700 pixels being completely covered in *Sargassum*. An equivalent computation for the RR data gives a value of 0.0004, so that in this case, the FR image appears to detect about 50% more than the RR. A further increase in spatial resolution may therefore give a further increase in coverage fraction, provided sufficient radiance resolution can be maintained. We suggest that estimates of *Sargassum* cover, based on MERIS RR imagery, may be up to a factor of two, below the more accurate value that would be derived from a hypothetical ideal sensor with high spatial resolution, so that fractional cover for this area of the northwest Gulf in late May and early June of 2005 is about 0.0008.

MODIS fluorescence data products (chlor_fluor_ht) and imagery for the entire Gulf of Mexico are available since September 2004 from the University of South Florida at http://modis.marine.usf.edu/weekly/gcoos/gcoos.index.html. These images were screened visually to see the frequency and coverage of similar slicks. Table I lists the number of days in each month when slicks were sighted in the Gulf of Mexico.

TABLE I
NUMBER OF DAYS IN EACH MONTH IN WHICH *Sargassum* SLICKS WERE DETECTED IN USF MODIS CHLOROPHYLL FLH (chlor_fluor_ht) IMAGES IN DIFFERENT LONGITUDE RANGES OF THE GULF OF MEXICO

Month	West Gulf West of 92W	Central Gulf 87 – 92 W	East Gulf East of 87 W
Sept 2004	2		
Oct 2004			
Nov 2004			
Dec 2004			
Jan 2005			
Feb 2005	1		
Mar 2005	1	1	
Apr 2005	5	1	
May 2005	11		
Jun 2005	13	2	
Jul 2005	12	1	2
Aug 2005	7	4	4
Sep 2005	2	1	1
Oct 2005	1		
Nov 2005			

The Gulf is divided into the western Gulf (west of 92 °W), the central Gulf (87° to 92 °W) centered roughly on the longitude of the Mississippi delta, and the eastern Gulf (east of 87 °W). Earliest sighting in 2005 was in the western Gulf in February. Numbers increased through the early summer and decreased after July to zero by November. Most slicks were found in the western Gulf. Smaller numbers were found in the central and eastern regions with a tendency for sightings to be later in the year in those areas. Limited data are available from MERIS for 2003, and show significantly fewer slicks compared to 2005.

The slick statistics in Table I will be affected by cloud cover, sunglint and viewing geometry, and also by the visibility of patterns formed by the slicks. Slicks are more visible when imaged at the center of the MODIS swath where resolution is close to the nominal 1 km. At the swath edges, the instantaneous field of view expands to 2×5 km, and images of narrow features are significantly degraded.

The MERIS spectra of these slicks indicate vegetation emerging above the water surface, as opposed to phytoplankton populations in the near-surface water (Fig. 4). Both sets of spectra in this figure show the chlorophyll “red edge,” with increased reflectance extending into the IR to wavelengths longer than 900 nm. This can be compared to the spectra of the near-surface blooms in coastal lagoons of the Gulf of Mexico (Fig. 3), which show a more isolated peak at 709 nm with radiance increase dropping to near zero by 754 nm. We interpret the spectra in the latter case as showing high concentrations of phytoplankton in surface waters. We interpret the spectra from the Baltic [Fig. 4(a)] as indicating a more buoyant organism (in this case, cyanobacteria) that has formed surface slicks. The drop in the radiance differences for wavelengths longer than 709 nm, due to absorption by water in the slick, is less marked, with significant radiance at the longest wavelengths near 890 nm. Spectra from *Sargassum* [Fig. 4(b)] show even higher radiance near 890 nm, with no significant drop in radiance between 709 and 754 nm. Also, the peaks at shorter wavelengths (500–650 nm) are less marked in the case of *Sargassum*. The difference spectra in this case are very similar to those of land vegetation.

III. DISCUSSION

The fractional cover value of 0.0008 estimated above, combined with an estimate of 3 cm for the average thickness of the *Sargassum* layer based on visual estimates (Fig. 1), gives a biomass volume of 25 $\text{cc} \cdot \text{m}^{-2}$, or mass of 25 $\text{g} \cdot \text{m}^{-2}$ (density = 1.0, since the weed is only slightly buoyant), approximately equivalent to a dry weight of 2 $\text{g} \cdot \text{m}^{-2}$ (dry weight about 8% of wet weight) a carbon weight of 1 $\text{g} \cdot \text{m}^{-2}$ (carbon weight about 50% of dry weight) and a chlorophyll pigment concentration of 20 $\text{mg} \cdot \text{m}^{-2}$ (pigment weight about 0.02 of carbon weight). This is a significant biomass for an oligotrophic area. The slicks were observed to cover a relatively large fraction of the western Gulf of Mexico during the summer of 2005. The least accurate number is probably the average *Sargassum* layer thickness. We plan more *in situ* and satellite observations to confirm the present interpretation and to refine the 3-cm estimate, though the actual thickness will be hard to determine and may also be highly variable with position.

Parr [16] estimated an average biomass of *Sargassum* as approximately 1 $\text{g} \cdot \text{m}^{-2}$ wet weight in the 1930s for the Sargasso Sea. The South Atlantic Fishery Management Council [18] estimated 0.8 to 2 $\text{g} \cdot \text{m}^{-2}$. The present satellite observations suggest concentrations of an order of magnitude greater (25 $\text{g} \cdot \text{m}^{-2}$) in the western Gulf of Mexico. Carpenter and Cox [4] use Parr’s biomass estimate to conclude that *Sargassum* productivity is only 0.5% of that for phytoplankton. The present observations suggest that in some areas, *Sargassum* productivity can represent a higher fraction, making a more significant contribution, near 10%, to total productivity.

The satellite observations show that most *Sargassum* is observed in the western Gulf, (west of 92° W), an area that was not visited by Parr [16] or Stoner [19]. Observations of *Sargassum* in the central and eastern Gulf are significantly less frequent (Table I), suggesting lower average concentrations comparable to 1 $\text{g} \cdot \text{m}^{-2}$ wet weight. Freely floating weed must be expected to reach highest concentrations in ocean areas where surface water remains for long periods in a slowly rotating gyre, such as the Sargasso Sea in the north Atlantic subtropical gyre, or the western Gulf of Mexico. Central and eastern areas of the Gulf, as defined in Table I, are subject to rapid flushing into the Gulf Stream by the loop current, which enters the Gulf from the south at about longitude 88° W and will affect surface waters west to about 90° W by sweeping them out of the Gulf around the southern tip of Florida. Average transit time for water in the central Gulf to exit in this way is one to two months (1000 km at 15 to 30 cm/s), fast enough to explain the low numbers in the “central” and “east” Gulf columns in Table I. By contrast, surface water could remain up to a year in the closed gyre of the western Gulf.

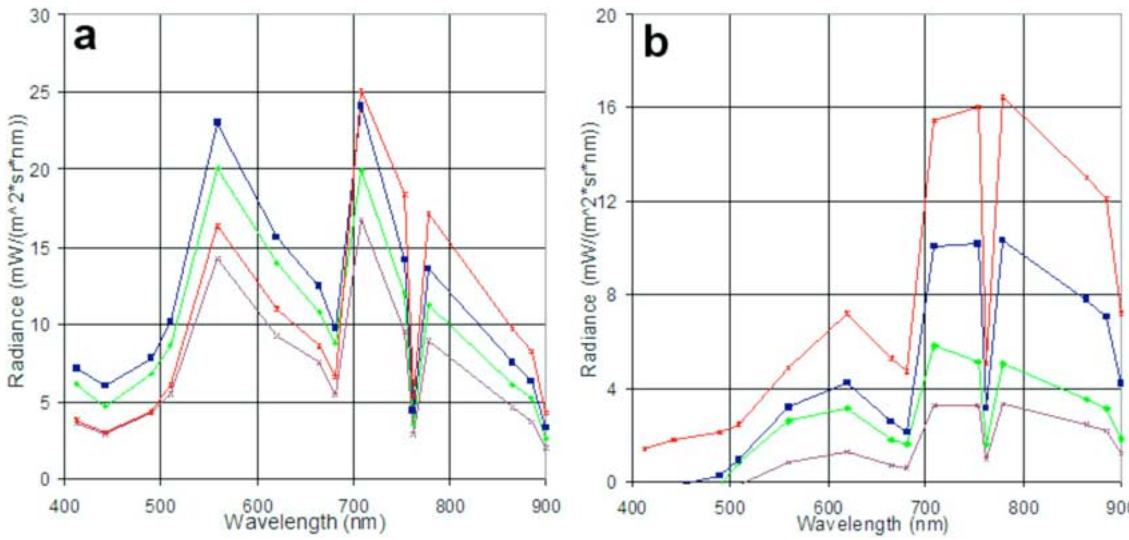

Fig. 4. Difference spectra showing radiance increases in Level 1 MERIS data due to a cyanobacteria bloom in the Baltic [(a) buoyant phytoplankton immersed in water] compared to increases observed over the *Sargassum* lines in the western Gulf of Mexico [(b) vegetation in air and submerged]. The sharp drop at 761 nm is due to absorption by atmospheric oxygen in the narrow MERIS band designed to measure this feature.

Can other floating organisms form similar lines that might be falsely detected as *Sargassum* by these satellite sensors? Blooms of the coccolithophorid *Emiliania huxleyi* or the blue-green algae *Trichodesmium spp.* result in "bright" pixels (i.e., positive contrast) in satellite imagery [2], [20], [21]. *Trichodesmium* blooms have been reported in different parts of the world, though these have covered smaller areas (e.g., [1] and [17]). However, the positive contrast of these organisms is mainly restricted to the visible, in particular, the blue-green wavelength range. Therefore, they do not significantly interfere with the atmospheric correction algorithm, which uses the near-IR wavelengths. Indeed, *Trichodesmium* slicks on SeaWiFS ERGB imagery are often brighter than the surrounding water, in contrast to the darker patterns shown in Fig. 2(d) due to erroneous atmospheric correction.

Oil slicks have been reported in [14], whose observations concentrated on a 200 × 100 km area south of the Mississippi delta. These are visible only through the reduction they cause in small-scale surface roughness, which makes them visible in sunglint and radar images. The spectrum of the radiance contrast for the sunglint will be the same as that of the incident sunlight, with no modification (i.e., red edge) due to vegetation. In fact, some of the slicks observed by Macdonald *et al.* could have been due to *Sargassum*, since floating weed also reduces small-scale water roughness.

IV. Conclusion

The MERIS and MODIS satellite images show extensive and frequent occurrence of slicks that we interpret as *Sargassum* over the western Gulf of Mexico between September 2004 and October 2005. These slicks are detected as brighter targets (i.e., higher signal than the surrounding water) on MERIS MCI imagery and darker targets on MODIS FLH imagery. The default data products of SeaWiFS are less effective in detecting such slicks. From a combination of visual observations, and the shape and "red edge" in the radiance spectra, we discount the possibility that these slicks are due to phytoplankton such as coccolithophores or the cyanobacteria *Trichodesimum*, or to oil or other surfactants.

The ship observations of Stoner [19] and Butler and Stoner [3] concentrated on the western Sargasso Sea. They included transects into the Gulf of Mexico, but not as far west as the areas that show maximum weed concentration in the satellite images. It is possible that the relative densities we observe between the western and eastern Gulf were the same at the time of these earlier observations. In that case, we would also expect to see high concentrations in the Sargasso Sea, though this is not shown by the limited data we have so far.

If confirmed, detection of *Sargassum* slicks by MERIS and MODIS indicates a useful new tool for monitoring *Sargassum* biomass. Compared to ship observations, satellite imagery should better define its geographic extent and seasonal and interannual variability. The observations indicate the value of the spectral bands in the range 670–710 nm, especially the 709-nm band of MERIS. Future satellite ocean color missions need to consider these bands as well as other near-IR bands to expand the capability of current ocean color sensors. Such bands are not planned for the U.S. VIIRS, for example.

Observations of the western Gulf in 2005 suggest that *Sargassum* can represent a significant fraction of total biological biomass and consequently productivity. Further research is required to confirm our interpretation and to understand *Sargassum*'s spectral characteristics, biooptical properties, and role in primary production. Observations can make use of a wide variety of optical and near-IR satellite sensors, including historical weather satellite images such as AVHRR (1-km resolution). Landsat TM/ETM+ (30 m) and SPOT (15 m) should also detect the patterns of floating weed, though they have less radiometric sensitivity, spectral resolution, and spatial coverage. Observations with MERIS and MODIS show that some lines are visible in sunglint patterns [for example in Fig. 2(a)] due to a reduction in surface roughness. They should therefore also be detectable as dark lines in synthetic aperture radar images, and could in some circumstances be confused with oil slicks.

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REFERENCES

[1] G. A. Borstad, J. F. R. Gower, and E. J. Carpenter, "Development of algorithms for remote sensing of *Trichodesmium* blooms," in *Marine Pelagic Cyanophyta: Trichodesmium and other Diazotrophs*, E. J. Carpenter *et al.*, Ed. Amsterdam, The Netherlands: Kluwer, 1992, pp. 193–210.

[2] C. W. Brown and J. A. Yoder, "Coccolithophorid blooms in the global ocean," *J. Geophys. Res.*, vol. 99, no. C4, pp. 7467–7482, 1994.

[3] J. N. Butler and A. W. Stoner, "Pelagic *Sargassum*: Has its biomass changed in the last 50 years?," *Deep-Sea Res.*, vol. 31, no. 10, pp. 1259–1264, 1984.

[4] E. J. Carpenter and J. L. Cox, "Production of pelagic *Sargassum* and a blue green epiphyte in the western Sargasso Sea," *Limnol. Oceanogr.*, vol. 19, no. 6, pp. 429–436, 1974.

[5] P. J. Curran, J. L. Dungan, B. A. Macler, and S. E. Plummer, "The effect of a red leaf pigment on the relationship between red edge and chlorophyll concentration," *Remote Sens. Environ.*, vol. 35, no. 1, pp. 69–76, Jan. 1991.

[6] A. J. Faller and A. H. Woodcock, "The spacing of windrows of *Sargassum* in the ocean," *J. Mar. Res.*, vol. 22, no. 1, pp. 22–29, 1964.

[7] J. F. R. Gower, R. Doerffer, and G. A. Borstad, "Interpretation of the 685 nm peak in water-leaving radiance spectra in terms of fluorescence, absorption and scattering, and its observation by MERIS," *Int. J. Remote Sens.*, vol. 20, no. 9, pp. 1771–1786, Jun. 1999.

[8] J. Gower, S. King, G. Borstad, and L. Brown, "Detection of intense plankton blooms using the 709 nm band of the MERIS imaging spectrometer," *Int. J. Remote Sens.*, vol. 26, no. 9, pp. 2005–2012, May 2005.

[9] D. N. H. Horler, M. Dockray, and J. Barber, "The red edge of plant leaf reflectance," *Int. J. Remote Sens.*, vol. 4, no. 2, pp. 273–288, 1983.

[10] C. Hu, F. E. Muller-Karger, C. Taylor, D. Myhre, B. Murch, A. L. Odriozola, and G. Godoy, "MODIS detects oil spills in Lake Maracaibo, Venezuela," *EOS AGU Trans.*, vol. 84, no. 33, pp. 313–319, 2003.

[11] C. Hu, F. E. Muller-Karger, C. Taylor, K. L. Carder, C. Kelble, E. Johns, and C. Heil, "Red tide detection and tracing using MODIS fluorescence data: A regional example in SW Florida coastal waters," *Remote Sens. Environ.*, vol. 97, no. 3, pp. 311–321, Aug. 2005.

[12] M. Kahru, *Satellite Images of Various Harmful Algal Blooms (HABs).* (2004). [Online]. Available: http://spg.ucsd.edu/Satellite_Projects/Various_HABs/Various_HABs.htm

[13] I. Langmuir, "Surface motion of water induced by wind," *Science*, vol. 87, no. 2250, pp. 119–123, Feb. 1938.

[14] I. R. MacDonald, N. L. Guinasso, Jr., S. G. Ackleson, J. F. Amos, R. Duckworth, R. Sassen, and J. M. Brooks, "Natural oil slicks in the Gulf of Mexico visible from space," *J. Geophys. Res.*, vol. 98, no. C9, pp. 16 351–16 364, 1993.

[15] D. Muraoka, "Seaweed resources as a source of carbon fixation," *Bulletin of the Fisheries Research Agency*, pp. 59–63, Supplement No. 1, 2004.

[16] A. E. Parr, "Quantitative observations on the pelagic *Sargassum* vegetation of the western north Atlantic," *Bull. Bingham Oceanogr. Collect.*, vol. 6, no. 7, pp. 1–94, 1939.

[17] R. K. Sarangi, P. Chauhan, S. R. Nayak, and U. Shreedhar, "Remote sensing of *Trichodesmium* blooms in the coastal waters off Gujarat, India using IRS-P4 OCM," *Int. J. Remote Sens.*, vol. 26, no. 9, pp. 1777–1780, May 2005.

[18] South Atlantic Fishery Management Council, *Fishery Management Plan for Pelagic Sargassum Habitat of the South Atlantic Region*, 2002. [Online]. Available: http://www.safmc.net/library/sargFMP.pdf

[19] A. W. Stoner, "Pelagic *Sargassum*: Evidence for a major decrease in biomass," *Deep-Sea Res.*, vol. 30, no. 4A, pp. 469–474, 1983.

[20] A. Subramaniam, C. W. Brown, R. R. Hood, E. J. Carpenter, and D. G. Capone, "Detecting *Trichodesmium* blooms in SeaWiFS imagery," *Deep-Sea Res. II*, vol. 49, no. 1–3, pp. 107–121, 2002.

[21] T. K. Westberry, D. A. Siegel, and A. Subramaniam, "An improved bio-optical model for the remote sensing of *Trichodesmium spp.* blooms," *J. Geophys. Res.*, vol. 110, no. C6, C06012, 2005. DOI: 10.1029/2004JC002517.

[22] O. Winge,"The Sargasso Sea its boundaries and vegetation," Report Danish Oceanographic Expedition, 1908–1910, Miscellaneous paper number 2, Copenhagen Vol.III, 1923.

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