Sargassum Watch Warns of Incoming Seaweed

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The *Sargassum* Watch System processes satellite data and feeds results to a Web portal, giving decision makers timely inforr on seaweed location and warnings for potential beaching events.

Boats cross a mass of *Sargassum* seaweed that washed ashore on the southern Caribbean island of Tobago in August 2015. These beachings are familiar sights on th northern coast of the Gulf of Mexico, but the events were less common in the southern Caribbean until recently. Credit: Flickr user rjsinenomine,

By Chuanmin Hu, Brock Murch, Brian B. Barnes, Mengqiu Wang, Jean-Philippe Maréchal, James Franks, Donald Johnson, Brian Lapointe, Deborah S. Goodwin, J Schell, and Amy N. S. Siuda 2 September 2016

One summer morning in 2011, the smell of rotting eggs marred "another day in paradise" for residents of the eastern Caribbean nations. The distinctive smell signal beaching of mountains of *Sargassum* seaweed on their shores.

The unprecedented event represented just the beginning of an annually recurring and growing region-wide phenomenon. The largest quantity and frequency increa *Sargassum* beachings (https://www.washingtonpost.com/news/morning-mix/wp/2015/08/14/paradise-lost-caribbean-beaches-face-a-massive-seaweed-invasion-ahead-of-winter-tourism-seasor occurred in 2015 (there have been fewer beachings so far in 2016). The algal masses covered popular tourist beaches, filled bays, and caused numerous environment economic problems.

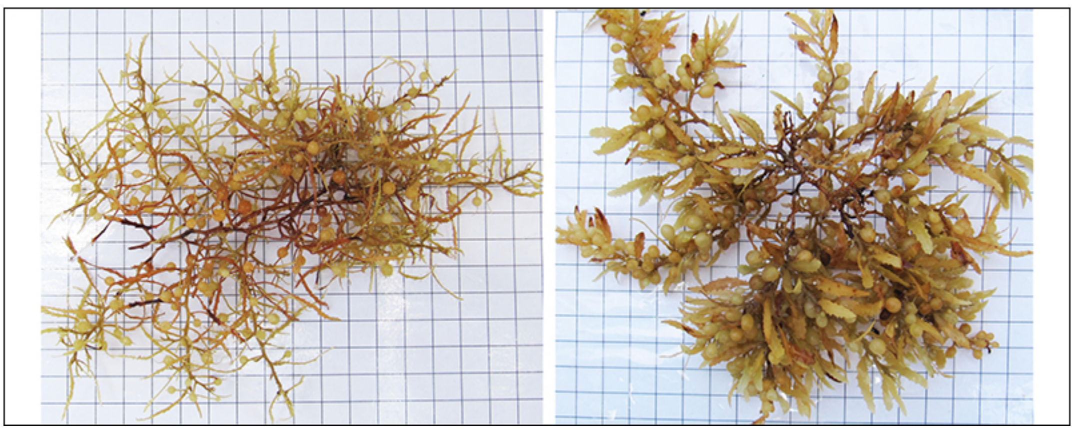
The *Sargassum* beaching events in the Caribbean, West Africa, and other regions have received wide media attention (http://www.newsweek.com/2015/07/10/sargassum-ru beaches-texas-tobago-347735.html), prompting action by regional governmental agencies and environmental groups seeking to understand this new phenomenon. In 201 excessive *Sargassum* beachings along the western Caribbean coast threatened the coastal economy in Mexico—the incidents became a cabinet-level crisis, and the M Navy was called to take action (https://www.washingtonpost.com/world/the_americas/mexico-deploys-its-navy-to-face-its-latest-threat-monster-seaweed/2015/10/28/cea8ac28-710b-11e5-ba1 318f8e87a2fc_story.html).

Short-term predictions of the location and quantity of *Sargassum* at sea are vital for field survey planning, tourism, and other business development.
Long-term predictions of *Sargassum* blooms and beaching events will require a thorough biological and ecological understanding, as well as integration of observat oceanographic and climate data into forecasting models. On the other hand, short-term predictions that rely on numerical models and timely information of the loc quantity of *Sargassum* at sea are vital for field survey planning and short-term management decisions, as well as for tourism and other business development.

Here we highlight recent activities regarding *Sargassum* observations. We also introduce a prototype integrated *Sargassum* Watch System to monitor and track *Sa* in near-real time using satellite imagery and numerical models and emphasize targeted research and monitoring needs.

Sargassum as a Habitat and a Marine Resource

Sargassum natans and *Sargassum fluitans* are mostly found in the Intra-Americas Sea (including the Gulf of Mexico and the Caribbean) and Atlantic Ocean. Unlik than 350 taxonomically identified ocean bottom-dwelling (benthic) *Sargassum* species worldwide, these are the only two holopelagic species of the *Sargassum* fam meaning that they spend their entire life cycle in surface water.



(left) *Sargassum natans* and (right) *Sargassum fluitans*. Each square represents 1 square centimeter. Credit: A. N. S. Siuda

The benthic species reproduce sexually, but S. *natans* and S. *fluitans* reproduce solely by vegetative fragmentation (https://en.wikipedia.org/wiki/Fragmentation_(reproducti Generally, *Sargassum* seaweed are not differentiated into true leaves, stems, and roots; rather, they have tough, leathery, densely branched thalli, composed of axes and air bladders. Both *S. natans* and *S. fluitans* serve as unique and important habitats for a diverse group of marine animals, providing food, shade, and shelter to shrimp, crabs, and turtles [*Witherington et al.*, 2012; *Lapointe et al.*, 2014].

Sargassum in the Atlantic Ocean is regarded as the "golden floating rainforest" by the Sargasso Sea Alliance (http://www.sargassoseacommission.org/index.php) [*Laffoley et* The Gulf Coast Research Laboratory (http://gcrl.usm.edu/) has identified 139 species of fish associated with *Sargassum*, which also represents a marine resource for fo fuel. *Sargassum* serves as fertilizer for the sand dune plant ecosystems that help protect shoreline stability and promote biodiversity of seashore birds, crabs, and ot invertebrates.

A Beach Nuisance

Although it's an ecosystem boon to the open ocean, excessive amounts of *Sargassum* on beaches in populated areas represent a nuisance and must be physically ren (http://www.jamaicaobserver.com/news/Gov-t-allocates-initial--5-million-for-removal-of-sargassum_19234892).

Sargassum beaching events are new to many residents in the southern Caribbean, West Africa, and Brazil but are well known in the northern Gulf of Mexico (espec

Texas), the Sargasso Sea, and the northern Caribbean islands. *Sargassum* emits hydrogen sulfide gas as it decomposes onshore, releasing an odor like rotting eggs. ' decomposition causes many environmental problems by attracting insects, smothering turtle nesting sites, and killing sea turtles and fish [*Feagin and Williams*, 20

Sargassum beaching on La Désirade east of Guadaloupe in the Caribbean, 28 April 2015. Credit: F. Mazéas

Sargassum beaching events cause economic problems as well [*Franks et al.*, 2011]. A survey of 424 private companies by the Chamber of Commerce of Guadeloupe that diminished tourism caused an economic loss of $5.5 million dollars for the first half of 2015. However, despite a handful of studies, the driving factors leading t increases in beaching events remain largely unknown. Addressing these unknowns will require coordinated research, but increased beaching events call for immedi effective monitoring and forecasting systems.

Sargassum Watch from Space

The University of South Florida's (USF) Optical Oceanography Laboratory (OOL) has been working on a virtual antenna system (VAS), which downloads and proce satellite data into customized images, since 2010. These images are distributed through a Web portal within 4–6 hours of the satellite overpass [*Hu et al.*, 2014], pr infrastructure to implement a *Sargassum* Watch System (http://optics.marine.usf.edu/projects/SaWS.html) (SaWS).

Specifically, the USF OOL has used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites to examine the re reflectance (enhanced reflectance in the near infrared) of floating vegetation, using a floating algae index (FAI) [*Hu*, 2009] or alternative FAI (AFAI) [*Wang and Hu* These indices are similar to the maximum chlorophyll index used for the first time by *Gower et al.* [2006] to detect *Sargassum* from space.

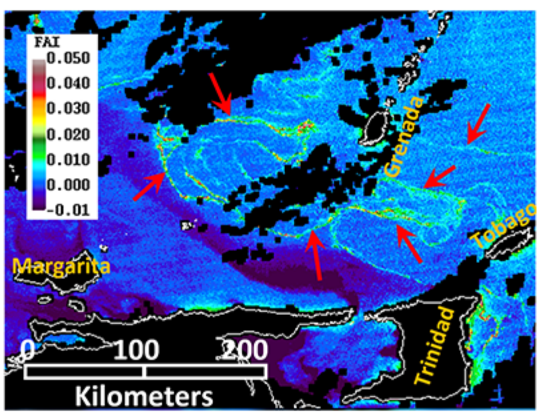


Fig. 1. This Visible Infrared Imaging Radiometer Suite (VIIRS) alternative floating algae index (AFAI) image taken on 4 February 2016 from the *Sargassum* Watch System (SaWS) shows large aggregations of *Sargassum* (elongated image slicks annotated by the red arrows) in the southern Caribbean (10°–13°N, 64.5°–60.5°W). Credit: USF OOL, NASA, NOAA

Because floating vegetation has enhanced reflectance in the near-infrared spectral bands, these products clearly show *Sargassum* aggregations as elongated slicks i imagery (Figure 1) that can be easily identified even with an untrained eye. The system covers the Intra-Americas Sea in subdivided regions (Figure 2), with the capa extend as far as West Africa and Brazil.

Tracking *Sargassum* Rafts

In addition to the AFAI imagery, SaWS also uses nightly updated surface current data from the Hybrid Coordinate Ocean Model (HYCOM), via the VAS. All data pr (AFAI, HYCOM currents, sea surface temperature, and surface color patterns, among others) can be displayed in Google Earth with a simple mouse click, thereby fa visualization and navigation (Figure 3).

Within Google Earth, once a *Sargassum* raft is identified, its latitude and longitude, combined with current speed and direction near the raft, can be used to predict movement of the raft and a possible beaching time—in essence, forming an early warning system. This method has actually been used by a company called Nova Blu Environment (http://www.novablue-environment.org/), which has released *Sargassum* beaching risk alerts every week to local authorities in Guadeloupe (French West In May 2014. Several alerts were correlated to actual *Sargassum* beaching sites identified by helicopter surveys.

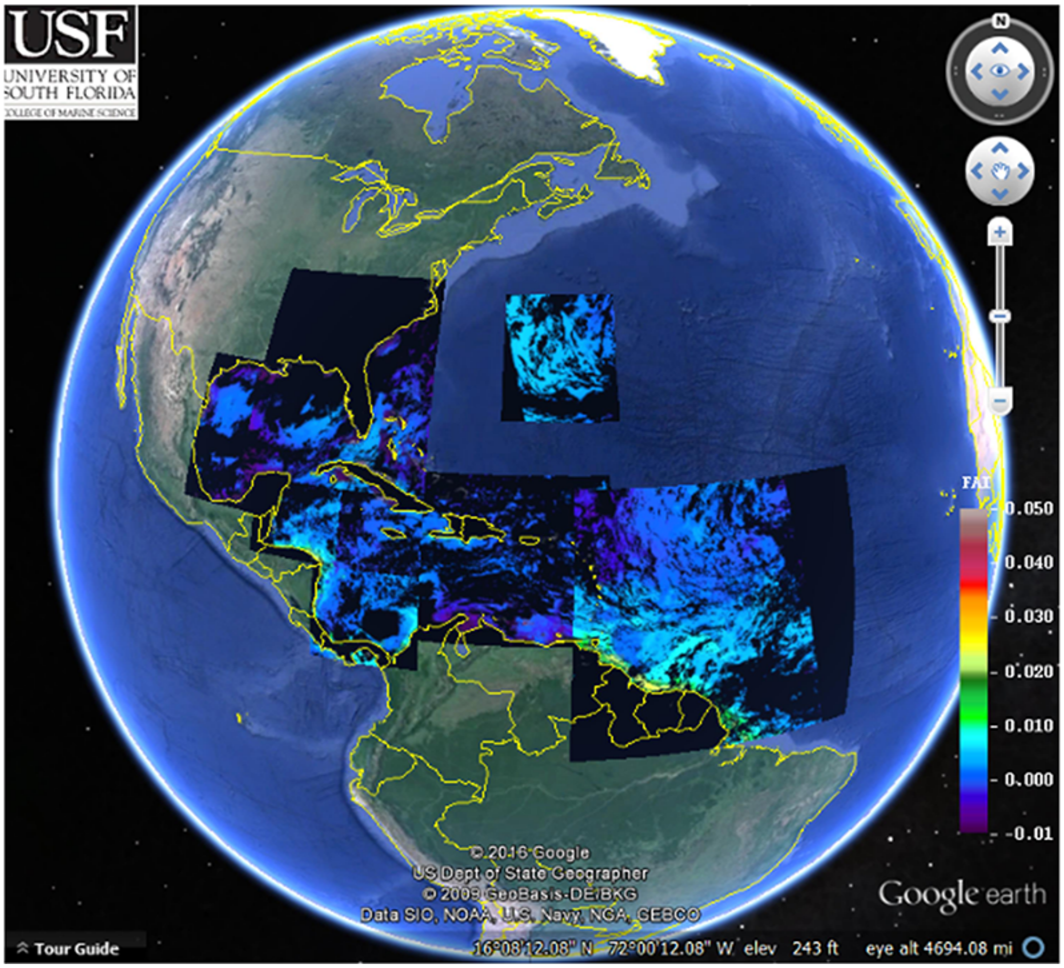


Fig. 2. Near-real-time SaWS at the University of South Florida covers the Intra-Americas Sea with NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and VIIRS. Selected regions are covered with Landsat 8. Credit: USF OOL, NASA, NOAA

Thanks to the watch system, many local groups have been able to monitor and track large *Sargassum* aggregations on an almost daily basis. In Puerto Rico, researc been using it routinely to detect *Sargassum* aggregations and conduct research, finding excellent accuracy of the system when tracking large rafts and ocean eddies University of Puerto Rico, personal communication, 2015).

Other *Sargassum* Tracking Remote Sensing Methods

The same red edge concept used on MODIS has been extended to Landsat sensors. Unlike MODIS's daily revisit cycle, Landsat passes a given region every 16 days. Landsat sensors have much higher (30-meter) resolution than MODIS, which can reveal small aggregations that are invisible in the 1-kilometer-resolution MODIS i Currently, SaWS produces high-resolution FAI imagery from Landsat 8 in several selected regions in the Caribbean. Similarly, Landsat instruments have been used early alerts on possible *Sargassum* beaching events along the Texas coast through a *Sargassum* Early Advisory System (SEAS) [*Webster and Linton*, 2013].

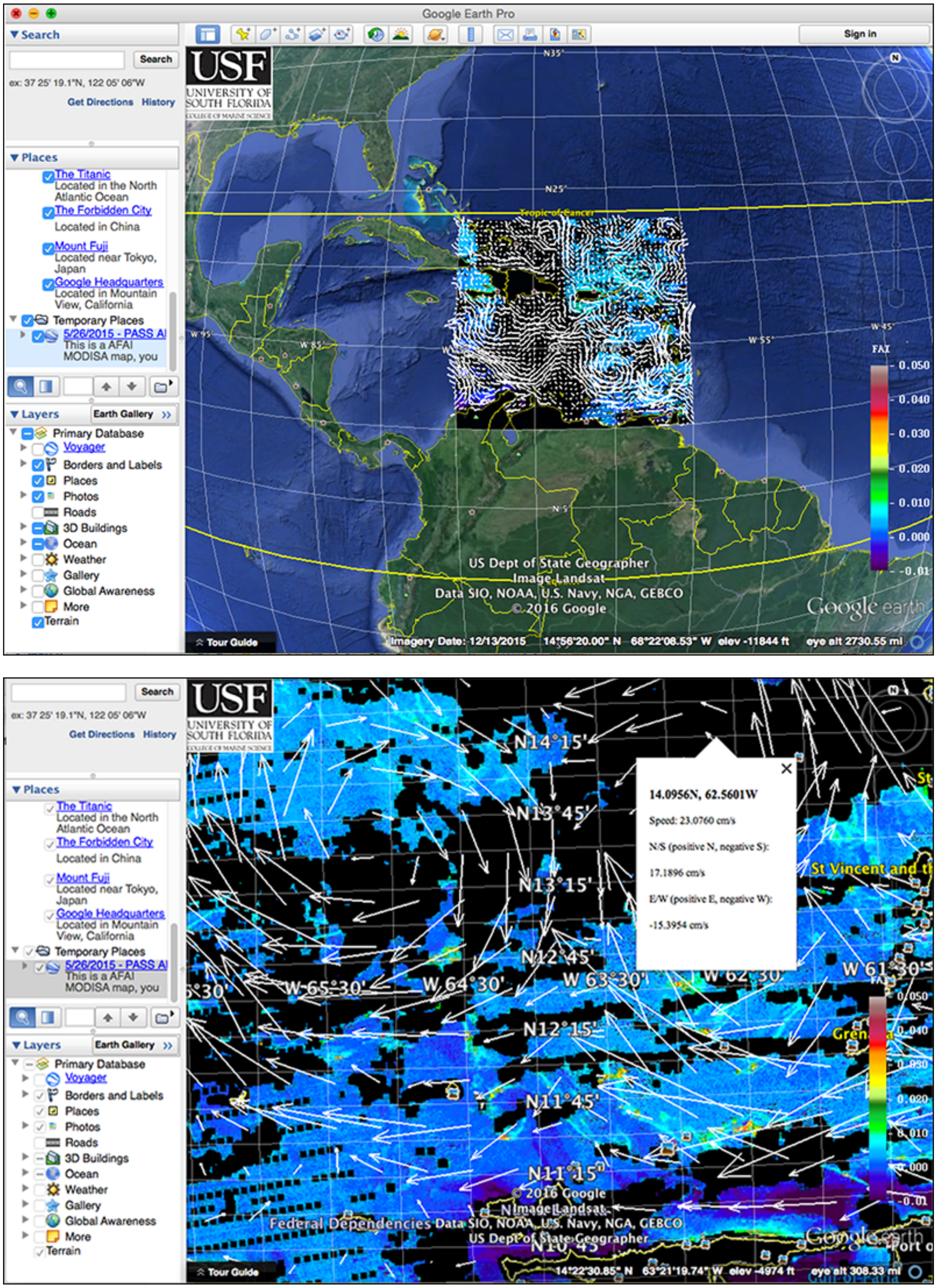


Fig. 3. An example showing how the SaWS works for the eastern Caribbean (ECARIB). (top) MODIS AFAI image from 26 May 2015 displayed in Google Earth with surface currents overlaid. (bottom) Close-up of the AFAI image revealing detailed distributions of large *Sargassum* rafts (green-yellow-brown colored slicks). For the live images on the SaWS website, a mouse click on any of the arrows reveals the current speed and direction. This capacity is available for the entire Intra-Americas Sea region in near-real time with daily updates.

Likewise, local groups have used aircraft to assess the extent and severity of *Sargassum* beachings in Guadeloupe (F. Mazéas and M. Laurent, DEAL Guadeloupe, pe communication, 2015). Between 2011 and 2015, eight 2-hour Civil Security helicopter flights were completed to document the most affected areas of Guadeloupe Isl a comprehensive report issued from each airborne survey.

A combination of the various systems may maximize the value of both spaceborne and airborne observations through coordinated efforts.

Sargassum Watch from Ships

Observing pelagic *Sargassum* is not new—it started with the voyage of Columbus and other early explorers and became a quantitative science almost a century ago [1939]. Shipboard studies in the 1980s and 1990s were the first to suggest that with a reproduction rate that doubles or triples biomass every 25 days [*Lapointe et al.* this vegetation was more productive than previously thought [*Lapointe*, 1995]. Systematic *Sargassum* surveys have been conducted by the Sea Education Associatio the 1970s during annually repeated 6-week cruises, resulting in biomass per unit area data for more than 7000 net tows between 1992 and 2015 (Figure 4).

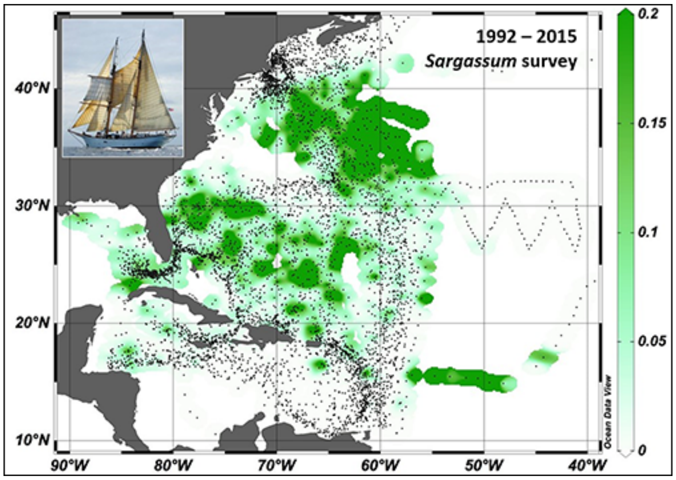


Fig. 4. Annually repeated pelagic (near-surface) *Sargassum* surveys by the Sea Education Association on board the SSV *Corwith Cramer* (inset photo) between 1992 and 2015 (these surveys will continue in the future). Each black dot represents 1 of the 6985 neuston net tows that determined pelagic *Sargassum* presence or absence and biomass per area. Rectangular neuston nets (1 meter wide by 0.5 meter tall, 335-micrometer mesh) are towed across the sea surface, where they collect floating *Sargassum* and associated small fauna. Color intensity indicates observed density (grams per square meter) of all *Sargassum* species.

Data synthesis is still underway, but preliminary results show distinct distribution patterns across time and space for each *Sargassum* species, as well as proliferatio previously rare morphological form (*Sargassum natans VIII*) and decreased abundance and diversity of associated fauna during the 2015 Caribbean inundation eve *et al.*, 2015].

Other researchers and volunteers have also made field observations, including *Sargassum* beaching times and locations. The Gulf Coast Research Laboratory mana portal (http://www.usm.edu/gcrl/sargassum/sargassum.observation.form.php) specifically designed for ad hoc reporting of *Sargassum* sightings made during at-sea encounters observations. Such information complements that obtained from systematic ship surveys to provide a more complete picture of *Sargassum* distributions.

Research Needs

Both remote sensing and ship surveys may provide information on the distribution, relative abundance, and long-term trend of this important marine habitat. *Wan* [2016] used MODIS data to provide a long-term time series for the central west Atlantic region (Figure 5) that showed dramatic increases in *Sargassum* abundance to 2015. However, a full understanding of *Sargassum* biology and ecology [e.g., *Carpenter and Cox*, 1974; *Lapointe*, 1995] requires efforts far beyond those outlined

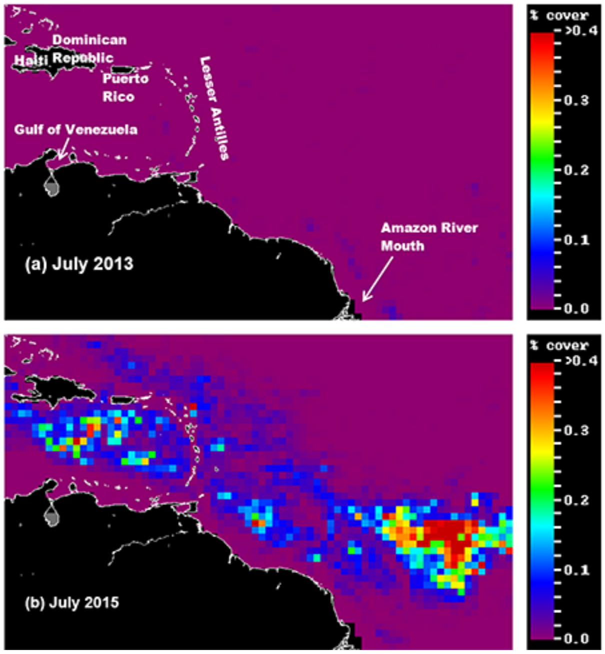


Fig. 5. Mean percentage cover of *Sargassum* in the central west Atlantic and eastern Caribbean (0°–23°N, 75°–38°W) for (a) July 2013 and (b) July 2015, determined from MODIS observations using an objective method [*Wang and Hu,* 2016]. The color scale indicates percentage of surface coverage (areal density). The integrated pure *Sargassum* coverage for July 2015 was estimated to be more than 3000 square kilometers.

For example, how much total biomass is in a certain region? What is the chlorophyll, carbon, nitrogen, phosphorus, and iron content of this biomass? How does the fauna community vary between geographic regions and *Sargassum* species or morphological forms? How does *Sargassum* influence the oceanic carbon and nutrie What environmental factors drive its productivity, growth, and distribution? How does *Sargassum* respond to such global changes as increasing reactive nitrogen a dioxide? How do ocean warming and changes in ocean currents affect *Sargassum*?

Without addressing these research questions, it is difficult to explain the sudden increases in tropical Atlantic and Caribbean *Sargassum* blooms after 2011. In situ observations of abundant *S. natans VIII* suggest that recent *Sargassum* blooms in the Caribbean did not originate from the Sargasso Sea [*Schell et al.*, 2015]. Result *Gower et al.* [2013] and our preliminary analysis also indicates a tropical Atlantic origin. However, we still don't know why the blooms tend to originate there.

Furthermore, even though *Sargassum* biomass per area may be comparable to that of water column phytoplankton, *Sargassum* has generally been considered insig marine productivity and is rarely addressed in oceanic biogeochemical studies. Clearly, because only a handful of studies focusing on its biogeochemistry and ecolog available, more coordinated research is urgently needed. The unprecedented beaching events in recent years may promote opportunities to conduct dedicated resea understand this ecologically and economically important marine algae.

Long-Term Perspective

Massive *Sargassum* beaching events are an entirely new phenomenon for many residents in the Caribbean and West Africa. The seaweed has caused many negative but at the same time it may also provide raw materials for commercial use. Local residents need a system to forecast *Sargassum* blooms and *Sargassum* beaching i long and short terms. This is essential for investment decisions in cleanup strategies and technologies and in development of value-added commercial products and manufacturing infrastructure.

The seaweed has caused many negative effects, but it may also provide raw materials for commercial use.

At present, no one can predict the long-term trend (https://www.oyster.com/articles/52838-dont-panic-caribbean-seaweed-this-year-may-not-be-that-horrible/) of *Sargassum* blooms unlikely that the beaching events of the past 5 years will stop. Continuous and improved monitoring and forecasting systems at regional and local scales are necessa management and decision making. The Visible Infrared Imaging Radiometer Suite (VIIRS, 2012 to present) is equipped with spectral bands similar to those of MOI currently, VAS generates and distributes VIIRS AFAI imagery in the same manner as MODIS (Figure 1). NASA and the European Space Agency are also planning se advanced ocean color missions (Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE), Geostationary Coastal and Air Pollution Events (GEO-CAPE), Sentinel-3) with spectral and temporal resolutions to enhance SaWS capabilities. Additionally, high-resolution sensors such as the MultiSpectral Instrument (MSI; 10–60 meters) o 2 (2015 to present) and follow-on sensors can also be used to track small *Sargassum* aggregations, similar to the use of the Landsat 8 Operational Land Imager (OL

Various governmental agencies are taking actions to facilitate research, monitoring, and forecasting. For example, a Gulf Coast *Sargassum* Symposium (http://www.gulfbase.org/event/view.php?eid=2gcss) in April 2015 brought together various stakeholders concerned with the effects of *Sargassum* on coastal states of the G Mexico to discuss the current status and future directions in *Sargassum* research, monitoring, and forecasting. The Predicting *Sargassum* Blooms (PSB-CARIB) pr been recently funded by the French Environment and Energy Management Agency, Regional Council Martinique, and Direction de L'environnement de L'aménage Logement Guadeloupe to study *Sargassum* blooms in the central Atlantic and the Caribbean. Similar projects in French Guiana, Mexico, and other countries or reg also underway.

SaWS received direct support from NASA to improve and enhance its capacity for near-real-time monitoring and tracking of *Sargassum* blooms (Figures 1–3). Furt NASA's Jet Propulsion Laboratory has partnered with the Sargasso Sea Commission to develop a prototype data portal to compile all relevant data (e.g., *Sargassum* and abundance, sea surface temperature, sea surface height, ocean currents, winds), which will help us understand spatial and temporal *Sargassum* distributions.

Collaboration and Coordination

With increased funding and research activities to study *Sargassum* ecology, biogeochemistry, and how *Sargassum* responds to environmental changes, our knowle *Sargassum* and our short- and long-term predictive capabilities are expected to improve significantly in the near future. At the same time, better collaboration and coordination will help research and monitoring efforts to develop long- and short-term forecasting. Moreover, improved public access to data products will assist wi management decisions and economic development.

Acknowledgments

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Correction, 6 September 2016: Donald Johnson has been added as a coauthor of this article. His name was omitted inadvertently.

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