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# A simple, fast, and reliable method to predict Sargassum washing ashore in the Lesser Antilles

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## ABSTRACT

Since 2011, the Lesser Antilles have faced major events of the washing ashore of pelagic Sargassum. Windward, exposed island coasts receive tons of algae that alter the quality of coastal ecosystems and the environment. The events repeated in 2012, 2014, 2015 and 2016. A major concern for local governments is to predict arriving floating algae and assess the risk of washing ashore. Here, we present a method to use a Sargassum Watch System (SaWS), based on satellite imagery and numerically-modelled surface currents, for near-real-time tracking of floating algae in the central Atlantic. The analysis of satellite data and numerical HYCOM surface ocean currents was used to predict washing ashore events days before they occur. These online products are integrated and made available to users in Keyhole Markup Language (KML) format and uploaded in Google Earth. Tracking of Sargassum slicks, combined with distance from coast and HYCOM current vectors' direction and speed, can provide an effective prediction tool for possible washing-ashore in specific locations. Comparisons of events between the years 2011 and 2015 show some intensification of the presence of Sargassum in the western Atlantic and a significant increase in the risk of Sargassum washing ashore on the beaches of small islands. The demonstration using simple analyses of existing near real-time online products provides a template for governmental agencies and environmental groups to use, effectively, existing resources towards coastal management.

## 1. Introduction

Events of washing ashore of pelagic Sargassum occurred in 2011, 2012, 2014, 2015 and 2016 in the Lesser Antilles and Caribbean region (Fig. 1). Abnormally large amounts of algae of the genus *Sargassum* washed up on the beaches of islands of the Lesser Antilles from the Virgin Islands to Barbados and Trinidad. Observations were also reported on the African coast, in Sierra Leone, with washing ashore never seen in the past (Széchy et al., 2012). Sargassum live at the surface of the ocean by means of small gas-filled vesicles acting as floats (Butler and Stoner, 1984; Woodcock, 1993). They can be seen from space. (Gower and King, 2011) used satellite images from the Medium Resolution Imaging Spectrometer (MERIS) to hypothesise that Sargassum in the north Atlantic were transported from the Gulf of Mexico following ocean currents. *Sargassum* occur commonly on the U.S. East Coast and the Caribbean and the Gulf of Mexico (Taylor, 1929) and can be conveyed as far away as Newfoundland to the north and Brazil to the south (Gower and King, 2011). Furthermore Gower and King (2011) delineated the usual distribution and passive movement of populations of Sargassum in the Gulf of Mexico and western Atlantic; based on a collection of images from 2002 to 2008 acquired by the MERIS satellite instrument, they identified a seasonal cycle showing that Sargassum appear in the north-west Gulf of Mexico in the spring (March-June) each year and are transported further to the Atlantic Ocean. Currents carry them to Cape Hatteras in July ("Sargassum jet") and their displacement ends north-east of the Bahamas in February the following year. The seasonal, subtropical North Atlantic current and the Azores anticyclone are the major influences on the Sargasso Sea. The circular, subtropical North Atlantic current (North Atlantic Subtropical Gyre) generally helps to contain the algae in an area that varies according to the weather. Regularly, small amounts of Sargassum drift away from the gyre south down to the Caribbean. Analyses of images collected from both 2011 and 2015 confirmed the suggestion of a new Sargassum zone of accumulation in the western Atlantic located at 7°N latitude and 45°W longitude (Franks et al., 2012; Gower et al., 2013; Johnson et al., 2014). However, the origin of the Sargassum in the central Western Atlantic remains unclear.

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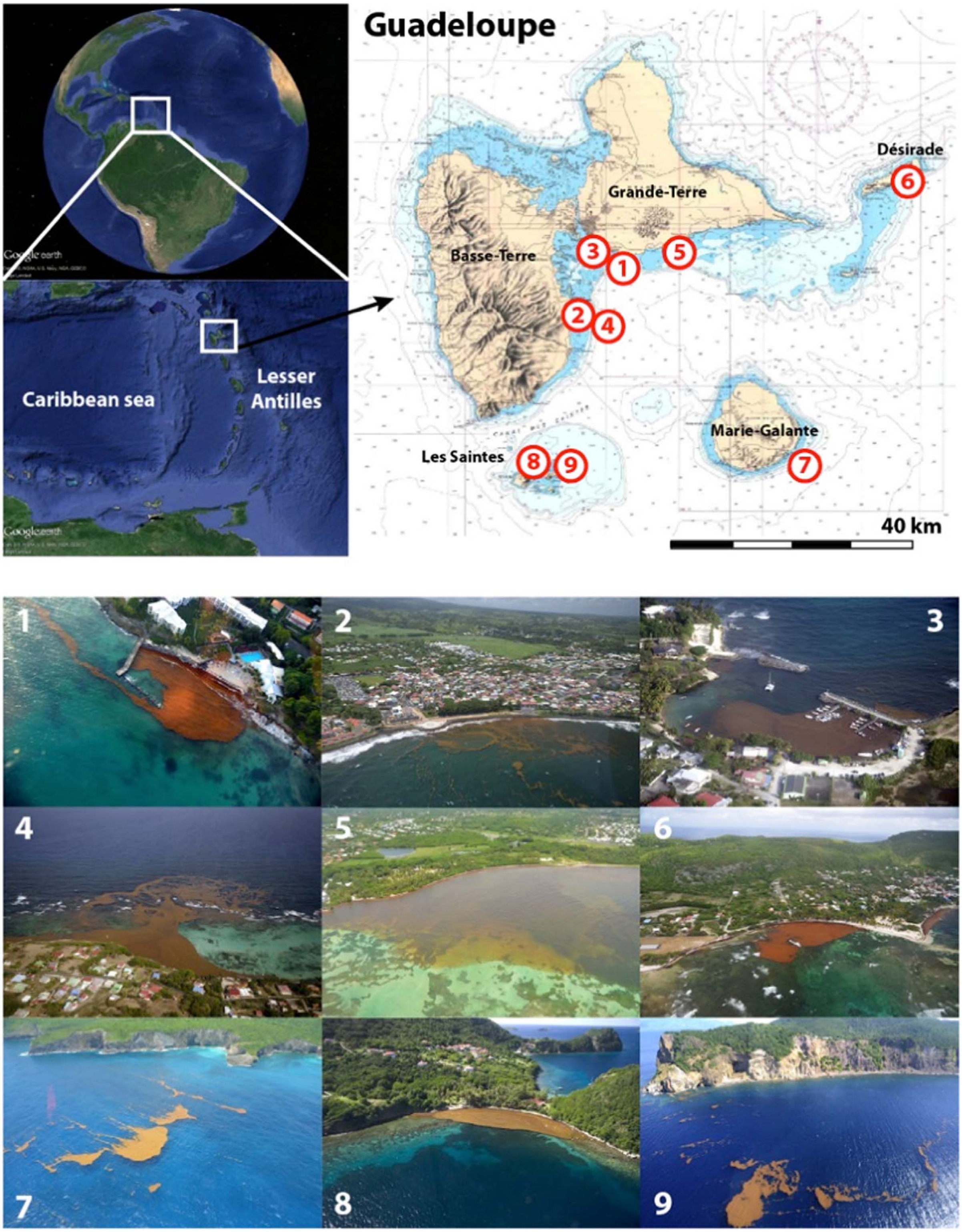

**Fig. 1.** Sargassum sightings in Guadeloupe Island (French Antilles), from helicopter survey on 22nd May 2015 (*Photos courtesy of F. Mazéas*). 1–5: Guadeloupe. 6: Désirade. 7: Marie Galante. 8–9 Les Saintes.

Each year, tons of algae accumulate on the exposed beaches of windward coastlines in the Lesser Antilles (Fig. 1). Subsequently, the coastal environment is subjected to significant damages and non-survival of many organisms. During their trip the rafts of algae accumulate a community of marine organisms composed of micro- and macro-epiphytes, fungi, over hundred species of invertebrates and fish, and four species of turtles (Colombini and Chelazzi, 2003; Huffard et al., 2014; Weis, 1968). These communities vary according to season, geographical area and age of the raft (Stoner and Greening, 1984). The presence of large quantities of Sargassum may also interfere and influence the sea-turtles' choice of nesting sites. Sometimes, if the algal biomass is excessive, turtles are unable to climb these obstacles and will lay their eggs in the Sargassum (Williams and Feagin, 2010), impacting reproductive effectiveness. Removal of algae from beaches may also lead to the destruction of sea turtles' nests.

When the rafts of seaweed wash up in tourist areas, local governments face the difficult choice of either cleaning up the beaches, or leaving the algae degrade naturally. This phenomenon occurs every year along the coast of Texas from March to August (Feagin and Williams, 2010). Negative economic impacts related to tourism are obvious (health hazard, odours, difficult access to the sea, reduced activity of small-boat). In contrast, positive effects of Sargassum are noticed. Sargassum left on the beach constitute a favourable habitat for shorebirds, and provide resources for detritivores (Gheskiere et al., 2006). Cleaning methods are often limited to scraping the beaches with trucks. The collected algal biomass is relocated to the dunes, or upper beach, to boost plant growth and dune stabilisation (Gheskiere et al., 2006; Nordstrom, 2003; Williams and Feagin, 2010). Such practices are inadequate in the Lesser Antilles as dunes are rare on the coastline, and collection of algae from the beach can cause negative effects by removing surfaces materials from beaches.

Early detection of Sargassum, risk assessment and alerts appear strategic elements in the process of helping the local populations to prepare for Sargassum washing ashore. Satellite-based macroalgae detection and tracing can be derived from MERIS (Gower, 2006) or the Moderate Resolution Imaging Spectrometer (MODIS) and Landsat sensors (Hu, 2009) in detecting macroalgae mats on the surface of the ocean based on the red-edge reflectance of vegetation. The algae-mats appear as slicks in MERIS and MODIS imagery. In particular, a customised data product (AFAI: Alternate Floating Algae Index, see below) used together with surface ocean currents also available in near real-time from a numerical model, can form a prototype Sargassum Watch System (SaWS, (Hu et al., 2016a). Local groups can use the SaWS on a routine basis to detect and trace Sargassum mats if they know how to make effective use of these products. Island authorities and managers expect reliable alerts to anticipate Sargassum washing ashore and mobilise technical teams, thus reducing timing and costs of cleaning operations. While the *Sargassum* detection method as well as time-series of *Sargassum* distributions between 2000 and 2015 in the Central West Atlantic (CWA) have been fully described in Wang and Hu (2016), and the description of SaWS is provided in Hu et al. (2016b), how to make effective use of SaWS for short-term prediction of *Sargassum* beaching has not been reported. Therefore, the objective of this work is to demonstrate and evaluate a simple and fast method for release of early-warning alerts of beaching of Sargassum risk in the Lesser Antilles, based on the MODIS AFAI products and analyses of surface currents. We show examples of how large Sargassum rafts were tracked during the year 2015 and how these tracks matched with actual beaching. In addition, a comparison of the 2011 and 2015 events is also performed, advocating the need for operational tools for prediction.

## 2. Materials and methods

### *2.1. Satellite images*

The Virtual Antenna System (VAS, (Hu et al., 2014)) has been established at the University of South Florida to download low-level satellite data distributed in near real-time by NASA, and generate and distribute various standard and non-standard data products, which are then distributed on the same day (within 4–6 h of satellite overpass) through a web portal (Hu et al., 2014). Among these non-standard data products are the AFAI images (1 km resolution in reflectance units) to detect ocean-surface features such as Sargassum, green macroalgae, and cyanobacterial mats. The AFAI images were derived from MODIS Rayleigh-corrected reflectance (Rrc, dimensionless) using the same band-subtraction design as the original floating algae index (FAI, (Hu, 2009)) but the red and near-infrared MODIS bands (667, 748, and 869-nm) are used to calculate AFAI in order to facilitate cloud masking (Wang and Hu, 2016). The floating algae detected appear as long curved lines (Hu et al., 2015), thus called image slicks, that can be traced over time. Both FAI and AFAI examine the relative height of the near-infrared reflectance, where macroalgae such as Sargassum would show enhanced FAI and AFAI values. The customised AFAI data product has been generated and distributed in near real-time for the Eastern Caribbean (10–23°N, 75–60°W), the Central Atlantic (22.0–0.0°N, 38–63°W), and other areas in the Intra-Americas Sea (IAS) since 2011 (http://optics.marine.usf.edu/projects/SaWS.html). MODIS AFAI Satellite images from January to December 2011 and January to December 2015 were analysed. Images from 2011 were used retrospectively to derive monthly time-series of Sargassum distributions in the Lesser Antilles and compare them with the 2015 event. Several images are collected every day between 1300 and 1800 GMT from multiple satellite overpasses from MODIS on Aqua and MODIS on Terra. Composite images were created as a combination of single images taken at different times for a single day.

### *2.2. Google Earth final product*

In addition to the MODIS AFAI imagery, surface currents from the Hybrid Coordinate Ocean Model (HYCOM) made available by the National Ocean Partnership Program (NOPP) are obtained, updated nightly, and made available via the VAS. All data products (AFAI, HYCOM currents) can be displayed in Google Earth, thereby facilitating visualisation and navigation.

### *2.3. Image processing in ImageJ*

Downloaded AFAI images from the Central Atlantic region were processed in ImageJ (Schneider et al., 2012) to isolate the Sargassum signal at the surface of the ocean. Only pictures showing typical "likely-Sargassum" signals were analysed to limit overestimation of signals. The.*png* images have a coverage of 2750×2420 pixels (1 pixel≈1 km$^2$) in Red, Green and Blue (RGB) format. Images are adjusted to RGB colour in ImageJ and colour threshold using the *default thresholding* method with *black threshold colour* and *RGB colour space with dark background* (Fig. 2a). This treatment removes the white contours of the islands and continent. *Colour balance* adjustment is used to change brightness and contrast of RGB images by modifying the pixel values (Fig. 2b). The Red, Blue and Green channels are split afterward to produce three single images using the *Image/Colour/Spilt Channels* menu (Fig. 2c). The Sargassum signal is visible in the Green Channel picture (Fig. 2d). We threshold this grey picture using the default black and white thresholding menu (*Image/Adjust/Threshold)* and adjust it to a level that isolates only the "likely-Sargassum" signal (Fig. 2e). Many isolated pixels (mainly cloud-shadow pixels with high AFAI values) can be excluded by using the *Process/Noise/Despeckle* menu.

This image is converted to binary (Fig. 2f). Nearshore pixels tend to have high AFAI values and false-positive signals can be detected, due to shallow waters, local eutrophication or sun glint effects (Hu et al., 2015). We applied a 10 km mask around each island and continent to exclude these pixels using the *Image calculator* menu subtracting image1 as the Mask and image2 as the Green channel picture (Fig. 2g). The subsequent picture is used again in the *Image calculator* tool as image2 with image1 as a Lesser Antilles map and the *Difference* operation option (Fig. 2h). The result is a picture showing only the "likely-Sargassum" signal and the contours of the islands (Fig. 2i). However, it is still necessary to closely examine the final image after processing, especially in areas of complex, cumulative AFAI false-positive pixels to exclude these areas from forecasting.

The final image is uploaded in Google Earth to replace the original AFAI image in the KML file. Surface current vector colours (originally white) are changed in Google Earth for better visualisation of the interactions between floating algae and currents.

Monthly composites were aggregated from single-day images of Sargassum signals in ImageJ using the *Image/Stacks/Images-to-Stack* menu. A *Z-projection* was applied with *Max-Intensity*-projection type

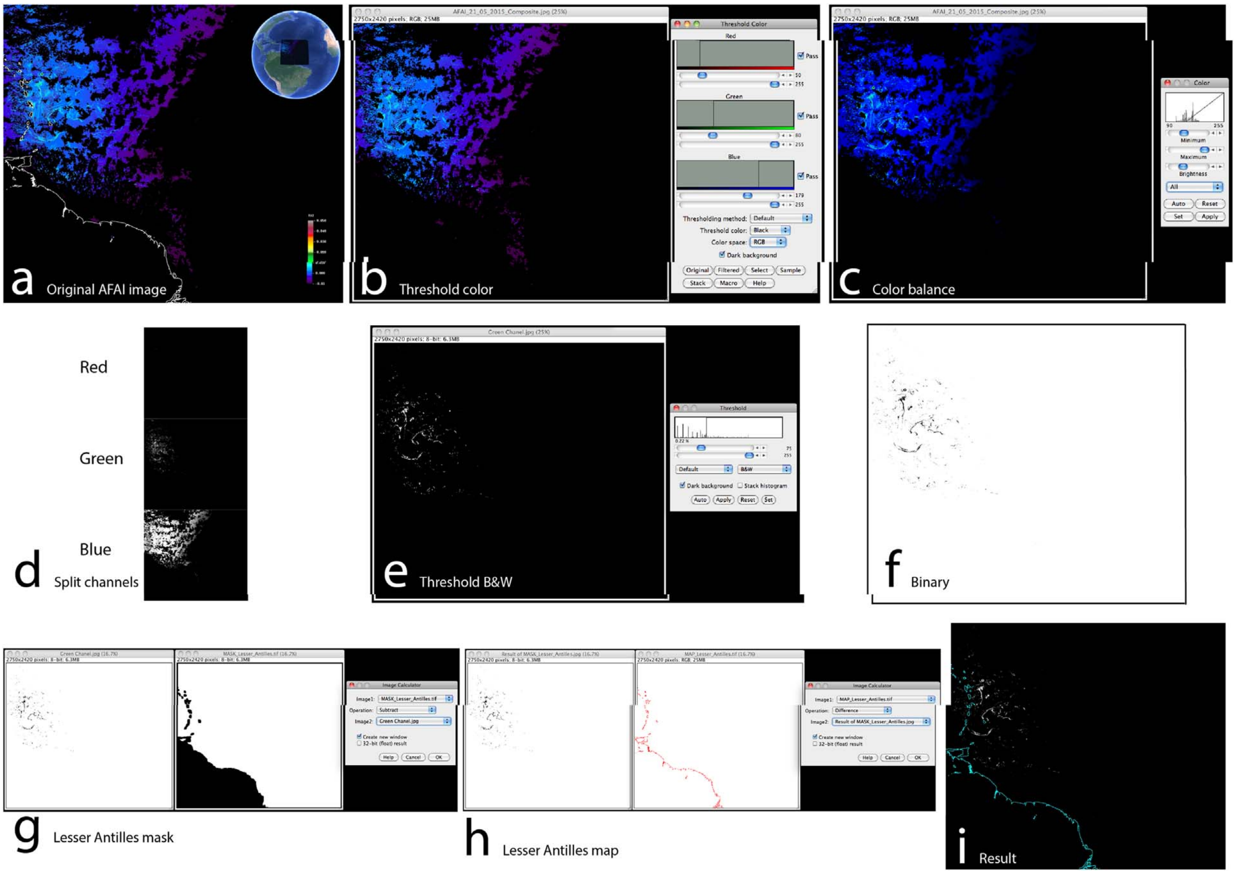

**Fig. 2.** Image processing steps in ImageJ from original AFAI image to Sargassum signal isolation. a) Original AFAI image with Sargassum signal detected. b) Threshold colour menu removes islands and land contours. c) Colour balance menu reduces colour information of the image to focus on Sargassum signal pixels (in blue-green). d) Colour-split channels tool separate Red, Green and Blue channel, Sargassum signal being visible on the Green channel result. e) The grey-scale Green channel picture is "thresholded" to isolate the Sargassum signal only. f) Image is converted to binary black and white. g) The Lesser Antilles Mask image is subtracted from the binary image result to remove false signals around the islands. h) The image result is used in the image calculator tool as image2 with image1 as a Lesser Antilles map and the Difference operation used to obtain the final image i). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(*Image/Stacks/Z-projection* menu) to gather the images in one single image representing the total "likely-Sargassum" signals detected each month.

In this simple process, no correction was applied to pixels contaminated with sun-glint as these pixels are either saturated under strong sun-glint in one of the three MODIS bands (the 667-nm band, with saturation radiance of 4.2 mW $cm^{-2}$ $\mu m^{-1}$ $sr^{-1}$, corresponding to about 0.02 $sr^{-1}$ sun glint reflectance, (Hu et al., 2012)) used to derive AFAI or tolerant to non-saturation sun glint (Hu, 2009), thus they do not affect the overall results. Although a more objective and sophisticated method has been proposed to remove the various image artefacts (Wang and Hu, 2016), such a method is not available to the general user-groups at large. The simple method on the user-end may therefore be transferable and implemented by different user-groups.

### 2.4. Risk assessment

Geographical coordinates of Sargassum rafts are generated in Google Earth. Sargassum slicks location detected on AFAI images can be combined with the HYCOM surface current vectors. We used current vectors (speed, orientation) adjacent to algal rafts to calculate the average speed of the current conveying Sargassum rafts (six vectors speed). The distance from the coastline is calculated using the *rule* tool in Google Earth.

The combination of speed of current, orientation and distance from the coast provides a window period when rafts of Sargassum are likely to arrive on the beaches.

This method has been used to detect rafts of Sargassum in the Lesser Antilles region, inform and release alerts to local authorities in Guadeloupe (French West Indies). Examples of the 2015 Sargassum event are presented. Between April 2015, 1st and December 2015, 31st, 304 daily composite images were examined. Rafts localised in an area of 10–300 km radius were referenced (latitude/longitude). Speed and direction of surrounding surface currents (HYCOM model) were analysed in Google Earth. HYCOM is a seven-days forecast model. Average speed of the surface current in the Lesser Antilles varies from 1 to 3 km $h^{-1}$, which gives a 168–504 km distance drifting from the original location where detected. Several alerts were correlated with actual sites of beaching of Sargassum identified by helicopter surveys over the Guadeloupe Island, but ground-testing did not systematically follow all released alerts and aerial surveys were done only twice in 2015. Reports from the Guadeloupe Regional Agency for Healthcare (ARS) detailed presence and visual estimates of Sargassum on beaches and at sea in several locations around the island, and were also used as reference for correlation with satellite Sargassum detection. However, ARS controls and reports were not done regularly and it has not been possible to correlate all alerts with actual occurrence or otherwise of beaching of Sargassum, nor was it possible to identify false positive or false negative alert. Weekly reports of Satellite image analysis were delivered, along with specific alert releases.

### 2.5. Prediction success rate and uncertainties

We compared high-risk prediction alert forecasts derived from satellite AFAI images combined with HYCOM analyses with actual beaching dates for the May-October 2015 period. Days of detection

**Table 1**
Alerts released for the Guadeloupe Island between May and November 2015. Latitude and longitude coordinates represent centroids location of major Sargassum MODIS raft threat. On several dates the island was surrounded by Sargassum leading to high-risk alerts for Sargassum washing ashore – no specific raft were identified on these dates (coded as "High Risk" in the table). ARS reports: field reports of the *Regional Agency for Healthcare (ARS)* in Guadeloupe on Sargassum beaching and $H_2S$ measurements. Number of alerts released between May and November 2015 for single-day alerts: 37. Number of ARS Sargassum beaching reports: 23. Prediction success rate: 62%.

| | | **Sargassum raft location** | | | | **Forecast** | |
|---|---|---|---|---|---|---|---|
| | **(1) Date of detection** | **Lat.** | **Long.** | **Average speed (km/h) HYCOM surface current vectors** | **Raft distance from Guadeloupe coastline (km)** | **(Risk of beaching – calculated from the 2 previous columns) (Days)** | **Reports on Sargassum beaching** |
| 1 | 21/05/15 | 15°27'31.54"N | 61°2'57.67"O | 2.53 | 48 | 0,8 | ARS Report 22/05<br>Helicopter survey 22/5 |
| 2 | 26/05/15 | High Risk | | | | | ARS Report 26/05 |
| 3 | 27/05/15 | High Risk | | | | | ARS Report 27/05 |
| 4 | 02/06/15 | 14°57'49.05"N | 60°41'51.14"O | 1.48 | 115 | 3.2 | ARS report 4/6 |
| 5 | 03/06/15 | High Risk | | | | | ARS report 4/6 |
| 6 | 04/06/15 | High Risk | | | | | ARS report 5/6 |
| 7 | 06/06/15 | High Risk | | | | | ARS report 8/6 |
| 8 | 9/06/15 | High Risk | | | | | ARS report 11/6 |
| 9 | 10/06/15 | High Risk | | | | | ARS report 11/6 |
| 10 | 11/6/15 | High Risk | | | | | ARS report 11/6 |
| 11 | 15/06/15 | 16°29'48.74"N | 61°10'50.86"O | 1.39 | 26 | 0.8 | ARS report 15/6 |
| 12 | 29/06/15 | High Risk | | | | | ARS report 29/6 |
| 13 | 1/07/15 | 16°29'58.94"N | 59°43'4.96"O | 1.4 | 150 | 4,5 | ARS report 6/7 |
| 14 | 10/7/15 | 14°58'17.38"N | 59°52'42.26"O | 1.09 | 200 | 5.4 | ARS report 17/7 |
| 15 | 17/07/15 | 16°12'39.46"N | 60°41'46.69"O | 1.83 | 57 | 1.3 | ARS report 17/7 |
| 16 | 19/07/15 | 15°57'31.97"N | 60°47'18.21"O | 0.95 | 51 | 2.2 | ARS report 22/07 |
| 17 | 19/07/15 | 15°46'51.26"N | 60°32'57.91"O | 0.95 | 82 | 3.6 | ARS report 22/07 |
| 18 | 24/07/15 | 16°11'31.36"N | 61° 1'32.29"O | 1 | 19 | 0.8 | ARS report 27/7 |
| 19 | 24/07/15 | 14°41'57.55"N | 60°26'30.29"O | 1.2 | 190 | 6.4 | ARS report 29/07 |
| 20 | 31/07/15 | 15°53'52.91"N | 60°47'35.83"O | 1.21 | 62 | 2.1 | ARS report 31/7 |
| 21 | 6/8/15 | 16°49'0.67"N | 61° 4'7.45"O | 1.7 | 70 | 1,6 | ARS report 7/8 |
| 22 | 09/08/15 | 16°12'43.96"N | 60°50'34.29"O | 1.92 | 44 | 0.9 | ARS report 11/8 |
| 23 | 09/08/15 | 16°11'34.05"N | 60°52'6.64"O | 2 | 30 | 0.6 | ARS report 11/8 |
| 24 | 12/8/15 | High Risk | | | | | ARS report 13/8 |
| 25 | 16/08/15 | 16°30'9.41"N | 61°17'38.28"O | 1.5 | 10 | 0.3 | ARS report 16/08 |
| 26 | 16/08/15 | 16°6'16.32"N | 60°59'41.77"O | 1.5 | 27 | 0.8 | ARS report 16/08 |
| 27 | 16/08/15 | 16°21'7.11"N | 60°43'27.75"O | 1.5 | 46 | 1.3 | ARS Report 16/08 |
| 28 | 17/8/15 | High Risk | | | | | ARS report 20/8 |
| 29 | 18/8/15 | High Risk | | | | | ARS report 20/8 |
| 30 | 01/09/15 | 16°0'20.66"N | 61°52'42.19"O | 1 | 10 | 0.4 | ARS report 2/09 |
| 31 | 01/09/15 | 16°14'51.10"N | 60°54'51.96"O | 1 | 25 | 1 | ARS report 2/09 |
| 32 | 03/09/15 | 15°56'9.60"N | 61°5'23.59"O | 0.94 | 10 | 0.4 | |
| 33 | 03/09/15 | 16°28'11.44"N | 61°3'46.77"O | 0.48 | 34 | 2.9 | |
| 34 | 08/09/15 | High Risk | | | | | |
| 35 | 10/09/15 | 16°1'28.08"N | 60°50'0.26"O | 1.02 | 43 | 1.8 | |
| 36 | 16/09/15 | High Risk | | | | | |
| 37 | 17/09/15 | High Risk | | | | | |
| 38 | 19/09/15 | High Risk | | | | | |
| 39 | 20/09/15 | High Risk | | | | | ARS report 24/9 |
| 40 | 24/09/15 | High Risk | | | | | ARS report 24/9 |
| 41 | 26/09/15 | High Risk | | | | | |
| 42 | 29/09/15 | High Risk | | | | | ARS report 30/09 |
| 43 | 12/10/15 | 15°8'24.61"N | 60°54'53.86"O | 2 | 86 | 1.7 | |
| 44 | 19/10/15 | 15°48'8.04"N | 61°28'54.74"O | 0.8 | 15 | 0.8 | |
| 45 | 19/10/15 | 16°35'0.91"N | 60°29'30.27"O | 1.15 | 60 | 2.2 | |
| 46 | 13/11/15 | 16°3'12.62"N | 60°48'5.79"O | 1 | 40 | 1.7 | |

from AFAI products were quoted as *Image dates* (1), *Risk of beaching* (2) was calculated from Sargassum location coordinates and average speed of currents (HYCOM) to predict day of likely washing ashore (n=days), *forecast* (3) of beaching date was made from (1) and (2), and *actual beaching date* (4) was obtained from the ARS reports (Table 1). Success rate is calculated as the ratio between Sargassum beaching reports and high-risk alert releases. ARS teams did not survey beaches every day, which does not mean beaching events did not occur. Also alert releases were not checked systematically and "no beaching" information was not reported. Some reports might also refer to previous beaching of Sargassum events or Sargassum accumulated on beaches during several days. However, we challenged our predictions with the actual beaching observations to assess forecast uncertainty for 34 values over the 46 high-risk alerts released. We calculated the difference between forecast beaching dates and actual beaching dates (observations). The mean difference represents the uncertainty in the forecast beaching timing. Zero value means accordance between observations [actual beaching (dates)] and forecast/predicted beaching dates, positive values means early arrival and negative values mean late arrival. The 95% confidence limit was calculated around the uncertainty estimates.

## 3. Results

### 3.1. Sargassum detection at large-scale

Floating algae were detected on MODIS satellite images in the western central Atlantic as early as 3rd February 2011 (Fig. 3). However, large amounts of Sargassum appeared significantly on images by May 2011, as also stated by Gower et al. (2013). The area

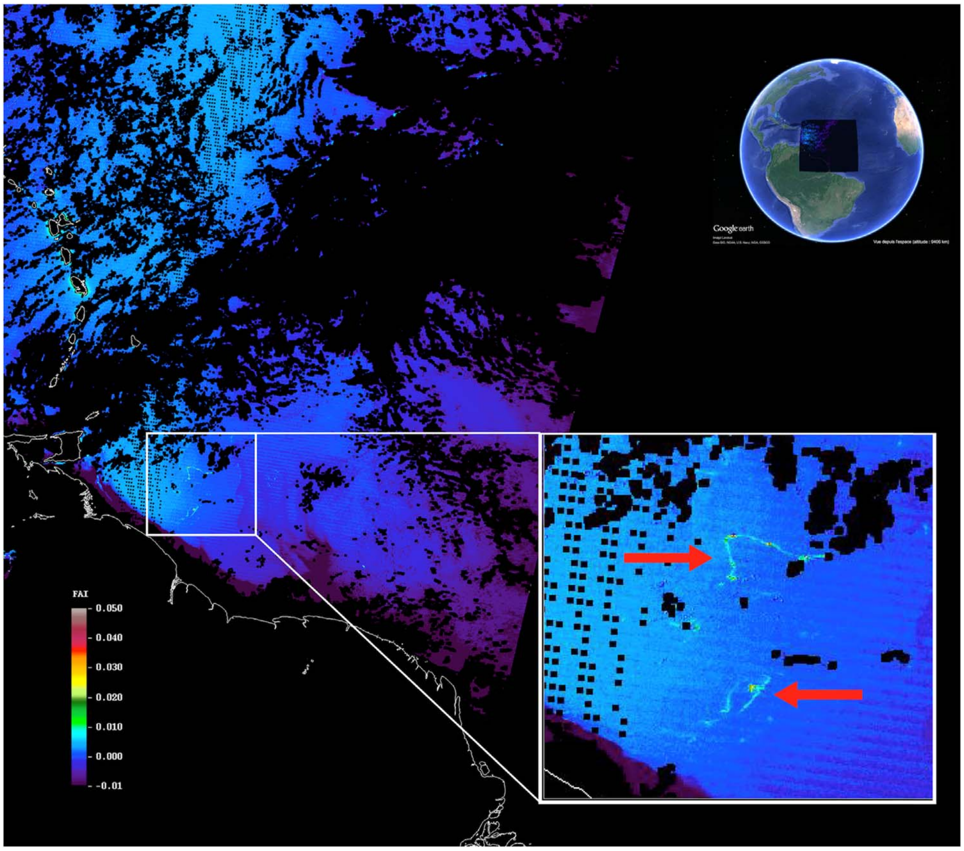

**Fig. 3.** Sargassum slicks (red arrows) detected north Guyana on 3rd February 2011 AFAI MODIS image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concerned was north Brazil, 1000 km east of the Amapá state and 600 km north of the Ceará state (0°N–45°W and 5°N–38°W).

The islands of Grenada and Martinique released first reports of abnormal amounts of Sargassum washing ashore in May 2011. July 2011 was the most significant period of massive beaching of Sargassum in the Lesser Antilles, reported by the islands' governmental agencies, north to the Virgin Islands and south to Trinidad and Tobago. The phenomenon lessened by October 2011, as shown in Fig. 4A. The maximum Sargassum signal covered the period May–September 2011, which correlates with the maximum beaching in the region. Soon after, Sargassum biomass reduced significantly and the situation returned to normal (no or few instances of floating Sargassum).

In 2015, Sargassum were visible all year long, however detection decreased in October 2015. The quantity of Sargassum detected was significantly higher in 2015 compared with 2011 as shown in Fig. 4B. Total cumulative "likely-Sargassum" 1-km pixels amounted to 177,300 in 2011 against 1,889,770 in 2015 over a 6,655,000 km$^2$ area, which represents 10.7 more instances of algae per annum over a four-year period. Presence of Sargassum in the Lesser Antilles seemed to be much more pronounced in 2015, although there is no existing detailed report of the amount of Sargassum appearing or collected on beaches.

Sargassum were detected in the Lesser Antilles as early as January 2015 compared with 2011 (detection in May). In January and February 2015, Sargassum were present above 12°N extending from the Lesser Antilles east to 38°W (Fig. 4B-1 and B-2). A similar pattern occurred in November and December. During the winter months, Sargassum slicks were mainly drifting towards the Lesser Antilles from the east, conveyed by the North Equatorial Current (NEC – east to west direction) (Molinari, 1983).

Sargassum distribution changed in March 2015 with slicks detected in the southern region 0°N–45°W and 5°N–38°W (Fig. 4B-3). During spring and summer 2015 (May to August), the major detection of Sargassum was located 12–3°N and 38–50°W, in the North Brazil Current (Fig. 4B-6). This retention zone allows the algae to be regularly conveyed along the north Brazilian coast toward the Caribbean. During the summer, Sargassum come from the south. The Hycom surface currents presented on Fig. 5 show that floating Sargassum passively follow these general circulation patterns. By August, the floating algae might be conveyed by the North Brazil Current Retroflection into the North Equatorial Counter Current, drifting to the east back to the Gulf of Guinea (Fig. 5). As a consequence, the quantity of Sargassum transported towards the Caribbean and Lesser Antilles was significantly reduced in October 2015.

While accumulating in the north Brazil region, patches of Sargassum are conveyed by the north Brazil current and the Guyana current and enter the Caribbean north Trinidad and Tobago. Large amounts of Sargassum drift with the Caribbean current to the north toward the Lesser Antilles and across the channels to the Caribbean Sea. These rafts can reach the coast of Colombia, Belize and the Greater Antilles. Eventually, they can reach the Gulf of Mexico, back in the greater loop described by Gower and King (2011).

### 3.2. Sargassum detection at small-scale regional level

MODIS images were analysed daily in 2015 to detect Sargassum close to Guadeloupe. On 21st May, 2015, one 18,000 km$^2$ raft of Sargassum was detected at the surface from the MODIS AFAI image (Fig. 5) along the east side of the Lesser Antilles. A raft 208 km long extended 50 km away from Guadeloupe south coast (15°27'31.54"N–61°2′57.67"W) down to Martinique Island, drifting at an average speed of 2.53 km h$^{-1}$ towards the north. Sargassum reached the coast of Guadeloupe at the same period as reported by local authorities from a helicopter survey on May 22nd (Fig. 6).

Another example from July 24th showed a Sargassum raft located

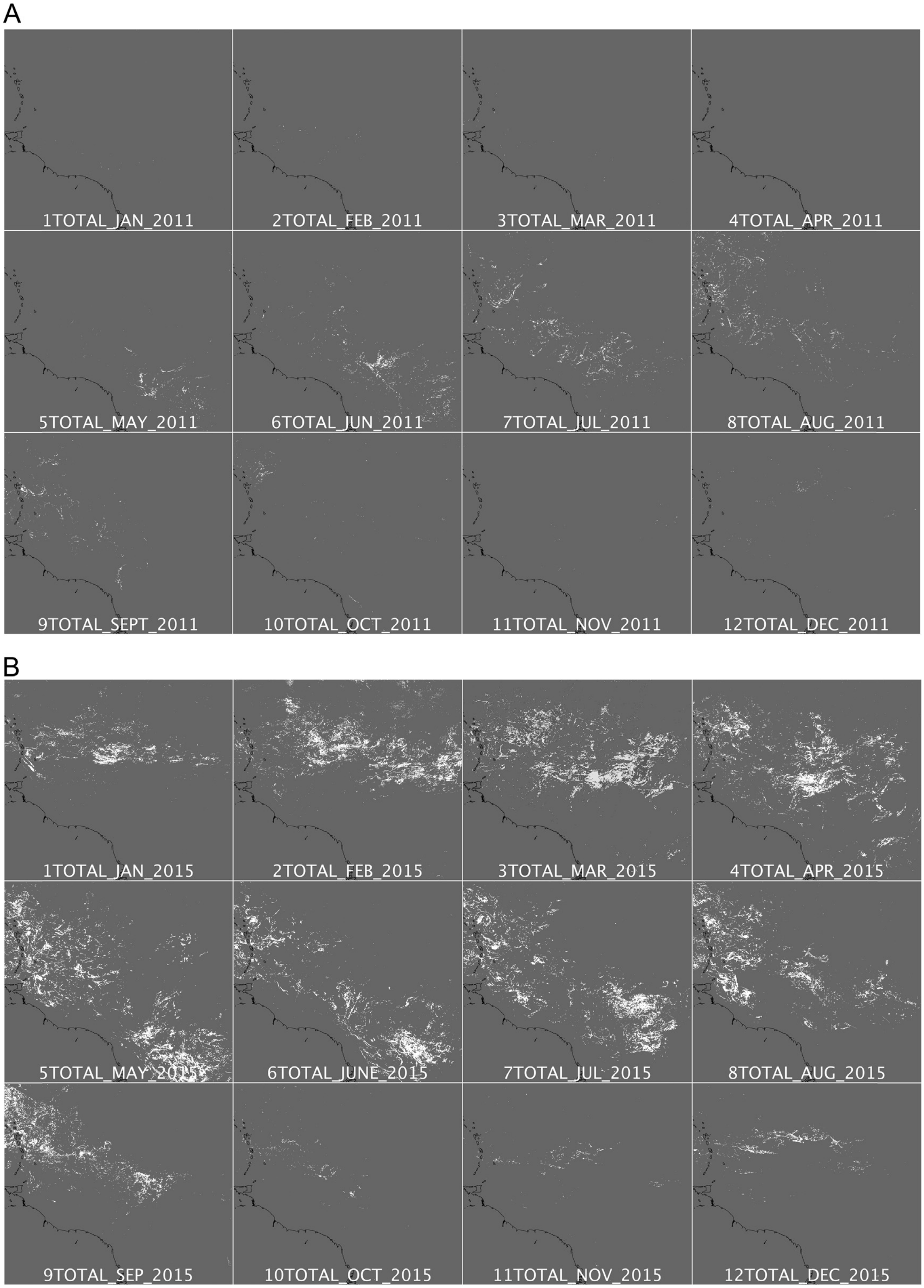

**Fig. 4.** Sargassum detection from MODIS AFAI satellite images for year 2011 (A) and 2015 (B). Single images are monthly composite Sargassum detection (combined pixels). Area of interest: Central West Atlantic (22.0–0.0°N, 38–63°W).

16°11'31.36"N–61°1′32.29"W at a distance of 19 km from the south-east coast of Guadeloupe with an average drifting speed of 1 km $h^{-1}$ toward the north-east (Fig. 6).

As a consequence, High Risk Beaching Alerts were released by the Company Nova Blue Environment (NBE - hired to do the survey) for careful attention on Wednesday 22nd May 2015, and Saturday 25th July 2015. Sargassum beaching was confirmed by local reports from the Direction Régionale de l'Environnement, de l'Aménagement et du Logement. Guadeloupe alerts released by NBE during the May-November 2015 period are listed in Table 1 (46 high-risk level alerts between 21st April 2015, and 13th November 2015,). Maximum number of alerts was released from May to September while the Sargassum were trapped in the North Brazil Current 8–13 alerts per month). Drifting of Sargassum reduced when the current system

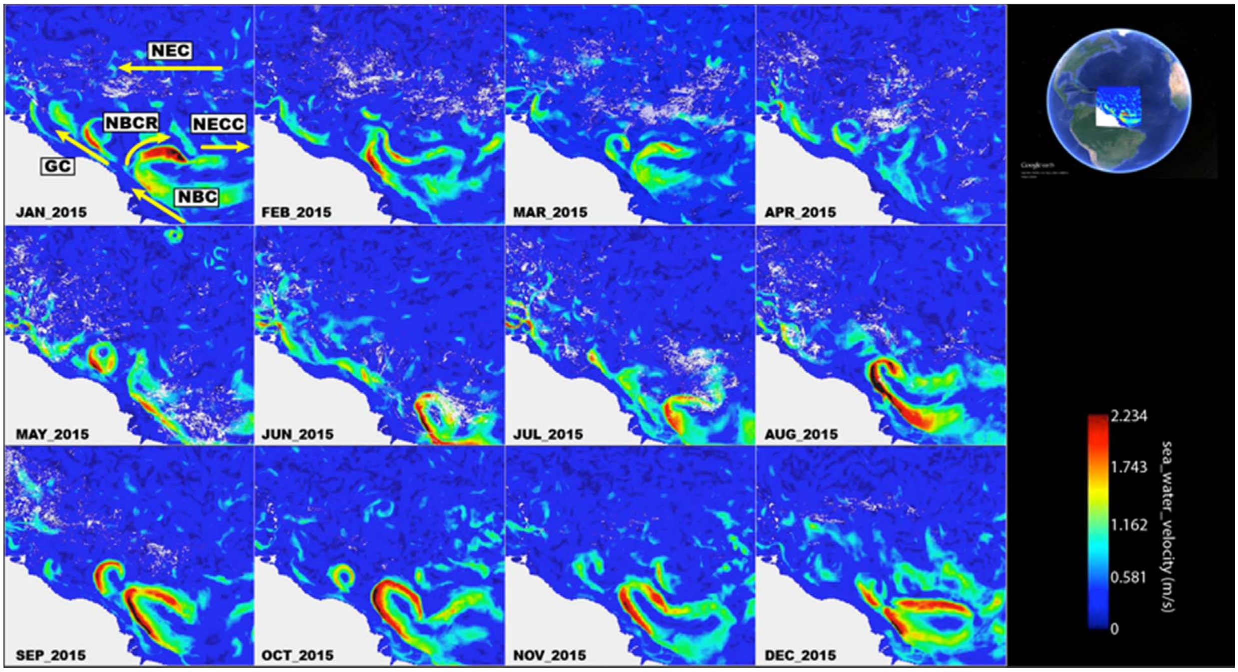

**Fig. 5.** Composite image of surface currents (colour – month average) in the region of interest (Central West Atlantic: 22.0–0.0°N, 38–63°W) and Sargassum signals (white). HYCOM & MODIS images. NEC: North Equatorial Current, NECC: North Equatorial Counter Current, NBC: North Brazil Current, NBCR: North Brazil Current Retroflexion, GC: Guyana Current. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

changed according to the consolidation of the North Equatorial Counter Current in late summer (Fig. 5).

Over the 46 alerts released between May and November 2015, 34 were related to actual Sargassum presence onshore, and 37 accounted for single-day alerts (=alert sent on the day of observation and a beaching risk less than 24 h) and were linked to 23 beaching reports. Success rate was then 62%. This means that for each alert there is a 62% chance that drifting Sargassum algae reach the exposed beaches. The average uncertainty of the forecast model (n=34) in the predicted beaching time was 0.03 day (95%low=−0.47; 95%high=0.42), and the uncertainty ranged from −3.4 to 3 days. According to these results, error was very low and average predictions quite precise. For longer drifting periods (rafts detected over 150 km from the shore or over 3 days Sargassum transportation), it is likely that the uncertainty in the predicted beaching time would increase. While these results are encouraging, it was not verifiable whether Sargassum washed ashore on the date of field observation or had accumulated on shore over the previous days. However, these results show that detection offshore is highly correlated with beaching of Sargassum. When Sargassum is detected on AFAI images at a distance of less than 150 km off the coast, there is a significant chance that beaching will occur, according to HYCOM surface current models. A few examples of Sargassum rafts identified far away from shore could be correlated with large beaching events, as on June 2nd. However, to reduce prediction errors, it seems reasonable to restrain washing-ashore forecasts to detection within a geographical limit of 50–100 km maximum off the coast. In the future, coastal beaching network reporting should be set up to correlate more precisely detection offshore and actual beaching.

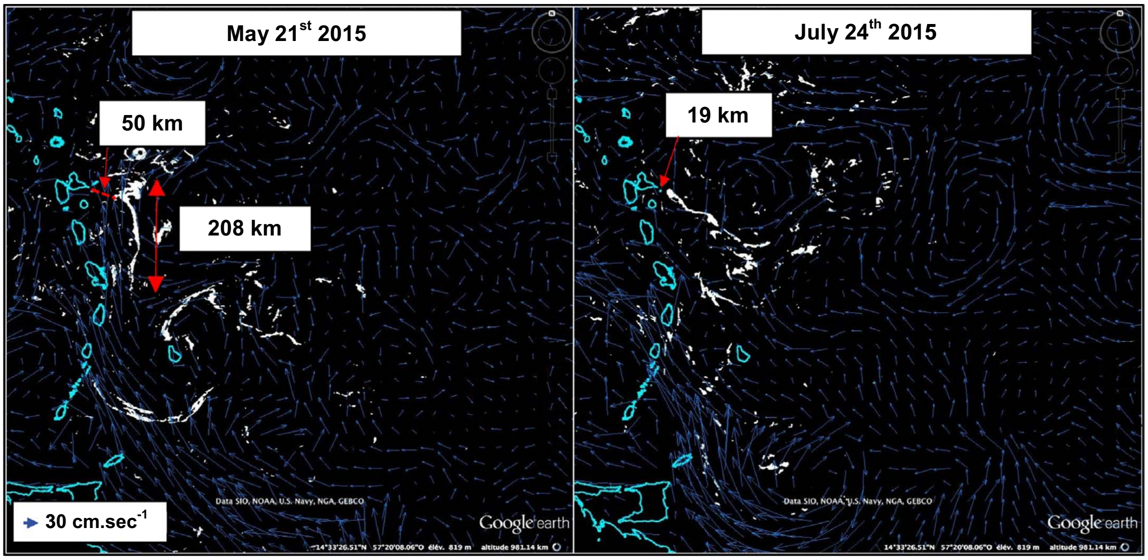

**Fig. 6.** Sargassum slicks detected on May 21th, 2015 and July 24th, 2015. Sargassum slicks in white. Islands contours in green, blue arrows=HYCOM surface currents. High risk of beaching alerts were released on these dates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

While it was possible to detect Sargassum rafts offshore, false signal (cloud shadow, coastal eutrophication) can alter actual floating algae signals by enhanced reflectance. However, Sargassum rafts have a typical signal shape, previously described as slicks forming long extended curved lines and contrary to phytoplankton blooms, are persistent and can be detected over several days (Hu et al., 2015). However, cloud cover can significantly limit the detection of floating algae at the surface of the ocean. As a consequence, the follow-up of identified slicks was often compromised by the random presence of clouds over the region and day-to-day follow-up was rarely possible. Areas of unclear signal and overlap of high AFAI source signals were also systematically removed. We chose to extract the "likely Sargassum" signal solely from the AFAI images for visual purpose mainly and better readability following the method described in Fig. 2. The thresholding of the Green Channel image (in grey scale) needs a visual examination of the result. A compromise between the Sargassum signal isolation and the loss of information has to be found. However, in some cases, the distinction between Sargassum signal and background noise cannot be done and these specific areas were removed from the total image. Usually, these areas correspond to sunglint areas or satellite path borders. In the end, when the image was not useful or too noisy for our purpose, it was not used for visual examination.

## 4. Conclusion and discussion

This method gives an overview of the Sargassum drifting process. Its use at small-scale regional levels reveals a useful tool for local governments to anticipate Sargassum washing ashore. The simple use of AFAI and HYCOM forecast in short-term prediction has worked efficiently during the year 2015 for Guadeloupe and French Antilles. This method requires visual analyses of the satellite images and reporting, which represents 1–2 h $\text{day}^{-1}$ work time. We based our protocol on simple treatment analyses and basic computing equipment accessible to any environmental agency, providing an early-warning operational system. Daily analysis of AFAI satellite products has allowed sufficient early detection to alert local authorities, saving time to prepare for the cleaning of beaches. Localities alerted with beaching risk can mobilise technical teams and operational equipment to reduce Sargassum impact. Moreover, the average uncertainty of the predicted beaching time was less than one day, which gives a good window for managers to prepare locally. While the 62% success rate in the predicted probability of Sargassum beaching does not appear very high, the prediction does provide valuable information for actions. The prediction is currently limited by three factors: 1) satellite imagery cannot always be used due to significant cloud cover and sun glint, and there is little room for improvement as these are natural phenomena; 2) the coarse-resolution (1-km) of MODIS makes it impossible to detect *Sargassum* rafts of $< 2$ m wide (Wang and Hu, 2016); 3) the visual interpretation of the HYCOM currents may not be as accurate as a particle tracing model to follow the detected *Sargassum* rafts. Therefore, in the future, even at a lower revisit frequency than MODIS, higher-resolution satellite imagery from Landsat or other similar sensors (e.g., those from the European Sentinel missions) may be used to detect smaller *Sargassum* rafts closer to coastline than those detected in MODIS imagery, thus complementing observations made possible by MODIS. Indeed, Landsat imagery has already been used in a Sargassum Early Advisory System (SEAS) to monitor potential *Sargassum* beaching along Texas coast (Webster and Linton, 2013) (http://seas-forecast.com/index.php), and has also been made available through SaWS for selected areas in the Caribbean. In addition, in the future the use of numerical models to trace the observed *Sargassum* rafts may provide a better estimate of *Sargassum* beaching than the simple interpretations here based on HYCOM currents.

Early detection does not prevent Sargassum from reaching the coastline, but it provides timely information for physical removal and collection of the algae onshore is the only option to reduce environmental nuisances. On the other hand, the amount of Sargassum that accumulates in bays and areas that are too difficult to access may cause significant damage to coastal ecosystems like mangroves and seagrass beds. Coral reefs are less exposed to Sargassum effects, but algae decomposition might alter water quality and cause mortality of benthic community organisms. Beside the negative effects of Sargassum arriving in large quantities, the algal biomass could represent an opportunity to develop new local industrial processes for fertilisers or animal food production. However, most of the islands do not have the industrial or technical capacity to treat the tons of algae they collect. So far, islands capacity to cope with the Sargassum biomass has been overwhelmed by the repeated events in 2011, 2012, 2014, 2015 and 2016. The Sargassum occurrence in this region of the western Atlantic is likely to continue in the future as it is directly linked to general current patterns in the central Atlantic (2016 was also a Sargassum year [data not presented] – early Sargassum detection in January 2017, pers. obs.). Near-real-time information on Sargassum rafts offshore is required to improve local monitoring capacities. Early detection comes among other aspects of the environmental crisis and will help coordination of networks, effectiveness of the response and rapid action. Thus, the utilisation of Sargassum-tracking information improves the efficacy and cost-effectiveness of regional monitoring programs. Efforts have to focus on better, precise early detection, collection at sea and on beaches, and utilisation of biomass.

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