Pelagic *Sargassum* in the North Tropical Atlantic: Efforts at Predicting Coastal Invasions

Sargassum Pelágico en el Atlántico Norte Tropical: Los Esfuerzos para Predecir Invasiones Costeras

Sargasses Pélagiques dans L'Atlantique Tropical Nord: Efforts de Prédiction des Invasions Côtières

DONALD R. JOHNSON[1*], JAMES S. FRANKS[1], JEAN-PHILLIPPE MARECHAL[2], and CHUANMIN HU[3]
[1]*Center for Fisheries Research and Development, Gulf Coast Research Laboratory, School of Ocean Science and Technology, University of Southern Mississippi, Ocean Springs, Missippi 39564 USA.*
[2]*Nova Blue Environment, 97233 Schoelcher, Martinique, French West Indies*,
[3]*College of Marine Science, University of South Florida, St. Petersburg, Florida 33701 USA.*

ABSTRACT

Pelagic *Sargassum* first appeared in massive quantities in the North Tropical Atlantic during spring of 2011. Not only did it appear in the Lesser Antilles where it was uncommon, but simultaneously appeared off NE Brazil, where it had never before been observed, and along West Africa from Sierra Leone to Benin in the Gulf of Guinea where it was rarely seen. Results from both model tracking and drifting buoys suggested that a consolidation/growth region occurs off West Africa extending into the Gulf of Guinea, with a second such region off NE Brazil associated with the North Brazil Current Retroflection (NBCR). The two regions are connected by the South Equatorial Current (SEC) and the North Equatorial Counter Current (NECC) forming the North Equatorial Recirculation Region (NERR). In the present study, we describe efforts at using current fields from archived model runs and drifting buoys together with Satellite images to predict arrivals in the Lesser Antilles in the spring and early summer of 2016. The basic transport pattern in the NERR associated with a regional bloom hypothesis seems well supported and fundamental to prediction of arrivals on both sides of the North Tropical Atlantic. During May 2016, *Sargassum* was first spotted off NE Brazil in the area normally dominated by the NBCR. Forward tracking using archived currents successfully indicated that it would arrive in the Lesser Antilles in late July. Cloud cover and high variability in historical current patterns create uncertainties.

KEYWORDS: Sargassum, tropical-Atlantic, model-tracking, satellite-images, prediction

INTRODUCTION

Holopelagic *Sargassum* (*natans* and *fluitans*) was first observed in unusually large quantities in the North Tropical Atlantic in 2011. Although it is common in the Gulf of Mexico (Comyns et al. 2000) and the Sargasso Sea (Winge 1923), it had rarely been observed in the Tropical Atlantic (need generic reference to distribution paper). Alarming quantities, however, arrived during spring and summer of 2011 on both sides of the North Tropical Atlantic (Johnson et al. 2012) – West Africa and the Lesser Antilles as well as off NE Brazil – suggesting that a unique, broad-scaled, event was occurring. Investigations (Franks et al. 2011, Franks et al. 2016) using currents from models and drifting buoys further suggested that these large quantities did not arrive *en masse* from the Sargasso Sea, as first expected, but likely bloomed in-situ after limited introduction via the Canary current along the coast of West Africa. Equatorial and North Atlantic climate indices reached historical peaks in 2010 - 2011, giving rise to the speculation (Franks et al. 2014, Franks et al. 2016) that the *Sargassum* bloom resulted from large oscillations and trends in climate, affecting both transport and growth/mortality rates.

Historical current patterns together with drifter tracks provided a basis for defining (Johnson et al. 2012) the North Tropical Atlantic current system in Lagrangian (drifter) terms as the North Equatorial Recirculation Region (NERR). Within the NERR two consolidation regions have been proposed (Franks et al. 2016), a broad region off West Africa including the Gulf of Guinea, and the North Brazil Current Retroflection (NBCR) area off NE Brazil (Figure 1). Recirculation within these two consolidation regions cover multiple years, allowing the possibility of substantial growth in a high nutrient, warm water environment, but the growth/mortality rates within each region remain unknown. Connection between the two consolidation regions are through the South Equatorial Current (SEC) and the North Equatorial Counter Current (NECC), which contain the NERR. Spectral analysis of color satellite images (Gower et al. 2006, Gower and King 2011) readily showed *Sargassum* in the NBCR consolidation region and transport connection to West Africa via the NECC (Gower and King 2013).

Surface drifter transport processes in the NERR are well defined in historical records but contain considerable yearly and seasonal variability. In this report we discuss an effort made in the Spring of 2016 to test prediction of *Sargassum* arrival events in the Lesser Antilles on a scale of months in advance using prior-year and historical fields of currents. Efforts to predict have been hampered by uncertainties in spotting *Sargassum* at a distance on approach to the Islands as well as tracking with current fields in an area with large current variations.

METHOD

Using images from the Moderate Resolution Imaging Spectroradiometer (MODIS: NASA; optics.marine.usf.edu/projects/saws.html), *Sargassum* was identified in a watch region of the western North Tropical Atlantic on 24 May 2016. Identification came by application of an algorithm (AFAI: Alternative Floating Algae Index) which detects peaks in reflectance in the near infrared (Hu 2009, Wang and Hu 2016). The AFAI has some improvements over the vegetative

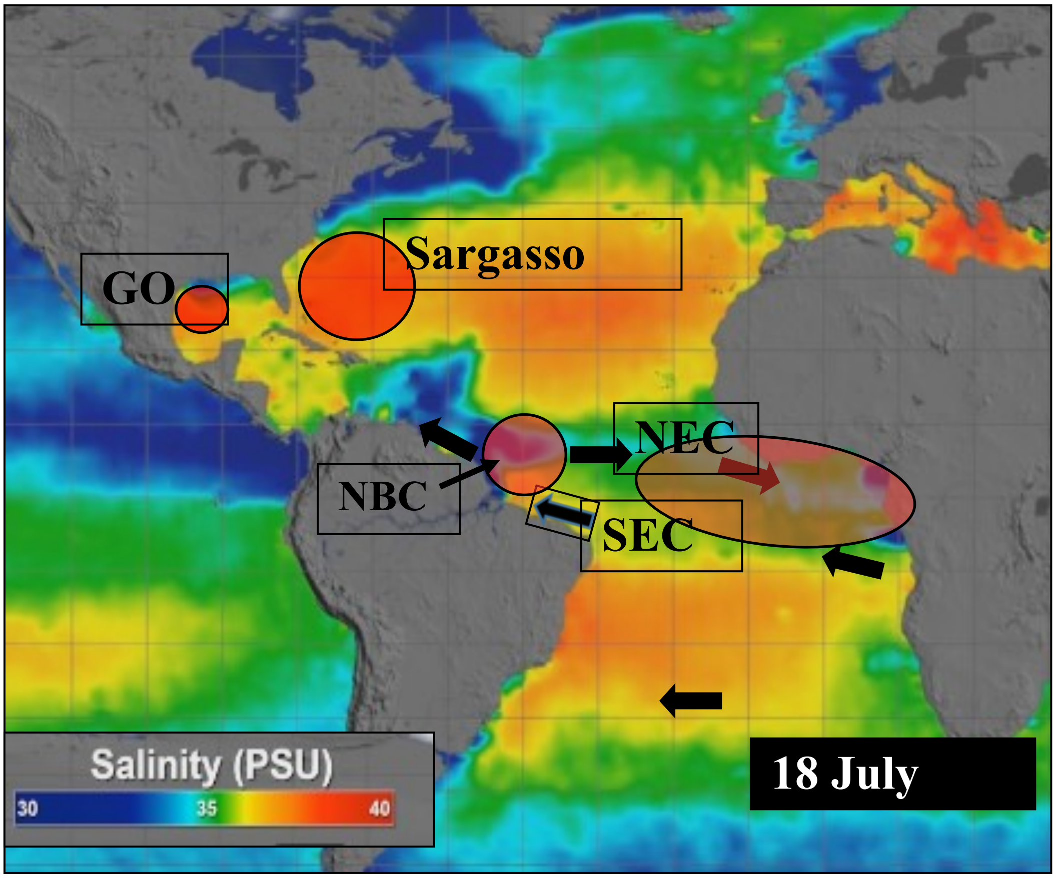

Figure 1. Pelagic *Sargassum* consolidation areas with principal current patterns in the North Tropical Atlantic. Image of Sea Surface Salinity from NASA Aquarius.

based index, first used by Gower et al. 2006 to detect *Sargassum* in color satellite images. The area of coverage in the *Sargassum* watch region (Hu et al. 2016) extends from the equator to 22°N and from 63°W to 38°W. This area covers the western half of the NERR and extends northward to cover the Lesser Antilles as well as the NE coast of South America from Brazil to Venezuela. The images were further processed to extract *Sargassum* identified pixels. The processed 24 May 2016 image (Figure 2) served as a base to test forward tracking using current fields to predicted arrival dates in the Lesser Antilles. Further images were processed in the same manner to confirm arrival dates.

The HYbrid Coordinate Ocean Model (HYCOM; Bleck 2002) is an ocean general circulation model run in forecast, hindcast and nowcast modes. The forecast extends to 5 days and the hindcast improves reliability. Archived data from the model runs are freely available (hycom.org) for download and use. An important feature of the model is that it is forced by real winds, climatological river runoff, and data assimilation of satellite altimetry. This latter feature requires that the model is phase-locked (space and time) to real events, providing a measure of assurance in predictive calculations.

HYCOM model data from 2011 - 2015 were used to forward track from 20 *Sargassum* locations identified in the 24 May 2016 image to arrival in the Lesser Antilles. For each model year parcels were launched on 24 May at the 20 locations, and the current field of that year was used to forward track the parcels in 1/10th of a day increments: $x + \delta x = x + u\delta t$, where the distance, x, is augmented by the current field, u, multiplied by the increment in time, t. Tests were made of an algorithm to incorporate sub-grid scale turbulence in the model: The Lagrangian Stochastic Method (LSM) is commonly applied in estimating the spread of larvae (Paris….) from a single spawning site. In this case, however, it is unclear how to apply this mechanism to the mats and lines of *Sargassum* which tend to bond together. The results of forward tracking shown here do not include an LSM.

In addition to the model data, a field of climatological currents was formed from satellite tracked mixed layer drifters. These drifter tracks and calculated current velocity data were obtained from a global data base (http://www.aoml.noaa.gov/phod/dac/index.php) covering the years 1979 - 2015 and from 15 S to 65 N in the Atlantic (6570501 data points). The day-of-year data were interpolated to 0.3° longitude/latitude using an algorithm derived from an exponential weighting scheme (Bretherton et al. 1976): $w_i = \exp(-d_i^2/r_d^2)$ where d_i is the distance in longitude/latitude of vector i from the grid point and $r_d = 0.6°$. This method of smoothing over space and time

Figure 2. MODIS image of 24 May 2016 showing *Sargassum* in the lower right quadrant.

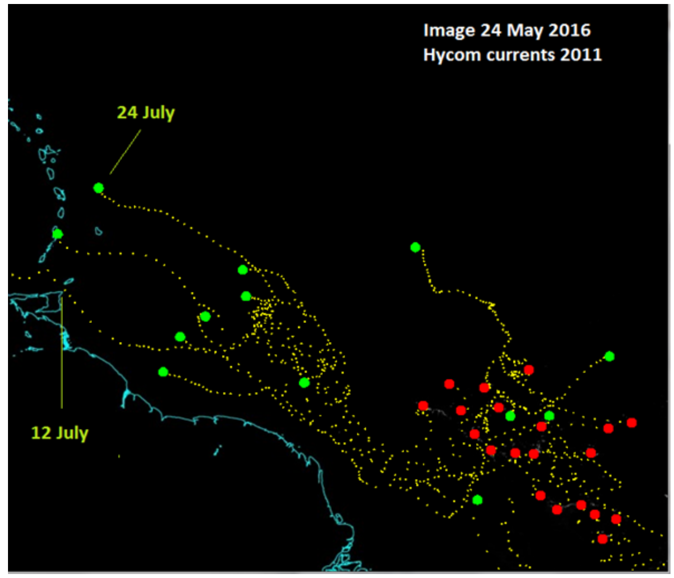

Figure 3. Forward tracks of parcels launched from 20 starting locations selected on the 24 May 2016 image.
Red dots: start
Small yellow dots: 1 day intervals
Green dots: Locations on 24 July

produces a climatological current field for forward tracking comparisons with the model.

RESULTS

Forward tracks from 24 May to 24 July using the HYCOM current fields for 2011 are shown in Figure 3. One track from the 20 launch sites passed through Trinidad -Tobago on 12 July and 2 other tracks reached the vicinity of the Lesser Antilles by 24 July. Seven launched parcels appeared to be *en route* to the Lesser Antilles, 4 remained in the NBCR and 6 were deflected back to the NERR. In total, 50% were trapped in the NERR and 50% spread toward the Lesser Antilles, reaching the islands as early as 12 July in this first test. Referring to Figure 3, it is interesting to note that rather than moving as a large assemblage to the Lesser Antilles, the *Sargassum* appeared to be detrained from the NERR.

Further efforts were made to track forward from the 24 May *Sargassum* locations using current fields from HYCOM models of years 2012, 2013, 2014, and 2015. First arrivals to the Lesser Antilles (reached the 60.8 W meridian) were noted for each of the years. Dates of first arrivals are given in Table I for all five model current years tested. Two additional current fields were tested and shown in Table I: HYCOM fixed field (parcels tracked through the non-changing current field of 24 May) and climatology from satellite tracked drifting buoys.

Table 1. Earliest arrivals in Lesser Antilles using HYCOM model years.

Year	Arrival
2011	12 July
2012	28 August
2013	8 August
2014	26 July
2015	3 August
Fixed field 24 May	North of Caribbean
Climatology	3 December

Results from Table I show earliest *Sargassum* arrival dates in the Lesser Antilles from the 24 May 2016 image locations were spread between 12 July and 28 August 2016 with the median as 3 August. Based on these results, notification of potential arrival in the Lesser Antilles was given as late-July, early-August. Although tracking with both the fixed field currents and climatology showed similar patterns to the yearly HYCOM such as recycling in the area, transport back into the NERR and westward transport of some of the parcels, they were clearly not useful for this scale of prediction.

Images of 12 July showed *Sargassum* close to Barbados. The next good image of 17 July (Figure 4) showed *Sargassum* passing through the islands into the Caribbean. Our subjective judgement based on the yearly HYCOM results was off by ~1-2 weeks.

There are two major reasons why improvements in forecasting accuracy on the scale we are testing might not be readily achieved using present technology. This area is within the Inter-Tropical Convergence Zone (ITCZ) for much of the year with attendant high cloudiness. Optical satellites that are used to image the *Sargassum* are limited by cloudiness. In addition, *Sargassum* appears to consolidate in areas such as the North Brazil Current Retroflection off northwest Brazil, but is spread out in smaller clumps much of the time. Without consolidation into large mats, a single pixel may not contain sufficient *Sargassum* to produce an unambiguous peak in the optical spectrum.

The second reason for difficulty is, of course, accuracy of the field of currents. HYCOM forecasts for 5 days, which is insufficient for the several month scales of interest being tested here.

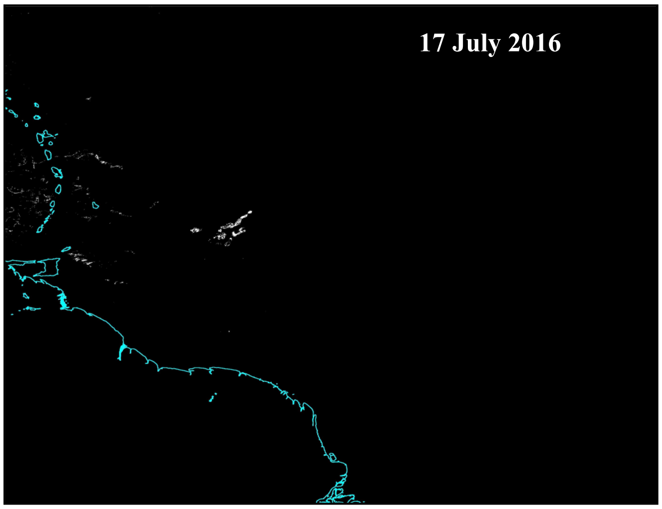

Figure 4. MODIS image of 17 July 2016 showing *Sargassum* streaming through the islands of the Lesser Antilles.

Seasonal Forecasts

Since pelagic *Sargassum* appears to be consolidating in both the eastern and western NERR with intermittent detrainment into the Caribbean, along the NE coast of South America and along west Africa, it seems possible to provide seasonal scale forecasts with better understanding of equatorial transport dynamics. In Figure 5, the locations of Sargassum from the 24 May 2016 image are taken as starting location and tracked forward in time to the end of two contrasting model years and backward to the beginning of the year.

The two model year transport patterns contain some similarities, but are also considerably different. The 2011 pattern clearly shows well established transport from the Gulf of Guinea and detrainment to the Caribbean. In contrast the 2012 image shows transport from the central NERR and weak detrainment to the Caribbean. From the Table I results, it is clear that the 2011 prediction was quite good in comparison to the 2012 model year prediction. This suggests that present-model-year back track patterns might be useful as a tool for establishing patterns and choosing the right model year for forward tracking. It also suggests that the developing patterns for the present-year in association with Atlantic climate indices and previous year model runs might be useful in seasonal scale forecasts.

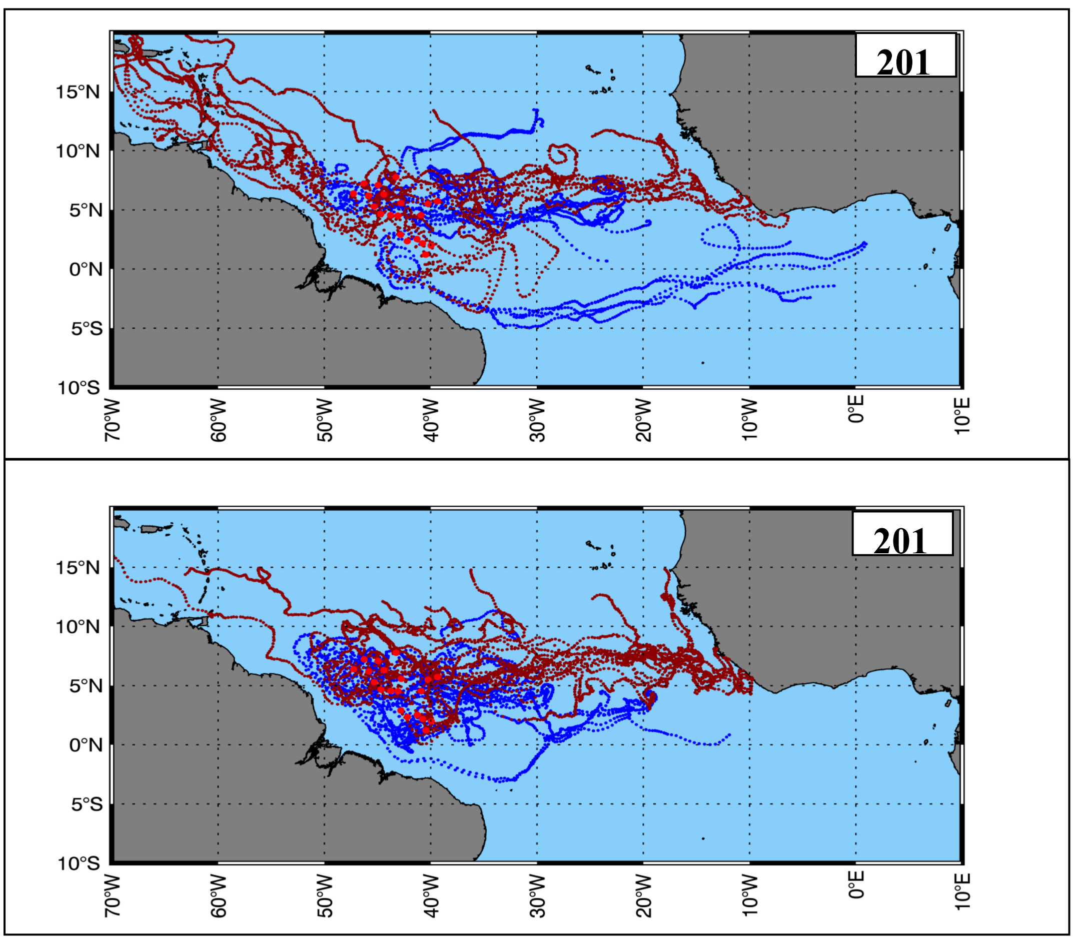

Figure 5. Forward tracks (maroon dots) and back tracks (blue dots) from starting locations (red dots) on 24 May 2016. Upper: model year 2011. Lower: model year 2012.

CONCLUSIONS

Predicting arrival of *Sargassum* events in the Caribbean over scales of months is difficult due to uncertainties in satellite sightings and in modeled transport dynamics. Inherent cloudiness associated with the ITCZ has a major effect on optical satellite images of pelagic *Sargassum*. To improve forecasts for the Caribbean, the scope of image analysis needs to include the eastern Tropical Atlantic and southward to about 5 S in the SEC. In-situ validation of spectral images in various regions of the NERR would be useful for improving the analysis of not only *Sargassum*, but the associated water content and sub-pixel spectral mixing involving smaller *Sargassum* structures.

The western North Tropical Atlantic current systems are influenced by:

i) Seasonal changes and dynamic instability of the NBCR, and
ii) Coastal currents along NE South America with seasonal changes in wind forcing and Amazon outflow.

Yet yearly Lagrangian (surface drift) patterns suggest that developing winter and early spring patterns may be important in establishing which prior year model run is most useful in the following spring/summer forecasts. With long periods spent in consolidation areas and in transit between these areas, there is considerable uncertainty on the mass of *Sargassum* involved in the Caribbean events. In this study we have tried to forecast arrival times, not quantities. Determination and inclusion of growth and death rates in the model transport algorithm will be needed for more accurate future forecasts including quantity.

ACKNOWLEDGEMENT

We appreciate funding for this project through ADEME Martinique, Collectivité Territoriale de Martinique, DEAL Guadeloupe.

LITERATURE CITED

Bleck, R. 2002. An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates. *Ocean Modeling* **4**:55-88.

Bretherton, F.P., R.E. Davis, and C.B. Fandry. 1976. A technique for objective analysis and design of oceanographic experiments applied to MODE-63. *Deep-Sea Research* **23**:559-582.

Comyns, B.H., N.M. Crochet, J.S. Franks, J.R. Hendon and R.S. Waller. 2000. Preliminary analysis of the association of larval fishes with pelagic *Sargassum* habitat and convergence zones in the Northcentral Gulf of Mexico. *Proceedings of the Gulf and Caribbean Fisheries Institute* **53**:636-645.

Franks, J.S., D.R. Johnson, D-S Ko, G. Sanchez-Rubio, J.R. Hendon, and M. Lay. 2011. Unprecedented influx of pelagic *Sargassum* along Caribbean island coastlines during summer 2001. *Proceedings of the Gulf and Caribbean Fisheries Institute* **64**:6-8.

Franks, J.S., D.R. Johnson and D-S Ko. 2014. Retention and growth of pelagic *Sargassum* in the North Equatorial Convergence Region of the Atlantic Ocean: A hypothesis for examining recent Mass strandings of Sargassum along Caribbean and West Africa shorelines. *Gulf and Caribbean Fisheries Institute*, **67**136.

Franks, J. S., D. R. Johnson and D-S Ko. [2016]. Pelagic *Sargassum* in the Tropical North Atlantic: invasive transport. *Gulf and Caribbean Research.* Accepted.

Gower, J. F. R. and S. A. King. 2011. Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic Ocean mapped using MERIS. *International Journal of Remote Sensing* **32**:1917 – 1929.

Gower, J.F.R., C. Hu, G.A. Borstad, and S. King. 2006. Ocean color satellites showextensive lines of floating *Sargassum* in the Gulf of Mexico, *IEEE Transactions on Geoscience and Remote Sensing* **44**: 3619-3625.

Gower J., E. Young, and S. King. 2013. Satellite images suggest anew *Sargassum* source region in 2011. *Remote Sensing Letters* **4**:764-773.

Hu, C. 2009. A novel ocean color index to detect floating algae in the global oceans. *Remote Sensing of the Environment* **113**:2118 -2129.

Hu, C., B. Murch, B.B. Barnes, M. Wang, J-P Maréchal, J. Franks, D. Johnson, B. Lapointe, D.S. Goodwin, J.M. Schell, and A.N.S. Siuda. 2016. Sargassum Watch warns of incoming seaweed. https://eos.org.

Johnson, D.R., J.S. Franks, J.S., D-S Ko, P. Moreno, and G. Sanchez-Rubio. 2012. The *Sargassum* Invasion of the Eastern Caribbean and dynamics of the equatorial North Atlantic. *Proceedings of the Gulf and Caribbean Fisheries Institute* **65**:102-103.

Wang, M., and C. Hu. 2016. Mapping and quantifying *Sargassum* distribution and coverage in the Central West Atlantic using MODIS observations. *Remote Sensing of the Environment* **183**:356-367.

Winge, O. 1923. *The Sargasso Sea, Its Boundaries and Vegetation*. Report on the Danish Oceanographic Expeditions 1908-1910 to the Mediterranean and Adjacent Seas, Volume III, Miscellaneous Paper Number 2. Copenhagen, Denmark. 34 pp.