Holopelagic *Sargassum* and the Complexities of Predicting Influxes and Impacts on Pelagic Fisheries of the Lesser Antilles

Sargazo Holopelágico y las Complejidades de Predecir las Afluencias y los Impactos en las Pesquerías Pelágicas de las Antillas Menores

Sargasse Holopélagique et Complexité de la Prévision des Afflux et des Impacts sur les Pêcheries Pélagiques des Petites Antilles

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ABSTRACT

Barbados, at 13ºN, is located near the separation between water masses of the North Atlantic Gyre and the system of equatorial currents whose origin, in part, is in the South Atlantic. Seasonal and inter-annual variations in local currents and water masses at Barbados are high due to variations in the boundary between the gyre and the equatorial current system. In observations and models, this boundary occurs near 15ºN with considerable fluctuation. Local *Sargassum* influx events can be back-tracked to a broad range of locations in the equatorial Atlantic, dependent on season and dominance of either system of currents. Complex forcing mechanisms driving seasonal variations in local *Sargassum* coverage include the Amazon River discharge, equatorial current branching and seasonal winds over the North Atlantic. We examined the impact of this tropical *Sargassum* bloom on major pelagic fisheries in Barbados with the result of a nearly 50% reduction of catch when *Sargassum* is present. Satellite-derived estimates of *Sargassum* coverage together with flyingfish, dolphinfish, and wahoo catch data over the last two decades illustrate the complex relationship between *Sargassum* and pelagic fisheries. These complex relationships regarding influxes and impacts on the pelagic fisheries will need further resolution to better inform future policy and management decisions towards adaptation of the fisheries sector. Efforts to predict *Sargassum* influx to the Lesser Antilles several months in advance are described.

KEYWORDS: Barbados, *Sargassum*, fishery impact, Atlantic and equatorial currents

INTRODUCTION

Commercial fisheries in the Lesser Antilles have been seriously impacted by the influx of unprecedented masses of holopelagic *Sargassum* (species *natans* and *fluitans*) since the spring/summer of 2011. Transported by ocean currents, small quantities of *Sargassum* have previously been noted throughout the tropical North Atlantic (tNA) including West Africa, but recent unusually large in-situ blooms (Johnson et al. 2013, Gower et al. 2013, Franks et al 2016) have created serious problems for economically important tourist and fisheries industries on both sides of the Atlantic. In this study we present efforts in quantifying the impact on fisheries of *Sargassum* transported through the Lesser Antilles (Figure 1) as well as predicting its arrival as it passes from the tNA into the Caribbean.

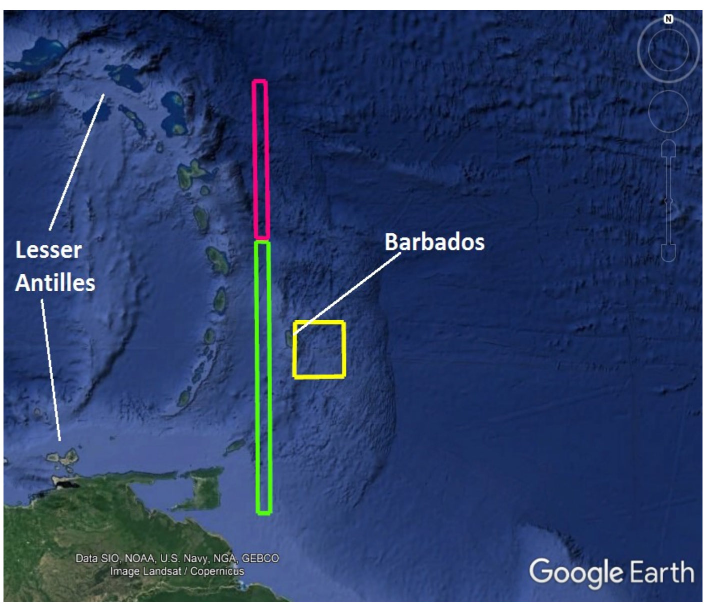

Figure 1. Lesser Antilles study area. *Sargassum* arrival in the yellow box is compared to fishery landings at Barbados. Predicted arrival of *Sargassum* is made for the green and purple rectangles (along 60° W meridian) separated at 15.4°N. The north rectangle is influenced principally by the North Atlantic Gyre and the south rectangle is influenced principally by equatorial currents.

Barbados, at 13°N and 59.5°W, is located near the separation between water masses of the North Atlantic Gyre and the system of equatorial currents whose principal origin is in the South Atlantic. Seasonal and inter-annual variations in local currents and water masses at Barbados vary according to the boundary between the gyre and the equatorial waters. In observations and models, this boundary occurs near 15°N, but with considerable variation. Local *Sargassum* influx events at Barbados, then, can be back-tracked to a broad range of locations in the equatorial Atlantic, dependent on season and dominance of either system of currents. Complex forcing mechanisms driving seasonal variations in local *Sargassum* influx include the Amazon River discharge and equatorial channel current systems, neither of which are adequately represented in available finite difference or diagnostic models. It also includes winter breakdown of the principal summer recirculation pattern in the tNA and a resulting connection between the tNA and the North Atlantic Gyre (Johnson and Franks 2018).

Flyingfish (dominantly *Hirundichthys affinis*) are important contributors to commercial fisheries from Dominica (15.3° N) to Trinidad and Tobago, and geographically coincident with the principal influx of water masses from the tNA. Peak catches are generally in arboreal spring from March through June, temporally coincident with the early arrivals of *Sargassum* (Franks et al. 2016) in this southern area. Flyingfish are batch spawners, depositing non-buoyant eggs on floating material from November through the following July (Oxenford et al. 1994, Khokiattiwong et al. 2000). They are commonly caught with a combination of gill nets or dip nets together with Fish Aggregation Devices (FADs) composed of palm fronds or sugar cane leaves (Oxenford et al. 2007, Headley 2010). With the advent of *Sargassum*, flyingfish have been noted to deposit their eggs on *Sargassum* mats rather than the FADs (Ramlogan et al. 2017) with the ability to capture these fish highly compromised. Local fishers (Anderson Kinch, *Personal communication*) have also noted that flyingfish appear to be fleeing *Sargassum* mats, possibly after a quick deposit of eggs, which may indicate predator avoidance behavior. Fouling of gear, including boat propulsion, has also been of significant consequence for the Barbados fishery.

Dolphinfish (*Coryphaena hippurus*) are the second major fish, by weight, harvested in the Barbados fishery. They are captured by hook and line. Since flyingfish are a principal food source for dolphinfish, it is not unexpected that dolphinfish are also associated with *Sargassum*. However, juvenile stages of dolphinfish use *Sargassum* mats (Comyns et al. 2002) and larger dolphinfish are caught more frequently outside the floating mats (Farrell et al. 2014). In consequence, dolphinfish that have been captured in the Barbados fishery during the *Sargassum* era tend to be low weight juveniles. Wahoo (*Acanthocybium solandri*) also use *Sargassum* during their juvenile stages (Comyns et al. 2002) and are a third fish of significant importance in Barbados, also caught by hook and line.

The first reported date of massive *Sargassum* beachings at Barbados was June 2011. In this study we compare time series of landing weights of the three fish species, flyingfish, dolphinfish, and wahoo, taken between 1994 and 2017 with a time series of arrival of *Sargassum* near Barbados (Figure 1) in order to quantify the difference in landings between historical (pre-June 2011) and *Sargassum* (since June 2011) eras. This overview provides a simple measure of impact that *Sargassum* has had on landings in the Barbados pelagic fisheries. It is not, however, a measure of population fluctuations for the three species.

Predictions of *Sargassum* arrivals allow both the fishing and tourism industries to adjust to conditions. However, predictions are presently being made using nowcasts out through 7-day forecasts (https://www.hycom.org/dataserver/gofs-3pt1/analysis), which is too narrow a window for adequate preparation. Using current fields from two climatological hydrographic models and from satellite tracked drifter records, together with color satellite imagery, we demonstrate the potential to predict *Sargassum* arrival in the Lesser Antilles on seasonal time scales.

METHODS

Barbados has the largest flyingfish fishery in the Lesser Antilles, accounting for approximately 62% of landings across the region (Headley 2010) and can be considered representative for regional *Sargassum* impact on fisheries, but not an exact representation. The Fisheries Division of Barbados (Ministry of Maritime Affairs and the Blue Economy) maintains an excellent record of landings and provided daily landings (Kg) by individual boats, by date (day/month/year), boat type (Moses/Day Boat/Ice Boat/Long Liner), and fish category (flyingfish/dolphinfish/wahoo). The record of landings in our data set extends from 1 January 1994 to 31 December 2017. It is expected that boat type will be a factor influenced by the presence of large mats of *Sargassum*, but our primary objective is a simple measure of overall impact on harvest regardless of gear or effort.

Archived currents for the prediction study come from three sources: satellite tracked mixed-layer drifters, Hycom (HYbrid COordinate Model), and Oscar (Ocean Surface Current Analysis Real-time):

i) Drifters: Satellite tracked mixed-layer drifters (drogue element at 15 m) are deployed around the globe, with data on position, temperature and a drogue-off flag. Current vector components are calculated at 6-hour intervals from sequential positions (Lumpkin et al. 2013) and the data archived at http://www.aoml.noaa.gov/phod/gdp. For our study a climatological field of currents was derived by interpolating current components to a 1/12th degree longitude and latitude grid at year-day time steps. Interpolation was done with a Gaussian interpolator with e-folding radius of 1 degree and cut-off of 2 degrees. The result is a highly smoothed 365-day field of currents on the Hycom grid. This is a climatological (averaged) field of currents from 1979 to 2017. The principal disadvantage of drifters for our study is the drag element at 15 m depth with unclear representation of currents at the surface.

ii) Hycom: A finite global difference numerical model at 1/12th degree grid with principal forcing from observed winds and observed satellite altimetry sea surface height (data assimilation). A significant advantage of Hycom is its ability to phase lock (time and location) into real events such as movement of strong current systems. Its disadvantage is poor representation at the equator and weak representation of major river discharge, such as the Amazon River. A climatological field was formed by taking the mean of currents from 2009 - 2016. Current fields can be obtained at http://www.hycom.org.

iii) Oscar: A diagnostic model using observed wind fields and observed satellite altimetry of sea surface height. Gridded fields at 1/3rd degree and 5 -day time intervals are interpolated (Gaussian) to 1/12th degree grid and 1-day interval. A climatological field was formed by taking the mean of currents from 2009-2017. Current fields can be obtained from https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg.

Using a simple forward tracking algorithm with these fields of currents, *Sargassum* is tracked from locations in the western tNA to the 60^{o} W meridian fronting the Lesser Antilles. The number of tracking points with dates of arrival serves as a simple prediction index. *Sargassum* locations are obtained from 7-day composite images of the Alternative Floating Algae Index (AFAI; Wang and Hu 2016) obtained at http://optics.marine.usf.edu. For comparison with fisheries landing data, sargassum in the box (Figure 1) fronting Barbados was obtained as monthly composites from the same source.

RESULTS

Records from flyingfish, dolphinfish and wahoo landings at Barbados showed a distinct and consistent decrease by weight during the *Sargassum* era (Figure 2). After June 2011, monthly landings of flyingfish decreased by 56.25%, dolphinfish by 41.5% and wahoo by 49.5% in comparison to landings averaged between 1994 and June 2011.A direct comparison of flyingfish landings at Barbados with *Sargassum* in the near area (see box in Figure 1) showed a clear linkage although not a linear connection. For ~2 years when *Sargassum* was not present within the *Sargassum* era, mid-2012 to mid-2014, landings of flyingfish returned to pre-Sargassum levels (Figure 3) but did not exceed these levels as might be expected if inhibited harvest increases the population size. Arrival of *Sargassum* in the Barbados box came in two-year pulses: 2011/2012, 2014/2015 and 2017/2018. Each pulse was successively larger, yet the impact on fisheries did not match the growing intensity of *Sargassum* coverage.

Sargassum pixel points in a composite image of the western tNA (Figure 4, left) were forward tracked from the end of October 2018, to provide a metric for an index of threat to fisheries of the Lesser Antilles. Selecting starting locations by pixel brightness, ~1000 points were forward

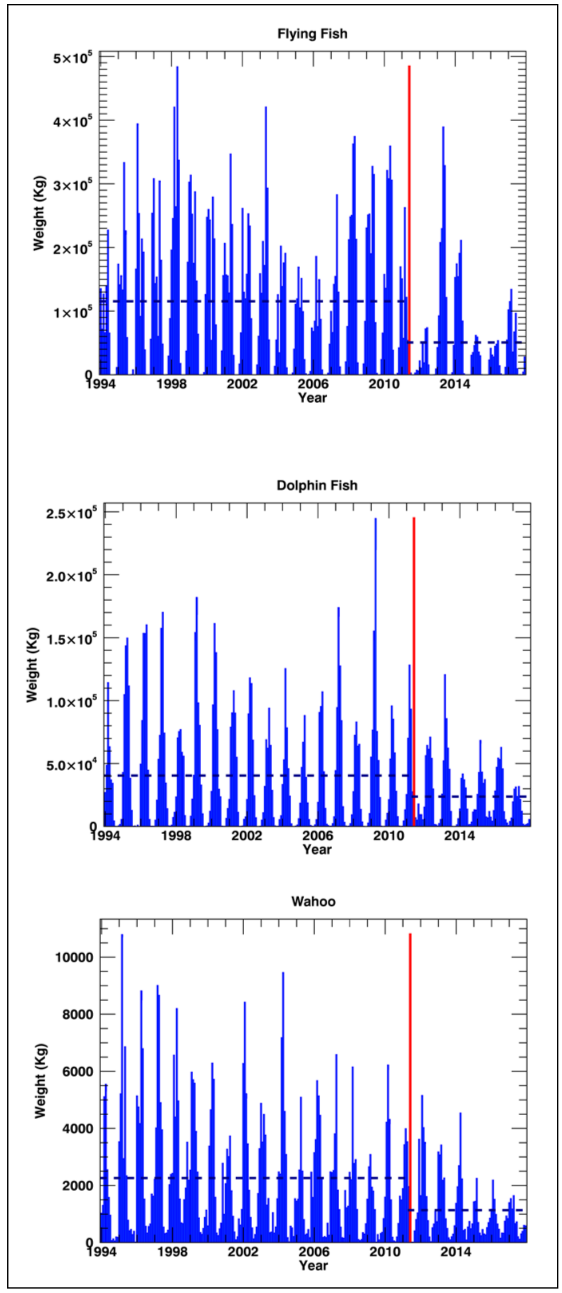

Figure 2. Monthly landings at Barbados of flyingfish (upper), dolphinfish (middle) and wahoo (bottom). The vertical red line is placed at June 2011, the first reported *Sargassum* event at Barbados, marking the start of the *Sargassum* era. Horizonal dotted lines are means of landings before and during the *Sargassum* era.

tracked until 31 January 2019 beginning on each of the 7 days of the composite image. The resulting tracks from the Hycom climatology model (Figure 4, right) cover the Lesser Antilles. From these tracks, a timeline of arrival at 60° W, separated into a north and south section (see Figure 1) produced an uncalibrated metric of threat (Figure 5). In the southern section, the threat showed two peak periods: beginning of November and end of December. In the northern section, a moderate threat begins at the end of November and continues until the last week in January 2019, when the threat increases rapidly. Comparison of threats generated by the drifter, Hycom and Oscar climatologies were not highly consistent in the north section but good in the south section.

DISCUSSION

Fisheries in Barbados are clearly impacted by the arrival of large quantities of *Sargassum* in offshore waters, but the reasons for the impact are not so clear and likely a combination of ecological and fishery effects. Although gear and boats are fouled by *Sargassum*, the use of FADs in the fishery to exploit the spawning behavior of flyingfish is likely compromised by mats of *Sargassum* which can serve the same purpose, thus reducing their catchability. It is odd, however, that there does not appear to be a direct relationship between quantity of *Sargassum* present and decreased weight of flyingfish landings, suggesting perhaps that a *Sargassum* abundance threshold to alter flyingfish catchability has already been reached. Flyingfish, dolphinfish and wahoo all have some connection to *Sargassum* and landings of all have decreased by ~50% in the Sargassum era (since June 2011).

It is surprising that, in a 2-year window with no *Sargassum* present, flyingfish landing weights returned to the pre-*Sargassum* era weights, but did not exceed them, as might be expected for an annual species, since harvest had been compromised in the intervening years. This suggests

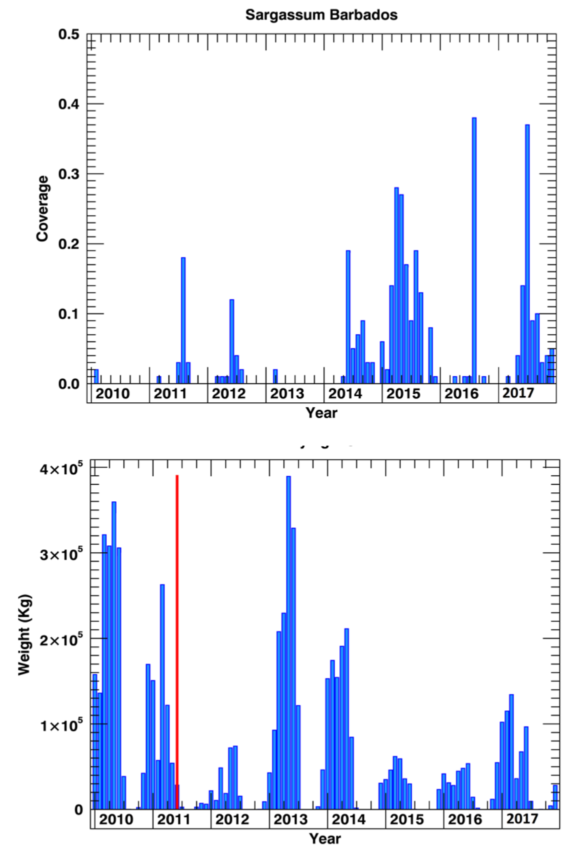

Figure 3. Comparison of monthly coverage of *Sargassum* (upper) in a box near Barbados (see Figure 1) with monthly flyingfish landings (lower) in the *Sargassum* era.

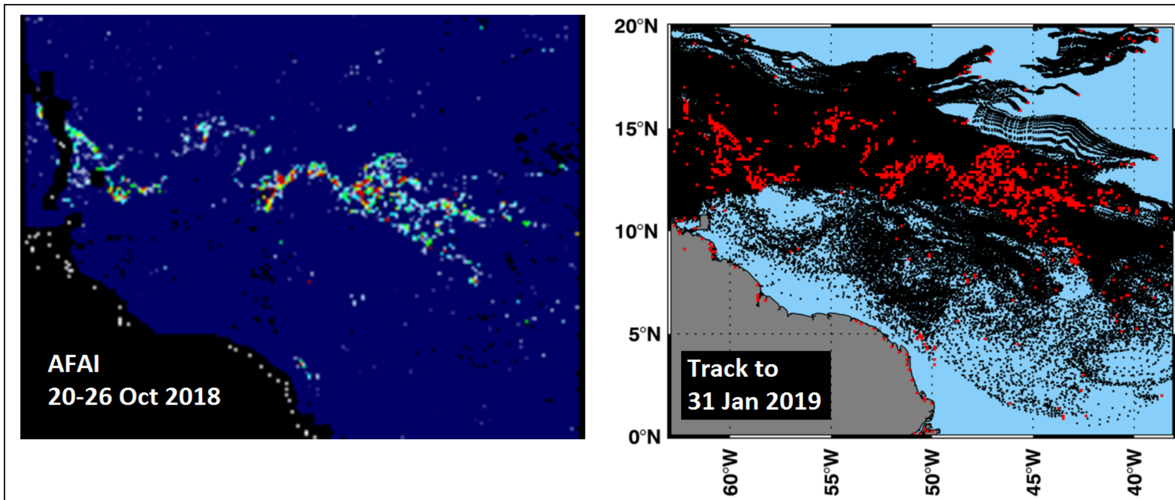

Figure 4. Composite imagery (left) of the Alternative Floating Algae Index from USF/Optical Oceanography Lab. The Lesser Antilles and the North East coast of South America are shown in black. Forward tracks (right) from the dates of the imagery (20-26 October 2018) to 31 January 2019. Red dots are starting locations selected from the composite image, black dots are daily positions of the water parcels tracking from the red dots.

that the Barbados fishery is not making a significant impact on population size of the eastern Caribbean flyingfish stock, a conclusion also reached by the sub-regional management plan for this stock (CRFM 2014).

Although not in the fishery data base, it has been noted by both fishers and processors that there has been a shift in the size of individual dolphinfish and flyingfish caught toward juveniles. Whether *Sargassum* has changed the spawning habits of these pelagic species, or other life history habits such as their annual migration routes is not known. According to fishers, the presence of *Sargassum* has also impacted the fishing effort of the fleet, particularly the frequency of trips by dayboats, and a switch to smaller mesh flyingfish gillnets by some, and a recent switch in target species in 2018 to the now abundant almaco jacks (*Seriola rivoliana*). Transport of *Sargassum* across the tNA could be a factor in connecting populations on both sides of the Atlantic.

Efforts at prediction of *Sargassum* arrival in the Lesser Antilles on seasonal scales has three main purposes. It provides notice to fishers and processors/vendors that adjustments need to be made because of coming threats, it provides a mechanism (validated tracking techniques) to determine the regions of *Sargassum* bloom and its path to the fishery, and it informs management initiatives being made by fisheries authorities. Since Hycom only forecasts for 7 days (https://optics.marine.usf.edu/projects/SaWS.html) either climatologies or currents from previous years must be employed for tracking on seasonal scales. A study using Hycom currents from years prior to the forecast years (Johnson et al. 2017) gave results that were highly scattered. In this study we have used climatologies from three different data sets, a finite difference model, a diagnostic model and observations together with composite images of the Alternative Floating Algae Index to provide a threat level. Future work will involve using the images to determine success of tracking using various current data sets and to validate the process.

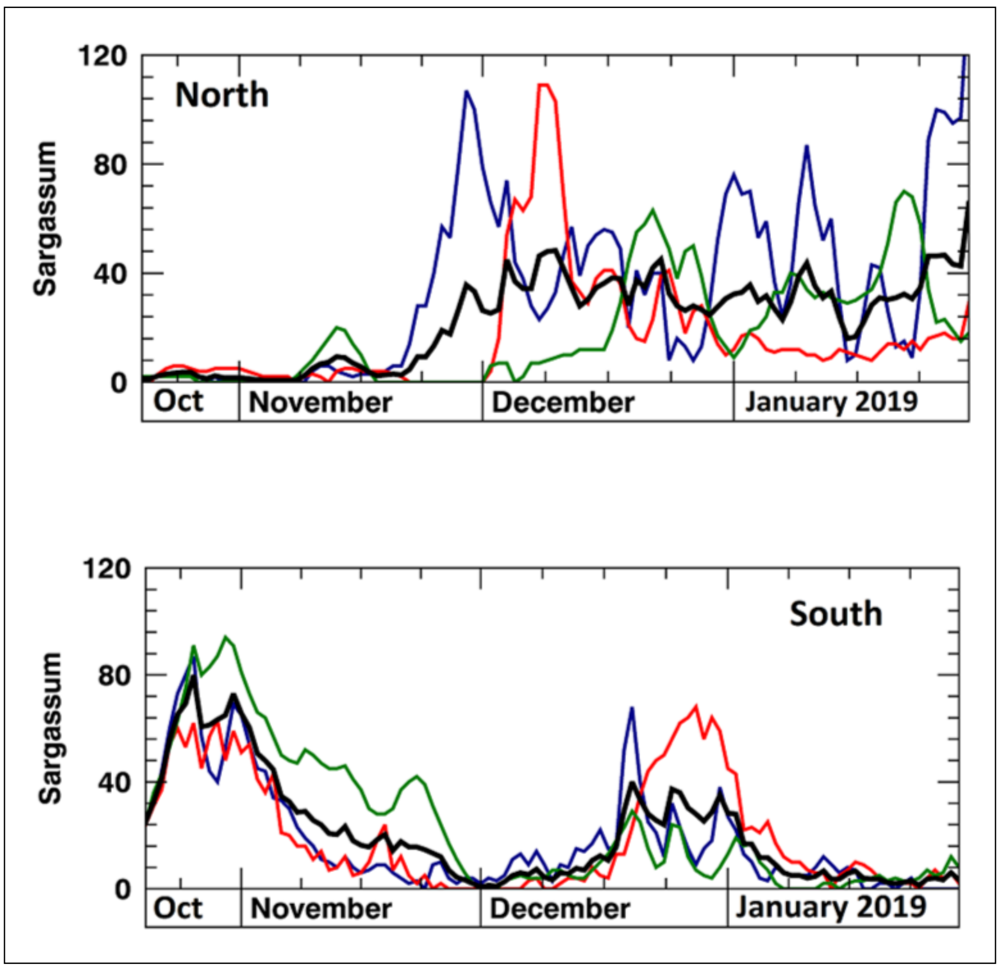

Figure 5. Predicted Sargassum threat composed of number of dots (figure 4) each day that pass the 60° W meridian in the north section (upper) and the south section (lower). Sections are separated at 15.4° N latitude. Blue line uses drifter currents, red line uses Hycom currents and green line uses Oscar currents. Black line is the average of the three data sets.

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