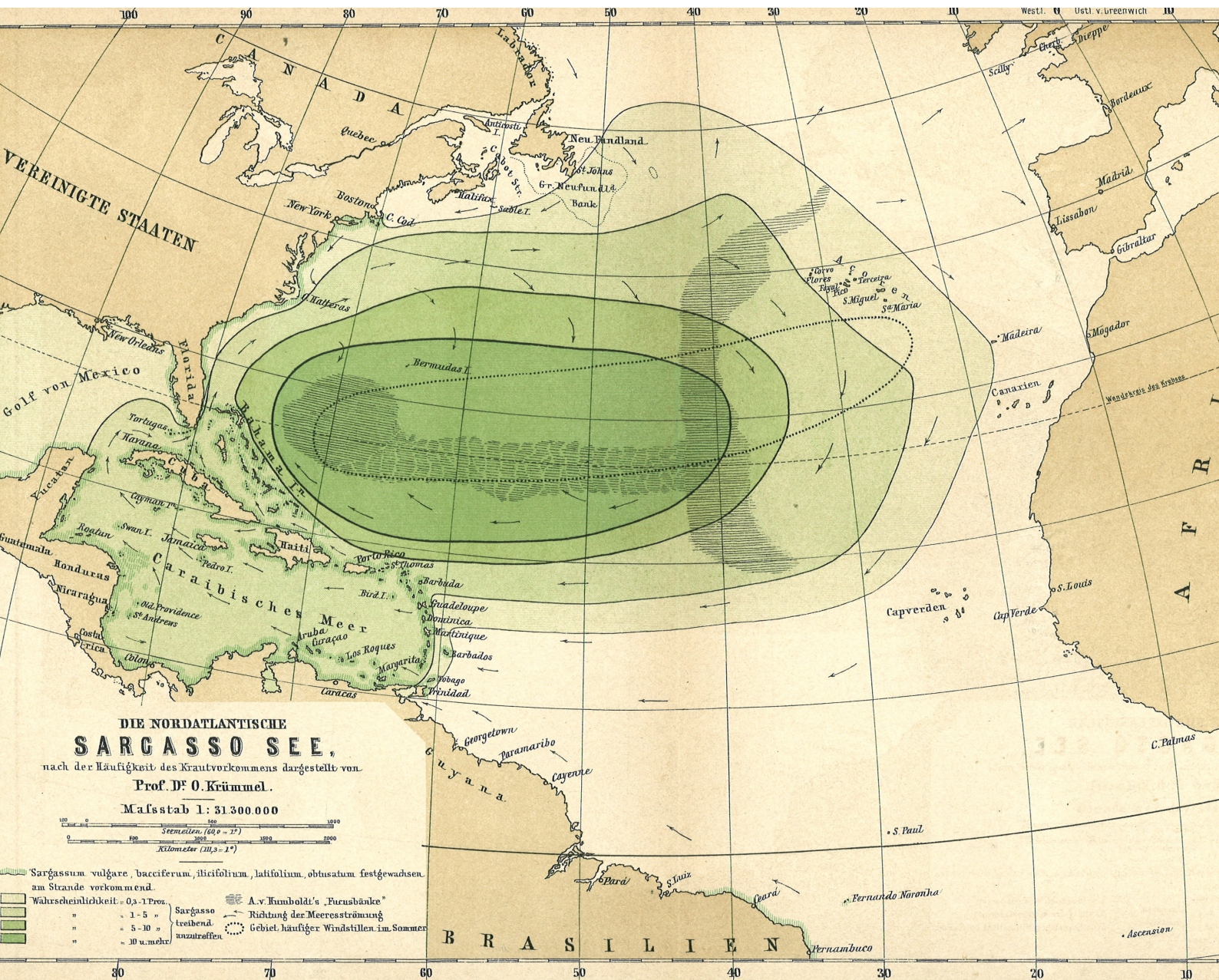


# Where is the Sargasso Sea?

## A Report Submitted to the Sargasso Sea Alliance

Jeff Ardron, Pat Halpin, Jason Roberts,  
Jesse Cleary, Russell Moffitt, Ben Donnelly



Number 2 Sargasso Sea Alliance Science Report Series



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The Sargasso Sea Alliance is led by the Bermuda Government and aims to promote international awareness of the importance of the Sargasso Sea and to mobilise support from a wide variety of national and international organisations, governments, donors and users for protection measures for the Sargasso Sea.

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Website is **[www.sargassoalliance.org](http://www.sargassoalliance.org)**

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## Foreword

**B**ETWEEN 2010 AND 2012 a large number of authors from seven different countries and 26 separate organisations developed a scientific case to establish the global importance of the Sargasso Sea. A summary of this international study was published in 2012 as the “Summary science and Supporting Evidence Case.” Nine reasons why the Sargasso Sea is important are identified in the summary. Compiling the science and evidence for this case was a significant undertaking and during that process a number of reports were specially commissioned by the Sargasso Sea Alliance to summarise our knowledge of various aspects of the Sargasso Sea.

This report is one of these commissioned reports. These are now being made available in the Sargasso Sea Alliance Science Series to provide further details of the research and evidence used in the compilation of the summary case. A full list of the reports in this series can be found in the inside back cover of this report. All of them can be downloaded from [www.sargassoalliance.org](http://www.sargassoalliance.org).

**Professor Howard Roe**

Science Advisory Committee Chair  
Sargasso Sea Alliance

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Science Coordinator  
Sargasso Sea Alliance



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## Executive Summary

**T**he definition of the Sargasso Sea began as an historical notion dating back hundreds of years, based on sailors' early encounters at sea with *Sargassum* algae, and later recognized for its unique ecology. Situated within the North Atlantic, it is a "sea within a sea", with its outer boundary determined by a combination of dynamic oceanographic factors (mainly currents), and biology—mainly the occurrence of aggregated mats of *Sargassum*. To date, there has been no agreed-upon definition or delineation of the Sargasso Sea, with many interpretations that have been mapped over the past century or so.

For the Sargasso Sea Alliance (SSA) to move forward in its work, some sort of operational delineation was required, forming the central purpose of this project. Working jointly with the SSA, we developed a simplified (ellipse) Study Area boundary based on generalized oceanographic and biological features that extends to the Mid-Atlantic Ridge (Figure 1).

Historically, the Sargasso Sea was mapped in areas that have since become part of the Exclusive Economic Zones (EEZ; 200 nautical mile limits) of coastal States. For pragmatic and political reasons, the SSA requested that the EEZs of affected Caribbean States and the US be excluded. The EEZ of Bermuda (UK) is still included, but an area extending 50 nm offshore from Bermuda has been excluded.

The final SSA Study Area boundary represents a good working compromise, taking into account many factors, as will be outlined in this report. While no single dataset perfectly fits, many fit well. We drew the

outer boundary as an ellipse so as to communicate that this is a generalized depiction. A boundary with many specific edges, would have imparted a false sense of accuracy. These are fluid boundaries, after all, defined by oceanography and floating aggregations of *Sargassum*.

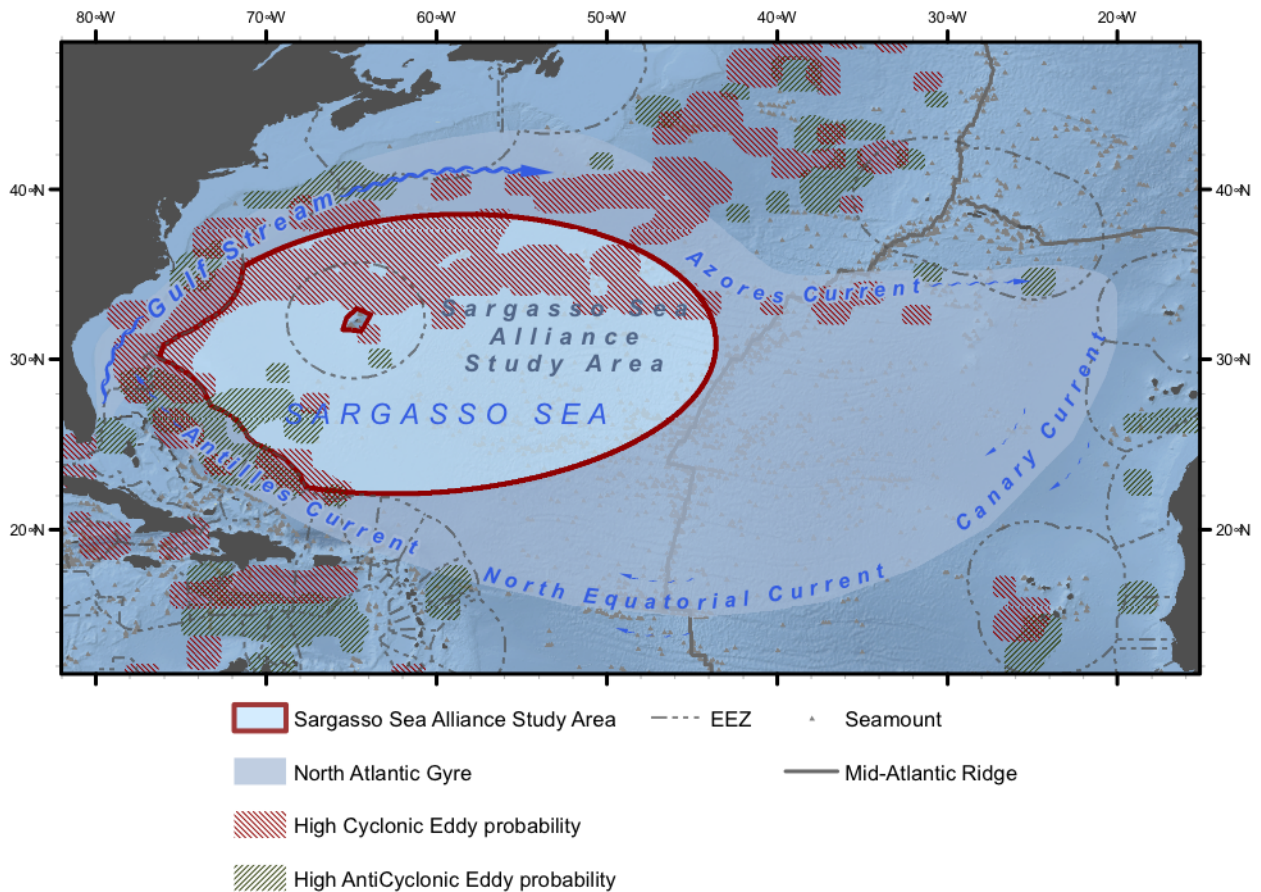
This project was successful in determining with the Sargasso Sea Alliance a Study Area boundary; however, the larger question of where the Sargasso Sea itself lies, remains only partially answered. It still holds a number of biological mysteries. At the most basic level, more needs to be understood about Sargasso Sea *Sargassum*, its life history, where it originates, how long it lives, and where it accumulates. In light of this we make the following three recommendations:

- 1.** The proposed SSA Study Area boundary be adopted by the SSA;
- 2.** The SSA encourage analysis and research relevant to delineating the Sargasso Sea, including:
  - a. further work on remote sensing of *Sargassum*, combining multiple data sources;
  - b. answering basic questions surrounding the life history of North Atlantic *Sargassum*;
  - c. developing a predictive habitat model for *Sargassum* mats.
- 3.** A biogeographic classification be undertaken for the Sargasso Sea Study Area and the wider North Atlantic Gyre.

# Where is the Sargasso Sea?

## Important Note

During the preparation of this report the map of the Sargasso Sea Alliance Study Area evolved from one showing an inner 50nm boundary around Bermuda to one with an inner boundary reflecting the the base of the Bermuda Rise. Areas with high probability of mesoscale eddies were also added. The area of the SSA study area in this final map is 4 163 499 km<sup>2</sup>. This final map is shown below as **FIG 1A** and can be compared with the earlier version shown below at page 6 as **FIG 1**.



**FIGURE 1A.** Sargasso Sea Study Area



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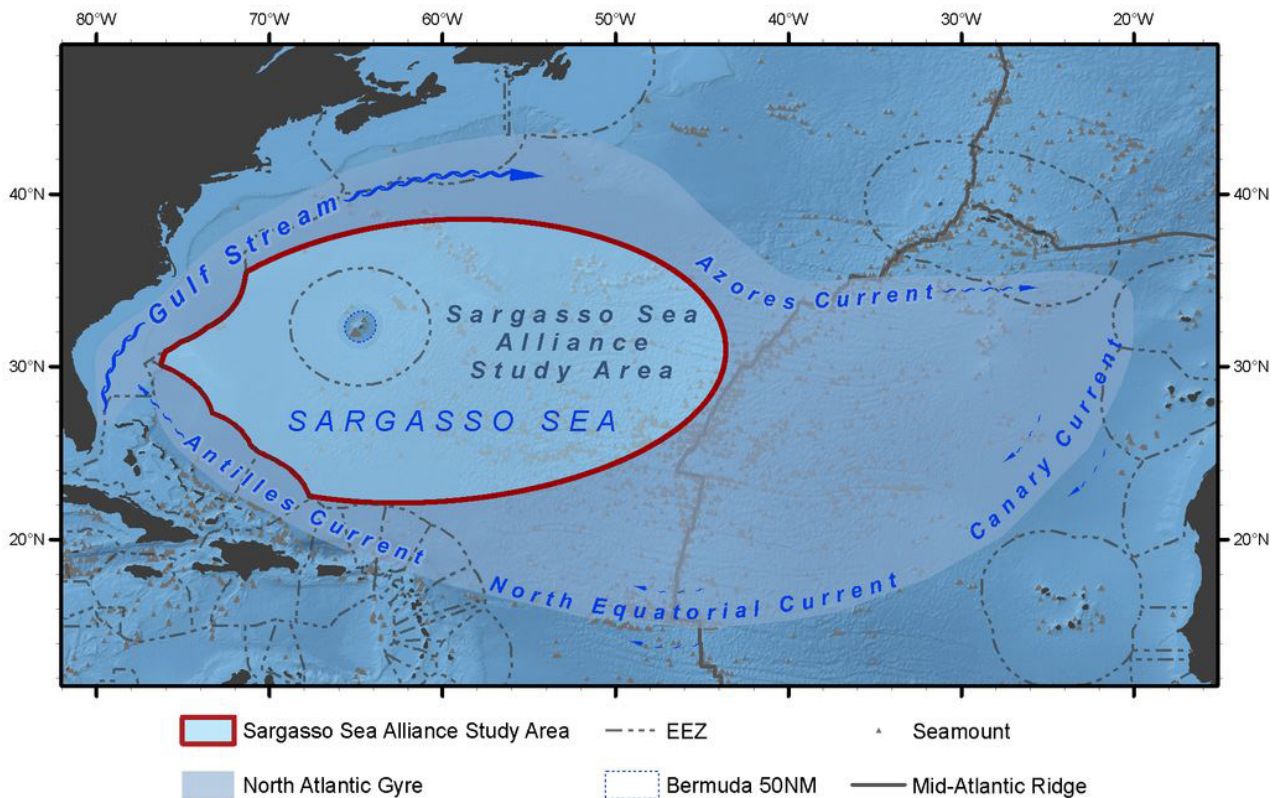
# Where is the Sargasso Sea?

## A Report Submitted to the Sargasso Sea Alliance

### Project Overview

This report presents the final results of a contract provided by the Sargasso Sea Alliance (SSA) to map the extent of the Sargasso Sea, taking into account historical conceptions combined with recent oceanographic and ecological information. In initial discussions, we were asked to consider sea surface temperature, remote satellite detections of *Sargassum*, research ship detections, and ocean currents, as well as any other factors that we thought were relevant. After the presentation of our initial results at a SSA science workshop in Bermuda (28-29 June 2011), we were asked to also take into account hypothesized eel spawning locations, regions of eddy activity (particularly in the north), “mode water” (a mass of warmer water in the central North Atlantic), and the *Mid-Atlantic Ridge*. A second set of results were shared with the SSA executive in July, and after further refinements, agreement was reached on final maps, mid-August. These included the SSA Study Area and also the inclusion of eddies to inform sub-divisions within the Study Area (FIGURE 1 and FIGURE 9).

This final report will roughly follow the above chronology of the project, with the discussion divided into three parts: *Historical Mapping*; *Physical and Oceanographic Considerations*; and, *Biological Considerations*. Technical details of the final Study Area ellipse are provided in *Appendix 1*.



**FIGURE 1.** Sargasso Sea Alliance Study Area, set within the context of the currents of the North Atlantic Gyre. Length and width of the current arrows represents the relative strength of the currents. Note that the Canary Current in particular is weak and diffuse, leaving the eastern extent of the gyre open to interpretation. The “bites” out of the Study Area ellipse exclude the EEZs of the US and neighbouring Caribbean States. There is a 50 nm exclusion around Bermuda, but otherwise its EEZ (as a UK overseas territory) is included. The Study Area is 4 151 565.1 square kilometres (1 602 928.2 square miles).



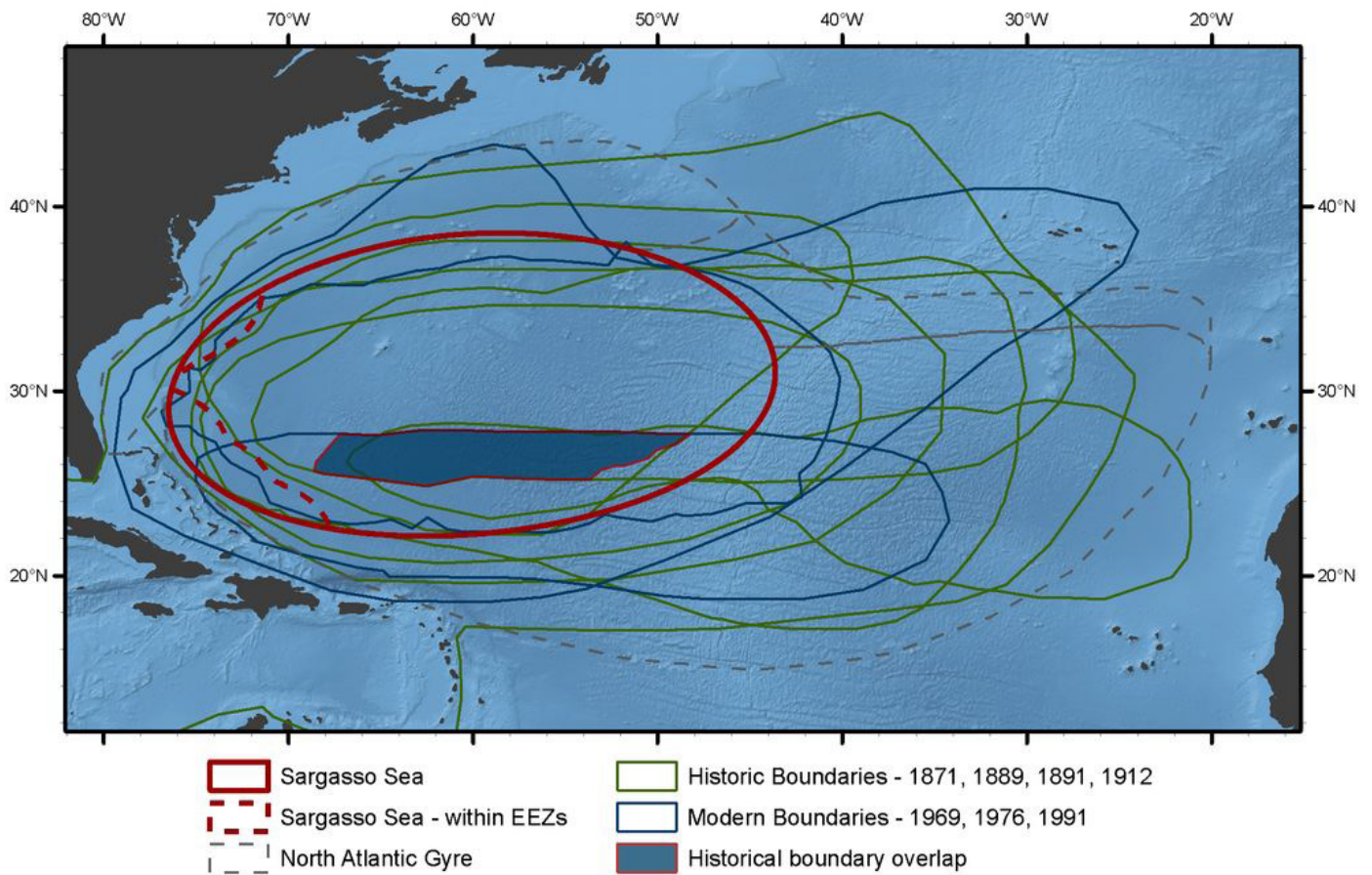
## Historical Mapping

To gain an historical perspective, the project drew upon earlier work done by Marine Conservation Institute that looked at past maps and references related to the extent of the Sargasso Sea (Gulick 2011). The boundaries of key historical maps were digitized and overlaid onto a single map (FIGURE 2).

With these historical lines all overlaid onto one

map, certain patterns that were not previously obvious come to light:

The area of overlap (shaded blue) is small; however, this is mainly because of the 1912 winter map by the US Hydrological Office (see discussion on next page). If that map is removed, the overlap converges in the centre of the Study Area ellipse.



**FIGURE 2.** Common historical delineations of the Sargasso Sea. (Digitized from Gulick 2011, with supplementary information provided by the author.)



**FIGURE 3.** excerpts of two maps produced by the United States Hydrographic Office, 1912. Light blue symbols in the centre of the maps represent *Sargassum*. The left panel is for August and the right, February. Note the significantly reduced extent of the *Sargassum* mapped on the right, winter panel.

There is a fairly strong convergence on the western side, moderate amounts on the south and north, and wide variation to the east, likely reflecting the strength (or variability) of currents in those regions (see discussion below).

The mapped area of the Sargasso Sea is generally shrinking over time. This could be due to more accurate mapping, diminishing levels of *Sargassum*, or both.

Strong seasonal variation in the spatial extent of *Sargassum* and of currents within the Sargasso Sea was noted as early as 1912 on maps produced by the US Hydrographic Office (FIGURE 3).

Considering seasonality of the Sargasso Sea adds several dimensions of complexity to the problem, some of which are discussed below. After presentation of those initial results at the SSA science workshop, it was decided that for ease of illustration and communication, a single boundary for all seasons would be used.

## Physical and Oceanographic Considerations

### Currents

The broader area under consideration in this project is the large section of the North Atlantic bounded by its circulating currents, which is sometimes known as the *North Atlantic Gyre* (pale blue area, FIGURE 1, above). However, typical for oceanic gyres in the northern hemisphere, due to Coriolis forcing, the western currents are more concentrated and hence more easily discerned

than the eastern, which are more variable, dispersed and weak. This vagueness of an eastern “edge” is reflected in the historical mapping which is also much more variable to the east (FIGURE 2).

As a subset of the North Atlantic Gyre, any analysis of the Sargasso Sea must also include consideration of the presence of *Sargassum* mats—discussed below. That is, the Sargasso Sea should be seen as a combination of oceanographic and ecological properties. With regards to oceanographic currents, however, these do offer guidance for the western boundary, and to some extent, to the north and south as well, and as such offer a good first dataset with which to begin formulating a boundary (FIGURE 4).

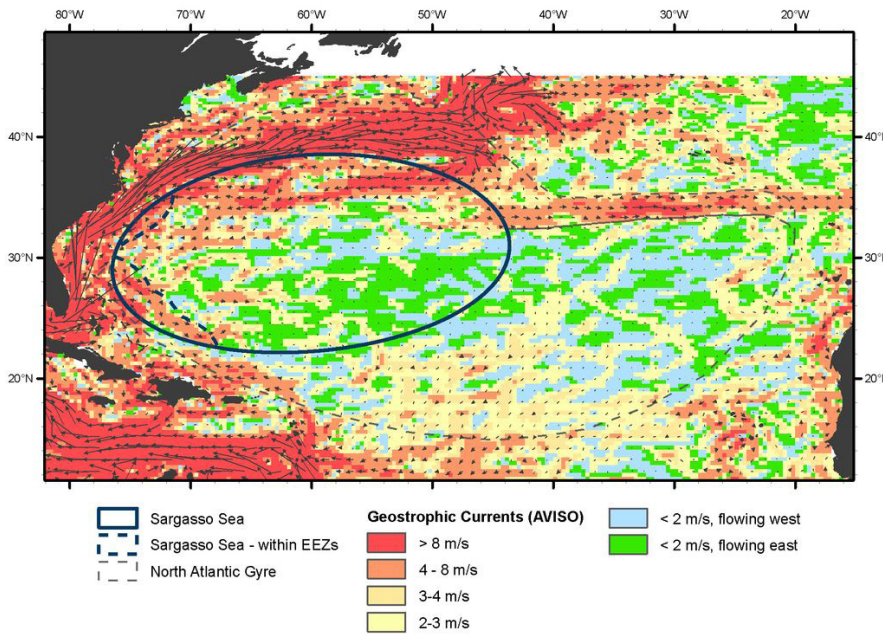
Above are summarized annual mean data for oceanic drifters (FIGURE 5). Again, these empirical data tell a similar story as the current dataset, with good evidence to support the western half of the elliptical SSA Study Area. However, the Canary Current, which is conveniently drawn in textbooks as closing the North Atlantic gyre in the east, is in fact widespread, weak, and variable.

### **Sargassum Dispersion Simulation**

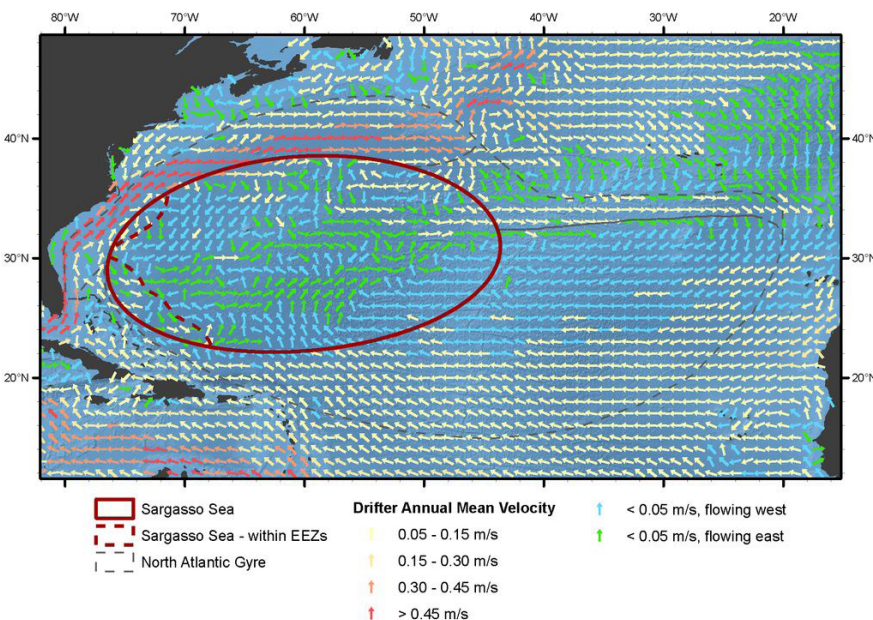
Distributions of *Sargassum* across the North Atlantic are poorly known (see *Sargassum*, below). In light of this, we attempted to build a simplified dispersion model, using what data were available to calibrate it, so as to get a better overall indication of what might constitute the Sargasso Sea, and in particular, how far east it may extend.

We modeled the flow of *Sargassum* from the northwestern Gulf of Mexico, a seasonal nursery area proposed by Gower and King (2011), into and around the north Atlantic gyre using the hydrodynamic modeling framework of Tremblé et al., (2008), as updated by Mora et al.,





**FIGURE 4.** Annual mean geostrophic currents. Note that the EEZ dashed lines coincidentally sub-divide the Antilles current in the southwest from the slower moving water within the ellipse’s interior. Data: AVISO.



**FIGURE 5.** Drifter mean annual velocity. These data are helpful in delineating the western half of the ellipse, but note that slow moving drifters (blue) spread right across the Atlantic, with little indication of the Canary Current that is said to travel southwards down the coast of Africa.

(2011), and implemented by the Marine Geospatial Ecology Tools software (Roberts et al., 2010). This framework simulates the dispersal of *Sargassum* from the nursery area by dynamic ocean currents using an advection transport algorithm (Smolarkiewicz and Margolin, 1998) and by turbulent diffusion. In this scheme, *Sargassum* is treated as a dye concentrated initially at the nursery area and spread by advection and diffusion as the simulation progresses.

To drive the model’s advection algorithm, we used ocean surface currents from the HYCOM + NCODA Global 1/12° Analysis (Chassignet et al., 2009; downloaded from <http://www.hycom.org/dataserver/glb-analysis> in June 2011), which couples a global, high-resolution implementation of the HYbrid Coordinate Ocean Model (HYCOM) with the Navy

Coupled Ocean Data Assimilation (NCODA) system. HYCOM + NCODA provides accurate daily estimates of the state of the global ocean by assimilating sea surface height, temperature, salinity, winds, and ice concentration measurements obtained by satellites and in situ sources (e.g. buoys, moorings, and drifters) into an ocean model that is tuned to perform well in both the deep open ocean, shallow coastal areas, and the mixed layer. In order to make the simulation computationally tractable in the time we had available for this analysis, we down-sampled the currents data to a resolution of 1/6°. The full spatial extent of the simulation was 15-47 °N, 12-98 °W. For the advection algorithm, we used a time step of 30 minutes, which met the stability criterion suggested by Smolarkiewicz (1983, Eq. 21).

To account for seasonal and inter-annual variability in currents, we simulated *Sargassum* dispersal for the entire duration of the HYCOM + NCODA dataset, 2004-2011. Although this time period encompasses episodic events such as several El Niño and La Niña events as well as predictable annual events such as hurricanes, it does not capture events that occur at decadal or longer scales (e.g., the shifts in the North Atlantic Oscillation). On the advice of Gower (pers. com. May 2011), we released *Sargassum* in the northwest Gulf of Mexico for the first week of February of every year of the study and then produced daily snapshots showing the positions of *Sargassum* throughout the Gulf and the Atlantic.

To produce a climatological representation of *Sargassum* density, we averaged the daily images for each month for all years. This produced 12 images that showed the simulated mean monthly density of *Sargassum* over the 2004-2011 period.

### Initial results

Our initial model did not include any mortality; *Sargassum* was permitted to drift for the full duration of the model period. In the results, over about a three-year period it would accumulate in the centre of the north Atlantic gyre (FIGURE 6), which has been shown to accumulate floating debris (Law et al., 2010).

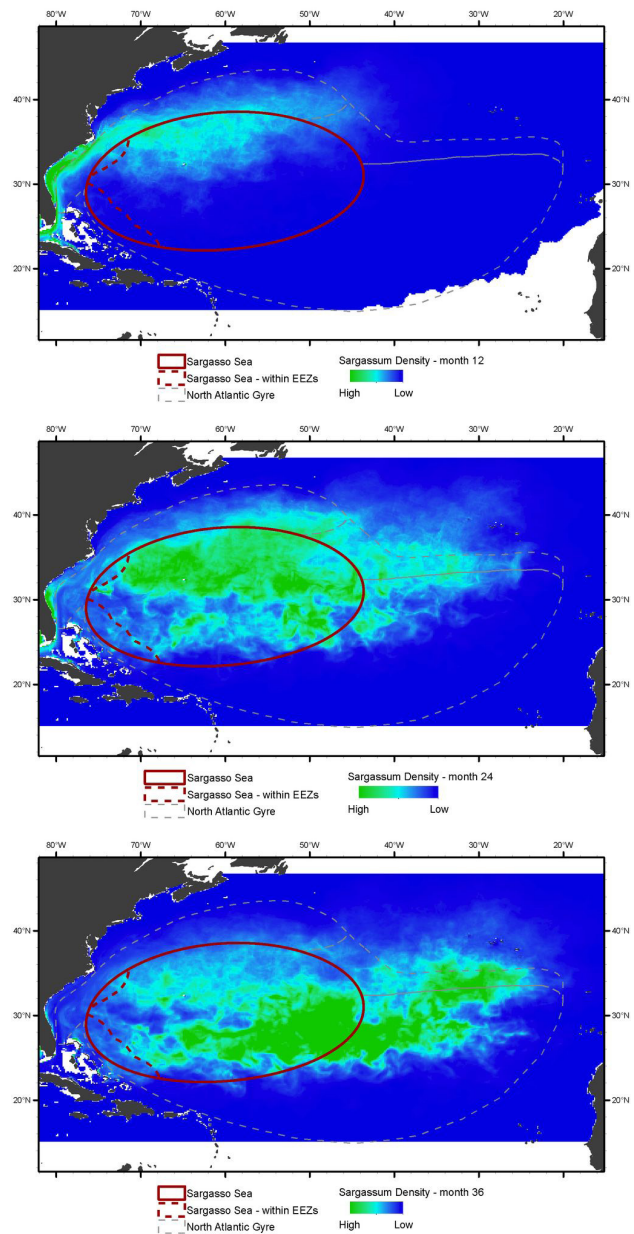
This “no-mortality” model was obviously not realistic, and while it modelled the accumulation of ocean debris reasonably well, it did not capture the densities of *Sargassum* known to lie further south and west. To improve it, we tried different mortality models.

### Mortality Model 0

In this model, *Sargassum* grows in February and lives for one year. After the end of the 12th month (January of the following year), it is all killed in a single event. However, because all of the *Sargassum* in the entire Atlantic was killed at the end of January, it must be replenished exclusively from the new stock that in the Gulf in February. By November/December, *Sargassum* has moved out from the Gulf Stream, matching many of the peak in situ observations north of 30 N. But there is no *Sargassum* in the south, because it does not live long enough to reach that region.

### Mortality Model 1

A clear problem with model 0 is that it does not allow



**FIGURE 6.** Simulated dispersion of *Sargassum* after one, two, and three years (top to bottom), with no mortality.

*Sargassum* to live long enough to reach southern areas. In model 1, we tried a basic approach to allow that to happen. *Sargassum* lives for 1 year with no mortality. Then, over the next 12 months, 1/12 dies each month, such that after 24 months, all *Sargassum* from that release cohort is dead. Model 1 was better, but it is not likely to be realistic, in that *Sargassum* starts dying just as the growing season starts (in February, after 12 months have elapsed). We postulated that it might die off mainly in the winter, and if it survives to another growing season it might continue to live until the following winter.

## Mortality Model 2

- Feb-Nov: no mortality'
- Dec-Feb: 1/6 of stock killed off per month, for each of these three months, leaving 1/2 the stock alive;
- Mar-Nov: no mortality;
- Dec-Feb: 1/6 stock killed off per month, killing off the remaining 1/2 stock.

The congruence of Model 2's May results with known distributions is actually worse than Model 1. This is perhaps because the 15-month-old stock suffered 50% mortality, compared to only 33% in Model 1, and the rest is killed the following winter, as in Model 1. As a result, there is less *Sargassum* in the Atlantic in May, compared to Model 1.

November: here we see an improvement compared to Model 1, with more *Sargassum* extending further south. This is because the 22-month-old stock has only suffered 50% mortality, compared to 83% in Model 1.

## Mortality Model 3

We wanted to see if we could improve Model 2 by allowing the *Sargassum* to live longer than two years:

Feb-Nov: no mortality

- Dec-Feb: 1/9 of stock killed off per month, for each of these three months, leaving 2/3 the stock alive
- Mar-Nov: no mortality
- Dec-Feb: 1/9 of stock killed off per month, for each of these three months, leaving 1/3 the stock alive
- Mar-Nov: no mortality
- Dec-Feb: 1/9 of stock killed off per month, for each of these three months, leaving none alive

The matchup with known May aggregations improves; now it is better than Model 1 (instead of worse), at least in the south. The simulated density increased in the center-north as well, and here it might be starting to overestimate. In November, continued extension of simulation results southward. Now we are starting to see the emergence of the stagnant patch in the central Atlantic (50 W, 28 N), and the smaller one northeast of there (35 W, 35 N).

## Summary of mortality experiments

Model 3 is probably the best of these attempts, but still suffers from problems:

1. In May, the region of peak density is not where we would expect it to be for that time of year. The *in situ* data show it between Bermuda and the Bahamas, not

north of 30 N. The same problem appears to come up when compared to Gower's data.

2. Massive quantities of *Sargassum* are present in the Gulf of Mexico year round, which is clearly not indicated by Gower & King's data.

## Future work

The short timeframe and limited budget of this project did not allow us any further opportunity to work on the model. It became apparent that a simplified approach was not working and that more sophisticated methods, requiring more time, would be needed. A better understanding of the life history of *Sargassum* would remove a lot of the guesswork involved in setting up the model's parameters. Other refinements could include:

- Kill *Sargassum* in high winds. This could help clean out the Gulf of Mexico in the fall and the northern part of the Atlantic in the winter. (There is an hypothesis that high winds could cause downwellings through Langmuir circulation that would sink *Sargassum*. We did preliminary work on this, but without any clear improvement in results.)
- Move *Sargassum* via direct wind forcing or with Stokes drift. This could help move *Sargassum* down from the northern part of the Sargasso Sea to the southern part in fall and winter. (We did preliminary work on this, but without any clear improvement in results.)
- Grow *Sargassum* throughout the growing months, including in the Atlantic. Multiple sources suggest that *Sargassum* actively grows throughout the Atlantic. By allowing it to grow in the southern, calm part of the Sargasso Sea, it could steadily build up there and better balance the northward skew we currently see.
- Release *Sargassum* further east in the Gulf, to promote its exit into the Atlantic earlier.

Release *Sargassum* in the middle of the Bahamas to see what happens. If it is somehow able to make it into the region towards Bermuda, then there could be a problem with HYCOM not modeling the shallow shelves around the Bahamas (e.g. Grand Bahama Bank).

Release *Sargassum* as well on the north coast of Brazil, where there is some recent satellite evidence suggesting this could be a second nursery area (Gower, pers. comm. July & Aug. 2011).

## Sea Surface Temperature

For this project, we were asked to consider sea surface



temperature. However, we found this feature to be too broad and gradual to be helpful in further delineating the Sargasso Sea. It is noteworthy is that the southern half of the Study Area is warmer than the north (FIGURE 7).

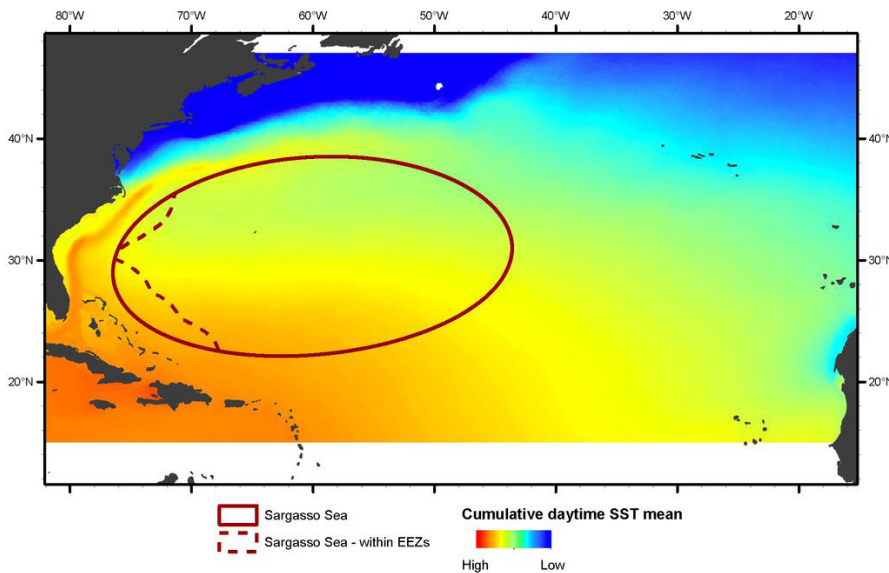
### Mode Waters

At the SSA science workshop, the relationship of *mode waters* to the Sargasso Sea was raised. These are somewhat stable water masses near the surface with homogenous temperature and density. They form in winter; in the Sargasso Sea, this happens in the northwest. It then fills the subtropical gyre. Sargasso Sea mode water is called the "18-Degree C Mode Water" or the North Atlantic Subtropical Mode Water (NASTMW –FIGURE 8). As can be seen, *deeper* mode waters lie mostly to the north of the Study Area, with an east-west extent that is similar

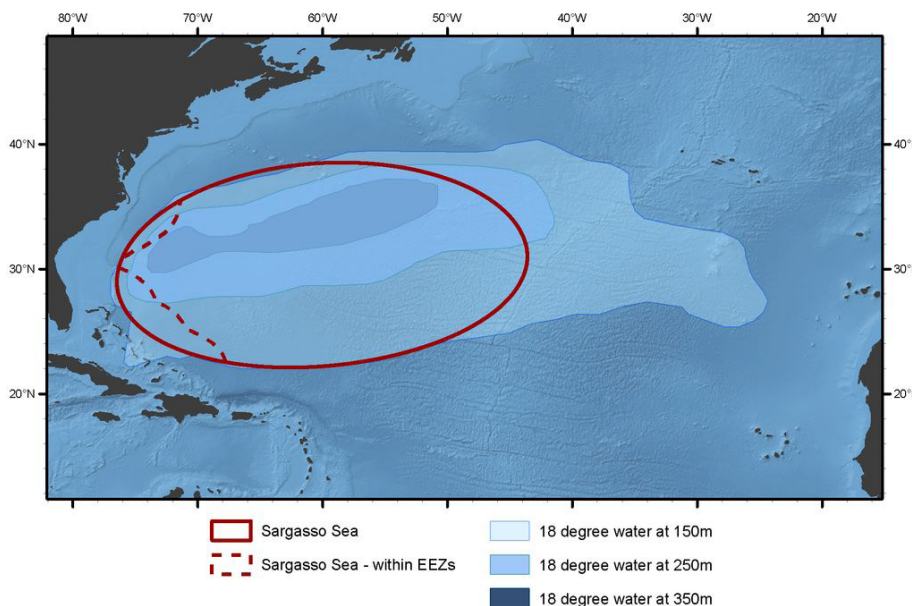
to the Study Area. The north-south extent of all mode waters fits into the Study Area. Regarding shallower mode waters, however, the question of the eastern extent of the Sargasso Sea is again raised.

### Eddies

The Gulf Stream is a major source of eddies throughout the North Atlantic. Eddies can offer a means of transport for various organisms and their larvae. Cyclonic eddies, more common in the northern hemisphere, encourage upwellings that can bring nutrients into sunlit surface waters, encouraging primary productivity and attracting many other species to feed. In the oligotrophic waters of the Sargasso Sea, these represent a likely important ecological mechanism, and occur mostly in the northern half of the Study Area (FIGURE 9–red



**FIGURE 7.**  
Annual mean  
sea surface  
temperature.



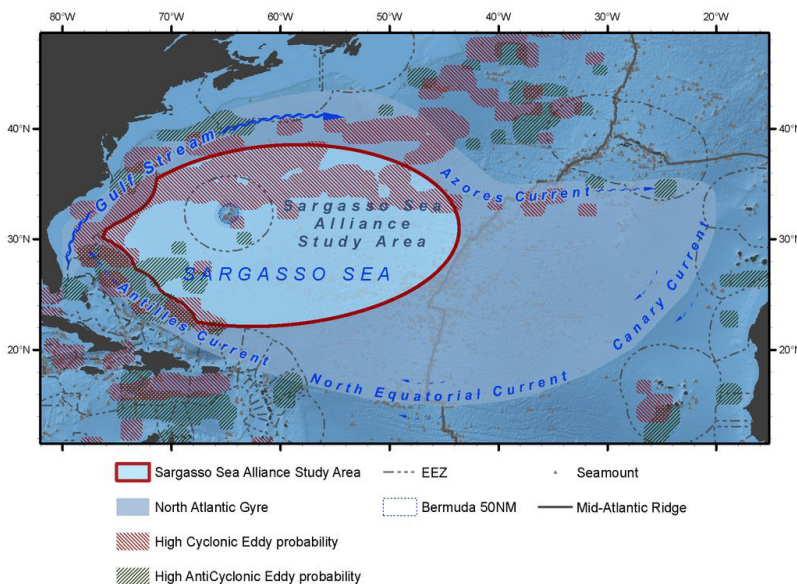
**FIGURE 8.**  
Mode water.  
Digitized  
from: Maze &  
Marshall, in  
press.

hatching). Anticyclonic eddies are less common in the Sargasso Sea, but are also important in that they tend to aggregate materials together towards their centres and hence could provide one mechanism by which *Sargassum* mats are formed (another mechanism would be wind-driven Langmuir circulation and the characteristic long windrows produced). Anticyclonic eddies are more likely to form in the southwestern “corner” of the Study Area (FIGURE 9—green hatching), though they can also form in the north.

## A Future Biogeography?

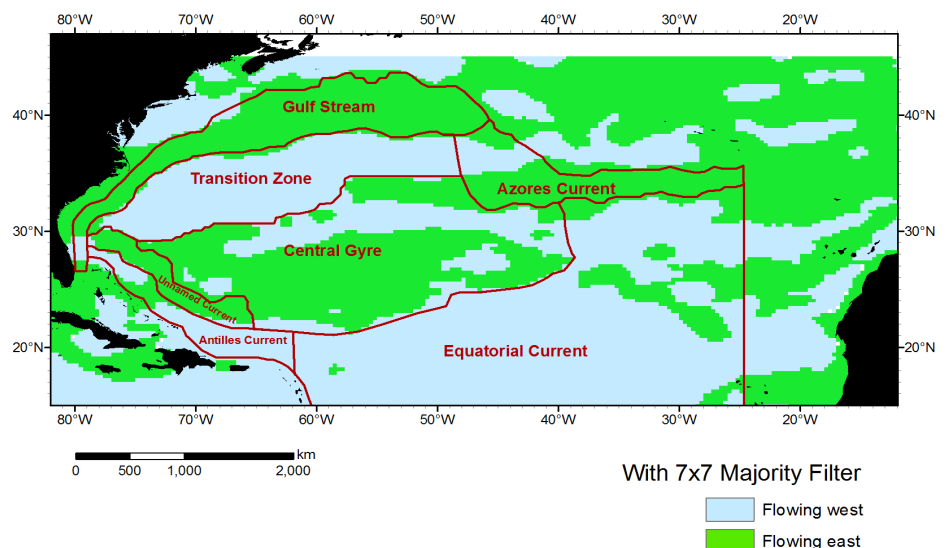
The SSA showed particular interest in eddies and their possible role in sub-dividing the Study Area into

biogeographic regions. Likewise, the above temperature data (SST and mode waters) both indicate possible sub-divisions of the Study Area. The question of biogeography will become especially important later when analysing the representativity of any networks of protected areas that are proposed or established. In a preliminary analysis, we considered broad provinces based on current regimes, and presented our results to the SSA in June and revisions in July (FIGURE 10 and FIGURE 11). However, developing a biogeographic classification of the Sargasso Sea is far outside the scope of this project, and so we had to leave our preliminary results as they were, as intriguing possibilities of what the future might hold.

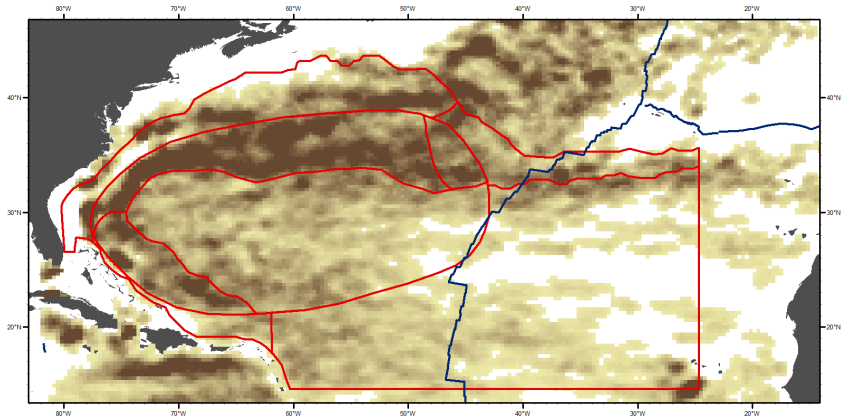


**FIGURE 9.** Eddies. High probability (threshold set at 0.065) of cyclonic eddies is noted in red, with anticyclonic in green. Note that eddies are not unique to the Sargasso Sea and extend northward throughout the Atlantic. However, they likely play unique ecological roles within the Sargasso Sea.

**FIGURE 10.** Preliminary development of possible sub-regions using climatological mean AVISO currents. The straight vertical edges to the right represent arbitrary eastern cut-off and are not meant to signify sub-regions.



**FIGURE 11.** Another variation of possible sub-regions and the annual mean probability of cyclonic eddies. The straight vertical edges to the right represent arbitrary eastern cut-offs and are not meant to signify sub-regions.



## Biological Considerations

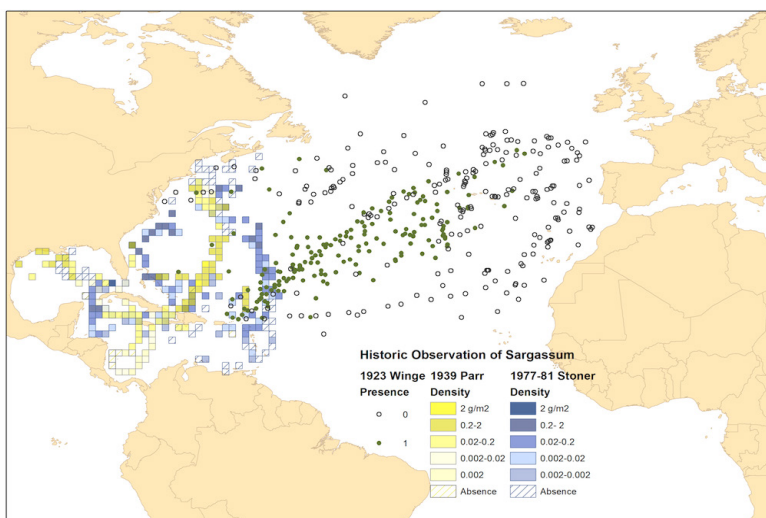
### *Sargassum*

Emblematic to the Sargasso Sea, *Sargassum* (composed mainly of *Sargassum natans* and *S. fluitans*) is widely known throughout the region. It was therefore surprising to us to find that it has been rather scantily studied. Basic questions such as how long it lives, appear to be unanswered. In the earlier years of the last century, there was some debate on whether *Sargassum* reproduced at sea, with a general belief that it did (Parr 1939, Winge 1923); however, this information appears to have been largely discounted in modern accounts which assume it does not (e.g. Gower and King 2011). Clearly, this is an area requiring further study.

For the purposes of this project, it was important to better understand where the large, ecologically important, mats of *Sargassum* were likely to accumulate. To first approach this question, historical accounts we considered,

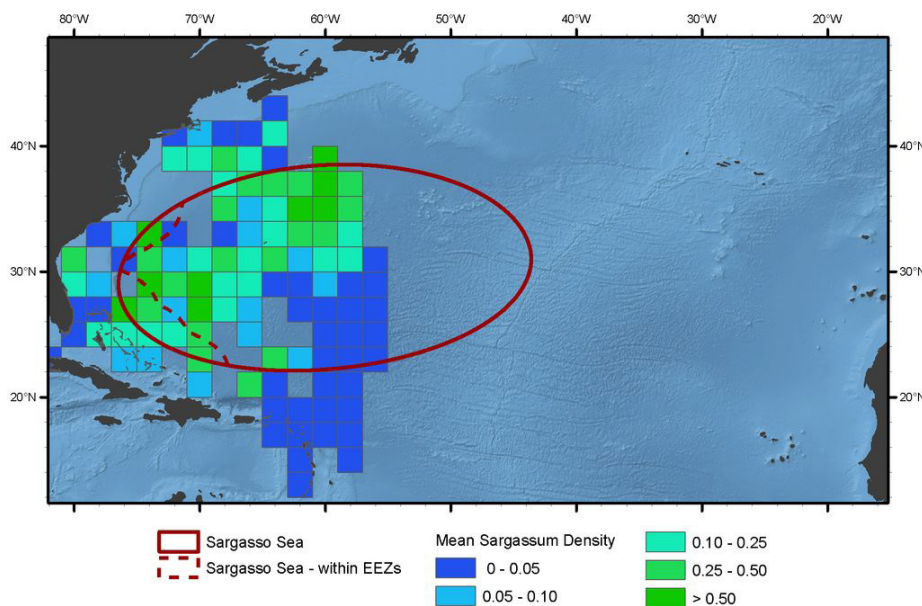
which we digitized (FIGURE 12). However, due to the patchy sampling, sometimes unclear sampling techniques, and the wide spread of time, we considered historical accounts which we digitised, other than that *Sargassum* was seldom found in the eastern North Atlantic, and if so, it was usually at the latitudes near the Azores, which strongly suggests Gulf Stream transport, outside of the currents said to contain the Sargasso Sea.

The Sea Education Association (SEA) kindly provided their 32-year *in situ* dataset. To protect their unpublished data, these are shown aggregated into large grid squares (FIGURE 13). These data were extremely helpful in the calibration of our dispersion model, as discussed above. However, the extent of the cruises did not allow for an answer to the eastern distribution of *Sargassum* in the Sargasso Sea.



**FIGURE 12.** Historic observations of *Sargassum*. Digitized from Winge 1923; Parr 1939; and Stoner 1983, Stoner & Greening 1984.





**FIGURE 13.** Sea Education Association (SEA) aggregated data. Greens are higher densities; blues lower; no square indicates no data collected in that area. Courtesy SEA.

### Satellite detection

Throughout the course of this project, a recurring comment has been that *Sargassum* can be readily detected through satellites, which should solve the question of its distribution. It turns out that the problem is not quite so easily solved, as discussed below.

Dr. Jim Gower and colleagues are the only researchers to have published on this topic (e.g. Gower et al., 2005; Gower & King 2008, 2011). We approached Dr. Gower, first through email, and later with an on-site visit to his facilities at the Institute of Ocean Sciences, in Sydney British Columbia. He generously provided our team with data grids derived from MERIS satellite data as well as computer code for his detection algorithm. We then applied a refined version of the approach that Dr. Gower and colleagues had pioneered, as follows.

### Methods

5-km resolution monthly maximum value composites of Maximum Chlorophyll Index (MCI, a measure of the height of the 709nm band relative to adjacent bands of the ESA MERIS sensor) were derived from 1-km resolution daily MCI grids. MCI grids from mid-2002 through mid-2011 were graciously provided by Jim Gower and Stephanie King of the Institute of Ocean Sciences, Fisheries and Oceans Canada.

"MERIS Counts" were calculated for each 1-degree bin in the Sargasso Sea and Gulf of Mexico using the techniques described in Gower & King (2011). We generated an improved mask on the MCI data to remove noise and interference with nearshore habitats

and shallow benthic features such as reefs before running the MERIS Count algorithm. We also identified a source of double counting in the original code used by Gower & King and created an improved processing algorithm. To derive MERIS Counts, monthly maximum composite MCI data were analyzed for each 1-degree bin and a portion of the histogram representing the background ocean signal without sensor noise is analyzed to determine an average background value for that cell. The amounts by which any pixels in the 1-degree block exceed the background value plus 0.4 mWm<sup>-2</sup>nm<sup>-1</sup>sr<sup>-1</sup> are summed. This is the MERIS Count and it represents the total quantity and magnitude of signals representing potential *Sargassum*. As defined in Gower & King (2011), one MERIS Count unit is equal to one mWm<sup>-2</sup>nm<sup>-1</sup>sr<sup>-1</sup>degree<sup>-1</sup>.

### Results

Monthly and seasonal climatologies of MERIS Count data were created from the monthly time series between June 2002 and May 2011. The seasonal climatologies are divided into 4 unequal seasons (2 major seasons of 4 months each and 2 transitional seasons of 2 months each): Season 1 (Jan, Feb, Mar, Apr) is dominated by either low detections or a cluster of detections in the southwestern quadrant of the North Atlantic subtropical gyre, Season 2 (May & June) is a transition period, Season 3 (July, Aug, Sept, Oct) is dominated by a large pulse of detections in the Gulf Stream plume and the northwestern part of the gyre, and Season 4 (Nov, Dec) is another transition period where detections shift from the north to the central and the southwestern areas of the gyre (FIGURE 14).

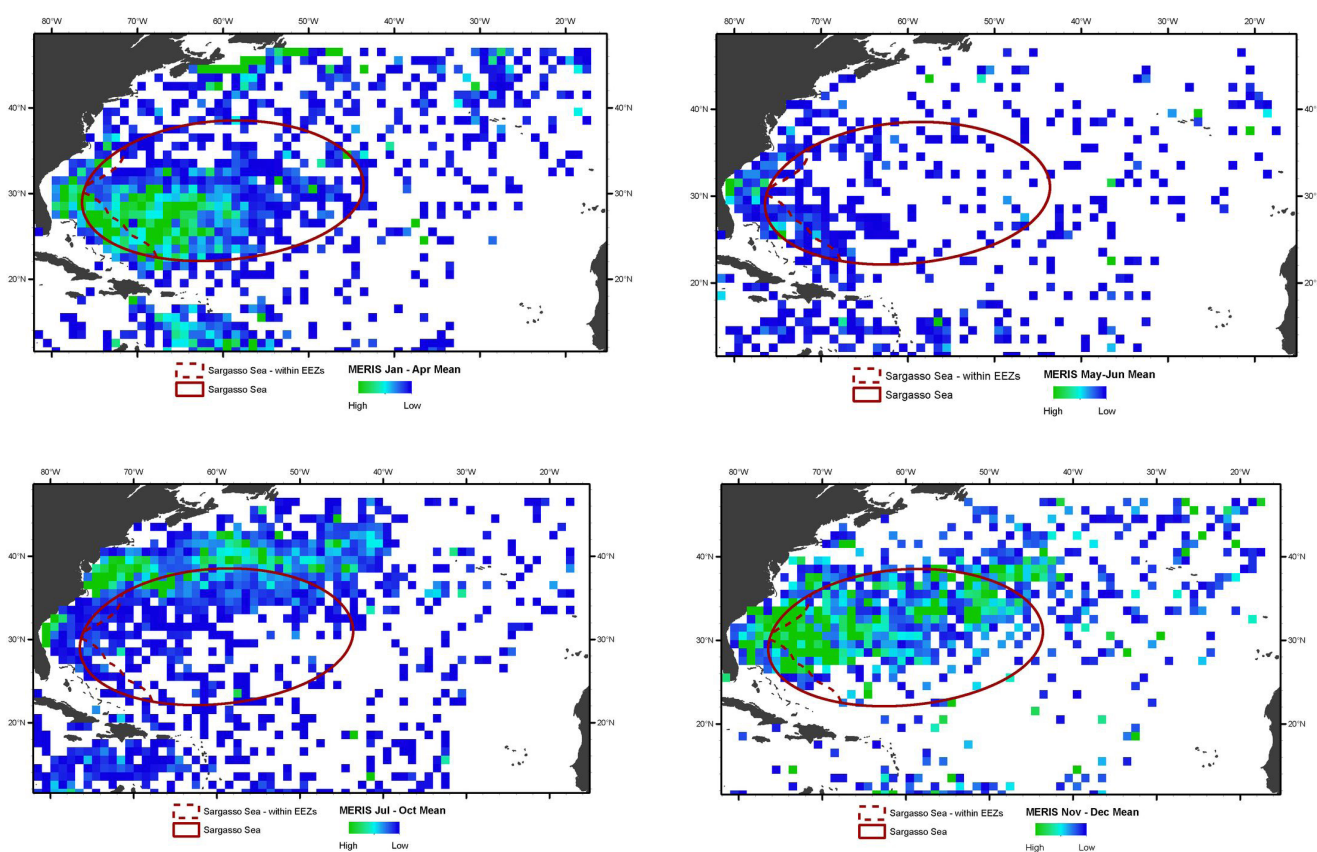
## Interpretation of results

Care has to be taken when interpreting the above results. First of all, there is a great deal of variability in these detections, which can be influenced from a variety of factors, ranging from showers of cosmic rays to sunlight glinting off the sea surface. Secondly, only large clumps of *Sargassum* can be detected by satellites; hence, detections are in part a function of where there are aggregating factors such as favourable winds and anticyclonic eddies. Areas of dispersed *Sargassum* will most likely not be detected, even though the *Sargassum* biomass of such regions could be as great, or greater, than areas where it has aggregated into mats. This could explain why *Sargassum* sometimes appears “out of nowhere”. It can “disappear” again if it is broken up into smaller mats, if it sinks, or if it is washed ashore (since land is masked out of the analysis).

From an ecological standpoint, the larger mats are likely of greater interest, and so the MERIS detections

favour the more ecologically significant patches. These satellite data indicate that *Sargassum* is only sometimes – perhaps half the year – in large enough aggregations to be detected significantly within the bounds of the Study Area. Vast amounts appear to be transported by the Gulf Stream northward, outside of the 18 degree Celsius water, where it will die and sink, having never known the Sargasso Sea. This is in agreement with our simulations as well. However, without a second data source with which to cross-validate, estimating the accuracy of the satellite detections is difficult; the data are very “noisy.”

The eastward extent of most detected aggregations would appear to be in alignment with the Study Area Boundary, though there are some scattered detections further east, which may be false positives or actual detections as well. Ship and/or aerial/drone surveys would help clear up some of these uncertainties.



**FIGURE 14.** mean detections of *Sargassum* using MERIS satellite data, 2002-2011. Detections fall into two major 4-month “seasons” (left column) with two two-month transitions (right column). Top left panel: Jan-April; top right: May & June; bottom left: July-Oct; bottom right: Nov & Dec. Green indicates higher detections, blue is low, and white is no detection/no data.

## Eels

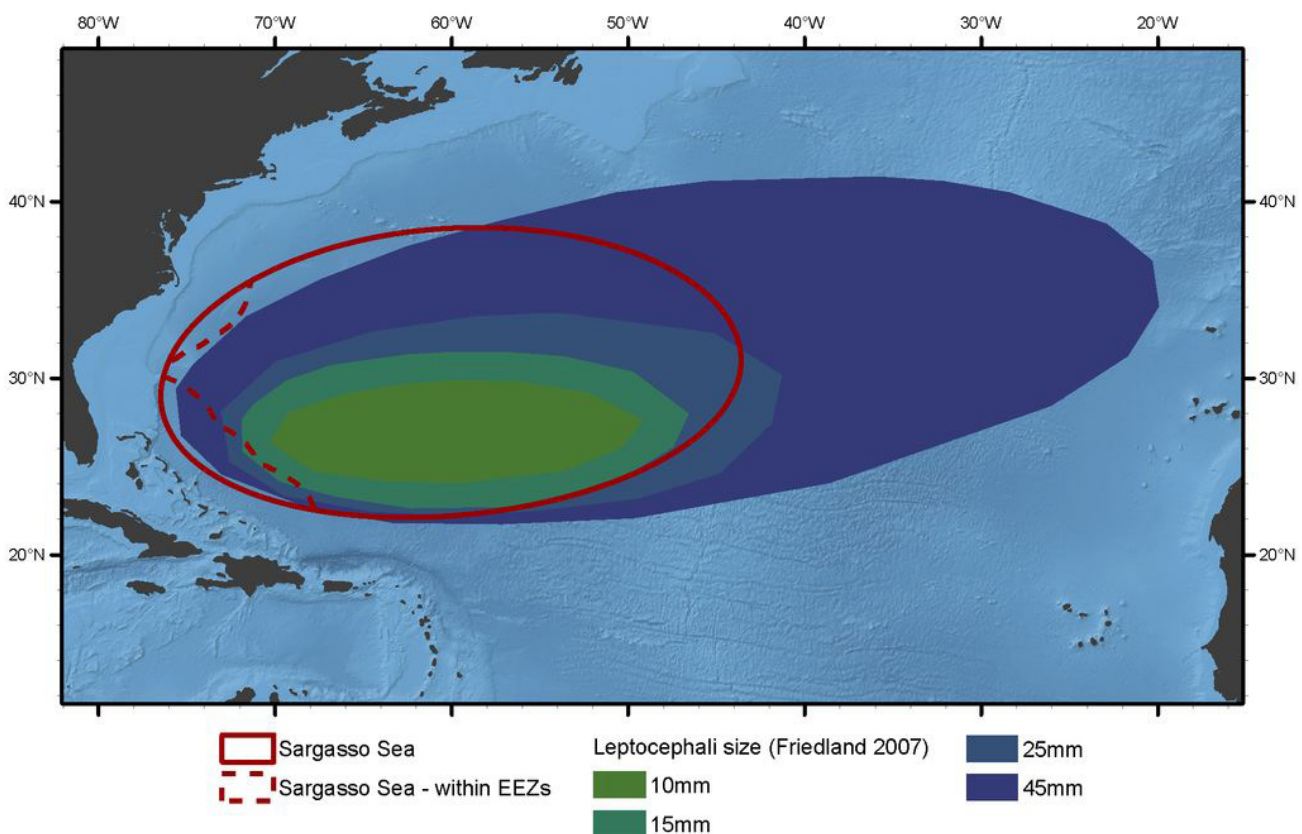
At the SSA science workshop, we were asked to map the postulated location of eel spawning grounds in relation to the Study Area.

The American eel (*Anguilla rostrata*) and the European eel (*A. anguilla*), both in decline, are catadromous, living most of their lives in the freshwater habitats of America and Europe and then traveling thousands of miles as adults to the Sargasso Sea to spawn (ICES 2008, Friedland et al., 2007). After spawning in the Sargasso Sea, eel larvae cross the Atlantic Ocean and metamorphose into glass eels that complete the migration into freshwater habitats of North America and Europe.

Friedland et al. reviews the state of knowledge relative to eel spawning in the Sargasso Sea in a paper

published in 2007. Exact location and circumstances of eel spawning remain unknown although there is evidence that certain oceanographic features such as thermal fronts may direct eels to spawning locations (McCleave 1987). Leptocephali (larval eels) of both species have a broad distribution in overlapping areas of the Sargasso Sea and tend to be most abundant in the upper 100m of the ocean.

Because the actual location of the eel spawning grounds is unknown, and the circumstantial evidence is very general, we must be cautious in our conclusions. For spatial information, we could draw upon one paper only (Friedland et al., 2007). At the scale of this exercise, based on this one paper, it would appear that the eel spawning grounds are most likely captured by the Study Area (FIGURE 15).



**FIGURE 15.** Eel leptocephali. Shapes generalized according to sizes of leptocephali collected, with smaller specimens found in the green areas and larger ones in the purple areas, suggesting a centre in the south-central portion of the Study Area. Digitized from Friedland et al., 2007.



# Conclusions

Choosing a fixed boundary for a body of water that is noted for the fluid, variable and seasonal nature of its constituent parts, is never going to be easy or exact! After some discussion, it was agreed internally that our initial analyses did not provide enough information to empirically determine the exact extent and full range of variability of the Sargasso Sea from existing data. This result reflected the complex, sometimes mysterious nature of the Sargasso Sea and its emblematic inhabitants. However, there was enough information to guide the delineation of an area of greater interest to the SSA—what would later become known as the *Sargasso Sea Alliance Study Area*. That decision could be based on the above analyses and datasets, in combination with pragmatic and political considerations. Below are the key elements of those discussions with the SSA, which led to the Study Area boundary.

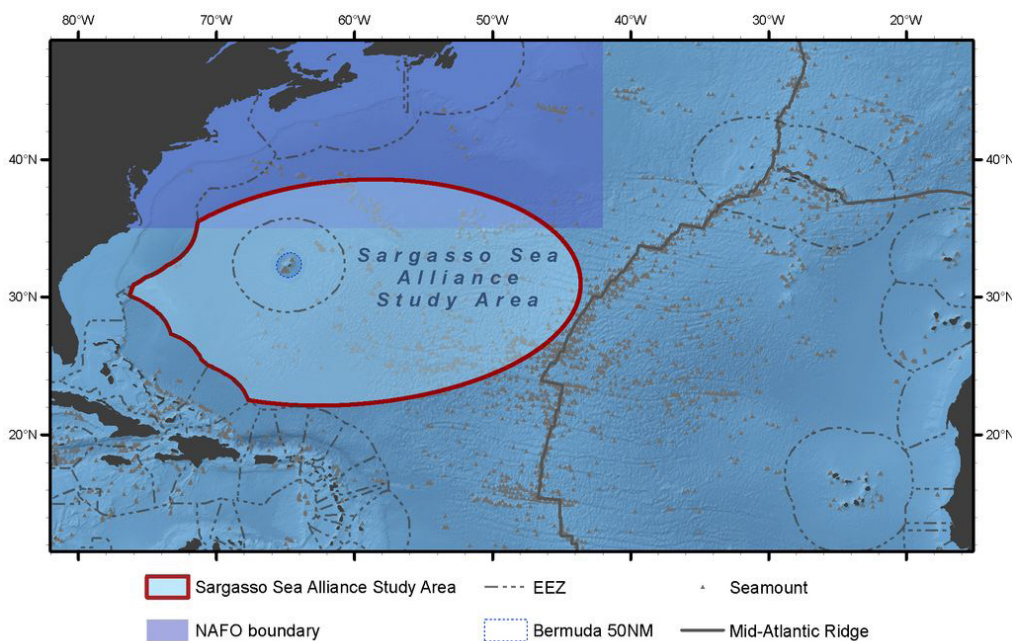
## Settling the eastern extent of the Study Area boundary

As discussed above, there is a great deal of uncertainty about the eastern extent of the Sargasso Sea. The current Study Area Boundary terminates further westward than any of the historical maps we found, and hence is a very conservative estimate, most likely cutting out some eastern components of the Sargasso Sea. That said, as seen in the maps above, it does a fairly good job fitting a number of datasets, ranging from deep mode water to large *Sargassum* detections, and it does capture most

of the eddies in the general region. An earlier version did go somewhat further eastward to better capture the eddy and current regimes, but this meant that it crossed over the *Mid-Atlantic Ridge* (MAR). The MAR had been suggested at the SSA science workshop as a possible eastern boundary, and later feedback from the SSA reinforced this point of view. There was a concern that including the MAR would introduce a different benthic ecosystem; hence, the final boundary was drawn to end just west of the MAR (FIGURE 16).

## Taking into account national and regulatory boundaries

The Sargasso Sea was first documented and studied at a time when a nation’s sovereign waters were said to be defined by the length of a cannon shot—generally 3 nm. Modern day Exclusive Economic Zones (EEZs), which extend 200 nm offshore, pose a new complication to those wanting to protect the Sargasso Sea. Hence, while the curving western side of the original ellipse that defines the Study Area follows the oceanographic features that would be said to best represent the Sargasso Sea, the SSA Study Area has had those portions that fall within EEZs removed. These “bites” out of the ellipse remove the EEZs of the US, The Bahamas, Turks and Caicos Is (UK), and the Dominican Republic. The EEZ of Bermuda (UK) has been retained since Bermuda is a founding member of the SSA and actively supportive of its work.



**FIGURE 16.** Study Area, Mid-Atlantic Ridge (brown line), and NAFO regulatory area (shaded purple).

There are two active regional fisheries management organizations (RFMOs) in the region –the International Commission for the Conservation of Atlantic Tunas (ICCAT) and Northwest Atlantic Fisheries Organization (NAFO). ICCAT’s remit extends across most of the North Atlantic and hence completely overlaps the Study Area. Most of NAFO’s regulatory area lies outside of the Study Area, but the southern edge of its boundary clearly overlaps (FIGURE 16). Because these are not sovereign boundaries, and indeed lie beyond national jurisdictions, it was felt best to not alter the Study Area to accommodate RFMOs, but rather to work with them on fisheries related issues that may arise within these areas of overlap.

### More questions than answers...

This project has unearthed several questions relevant to delineating the Sargasso Sea. At the root to answering the overarching question *Where is the Sargasso Sea?* is the related question: *Where is the Sargassum?*

Existing satellite analyses, as carried out in this project, can help answer this question in recent years, but cannot provide the acuity or time series necessary to create a definition of the Sargasso Sea that reflects historical aggregations, and hence may not stand the test of time. Certainly, more work on combining other remote sensing data sources would help improve this situation, and is one of our recommendations (below). However, satellite data alone are hampered without also understanding the bigger picture:

- Is the distribution of large mats of *Sargassum* changing over time?
- Has *Sargassum* biomass changed since the Sargasso Sea was first conceptualized? (Stoner (1983) argues it is decreasing.)

In all likelihood, it will be some years before the answers to these questions are known, if ever. In the meantime, we

could do a much better job of modelling the dispersion and accumulation of *Sargassum* if we had answers to the following four questions, which we posed at the SSA science workshop:

1. Should we consider seasonality?
2. How long does *Sargassum* live?
3. Is the Sargasso sea fed entirely by the Gulf of Mexico supply of *Sargassum* (e.g. is there another source)?
4. Is it possible that the Sargasso Sea population is (at least in part) self-sustaining? (per Parr 1938)

We received a tentative “no” for the first question. While the other three spawned good discussions, they remain unanswered. For this reason, we have left them in bold. There are many other questions too, such as where the eels actually spawn. However, in order to get started, we feel that these three questions, all relating to the life history of *Sargassum*, are the most pressing. Without knowing a little bit more about *Sargassum* in the North Atlantic, it will be very hard to delineate the eponymous Sargasso Sea.

### Recommendations

1. The proposed SSA Study Area boundary be adopted by the SSA;
2. The SSA encourage analysis and research relevant to delineating the Sargasso Sea, including;
3. Further work on remote sensing of *Sargassum*, combining multiple data sources;
4. Answering basic questions surrounding the life history of North Atlantic *Sargassum*;
5. Developing a predictive habitat model for *Sargassum* mats; and
6. A biogeographic classification be undertaken for the Sargasso Sea Study Area and the wider North Atlantic Gyre.

## Acknowledgements

This work was supported by the Sargasso Sea Alliance (SSA). We would like to thank all the SSA members for their helpful input, in particular Prof David Freestone, Prof Dan Laffoley, and Dr. Howard Roe for their efforts in shaping the final version of the Study Area map. Thanks also to Dr. Tony Knapp and the Bermuda Institute of Ocean Sciences for hosting the scientific workshop that reviewed the preliminary results. Thank you to the Sea Education Association (SEA) for providing us with its unpublished cruise data; and, to Drs Jim Gower and Stephanie King for sharing their data and expertise in remotely identifying *Sargassum*. Finally we wish to acknowledge our respective institutions, Duke University Marine Geospatial Ecology Lab and Marine Conservation Institute, for their support when this project ran into overtime.

# Appendix 1

## Technical attributes of the Sargasso Sea Study Area (SSASA)

**Area of the SSASA:** The area of the final SSA study area is 4 163 499 km<sup>2</sup>.

**Bounding box of the SSASA:** 38.542028 degrees north latitude to 22.115905 N; 76.308050 degrees west longitude to 43.612929 W.

### Ellipse upon which the SSASA is based:

- Centre: 30.35 N, 60.2 W.
- Semi-minor axis: 900 km.
- Semi-major axis: 1590 km.
- Azimuth (Major axis clockwise rotated from N): 84 degrees.

- Bounding box of the ellipse, before removal of EEZs: 38.542028 degrees north latitude to 22.115905 N; 76.453398 degrees west longitude to 43.612929 W.
- Area of ellipse, before removal of EEZs: 4 480 221.4 square kilometres (1 729 823.15 square miles [mi<sup>2</sup>]).
- Area of ellipse removed that fell within US EEZ: 63 115.5 km<sup>2</sup> (24 369.0 mi<sup>2</sup>).
- Area of ellipse removed that fell within Caribbean EEZs: 239 375.5 km<sup>2</sup> (92 423.4 mi<sup>2</sup>).
- Area of ellipse removed that fell within 50 nm of Bermuda: 26 165.3 km<sup>2</sup> (10 102.5 mi<sup>2</sup>).

All calculations were done using GIS with a North American Albers Equal Area Conic projection with the central meridian set to 60 W.

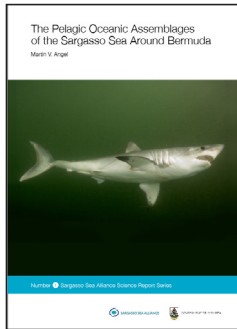
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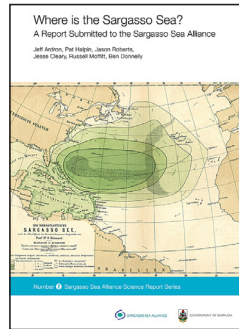
# Sargasso Sea Alliance Science Series

The following is a list of the reports in the Sargasso Sea Alliance Science Series. All can be downloaded from [www.sargassoalliance.org](http://www.sargassoalliance.org):



**1**

**Angel, M.V. 2011.** *The pelagic ocean assemblages of the Sargasso Sea around Bermuda.* Sargasso Sea Alliance Science Report Series, No 1, 25 pp.



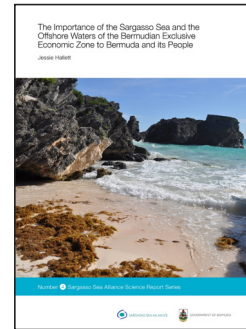
**2**

**Ardron, J., Halpin, P., Roberts, J., Cleary, J., Moffitt, M. and J. Donnelly 2011.** *Where is the Sargasso Sea?* Sargasso Sea Alliance Science Report Series, No 2, 24 pp.



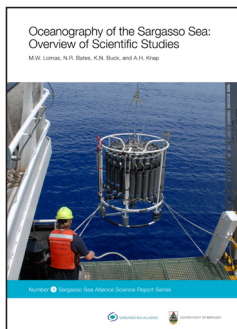
**3**

**Gollock, M. 2011.** *European eel briefing note for Sargasso Sea Alliance.* Sargasso Sea Alliance Science Report Series, No 3, 11 pp.



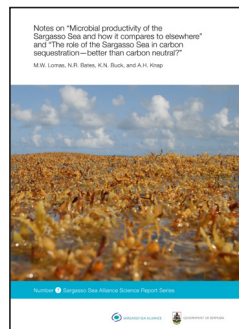
**4**

**Hallett, J. 2011.** *The importance of the Sargasso Sea and the offshore waters of the Bermudian Exclusive Economic Zone to Bermuda and its people.* Sargasso Sea Alliance Science Report Series, No 4, 18 pp.



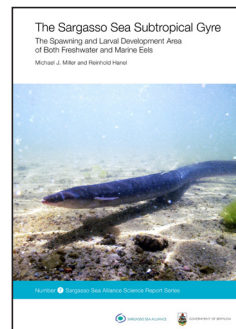
**5**

**Lomas, M.W., Bates, N.R., Buck, K.N. and A.H. Knap. (eds) 2011a.** *Oceanography of the Sargasso Sea: Overview of Scientific Studies.* Sargasso Sea Alliance Science Report Series, No 5, 64 pp.



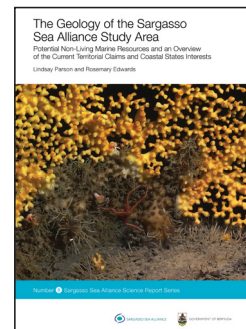
**6**

**Lomas, M.W., Bates, N.R., Buck, K.N. and A.H. Knap. 2011b.** *Notes on "Microbial productivity of the Sargasso Sea and how it compares to elsewhere" and "The role of the Sargasso Sea in carbon sequestration—better than carbon neutral?"* Sargasso Sea Alliance Science Report Series, No 6, 10 pp.



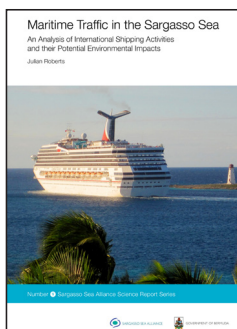
**7**

**Miller, M.J. and R. Hanel. 2011.** *The Sargasso Sea subtropical gyre: the spawning and larval development area of both freshwater and marine eels.* Sargasso Sea Alliance Science Report Series, No 7, 20 pp.



**8**

**Parson, L. and R. Edwards 2011.** *The geology of the Sargasso Sea Alliance Study Area, potential non-living marine resources and an overview of the current territorial claims and coastal states interests.* Sargasso Sea Alliance Science Report Series, No 8, 17 pp.



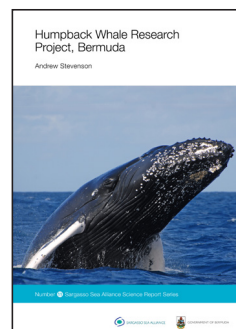
**9**

**Roberts, J. 2011.** *Maritime Traffic in the Sargasso Sea: An Analysis of International Shipping Activities and their Potential Environmental Impacts.* Sargasso Sea



**10**

**Siuda, A.N.S. 2011.** *Summary of Sea Education Association long-term Sargasso Sea surface net data.* Sargasso Sea Alliance Science Report Series, No 10, 18 pp.



**11**

**Stevenson, A. 2011.** *Humpback Whale Research Project, Bermuda.* Sargasso Sea Alliance Science Report Series, No 11, 11 pp.



**12**

**Sumaila, U. R., Vats, V., and W. Swartz. 2013.** *Values from the resources of the Sargasso Sea.* Sargasso Sea Alliance Science Report Series, No 12, 24 pp.



Since the initial meetings the partnership around the Sargasso Sea Alliance has expanded. Led by the Government of Bermuda, the Alliance now includes the following organisations.

<b>PARTNER</b>	<b>TYPE OF ORGANISATION</b>
<b>Department of Environmental Protection</b>	Government of Bermuda
<b>Department of Conservation Services</b>	Government of Bermuda
<b>Mission Blue / Sylvia Earle Alliance</b>	Non-Governmental Organisation
<b>International Union for the Conservation of Nature (IUCN) and its World Commission on Protected Areas</b>	Multi-lateral Conservation Organisation
<b>Marine Conservation Institute</b>	Non-Governmental Organisation
<b>Woods Hole Oceanographic Institution</b>	Academic
<b>Bermuda Institute for Ocean Sciences</b>	Academic
<b>Bermuda Underwater Exploration Institute</b>	Non-Governmental Organisation
<b>World Wildlife Fund International</b>	Non-Governmental Organisation
<b>Atlantic Conservation Partnership</b>	Non-Governmental Organisation