Quantifying Sargassum Boundaries on Eastern and Western Walls of the Gulf Stream Protruding Near Cape Hatteras into Sargasso Sea Bermuda/Azores

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***Abstract* - The Sargasso Sea has been a ocean life habitat for millions of years, yet accurate assessment of the boundary area and detection of these relatively small sea surface features using Landsat series and Moderate resolution Imaging Spectroradiometer (MODIS) instruments have been found to have difficulty or even impossible due to lack of spatial resolution, coverage, recurring observance, and algorithm limitations to identify pelagic species of *Sargassum*. *Sargassum* rafts tend to be elongated, curved in the upwind direction and warmer than the surrounding ocean surface. Long weed 'trails' extending upwind from the rafts are evidence of plants dropping out and being left behind. Satellite data utilizing a simple ocean color indexes such as the floating algae Index and Normalized Differential Vegetation Index (NDVI) have been established to detect floating algae in open environments using MODIS instruments. Floating Algae Index (FAI) has shown advantages over the traditional NDVI and Enhanced Vegetation Index (EVI) because FAI is less sensitive to changes in environmental and observing conditions (aerosol type and thickness, solar/viewing geometry, and sun glint) and can see through thin clouds. The baseline subtraction method provides a simple yet effective means for atmospheric correction. The algorithms assisted in identifying the boundary area of the Sargasso Sea and the path of this floating alga past Cape Hatteras into the Atlantic Ocean. Due to the fact that similar spectral bands are available on many existing and planned satellite sensors such as Landsat series observations satellites, the NDVI and FIA concept was extendable to establish a long-term record of these ecologically biological dependent ocean plants.**

I. INTRODUCTION

A. Sargasso Sea

The famous *Sargasso* Sea, located geographically in the legendary "Bermuda Triangle" or more accurately in the so called North Atlantic Subtropical Gyre with the western wall formed by the north and the north-eastern flowing powerful 'Gulf stream [1]. Columbus was the first see the floating weeds grew. 'Sarga' means grape in Portuguese and the sailors from Portugal compared the round air bladders of *Sargassum* to sea grapes [1]. Spanish historian Oviedo came up with first name Sargasso Sea in 1514 for the vast surface covered by these floating weeds. There was a controversy about where *Sargassum* weed came from. Some believed that it grew on the sea floor below and floated to the surface. German botanist Meyen in 1834 was the first to prove that *Sargassum* continues to grow as it floats in the sea. In 1852 Major James Rennell was the first to prove that *Sargassum* was brought in from the Gulf of Mexico by the Gulf Stream to the Sargasso Sea [1]. Over the years of human exploration, curiosity has sparked researchers to begin the documentation of crude first-hand accounts of a vast phenomenon.

3.5 million Years ago, after the formation of the Isthmus of Panama separating the Atlantic ocean from the pacific ocean, Sargasso evolved 40 million years ago just around the time of the last Basilosaurus ("king lizard") that lived. First fossil of b. cetoides was discovered in the United States and was initially perceived to be a reptile but was later found to be a marine animal. Two species occur in the *Sargassum* Sea are S.fluitans with large lanceolate leaves and S. natans with fine delicate leaf structure (see figure 1) [1].

Fig. 1. Windrow of Sargassum in the Gulf Stream

Sargassum includes benthic and pelagic species. S.natans and S. fluitans became highly brancehed with thalluses with numerous pneumatcyst that contain oxygen, nitrogen, and carbon dioxide to give buoyancy to the brownish algae (see image 2). Sea surface winds make *Sargassum* to aggregate and form lengthy windrows. As the gasses in the pneumatcyst lose their gases, *Sargassum* can reach 100 meters below the seas surface ore even the sea floor [1].

Fig. 2. Sargasso pneumatcyst and branched thalluses

The Sargasso Sea is a vast area that is located east of Cape Hatteras, North Carolina, north of the Caribbean islands, includes the Bermuda Triangle as well as the Tropic of Cancer, and extends Far East into the North Atlantic Ocean [1]. The sea is named for the *Sargassum*, a genus of macro algae, that blankets the surface, stretching for "miles and miles", prominent during late spring into early August [1]. Four currents act on the Sargasso Sea, manipulating its outward extension: the Gulf Stream on the West, the North Atlantic current on the North, the Canary current on the East, and the North Equatorial current on the South (see figure 3).

Fig. 3. Sargasso Sea Currents

Mid-ocean Sargasso Sea is between several currents. The Gulf Stream on the west, North Atlantic Drift to the north, Azores- Anticyclonic current to the Northeast, Southward-flowing Canary Current to the east and the wet-ward flowing North Equatorial Current to the south [1].

Unfortunately many organisms that inhabit *Sargassum* are under threat of harvesting due to its apparent source of as a natural resource in the no man's sea for using it as fertilizer and cattle feed. Fisheries Management Council established Maximum Sustainable Yield (MSY) and declared that *Sargassum* will be protected within the international waters. There are even plans to accelerate the growth rate to be able to exploit and maximize the allowed MSY for industries such as medical use to explore antibiotic compounds [1].

The illegal, unregulated, or unreported fishing by foreign fleets from other nations such as Spain and Russia at large seamounts could disrupt the entire food chain, which can for warn of an ecosystem collapse [1].

NOAA National Marine Fisheries Service (NMFS) has developed management tools to mitigate the influence of fishing practices on Vulnerable Marine Ecosystems (VMEs) such as deep-water coral habitats by designating these offshore areas as Federal Fisheries management zones (FFMZ), Essential Fish Habitats, Habitat Areas of Particular Concern (HAPC), National Monuments, and National Maine Sanctuaries (MPAs). The Magnuson-Steavens Fishery Conservation and Management Act stipulates that the regional fishery management council (SAFMC has the responsibility to identify, describe, conserve, enhance and minimize the adverse impact of fishing in the designated conservation area [1].

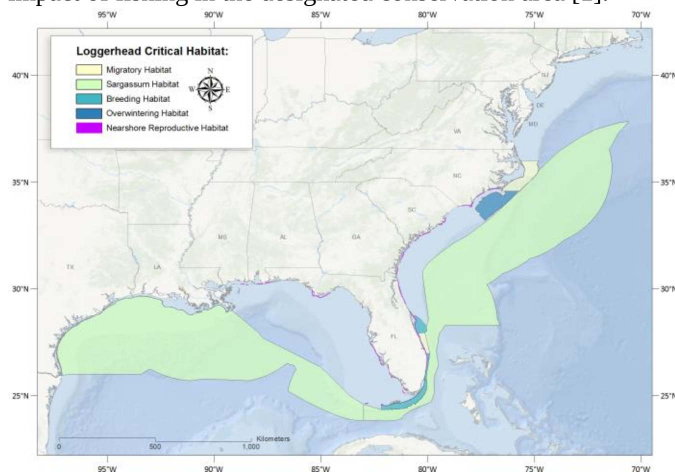

Fig. 4. AOI and path of Sargassum from GOM to Sargasso Sea

There is much difference on opinion for if protection areas are hampering the local economy. Many who fish these areas have the idea of "freedom to fish" which precludes any concept of disallowing fishing in any ocean zone, especially in the high seas [1].

With the ability to understand that every biome has an effect on another, the idea of protecting an ocean ecosystem calls for protecting not just the sea floor, but the surface ecosystem above. This idea is attracting support since the Atlantic Ocean is one huge ecological unit [1].

The importance of the Sargasso Sea is that it provides shelter and protection for marine animals such as fish and sea turtles. Migratory fish such as sword fish, bill fish, alfonsino, sharks and tuna use this corridor of seamounts in their transatlantic migration. The sea also serves as a breeding ground for both the European and American eels, in addition to, feeding grounds as well as nurseries for migrating fish [1]. On top of the *Sargassum* canopy a unique species of shrimp, crab and fish inhabit the top.

Considering the effect of strong winds and currents (i.e. hurricanes), these elements combined with the Sargasso Sea have led to significant changes in the ecosystem of the area [1]. To be specific, because of the sea serves as a pelagic habitat for phytoplankton, varying species of fish, and

On one hand, *Sargassum* has also had its influence on local environments and the economy. On the beaches the smell and the amount of work required to remove it(figure 5). [1]. Many of the commercial fishing fleet targets these seamounts. Pauly and myers and worms cautions that fishing at the top of the tropic pyramid could disrupt the ecosystems. [1]

Fig. 5. *Sargassum* washed ashore on the coast of GOM

Sargassum also plays a role in defining ocean productivity and (climate change) carbon flux [3] and is now considered a critical protected marine habitat and its harvesting in some ocean regions is regulated to protect the associated marine species at the south Atlantic Fishery Management Council, 2002 [4]. Some species of floating algae can also be used for human food and phycocolloid production. Conversely, excessive amount of floating algae in coastal oceans can cause significant adverse impact on local environments and economy. Dead algae washed onto the beaches must be physically removed in a prompt fashion, and represents an economic burden to local management in the Gulf of Mexico.

B. Deep Horizon Oil Spill

The Deepwater Horizon Oil Spill occurred on April 20, 2010 and greatly affected the Gulf of Mexico. The spill released 4.9 million gallons of crude oil and other unknown gases into the Gulf, which is about 7.5 full Olympic size swimming pools, making it the largest offshore oil spill in U.S. history. Because of the tragic explosions related to the spill, 11 people were killed [4]. The spill was capped on July 15, 2010 (87 days later) in the Gulf of Mexico.

Fig. 6. Deep Water Horizon Event in the GOM

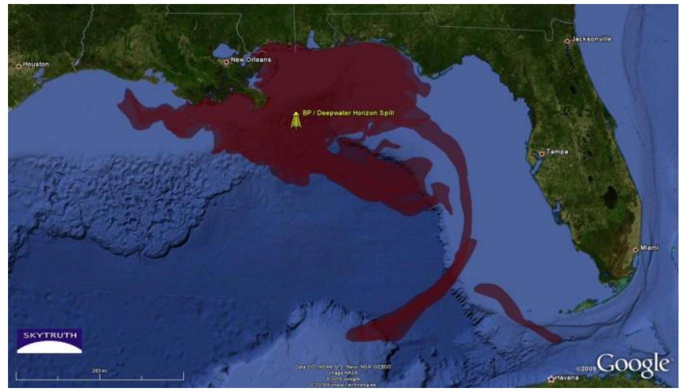

Fig. 7. Recorded amounts of Oil leaked into the GOM

C. Oils Effect on Sargassum

Over several decades, there have been a number of field and laboratory studies investigating the ecological impacts of oil spills in the aquatic environment. Of these studies only a handful focused on phytoplankton, and the results have varied substantially. Some studies observed an increase in phytoplankton growth while others found inhibition of photosynthesis [4]. This would have one believe that oil is a growth accelerator from those conclusions.

FLH is a proxy for phytoplankton biomass, and patches are higher than in any August between 2002 and 2009 suggest that 11,100 km of the Northeastern Gulf of Mexico (NEGOM). Water was significantly greener during August 2010 even when compared to July 2002 and March 2010 together [4].

Contrary the IXTOC-1 oil spill in the southern Gulf of Mexico during 1979 in which chemical dispersants add another complexity for no record of their short or long term affect.

Based on indirect evidence through satellite observations, and modeling, the lack of ground truth or field observations before and after the Deep-Horizon event were to scarce to definitely make a conclusion of oils affect in Pelagic organisms[4].

D. Satellites

The MODIS instrument is capable of detecting thin algae lines >4-5 m in width once they form long slicks [5 Hu]. By itself MODIS "provides near daily and synoptic coverage"due to its polar orbit around the earth; however, MODIS is not completely effective in detecting *Sargassum* alone. With pixels downscaled from 500 meters to 250 meters identifying lengthy slick like floating *Sargasum* from the Gulf of Mexico thru clouds on the late spring thru fall. "it cannot capture small *Sargassum* patches and slicks". Landsat ™ and ETM+ is used to compliment MODIS by providing coverage every 16 days at the same location, which is why both instruments are used for mapping [5]. Landsat has the ability to produce 30 meter resolution that can be down scaled with the panchromatic channel. Only difference from the MODIS and Landsat satellites is the frequency of reoccurring visits. Still cloud cover is more of a detrimental to MODIS at best 250 meter resolution.[6]

E. Identifying Sargassumin the Sea

Observations from ships like Dr. Greorty has done first hand have been impeded by the large and Variable area over which *Sargassm* is dispersed by ether Sea winds or bounding currents. Recently the ability to visualize the seasonal pattern in which *Sargassum* originates in the Gulf of Mexico on its path via the Gulf stream up past Cape Hatteras at the "Sargassum jet.," then end North East of the Bahamas in the coming February [3].

Free floating pelagic species of *Sargassum* have been recorded since the 1500's [1] only recently has been detected in satellite images. To be detected, *Sargassum* must be dense enough and cover enough area to be detected on the resolution of the satellites instrument.[5]

Rouse's 1973 concept of Normalized Difference Vegetation Index (NDVI) using Mulstispectuaral scanner data from Landsat was defined as

$$NDVI = (Rnir - Rred) / (Rnir + Rred)$$

Where Rnir and Rred are the reflectance in the near-infrared (NIR) and red bands, the difference between the NIR and the Rred bands serves as an index (0.0 – 1.0) of the vegetation density. The sum of NIR and Rred can partially remove the atmospheric effects from different measurements. Both NDVI values of water and floating algae and nearby waters are sensitive to variable environmental and quantitative analysis. Since the visual contrast between floating algae and nearby waters make it difficult to implement routine applications on many passes in one area over different spatial times [7].

Floating Algae Index (FIA) is introduced for mapping floating algae such as *Sargassum* in various aquatic environments (Coastal, Ocean, and Lakes) and can be applied to several existing and planned satellite instruments, such as MODIS and Landsat. Advantages of the FAI concept were exemplified in application over the yellow, East china [7].

RED-NIR-SWIR (short-wave infrared) wavelengths strongly absorb light on water sources in contrast to land surfaces. Water is opaque or "black" in SWIR wavelengths even in most turbid environments which provides the ability to correct for the atmospheric effects[7].

$$FAI = R_{rc,nir} - R'_{rc,nir}$$
$$R_{rc,nir} = R_{rc,nir} + (R_{rc,swir} - R_{rc,red}) * (\lambda_{nir} - \lambda_{red}) / (\lambda_{swir} - \lambda_{red})$$

This Vegetation index visualized the floating algae in the yellow sea which shows the main difference between NDVI and FIA is the amount of Atmospheric obstruction which could be an issue when dealing with high cloud days in the Atlantic coast.

The FAI concept can be applied to any satellite sensor that is equipped with three spectral bands in the red, NIR and Swir. This means we can calibrate any satellite with these bands to be derived. Data comparison in the previous studies showed that FAI is more advantageous than the traditional NDVI due to its less sensitivity to changes in the atmosphere [7].

This research was aimed at investigating regional trajectories and boundary area of the Sargasso Sea with Landsat series archive. The objectives were to (1) investigate the spectral temporal characteristics of *Sargassum* slick patches traveling the Gulf of Mexico past Cape Hatteras into the Sargasso Sea using NDVI and FIA index's. (2) Identify the values of NDVI and FIA when *Sargassum* is found. (3) Compare the amount of *Sargassum* thru the years 2006 to 2015 found and correlate the Deep Horizon oil spill to the comparison. The methods and application used were discussed and how to potential enhance the system to map the Boundary of the Sargasso Sea.

II. METHODOLOGY

A. Study area

The region selected to search for and evaluate *Sargassum* is the Gulf of Mexico, as well as, a large area off the east coast of the United States in what is called the Sargasso Sea. This region was selected due to the observed migration of the Sargasso population between the Gulf and Sargasso Sea between July and august. Due to Sargasso paths proximity to the 2010 deep-water horizon oil spill, which caused extensive amount of oil into the Northeastern Gulf of Mexico changes to its ecological surroundings. Within this region quantification on the boundary area of the "Sargasso jet" along the Gulf Stream is crucial to understanding the impact of the oil spill on *Sargassum*. The areas of interest are primarily between Cape Hatteras and the Bermuda since this is the last segment of its travels into the Atlantic. In order to begin efforts to quantify the *Sargassum* present the Band wavelengths must be configured for the Landsat band multispectral characteristics. In which the algorithm was established for Landsat FIA.

$$Landsat\ FIA = B4 - (B3 + (B6 - B3)*(B4 - B3)/(B6 - B3)$$

From April to August is when *Sargassum* is exchanged between the Gulf of Mexico and the *Sargasso* Sea via the Gulf Stream. The years encompassed by this timeline are centered around the Deep water Horizon oil spill that started on the 20th of April, 2010. The intention behind this was to determine the effect of this oil spill on the *Sargassum* population by quantifying it before and after the oil spill.

B. Data selection

A large quantity of the data collected was provided by the United States Geological Survey (USGS) and consists of imagery from the Landsat series 7 and 4-5 satellites. The Area Of Interest (AOI) within the July to August timeframe. Data was collected from 2015 through to June 2012. Data that was selected from the Landsat satellites needed to meet several requirements in order to be useful to the research. The most important of these is minimum amount of cloud coverage. Images that contain large amounts of cloud coverage or light cloud coverage loosely covering a vast area are incompatible for analysis due to the nature of NDVI image processing. Among other prerequisites for Landsat imagery to be applicable to the research is for the images to have been taken within the July - August timeframe, as well as, within the boundaries of the area of interest around the Sargasso Sea.

C. Image processing

Processing and examination of the image files that were downloaded and expanded was accomplished using the software called ENVI. Image processing was done by importing Bands 1-5 and 7 from the expanded Landsat files. These bands were then combined into a coherent data stack and reordered from descending to ascending band order. This data stack is then used to create an NDVI stack using bands 3 and 4.

Before creation of the Index's, the individual bands had to be corrected for radiance. To do that ENVI software application has a pre-processing application to change from reflectance to radiance. The bands that needed to be preprocessed were Rred, Rnir, and SWIR (Landsat bands 3, 4, and 6) which are used for NDVI and FIA respectively.

Then the Basic Band math was used to input the Index's algorithms and apply the bands to the applicable variable. With the bands configured and the indexes produced the new products were loaded into three separate display windows, a RGB for color and to distinguish between land cloud and open water and the other two for the Vegetation Index and Floating Algae Index. This NDVI filtered image is compared to a red, green and blue (RGB) render of the same area in order to help identify *Sargassum* and differentiate it from different environmental factors such as clouds and land.

D. Processing methods

NDVI proved to be the most successful method with which processing was accomplished within ENVI. It is likely this is due to the built in nature of the NDVI equation that is used to process the imagery.

$$NDVI = (Rnir - Rred)/(Rnir + Rred) \qquad (1)$$

In 'Equation 1' R_{nir} and R_{red} represent the reflectance in the near infrared (NIR) and red bands. In the case of Landsat series satellites these are the 3rd and 4th bands of the multispectral imagery. Due to it being a built in function of the ENVI software is was moderately simple to process the imagery using this function.

This implies the scale of the heatmap was reversed using this equation within ENVI.

$$FAI = R_{rc,nir} - R'_{rc,nir}$$
$$R_{rc,nir} = R_{rc,nir} + (R_{rc,swir} - R_{rc,red}) * (\lambda_{nir} - \lambda_{red}) / (\lambda_{swir} - \lambda_{red})$$

Within this equation the variables λ_{RED}, λ_{NIR}, and λ_{SWIR} refer to 645, 859, and 1240 nm wavelengths respectively. For context in landsat 4-5 this refers to the 3rd, 4th, and 6th bands.

E. Identifying Sargassum

Identifying *Sargassum* is accomplished by comparing the NDVI filtered image with a RGB version of the same image. the NDVI image is searched for bright wisps in the otherwise dark water. The area is then looked over in the RGB version to make sure the bright area is not a piece of land, a sandbar or clouds and other atmospheric obstructions.

F. Results

Identifying *Sargassum* is very rigorous feat to find Index values on an anomaly that is believed to be either a large plume of *Sargassum* by comparing the NDVI filtered image with a RGB version of the same image. The NDVI images was scanned for bright wisps in the otherwise dark water which the AOI would be concluded as *Sargassum* patch. The area is then looked over in the RGB version to make sure the bright area is not a piece of land, a sandbar or clouds and other atmospheric obstructions.

FAI was tested within the ENVI software; however, it did not provide the anticipated results of providing an Index. When tested using ENVI and the multispectral imagery provided by Landsat models the FAI processing even with Radiance corrected Spectral bands failed to remove cloud coverage from the images as well. It also returned results inconsistent with provided examples of what FAI was intended to return compared to the NDVI index of vegetation located on land. One such inconsistency was with inversion of the Gray Scale. Rather than the anticipated dark black water surfaces denoting the lower end of the Gray scale it returned results in which the water and land were both a light grey, clouds and coastlines contrasting this in a dark grey to black was observed.

Fig. 8. USGS AOI image preview of pass

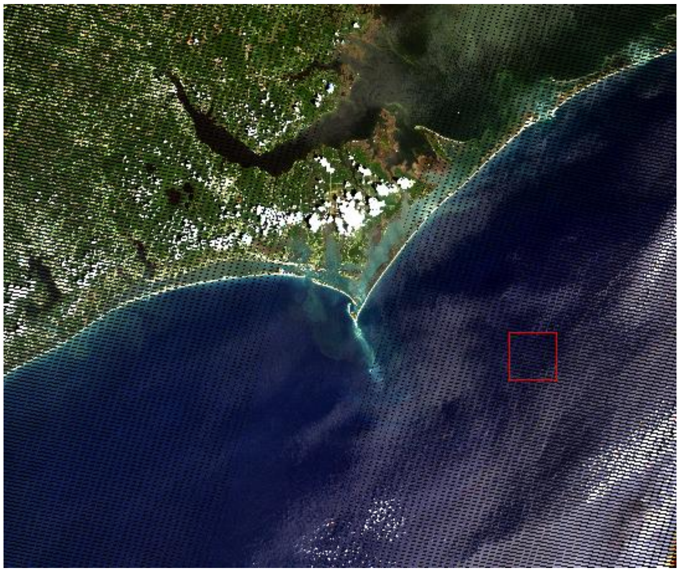

Fig. 9. RGB off the Coast of Cape Hatteras July 17th 2015

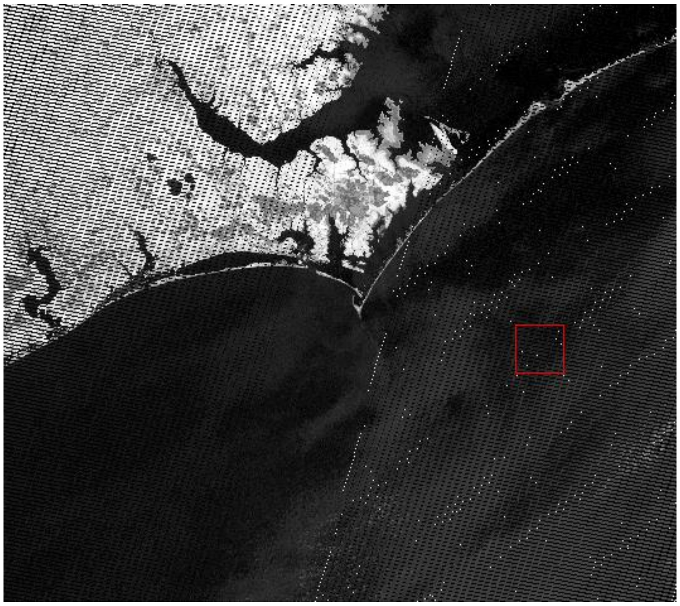

Fig. 10. NDVI off the Coast of Cape Hatteras July 17th 2015

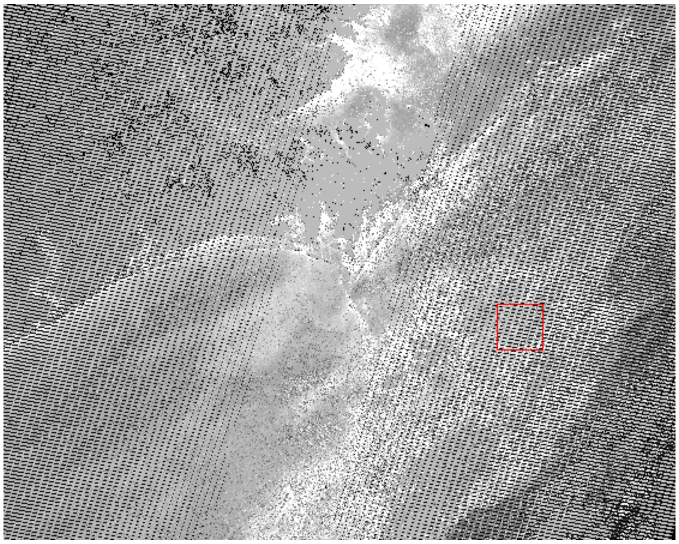

Fig. 11. FIA off the Coast of Cape Hatteras July 17th 2015

III. DISCUSSION

The Satellite covers only so much of the earth each day and at different times. To compare of the amount of *Sargassum* over the years in the same time frame in the same specific location is next to impossible using Landsat data. Further useful observations were reduced by frequent cloud, sun glint, and data gaps in the images. The amount of usable passes from USGS data library are next to the amount of two passes a month in the same area with cloud cover less than 30%. *Sargassum* that is evenly distributed may not be detected unless it is “aggregated” in concentrated windrows.

Since some of the AOI is directly off the coast some benthic vegetation and coral reefs in shallow water can cause false positive with a very low NDVI index. These can be ruled out because the shape of the anomaly is not elongated windrowed with a curl toward them wind direction.

With the lack of sufficient ground truth or in situ recordings of GPS locations of where larger patches of *Sargassum* are present floating it is difficult to classify these Sea Surface anomalies through the NDVI index because values for items which were believed not to be clouds or low clouds have negative index values just like the low clouds in the area. A targeted approach is missing which would help pin point times and locations to immediately target reported *Sargassum* in the area.

Previous studies suggest that *Sargassum* Amounts are regularly greater in the Gulf of Mexico than in the Atlantic [3] with 250 meter resolution. MODIS is capable of detecting thin algae lines. 4-5 meters in width once they form long slicks greater than 500 meters. However it cannot capture small *Sargassum* patches and slicks. Landsat series provides lower amount of coverage days for the same location but can be used to visualize and estimated 2 meter slick width.

A better system to monitor the Sargasso Sea in needed if a clearer understanding of how much *Sargassum* travels past the Cape Hatteras and the size of the boundary area out to the

Bermuda. A closer look is needed, one that is not above the clouds so that hidden *Sargassum* can be viewed.

IV. FUTURE WORK

In the future, the research can be continued in several ways. The continuation of image processing is an important task that could be continued in further research. Despite downloading an abundance of data from USGS only a fraction of this data was processed through ENVI. Some of the passes that were previously processed need to be corrected for radiance and the FIA algorithm need to be correctly transformed from MODIS bands to Landsat.

Imagery that is processed was only given a cursory look over before continuing on to process more of the passes to increase the size of the data pool. As a result, a large majority of the data remains unexamined, preventing the team from reaching an answer to our initial research question.

Expanding the search timeline by several years such as from 2005 through 2015 would determine if changes over time were in fact a result of the oil spill or just a consistent multi year cycle in which the oil spill may have only played a minor part in.

Adding data from TeraScan will allow us to fill the gaps in data where passes are incomplete, missing, or obstructed. Aqua and Terra, using MODIS instruments available through the TeraScan system to collect further NDVI data because TeraScan needs to have the FIA algorithm embedded to the post processing.

To develop a more accurate system to map the boundary of the *Sargassum*, a system of remote sensing needs to be deployed in the Gulf Stream, Cape Hatteras, and out in the Bermuda. The system needs to be able to identify *Sargassum* over a large area underneath the clouds to have un-obstructed view of the Sea surface.

Quad copter drones are the perfect equipment for this system; they operate on electricity and can be charged by solar panels. Drones should be mounted to a buoy systems spread over the area of Sargasso path from the Gulf to the Sargasso Sea. Have them rise just below the low clouds and identify *Sargassum* as satellites overhead fly past. This will help supplement the large coverage area with precise data from Drone nodes locate under the swath length of each pass of MODIS and Landsat.

Having the drones' survey only when a satellite passes will help to save energy but as well have one simultaneous survey at sun elevation above 60 degrees to limit sun glint and reflectance. Better resolution and more constant data that will help monitor the Sargasso Sea for the entire year. Many environmental challenges need to be address if Quad drones are left in salty waters.

There is more than one way to conduct remote sensing on the Sargasso Sea but the flaws are costing information and time. Flights over the Sargasso Sea are costly and only cover what it flies over that day. Atmospheric Satellites miss data due to clouds and other atmospheric variables which cause anomalies smaller than the pixel resolution to be left to monthly compositions to evaluate the quantity of *Sargassum* detected and not what the actual daily amount is. This can be done better.

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