The Factors of the *Sargassum* Migratory Loop System: Determining the Influential Fluctuating Dynamics Primarily Responsible for the Anomalous 2014, 2015 *Sargassum* Seasons

Los Factores del Sistema de Bucle *Sargassum* Migratorias: La Determinación de los Influyentes Flotante Dinámica de los Principales Responsables de la Anómalo 2014, 2015 Sargassum Estaciones

Les Facteurs du Système de Boucle *Sargassum* Migrateurs : Déterminer les Influents Flottant Dynamics principalement Responsable de la Anomalous 2014, 2015 *Sargassum* Saisons

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ABSTRACT

An analysis of the variables within the *Sargassum* Migratory Loop during the 2014 and 2015 *Sargassum* seasons was conducted. In 2014 the Gulf of Mexico experienced the largest landing of *Sargassum* in recorded history but practically no landings in 2015. Whereas in 2015 the nations in the Caribbean Sea experienced the largest landing that can be remembered for the area. Based on the observations using the Webster SEAS predictive model it appears that the factors responsible are a combination of the flooding of the Amazon River Basin, and the irregular fluctuation of the Azores High Pressure System that occurred during those two years. As a result of the abnormal number of cold fronts that passed over the south-western Gulf Coast in 2014 and the shifting of oceanic currents further south thus driving *Sargassum* into the area enriched by the Amazon flood waters. The cold fronts held the *Sargassum* offshore, in nutrient rich water, allowing extra time to grow before landing on the beaches in 2014. The southern shift in currents continued and thus held the *Sargassum* in that growth area and in the Caribbean Sea.

KEY WORDS: *Sargassum*, predictive model, population dynamics, migratory loop

INTRODUCTION

At this juncture they came upon what looked like huge pastures of grass on the sea; thinking they had come to drowned continents and they were lost, the men redoubled their complaints. And for those who had never seen such a thing doubtless it was a fearful sight. (Carillo 2000)

Sargassum natans and *Sargassum fluitans* have had a sordid past in the Gulf of Mexico, Caribbean, and Atlantic. We have evidence of Sargassum as far back as Columbus's voyage, the *Galveston Daily News* has records of Sargassum during the American Civil War, the Great Depression, and the Cold War. There have been tales of its monstrous abilities, recipes to eat it for dinner, and tales of the mysterious origin. For decades Sargassum has landed on beaches and coasts as it moved through the Caribbean, Atlantic and Gulf of Mexico. This route has been dubbed the Sargassum Migratory Loop System by the Sargassum Early Advisory System (SEAS) (Webster et. al. 2013). The increased understanding of the system has influenced the science, culture and responses surrounding the Sargassum. SEAS has forecasted the Sargassum inundations of the Gulf of Mexico and Caribbean at 97% accuracy for the last four years (Frazier et. al 2015). The SEAS has aided the coastal managers by allowing preparation as well as better asset allocation. Moreover, the SEAS system has led to a more complete understanding of the macroalgae life cycle and is naturally expanding into further research.

BACKGROUND

A stepwise approach is necessary to study the variables that make up the *Sargassum* Migratory Loop (Webster et. al 2013). The following is a shortened explanation of the system: for a more complete description the paper by Jeff Frazier et al. (2015) should be referenced. These sequence of events are also depicted in Figure 1 below:

i) The Loop system forms in the Sargasso Sea, a low nutrient area due to the prevailing currents in the North Atlantic.
ii) The Sargassum remains within the North Atlantic Gyre until the prevailing currents are disrupted by the clockwise rotating winds of the high pressure systems such as the Azores High Pressure System (Frazier et. al, 2015).
iii) Azores High Pressure System serves as the initial energy required to send "pulses" of Sargassum into motion within the *Sargassum* Migratory Loop (Webster et. al, 2013).
iv) The mats of *Sargassum* that are pushed into the Caribbean Current are driven by the combination of surface current and wind currents into the Gulf of Mexico or into the coasts along this trajectory (Frazier et. al, 2015).
v) The *Sargassum* is brought swiftly through the Yucatan Passage due to the following two reasons.
   - ⇒ At this divergence the *Sargassum* either is taken back into the Atlantic and the Sargasso Sea via the Gulf Stream.
   - ⇒ It is driven north-west into the Gulf of Mexico.

vi) If the *Sargassum* remains in the Gulf of Mexico, it is transported by the thermohaline-driven gyres and atmospheric forces.

vii) It will remain in the local currents and under atmospheric influence until it either makes landing along the coastlines bordering the Gulf of Mexico or is swept back into the Gulf Stream.

viii) This *Sargassum* Migratory Loop serves to reintroduce *Sargassum* back into the Sargasso Sea thus perpetuating its existence.

ANALYSIS

The *Sargassum* Migratory Loop System is a system subject to occasional, perhaps even periodical variations in its area of influence. Such variations we theorize are the causative agents for the 2014 and 2015 *Sargassum* season phenomena. The 2014 *Sargassum* season experienced by the Gulf of Mexico is thought to be the largest *Sargassum* inundation in history. The 2015 *Sargassum* season in the Caribbean is considered by many to be the most *Sargassum* landings that the area has ever experienced. To determine why these events have occurred, the specific driving forces within the *Sargassum* Migratory Loop were analyzed.

The North Atlantic Oscillation is the influencing factor that controls the high pressure systems that trigger and drive *Sargassum*s movement. The annual flooding of the Amazon and Orinoco River Basins flush nutrients into the Caribbean Sea that induce the growth rates achieved by the *Sargassum*. The thermohaline driven oceanic currents have shifts that can be observed over these two seasons. These three variables are responsible for the atypical landings occurring in the Caribbean Sea for the 2015 *Sargassum* season. Atmospheric cold fronts played a large part in the landings in the Gulf Coast in 2014. There were holding off the potential landings and allowing the *Sargassum* to be further exposed to the nutrient bath of the Gulf of Mexico. This suspension made the imminent landing of the mats the colossal event that it was.

Data from 201 - 2015 was collected from Weather Underground and Landsat imagery as described by Webster and Linton (2013). In 2014, there were 26 cold fronts that came through Houston before May 1st. It is hypothesized that these cold fronts pushed the *Sargassum* into the Southern Gulf of Mexico. It was this occurrence that kept the *Sargassum* mats in the nutrient rich Bay of

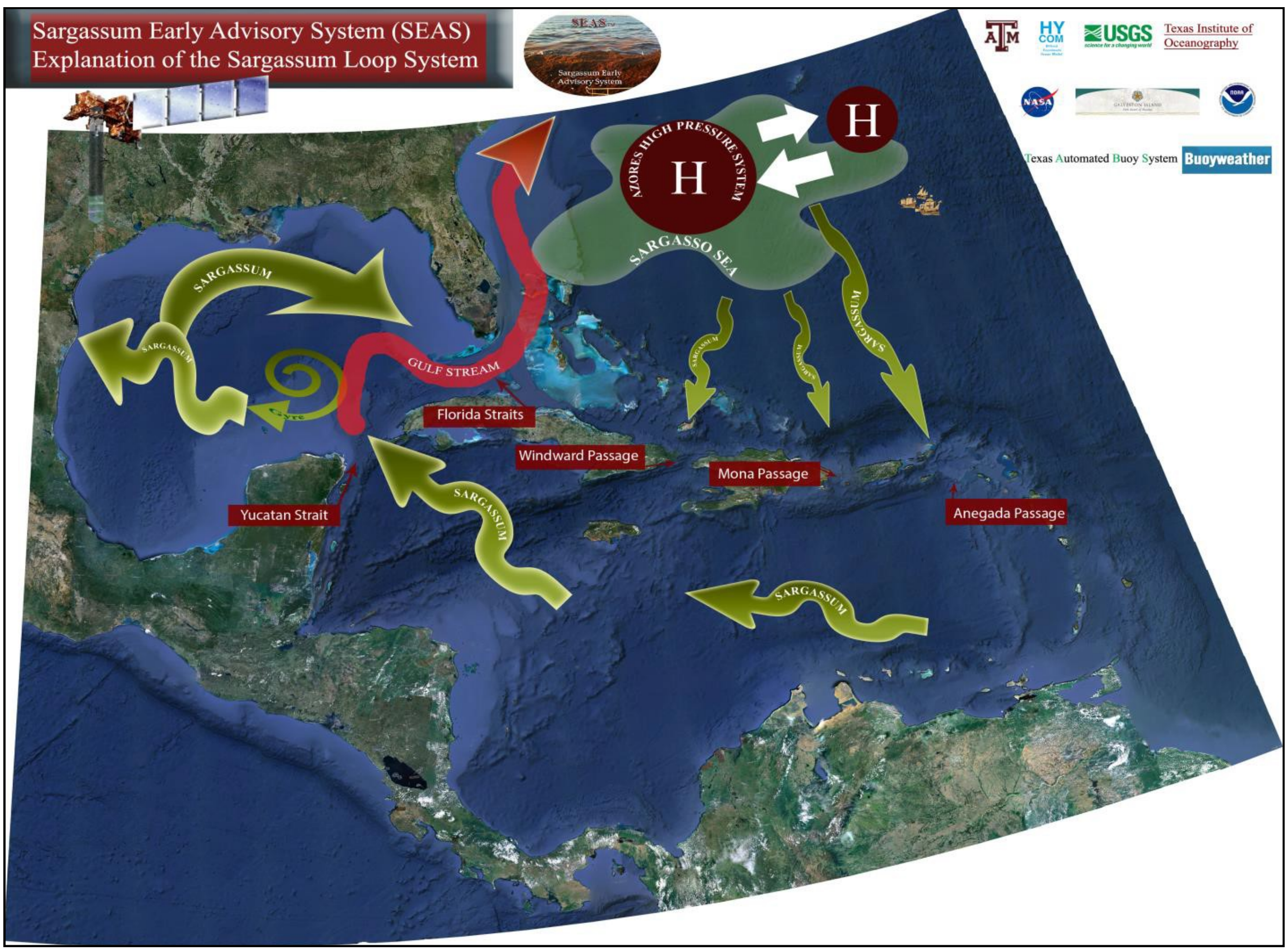

Figure 1. Sargassum Loop System – This graphic represents the Sargassum Migratory Loop System, the route and factors at play.

Campeche. The vegetative growth of the algae make well-mixed nutrient- rich waters the optimal conditions for maximum *Sargassum* growth (Lapointe 1993). The Bay of Campeche's environment meets these conditions and allowed the *Sargassum* to experience a significant bloom in growth before it made landfall.

The *Sargassum* season of 2015 has been a lighter than average year for the Gulf Coast, appearing to be an outlier on the opposite end of the spectrum from the 2014 season. Landings have occurred in the Caribbean Islands, the Yucatan Peninsula, and the Atlantic Coast of Florida. The lack of *Sargassum* landings of the Gulf Coast can be attributed to the other deciding factors in the *Sargassum* Loop. The *Sargassum* that has made it into the Gulf of Mexico has been pushed out into the Atlantic Ocean.

The 2009 - 2014 *Sargassum* seasons can be compared to the cold fronts utilizing a means of quantifying the *Sargassum* landings; a data bank of newspaper complaints lodged with cities that were major hubs along the Texas coastline. This serves as a proxy variable for the excessive *Sargassum* wracks that were making landing at the time. Until recently, accurate reports of the true volume of *Sargassum* landing were not recorded. This proxy variable will be used in the comparison.

It is hard to extrapolate a scientifically sound conclusion from the data in Table 1. Intuitively the concept of being held in an area of high nutrients for an extended period of time causing exceptional growth makes sense. Taking into account previous work on *Sargassum*'s life cycle, some preliminary conclusions can be assumed. Gower and King (2012) pointed to the Bay of Campeche as a location fit for rapid vegetative growth. Lapointe's work also hinges on the availability of nitrate, phosphate, ammonia, and Iron (Lapointe 1993). With the collimation of these works, there is strong evidence suggesting that time spent in neritic waters, such as the Bay of Campeche, will result in a significant increase in biomass. Exploring this correlation will become more feasible as systems of collecting *Sargassum* volumetric data are developed. Moving forward, the need for continued study in this area is clear, and in depth research into the unexplored minutia of *Sargassum*'s life cycle is highly encouraged.

The NAO was thought to be the "missing piece" in explaining *Sargassum*'s migratory loop. (Webster et. al, 2013) The positive mode indicated by the red portions of Figure 2. represent the periods of time when the Azores high pressure system is acting upon the Sargasso Seas (Figure 3.) As stated in the stepwise analysis of the *Sargassum* Migratory Loop System, despite *Sargassum*'s lack of freeboard the initiation of the *Sargassum* migration is most closely correlated with the Azores High Pressure System. The high pressure climatic phenomenon generates southbound winds over the Sargasso Sea, these anticyclonic winds cause a clear migration of the *Sargassum* into the lower latitudes (Frazier et. al. 2015).

Table 1. Comparison of Complaints of Sargassum Landings vs Cold Fronts - The data were collected from Weather Underground and the Galveston Daily Article Collections at the Galveston Rosenberg Library

Sargassum Season	2010	2011	2012	2013	2014
# Complaints Lodged	0	4	4	1	30
# Cold Fronts	22	18	20	20	26

These data were collected from Weather Underground and the Galveston Daily Article Collections at the Galveston Rosenberg Library. It is a partial picture that indicates that when Sargassum is in the system and suspended in the Gulf of Mexico cold fronts can increase the time spent in neritic waters increasing the biomass that can make landing.

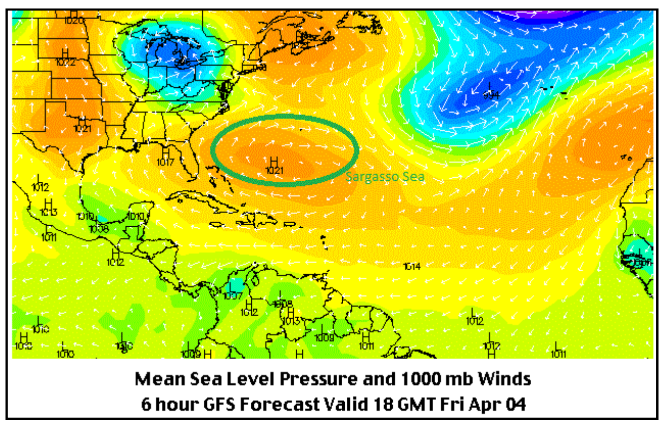

Figure 3. Azores High Pressure System Graphic **–** The Azores High Pressure System often manifests anticyclonic winds overtop the Sargasso Sea. These winds force mats of Sargassum via Langmuir cells (Xu, 1997) into lower latitudes where they are affected by the well-defined Caribbean currents.

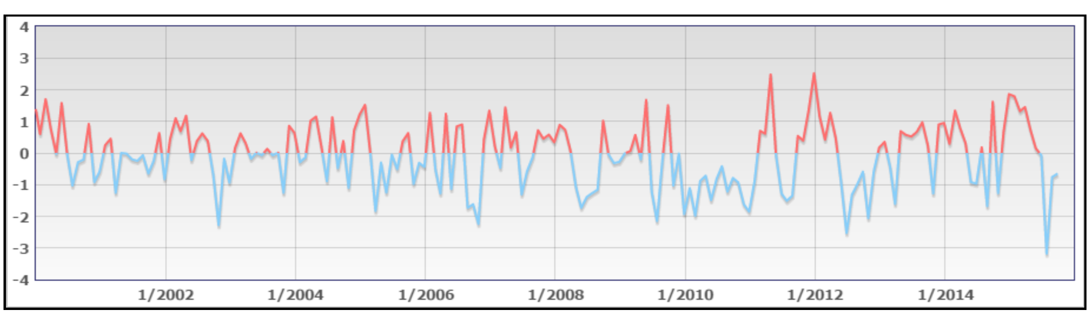

Figure 2. North Atlantic Oscillation (NAO) – This line graph represents the climatic fluctuations of the NAO's atmospheric pressure between the Icelandic low and Azores high.

It is this driving force and initial energy that also has such a pivotal part in determining the *Sargassum*'s trajectory . Once in the Caribbean the anticyclonic winds of the Azores High assist the Caribbean current and loop current in carrying the *Sargassum* through the Yucatan Strait and into the Gulf of Mexico. In 2015 this process was halted when the anticyclonic winds of the Azores High shifted more west than previously observed. (Figure 4) This shift is also visible in the surface currents (Figure 5). This change in the atmospheric conditions is partly responsible for the landings that have been experienced this year. Its effects have been seen in the overall patterns of movement in the *Sargassum*.

The Summer of 2014 was a historic and outlying landing of *Sargassum* with Galveston Island receiving a minimum 49,445.83 tons of *Sargassum*. The amount of *Sargassum* that lands each season is determined by an accumulation of variables. These variables are defined as the *Sargassum* Migratory Loop System including the Azores high pressure system, North Atlantic Gyre, Langmuir Circulation, Gulf Stream, and available nutrients (Webster and Linton 2013). One variable that must be further investigated is the interplay between the weather patterns within the Gulf of Mexico and *Sargassum*'s seasonal arrival. Weather patterns that are thought to hold special significance are the cold fronts that move through the Gulf Coast. For the purpose of this research, a cold front will be defined as a weather pattern that shifts from southerly winds to northerly based winds. This pushes cold air masses toward the Gulf of Mexico and the resulting winds drive the *Sargassum* that is circulating in gyres into the Southern Region of the Gulf. This area, known as the Bay of Campeche, has been attributed to incredible capacity for *Sargassum* growth in past research (Gower and King 2012). This research seeks to examine whether or not the amounts of *Sargassum* that makes landing each season are affected by the cold fronts that pass through Texas from December 1st through April 30th.

It is agreed upon that the Sargasso Sea lacks the necessary nutrients to allow for *Sargassum*'s continued existence and growth. The *Sargassum* migration is the "unique phenomenon" that has facilitated the adaptation and growth of *Sargassum*. Every season it creates a significant amount of "new" neritic *Sargassum* which can be transported from the neritic shelf waters of the U.S. Gulf States into the Gulf Stream and thereby the Central and

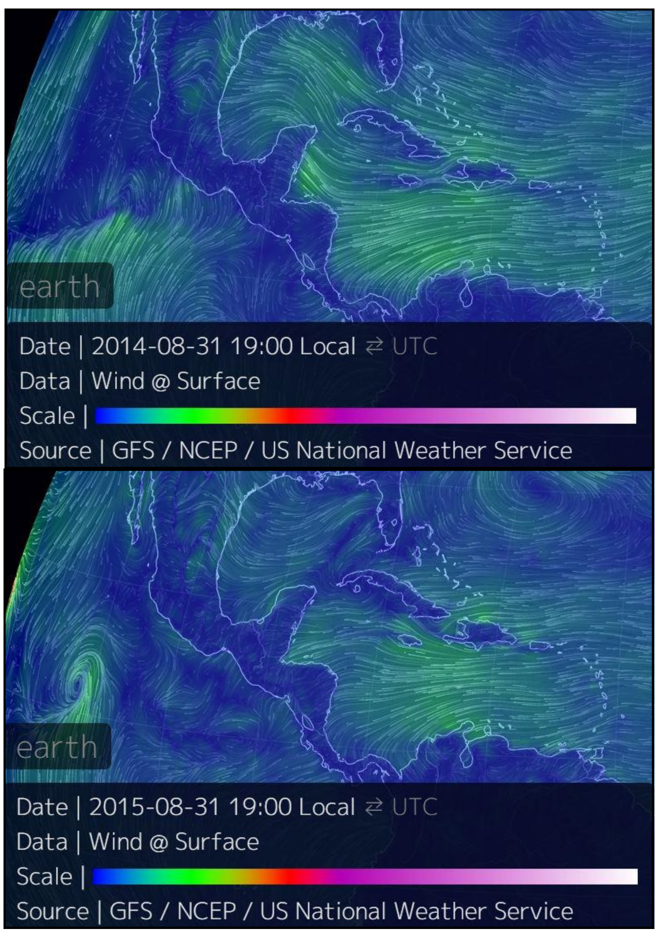

Figure 4. Null School Earth Air Surface Wind – This model, made possible by Cameron Beccario is useful in observation and forecasting the interplay between the driving variables of the Sargassum Migratory Loop System.

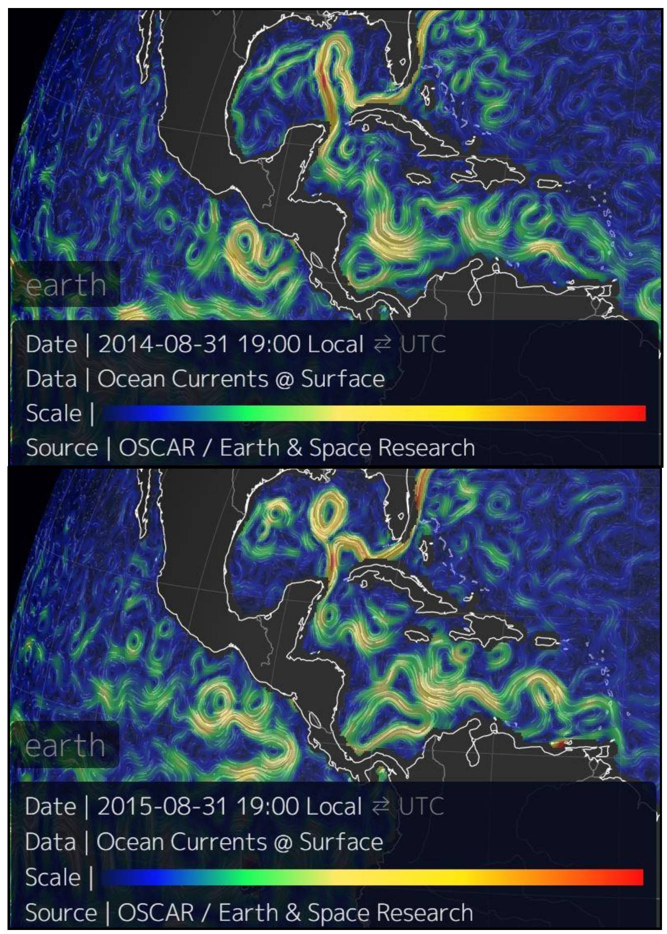

Figure 5. Null School Earth Oceanic Currents 08/31/2015 – The Null School tool shows the Caribbean and Loop Current Westerly shift leading to the direct impact of the Yucatan Peninsula.

Northern Sargasso Sea. An important aspect of the *Sargassum* Migratory System is the nutrients available to the *Sargassum*. The factors that input the nutrients into the coastal water have been noted before as continental runoff via rivers, submarine groundwater discharge, shelf-break upwelling, benthic sediment regeneration, and atmospheric inputs. (Lapointe 1994)

The growth of the *Sargassum* is affected by nutrient and temperature conditions along the migration. Nutrient availability and temperature can affect the quantity of *Sargassum* in the *Sargassum* Migratory Loop System (Frazier et. al. 2015). Caribbean Basin Rivers of South America are pivotal in this nutrient input. This has been a large factor in many atypical *Sargassum* landing events including the 2014 - 2015 *Sargassum* phenomena. Of the rivers that discharge into the Caribbean, the Amazon and Orinoco Rivers contribute the most discharge with 220,000 and 38,000 cubic meters per second, respectively. The Amazon's discharge carries with it 220 mg/L of sediment while the Orinoco carries 80 mg/L; these two rivers experience flooding seasonally (Lewis et. al, 1995). The rainy season from April to October brings approximately 2000 mm of rain to the river basins. The Orinoco discharges 2300 m^3/s during its wet season and the Amazon expels an estimated 1.3 million tons of sediment daily (Encyclopedia Britannica Inc. 2015). With this massive outflow of nutrients, these rivers play a very large role in any sort of biological growth in the Caribbean.

The nutrient discharge in this area is taken up partially by the *Sargassum* moving into the Caribbean via the Greater and Lesser Antilles Caribbean passages. The *Sargassum* driven by the anticyclonic winds passes through the straits between Caribbean Islands. Table 2 shows the specific counts of satellite images with *Sargassum* identified. Four Caribbean passages are consistently analyzed in order to provide local and long-range forecasts. The Mona Passage had the most *Sargassum* identified, the Eastern Passage (included in the SEAS Barbados advisory) and Windward Passage followed closely behind. The *Sargassum* season of 2015 brought about the extreme inundation of the Caribbean Islands. The atmospheric and oceanic currents shifted during this period as shown in Figure 4. This shift caused an increase in the amount of *Sargassum* that passed through the Anegada, and Barbados Passages. Anegada increased form 20% of images containing *Sargassum* to 63%, while Barbados had 84% percent of images contain *Sargassum* this year. Mona and Windward had a 25% and 50% decrease, respectively, between the 2014 and 2015 *Sargassum* seasons. This decrease of *Sargassum* in the more northern passages coupled with the changes in the loop system's track could be why the Gulf has not seen the *Sargassum* inundations that the Caribbean has.

Table 2. Caribbean Passages and the Number of Images with Sargassum Identified from 1984 – 2015, 677 Satellite images were analyzed between the years of 1984 - 2015, as part of the Sargassum Early Advisory System.

Passage	Sar. ID	Percent
Anegada	30	15%
Barbados	62	40%
Mona	56	47%
Winward	48	39%

677 Satellite images were analyzed between the years of '84-'15

The most obvious trends in the data in Figure 6 are the events in 2014 and 2015. Statistical correlations must be run in order to mathematically discern the variables that have the highest association with *Sargassum* Landings. Figure 6 depicts the results of analyzing 677 Landsat 7 and 8 images. Webster hypothesized that the *Sargassum* cycles that occur on the Texas' Gulf Coast are linked with the Atlantic Multidecadal Oscillation temperature variations. From the appearance of *Sargassum* entering the system via the Caribbean Passages smaller patterns emerge and suggest that other variables are influencing different cycles and fluctuations based on their location and strength. This is only theoretical but will be investigated using statistic software and multiple variables to run mathematical correlations. The in-depth analysis of the variables related to the *Sargassum* Migratory Loop System is now being conducted by SEAS. The mathematical correlations found via this study will lead to a definitive understanding of the migratory loop systems drivers as they related to landings. For the dependent variable SEAS is using the historical proxy-variable of the *Galveston Daily News* and the indexed records of complaints regarding *Sargassum* on the beach (Table 3).

In a preliminary attempt to access a correlation between the *Sargassum* Migratory Loop, the NAO Index and the recorded *Sargassum* complaints were compared. Some correlation can be derived at the 10% error level. This implies acceptance of a 10% error margin: This is acceptable seeing that the proxy variable is loose and based on situations that cannot be calculated. The number of complaints submitted to the *Galveston Daily News* is dependent upon personal thresholds, contemporary attitude toward Sargassum, and the specific area where landings have occurred. While we acknowledge these flaws, it has still been invaluable in developing a *Sargassum* cycle, and has been useful in developing mathematical correlations between the drivers of the cycle (Webster et. al. 2015). SEAS will continue to seek a more concrete proxy for areas outside of Texas and is interested in collecting more data for this purpose.

CONCLUSION

The *Sargassum* Early Advisory System has served to create a means of providing forewarnings about *Sargassum* inundations that overwhelm local systems. This coverage has been steadily extending outward since the formation of SEAS to include new areas of the Caribbean and Gulf of Mexico. Beyond the seasonal projections of *Sargassum*, SEAS has also sought to understand and share the intricate facets of the Sargassum Migratory Loop System. The shifting of the NAO's high pressure system, the subsequent deviation of the Caribbean currents, and the flood influenced introduction of nutrients have led to the swinging extremes of the 2014–2015 *Sargassum* Seasons. On November 15 2015 Sargassum was identified in

Landsat 7 and Landsat 8 imagery in the Southern and Central Texas Coast. It is bizarre to see *Sargassum* coming this close to the coast this late in the season. This is a result of the late *Sargassum* flow into and through the Caribbean that has been experienced firsthand by the countries there. SEAS will continue this study; a mathematical correlation and if possible a means of calculating the likelihood of *Sargassum* landings must be established. A further understanding of the growth rate of *Sargassum* is being pursued; if this is understood then the forecasts of *Sargassum* could include an estimate of the biomass to land along the coasts. Further proxy variables and data records of *Sargassum* Landings and *Sargassum* Migratory Loop Factors need to be identified and integrated into the *Sargassum* Early Advisory System.

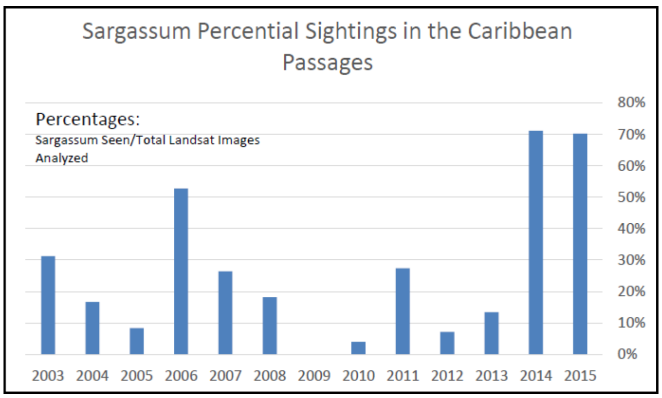

Figure 6. Sargassum Percentile Sightings – 677 images were processed in order to attain the average percent of images when Sargassum sightings and total images processed were compared.

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Table 3. Poisson regression of Lodged Sargassum Complaints and North Atlantic Oscillation - This regression was run using the *Galveston Daily News* record of Sargassum Complaints and the North Atlantic Oscillation (NAO) Index. This index outlines the difference between the Subtropical (Azores) High and the Subpolar Low.

Poisson regression				Number of obs	=	750
				LR chi2(12)	=	217.80
				Prob > chi2	=	0.0000
Log likelihood = -353.62558				Pseudo R2	=	0.2354

compiants	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
oscilliation	.1538291	.0872974	1.76	0.078	-.0172707	.3249288
month						
2	14.08277	1139.035	0.01	0.990	-2218.384	2246.55
3	15.18068	1139.034	0.01	0.989	-2217.286	2247.647
4	16.63827	1139.034	0.01	0.988	-2215.828	2249.105
5	17.35231	1139.034	0.02	0.988	-2215.114	2249.819
6	18.09328	1139.034	0.02	0.987	-2214.373	2250.56
7	17.20085	1139.034	0.02	0.988	-2215.265	2249.667
8	15.90635	1139.034	0.01	0.989	-2216.56	2248.373
9	15.48409	1139.034	0.01	0.989	-2216.982	2247.951
10	15.22097	1139.034	0.01	0.989	-2217.246	2247.687
11	.0034668	1617.089	0.00	1.000	-3169.433	3169.44
12	.0094459	1616.303	0.00	1.000	-3167.887	3167.906
_cons	-18.23885	1139.034	-0.02	0.987	-2250.705	2214.227