AN ANALYSIS OF THE FACTORS THAT INFLUENCE THE SARGASSUM

MIGRATORY LOOP

A Thesis

by

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ABSTRACT

Certain variables suspected to influence the behavior of the Sargassum Migratory Loop System (SMLS) were examined using Robert Webster's *Development and Implementation of Sargassum Early Advisory System (SEAS)*. This analysis of the SMLS during the 2014 and 2015 Sargassum seasons was conducted as a case study to assign quantifiable weights to the behavioral characteristics of the SMLS. In 2014, Galveston, Texas experienced the largest landing of Sargassum in recorded history; in stark contrast it received practically no landings in 2015. The nations in the Caribbean Sea experienced an exceptionally large influx of Sargassum during the 2015 season. Based on the observations, it was theorized that among the causative factors for Texas were twenty-six cold fronts that occurred on the Upper Texas Coast in 2014, which held the Sargassum offshore in the nutrient-rich waters of the Gulf of Mexico. This period of suspension afforded the biomass an extended period of growth before landing. Similarly, in 2015 sustained southward fluctuations of the North Atlantic high pressure system forced Sargassum into contact with the nutrient-rich waters of the Orinoco and Amazon flood waters, thus producing enhanced growth of the Sargassum and its containment in the Caribbean Sea. Both of these instances involved specific atmospheric drivers influencing the flow of the Sargassum as it made its way through the SMLS. The areas the Sargassum was suspended in were high in nutrients due to the flushing of runoff from nearby shores. The annual flooding of the Amazon and Orinoco create a plume of neritic water that has been shown to cause increased growth as the Sargassum pass through that portion of the SMLS. The Gulf of Mexico, particularly the area known as the Bay of Campeche is so nutrient-rich that it has been thought to be the source of Sargassum.

For this case study the relevant factors include a combination of atmospheric forces known as teleconnection patterns, oceanic currents, and nutrient availability. A greater understanding of the relationship between these variables in the SMLS is a natural and necessary step. The extreme differences in the Sargassum landings between the 2014 and 2015 Sargassum seasons point to which variables drive the Sargassum's movement to the greatest extent. Analyzing the relationship has increased forecasting accuracy and helps explain why particular seasons are seemingly incongruent with the current understanding of the causes.

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1. 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. Evidence of Sargassum exists as far back as Columbus's voyage; the Galveston Daily News has been in continual publication since 1842 thus creating a long and uninterrupted data set. There have been tales published of Sargassum's sinister nature, recipes on how to eat it for dinner, and tales of the mysterious origin. For decades Sargassum has landed on coasts as it moved through the Atlantic, Caribbean 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. The SEAS has forecasted the Sargassum landings 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 resource allocation. Moreover, the SEAS has led to a more complete understanding of the macroalgae's life cycle and the system thus derived naturally leading into further research.

2. BACKGROUND

A stepwise approach is necessary to best explain the variables that are currently attributed to the Sargassum Migratory Loop (Webster et. al, 2013). Below is a brief explanation of the individual stages of the Sargassum Migratory Loop system; for a more complete description see Frazier et al (2015). These sequences of events are also depicted in Figure 1 below.

1. The Loop system forms in the Sargasso Sea, a low nutrient area caused by the prevailing currents in the North Atlantic.

2. 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).

3. These high pressure systems serve as the initial energy pushing "pulses" of Sargassum from the Sargasso Sea into the Sargassum Migratory Loop (Webster et. al, 2013).

4. The mats of Sargassum are pushed into the Caribbean Current and are driven by the combination of surface currents and wind currents into the Gulf of Mexico or into the coasts along this trajectory (Frazier et. al, 2015).

5. The Sargassum is brought swiftly through the Yucatan Passage for the following two reasons.

    a. At this divergence the Sargassum either is taken back into the Atlantic and the Sargasso Sea via the Gulf Stream, or

    b. it is driven north-west into the Gulf of Mexico.

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

7. 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.

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

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

3. METHODOLOGY

The Sargassum Migratory Loop System is a system subject to occasional, perhaps even periodical variations in its primary variables of influence. Herein it is hypothesized that such variations 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 Sargassum Season of 2015 was 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. In 2014 landings 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 factors in the Sargassum Loop. The Sargassum that has made it into the Gulf of Mexico has been pushed out into the Atlantic Ocean by the strong loop current and low resistance by atmospheric winds.

4. THEORETICAL FRAMEWORK

It has been hypothesized that the Sargassum cycles that occur on the Texas gulf coast are linked with the Atlantic Multidecadal Oscillation temperature variations (Webster, 2013). 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. Some of the main factors considered in this study are discussed as follow.

Atmospheric Forces

Due to Sargassum resting approximately within the first meter of the water column, the two main forces that affect it are ocean currents and atmospheric drivers. The effects of the ocean currents are more apparent because they are well mapped and tend to be static in location, direction, and intensity. With no freeboard, meaning the majority of Sargassum's physical structure rests below the water line, one would expect Sargassum to have little response to atmospheric conditions; however, the initiation of Sargassum migration is thought to be most closely correlated with the Azores High Pressure System (Frazier, 2013).

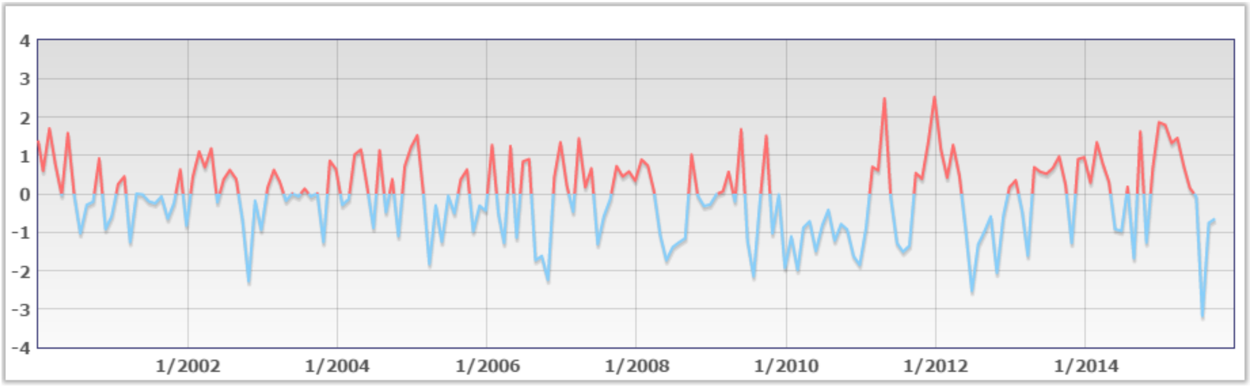

Figure 2. North Atlantic Oscillation (NAO) Index – This line graph represents the climatic fluctuations of the NAO's atmospheric pressure between the Icelandic low and Azores high.

The NAO was considered to be the "missing piece" in explaining Sargassum's migratory loop (Webster et. al, 2013). The positive mode indicated by the red line in Figure 2 represents the periods of time when the North Atlantic Oscillation is acting upon the Sargasso Sea. The extent of the influence of the NAO can be seen in the positive mode example in Figure 3. As underlined 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 related with the Azores High Pressure System. The high pressure climatic phenomenon generates southbound winds over the Sargasso Sea, which are referred to as "anticyclonic winds". These anticyclonic winds may cause a migration of the Sargassum into the lower latitudes (Frazier et. al, 2015).

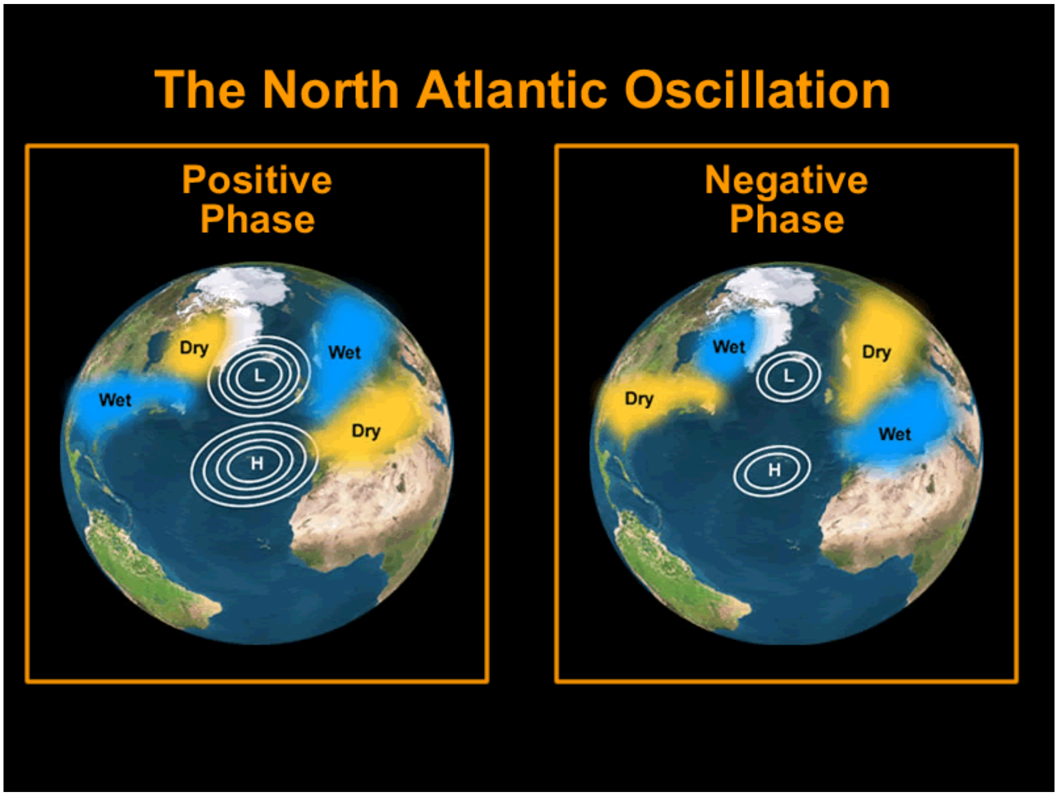

Figure 3. North Atlantic Oscillation – The interactions between the Azores High Pressure System and Icelandic Low Pressure System determine the direction and force of the anticyclonic winds that influence the Sargasso Sea. Reprinted from UCAR Windows to the Universe.

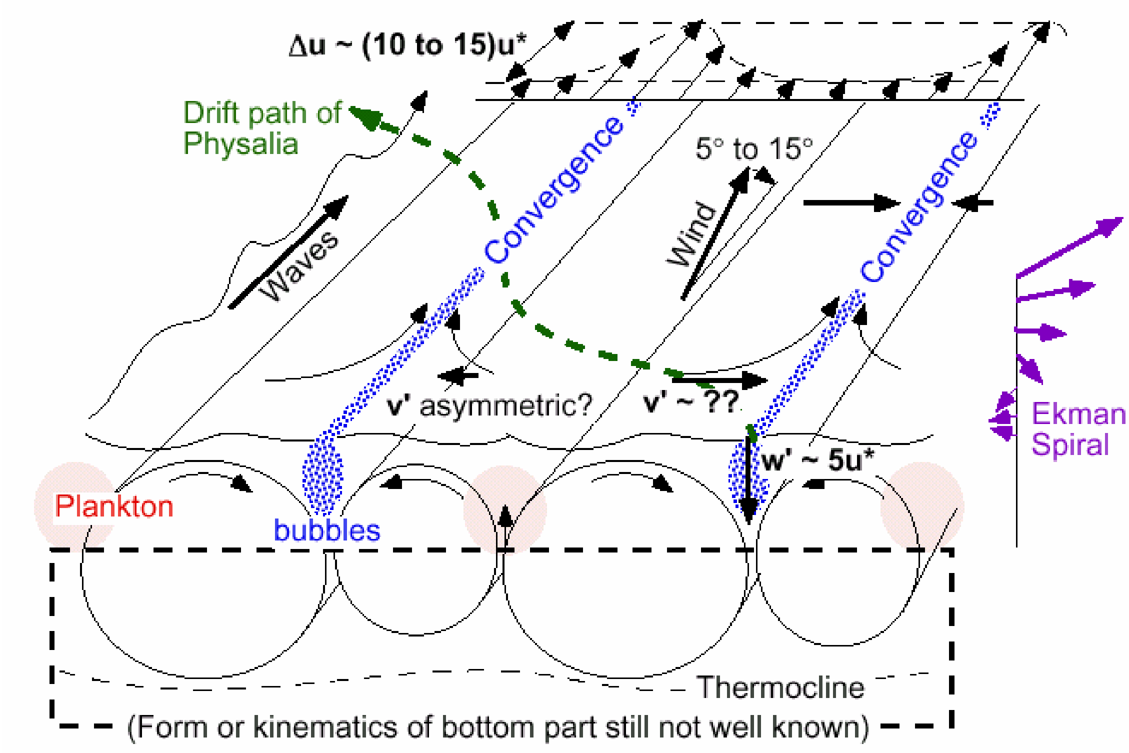

Figure 4. A Sketch of Langmuir Circulation - Reprinted from Chubarenko O.B. 2006

Winds force mats of Sargassum via Langmuir cells of alternating convergence and divergence which transport flotsam and jetsam approximately parallel to the direction of the wind. This pushes the Sargassum into lower latitudes where they are affected by the well-defined Caribbean currents (Xu, 1997). Once in the Caribbean the anticyclonic winds of the Azores High assist the Caribbean current and Gulf of Mexico 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; these patterns are depicted in Figure 5. Changes in the atmospheric conditions are 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.

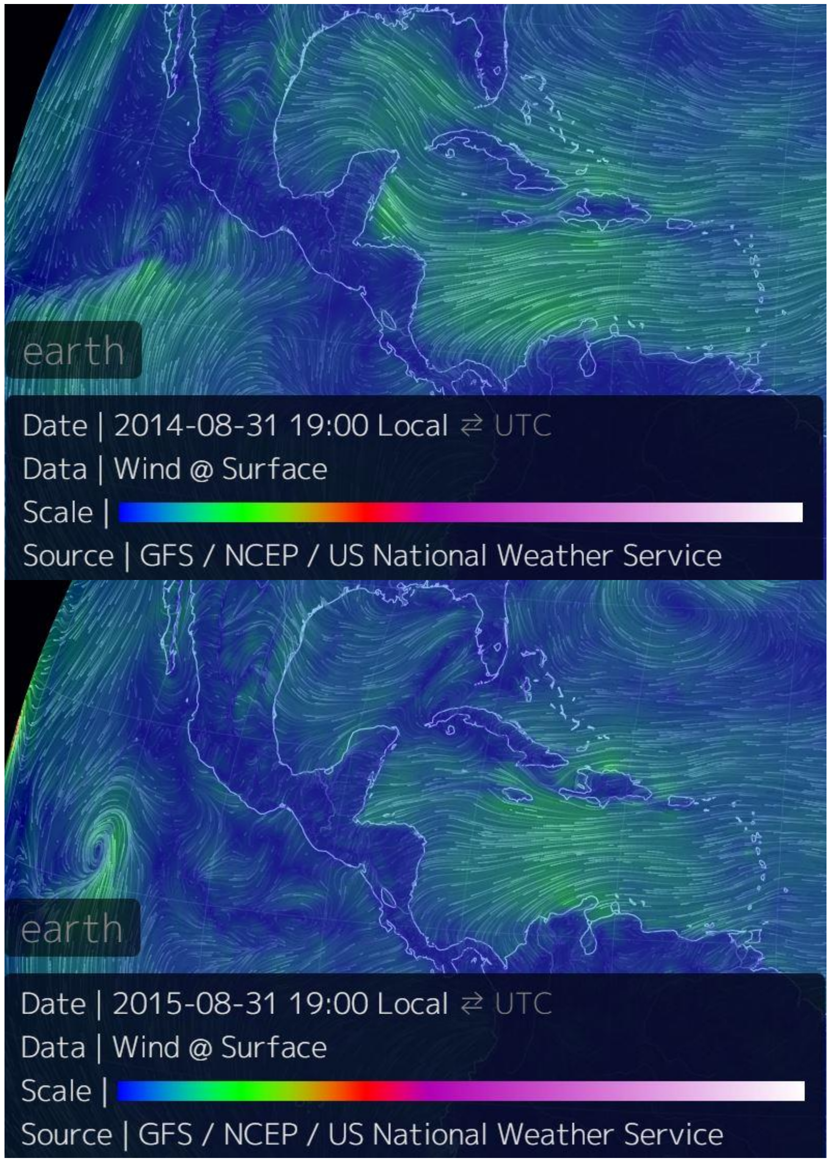

Figure 5. Null School Earth Air Surface Wind – This model, made possible by Cameron Beccario is useful in observation and forecasting the interplay between the driving variables of the Sargassum Migratory Loop System.

5. SARGASSUM LANDING DATA

In past studies the number of complaints submitted to the *Galveston Daily News* was utilized as a proxy-variable for Sargassum. It was admittedly dependent upon personal characteristics, socio-economic and demographic conditions, contemporary attitude toward Sargassum, and the specific area where landings have occurred. As such, complaints are more of a socio-economic variable in nature rather than the proxy for physical quantity, likely explaining the lack of significance of seasonal variables in previous models. While I acknowledge these flaws, it has been invaluable in developing a Sargassum cycle, and has been useful in establishing preliminary relationship between the main drivers of the cycle (Webster et. al, 2015).

For this study the SEAS has identified a better variable for Sargassum landing. The Sargassum sightings variable was derived by taking the Landsat image archive and creating a binary variable to demarcate the presence or absence of Sargassum within the imagery. 9000 images were counted for all locations and a monthly time series was created for this variable. During the months when no images were detected the counts were coded as zeros. The final sample covers the period of 1982-2015 and contains 331 observations.

Figure 6 shows the disparagement between submitted complaints and Sargassum Landsat images containing Sargassum, except for the year 2014 with high Sargassum landings when the two variables line up well with each other. Table 1 reports the summary statistics of variables used in the regression. The sample average image count for the Sargassum is 6, minimum 0 for the months with no Sargassum spotted and the maximum goes to as high as 75 recorded during 2014 and 2015.

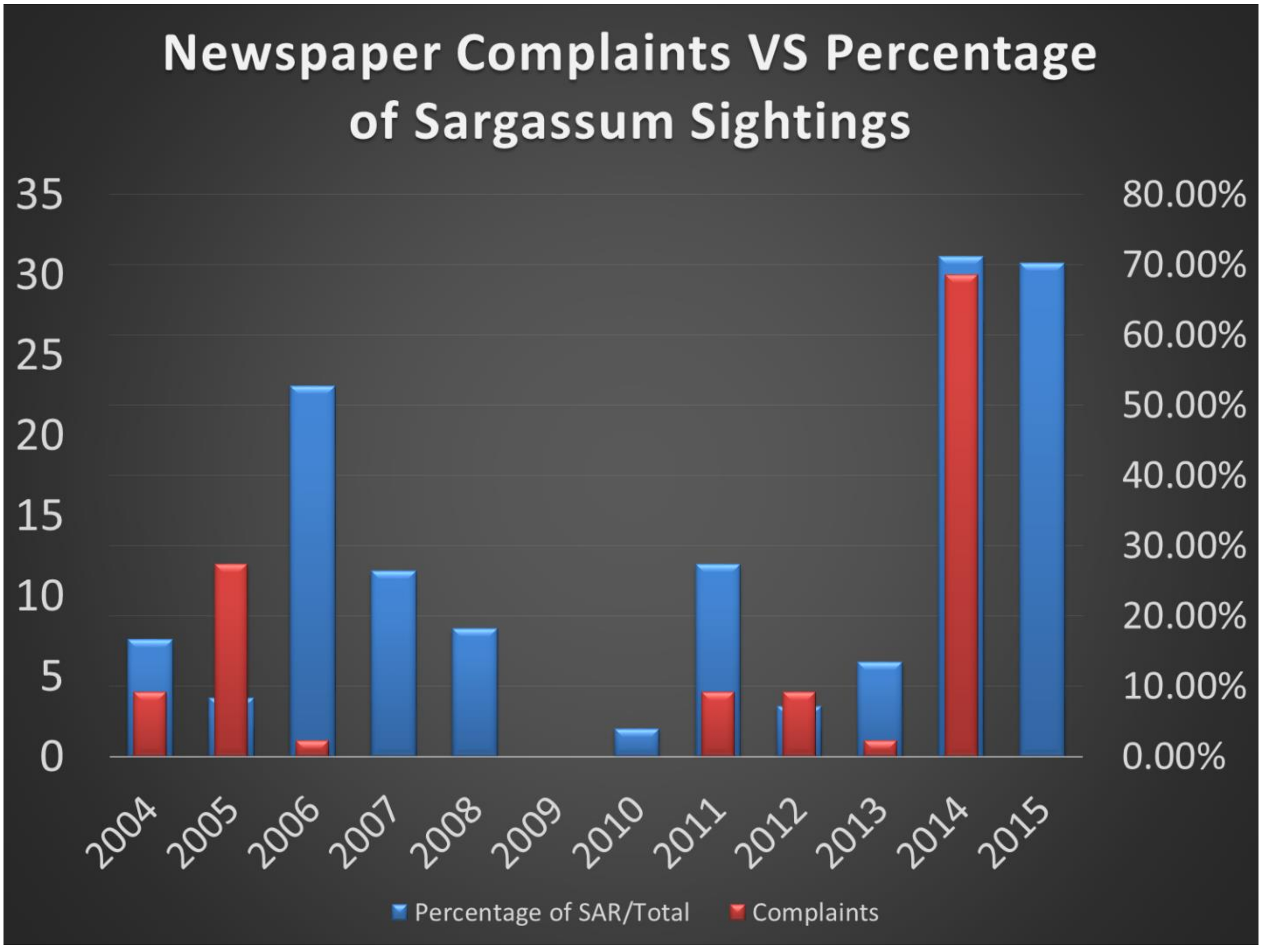

Figure 6. Sargassum Percentile Sightings – 667 images were analyzed in order to attain the average percent of images when Sargassum sightings and total images processed were compared, these were compared to the Galveston Daily Newspaper submitted complaints.

The predictors in the model consist of three teleconnection patterns which are the means of classifying and measuring the large scale patterns of pressure and circulation anomalies that naturally occur in the chaotic atmospheric system (NOAA, 2008). The most well-known teleconnection pattern to the SEAS is the North Atlantic Oscillation (NAO) Index. The NAO Index is a measure of the difference between two permanent pressure systems in the Atlantic. The first system is a permanent low pressure system over Iceland (Icelandic Low) and the second permanent high-pressure system over the Azores (the Azores High). The strengths and positions of the two systems control the direction and strength of the local system winds. The East Atlantic pattern (EAP) is another mode of low-frequency variability over the North Atlantic. The strongest distinction between these two teleconnection patterns is the EAP's strong subtropical link in association with modulations in the subtropical ridge intensity and location (NOAA, 2012). These two pressure systems are measured in hectopascals or millibars, the indices are created by analyzing their fluctuations. The final teleconnection pattern examined in this study is the fluctuation between El Niño and La Niña episodes known as the Oceanic Niño Index (ONI). Those episodes are calculated using an average of ERSST.v4 SST anomalies in Niño 3.4 region (5°N-5°S, 120°-170°W) over three month periods and are based on a threshold of +/- 0.5°C (NOAA, 2015). These Indices come from the National Weather Service Climate Prediction Center and NOAA.

The sample average NOA is 0.023 hPa, while the sample averages for ONI and EAP are approximately 0.008 hPa and 0.10 °C, respectively.

Table 1. Summary Statistics - Summary statistics are based on the sample of 331 monthly annual observations and covers 1982-2015

Variable	Mean	Std. Dev.	Min	Max
Sargassum	6.3142	13.9311	0	75
ONI	0.00846	0.78512	-1.8	2.3
NAO	0.02305	0.9711	-3.18	2.56
EAP	0.10444	0.97844	-2.46	2.39

6. METHODS

In order to quantify the relationship between the variables involved in the Sargassum Migratory loop system a Poisson regression analysis was conducted. The variables that cannot be quantifiably analyzed will be considered qualitative variables and a dummy variable will be created in order that they can be analyzed and manipulated in this fashion. This will highlight the variables with the most significant effect on the appearance of Sargassum in areas of study along the SMLS.

To estimate the effects of the NAO, EAP and ONI on the Sargassum landing, the model given in equation (1) is estimated:

$$Sargassum_t = \beta_0 + \beta_1 NAO + \beta_2 EAO + \beta_3 ONI + \sum_{i=1}^{11} \gamma_i D_i + t + e_t \quad (1)$$

where, the dependent variable is the count of Sargassum Sightings in month-year t. β_1 is the coefficient associated with North Atlantic Oscillation (NOA), β_2 captures the effect of the Eastern Atlantic Pattern Index (EAO), β_3 and is the coefficient associated with the Oceanic Niño Index (ONI). D_i is the dummy variable corresponding to the month i, and γ_i is the respective coefficient associated with that month. There are 11 such monthly dummies included in the model and the omitted category corresponds to the first month. Correspondingly, the coefficient γ_i is interpreted relative to the omitted category. t is the variable capturing the linear time trend in the model, and last e_t is an error term. Since the dependent variable is the count variable, I employ the Poisson regression, the best suited for this type of data.

7. RESULTS

In column (1) of Table 2 results from the Poisson regression are reported, while column (2) reports incident rate ratios (IRR) associated with the model coefficients. Significant Wald chi-squared test statistics indicates overall significance of the model.

The models with and without linear time trend were estimated and the one with the largest Log Pseudolikelihood was selected. The positive and significant coefficient associated with the NAO supports the hypothesis that increase in NAO represents as a triggering mechanism in the SEAS. The regression results also show the ONI as positive and significant. These results imply that the NAO and ONI have significantly positive effects on the number of Sargassum sightings, and therefore Sargassum landings. The regression coefficient associated with EAP is also positive, but is statistically insignificant. The regression shows as the NAO pressure increases by one Hectopascal (hPa) the incidence rate of Sargassum sightings is expected to change by a factor of 1.15083, or increase 15.1%. The results also indicate that as the ONI increases by one degree Celsius, the incidence rate of Sargassum sightings is expected to change by factor of 1.279246, or increase 27.9%. This suggests that ONI has almost twice the effect of that of NAO on Sargassum sightings, and potentially on landing.

Table 2. Poisson Regression of Sargassum Sightings in Landsat Imagery, El Niño/La Niña Fluctuations (ONI), North Atlantic Oscillation (NAO) and East Atlantic Pattern (EAP) – The dependent variable is the count of Sargassum sights. The standard errors are reported in parenthesis. Month of January is an omitted category; * $p<0.1$; ** $p<0.05$; *** $p<0.01$

	Poisson Regression Results	Incident Rate Ratio
ONI	0.2463***	1.279***
	(7.07)	(0.04)
NAO	0.1405***	1.1508***
	(4.84)	(0.03)
EAP	0.0213	1.0215
	(0.70)	(0.03)
February	0.3417**	1.4073**
	(2.20)	(0.22)
March	0.5439***	1.7227***
	(3.71)	(0.25)
April	0.5570***	1.7455***
	(3.85)	(0.25)
May	1.2068***	3.3428***
	(9.02)	(0.45)
June	1.3493***	3.8547***
	(10.01)	(0.52)
July	1.2205***	3.3889***
	(9.19)	(0.45)
August	1.2231***	3.3973***
	(9.14)	(0.45)
September	0.9300***	2.5344***
	(6.82)	(0.35)
October	0.6929***	1.9996***
	(4.69)	(0.30)
November	0.0122	1.01231
	(0.07)	(0.17)
December	0.1207	1.1283
	(0.75)	(0.18)
T	0.0200***	1.0202***
	(43.18)	(0.00)
Constant	-3.7644***	0.0232***
	(21.47)	(0.00)
Wald Chi2	4,547.00	
Pseudo R-squared	0.72	
Log Pseudolikelihood	-873.51	

The significant coefficients associated with the monthly dummies indicate that the Sargassum sightings are higher relative to January and the largest increase in the incidents rate is during the May to September months. This is not surprising as this is recognized as the time period that Sargassum can be expected to make landing along the SMLS. Last, the coefficient associated with the linear trend variable is positive and significant, suggesting that the Sargassum incidents are trending upwards. Although this trend may be a result of increased sample size in recent dates compared to historic sampling.

8. DISCUSSION

The annual flooding of the Amazon and Orinoco River Basins contribute excessive nutrients that are flushed into the Caribbean Sea inducing further growth of the Sargassum. Finally the thermohaline driven oceanic currents and atmospheric forces drive the Sargassum throughout the Sargassum Migratory Loop System. These variables are responsible for the atypical landings occurring in the Caribbean Sea for the 2015 Sargassum season. It is the annual fluctuations of the variables that combine to create different outcomes. Each force drives the Sargassum to a particular degree and serves to amplify or diminish the others. The study period is a case study of two very dissimilar outcomes and has shed light on the composition of the natural drivers that amalgamate each year.

The summer of 2014 was an outlier in terms of Sargassum landing, with Galveston Island receiving a minimum 49,445.83 tons of Sargassum. These variables are defined as the Sargassum Migratory Loop System and include but are not limited to the Azores high pressure system, North Atlantic Gyre, Langmuir Circulation, Gulf Stream, and available nutrients (Webster, 2013).

I must also examine whether or not the amounts of Sargassum that made landing in the 2014 year was affected by the cold fronts that pass through Texas from December 1st through April 30th. Noteworthy atmospheric forces were seen on the Gulf Coast in 2014 when cold fronts held off the potential landings and allowed the Sargassum to be further exposed to the nutrient bath of the Gulf of Mexico. This suspension within nutrient-rich waters allowed for massive Sargassum growth making imminent a colossal landing event. 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 portion of the study is centered on a local phenomenon rather than a system-wide driver.

Mean Atmospheric Pressure data spanning from 2010-2015 was collected from Weather Underground and Landsat imagery as described by Webster (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 and kept the Sargassum mats in the nutrient-rich Bay of Campeche. The vegetative growth of the algae mixed with nutrient-rich waters make 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 2010 – 2014 Sargassum seasons can be compared to the cold fronts that passed over the Texas coast. Absent historical data on volume of Sargassum landing, as a means of quantifying the Sargassum, Webster established 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. Table 3 reports the number of complaints and cold fronts recorded during 2010-2014.

Table 3. Comparison of Complaints of Sargassum Landings vs Cold Fronts - The data were collected from Weather Underground and the Galveston Daily News 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

Given limited number of observations, it is challenging to extrapolate a scientifically sound conclusion from the data presented in Table 1. Intuitively, cold fronts likely kept the Sargassum in an area of high nutrients for an extended period of time, causing exceptional growth. Gower and King (2012) point out that the Bay of Campeche provides a unique location for rapid vegetative growth. Lapointe's research on Sargassum growth and nutrient correlations describe nitrate, phosphate, ammonia, and iron as pivotal (Lapointe, 1993). With the concordance of prior research, there appears to be strong indications suggesting that time spent in neritic waters, such as the Bay of Campeche, will result in a significant increase in biomass.

For the case study of 2014 and 2015 the primary drivers in determining the location and volume of Sargassum landings has been shown to be the availability of coastal nutrients caused by annual flooding of the Orinoco and Amazon rivers as well as neritic contributions from the coasts along the SMLS. As systems of collecting Sargassum volumetric data are developed exploring this relationship will become more feasible. 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.

Oceanic Currents

Figure 7 shows representative paths of the thermohaline driven surface currents for both the 2014 and 2015 Sargassum seasons. Ocean currents are the most obvious transporter of the Sargassum through the Sargassum Migratory Loop System. Northern Atlantic Gyre is a compilation of oceanic currents that suspend Sargassum in the area known as the Sargasso Sea. The Sargassum is forced into the center of the gyre and remains there until the aforementioned Azores High Pressure System forces mats of Sargassum into the Caribbean Sea. Once in the Caribbean Sea the prevailing currents there become the primary driver of the mats. These currents can be very direct, traveling from the Antilles straight into the Gulf of Mexico, or they can spin off into a number of eddies. In 2014 the Caribbean Current was fairly direct in forcing the Sargassum within its bounds swiftly into the Gulf. In 2015 the current formed much more distinct and stronger eddies which kept the Sargassum in the Caribbean Sea longer. This time spent recycling through the nutrient-rich waters provided a hydroponic situation for the Sargassum. As it grew some would make landing, while other mats remained in the sea continuing to grow. This much more meandering path is a large factor in the increased landings in the Caribbean. The variations in ocean current path may be in part caused by the North Atlantic Oscillation and El Nino which appeared to be strongly influencing the currents in the region. Another variation between 2014 and 2015 ocean currents is the trajectory of the Caribbean Current that moves through the Yucatan Passage. In 2014 it was unimpededly flowing swiftly into the Gulf and Loop Current transporting Sargassum to the Gulf of Mexico. In 2015 the current was shifted starkly west, driving the Sargassum right into the region of Quintana Roo, Mexico. The direct effect of this shift is that the Yucatan has been inundated with Sargassum. An indirect effect is that much of the Sargassum that traditionally makes its way to the Gulf coast did not.

Nutrient Availability

It is agreed upon that the Sargasso Sea lacks the necessary nutrients to allow for Sargassum's continued existence and growth there. 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 Northern Sargasso Sea. An important aspect of the Sargassum Migratory System is the level of 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)

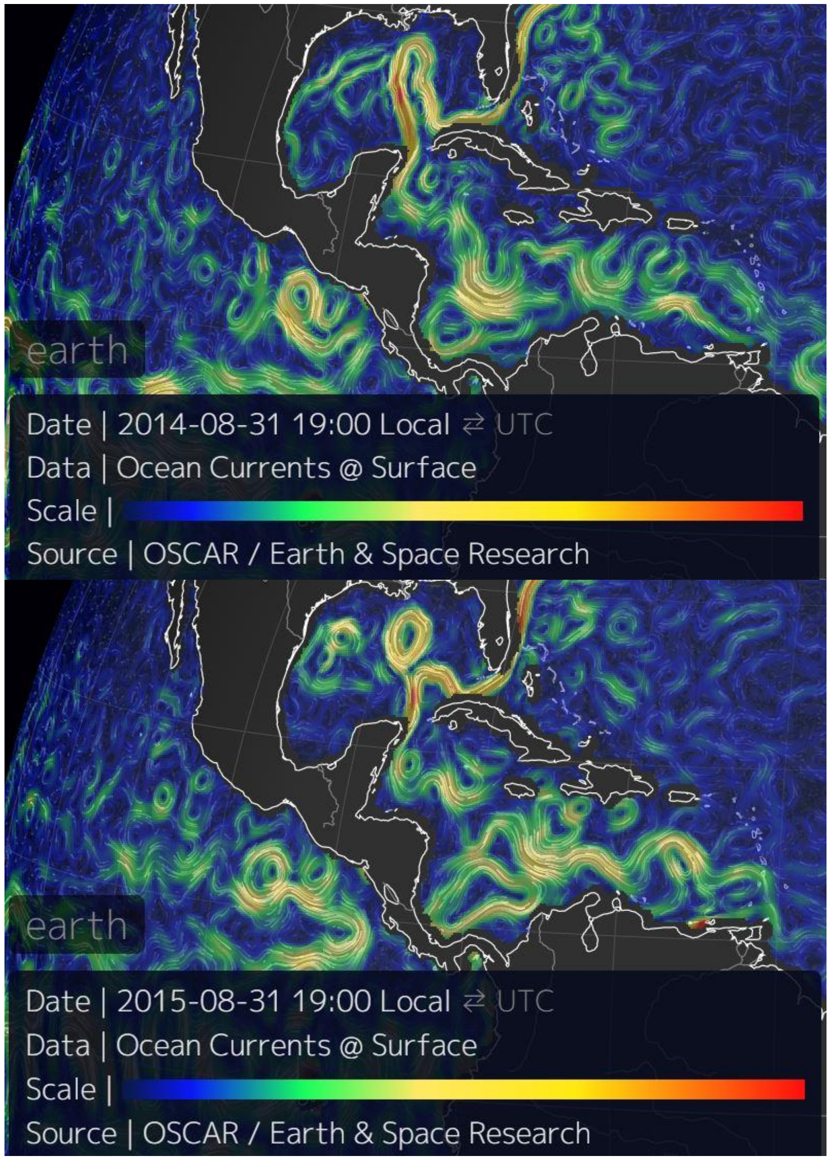

Figure 7. Null School Earth Oceanic Currents – The Null School tool shows the Caribbean and Loop Current Westerly shift leading to the direct impact of the Yucatan Peninsula.

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 and 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 Jr. 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 (Encyclopædia 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 4. Caribbean Passages and the Number of Images with Sargassum Identified from 1984 – 2015 677 Satellite images were analyzed between the years of '84-'15, as part of the Sargassum Early Advisory System.

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

Table 4 indicates 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. 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 indicative of why the Gulf did not experience the Sargassum inundations that the Caribbean did.

9. CONCLUSION

This thesis estimates the effects of the ONI, NAO, EAP and nutrient availability on Sargassum occurrence using the yearly monthly observation of satellite images as the dependent variable. The local atmospheric and teleconnection patterns have been shown to have a significant role in the movement of Sargassum mats. This study was able to show that when the Sargassum is within the SMLS cold fronts like were experienced off the coast of Texas in 2014 can enable longer periods of nutrient exposure. This local pattern of holding Sargassum within neritic gyres must be accounted for as Sargassum moves through the SMLS and experiences increased vegetative fragmentation along the way.

It is beneficial to go beyond the hypothetical and move into an analytical study of these variables. While Sargassum and its movements have been long studied the lack of solid variables, or even proxies has hampered the ability to run an analytical model. This model suffers from some omission bias due to the lack of data and sample size. This error was minimized by utilizing the maximum amount of records available. The results of the Poisson regression indicate that the ONI and EAP need to be integrated into any Sargassum forecasting model. The NAO has been proven useful in the current SEAS model and may yet be proven significant in some capacity but the intricacies of the ONI and EAP must be further examined beyond what can be performed within the scope of this study. A proper understanding of which variables contribute most significantly to the initiation of the SMLS will lead to better forecasting for all coasts along its track.

Further tools should be developed from the SEAS model as a base. A clear area with room for improvement is in the remote sensing imagery processing. A fully automated system must be properly developed and implemented. A highly useful multidisciplinary result would be a tool that utilizes color and pattern recognition in order to identify the Sargassum mats and slicks, and then converts them into a GIS shape file. These shape files could be saved and manipulated showing growth over time, movement, and fragmentation. This sort of utility would open a door to many applications for the SEAS model including oil, debris, and biological tracking and forecasting.

The oceanic currents and local gyres are highly important to the SMLS and at this time seem well defined and utilized within the current SEAS model. The movement of the current passing through the Yucatan Strait should be more closely observed moving forward as it appeared to play a role in the shift between the 2014-2015 Sargassum seasons. The local gyres within the Gulf of Mexico and Caribbean are encapsulated well by models such as the earth.nullschool model developed by Cameron Beccario, as well as more traditional models such as NOAA. It stands to reason that the shifts in the teleconnection patterns explored in this study play a role in influencing the smaller, local patterns.

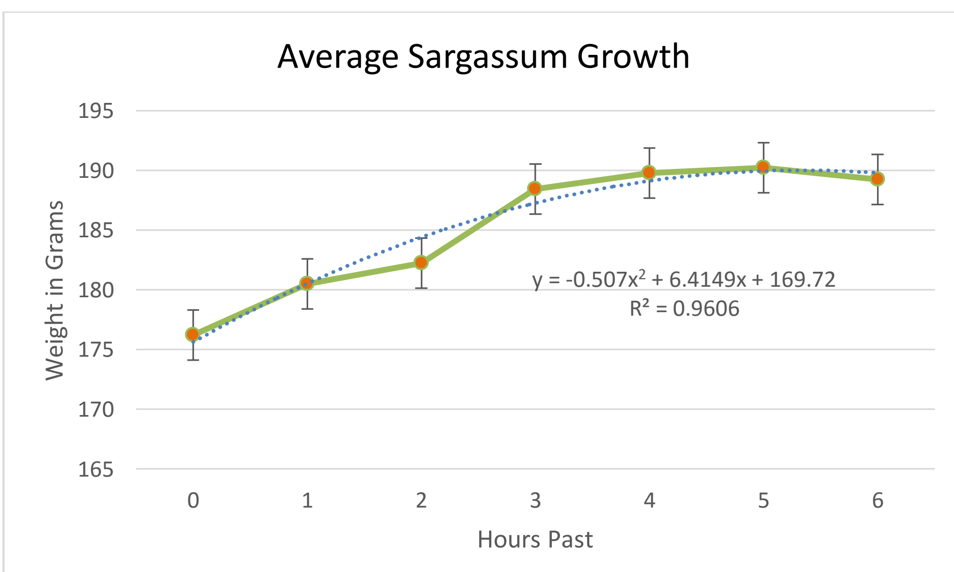

Figure 8. Average of 15 Sargassum Growth Observations – the averages of these tests is fit well with a second order polynomial.

Based on the data collected over the 2014 summer the Sargassum was observed undergoing vegetative fragmentation at rates of 6.4 grams an hour (Hill, 2014). This rate of growth is worth further exploration. The ability of Sargassum to increase at high rates while suspended in gyres or kept off coast by cold fronts must be accounted for in future forecasting models. There is a strong correlation between the levels of Iron, Phosphate, Ammonia and Nitrate that was unable to be well defined due to the lack of Sargassum in 2015.

For future efforts to understand fluctuations of Sargassum landing volumes the SMLS remains a complex system with minutia that demands future investigation.

REFERENCES

Beccario Cameron, earth.nullschool.net, Copyright © 2016. Page updated every three hours. Web 1 March, 2016. < http://earth.nullschool.net/>

Carillo, Jesús Editor, Avalle-Arce, Diane translator, REPERTORIUM COLUMBIANUM, Volume IX OVEIDO ON COLUMBUS; 2000 Brepols Publishers n. v., Turnhout Belgium ISBN 2-503-51030-2

Chubarenko O.B., Baulder Henning, Dispersion of Material in a shallow and deep basins limited by Langmuir circulation, Moscow Institue of Physics and Technology, Biological Station Zingst, Rostock University.

Climate Prediction Center Internet Team, National Oceanic and Atmospheric Administration, "East Atlantic". Page last modified: January 10, 2012. Web 17 February, 2016 <http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml>.

Climate Prediction Center Internet Team, National Oceanic and Atmospheric Administration, "Historical El Nino/La Nina episodes (1950-present)". Page last modified: November 4, 2015. Web 17 February, 2016 <http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml>.

Climate Prediction Center Internet Team, National Oceanic and Atmospheric Administration, "North Atlantic Oscillation". Page last modified: December 12, 20015. Web 17 February, 2016 <http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>.

Climate Prediction Center Internet Team, National Oceanic and Atmospheric Administration, "Teleconnection Introduction". Page last modified: May 8, 2008. Web 17 February, 2016 <http://www.cpc.ncep.noaa.gov/data/teledoc/teleintro.shtml>.

Crist, Raymond E., Alarich R. Shultz, James J. Parsons, Ed., "Amazon River; River, South America." Encyclopædia Britannica. Encyclopædia Britannica Online. Encyclopædia Britannica Inc., 2015. Web. 30 Oct. 2015 <http://www.britannica.com/place/Amazon-River/People>.

Frazier, Jeff, Author. Linton, Tom. Webster, Robert. 2013, Advanced Prediction of the Intra-Americas Sargassum Season through Analysis of the Sargassum Loop System Using Remote Sensing Technology

Gomez, F. Mercedes, Dieter Brunnschweiler, William M. Denevan., "Orinoco River". Encyclopædia Britannica. Encyclopædia Britannica Online. Encyclopædia Britannica Inc., 2015. Web. 30 Oct. 2015 <http://www.britannica.com/place/Orinoco-River>.

Gower, Jim. & King, Stephanie. Satellites Suggest a New Source of Caribbean Sargassum. British Columbia, Canada. Fisheries and Oceans Canada, Institute of Ocean Sciences. 2012.

Hill, Brandon. Thomas Linton, Robert Webster. 4 September 2014. Sargassum Early Advisory System (SEAS): Developing the Standard Operating Procedure of Investigating the Hourly Growth Rate of Sargassum While Suspended in the Neritic Coastal Waters off of Galveston, Texas. Unpublished Undergraduate Research Thesis, Texas A&M University at Galveston

Hill, Brandon. Thomas Linton, Robert Webster, Morgan Beaver, Mike Wurl, Kyle Robertson. 23 February 2015. Investigation into Neritic Water Conditions as Primary Driver of Vegetative Fragmentation Rates of Sargassum Naitans and Sargassum Fluitans. Unpublished manuscript, Texas A&M University at Galveston.

Lapointe, B. E. 29 December 1994. A comparison of nutrient-limited productivity in Sargassum natans from neritic vs. oceanic waters of the western North Atlantic Ocean

Lewis, W.M. Jr., S.K. Hamilton, and J.F. Saunders, III. 1995. Rivers of Northern South America. Pp. 219-256 in: C. Cushing and K. Cummisn (eds.). Ecosystems of the World: Rivers. Elsevier, NY.

Linton, Thomas. Robertson, Kyle. 2015. Texas Coast Dodges Seaweed This Summer. Published Friday, August 20, 2015. Texas A&M Today.

Masters, Jeff. "Dr. Jeff Masters' WunderBlog." March Like a Lion: Record Cold in Midwest, 319 Heavy Snow in Mid-Atlantic. Weather Underground, 01 Mar. 2014. Web. 03 Mar. 2014. 320, http://www.wunderground.com/data/640x480/huratl_slp.gif#Mean%20Sea%20Level

Schell, J.M., D.S. Goodwin, and A.N.S. Siuda. 2015. Recent Sargassum inundation events in the Caribbean: Shipboard observations reveal dominance of a previously rare form. Oceanography 28(3):8–10, http://dx.doi.org/10.5670/oceanog.2015.70.

UCAR Windows to the Universe, http://windows2universe.org/ from the National Earth Science Teachers Association (NESTA). UCAR and NCAR, 2000 - 2010. © 2012 National Earth Science Teachers Association. Accessed on 3/8/2016

Webster, R., Linton, T.L., 2013. Development and implementation of Sargassum Early Advisory System (SEAS); Shore and Beach Vol. 81, No. 3

Xu, Z., 1997. Flow near the sea surface: Steady currents and Langmuir circulations, Ph.D. thesis. Retrieved from ProQuest Dissertations and Theses. University of Michigan. Publication Number: AAI9732207; ISBN: 9780591417173. Dissertation Abstracts International, 58(05), Section B, p. 2334. (133 p)