Advanced prediction of the Intra-Americas Sargassum Season through Analysis of the Sargassum Loop System Using Remote Sensing Technology

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Abstract

Sargassum is a common type of seaweed observed in the Sargasso Sea, located in a portion of the western mid-Atlantic. Seasonally Sargassum inundates the beaches of Texas and the cost for its removal results in great strain on the coastal economies. Although this is an annual occurrence its cyclic migration patterns are relatively unknown. The research reported herein investigates the following null hypothesis, that Sargassum does not enter the Gulf of Mexico via the northern passages of the Caribbean and Yucatan Strait, where it amasses on the shores of the Gulf Coast or gets carried out the Florida Strait, in what is known as the Sargassum loop System. Once a seasonal migration patter is discerned, it is then hypothesized that certain aspects of the upcoming Sargassum season can be predicted in advance, using satellite imagery to monitor the corridors between the Sargasso Sea and the Gulf of Mexico.

The Sargassum season was previously thought to be erratic and unpredictable, however the theory of the Sargassum loop system sheds light on the seasonal migration patterns of the macro-algae. Through use of NASA’s Landsat satellite imagery the presence and abundance of Sargassum has been analyzed. Based on several factors, such as ocean currents, wind patterns, time of the year, and size of seaweed mats, the arrival and intensity of the upcoming Sargassum season can be approximated prior to its arrival in the Sargassum loop system. The Sargassum season starts months in advance in the Sargasso Sea when high pressure anomalies form. Their formation creates circulating northern wind currents that direct Sargassum southbound into the Caribbean latitudes. Once Sargassum has entered the Caribbean Passages, the Gulf Stream carries it westward, where depending on the direction and magnitude of ocean and wind currents, the Seaweed can take from two to five months to reach the Texas Coast. The Sargassum that does not reach land is flushed out through the Florida Straits and returns to the Sargasso Sea. This creates the Sargassum loop system. This, if monitored correctly, assists in forecasting the upcoming Sargassum season. Remote sensing, along with data from other ocean monitoring devices provides the necessary data for use in a Sargassum Early Advisory predictive model that allows for a more advanced warning of its arrival.

Additional Key Words

Satellite Imagery, Sargasso Sea, Sargassum Early Advisory System, Azores High Pressure System

Introduction

Sargassum is a free floating brown algae that has for thousands of years washed ashore on the coast of Texas during the summer months. Still, little is known about the path it takes to reach the coasts of the Western Gulf of Mexico. For centuries, Sargassum has been looked on as a plague because of its unsightliness and pungent odor produced by its decay. However, recent discoveries suggest that Sargassum mats deliver several benefits that are essential to the health of the oceans' and coastal ecosystems. These recent findings are revealing more positive aspects of Sargassum and are turning the tide on its historically negative image.

Until recently, there has never been a way to predict where Sargassum is going to land and in what quantities. This creates a bigger issue because there are not enough resources to sufficiently provide the entire coast with adequate Sargassum mitigation equipment during the peak of the Sargassum season.

In 2010, principle investigator Dr. Thomas Linton and Doctoral candidate Robert Webster initiated the Sargassum Early Advisory System (SEAS) program. It was a program, in which, through use of remote sensing technology, it would be possible to locate Sargassum mats (wrack) off the Texas Coast and predict, well in advance, when it would make landfall using remote sensing technology. By examining current satellite imagery from NASA's Landsat database, the SEAS program monitored for and analyzed Sargassum patterns in the Gulf of Mexico. Using oceanic and wind vector data, the program was able to create an approximate set and drift for the mats. These techniques allowed the SEAS program to effectively forecast the 2011 Sargassum season and send out advisories predicting the landfall of Sargassum mats with a success rate of 84%. A successful advisory is defined as predicting a significant Sargassum wrack (enough to form a windrow) on the beach arriving within an eight day period. Before the SEAS program began, coastal communities had no means of determining where Sargassum would make landfall, nor in what volume. This caused the Sargassum relocation equipment to be spread thinly across the coast. This caused delays in response time. The advisories alerted coastal managers of the size and approximate location of an upcoming Sargassum episode, so that they could allocate and concentrate their Sargassum mitigation efforts more efficiently.

Satellite imagery limitations restricted the SEAS program's advisories to a maximum forecast period of sixteen days. Further, the satellite imagery did not detail the initiation and the intensity of the upcoming Sargassum season until it had arrived. In order to provide a more robust advisory, several months in advance of the season, the SEAS program looked to expand its area of observation.

An atypical and unusually massive Sargassum event in the Southern Caribbean in 2011 initiated the expansion of the SEAS program, expanding its monitoring efforts to the Caribbean and Sargasso Sea. This paper theorizes that the observations in historical imagery of the newly incorporated region reveal a seasonal pattern of Sargassum migration. Annually, Sargassum is witnessed migrating south out of the Sargasso Sea and into the Caribbean, where it is swept northwest into the Gulf of Mexico by the Gulf Stream. Here it is theorized that Sargassum either washes ashore on the western coasts of the Gulf or is swept back out into the Atlantic, carried by the Gulf Stream current. This yearly voyage has been deemed the Sargassum loop current (Figure 1). The research reported in this paper attempts to document this Sargassum loop system so that it can be monitored and analyzed using remote sensing technology. This in turn, allows for an advanced forecast of the upcoming Intra-American Sargassum season.

Since Sargassum rests atop of the water column, the two main forces that affect it are ocean currents and wind currents. The effects of the ocean currents appear more apparent because they are well mapped and tend to be static in location, direction, and intensity. The Sargasso Sea is formed by the circulation of the North Atlantic Gyre. Sargassum accumulates in the center of the Gyre as a result of this phenomenon, until other, more prevailing forces affect its location. Wind currents have a surprisingly significant impact on Sargassum. With no freeboard, one would expect Sargassum to have little response to atmospheric conditions, however, this study suggests that the initiation of Sargassum migration is most closely correlated with the Azores High Pressure System. This high pressure weather phenomenon generates southbound winds over the Sargasso Sea, causing the Sargassum to migrate into lower latitudes. The mechanism leading to this magnitude of effect by wind intensity and direction on Sargassum, is still being studied, however the distinct correlation of wind patterns and seaweed migration can be inferred.

The main force that drives wind is known as an atmospheric phenomenon called the North Atlantic Oscillation occurs over the Northern Atlantic Ocean. In this phenomenon, a series of pressure systems, alternating between high pressure and low pressure, move across the northern hemisphere of the Atlantic Ocean (Figure 2).

When a high pressure system has moved into the region of interest, it is said to be in a positive mode. The high pressure systems are characterized as having a mean sea level pressure of at least 1010 millibars, but commonly range between 1020 to 1030 millibars, and is anticyclonic, meaning it rotates clockwise. One particular high pressure system situated in this region is commonly referred to as Azores High Pressure System, and oscillates from the Eastern to the Western Atlantic, frequently around latitudes of 30 degrees.

The Azores High Pressure System is theorized to be the initiating force behind Sargassum migration from the Sargasso Sea to the Gulf of Mexico. During the winter and spring months, the Azores Pressure System shifts over to the Eastern Atlantic where it resides over the Sargasso Sea (Figure 2). Anti-cyclonic conditions create swift northwesterly winds over the Sargasso Sea. These winds are believed to be a strong enough driving mechanism to push the floating algae out of the North Atlantic Gyre and down south toward the Caribbean, initiating the Sargassum Loop System.

During the summer season, a Sargassum accumulation off the western coast of the Gulf of Mexico creates a second Sargassum reservoir, from which the seaweed washes ashore in massive quantities. Such occurrences have been documented, in newspapers, on the coast of Texas dating back to the late eighteen hundreds. While the intensity of the summer Sargassum episodes have varied greatly from year to year, it has continued to occur, without explanation. Until now, little was known about the driving mechanism and origin of this seasonal Sargassum cycle. The research findings set forth in this paper describe the studies undertaken to explain the underlying mechanism by which the annual season of Sargassum occurs, as well as the area of origin of the wracks seen on the Texas Gulf Coast.

In 2009, Dr. Thomas Linton and Doctoral candidate Robert Webster formed the Sargassum Early Advisory System (or SEAS). The SEAS program set out to predict upcoming Sargassum events on the Texas Coast, utilizing remote sensing technology. Using satellite imagery, the coastal waters of Texas were monitored and analyzed for presence of Sargassum (Webster 2014).

By 2012, the SEAS program had refined its process of forecasting seaweed episodes to provide up to 97% accuracy. However, the most advanced warning of an impending episode an advisory could give at the time was sixteen days (Webster 2014). The mechanism that initiates the Sargassum season on the Texas Coast had yet to be discovered. Once this was determined, it was theorized that entire Sargassum seasons could be forecasted, giving unprecedented forewarning to the coastal communities in Texas.

So where does Sargassum originate from and where does it congregate during winter months? One source suggests that a reservoir of Sargassum forms in the Bay of Campeche annually during the winter months, then drifts north and amasses in spring and summer months, depositing on the shores of the Gulf of Mexico (Gower and King 2012). A review of historic satellite imagery showed no observable amounts of Sargassum in that area during the winter months. The concept of Sargassum originating in the Sargasso Sea, along the Mid Atlantic Bight, seemed evident; however the path from the East coast of the United States to the Western Gulf of Mexico appeared much less certain. The path from the Atlantic through the Florida Straits to the

Gulf was the most direct. However a close examination of the currents between Florida and Cuba shows that the swift Gulf Stream is heading easterly and directly opposing the route which Sargassum must take to get to the Western Gulf of Mexico.

In 2011, an atypical event occurred in the Southern Caribbean islands that initiated the idea that Sargassum may drift as far south as the Caribbean from the Sargasso Sea. It was theorized that if Sargassum could seasonally drift to tropical latitudes, then it could utilize westerly Caribbean currents to enter the Gulf through the Yucatan Passage. But if this event in 2011 was so uncommon, how could a seasonal occurrence of Sargassum in the Caribbean go unnoticed for so long? An in-depth examination of the 2011 Sargassum episodes in the Southern Caribbean revealed the connection between the Sargasso Sea and the seasonal Sargassum in the Gulf of Mexico.

Analysis

The 2011 Southern Caribbean Sargassum event generated the theory that Sargassum has the ability and resiliency to migrate from the Sargasso Sea into tropical waters. However, since Sargassum sightings have been sparsely recorded in the historical archives of the Southern Caribbean, one can deduce that an irregular occurrence sparked this 2011 phenomenon. This means that Sargassum could potentially migrate south annually, however, under normal conditions, it won't propagate as it did in 2011. So what happens to the Sargassum once it enters the Caribbean Sea?

Hypothesis 1) Annually, atmospheric wind currents drive Sargassum south out of the Sargasso Sea into the Northern Caribbean, where the Gulf Stream carries it into the neritic Gulf of Mexico. Once in the Gulf, it amasses and is either carried west by prevailing wind currents or carried out the Florida Strait back to the Sargasso Sea via the Gulf Stream, in what is known as the Sargassum loop system.

The Azores high pressure system produces concentrated northern winds across the Sargasso Sea, which pushes a portion of the sea of macro-algae out of the North Atlantic Gyre and into the Caribbean. Once in the Caribbean, the anti-cyclonic wind currents assist the Gulf Stream in carrying the Sargassum through the Yucatan Strait and into the Gulf of Mexico. Sargassum is then carried through the loop current, where wind or fluctuations in the loop current can cause the algae to break off and drift westward, where it will land on the Texas Coast. The remaining Sargassum that does not deviate from the loop current is carried back out into the Mid Atlantic bight, where it returns from its Intra-Americas journey.

In order to investigate the theory of the Sargassum loop system, The SEAS program expanded their area of observation to the northern Caribbean and southern Sargasso Sea regions. Using historic satellite imagery, the Sargassum loop system can be observed as it occurs annually throughout the Intra-Americas. An examination of this archived imagery reveals several patterns that occur seasonally and could be an earlier indication of the Sargassum migration, allowing for a more advanced prediction of the impending Sargassum season.

Hypothesis 2) The Impending Sargassum season for the Intra-Americas can be predicted in advance by comparing migration patterns of Sargassum in current satellite imagery to the migration patterns of Sargassum in historic satellite imagery.

Satellite imagery with sufficient resolution to see Sargassum is archived as far back as 2000. During the period of January of 2000 to May of 2013, the Landsat satellites created an archive of 347 images for each passage, not accounting for any imagery that is unusable, such as complete cloud cover, or data missing from the satellite imagery database. In order to obtain an appropriate sample of images of the passages, 70 images (or 20 percent of the archived database) of each passage were analyzed for the presence of Sargassum (figures 3a and 3b for example). Sargassum manifests in two forms. If the pelagic mat is large enough, it will produce a green glow in the satellite image, this is due to the vegetative growth filter added to the landsat images. The second manifestation of Sargassum is what is referred to as a ‘slick’ meaning that Sargassum itself cannot be seen in the image, however its presence at the ocean surface disrupts the surface tension and wave attenuation, thus creating a darker slick around the otherwise invisible mat. An examination of archived satellite imagery of the newly expanded area of observation revealed that not only has Sargassum been historically present, but also that it was seen in patterns that appeared to repeat annually.

Several patterns involving the southern migration of Sargassum emerged from the historical analysis of Caribbean Satellite imagery. The first pattern involves the initiation of Southern migration of Sargassum which starts as early as December, but typically occurs between February and April (See Table 1). Sargassum can be seen breaking away from the typical boundaries of the Sargasso Sea set by the motion of the North Atlantic Gyre. It is theorized that seasonal northerly winds produce adequate locomotion for the Sargassum to break away from its origin, pushing it south, toward the Caribbean. Although gyrating currents formed from the Coriolis Effect are strong enough to concentrate the Sargassum into the center of the gyre, these forces are relatively weak compared to locomotive forces produced by the wind and the Gulf Stream. Even though Sargassum has little to no freeboard, wind currents still affect Sargassum drift significantly. The estimated time it takes to get from the Sargasso Sea to the Gulf Coast is roughly two to five months, so the long range prediction indicates the initiation, intensity, and climax of the upcoming Sargassum season. This is shown in Table 1, which lists the number of sightings of Sargassum seen in each month. A spike in observations occurs during the winter to spring months (March through May). This precedes the Sargassum episodes seen on the Texas Coast by two to five months. For accurate and precise forecasting, the prediction of landfall is not made until after the Sargassum has entered the Gulf of Mexico.

Once it has broken free from the North Atlantic gyre, a second pattern begins to manifest. As the free-floating algae reaches the Northern Caribbean Islands, it either washes ashore on the islands of Cuba, Haiti, Dominican Republic, and/or Puerto Rico, or it gets funneled through the passes between the islands and into the Caribbean Sea (See Figures 3 and 4). Because of the passage are narrow, monitoring the Windward, Mona, and Anegada Passages are emphasized.

Once Sargassum has reached the neritic waters of the Caribbean Sea, the chemistry of the water is more favorable for Sargassum growth. The shallow, coastal waters have relatively high concentrations of nutrients such as carbon and phosphorous, compared to the nutrient poor waters of the Atlantic. Once in the Caribbean, the Sargassum mats start to increase in size.

The third and final pattern that emerged from the examination of the historical Caribbean satellite imagery is observed once the Sargassum has reached the Caribbean. Sargassum is seen migrating westerly once in the Caribbean Sea (Figure 5). An analysis of the Gulf Stream shows a relatively concentrated current from east to west in the Caribbean Sea, which is theorized to assist Sargassum in its annual migration (Figure 6). It is observed exiting the Caribbean through the Yucatan Passage where it arrives in the Gulf of Mexico. This seasonal Sargassum migration theory connects the Sargasso Sea, or the origin, to the Gulf, where it can be seen deposited along the coastline of Texas.

This annual voyage that Sargassum makes has been called the Sargassum loop system. During the winter months, atmospheric conditions create northerly winds that initiate Sargassum's yearly migration south, through the Northern Caribbean passage (Table 1). Once it reaches the Caribbean, it is caught in the Gulf Stream, where it is taken by concentrated surface currents into the Gulf of Mexico.

The discovery of this Sargassum loop system now allows for the monitoring, analysis, and long range forecasting of the Texas' annual Sargassum season via remote sensing. Since seaweed that eventually lands on the Texas coast has drifted south through the Caribbean passages several months prior, one can use this foresight to advise the coastal communities of the forecast for the initiation of the upcoming Sargassum season, as well as the intensity of the Sargassum episodes expected to occur that season, and the commencement of landfall events.

The start of the Sargassum season occurs several months after atmospheric conditions allow Sargassum to migrate south out of the Sargasso Sea and into the Caribbean. Since there is still a distance of over 3,000 miles to be traveled, several factors can affect the Sargassum before it makes landfall on the Texas coast. Variables, such as oceanic and atmospheric conditions are dynamic, growth rates are affected by nutrient and temperature conditions during the migration, which can affect the quantity of Sargassum in the Sargassum loop system, as it amasses. Not all Sargassum that journeys into the Gulf will make landfall on the coast, but instead be discharged through the Florida Straits. Because of these reasons, at this point in the loop system, exact landfall dates cannot be predicted.

Relative correlations between the amount of Sargassum that can be seen in the passages and the amount that makes landfall can be made. It is observed that Sargassum is more commonly sighted in the passages during seasons of heavier Sargassum inundations, such as the 2008 and 2011 Sargassum seasons, of the coastal communities of the Gulf (Table 2). In contrast, during lighter years of Sargassum episodes, such as the 2006 and 2010 Sargassum seasons, Sargassum sightings in the Caribbean passages occur less commonly (Table 2). The frequency of Sargassum sightings in the passages can be directly correlated with the abundance of Sargassum in the Gulf and therefore, can forecast the intensity of the upcoming season, however one cannot extrapolate an absolute volume.

The end of the Sargassum season occurs when atmospheric conditions that encourage Sargassum become reduced in frequency and intensity, reducing the locomotive energy in the wind, the driving force of the Sargassum migration. This termination of the seaweed season is observed in both the degradation of the northerly winds over the Sargasso Sea and in the absence of Sargassum in the Caribbean passages.

There are a few caveats in the advanced prediction of the upcoming Sargassum season. First, the model used to predict the set and drift of flotsam and jetsam (floating debris) in the Gulf of Mexico is still in the experimental phase. Several entities have attempted to create drift models, such as NASA's debris prediction model, Coast Guard's Oil prediction model, and NOAA's trash and flotsam predictive model, however none have proven accurate or effective for Sargassum prediction or for their orignal intended purposes. This forces us to use a more simplistic and experimental model of vector addition. Once Sargassum is located, the regional ocean and wind currents are obtained and overlaid over the mat of Sargassum. It is known that wind has a stronger effect on Sargassum than ocean currents, despite Sargassum having a negligible amount of freeboard, allowing it to be more affected by air. Because of this, the wind current is given more weight when modeling the drift of the seaweed mats. The exact effect that wind and water currents have on Sargassum is still unknown. However. It is noted that flotsam and jetsam travel at a rate of 3 percent of the currents acting upon it (Gyory 2013). i.e. If ocean and atmospheric currents are acting on Sargassum at a rate of 15 knots, the Sargassum mat is only drifting at a rate of 0.45 knots. This prediction model is simplistic and is still in the early experimental stages of development.

Another constraint on long range forecasting is provided by the dynamic variables. Since Sargassum is being forecasted months in advance, there are several factors such as ocean and atmospheric conditions that change daily, and cannot be accurately incorporated into the model. Because of this, a more simplistic average is being taken of the wind and ocean currents. Another variable that affects the drift of Sargassum is the bathymetry, which affects wave patterns and tidal cycles. Since Sargassum must travel a minimum of 1,800 miles, accounting for the bathymetry and the added variables that it entails, it is impractical to incorporate them into the model. These discrepancies in the modeling for Sargassum set limitations on the accuracy of Sargassum predictions.

Expanding the SEAS program's area of observation into the Caribbean has increased the forewarning time from sixteen days to up to two to five months in advance. Knowledge of the initiation and intensity of the upcoming summer seaweed episodes allows coastal communities to allocate the necessary resources and better prepare for the impending Sargassum season.

Conclusion

The increased foresight brought on the by expanding the SEAS's area of observation into the Caribbean, allows for the forecasting of Sargassum in the Gulf of Mexico months in advance. It also helps explain the secret to the sustainability of the Sargasso Sea, an oasis of vegetation located in a nutrient-barren region. The 2011 massive Sargassum event in the Southern Caribbean was then thought to be generated by unusually massive flooding. Although it may have seemed like a dead end, this investigation of the unusually massive Sargassum episode led to the theory of Sargassum's annual migration from the Sargasso Sea to the Gulf and the creation of the Long range forecasting of Sargassum in the Caribbean Sea. Previously, Sargassum could not be forecasted until it had reached the coastal waters of the Gulf of Mexico. This expansion of the SEAS program allows for the upcoming Sargassum season on the Texas Coast to be forecasted months in advance. The frequency of appearance and volume of Sargassum in the Caribbean passages during the winter and spring months are indications of the initiation, intensity and eventually the commencement of Sargassum season in the Caribbean and Gulf of Mexico.

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Figures and Tables

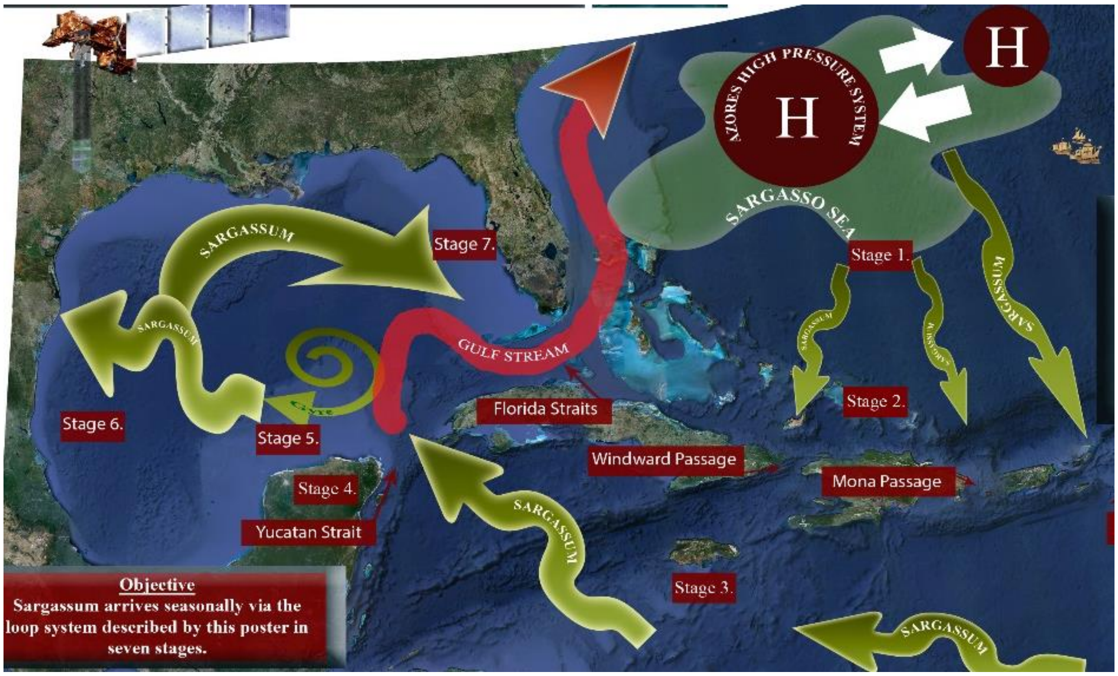
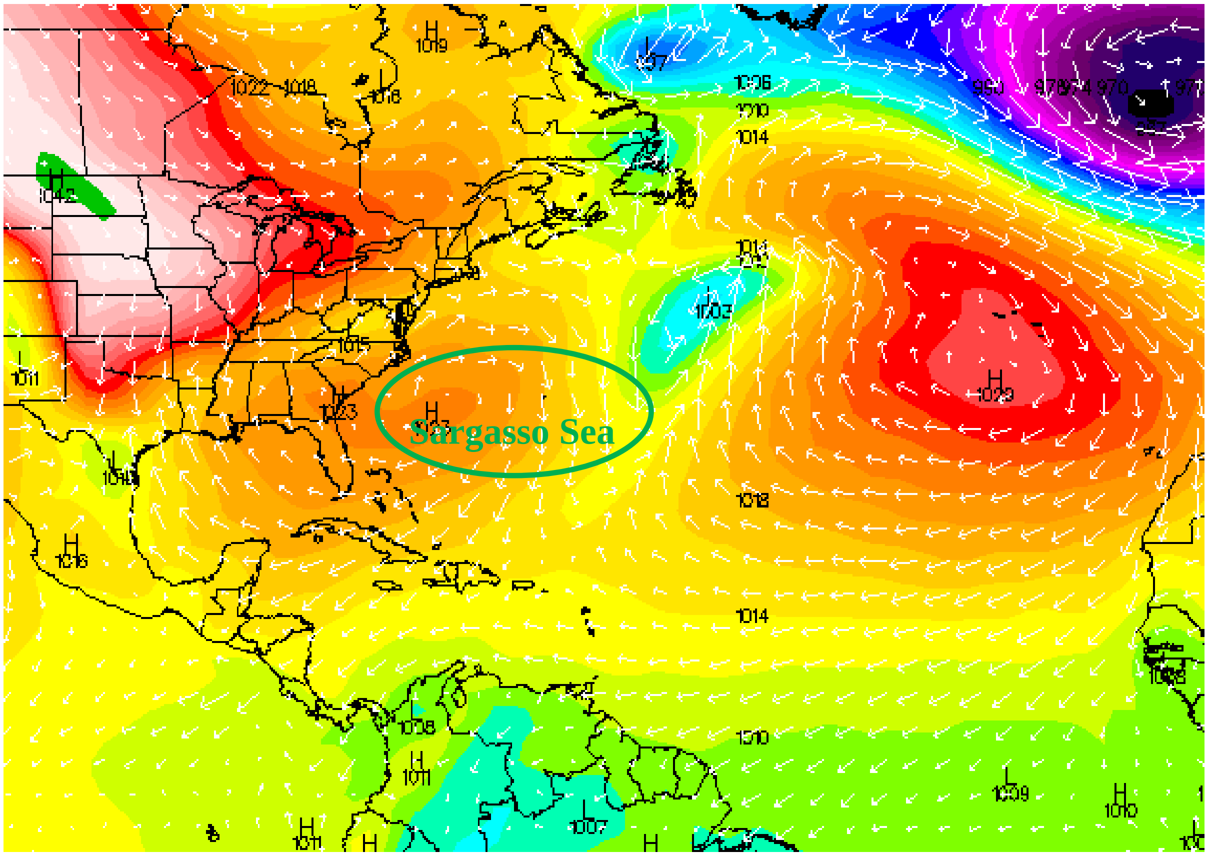


Figure 1 *Sargassum* loop system-This graphic represents the *Sargassum* loop system that initiates in the Sargasso Sea, as developed by the SEAS program. Atmospheric conditions create wind patterns that push *Sargassum* south, into the Caribbean where it is pushed west, by the oceanic and atmospheric currents carrying it into the Gulf of Mexico. There it either washes ashore on the Gulf Coast or gets swept out the Florida Strait via the Gulf Stream (Webster, 2014)



Mean Sea Level Pressure and 1000 mb Winds

6 hour GFS Forecast Valid 18 GMT Sun Mar 02

Figure 2 Azores High Pressure System Graphic–The Azores High Pressure system creates anticyclonic winds over the Sargasso Sea and becomes the driving mechanism behind the migration of *Sargassum* (Masters, 2014)

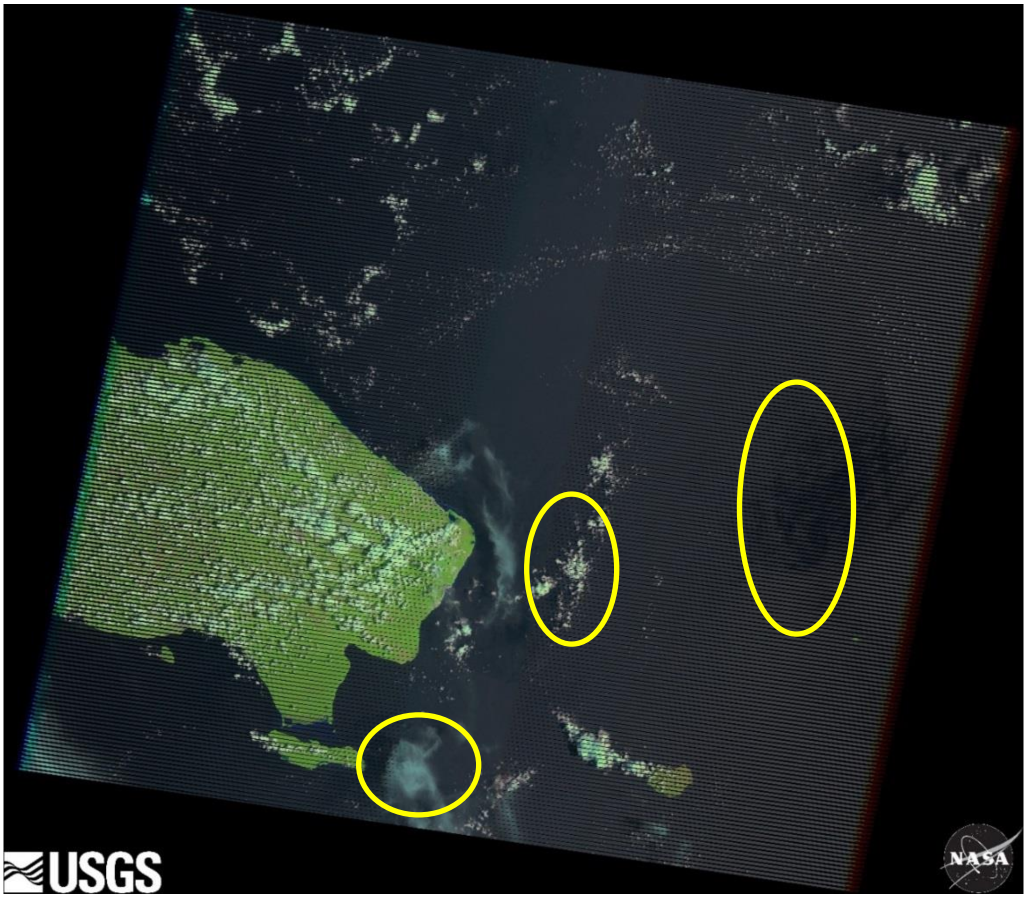


Figure 3a Mona Passage Satellite Image–This graphic illustrates a satellite image of *Sargassum* migrating through the Mona Passage into the Caribbean Sea. *Sargassum* and its slicks are denoted by the yellow oval (United States Geological Survey, 2014).

Figure 3b Mona Passage Satellite Image Magnified–A magnified view of these images reveal a linear green glow or if the mat is too small to be seen in the image, a darker outline in linear patterns. This is because the size of the mat is too small to be seen in the image, only the disturbance of the wave attenuation around it can be seen (United States Geological Survey, 2014).

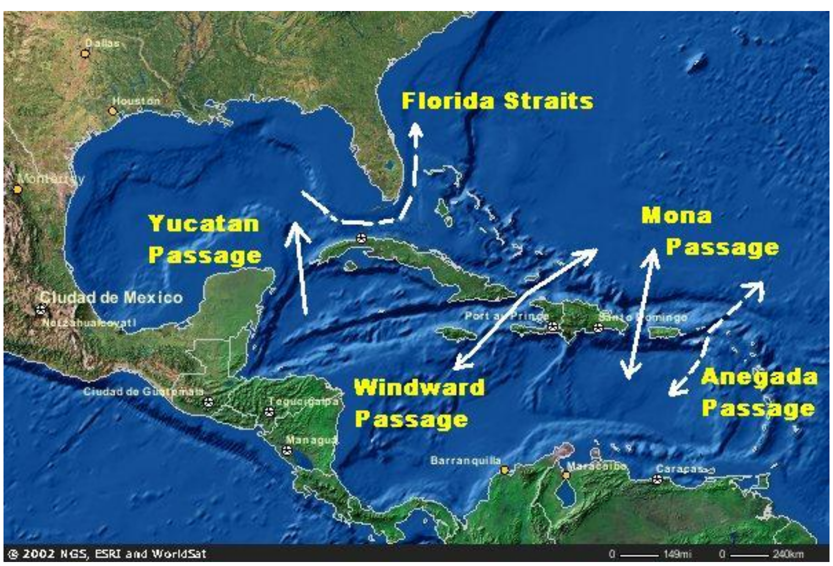


Figure 4 Caribbean Passages – This figure shows a map of the Caribbean. The Northern Caribbean Passages, referred to as the Windward, Mona, and Anegada Passages, are where *Sargassum* is most frequently observed (Webster, 2014).

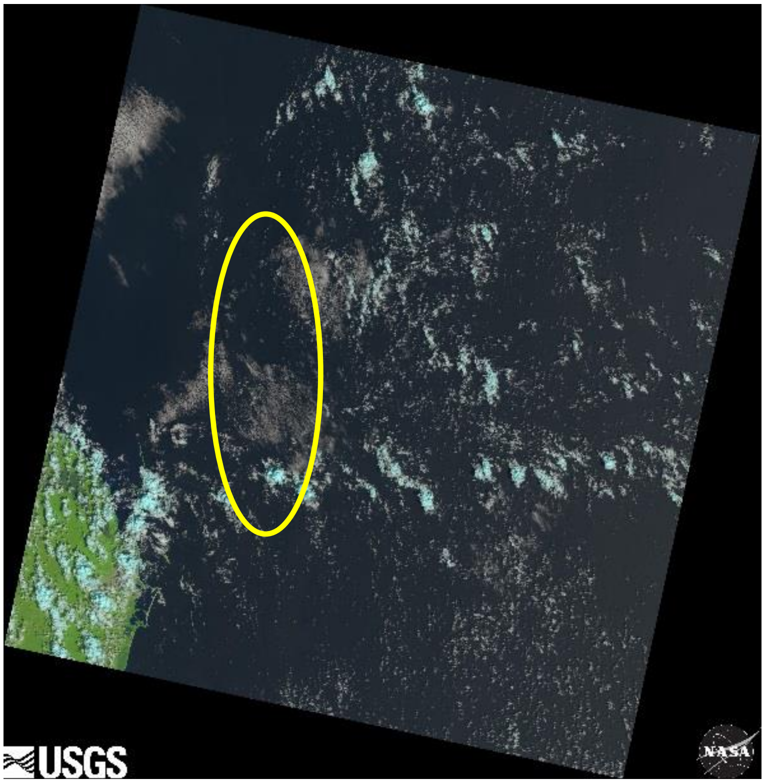


Figure 5 Yucatan Strait Satellite Image – A satellite image of the Yucatan Strait on March 22, 2014 illustrating *Sargassum* moving westward via the Gulf Stream. Sargassum manifests itself in the form of a slick. Since the size of the mat is too small to be seen in the image, only the disturbance of the wave attenuation around it can be seen (United States Geological Survey, 2014).

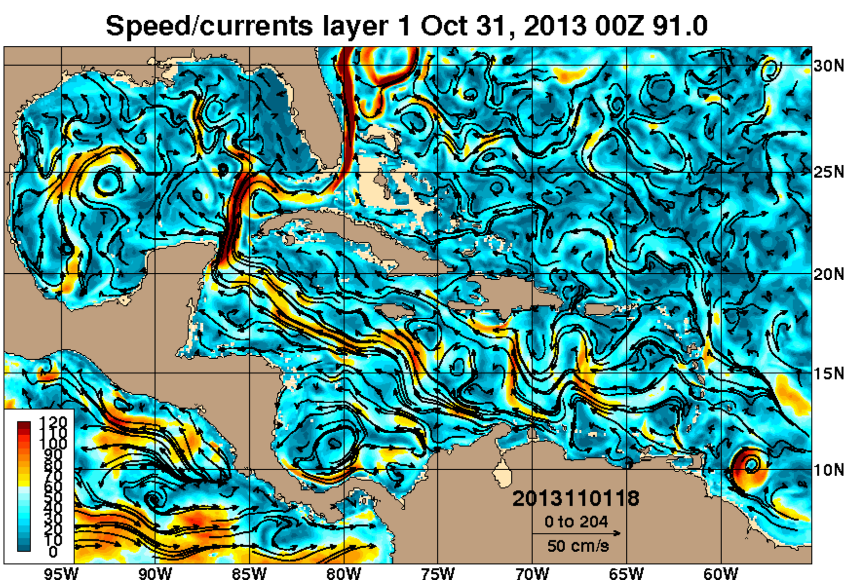


Figure 6 Gulf Stream Current Graphic-This graphic represents the Gulf Stream that generates a western current in the Caribbean. The current is then pushed

north into the Gulf of Mexico where it ‘loops’ and exits out of the Gulf via the Florida Strait (HYCOM, 2014).

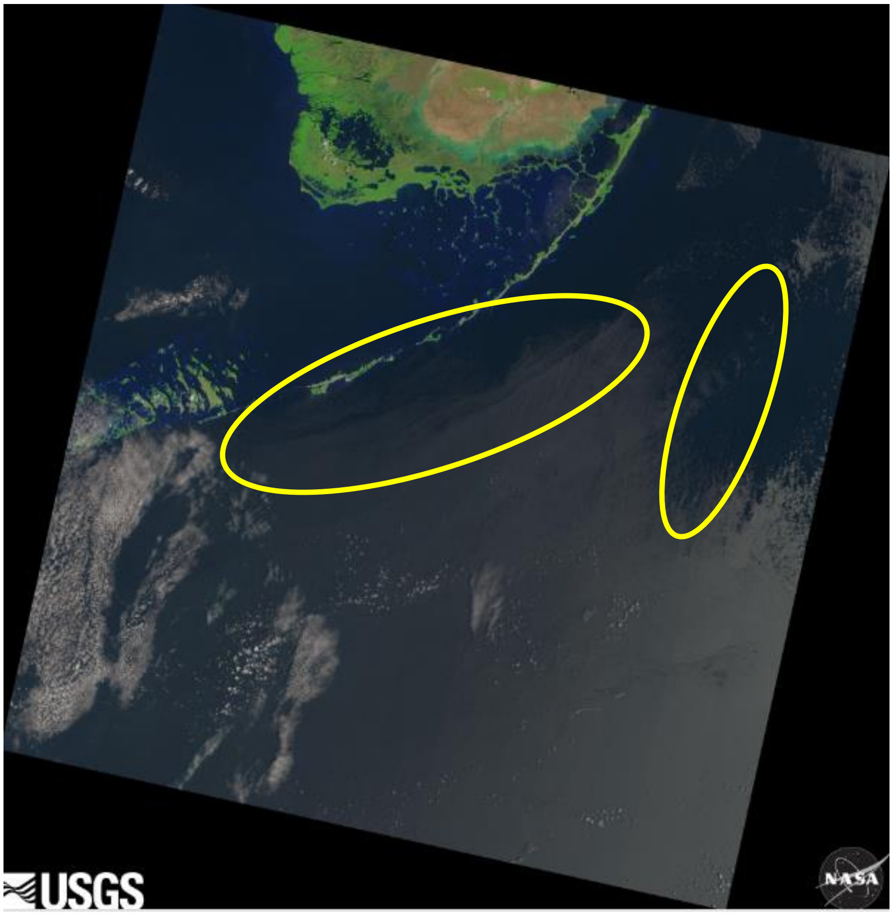


Figure 12 Florida Strait Satellite Image–a Satellite image of the Florida Strait On April 24, 2014 illustrates *Sargassum* exiting the Gulf of Mexico via the Florida Strait and rejoining the Sargasso Sea (United States Geological Survey, 2014).

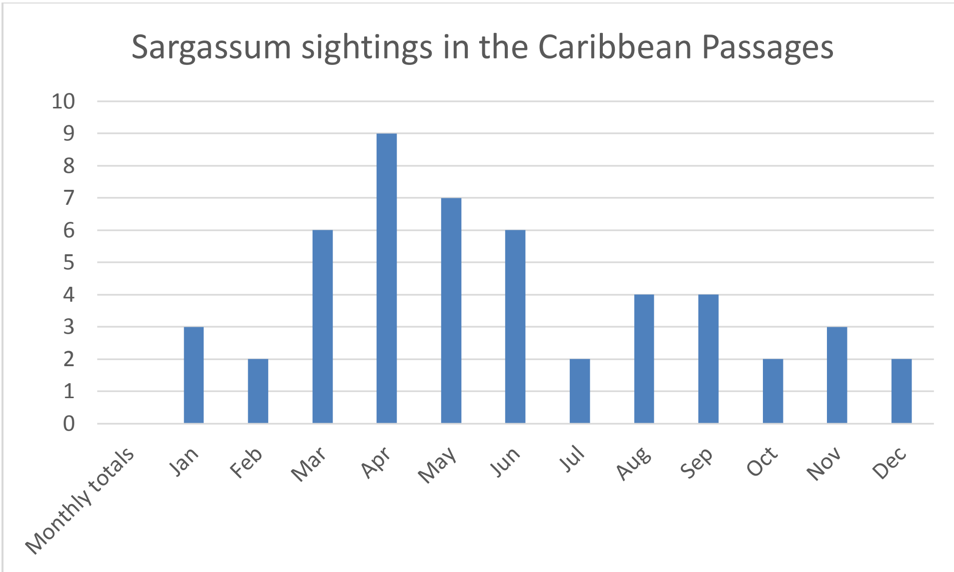


Table 1 *Sargassum* Sightings in the Caribbean Passages–This graphic illustrates the number of times *Sargassum* has been spotted in the passages in a single month. Historic satellite imagery was obtained and analyzed to review when *Sargassum* begins its journey through the *Sargassum* loop system.

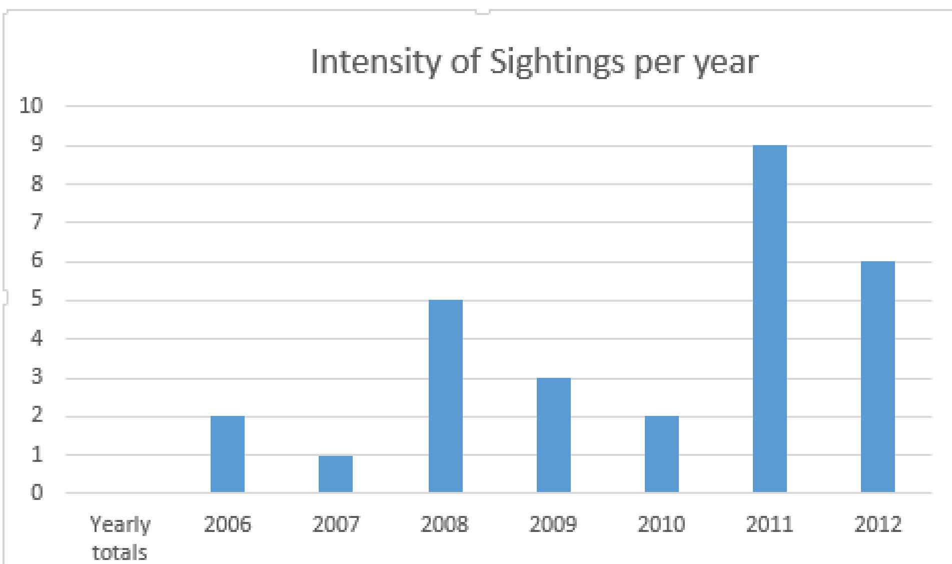


Table 2 Intensity of *Sargassum* Sightings per Year–This graphic depicts the annual difference between *Sargassum* sightings in the Caribbean Passages. Note that during the 2008 and 2011 seasons, more *Sargassum* was seen the Caribbean Passages, which correlates to the relatively higher rates of *Sargassum* events on the Texas Coast. The 2007 and 2010 years yielded less *Sargassum* in the passages, which correlates to the lower volumes of *Sargassum* seen in the Gulf of Mexico. This denotes that the intensity of the upcoming *Sargassum* season is reflective in the Caribbean Passages during preluding months.