Development and implementation of *Sargassum* Early Advisory System (SEAS)

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ABSTRACT

The Texas Gulf Coast consists of 367 miles of coastline, primarily sandy beaches. The slight slope of these beaches creates many large expanses of beach where the public can enjoy a variety of activities such as beach combing, surfing, swimming, and surf fishing. Communities that manage these areas rely heavily on tourism as a primary source of income. Texas beach tourism generates approximately $7 billion per year, according to the Texas General Land Office's (TGLO) website (http://www.glo.texas.gov). Public use of these beaches can be severely restricted by the periodic mass landings of the free-floating plant *Sargassum,* commonly referred to as seaweed. These *Sargassum* episodes often occur with little or no warning. They can last for weeks at a time, usually during the prime tourist season, and hence they negatively affect the economies of the regions. Beach managers have relied on emergency funds to assist in relocating heavier-than-normal *Sargassum* from the water's edge. This creates an unexpected hardship, since their annual budgets have little or no room for unforeseen expenditures. To assist beach management efforts, scientists at Texas A&M University at Galveston have been investigating the use of satellite imagery to forecast *Sargassum* landings along the Texas coastline. This *Sargassum* Early Advisory System (SEAS) is designed to give coastal managers as much warning as possible, allowing them to adjust their allocation of resources for the management of *Sargassum* landings. SEAS model uses satellite imagery from Landsat Data Continuity Mission (LANDSAT) satellites to track the movement of *Sargassum* as it approaches each sector along the Texas Gulf Coast. During 2012, a total of 38 advisories were sent out to coastal managers along the Texas Gulf Coast. Of those, 12 predicted *Sargassum* landfalls in their respective areas. All of the 12 experienced significant *Sargassum* landfalls within seven days of notice. There were five overcast flyovers that we were not able to give possible landfall advisories; of those, three experienced significant *Sargassum* landings.

ADDITIONAL KEYWORDS: *Sargassum* sea wracks, *Sargassum* rafts, *Sargassum* slick, Sargasso Sea, Holopelagic, Vegetatively, Pods, Weedlines, Windrows, Pneumatocyst, *Sargassum* lines.

Article submitted 26 August 2012, revised and accepted 25 March 2013.

Sargassum is a holopelagic brown algae that derives its name from the small, gas-filled bladders that serve as flotation devices (Dickson 1894). One of the first documented sightings of *Sargassum* occurred when Portuguese sailors, sailing to the New World with Christopher Columbus, noticed the plants floating on the ocean surface (Dickson 1894). The sailors termed the floating plants "salgazo" because the algae's flotation devices reminded them of a small variety of grapes native to their homeland (Dickson 1894). From this term, the common name *Sargassum* was derived. The two most common species of floating *Sargassum* are *sargasso natans* and *sargasso fluitans* (Conover and Sieburth 1964). These two species are very similar, and many weed lines contain both species. They reproduce vegetatively and remain completely pelagic during their lifecycle (Hemphill 2005). Most of the *Sargassum* found in the Gulf of Mexico originates from the Sargasso Sea (Stoner and Greening 1984). *Sargassum*'s movement is controlled by surface currents (Gower and King 2008). As segments of *Sargassum* break away, the currents and winds carry them in a multitude of directions. With some being directed toward the coast via surface currents, these sections eventually wash ashore on the Texas Gulf Coast beaches, where they are termed *Sargassum* "wracks" (Colombini and Chelazzi 2003).

As far back as the earliest issues of Texas coastal newspapers, beach management along the Texas coast has had to deal with massive periodic landings of *Sargassum*. These landings often come with no warning, and they can last for weeks at a time. The economies of the coastal regions of Texas rely heavily on tourism. Therefore, if an unexpected *Sargassum* inundation occurs during the tourist season, tourist activity can be severely curtailed, resulting in an adverse economic impact to the area. Beach managers have had to rely on emergency funds to relocate the *Sargassum* to less populated locations along the beach. Because of the possibility of increased coastal erosion the Texas General Land Office does not allow the complete removal of *Sargassum* from the beach (GLO 2002). The raking and removal of *Sargassum* from the Texas beaches can cost public entities along the Texas Gulf Coast more than $2.91 million per year.

In an attempt to provide beach managers an early advisory system for *Sargas-*

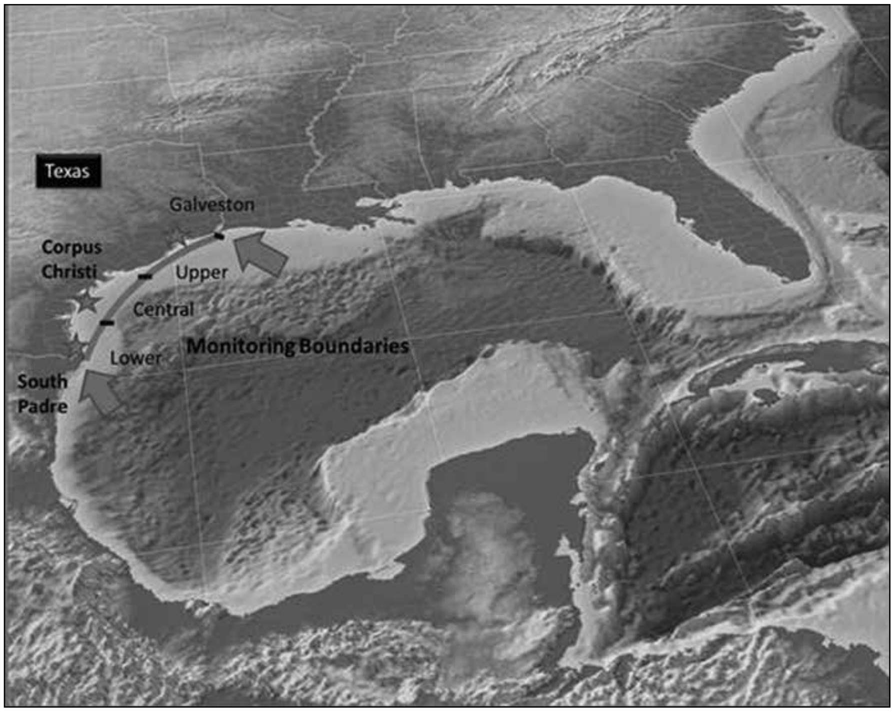

Figure 1. Shaded relief images showing monitoring sectors and ground truth locations along the Texas Gulf Coast. Image courtesy of AOL search.

Table 1. Occurrences of Sargassum complaints found in local newspapers.

Location	Year	Number of *Sargassum* references	Valid	Invalid
Galveston	1866-2008	1810	165	1645
Corpus Christi	1930-1977	842	85	757
South Padre/Brownsville	1900-1977	645	17	628

Valid references included actual complaints and/or observations of *Sargassum* on beaches.

sum landings, a scientific and management team at Texas A&M University at Galveston developed a proactive strategy to replace the reactive strategy traditionally used by beach managers. Using recent advances in the analysis of satellite imagery and other data, the team was able to give beach managers up to a two-week notice of *Sargassum* landings along the Texas coastline. The initial part of the management strategy utilizes satellite imagery, data from weather buoys, and the application of a *Sargassum* Predictive Model. Using these tools, the team has implemented the *Sargassum* Early Advisory System (SEAS).

Coastal newspapers, including *Galveston Daily News,* were used to build historic data sets of cyclical heavy landings of *Sargassum* on the Texas coast. During the last 150 years, many of these newspapers have been kept on microfilm for ease in data collection. Several years ago, the Galveston newspaper, in particular, had volunteers create index files for specific searches including seaweed, which became invaluable in developing a *Sargassum* cycle.

Sargassum System Loop

The SEAS team has expanded its imagery analysis to include the Atlantic Ocean, including the Caribbean Sea, and found evidence of *Sargassum* movement from the Sargasso Sea through the Caribbean Sea and into the Gulf of Mexico. Continued analysis of the temporal position, oscillation, and intensification of the Azores high-pressure system over the Sargasso Sea reveals a strong correlation between those traits and the *Sargassum* landing cycles reported in local historical newspaper records (e.g. the *Galveston Daily News*, which has been continuously published since 1842). This shift in the Azores high-pressure system represents the initial energy required to send pulses of *Sargassum* into the Caribbean Current, thereby starting the loop system. Historical observations and numerical models indicate that as surface current flows enter the Caribbean Sea, the majority of the surface water enters through the southern Windward Islands of Grenada, St. Vincent, and St. Lucia Passages (Gyory *et al.* 2013). The surface current then continues westward, and the Caribbean Current creates surface transportation for the *Sargassum* as it transverses the Caribbean Sea (Stoner and Greening 1984; Gyory *et al.* 2013). The surface currents turn sharply northward and enter the Gulf of Mexico as a narrow boundary current along the coast of the Yucatan Peninsula (Gyory *et al.* 2013). This Yucatan Current flows directly into the Gulf of Mexico through the Yucatan Channel and then enters the Loop Current. The Loop Current's flow varies, sometimes forming a direct path to the Florida Current and sometimes stretching as far north as the Mississippi River Delta (Gyory *et al.* 2013). The Loop Current eventually returns to its direct configuration by slowly pinching off its extension to form a large, warm-core ring, called an eddy, that propagates westward at speeds of approximately 1-3 miles per day (Gyory *et al.* 2013). Eddies provide the surface energy needed to move the *Sargassum* to the near coastal waters of the Mexico and Texas Gulf Coast.

STUDY AREA

For the implementation of the SEAS project, the Texas coast has been divided into three monitoring sectors: the upper coast, the central coast, and the lower coast. These sectors, which cover the Texas Gulf's coastline, begin at Sabine Pass and continue south to Brazos Santiago Pass in South Padre Island, as seen in Figure 1.

The upper sector's central study area includes Galveston, the Bolivar Peninsula, and Surfside. The central sector includes Corpus Christi and Port Aransas. The lower sector covers South Padre Island. Each sector has ground-truth locations where the SEAS team collaborates with local beach managers and municipalities who provide *in situ* data. The SEAS team keeps in close contact with these organizations and individuals by sending updated images of nearby coastal waters. The local contacts provide ground truthing data by documenting *Sargassum* landings through emails. Ground-truthing data include photographs from beach cams, field support, and a research vessel that reports the coordinates of *Sargassum* wracks offshore.

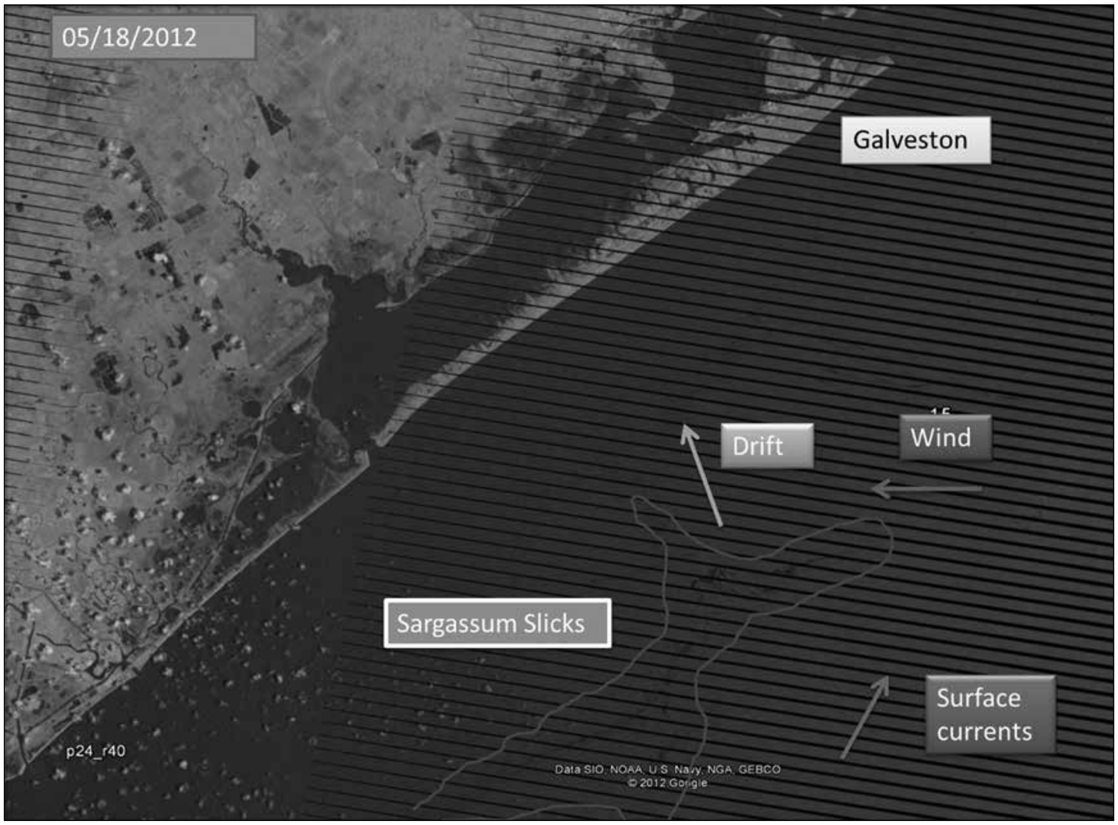

Figure 2. Satellite imagery with large *Sargassum* slick present direction of wind and surface currents are calculated to get an average drift direction. A LANDSAT image from Galveston's near coastal waters, taken 18 May 2012. Data available from the U. S. Geological Survey.

METHODOLOGY

There are three components to the SEAS methodology for predictions: satellite imagery, the *Sargassum* System Loop, and historical data trends. Satellite imagery is monitored during the *Sargassum* season, which lasts from January through August. Once *Sargassum* slicks are located and identified, SEAS monitors speed and direction of surface current and wind speed. After determining the direction and speed of the *Sargassum* drift, the predictive model calculates the distance to shore. An initial estimate of landfall is predicted while the model continues to monitor changes in all variables.

Satellite imagery

The three sectors are monitored by LANDSAT satellite system. The LANDSAT imagery has a much higher resolution, but its images are only available once every 16 days. The files are enlarged to make smaller *Sargassum* slicks more clearly discernible. This satellite imagery system provides a snapshot of probable *Sargassum* sightings. Once the satellite imagery suggests probable sightings, surface steering systems such as surface and wind currents are monitored to predict the landing location.

Current and wind

Surface currents have two distinct drivers. First are the upper-level currents. Data on these currents are retrievable through near-shore weather buoys that are maintained by the Geochemical and Environmental Research Group (GERG) of Texas A&M University. Each observation zone has at least one buoy in close proximity to the coast, as depicted in Figure 3. These buoys have current meter gauges, fixed at a depth of two meters, to detect current direction and speed. Detailed locations and real-time and historic data are available at the Texas Automated Buoy System website (http://tabs.gerg.tamu.edu/Tglo/).

The second driver of surface currents is surface wind, which can affect currents for less than 1 meter in depth (Xu 1997). The directions and speeds of these surface currents are obtained as the sum of the Ekman spiral and a Stokes drift (Xu 1997). The computed surface mass transport speed is roughly equal to three percent of the wind speed, and it is approximately 10 degrees to the right of the wind direction in the Northern Hemisphere (Xu 1997).

Using the mariners' set and drift method for our application, we use the 2-meter-depth ocean current as our set (i.e. initial direction and speed of movement) and the adjusted surface winds as our drift. Based on these figures, the relative speed and direction of the *Sargassum* can be calculated, and the landing location can then be predicted (Figure 3). Beach cameras and coastal managers' feedback at each sector can confirm the predicted landings.

Once *Sargassum* sightings have been detected on the satellite imagery and once the steering systems have been analyzed, the *Sargassum*'s direction and speed are plotted. If a probable landfall can be established, then an estimated landfall timeframe is reported to the appropriate sector's beach manager. The landing is confirmed by ground truthing, feedback from managers, and observations of the team's multiple beach cameras strategically located within the three monitoring sectors. The cameras are located at South Padre, Port Aransas, Surfside, Galveston, and the Bolivar Peninsula.

HISTORICAL RECORDS

During the last 150 years, there have been reports of periods in which frequent, heavy *Sargassum* landings plagued Texas beaches. The team's initial efforts of beach coring (the extraction of one-meter-depth core samples along the beach face) proved ineffective because of *Sargassum*'s rapid decomposition after it makes landfall. Hence, the team's historic research shifted toward archived newspapers in the municipal libraries located along the Texas coast (see Figure 3).

Figure 3. Image of Galveston shoreline, circa 1894, with two distinct lines of *Sargassum* wracks along the beach. Courtesy of the Galveston and Texas History Center, Rosenberg Library.

Archived data from each sector's local newspaper were searched for *Sargassum* references (Table 1). Historic newspapers such as *Galveston Daily News* were examined to find articles mentioning any excessive presence of *Sargassum* on Texas coastal beaches. The search included the term "Sargassum" as well as other words used to describe the plant, such as seaweed, hollyweed, iodineweed, gulfweed, and ironweed. The resulting references were further investigated to determine whether there were actual complaints about, or observations of, excessive *Sargassum* wracks on the beach, and marked as valid or invalid, respectively.

The earliest reported efforts of Galveston businesses to control the excessive beach cast of *Sargassum* date back to 1935; Galveston laborers carefully loaded excessive *Sargassum* onto barges, towed them offshore, and then pushed the seaweed off the barge, only to see the *Sargassum* return to the beach. This event was described by a Brownsville reporter who watched the laborers' efforts (Buell 1935). Earlier, in 1930, a contest was held by Galveston's Chamber of Commerce to solicit ideas and solutions for the beach cast of seaweed. A local gardener won the $10 prize for the idea of using *Sargassum* for fertilizer around pumpkin vines (*Galveston Daily News*, 17 August 1930).

Table 2. Sargassum cycles in Galveston from 1891 through 2007.

***Sargassum* peak years (Galveston sector)**	**Number of valid complaints**
1891-1897	12
1931-1936	18
1954	16
1962-1969	35
1989	20
1999-2007	36
Other years	28

The earliest historic record of *Sargassum* on the beach dates back to 27 January 1864, when a report was filed in the Galveston newspaper. Confederate military scouts, who saw no chance of escaping from Union soldiers, abandoned their horses and secreted themselves in the sand hills. They covered themselves with sand and seaweed and remained there until the enemy passed; then they crawled out of their holes and made for camp (*Galveston Weekly Newspaper*, 27 January 1864).

RESULTS

Historical newspapers

A historic timeline was created for each city along the Texas coastline, including Galveston, Corpus Christi, and South Padre Island (Brownsville). These cities were targeted because of their proximity to the Texas coastline. Articles that included complaints or reports of excessive *Sargassum* wracks were filed by location and date. For example, using the Galveston historic newspaper's data and searching between 1866 and 2008, the team found 1,810 references to the *Sargassum* plant. The majority of these articles discussed elixirs, used-car salesmen, baseball teams, and crossword puzzles, rather than the actual plant, and such references were considered invalid for our purposes. The search also revealed 164 articles related to excessive *Sargassum*, and these 164 references were categorized by their dates of publication.

A cyclical pattern was observed, beginning with a phase that lasted from 1891 through 1897; during that time, 12 references of excessive *Sargassum* on Galveston's beaches were reported. On the other hand, between 1898 and 1930 — a period of 32 years — there were only two references of Sargassum landings. As a result of this analysis, a cyclical

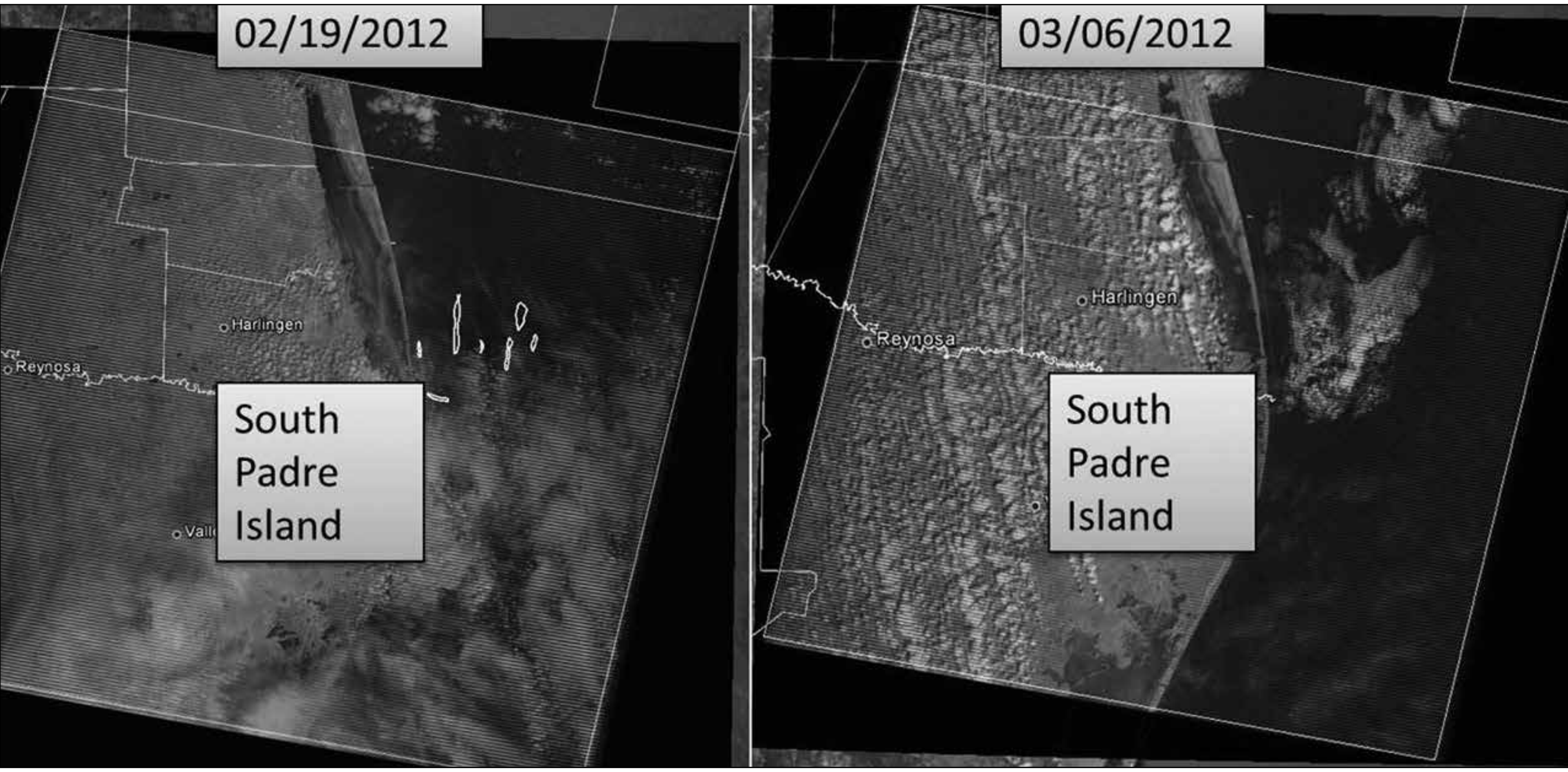

Figure 4. Landsat visual assistance from Robert Hardy from the Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute. The irregular white shapes represent *Sargassum* lines, as depicted on satellite imagery. Data available from the U.S. Geological Survey images, overlaid onto Google Earth.

pattern has been identified over the last 117 years. There are six to eight years of excessive *Sargassum* wracks on the beach, followed by 30 to 35 years during which *Sargassum* is not a significant issue. Anomalies to this pattern have occurred during only two years, 1954 and 1989, where there were numerous *Sargassum* reports (16 and 20, respectively), surrounded by years of few or no *Sargassum* reports. There are four cycles and two anomalies of heavy *Sargassum* landings, creating a cycle that spanned 32 years and accounted for 83% of all *Sargassum* complaints during the last 117 years of *Galveston Newspaper*'s historic data (Table 2).

All of the significant references were categorized by months, which revealed that June accrued the most references in Galveston. In Corpus Christi, May had the most references, and in South Padre (Brownsville), the most references occurred in April.

Archived satellite imagery

The SEAS team correlated archived satellite imagery in conjunction with the archived newspaper articles from the *Galveston Morning News*. The most recent period of heavy *Sargassum* landings occurred between 1999 and 2007. The LANDSAT imagery for the upper Texas coastline during that time contained minimal cloud cover and hence provided optimum imagery for comparison with the articles. For example, the 6 March 2000, LANDSAT satellite imagery off the coast of Galveston depicted several *Sargassum* slicks approximately 30 miles off shore. Twelve days later, on 18 March 2000, numerous *Sargassum* landings were reported along Galveston Island in the *Galveston Morning News*. The SEAS team assessed subsequent years for archived satellite imagery and cross-referenced the sightings with newspaper articles or reports of *Sargassum* landings. On 12 May 2001, several *Sargassum* lines were captured with LANDSAT imagery. Fifteen days later, large amounts of *Sargassum* landed on the beach and were reported "as a nuisance" in the *Galveston Morning News*.

Subsequent years showed similar cycles. Satellite imagery from 2002 through 2005, for example, showed *Sargassum* lines. The period between 2006 and 2010 showed a significant decline in *Sargassum* landings; only a few complaints were published in the local newspapers. In 2011, there were two significant episodes of *Sargassum* wracks on Galveston's beaches. Prior to both landings, multiple *Sargassum* slicks were depicted in both satellite imageries (Table 3).

Based on these findings, the SEAS team began developing a model to predict *Sargassum* landings by monitoring all available satellite imagery for *Sargassum* slicks. On 4 February 2012, *Sargassum* was depicted on satellite imagery in the near coastal waters of Padre Island, Texas. Based on the surface currents from the north, which were moving at 0.34 nautical miles per hour, and winds from the northeast at 15 nautical miles per hour, the SEAS team issued an advisory to the beach managers, predicting a *Sargassum* landing on South Padre Island on 8 February 2012. The accuracy of the landfall was within 10 hours.

The SEAS team located via satellite imagery a potential *Sargassum* landing and issued an advisory for beach managers on 12 February 2012, when *Sargassum* was located 75 miles north of South Padre Island. Both the surface current and the wind current were driving the *Sargassum* toward the south, and within four days, *Sargassum* made landfall on South Padre's shoreline. On 19 February

Table 3. Time span between satellite images and actual Sargassum landings on Galveston Island

Date of image	Date of landing	Galveston newspaper articles
3/6/2000	3/18/2000	"Large amounts of seaweed piled up on the beach."
5/12/2001	5/27/2001	"Large amounts of Sargassum were present on beaches, but the plant was not harmful."
4/21/2002	5/14/2002	"Huge mats of Sargassum, as large as several football fields, washed up on Galveston's beaches."
6/4/2004	6/7/2004	"Large mats of Sargassum landed on the beaches."
6/15/2005	6/23/2005	"A Sargassum smell returned to the island."
4/27/2011	5/13/2011	"A large amount of Sargassum hit Galveston's beaches."
5/13/2011	5/26/2011	"More Sargassum hit Galveston's beaches."

2012, *Sargassum* lines were depicted on satellite imagery. These *Sargassum* slicks were located 10 miles off shore from South Padre Island. Using the surface currents, which were moving due east at 0.46 nautical miles per hour, and a light onshore wind of 5 nautical miles per hour, the SEAS team accurately predicted that these *Sargassum* slicks would not land on the nearby beaches. This finding was confirmed on 6 March 2012, when the *Sargassum* slicks had moved away from the shore without making landfall (Figure 4).

Another prediction and advisory occurred on 24 March 2012, when several large *Sargassum* slicks were depicted on satellite imagery, approximately 90 nautical miles off the Upper Texas coast. Surface currents were variable, but the average direction and speed of the currents was 0.32 nautical miles per hour, with surface movements heading, on average, north by northeast. The average wind speed was 15 nautical miles per hour from the southeast. The SEAS team predicted a probable *Sargassum* landing on Galveston's beaches within 14 days. Beach managers were advised of the incoming *Sargassum* and were able to prepare for the landfall. On 3 April 2012, large amounts of *Sargassum* landed on Galveston's beaches.

CONCLUSIONS

Using a variety of data sources to form a predictive model, we can accurately predict landings of *Sargassum* on Texas beaches. There is a clear need for a *Sargassum* early advisory system for Texas coastal managers. The SEAS team has responded by developing the ability to detect *Sargassum* slicks in the near coastal waters along the Texas coastline by using its short-term predictive model. Once the *Sargassum* slicks are detected, the team uses both ocean surface currents and surface winds to predict probable *Sargassum* landings. During the 2012 *Sargassum* season, the team was able to give as much as 14 days of notice for each *Sargassum* landing. This information gave beach managers the necessary time to reschedule in advance personnel and rent vital equipment, at a reduced cost, to assist in their management of the *Sargassum* wracks on their beaches.

However, there is a distinct need for the SEAS team to increase its abilities to predict *Sargassum* arrivals on a seasonal basis so that coastal budgets can more accurately reflect beach maintenance funding requirements. With adequate funding, the team will be able to monitor the *Sargassum* migratory loop system and address these needs. In Phase 2, the team will expand its use of LANDSAT imagery to track the *Sargassum* contained in eddies that are drifting in the Gulf of Mexico. The team will test theories about why some eddies drift westward until they nearly reach the northern Mexico coastline before dissipating, leaving their *Sargassum* slicks to drift northward. The team will track *Sargassum* slicks that move through the Yucatan straights and enter the Loop Currents. The SEAS team has already taken pictures of *Sargassum* windrows as they move through the Caribbean seas. In Phase 2, the team will begin analyzing all available satellite imagery in order to monitor this movement remotely. Additionally, the team has begun to compile a detailed database of *Sargassum* references in the Windward Islands. To pursue the ultimate goal of seasonal prediction, key data sets with the historic *Sargassum* landings and the Oscillation of the Azores high-pressure system will be analyzed. If the North Atlantic Oscillation (NAO) and *Sargassum* landings are, in fact, interrelated, then this connection could provide the missing piece needed to create seasonal predictions of *Sargassum* landings on the Texas Gulf Coast.

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