GROUND TRUTHING *SARGASSUM* IN SATELLITE IMAGERY:

ASSESSMENT OF ITS EFFECTIVENESS AS AN EARLY WARNING SYSTEM

A Thesis

by

WENDY HAMMOND TABONE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF MARINE RESOURCES MANAGEMENT

December 2011

Major Subject: Marine Resources Management

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Approved by:

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ABSTRACT

Ground Truthing *Sargassum* in Satellite Imagery: Assessment of Its Effectiveness as an Early Warning System. (December 2011)

Wendy Hammond Tabone, B.A., University of Houston-Clear Lake

Co-Chairs of Advisory Committee: Dr. Thomas La Rue Linton
Dr. Wyndylyn M. von Zharen

Large aggregations of *Sargassum,* when at sea, provide important habitat for numerous marine species of vertebrates and invertebrates. It is especially important for the young of several species of sea turtles. However, when large aggregations of *Sargassum* come ashore on beaches frequented by tourist it is often viewed as a nuisance or even a health hazard. It then becomes a burden to beach management and has to be physically removed as quickly as possible. Many Gulf coast beaches suffer from *Sargassum* accumulation on a regular basis. Timely information on the size and location of the *Sargassum* habitat is important to developing coastal management plans. Yet, little is known about the spatial and temporal distribution of *Sargassum* in the Gulf of Mexico. There is no systematic program to assess the distribution of the macroalgae, therefore practical management plans are difficult to execute.

In 2008, Gower and King of the Canadian Institute of Ocean Sciences along with Hu of the University of South Florida, using satellite imagery, identified extensive areas of *Sargassum* in the western Gulf of Mexico. These were not confirmed with ground

truthing data. To date ground truthing observations have not been directly compared with the corresponding satellite images to confirm that it was in fact *Sargassum*, as the satellite images suggested.

By building on the information and research methods of Gower and King, current ground truthing data taken from Texas Parks and Wildlife Gulf trawl sampling surveys was analyzed. In addition, shoreline information and imagery was used to substantiate the data derived from current Moderate-resolution Imaging Spectroradiometer (MODIS) Enhanced Floating Algae Index (EFAI) images. As part of the NASA sponsored research project *Mapping and Forecasting of Pelagic Sargassum Drift Habitat in the Gulf of Mexico and South Atlantic Bight for Decision Support*, NASA satellite MODIS EFAI images provided by Dr. Hu were used to identify and substantiate corresponding floating *Sargassum* patches in the Gulf of Mexico.

Using the most recent advances in technology and NASA satellite remote sensing, knowledge can be obtained that will aid future decision making for addressing *Sargassum* in the Gulf of Mexico by substantiating the data provided by satellite imagery. Findings from this research may be useful in developing an early warning system that will allow beach managers to respond in a timely manner to *Sargassum* events.

DEDICATION

This thesis and the success of my research are dedicated to my children Sierra, Sianna and Christian Tabone. I hope I have made you proud.

ACKNOWLEDGEMENTS

This research was supported by the NASA ROSES-2009: Gulf of Mexico Grant *Mapping and Forecasting of Pelagic Sargassum Drift Habitat in the Gulf of Mexico and South Atlantic Bight for Decision Support,* the University of South Florida and Texas A&M University. I am especially grateful for my internships with NOAA, Texas Sea Grant and Texas Parks and Wildlife for opening my world up to the wonders of a career in the Marine Sciences.

I would like to thank my committee co-chairs, Dr. Linton and Dr. von Zharen, for their guidance and support throughout the course of this research. Dr. Linton had the vision to see the importance this research can have on the Texas coast and beyond. I am extremely grateful for the faith he placed in me to undertake such an important project. Dr. von Zharen's diligent guidance, motivation, support, editing skills, and encouragement throughout this entire process was invaluable. I would have never attained the courage and ability to undertake and complete such complex research without her brilliant instruction, wonderful enthusiasm and tireless positive attitude. I would also like to thank my committee members, Dr. Lesko, and Dr. Schlemmer for their support and guidance throughout the process that resulted in the completion of my master's program. Dr. Hu and his team at the University of South Florida, thank you for your brilliant work that made this project a success.

Thanks also go to my friends and colleagues with Texas Parks and Wildlife's Coastal Fisheries Division. I am eternally grateful to Mr. Bill Balboa for allowing me access to the Gulf trawl data. Not only did he provide me the opportunity to live my dream, get my feet wet and get a paycheck, his generosity saved this project and my thesis!

I also want to extend my gratitude to my friends and colleagues at Texas A&M Galveston, Texas Sea Grant and NOAA's OLE for making my graduate program a wonderful experience. I especially want to thank SA Matt Clark, SA Charles Tyer, Lyndsey Howell, Alyson Azzara, T. C. Riddle, Sarah Norman and Bill Elizondo. I am truly blessed to have worked with such wonderful, brilliant and generous friends.

Finally, thanks to my mother, my husband and my three beautiful children for their encouragement, faith, patience and love. It was not an easy journey from stay at home mom to graduate student; I could not have accomplished so much without each of you supporting me.

NOMENCLATURE

CCA	Coastal Conservation Association
Chl-a	Chlorophyll a
CI	Color Index
EFAI	Enhanced Floating Algae Index
EOS	Earth Observing System
ERGB	Enhanced Red Green Blue Image
ESA	European Space Agency
EVI	Enhanced Vegetation Index
FAI	Floating Algae Index
FLH	Fluorescence Line Height Image
GBS	Galveston Bay System
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GOM	Gulf of Mexico
GPS	Global Positioning System
MCI	Maximum Chlorophyll Index
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate-resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
RGB	Red Green Blue Image

RRC	Rayleigh-corrected Reflectance
SABS	San Antonio Bay System
SeaDAS	SeaWiFS Data Analysis System
SLS	Sabine Lake Bay System
SPI	South Padre Island
SST	Sea Surface Temperature Image
TPWD	Texas Parks and Wildlife Department
TGLO	Texas General Land Office
USF	University of South Florida
VIIRS	Visible Infrared Imager/Radiometer Suite
WGOM	Western Gulf of Mexico

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 Background

Sargassum is a pelagic plant of the brown algae family. It occurs primarily in the North Central Atlantic Ocean and the Gulf of Mexico (GOM). *Sargassum natans* and *Sargassum fluitans* are the two species of *Sargassum* that commonly inhabit U.S. waters (Figure 1). These two species are holopelagic and are frequently found floating together. Aggregations of floating *Sargassum* provide important habitat including, food, shade, and shelter from predators, for fish, shrimp, crabs, and other marine organisms, as well as several threatened species of turtles (Evans, 1998). Many sports fishers seek out the "weed lines" for prime fishing areas (Ferrell, 2001). Numerous species of game fish are known to feed and congregate around these floating mats of Sargassum (Viles, 2009).

Often large amounts of Sargassum, cast up on Texas beaches. Tourism makes a substantial contribution to the economy of coastal Texas with visitors to the beach a primary draw (Viles, 2009). Excessive *Sargassum* on beaches is often viewed as a persistent nuisance and is a burden to beach managers since it has to be physically removed as quickly as possible. Many Gulf coast beaches suffer from Sargassum accumulation on a regular basis (Viles, 2009).

This thesis follows the style of *Remote Sensing of Environment*.

FIGURE 1 *Sargassum fluitans* and *Sargassum natans* (Rooker, 2011).

For example, the beaches of Galveston Island experience *Sargassum* castings typically during late spring/early summer – the height of the tourist season and therefore of significant economic importance to the island and county. The accumulation inspires much debate on management plans among numerous stakeholders including property owners, business owners, recreational fishers, tourists, and local municipalities and governments. Previous data from the Galveston Park Board of Trustees suggest that annual management costs of a *Sargassum* landing event can reach over $200,000 for a light event to more than $800,000 for a heavy event (Hu, Muller-Karger, Chambers, Linton, Witherington, & Lapointe, 2009).

All along the Texas coast heavy machinery is used, often on a daily basis, to remove *Sargassum* from the beach (Viles, 2009). Timely information on the size and location of the *Sargassum* habitat is important to developing coastal management plans.

Currently, stakeholders have no means to predict *Sargassum* landing events. Beach managers would be able to prepare resources in advance of *Sargassum* landings if a reliable system were in place that would provide advance warning. However, little is known about the spatial and temporal distribution of *Sargassum* in the GOM. There is no systematic program to assess *Sargassum* distribution therefore practical management plans are difficult to formulate.

The origin of *Sargassum* has long been assumed to be the Sargasso Sea, a region in the middle of the North Atlantic Ocean that is dominated and maintained by a pattern of ocean currents (McKenna & Hemphill, 2010). It is bounded on the west by the Gulf Stream; on the north by the North Atlantic Current; on the east by the Canary Current; and on the south by the North Atlantic Equatorial Current (Figure 2). However, in 2008, Gower and King of the Canadian Institute of Ocean Sciences, used satellite imagery to produce data that suggest *Sargassum* is primarily "born" in the northwest Gulf of Mexico during the spring months (Gower & King, 2008); therefore, my research seeks to establish a ground truth basis for developing a protocol to identify *Sargassum* on Enhanced Floating Algae Index (EFAI) filtered satellite images.

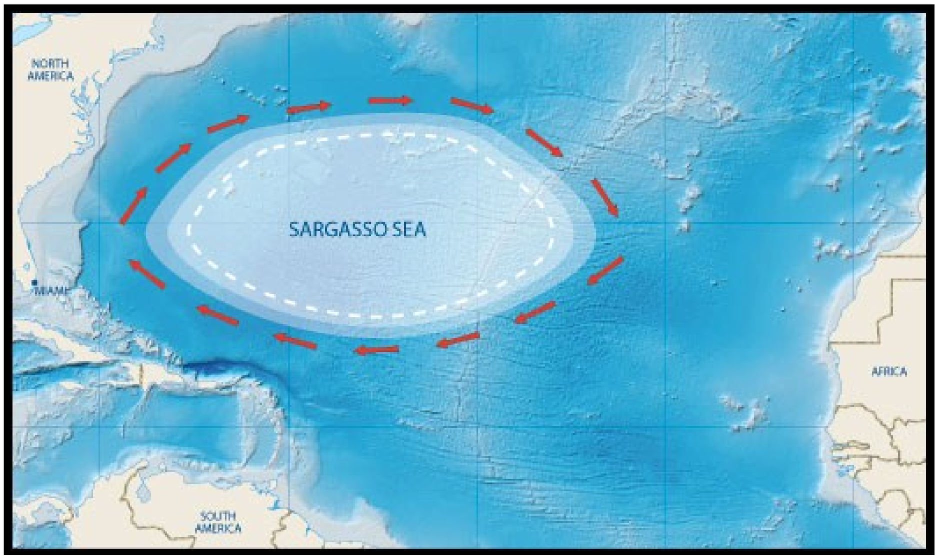


FIGURE 2 Map of the Sargasso Sea (Dougherty, 2011)

The remote sensing products used in this research are available as a result of the NASA ROSES-2009 grant project*: Mapping and Forecasting of Pelagic Sargassum Drift Habitat in the Gulf of Mexico and South Atlantic Bight for Decision Support,* herein after referred to as the NASA *Sargassum* project. The success of this project is a result of joint research efforts among the University of South Florida, Texas A&M University at Galveston, Florida Fish & Wildlife Conservation Commission, and Florida Atlantic University. The project seeks to fill gaps in the knowledge regarding *Sargassum* abundance/distributions and their future trends. The research team seeks to produce a suite of end products that will aid stakeholders in making management and research decisions using the most recent advances in algorithm development and NASA Earth Observing System (EOS) data. This portion of the project produced a basis for substantiating *Sargassum* evidence that the EFAI images suggest. Future researchers may be able to apply this protocol for developing an early warning system for *Sargassum* accumulation.

1.2 Remote Sensing

Remote sensing is the art, science, and technology of acquiring information about a subject through the analysis of data acquired by a device that is not in contact with the subject under study (Lillesand, Kiefer, & Chipman, 2004). Remote sensing is typically conducted by means of sensors that can detect objects and features that are not in direct contact with the sensor instruments (Figure 3).

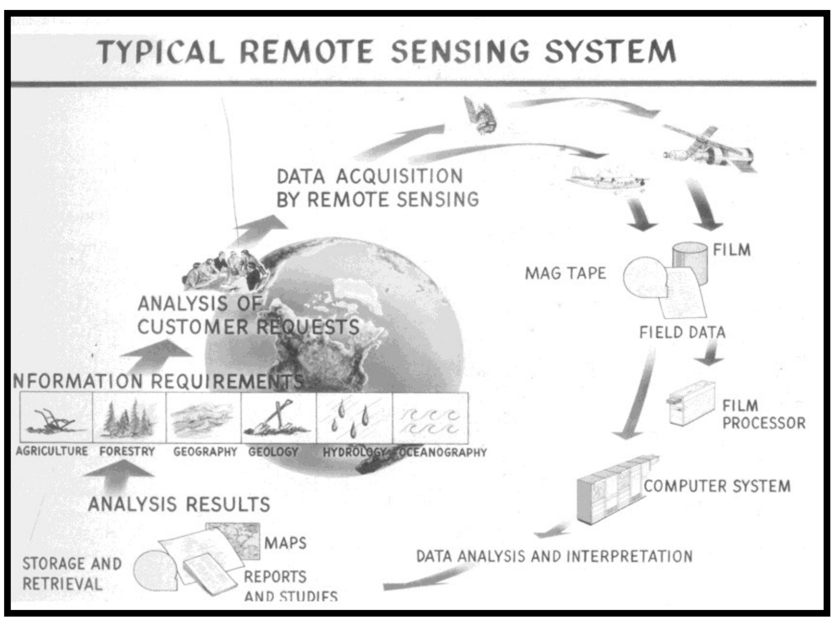


FIGURE 3 Typical remote sensing system (Short, 2011).

Remote sensing of natural features such as bodies of water consists of data acquisition, analysis, and interpretation of electromagnetic energy or light emitted and reflected by the feature (Short, 2011). Vegetation can be identified using remote sensing operations. Plant matter can be distinguished from most other materials by virtue of its notable absorption in the red and blue segments of the visible spectrum and its higher green reflectance (Short, 2011). In particular, marine and fresh water vegetation can be detected by remote sensing means.

A Floating Algae Index (FAI) is used to detect vegetative material on the ocean's surface such as *Sargassum*, green macroalgae, and cyanobacteria. Hu demonstrated that FAI is a stable index that can be used to distinguish floating *Sargassum* under a number of atmospheric variables and observing conditions (Hu, 2009). FAI is derived as the reflectance at 859 nm (after correction for gaseous absorption and molecular scattering), referenced against a linear baseline between 645 nm and 1240 nm (Hu, 2009). FAI has been used to study Qingdao, China's green tides (*Ulva prolifera* blooms), cyanobacteria blooms in Taihu Lake, China and to detect Trichodesmium blooms in coastal waters of the west Florida shelf (Hu, Cannizzaro, Carder, Muller-Karger, & Hardy, 2010).

This research used Enhanced Floating Algae Index (EFAI) images. As with FAI, EFAI detects ocean surface features such as *Sargassum*, green macroalgae, and cyanobacteria. EFAI is nearly identical to FAI except that one of the spectral bands to construct the background is 667 nm instead of 645 nm. Thus, it is more sensitive than FAI in detecting subtle ocean surface features.

Using remote sensing data in the form of optical radiance images from the Medium Resolution Imaging Spectrometer (MERIS), Gower and King along with Hu identified extensive areas of *Sargassum* in the western Gulf of Mexico in the summer of 2005 (Gower, Hu, Borstad, & King, 2006). Their data suggest that it is then transported through the Straits of Florida and out into the open Atlantic Ocean. *Sargassum* mats then converge off Cape Hatteras, North Carolina before ending northeast of the Bahamas in February of the following year.

1.3 Research

Lack of research dedicated to the spatial and temporal distribution of *Sargassum* in the Gulf of Mexico, as opposed to the North Atlantic, has hampered efforts to predict and address the movements of pelagic *Sargassum* onto Texas beaches. Prior to Gower and King's research, previous efforts relied on records from ship surveys that were not dedicated to *Sargassum* assessments, or from very sporadic and expensive aircraft surveys (Gower & King, 2008). Reports of *Sargassum* accumulations near shore and on the beach are found in local news media or when fishers decide to report these, but there is no systematic program to assess the distribution of this macroalgae. Therefore, the distribution, including seasonal, inter-annual, and long-term variability, is unknown at this time. Furthermore, ground truth data have not previously been reconciled with the corresponding satellite images to provide credibility to the evidence of *Sargassum* that the satellite images suggest. For this part of the NASA *Sargassum* project, NASA satellite Moderate-resolution Imaging Spectroradiometer (MODIS) images were used that had been filtered by Dr. Hu's research team at the University of South Florida, to identify corresponding floating *Sargassum* patches in the GOM.

By building on the information and research methods of Gower and King, current ground truth data taken from Texas Parks and Wildlife Department's (TPWD) Gulf trawl surveys were used to substantiate the data derived from current MODIS images. This method of using satellite data to map *Sargassum* distributions has been successfully used by Gower (Gower, Hu, Borstad, & King, 2006) and Gower and King (Gower & King, 2008) and recently updated by Hu (Hu, Cannizzaro, Carder, Muller-Karger, & Hardy, 2010). Consistent, reliable ground-truth data, however, have not previously been used to support the findings that the satellite images suggest.

1.4 Ground Truthing Data

Ground truthing is the process of gathering data in the field that either complements or disputes airborne remote sensing data collected by aerial photography or satellite images (Groundtruthing, 2011). Ground truthing can be used to describe techniques used in analysis of the reliability of data derived from a range of remote sensing applications in which data are gathered remotely. In remote sensing, this is especially important in order to compare image data with real features and materials. The collection of ground truth information enables calibration of remote-sensing data, and aids in the interpretation and analysis of what is being sensed.

More explicitly, for this project, ground truthing refers to the process in which satellite images are compared to geographically corresponding data that was collected independently in order to verify the contents that the remote images suggest. In this case, ground truthing is done within the same area of the Gulf of Mexico in which the MODIS images were taken. It also involves using GPS technology to gather coordinates at the sample sights and comparing those with the coordinates of the image being analyzed. Ground truthing data are important in the initial clarification of a remote image's content, and also help with atmospheric correction since images from satellites obviously have to pass through the atmosphere and can get distorted because of absorption in the atmosphere or excessive cloud cover. Therefore, the collection and analysis of ground truthing data are important tools in substantiating and identifying objects and data in satellite photos.

The first source for my ground truthing data was Texas Parks and Wildlife Department's (TPWD) Gulf Trawl database. TPWD's Dickinson Marine Lab field office conducts a long term resource monitoring program based on random sampling to assess changes in the abundance and size of organisms, their spatial and temporal distribution, species composition and environmental parameters (Andrade, Fisher, Bowling, & Balboa, 2009). Coastal areas of the Gulf of Mexico are divided into a grid that is then randomly selected for surveying. All organisms, both flora and fauna, captured in TPWD Coastal Fisheries sampling gear are identified, measured and recorded. In addition, at each selected station, water depth and temperature, dissolved oxygen levels, salinity and turbidity are recorded before sampling begins. A 6.1 m (20 ft.) wide otter trawl with 38 mm (1.5 in) mesh is deployed and towed at 3 mph for 10 minutes parallel to the fathom curve within the selected stations parameters (Andrade, Fisher, Bowling, & Balboa, 2009).

A second source for ground truthing data came from a *Sargassum* occurrence journal that was kept for the months of February to May 2011. *Sargassum* notations from beach cams, surf reports and NOAA beach surveys were documented as supporting ground truth data of *Sargassum* accumulation onshore (APPENDIX C).

1.5 Objectives

Using the most recent advances in both technology and NASA satellite remote sensing, this research will contribute to the knowledge of the abundance and distribution of *Sargassum* in Texas waters which in turn will aid future decision making regarding the harvesting, research, and beach management of *Sargassum* in Texas coastal waters. By developing and implementing a protocol to substantiate the data provided by satellite imagery, the ground work will be set for the development of a prototype system for tracking and predicting *Sargassum* inundations. An early warning system will benefit stakeholders in the private sector as well as scientists by providing a proactive planning tool.

CHAPTER II

LITERATURE REVIEW

2.1 *Sargassum*

2.1.1 Early Studies

The Sargasso Sea is the only sea without land forming its boundaries. In the absence of a coastline to delineate its margins, biological features, oceanic gyres, and currents have been used to describe the sea's location and extent. This unique marine ecosystem is confined by currents circulating around the North Atlantic sub-tropical gyre and is thus far, believed unique in its ability to sustain a community of continuously pelagic drift algae (McKenna & Hemphill, 2010). The Sargasso Sea provides habitats, spawning areas, migration pathways, and feeding grounds to varied types of flora and fauna, including endemic, endangered, and commercially important species (McKenna & Hemphill, 2010).

Much of the early research that was conducted on *Sargassum* focused on this North Atlantic Area known as the Sargasso Sea as opposed to the vegetation itself. In the days of wooden sailing ships, the Sargasso Sea was identified as an area to be avoided. Tales of crews dying of thirst and starvation after their vessels were caught in the dense mats of *Sargassum* that collected in the oceanic gyre flourished after they were reported by lucky survivors (Quigg & Wardle, 2008). Imaginative nineteenth-century paintings often depicted sailing vessels being consumed by the seaweed that gives the area its name. Portuguese sailors noted the floating macroalgae's air-filled bladders' resemblance to grapes and thus deemed it salgazo, the Portuguese word for grape (Ferrell, 2001).

Much like the myths of the Bermuda Triangle, the legends of the Sargasso Sea have some basis in fact. Some of the sea's illustrious reputation comes from its location. In the almost windless latitudes, ships would often flounder within the area, virtually immobile without great gusts to fill their sails. Sailors from the time of Columbus described and recorded great ominous, floating mats of drifting sea weed. During Columbus's lifetime, stories abounded regarding ships that became stuck in the seaweed, and mythical monsters that emerged from the seas and swallowed whole crews and vessels. Columbus and his men were familiar with these stories and his anxiety about their voyage through the still waters of the Sargasso Sea is apparent from the ship's log in which he wrote: "We saw much weed of the kind I have already mentioned, even more than before, stretching to the north as far as you can see. In a way this weed comforted the men, since they have concluded that it must come from some nearby land. But at the same time, it caused some of them great apprehension because in some places it was so thick that it actually held back the ships" (Columbus, 1987).

Most of the early studies regarding *Sargassum* were attempts to apply a semi-quantitative approach to shipboard sightings of the floating sea weed. In 1878, German scientist O. Krummel based his investigations on records provided by German ships crossing the North Atlantic. From the ships' log-books, he derived calculations on *Sargassum* quantities that he used to define the boundaries of the Sargasso Sea.

Krummel's research resulted in one of the first charts mapping the distribution of pelagic *Sargassum* (Parr, 1939). In 1923, Winge attempted a different approach from Krummel's for gathering *Sargassum* samples for study by using research and merchant ships as the source for his data (Winge, 1923). Quantities and collection methods differed from ship to ship and therefore, Winge's findings are used primarily for determining boundaries for the presence or absolute absence of the buoyant macroalgae. Furthermore, he concluded from his studies that pelagic *Sargassum* grows and reproduces within the confines of the Sargasso Sea as opposed to being separated from a growing substrate on a distant shore or bank (Stoner, 1983).

2.1.2 Recent Studies

In 1939, A. E. Parr, an oceanographer at Yale University, completed a landmark study of *Sargassum* and the Sargasso Sea. Parr reported on "a series of hydrographic cruises to the Central American Seas on the research ship "Atlantis," sponsored jointly by the Woods Hole Oceanographic Institution and by Yale University" (Parr, 1939). Building on the early work of Krummel and Winge, Parr developed a protocol that would scientifically quantify and describe pelagic *Sargassum* and the Sargasso Sea. A surface scoop-net, explicitly designed for collecting *Sargassum*, was towed by the research vessel between predetermined areas. During the voyage, the net was towed "over a cumulative distance of seven thousand (6998) nautical miles, with a total of nearly five thousand (4759) pounds of pelagic weeds bought on board for sorting and weighing" (Parr, 1939). Parr was particularly concerned with describing the flora's physiology along with their quantitative distribution in the area. Extensive illustrations and descriptions were created based on the samples collected. Emphasis was placed on the two most common taxonomic species collected; *Sargassum fluitans* and *Sargassum natans.* Parr reported that *natans* and *fluitans* comprised "99 per cent of the total pelagic vegetation of the investigated portion of the Sargasso Sea proper" (Parr, 1939).

Following Parr's published study in 1939, subsequent research was largely dedicated to physiology and sinking rates (Howard & Menzies, 1969), drift row formation (Faller & Woodcock, 1964), and associated biota ecology (Adams, 1960) (Bortone, Hastings, & Collard, 1977) (Dooley, 1972) (Fine, 1970) (Ryland, 1974).

Until Stoner published his article in 1983, prior records on the abundance of *Sargassum* primarily came from Parr's research in 1933 and 1935. Observations made from the R.V. *Westward* led Stoner to the conclusion that the biomass of the pelagic algae was diminishing. A comprehensive quantitative study was subsequently undertaken. "Dramatically less *Sargassum* was found in the Sargasso Sea than reported by Parr" (Stoner, 1983). Stoner concluded that pelagic *Sargassum* in the Sargasso Sea and the Gulf of Mexico had declined significantly in the years since Parr's study. He hypothisized that the decline could be due to environmental changes due to natural or anthropogenic catalysts, ocean climate deviations, or chemical pollutants but was unable to definitively determine the cause or causes in the biomass change.

The following year, 1984, Stoner revisited his findings and upon reanalysis determined that, in fact, there was "no signicant change in the biomass of *Sargassum* from 1933 to 1981, except for an area northeast of the Antilles" (Butler & Stoner, 1984). Apparently, upon reflection of the statistical data, when revised analyses were conducted and collection differences were considered, the data did not show massive declines in pelagic *Sargassum* as Stoner had first believed. Even with the discrepancies of the 1983 and 1984 studies, the scientific gains accomplished by Stoner are noteworthy for the attention they drew to the status and health of the *Sargassum* biomass within the Atlantic ocean.

2.2 Remote Sensing

2.2.1 Gower and King

In 2006, Gower, Hu, Borstad and King published an article, "Ocean color satellites show extensive lines of floating *Sargassum* in the gulf of Mexico", in which they presented satellite imagery that they interpreted as showing extensive lines of floating *Sargassum* in the western Gulf of Mexico (Gower, Hu, Borstad, & King, 2006). Their publication was one of the first reported studies focusing on the observations of *Sargassum* using remote sensing technology. Using optical radiance data from satellites, the researchers were able to identify extensive lines of floating *Sargassum* in the western Gulf of Mexico in the summer of 2005.

Data were generated from satellite observations using images from the European Space Agency's (ESA) Medium Resolution Imaging Spectrometer (MERIS) and

NASA's Moderate Resolution Imaging Spectro-radiometer (MODIS) satellites. The collective satellite data from both sensors indicated a seasonal cycle of weed density in different areas of the Gulf of Mexico. The data also suggested that *Sargassum* biomass was greater than previously assessed and perhaps played a more important role in oceanic productivity than previously considered.

The success in detecting *Sargassum* slicks with remote sensing technology provided a useful tool in the quest to monitor the biomass of floating algae. Further research was needed to confirm the researchers' interpretation of the data. In response, a wider ranging study was planned.

In 2008, Gower and King published a landmark study that firmly turned *Sargassum* research in a completely new direction; the Gulf of Mexico. What they hinted at in their 2006 article, they confirmed in 2008. Using satellite imagery, they presented the first mapping of the full distribution and movement of the population of *Sargassum* in the Gulf of Mexico and western Atlantic (Gower & King, 2008). Focusing on the years 2002 to 2008, their findings reenforced a proposed seasonal pattern in which *Sargassum* originates in the northwest Gulf of Mexico (Gower & King, 2008). Satellite images were interpretted as evidence that *Sargassum* is advected into the Atlantic in about July, appearing east of Cape Hatteras as a "*Sargassum* jet", and ending northeast of the Bahamas in February of the following year (Gower & King, 2008). This pattern appeared consistent with historical surveys performed by Parr, with the exception of the Gulf of Mexico origination detail.

The authors' made a case that *Sargassum* was an ideal candidate for remote sensing applications because the macroalgae are long lived, buoyant, and have a spectral image that strongly contrasts with surrounding water. Furthermore, they pointed out that previous limitations with remote sensing of *Sargassum* had recently been resolved. Technological advances in the application of sensor bands had addressed the lack of previous applications to detect a signal in the presence of cloud, haze and sunglint.

Using data from the European Space Agency's (ESA) MERIS sensor, they showed a highly variable yet emerging cycle of *Sargassum* distribution in the Gulf of Mexico and North Atlantic. A Maximum Chlorophyll Index (MCI) was used which provided a improved discrimination between floating and coastal vegetation and intense plankton blooms. Further analysis showed a significant rise in *Sargassum* biomass in the northern Gulf of Mexico with corresponding decreases in the Atlantic prior to injection from the Gulf. The team acknowleged the limitations of satellite derived remote sensing due to spatial resolution, cloud cover, sunglint, and mixing of floating algae below the surface line by wind.

2.2.2 Hu

Following his success with Gower in detecting *Sargassum* from satellite images, Hu published his further investigations: "A novel ocean color index to detect floating algae in the global oceans." Accurate and timely detection of varied types of floating algae using satellite data and algorithms had traditionally been difficult. The problems first faced by Gower's team - lack of spatial resolution, coverage, satellite revisit frequency, and algorithm limitations - still plagued researchers in their quest for an efficient and accurate means of detecting and tracking floating algae. Hu proposed using a simple ocean color index, the Floating Algae Index (FAI), for detection of floating algae in open ocean environments (Hu, 2009) using the medium-resolution (250- and 500-m) data from operational MODIS (Moderate Resolution Imaging Spectroradiometer) instruments. FAI is defined as the difference between reflectance at 859 nm (vegetation "red edge") and a linear baseline between the red band (645 nm) and short-wave infrared band (1240 or 1640 nm) (Hu, 2009).

Hu reported that with the use of data comparison and model simulations, FAI displayed advantages over the traditional NDVI (Normalized Difference Vegetation Index) or EVI (Enhanced Vegetation Index). He reasoned that since FAI is less sensitive to changes in environmental and observing conditions (aerosol type and thickness, solar/viewing geometry, and sunglint) and can "see" through thin clouds, that it was a more effective and reliable index for use in remote sensing research of floating *Sargassum*. A baseline subtraction process produced a less complicated but equally operational means for atmospheric correction. Research proved that floating algae could definitely be identified and delineated in various ocean waters, including the North Atlantic Ocean, Gulf of Mexico, Yellow Sea, and East China Sea (Hu, 2009). Due to the fact that comparable spectral bands exist on many current and, at the time, scheduled satellite sensors, including Landsat and VIIRS (Visible Infrared Imager/Radiometer Suite), Hu proclaimed that the FAI concept could present a platform for establishing a comprehensive research basis for significant ocean plants. Thus, Hu showed that FAI could be used as a reliable index for detecting and tracking floating algae distributions in the world's oceans.

CHAPTER III

METHODS AND MATERIALS

3.1 Overview

Coastal Conservation Association (CCA) funds summer internships/scholarships for Marine Science students at Texas A&M coastal campuses. Scholarship recipients work with Texas Parks and Wildlife (TPWD) coastal fisheries biologists in bay systems along the Texas coast. As part of my CCA/TPWD summer internship, I accompanied TPWD Dickinson Marine Lab staff on Gulf Trawl sampling surveys.

The data collected from these sampling trips form the basis of the ground truthing data used to compare to the EFAI satellite images. Data were collected from three major bay area systems: Galveston Bay System (GBS); Sabine Lake System (SLS); and San Antonio Bay System (SABS). The Galveston Bay area TPWD Gulf trawl data for the months of June – August 2011 are a result of the CCA internship sponsored sampling trips in which I participated. TPWD adheres to strict sampling protocols that result in valuable and accurate scientific data.

In addition, beginning in February of 2011 to May 2011, a journal was kept of notable *Sargassum* occurrences along the Texas coast. Beach cams, surf reports, websites, NOAA beach surveys, and beach observations were all documented for comparison with corresponding satellite data.

Along the Texas Gulf Coast beach communities, coastal resorts and beach managers administer and post beach websites and remote web cams as a form of public information and publicity for particular areas. By tracking the information and trends provided by these sources, the occurrence of *Sargassum* movements were tracked along the Texas coast and onto beaches. In addition, weekly NOAA administered Sea Turtle Stranding Network beach surveys provided an additional source of information for beach castings.

Data collected from the TPWD Gulf of Mexico trawls were used along with the supporting data provided from beach web cams, reports, and the *Sargassum* log to compare with corresponding EFAI satellite images obtained from Dr. Hu and the University of South Florida team.

3.2 Study Area

3.2.1 TPWD Data

Texas Gulf coast waters support important recreational and commercial fisheries. Monitoring of the ecosystem on which they depend for their existence helps to determine whether populations are increasing or decreasing and whether management actions may be necessary. Scientific monitoring of these biological resources is conducted by the TPWD. Along with fisheries-dependent commercial and recreational harvest data, fisheries-independent data are used to assess population trends in organisms. TPWD utilizes several sampling gears for fisheries-independent monitoring of finfish and shellfish communities. They include: 1) bag seines for collecting smaller organisms in near shore environments; 2) trawls for collecting organisms found on or near the open bay bottoms and coastal Gulf of Mexico (GOM) areas; 3) gill nets for catching larger fish near shore; and 4) oyster dredges for sampling the oyster reef community. The data generated by TPWD are some of the best coastal fisheries data in the United States (National Biological Information Infrastructure, 2011). Not only does TPWD use multiple gears in a random sampling protocol, they identify (to the lowest taxonomic unit possible) and count everything that they collect.

Collected data include spatial and temporal information describing the sample location and time, collection gear information, hydrological data (e.g., dissolved oxygen, water temperature, and salinity), weather conditions, species caught, number of each species captured, and vegetation occurrences (National Biological Information Infrastructure, 2011).

The TPWD's Coastal Fisheries Division samples ten estuarine systems (Sabine Lake, Galveston Bay, Cedar Lakes, East Matagorda Bay, West Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, Upper Laguna Madre and Lower Laguna Madre) and five Gulf areas within the Texas Territorial Sea (shoreline to nine nautical miles offshore) (Andrade, Fisher, Bowling, & Balboa, 2009) (Figure 4).

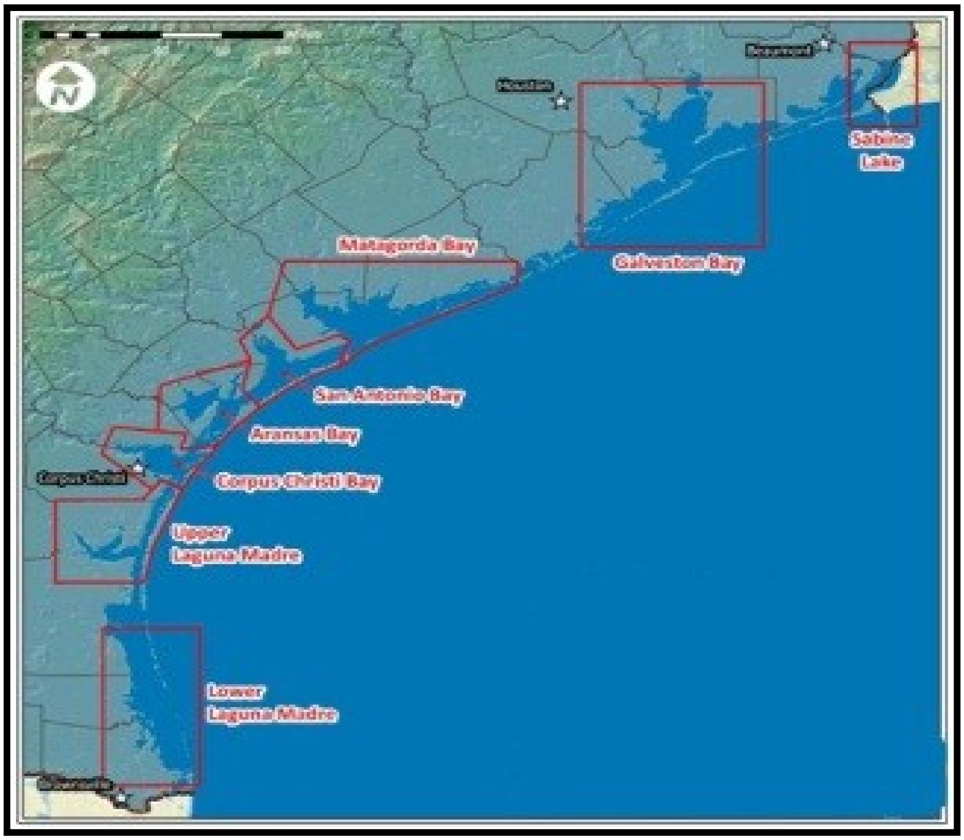


FIGURE 4 TPWD's Gulf of Mexico sampling areas. (National Biological Information Infrastructure, 2011)

Three GOM areas were sampled and data obtained was used for this study:

Sabine Lake System (SLS). All waters, including all saltwater bayous, bounded by a line behind the surfline from the north edge of Sabine Lake where the mouths of the Sabine and Neches Rivers enter the Lake to the bridge over the ICWW at High Island.

Galveston Bay System (GBS). All waters, including all saltwater bayous, bounded by a line behind the surfline from the bridge over the Inter Coastal Water Way (ICWW) at High Island to the southwestern shoreline of Drum Bay and the north edge of Trinity Bay where the Trinity River enters the bay.

San Antonio Bay System (SABS). All waters, including all saltwater bayous, between the eastern edge of the Chain of Islands in Pass Cavallo to the Chain of Islands in the western edge of Ayres Bay and all waters from the mouth of the Guadalupe River including Mission Lake, Guadalupe Bay and the lower delta of the Guadalupe River.

Monthly Gulf trawl sample areas are randomly selected from available TPWD Coastal Fisheries Gulf of Mexico sample grids within 15 miles both sides of a major pass and within the Texas Territorial Sea (Andrade, Fisher, Bowling, & Balboa, 2009). In the field, TPWD ecosystem members locate the trawl starting point in each selected grid by utilizing the Global Positioning System (GPS). GPS is a space-based global navigation satellite system (GNSS) that provides location and time information.

3.2.2 University of South Florida EFAI Satellite Images

Satellite data image areas for the Northwest Gulf of Mexico-Galveston Area were defined by the University of South Florida Team. The Galveston region was designed to show the Northwest part of the Gulf of Mexico with focus on the Galveston Island near shore area and is bounded by these coordinates: 29.8°N, 93.5W and 27.8°N, 96.5°W (Figure 5). Sabine, Galveston and San Antonio Bay Systems fall within these bounds. In April of 2011, a satellite image dedicated website was set up and made available on a daily basis for image retrieval and analysis by the University of Florida's Optical Oceanography Laboratory.

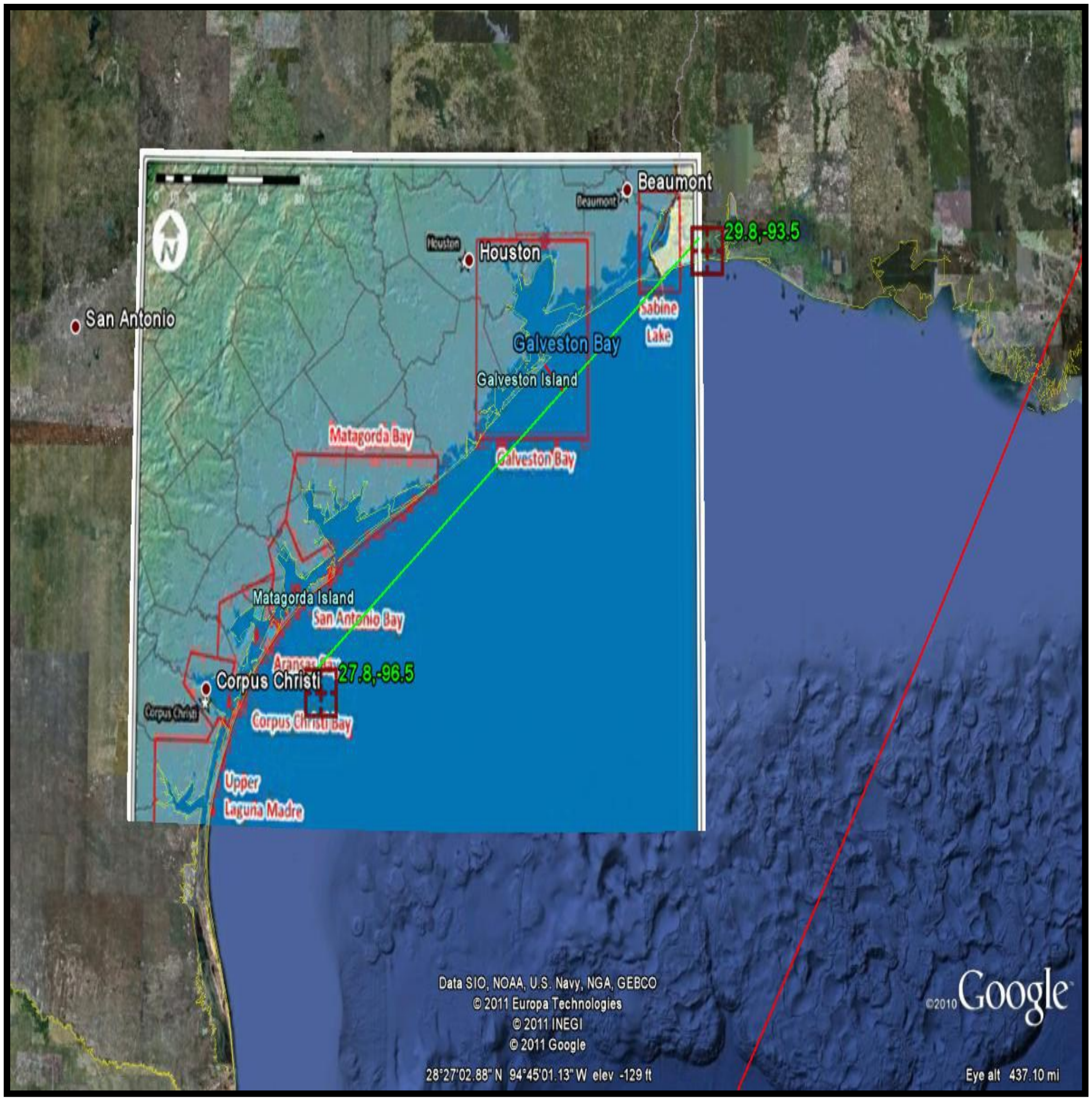


FIGURE 5 TPWD bay systems superimposed on Google Earth image with EFAI satellite image bounds.

3.3 Ground Truthing Data

3.3.1 TPWD Gulf Trawls

TPWD's Coastal Fisheries resource monitoring data were collected in accordance with a stratified cluster sampling design; each bay system and Gulf area serves as non-overlapping strata with a fixed number of samples performed per month. A cluster sample is a type of probability sample where each sample unit is a collection, or cluster, of elements (Castillo, 2009). Specific locations were sampled and every organism, including vertebrates, invertebrates, and vegetation, encountered at each location is identified and recorded. Sample locations were drawn independently and without replacement for each combination of gear, stratum, and month (Andrade, Fisher, Bowling, & Balboa, 2009).

Samples were collected within daylight hours 1/2 hour before sunrise to 1/2 hour after sunset. Gulf trawl samples were collected twice per month with the first half of the samples collected during the 1st through 15th of the month and the remainder collected during the 16th through the end of month. Each Gulf trawl sampling trip was equipped with a standardized trawl net with tail float attached. Coastal Fisheries trawls were 6.1m (20ft) otter trawls with 38mm (11/2in) stretched nylon multifilament mesh throughout. Trawl doors were 48in long and 20in wide constructed of 1/2in plywood with angle iron framework and iron runners (Andrade, Fisher, Bowling, & Balboa, 2009). Additional sampling equipment included a tow bridle, water sampler, GPS, map, YSI meter, turbidity bottles, data sheets, pencils, back-up gear, baggies for sample transport, special studies equipment, measuring board, and bucket or basket to handle catch.

At each predetermined Gulf trawl sampling station, a water sample and hydrological data 0.3m off the bottom were collected. The trawl was deployed using the prescribed amount of bridle and towline for the site's water depth. Trawl time began when all slack was removed from bridle and the winch had been "locked down". GPS coordinates were recorded at the beginning of each tow. The trawl was then towed at 3mph for 10 minutes parallel to fathom curve. The direction of the first trawl tow was randomly selected and then alternated for subsequent trawl tows. When the trawl sample was complete, GPS coordinates were recorded in a standardized TPWD Meteorological and Hydrological data sheet (APPENDIX A). From each trawl, vegetation both dead and alive was identified and recorded on the TPWD Marine Resource Monitoring Data sheet (APPENDIX B). Gulf trawls for NOAA's SeaMap program estimated vegetation density from the percent of gear covered or filled with vegetation and recorded with a corresponding density code. If no organisms were present, it was recorded as NOCATCH. If no vegetation was present it was recorded as VEGNONE.

3.3.2 Beach Surveys, Reports and Web Cams

South Padre Island (SPI), at the southern tip of Texas' Gulf Coast, is often historically one of the first places that *Sargassum* begins showing up on Texas beaches. Located closest to the Yucatan Peninsula, it is not surprising that this area receives the first traces of *Sargassum* accumulations on its beach front. If traditional assumptions of an annual influx of *Sargassum* from the Atlantic by way of the Caribbean prove to be true, it would be logical to conclude that South to North currents would facilitate such a scenario. The South Padre Island Beach and Surf report is a streaming real time web cam and written report that allows daily monitoring of *Sargassum* on beaches of the island (Figure 6).

SPadre.com

Date: Sunday September 18, 2011
Time: 9:00am
Island Weather: Partly cloudy
Wind: SE @ 5-15
Water Temp: 83
Water Clarity: Clear green
Rip Current Risk: Low
Seaweed: None
Jellyfish: None
Tides: Low 12:55pm 0.4' / High 12:00am 1.8' / tide chart
Wave Size: 1-2'
Wave Direction: SE
Mansfield Buoy: 4' @ 5seconds from ESE / Wind: SSE @ 11-13kts
200 Mile Buoy: 2' @ 4seconds from SE / Wind: SE @ 9-11kts
Surf Conditions: Small windchop with light SE wind.
Surf Forecast: Small surf with light SE to E wind through the week.
Weather Forecast: Partly cloudy with light SE to E wind through the week.
Tropical Weather Outlook: Tropics are quiet. Hurricane Center.

FIGURE 6 South Padre Island Beach and Surf Report (South Padre Island Beach and Surf Report, 2011)

Galveston Island also has regular streaming beach and surf cams but no accompanying written beach reports.   Numerous Galveston Island webcams are located throughout the city from Stewart Beach to Seawall Boulevard providing webcam images that update continuously throughout the day. Webcams in Surfside Beach, Freeport Jetties, Matagorda Island, and Sargent Beach were also monitored but their unreliability due to frequent technical and management issues made them only an occasional tool for added information on *Sargassum* accumulations (Figure 7).

FIGURE 7 Beach and surf web cams.

By keeping a journal of visual signs of *Sargassum* on Texas beaches**,** (APPENDIX C), I was able to keep track of castings and follow trends that supported my other ground truthing methods. Weekly beach surveys are conducted by NOAA Sea Turtle Facility staff and volunteers. As a NOAA intern, I participated in weekly beach surveys that consisted of driving approximately 75 miles along the beach from McFadden National Wildlife Refuge on Bolivar Peninsula to Surfside Beach (Figure 8). This area falls within my geographic study area and provided a visual source for accounting or discounting Sargassum sightings from other sources.

FIGURE 8 NOAA beach survey areas from McFadden Wildlife Refuge to Surfside Beach.

3.4 MODIS Images

The Moderate-resolution Imaging Spectroradiometers (MODIS) are key scientific instruments launched into the Earth's orbit by NASA in 1999 on board the Terra Satellite, and in 2002 on board the Aqua satellite (Maccherone, 2011). MODIS captures data in 36 spectral bands ranging and at varying spatial resolutions and remotely takes images of the entire Earth every 1 to 2 days. They are designed to provide measurements in large-scale global dynamics including changes in Earth's cloud cover, radiation budget and processes occurring in the oceans, on land, and in the lower atmosphere.

For each day, there are nine image products produced in two different processing streams, SeaDAS and RRC. The SeaWiFS Data Analysis System (SeaDAS) is a comprehensive image analysis package for the processing, display, analysis, and quality control of ocean color data (Ocean Color SeaDAS, 2011). In the SeaDAS stream, products include: a CHLO A (Chlorophyll a) image, an ERGB (Enhanced RGB) image, a FLH (Fluorescence Line Height) image, and a SST (Sea Surface Temperature) image. In a second unique Rayleigh-corrected reflectance (RRC) processing stream, products include: a ci (Color Index) image, an EFAI (Enhanced Floating Algae Index) image, a FAI (Floating Algae Index) image, a FLH (Fluorescence Line Height) image, and a normal RGB image.

The proof-of-concept in using FAI satellite data to map Sargassum distributions has been shown by Gower (Gower, Hu, Borstad, & King, 2006), Gower and King (Gower & King, 2008) and Hu (Hu, Cannizzaro, Carder, Muller-Karger, & Hardy, 2010). Hu reported improved remote sensing detection capabilities (Hu, Cannizzaro, Carder, Muller-Karger, & Hardy, 2010) by replacing the original 645-nm band in the FAI with the 667-nm band. This replacement led to EFAI, although it was not referred to this name in the previously published paper (Hu, Cannizzaro, Carder, Muller-Karger, & Hardy, 2010). EFAI images were used for this study due to their greater ability to distinguish aquatic surface features including *Sargassum*.

Water strongly absorbs light in the RED-NIR-SWIR (short-wave infrared) wavelengths (Hu, 2009). Due to this high absorption, water is black or opaque in the SWIR wavelengths (Wang & Shi, 2005). Floating algae, on the other hand, has a higher reflectance in the NIR than in other wavelengths and can therefore be distinguished from the surrounding water.

3.5 Data Analysis and Comparison

To analyze the raw data collected for TPWD's Gulf of Mexico trawl survey trips, I organized the data sheets collected from each bay system area, Sabine Lake System (SLS), Galveston Bay System (GBS) and San Antonio Bay System (SABS), into a database that was ordered by month and day (APPENDIX D). It was then necessary to convert the TPWD recorded coordinates from degrees, minutes, and seconds data to decimal degrees latitude and longitudes so that the data could be plotted in Google Earth.

Google Earth is a free, web-based, computer-generated globe, map, and geographical information software program. It maps the Earth by superimposing visual data obtained from satellite imagery, aerial photography, and GIS information and provides applications that allow for overlay of outside images. The satellite images were configured by USFT to allow application and overlay using Goggle Earth software. The location of the converted TPWD survey coordinates were plotted in Google Earth to allow a visual mapping of EFAI satellite images and *Sargassum* collection points from TPWD survey data.

Then the satellite images were viewed for the corresponding month and day. Both satellite passes were utilized to determine if a usable image existed. If sunglint or cloud cover obscured or distorted the image, one day ahead and one day previous to the data date were examined. Sunglint, a phenomenon that occurs when the sun reflects off the surface of the ocean at the same angle that a satellite or other sensor is viewing the surface, caused considerable distortion of images during this study (Ramachandran, 2010). In sunglint affected images, smooth ocean water becomes a silvery mirror, while rougher surface waters appear dark in MODIS RGB images (Figure 9a). When sunlight illuminates a water body, such as a lake, stream, or, ocean, a portion of the light will penetrate the water body while the remainder will be reflected into the atmosphere from the water surface. When viewed from a satellite, the sunglint reflected from the water's surface appears as a circular bright area. The presence of waves tends to disperse the surface-reflected light, and the result is a spreading of the sunglint pattern (Sunglint in Astronaut Photography of Earth, 2003). In addition, EFAI satellite images at times completely saturate under sunglint, distorting any features on the water's surface (Figure 9b). It should be noted that partial sunglint in EFAI images can still yield useable data.

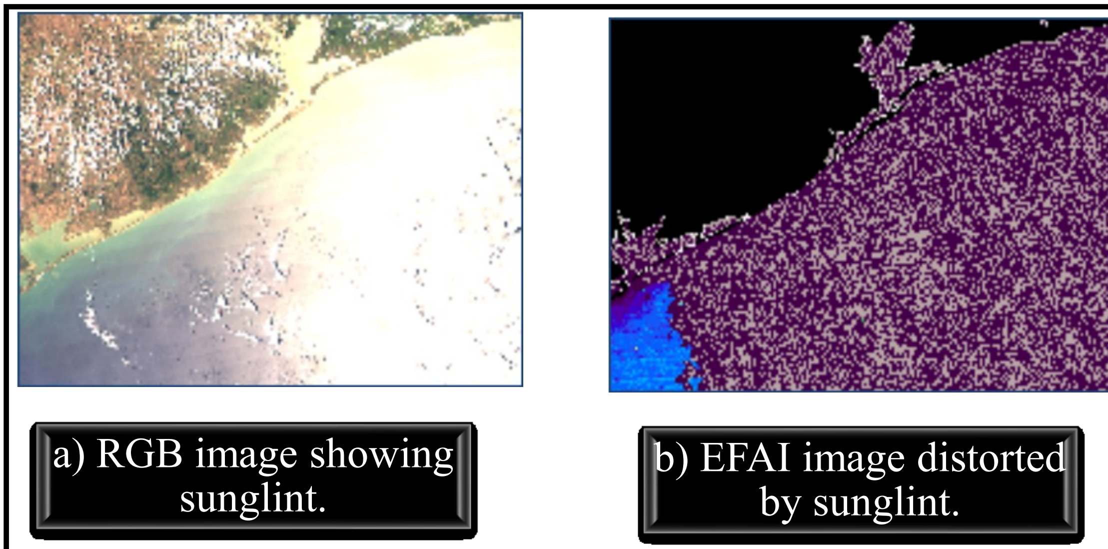


Figure 9 RGB and EFAI images showing significant sunglint.

Clouds can at times show high FAI values and appear as thin lines or small patches that resemble floating algae (Figure 10a). This can usually be discounted by overlaying or side by side comparison between an RGB image and the corresponding EFAI image (Figure 10b). Atmospheric clouds, however, can also distort EFAI images much like sunglint, thus distorting the image and preventing conclusive identification of surface features (Figure 10c and 10d).

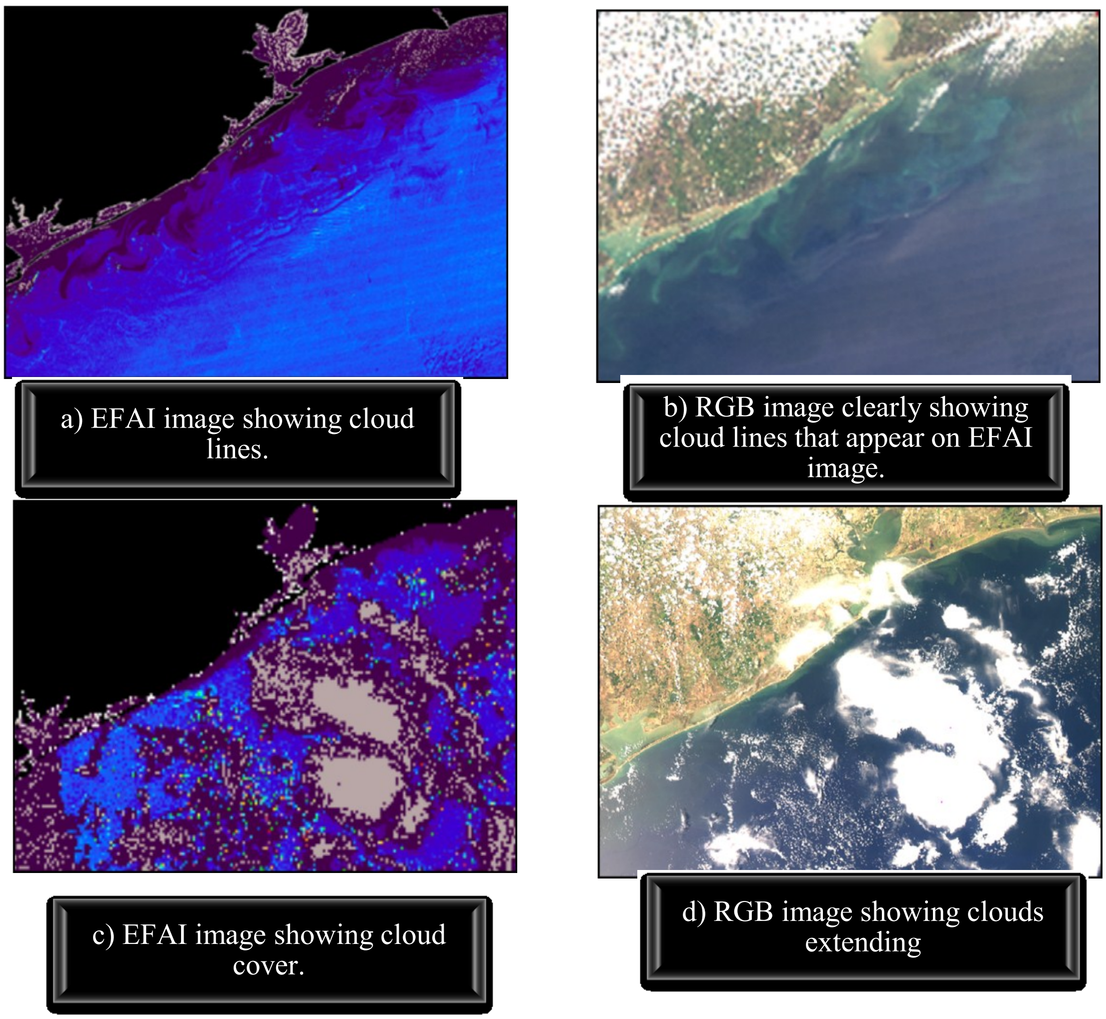


Figure 10 Comparison of cloud expression on EFAI and RGB images.

Collection of *Sargassum* noted in the TPWD trawl data or the *Sargassum* log was compared to the EFAI satellite images for the same days (Figure 11). If *Sargassum* were detected in the EFAI satellite images, the EFAI image was overlaid in Google Earth and the TPWD trawl data GPS coordinates were plotted. If the ground truthing data came from the *Sargassum* log, the only difference in protocol was that off shore coordinates could not be plotted. For EFAI images that were inconclusive due to partial sunglint or cloud cover, I took the additional step of applying ocean surface current data to support the evidence of *Sargassum* noted on the EFAI images. This step allowed for visual verification or discount of the occurrence of *Sargassum* that the satellite images suggested. The direct comparison of the ground truthing data indicating the presence of *Sargassum* to the corresponding EFAI satellite images is the first step in validating the reliability of *Sargassum* tracking by remote sensing means.

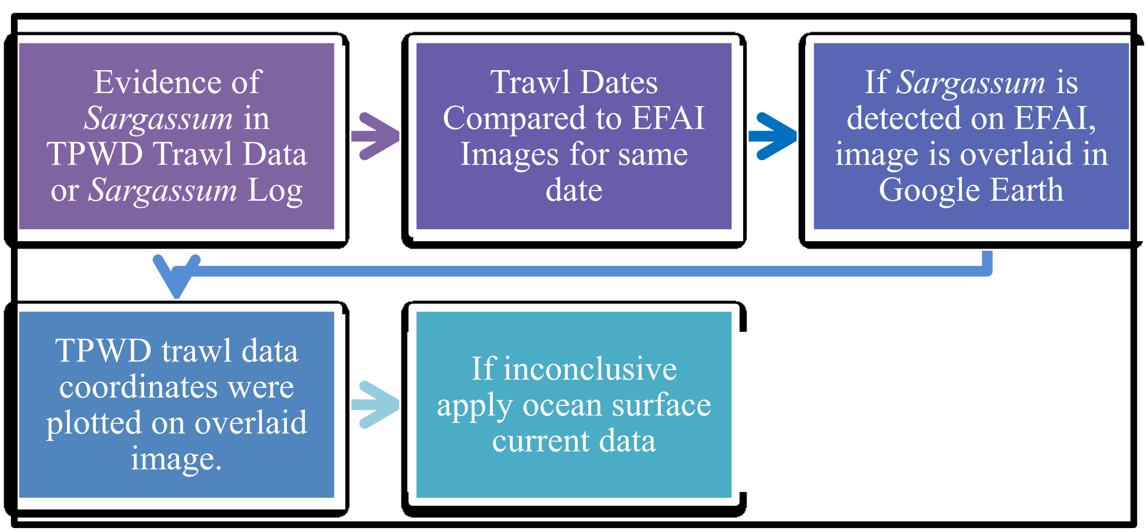


Figure 11 Process for *Sargassum* / EFAI image comparison

CHAPTER IV

RESULTS

4.1 Overview

In order to develop a protocol that can be applied in the future to track *Sargassum* movements in the Gulf of Mexico and to aid in the future development of an early warning system for *Sargassum* detection, ground truthing to substantiate the information derived from EFAI satellite images must be done. TPWD Gulf trawl sampling data that coincided with satellite overpasses and resulting images were collected and correlated to the geographic area within the GOM.

The method I followed for correlating the ground truthing data with satellite images followed a systematic month by month approach. The TPWD Gulf trawl data were compared to the EFAI satellite images for the same calendar day. In most cases, the date of the TPWD trawl was used in addition to the preceding and succeeding days for comparison. This method allowed for increased comparison days by allowing for unusable trawl data/EFAI images that were corrupted by sunglint or cloud cover.

The information from the beach survey log from beach cams, reports and eye witness accounts of *Sargassum* occurrences was applied to EFAI satellite images for the near shore waters from Surfside Beach to McFadden Wildlife Refuge on Bolivar Peninsula. The total ground truthing data days were compiled within a table for each month in the study.

4.2 Month by Month Analysis and Comparison of TPWD Gulf Trawl and Beach Survey Data Compared with EFAI Satellite Images

For the months of January through July 2011, I undertook a systematic approach for reconciling the EFAI satellite images with the corresponding TPWD trawl data, starting with the first available trawl information for each month. Gulf trawl samples are collected twice per month; the first half of the samples are collected during the 1st through 15th of the month and the remainder are collected during days 16th through the end of month (Andrade, Fisher, Bowling, & Balboa, 2009). In addition, I compared information on beach accumulation of *Sargassum* from the beach cam, report and survey log (APPENDIX B).

4.2.1 January 2011

The month of January provided four sets of TPWD Gulf trawl data from the Galveston and San Antonio Bay Systems (Table 1). The corresponding satellite images were all distorted or obscured by either sunglint or cloud cover (Figure 12). The Galveston Area did not report *Sargassum* in any of their sampling surveys. The San Antonio Bay System reported light *Sargassum* in their trawl data throughout the month. This information was consistent with prior data that suggest *Sargassum* occurrences are typically light in January (Viles, 2009). No correlations from ground truthing data and satellite images could be made due the lack of useable satellite images and absence of *Sargassum* for portions of the month.

Table 1 January 2011 *Sargassum* / Image comparison

Date	Area	**Image Quality**	***Sargassum* reported**	***Sargassum* Detected on EFAI image**
1/3/11		Cloud cover	No	No
1/4/11	SABS	Sunglint/distorted	Yes - TPWD Gulf Trawl	No
1/5/11		Sunglint/distorted	No	No
1/6/11		Cloud cover	No	No
1/7/11	GBS	Cloud cover	Yes - TPWD Gulf Trawl	No
1/8/11		Sunglint/Cloud cover	No	No
1/16/11		Sunglint	No	No
1/17/11	SABS	Sunglint	Yes - TPWD Gulf Trawl	No
1/18/11		Sunglint	No	No
1/19/11	GBS	Sunglint	No -TPWD Gulf Trawl	No
1/20/11	Area	Sunglint	No	No

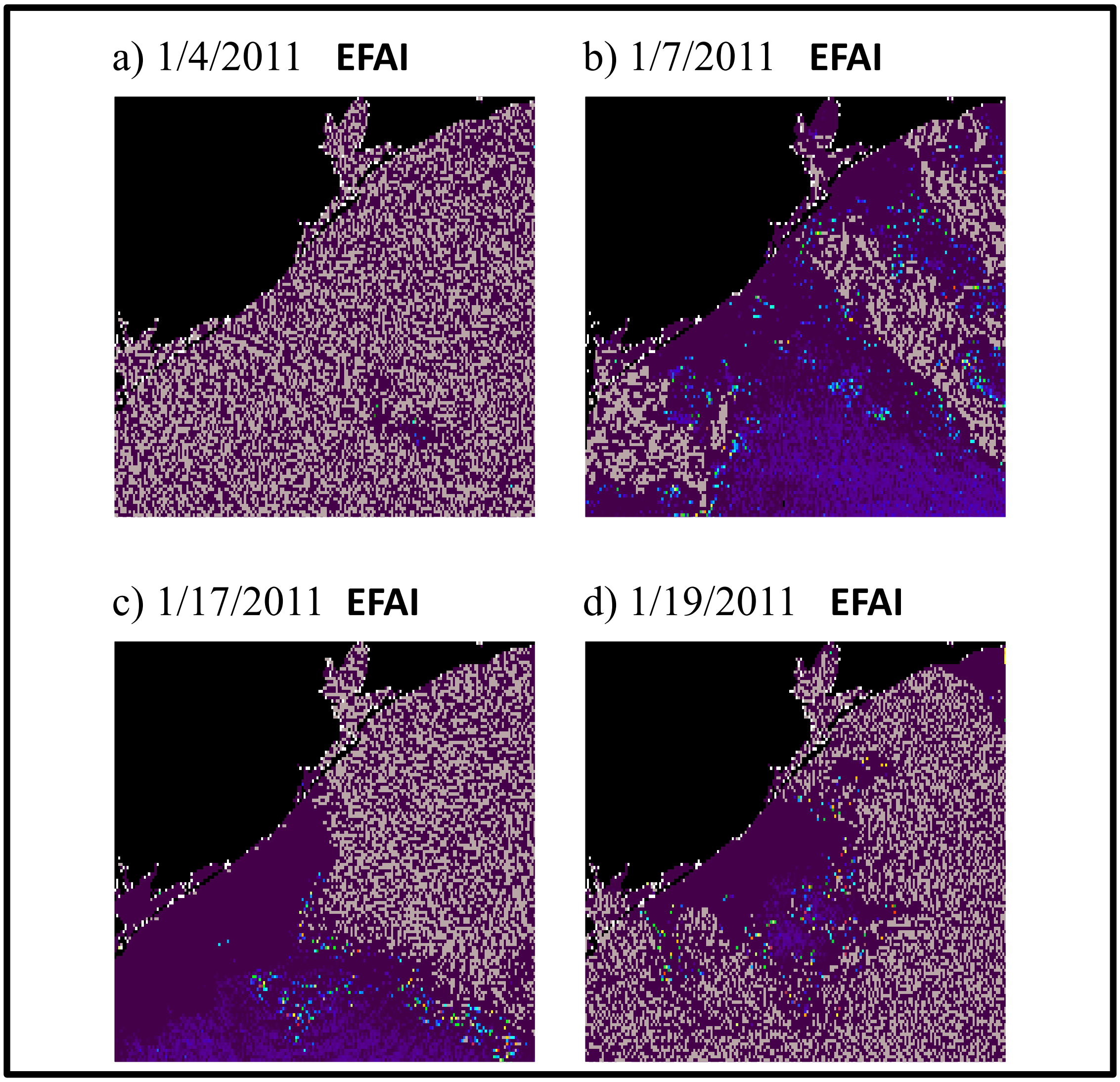


Figure 12 January 2011 – EFAI satellite images showing sunglint and cloud cover distorting the study area.

4.2.2 February 2011

February provided four days of TPWD Gulf trawl data from the Galveston Bay System (GBS) and San Antonio Bay System (SABS), for comparison with EFAI Satellite images (Table 2). I analyzed seven additional days of GBS information from Galveston Island cams and NOAA beach survey data. SABS is the only area that reported *Sargassum* in their sample trawls. Useable EFAI images were produced from early in the month but no *Sargassum* was detected on any of the images (Figure 13). *Sargassum* is traditionally light in the western GOM this time of the year (Gower & King, 2008). The lack of evidence from the EFAI images may be due to the absence of large contiguous mats of floating *Sargassum* as opposed to small floating balls that are not easily identified on EFAI images. As noted by Hu (Hu, 2009) the ability to detect ocean surface features is dependent on the sensitivity of the satellite sensor and the subject size. If large floating mats are not present, intermittent *Sargassum* may be undetectable.

Table 2 February 2011 *Sargassum* / Image comparison

Date	Area	Image Quality	*Sargassum* reported-Source	*Sargassum* Detected on EFAI image
2/3/11	GBS	Sunglint	No-Galveston Cams	No
2/11/11	SABS	Fair/Sunglint	Yes-TPWD Gulf Trawl	No
2/12/11	GBS	Useable	No - TPWD Gulf Trawl	No
2/13/11		Fair/Sunglint	No	No
2/15/11	GBS	Fair/ Clouds	No-Galveston Cams	No
2/16/11		Cloud cover	No	No
2/17/11	SABS	Sunglint/Clouds	No-TPWD Gulf Trawl	No
2/18/11	GBS	Fair	No- Galveston Cams	No
2/21/11	GBS	Useable	No- NOAA Survey	No
2/22/11		Sunglint/Clouds	No	No
2/23/11	GBS	Sunglint	No - TPWD Gulf Trawl	No
	GBS	Sunglint	No – Galveston Cams	No
2/24/11		Sunglint	No	No
2/27/11	GBS	Sunglint	No- Galveston Cams	No
2/28/11	GBS	Cloud Cover	No- Galveston Cams	No

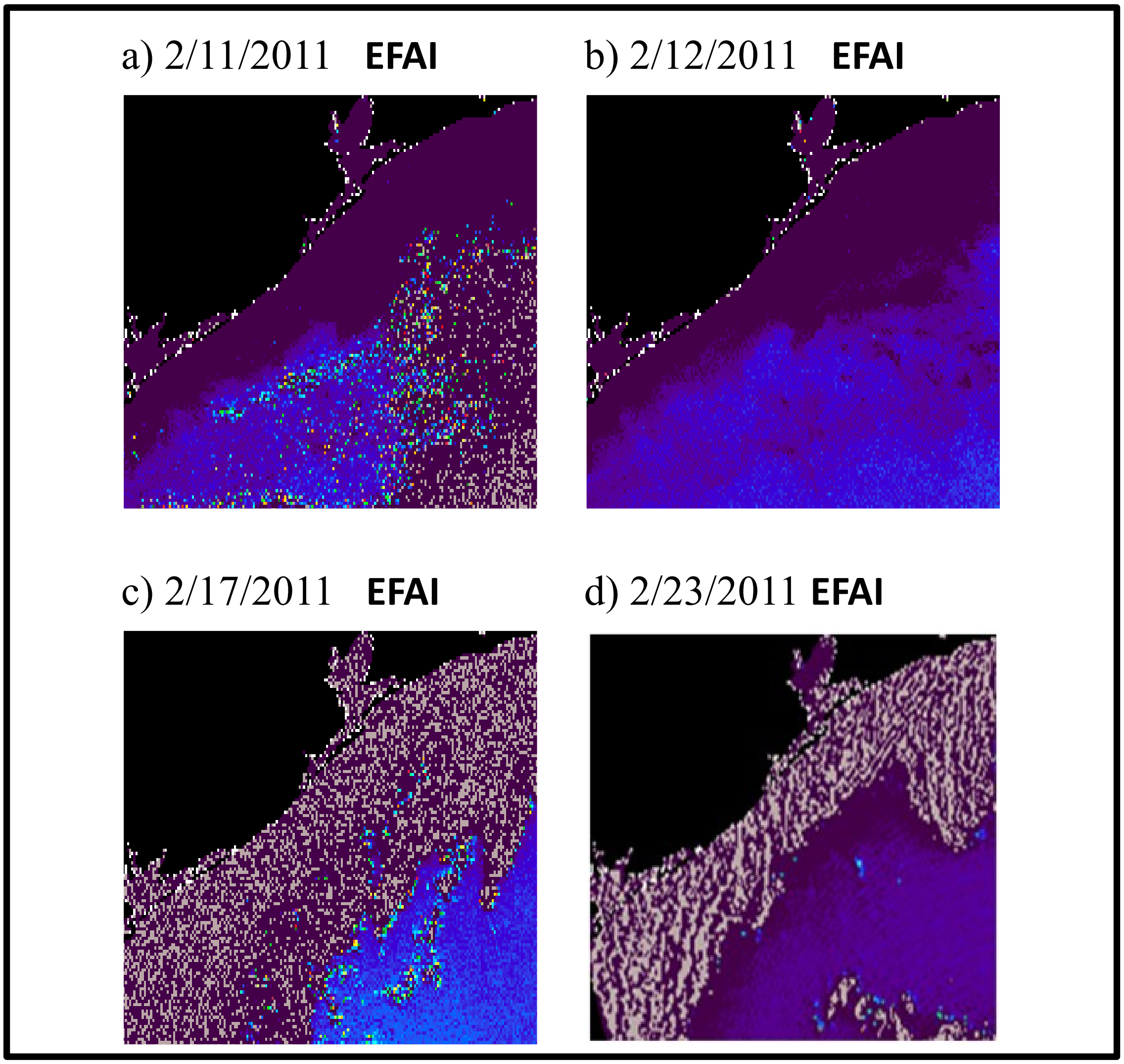


Figure 13 February 2011 – EFAI satellite images showing no evidence of *Sargasssum*. Image 5a is undistorted, whereas a, c and d show sunglint.

4.2.3 March 2011

For the month of March, three days of Gulf trawl data were obtained from the Galveston Bay System (GBS) and San Antonio Bay System (SABS). The GBS and SABS ecosystem crews both sampled on the 16th of the month (Table 3). Several useable EFAI satellite images were produced, but no definitive *Sargassum* lines were detected on the EFAI images (Figure 14). The beach cam and survey log provided five additional days for comparison with EFAI satellite images with two days of Sargassum detected on Galveston beaches. The EFAI image for March 23rd was inconclusive due to swirling surface currents that made it difficult to distinguish if the lines on the image were *Sargassum* or the leading edge of clouds. Cloud pixels can reflect high EFAI values (Hu C. , 2009) and are at times hard to distinguish from lines of *Sargassum*. A side by side comparison with an unfiltered RGB image shows the swirling effect clouds sometimes produce on satellite images (Figure 15). The pattern created by clouds can mimic the appearance of floating lines of *Sargassum*; however when the EFAI image is compared side by side with unfiltered RGB image the cloud swirl is detected. The predominant lack of conclusive evidence for identifying *Sargassum* lines was possibly due to the excessive cloud cover and sunglint on the days that sampling was performed.

Table 3 March 2011 *Sargassum* / Image comparison

Date	Area	Image Quality	*Sargassum* reported-Source	*Sargassum* Detected on EFAI image
3/1/11		Fair	No	No
3/2/11	SABS	Useable	YES - TPWD Gulf Trawl	Possible
	GBS	Useable	No – Galveston Cams	No
3/3/11		Cloud cover	No	No
3/7/11	GBS	Clouds	No-Galveston/Surfside Cams	No
3/9/11	GBS	Clouds	YES-NOAA Survey	No
	GBS	Clouds	No-Galveston/Surfside Cams	No
3/10/11		Useable	No	No
3/11/11	GBS	Useable	No-TPWD Gulf Trawl	No
3/12/11		Sunglint	No	No
3/15/11		Useable	No	No
3/16/11	GBS & SABS	Clouds	YES - TPWD Gulf Trawl	No
	GBS	Clouds	YES-Galveston Cams	No
3/17/11		Useable	No	No
3/23/11	GBS	Useable	YES- Galveston Cams	Possible

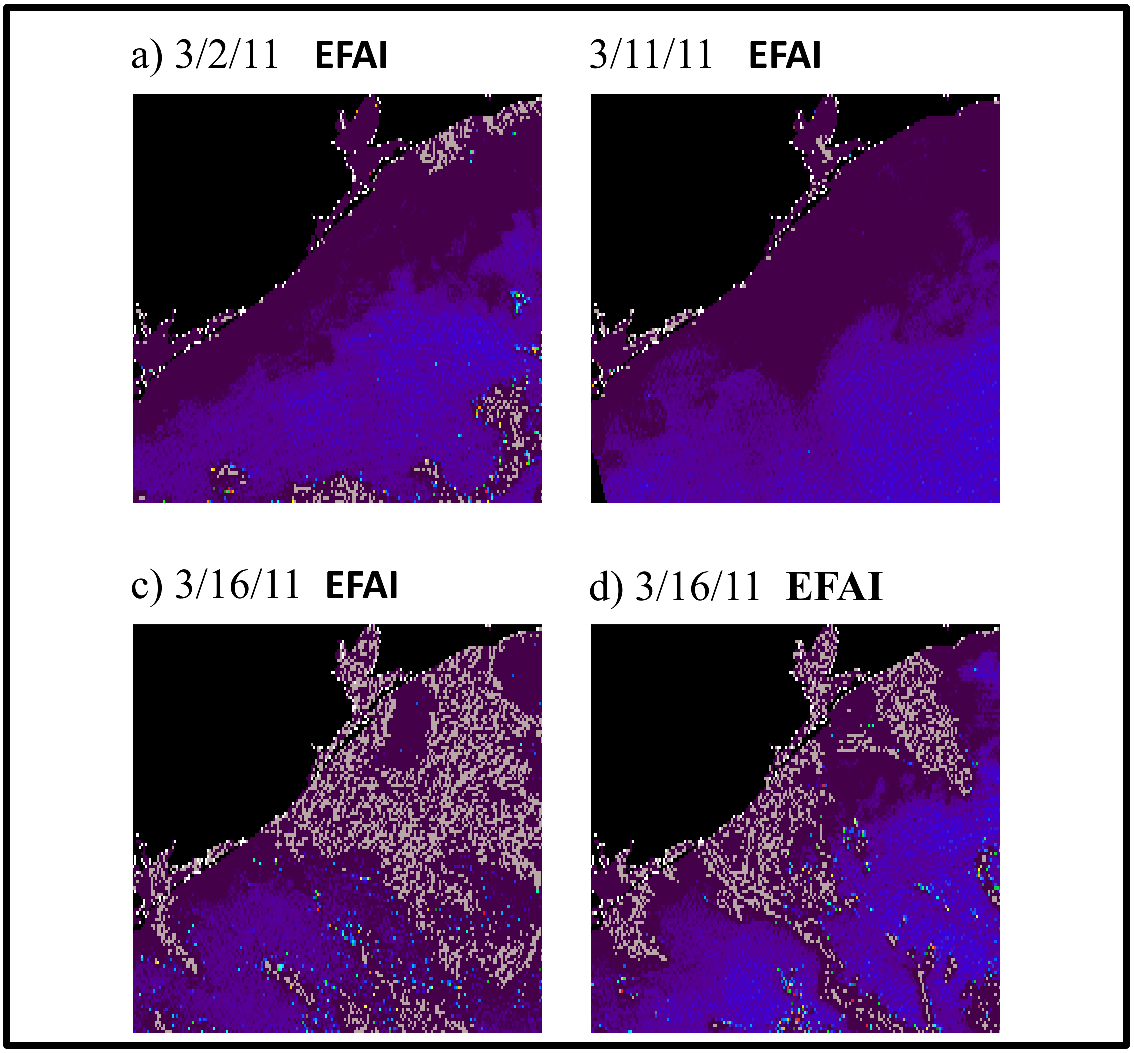


Figure 14 March 2011 – EFAI satellite images showing clouds swirls on 7a and 7b and sunglint on 7c and 7d.

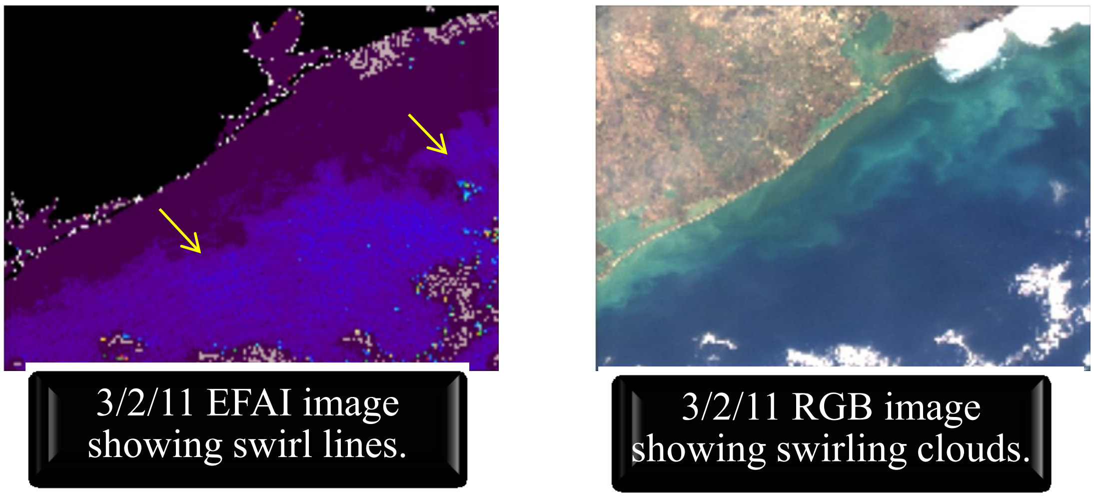


Figure 15 Side by side comparison of EFAI and RGB images: the swirling effect clouds can cause.

4.2.4 April 2011

April resulted in four days of TPWD Gulf trawl data reporting *Sargassum* in nets and the first decisive evidence of *Sargassum* lines on corresponding EFAI satellite images (Figure 17). Data from both Galveston and San Antonio Bay Systems were used for comparison with EFAI images (Table 4). The beach cam and survey log produced five additional days of data and *Sargassum* was identified on corresponding EFAI images. The EFAI image from April 20, 2011 showed *Sargassum* rows adjacent and offshore of Galveston Island (Figure 16). Large lines of *Sargassum* were visible on the

April 27, 2011 EFAI image extending from Galveston south to San Antonio Bay (Figure 18).

Table 4 April 2011 *Sargassum* / Image comparison

Date	Area	Image Quality	*Sargassum* reported – Source	*Sargassum* Detected on EFAI image
3/31/11		Sunglint	No	No
4/1/11	GBS	Sunglint	Yes- TPWD Gulf Trawl	No
4/2/11		Sunglint	No	No
4/4/11		Sunglint	No	No
4/5/11	SABS	Sunglint & Cloud Cover	Yes- TPWD Gulf Trawl	No
4/6/11		Sunglint	No	No
	GBS	Sunglint	No-Galveston Cams	No
4/11/11	GBS	Clouds	YES- NOAA Survey	No
4/12/11	GBS	Useable	YES-NOAA Boat	Possible
4/15/11	GBS	Sunglint	No- Galveston Cams	No
4/20/11	GBS	Clouds	No- Galveston Cams	YES
4/26/11		Sunglint	No	No
4/27/11	SABS	Useable	Yes-TPWD Gulf Trawl	YES
	GBS	Useable	Yes- Galveston Cams	YES
4/28/11	GBS	Useable	Yes-TPWD Gulf Trawl	Possibly
4/29/11		Sunglint & Cloud Cover	No	No

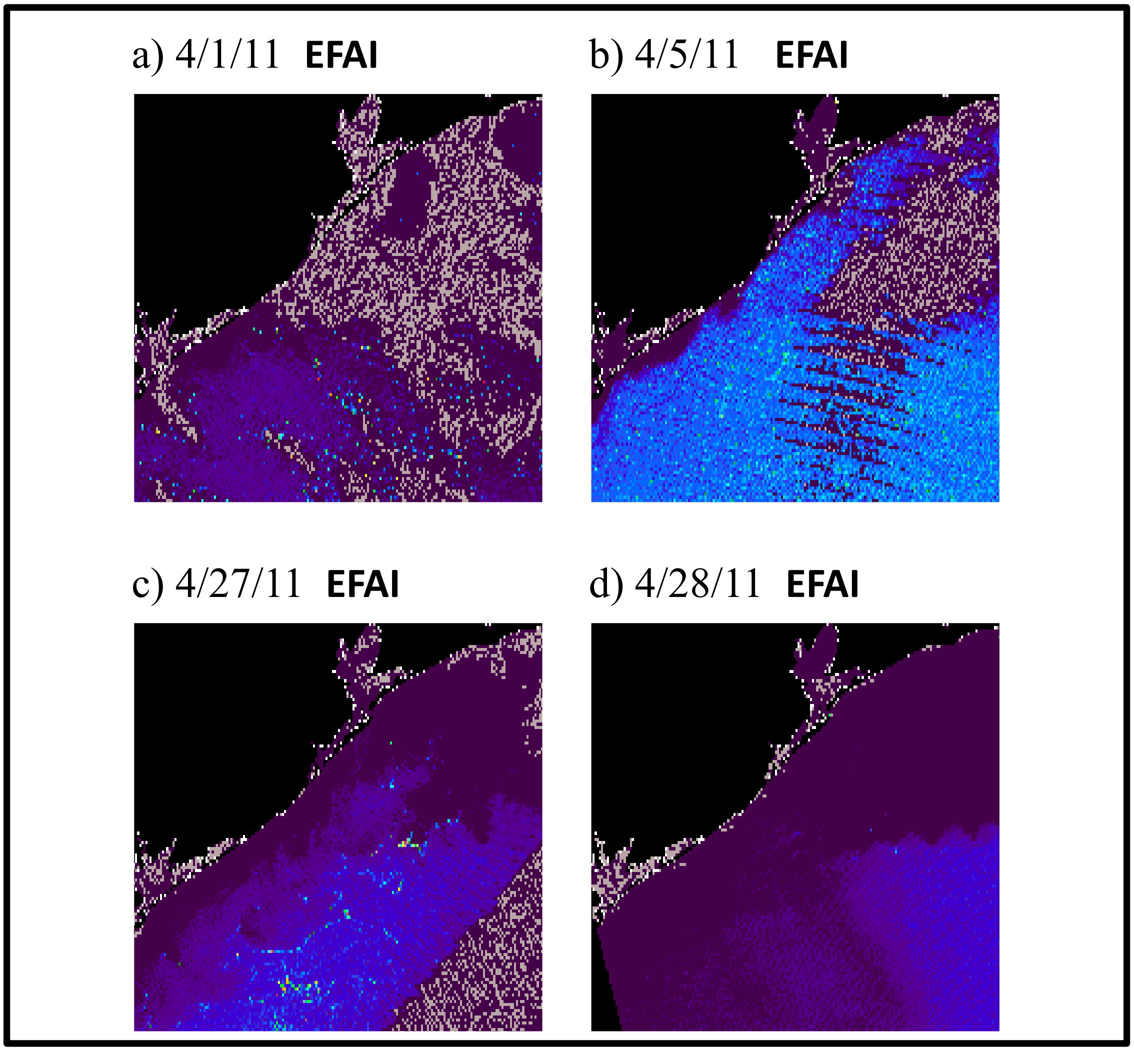


Figure 16 April 2011 – EFAI satellite images showing sunglint early in the month on 9a and 9b. Image 9c shows lines of *Sargassum* along the Galveston coast.

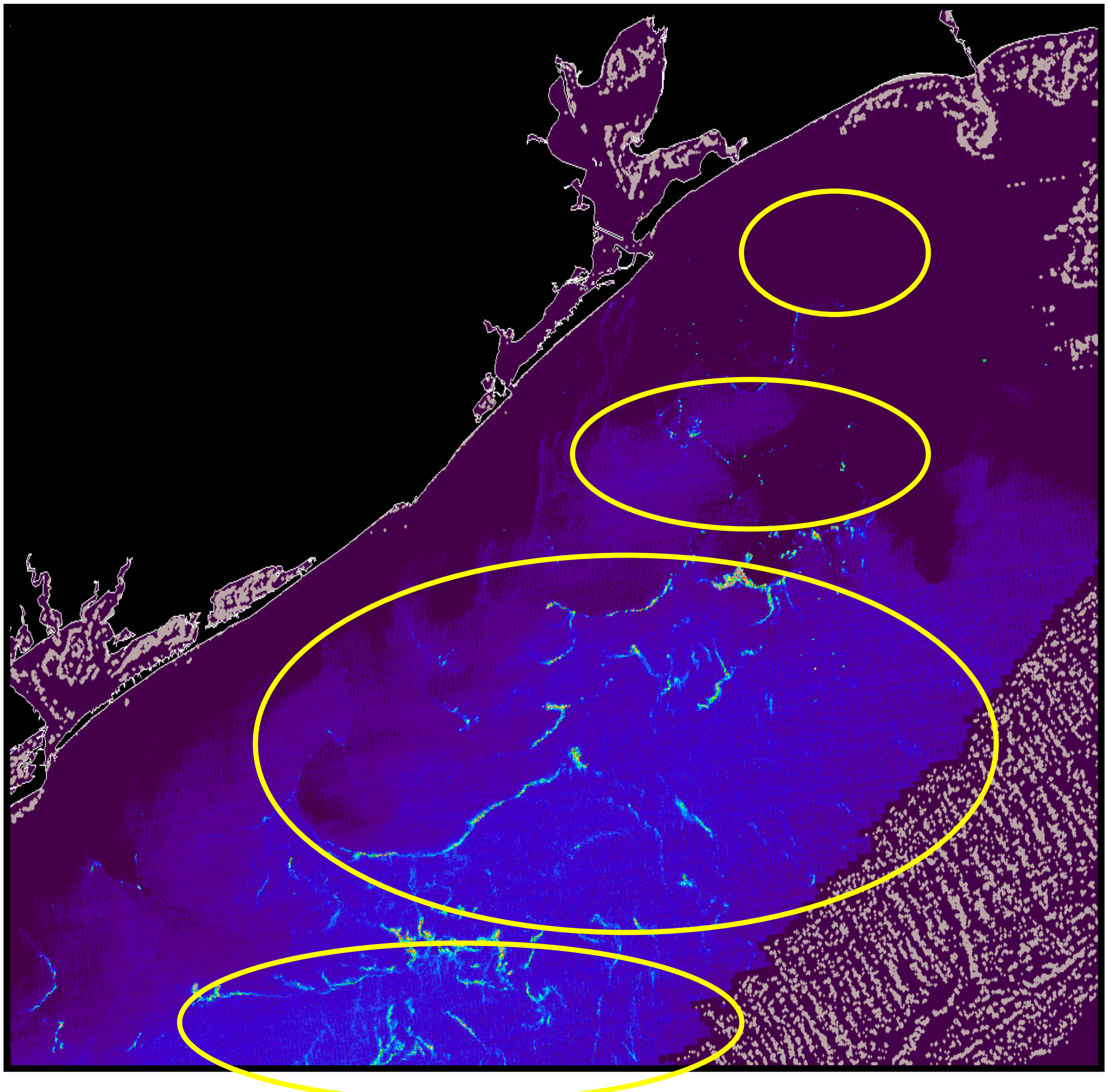


Figure 17 April 27, 2011 Large lines of *Sargassum* adjacent to the Texas coast visible on EFAI image.

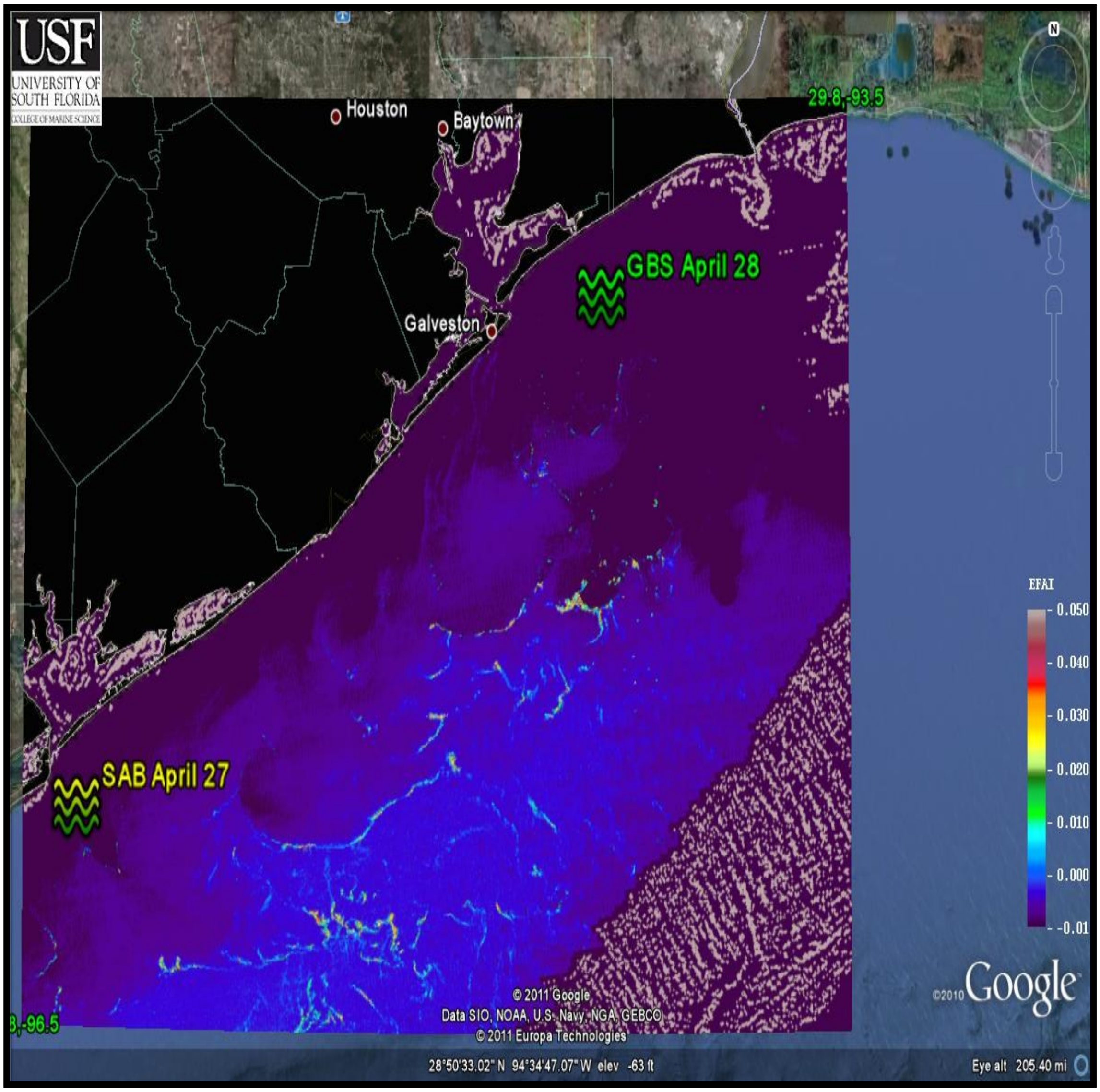


Figure 18 April 27, 2011 EFAI image overlaid on Google Earth with Gulf trawl data locations. Multiple *Sargassum* lines are visible in proximity to the trawl locations.

4.2.5 May 2011

For the month of May three days of ground truth data were available from TPWD Gulf trawls (Table 5). Galveston and San Antonio Bay Areas sampled early in the month on the fifth and sixth respectively. Both GBS and SABS deployed their trawls on May sixteenth for their second half of the month Gulf sampling. It is common for TPWD survey crews to sample on common fair weather days. However, even with a reduced number of trawl days, May produced several relatively conclusive comparative EFAI images with representative *Sargassum* lines (Figure 20 and Figure 21). Heavy *Sargassum* was reported on Galveston beaches and was visible on beach cams. Sunglint and cloud cover obscured the EFAI images for several days, however when good images were available *Sargassum* was evident (Figure 19). This is suggestive of the increase in biomass of *Sargassum* in relation to the areas being sampled.

Table 5 May 2011 *Sargassum* / Image comparison

Date	Area	Image Quality	*Sargassum* reported - source	*Sargassum* Detected on EFAI image
5/4/11		Clouds	No	Yes
5/5/11	SABS	Cloud cover	Yes-TPWD Gulf Trawl	Possibly
5/6/11	GBS	Useable	Yes-TPWD Gulf Trawl	Yes
5/7/11		Sunglint	No	No
5/11/11	GBS	Sunglint	Yes-Galveston Cams	No
5/12/11	GBS	Sunglint	Yes-Galveston Cams	NO
5/13/11		Useable	No	Yes
5/15/11		Sunglint	No	Yes
5/16/11	GBS & SABS	Useable	Yes-TPWD Gulf Trawl	Yes
5/17/11		Useable		Yes
5/20/11	GBS	Sunglint & Clouds	Yes-NOAA Survey	No
5/25/11	GBS	Clouds	Yes -Galveston Cams	No

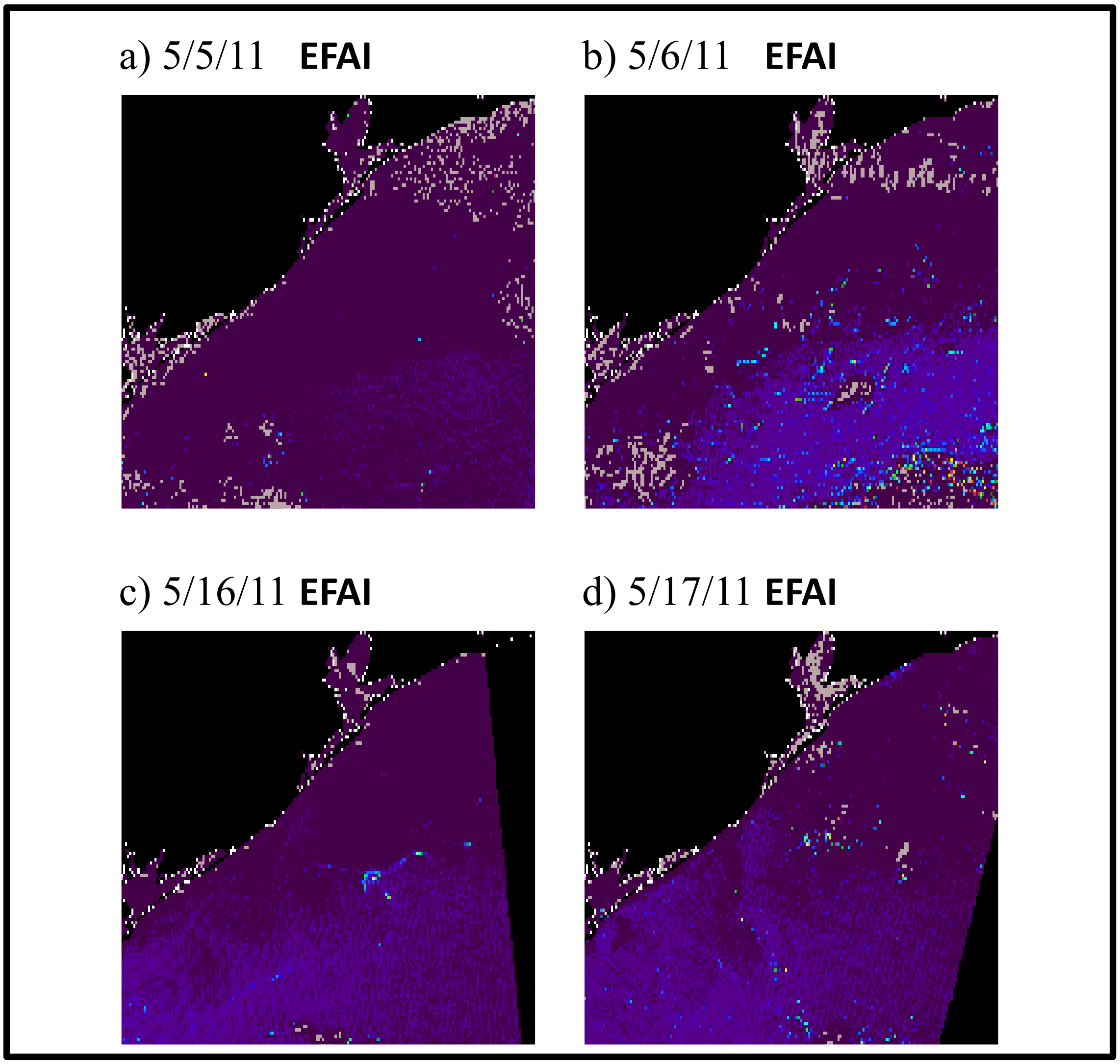


Figure 19 May 2011 – EFAI satellite images show evidence of lines of *Sargassum* on all four images.

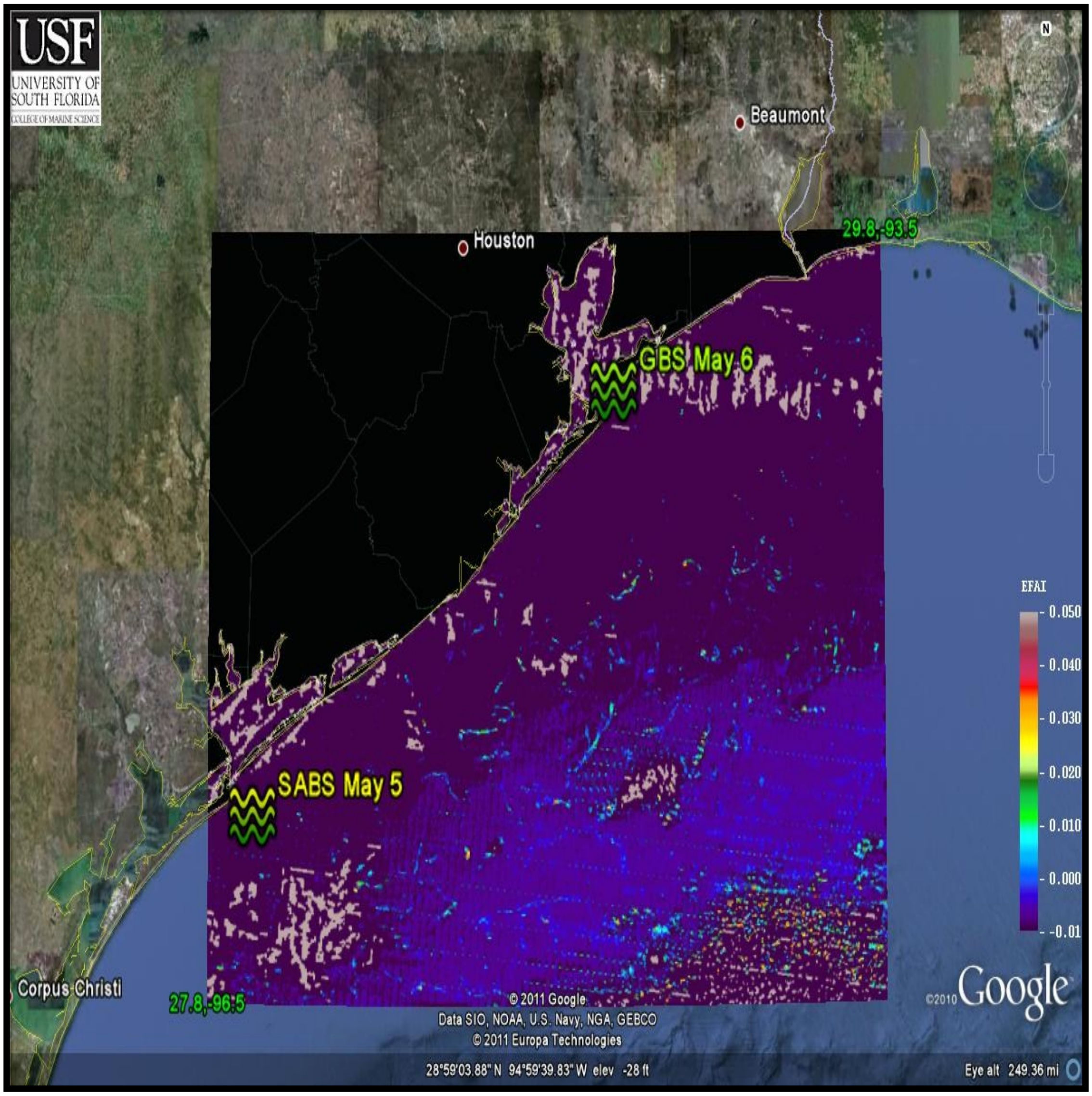


Figure 20 May 6, 2011 EFAI image overlaid on Google Earth with Gulf trawl data locations. Multiple *Sargassum* lines are visible between the two trawl locations.

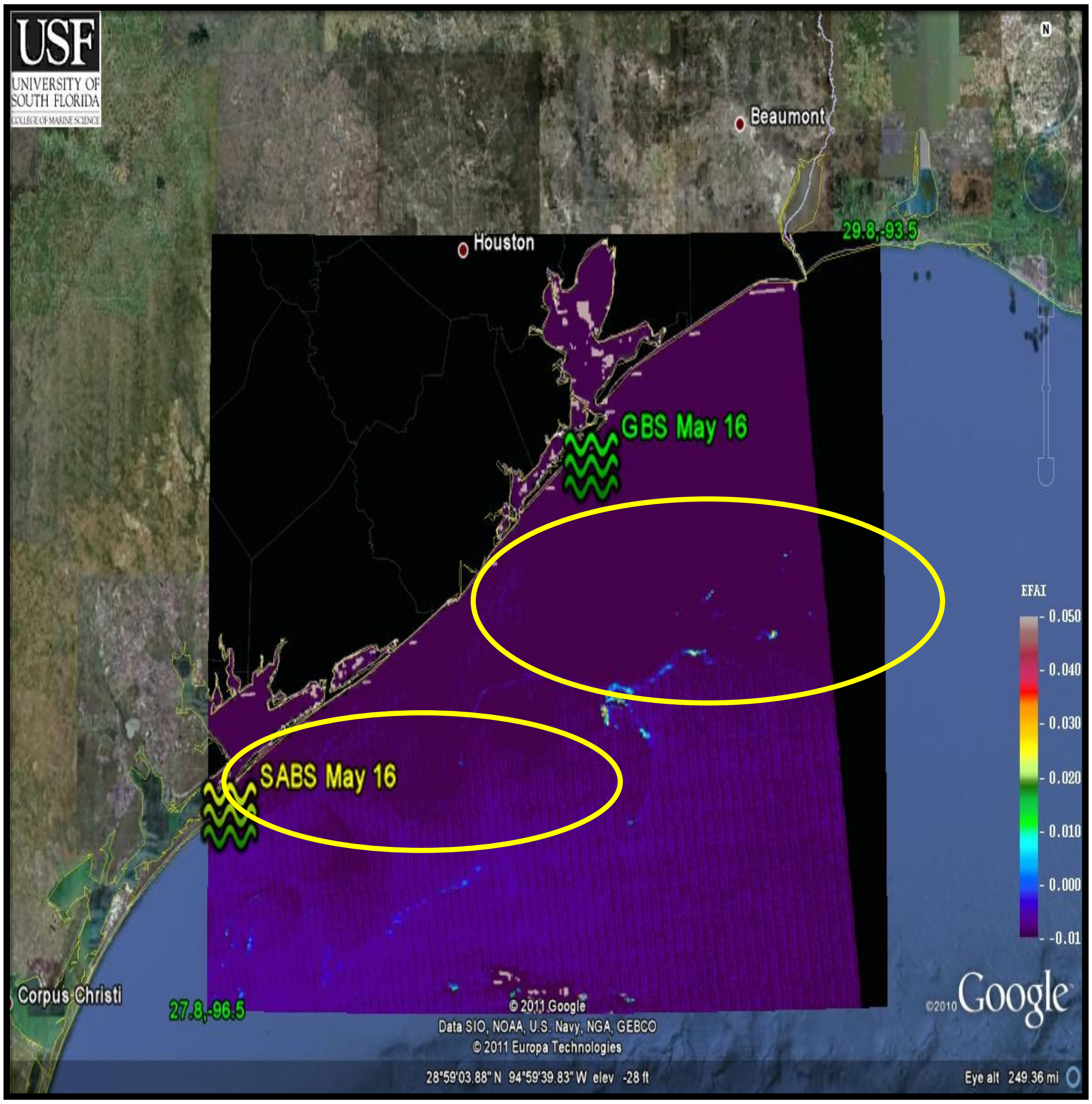


Figure 21 May 16, 2011 EFAI satellite image overlaid on Google Earth with Gulf trawl data locations showing *Sargassum* lines in proximity to trawl locations.

4.2.6 June 2011

Sunglint and cloud cover obscured most of the EFAI satellite images for the five days of Gulf trawl data for the month of June (Table 6). The June 1st image had faint lines that suggested of *Sargassum,* however the cloud cover made conclusive identification difficult (Figure 22). The EFAI image on Google Earth was overlaid and plotted the ground truth coordinates from the SABS and GBS. Then a side by side comparison was made of currents from the archived currents database Experimental Real-Time Intra-Americas Sea Nowcast/Forecast System (Figure 23). The surface current data (Figure 23b) shows an East to West convection. This suggests that the lines on the EFAI image are *Sargassum.* *Sargassum* was collected in trawls from waters adjacent to the suggestive lines on the EFAI and currents were pushing towards shore. This evidence, although not conclusive, suggests that even with sunglint distortion, at times *Sargassum* can be tracked on EFAI images. The remainders of the month's EFAI images corresponding to ground truthing data evidence were inconclusive due to distortion by sunglint and clouds.

Table 6 June 2011 *Sargassum* / Image comparison

Date	Area	Image Quality	*Sargassum* reported - Source	*Sargassum* Detected on FAI image
6/1/11	SABS	Fair/Sunglint	Yes-TPWD Gulf Trawl	Yes
6/2/11	GBS & SLS	Sunglint	Yes-TPWD Gulf Trawl	No
6/3/11		Sunglint	No	No
6/22/11		Sunglint	No	No
6/23/11	SABS & GBS	Sunglint & Clouds	Yes-TPWD Gulf Trawl	No
6/24/11		Sunglint	No	No
6/26/11		Clouds	No	No
6/27/11	SABS	Clouds	Yes-TPWD Gulf Trawl	No
6/28/11		Clouds	No	No
6/29/11	SLS	Clouds	Yes-TPWD Gulf Trawl	No
6/30/11		Clouds	No	No

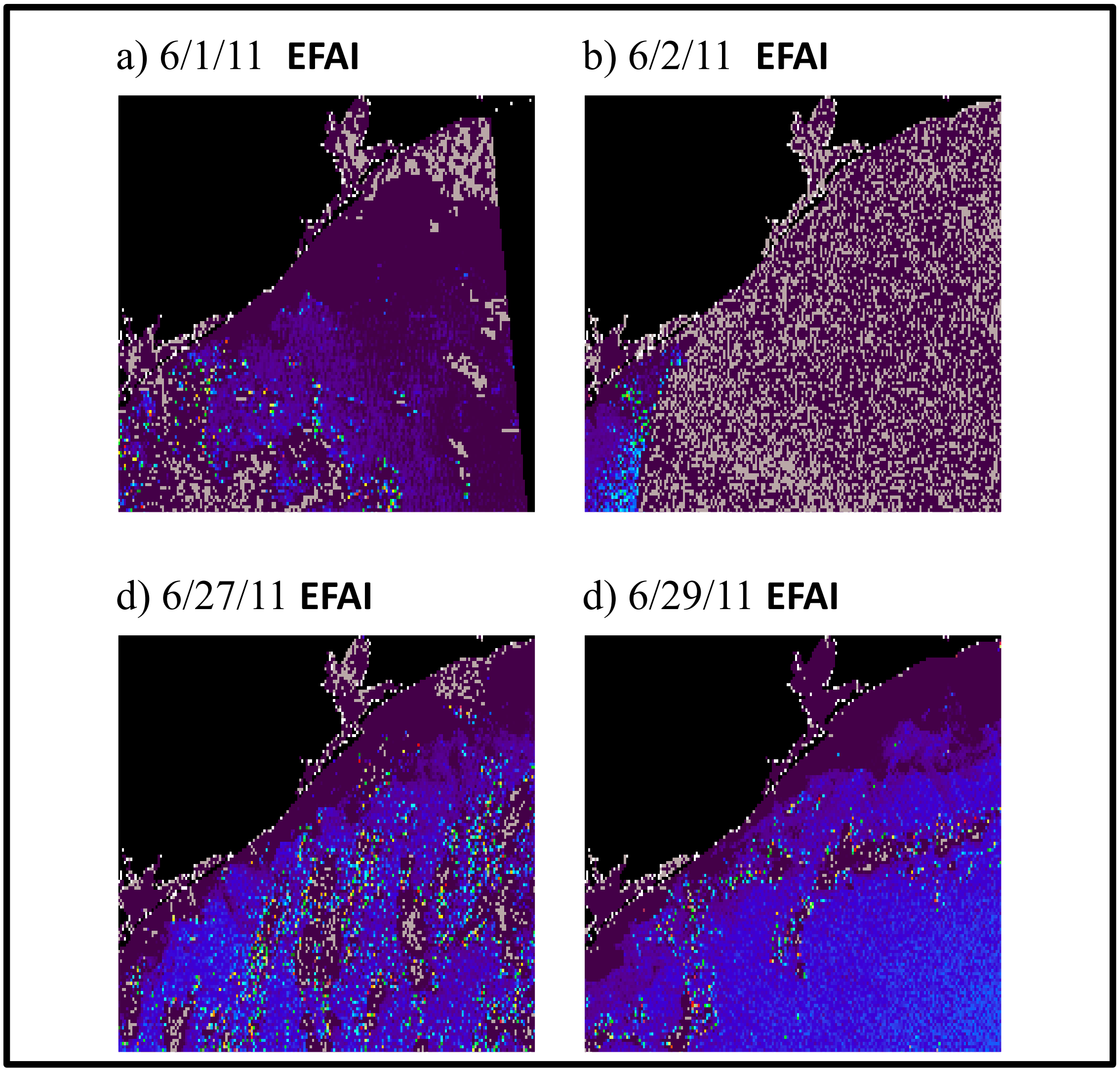
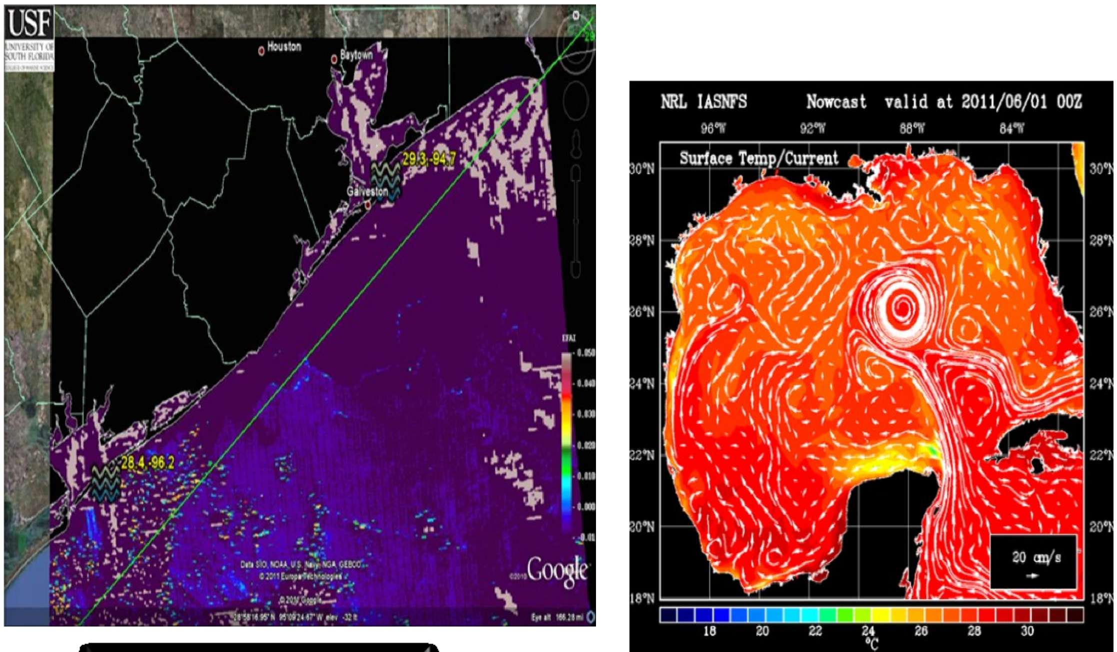


Figure 22 June 2011 – EFAI satellite images showing faint lines of *Sargassum* on 13a and expansive sunglint covering the study area on the remaining images.



a) 6/1/11 EFAI image showing faint lines of Sargassum

b) 6/1/11 Surface currents images

Figure 23 Side by side comparison of June 1st overlaid Google Earth EFAI image and surface currents data from the same day (Experimental Real-Time Intra-Americas Sea Nowcast/Forecast System, 2011).

4.2.7 July 2011

July provided five days of Gulf trawl data for EFAI comparison (Table 7). *Sargassum* was reported on trawl reports by all three sampled bay systems however, cloud cover and sunglint were a continuing problem and obscured any conclusive evidence of *Sargassum* on the EFAI images (Figure 24).

Table 7 July 2011 *Sargassum*/Image comparison

Date	Area	Image Quality	*Sargassum* reported - Source	*Sargassum* Detected on EFAI image
7/1/11	SLS	Cloud cover	Yes-TPWD Gulf Trawl	No
7/2/11		Sunglint & Clouds	No	No
7/4/11		Clouds	No	No
7/5/11	SABS	Fair/Clouds	Yes-TPWD Gulf Trawl	No
7/6/11		Clouds	No	No
7/7/11	GBS	Fair	Yes-TPWD Gulf Trawl	No
7/8/11		Sunglint & Clouds	No	No
7/17/11		Clouds	No	No
7/18/11	SABS	Sunglint & Clouds	Yes-TPWD Gulf Trawl	No
7/19/11		Clouds	No	No
7/20/11	SLS & GBS	Cloud cover	Yes-TPWD Gulf Trawl	No
7/21/11		Clouds	No	No

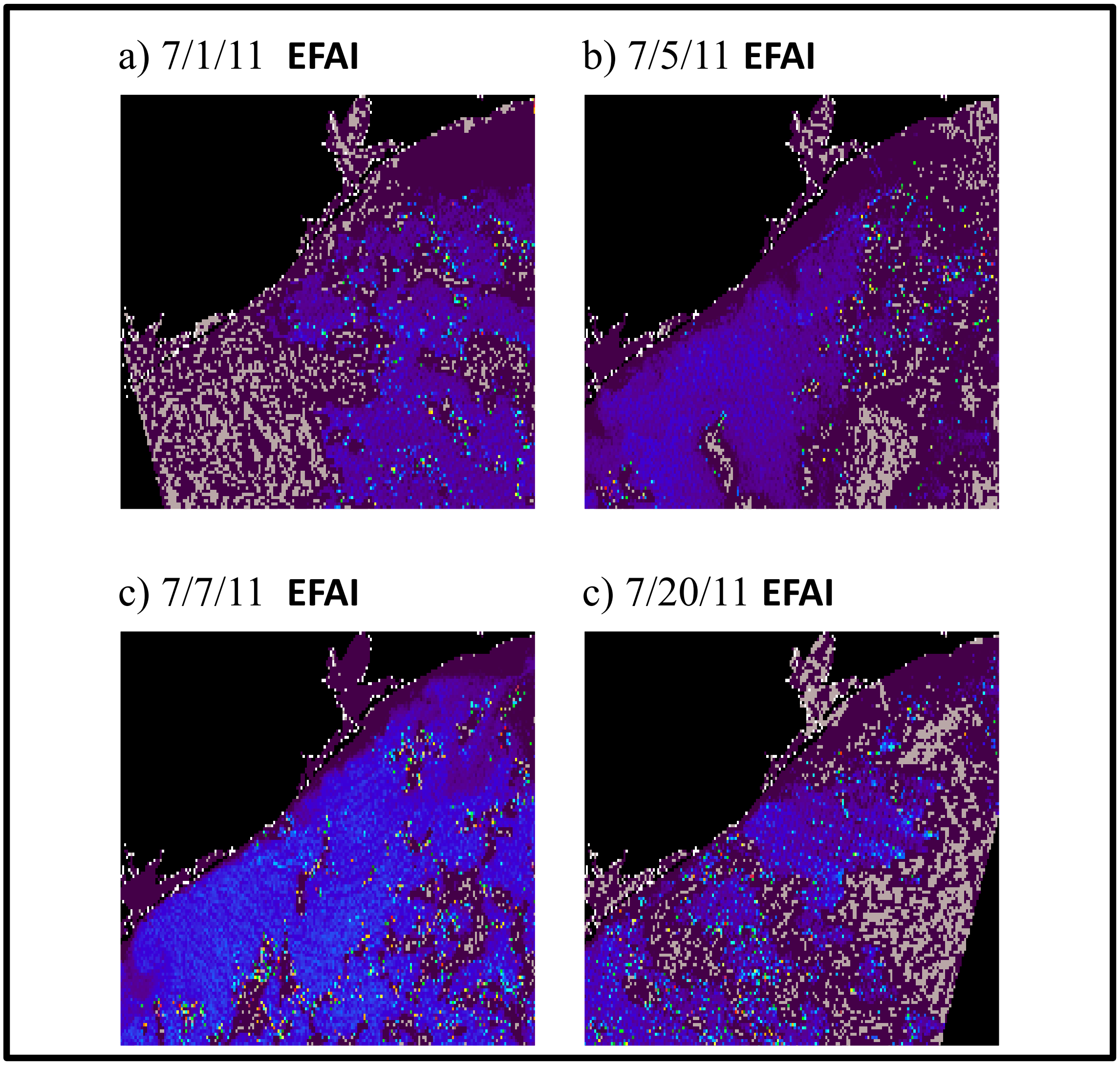


Figure 24 July 2011 – EFAI satellite images showing scattered sunglint and clouds obscuring EFAI images on the study area.

4.3 Statistical Analysis of Ground Truthing Data and EFAI Satellite Images

As part of the research for determining the applicability of using EFAI satellite images for tracking and forecasting *Sargassum* movements within the Gulf of Mexico, the total ground truthing days for each month were compared, January through July, with the total number of usable EFAI satellite images for the corresponding days (Table 8).

Table 8 Total ground truthing days vs. distorted and useable EFAI images

Month	Total Ground Truthing Days	Distorted EFAI Satellite Images	Usable EFAI Satellite Image	Percent of Useable Images per Month
January	4	4	0	0%
February	10	5	5	50%
March	6	3	3	50%
April	9	6	3	33%
May	7	5	2	29%
June	5	4	1	20%
July	5	3	2	40%
TOTALS	46	30	16	35%

A total of 46 ground truth data days were directly compared with the corresponding EFAI satellite images. Of those 46 days, 65% of the EFAI satellite images were distorted due to sunglint or cloud cover. Useable images were available 35% of the time (Table 9).

Table 9 For the 46 ground truth data days, 65% of the EFAI images were distorted and 35% were useable for detecting *Sargassum*.

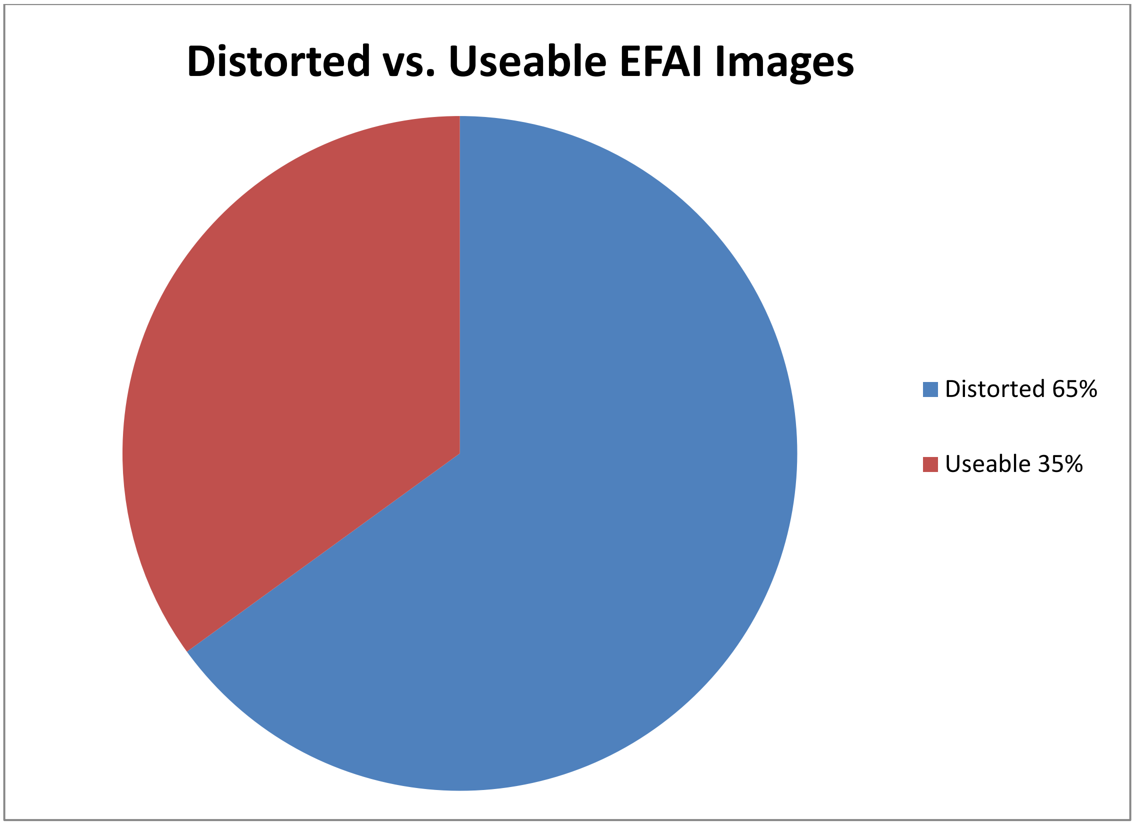
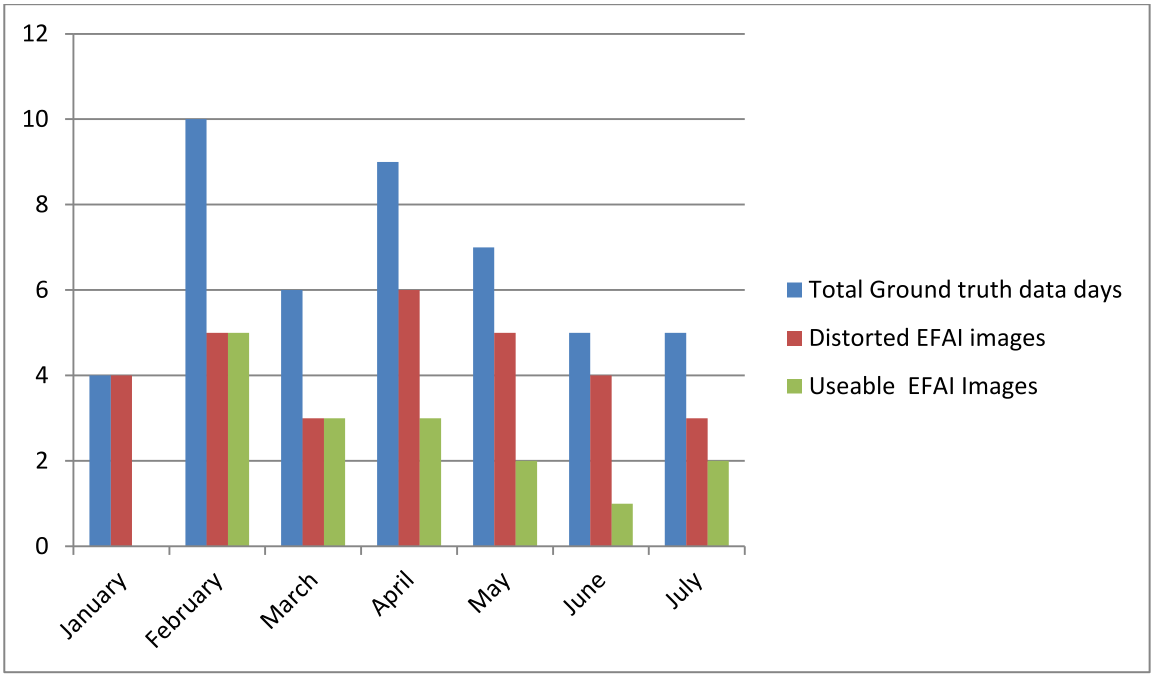


Table 10 Comparison by month of total ground truth data days vs. distorted and useable EFAI satellite images.

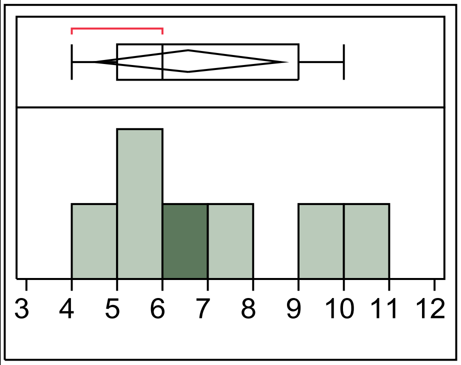


Further analysis of the number of ground truthing days per month indicates a need for a greater sample size of ground truthing days per study period (Table 10). This would yield more comparison applications by allowing for technological errors due to atmospheric conditions.

Analyses were also run for the distorted sample days and useable sample days. Again, these results were inconclusive due to small sample size (Table 11).

Table 11 Analysis of the sample size of ground truth days per month.

Distributions of Ground Truth Days by month



Quantiles

100.0%	maximum	10
99.5%		10
97.5%		10
90.0%		10
75.0%	quartile	9
50.0%	median	6
25.0%	quartile	5
10.0%		4
2.5%		4
0.5%		4
0.0%	minimum	4

Mean	6.5714286
Std Dev	2.2253946
Std Err Mean	0.8411201
Upper 95% Mean	8.6295753
Lower 95% Mean	4.5132819
N	7

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The application of EFAI satellite images for identifying, tracking, and mapping *Sargassum* in the Gulf of Mexico, clearly provide an improved source for data acquisition and analysis compared to previous methods of utilizing ship surveys and beach casting reports. However, limitations due to spatial resolution, cloud cover, and sunglint do exist. As with other remote sensing applications, the ability to effectively identify the targeted subject from space is primarily limited by satellite revisit frequency and spatial resolution. In addition, the short term data set on which this study was based upon, limited the effectiveness of using satellite imagery to track and predict *Sargassum* movements.

Lack of useable and undistorted images for comparison with corresponding ground truthing data was an ongoing problem throughout this study. As previously mentioned, EFAI saturates under sunglint, clouds, or thick aerosols. EFAI is more sensitive than FAI to detect subtle ocean surface features, but it saturates more readily and often provides less coverage than FAI. However, continued improvements in algorithm applications and technology will in all probability address these problems.

FAI was successfully used by Gower and King and subsequently by Hu and although EFAI is a new application, its suitability for tracking and identifying *Sargassum* is promising. Long term use of EFAI, will undoubtedly refine its effectiveness in detecting *Sargassum* slicks not only in the Gulf of Mexico but around the world.

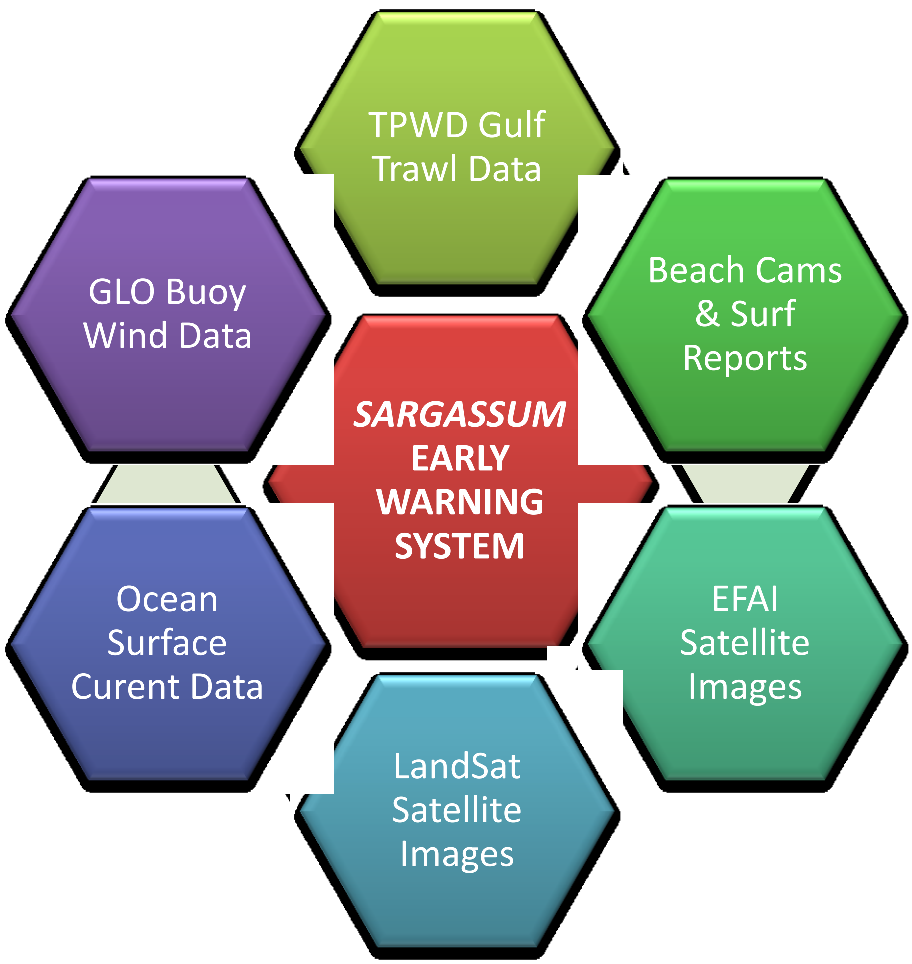
MODIS offers the advantage over previous satellites of covering wide paths of the Earth and providing near-daily images. Yet it must be noted that any satellite may miss significant quantities of *Sargassum* if it is too evenly distributed or mixed beneath the water's surface by wind. In addition, lines of *Sargassum* can be much smaller than the best MODIS resolution, therefore not detectable at the present time using existing technology. This limitation can be addressed by the introduction of Landsat data that was not available at the time of this study, to complement the MODIS findings. Cloud-free data from Landsat and MODIS have been compared and results suggest that *Sargassum* identified on MODIS images appear on corresponding Landsat images, but some *Sargassum* lines can only be identified by Landsat due to the small size of the slicks (Hu, 2009). Landsat coverage was not available or applied to this study's analysis; however, Landsat image coverage incorporates near-shore waters and would be useful in future studies using TPWD Gulf trawl data from state waters.

The TPWD Gulf trawl and beach log ground truthing information were limited to the available data from 2011 and three Texas bay area systems. By extending the parameters of research to include multiple years and greater geographical areas, satellite imagery can play an important role in detecting *Sargassum* biomass and trends of movement. At the present time, application of real time MODIS EFAI images are not consistent enough, (due to sunglint, cloud cover and spatial limitations), to solely base an effective early warning system for *Sargassum* tracking on. However, continual technological improvements in algorithm applications ensure future satellite data products will address current limitations and improve reliability.

A *Sargassum* early warning system offers numerous advantages for beach managers. Advance warning of a *Sargassum* event would enable management agencies to schedule work crews in preparation of landfall. Knowledge of the size and scope of the *Sargassum* event along with estimated landfall would allow managers to plan for the needed resources and equipment in advance. In addition, Federal and State agencies that manage fisheries and fishery habitat would benefit from information on the size and location of *Sargassum* habitat.

In addition to the aforementioned information from EFAI images, web cams, beach logs, TPWD Gulf trawl data, surface currents and Landsat images, another factor needs to be considered and entered into the equation for developing an early warning system – wind (Table 12). Specifically the influence wind has on *Sargassum* landings needs to be explored further. The Texas General Land Office (TGLO), in cooperation with Texas A&M University, maintains a series of instrumented buoys off the Texas coast. In particular, TGLO TABS Buoy B is about 40 nautical miles offshore of Galveston. Wind speed as well as direction is continuously recorded by the buoy system's monitoring devices. Data recorded at this buoy could be used in conjunction with the existing sources to predict when *Sargassum* events might occur.

Table 12 Components for a *Sargassum* early warning system.



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APPENDIX A

TPWD MARINE RESOURCE/HARVEST MONITORING HYDROLOGICAL AND METEOROLOGICAL FORM

TEXAS PARKS AND WILDLIFE

MARINE RESOURCE/HARVEST MONITORING - Meteorological and Hydrological Data

MAJOR AREA:_______ MINOR BAY:_______ STATION: _____ Alt: ____

GEAR/STRATUM: ____ GEAR SIZE (m)/DAY TYPE: __________

COMPLETION DATE (mm-dd-yyyy): ________ COMPLETION TIME (hhmm): _____

Special Studies Code: ____________ Surface Area:________

Common Gear/Stratum Codes

1. Gill net 5. Shrimp trawl 7. Bag 16. Oyster dredge 82. Boat-access site

CONDITIONS WHEN SAMPLING BEGAN:

Start date (mm-dd-yyyy): _________ Start time (hhmm): _____________

Start lighting condition: 1. Daylight 2. Night 3. Twilight

Latitude____________________ Longitude____________________

Wind speed (mph): Wind direction: 1. N 2. NE 3. E 4. SE 5. S 6. SW 7. W 8. NW

Cloud cover (%): 1.0-9 2. 10-25 3.26-50 4.51-75 5. 76-90 6.91-100

Barometric pressure (00,01 Precipitation: 1. Yes 2. No Fog: 1. Yes 2. No

Wave height (ft): 0.0,1 1.0,1-0.4 2.0.4-1,2 3.1.2-3,0 4.3,0-5,0 5.5,0-8,0 6.8,0-12,0 7.12,0-16,0

Tide: observed: 1. Slack 2. Ebb 3. Flood published: 4. Slack 5. Ebb 6. Flood

Shallow water depth (0,1 Deep water depth (0,1

Max, station water depth (0,1

Temperature (0,1 Dissolved oxygen (0,1 ppm): ____ Salinity (0,1

Turbidity (NTU): _____

Bottom type (circle all types present): 1. Clay 2. Silt 3. Sand 4. Shell 5. Gravel 6. Rocks

Authority notified___________________________________

Completion lighting condition: 1. Daylight 2. Night 3. Twilight

CONDITIONS WHEN SAMPLING WAS COMPLETED (see operations manuals to determine when to complete):

Latitude (deg-min-sec): ______________________Longitude________________________________

Wind speed (mph): Wind direction: 1. N 2. NE 3. E 4. SE 5. S 6. SW 7. W 8. NW

Cloud cover (%): 1.0-9 2.10-25 3.26-50 4.51-75 5.76-90 6.91-100

Barometric pressure (00,01 Precipitation: 1. Yes 2. No Fog: 1. Yes 2. No

Wave height (tt): O. 0,1 1. 0,1-0.4 2. 0.4-1.2 3. 1,2-3,0 4. 3.0-5,0 5. 5.0-8,0 6. 8.0-12.0 7. 12,0-16.0

Tide: observed: 1. Slack 2. Ebb 3. Flood published: 4. Slack 5. Ebb 6. Flood

Shallow water depth (0.1 Deep water depth (0,1

Max, station water depth (0.1

Temperature (0,1 Dissolved oxygen (0 1 ppm): ____ Salinity (0.1

Turbidity (NTU): _____

Bottom type (circle all types present): 1. Clay 2. Silt 3. Sand 4. SheilS. Gravel 6. Rocks

SAMPLE DISPOSITION: ____________________________

APPENDIX B

TPWD MARINE RESOURCE MONITORING – DATA FORM

TEXAS PARKS AND WILDLIFE

MARINE RESOURCE MONITORING — DATA

MAJOR AREA	MINOR BAY	STATION	COMP. DATE (mm-dd-yyyy)	COMP. TIME (hhmm)	GEAR CODE	GEAR SIZE (m)	Mesh Size (mm)	Dgms	Subsample (%)	User Def. Field	Page	Total Pages	Special Studies Code

COMMENTS:

Line No.	Species Name	Species Code	Number	Length T, S or F	Weight		Sex	MS	Tag Number R, C, L, A, B or D	User-Defined Fields (14)														Comments
					G	D				a	b	c	d	e	f	g	h	i	j	k	l	m	n	
1																								
2																								
3																								
4																								
5																								
6																								
7																								
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11																								
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13																								
14																								
15																								
16																								
17																								
18																								
19																								
20																								

APPENDIX C

BEACH REPORT, CAM AND SURVEY LOG

Date	Source	Sargassum reported	Notes
2/2/11	SPI Report & Cam	No	
2/3/11	Galveston Cams	No	
2/10/11	SPI Report & Cam	No	
2/12/11	SPI Report & Cam	No	
2/15/11	Galveston Cams	No	
2/17/11	SPI Report & Cam	No	
2/18/11	Galveston Cams	No	
	Sargent Cam	No	
	Surfside Cam	No	
2/19/11	SPI Report & Cam	No	
2/21/11	NOAA Beach Survey	No	
2/22/11	SPI Report & Cam	No	
2/23/11	Galveston Cams	No	
	Sargent Cam	No	
	Surfside Cam	No	
2/25/11	SPI Report & Cam	No	

2/27/11	Galveston Cams	No	
	Sargent Cam	No	
	Surfside Cam	Not Available	
2/28/11	SPI Report & Cam	No	
	Galveston Cams	No	
3/2/11	SPI Report & Cam	YES	Listed as Light
	Galveston Cams	No	
	Sargent Cam	Not Available	
	Surfside Cam	No	
3/4/11	SPI Report & Cam	YES	Listed as Light
3/7/11	SPI Report & Cam	YES	Listed as Light- 5th cons. day
	Galveston Cams	No	
	Surfside Cams	No	
3/9/11	NOAA Beach Survey	YES	Light/Moderate on Boliver
	Galveston Cams	No	
	Surfside Cams	No	
	Sargent	Not Available	
3/14/11	SPI Report & Cam	No	Listed as none
3/16/11	Galveston Cams	YES	Light balls on beach
	SPI Report & Cam	No	Listed as none
	Surfside Cam	No	
3/18/11	Sargent Cam	Not Available	

3/23/11	Galveston Cams	No	
	Surfside Cam	No	
	Sargent Cam	Not Available	
4/6/11	Galveston Cams	No	
	Surfside Cam	No	
4/11/11	NOAA Beach Survey	YES	Med/Hvy with balls in surf
4/12/11	NOAA Gear Boat	YES	N 29°48.182' W 93°57.255'
4/15/11	SPI Report & Cam	YES	Light
	Galveston Cams	No	Not visible but beach was raked
4/20/11	Galveston Cams	No	
4/27/11	EFAI Sat Images	YES	*Heavy per Hu
	Galveston Cams	YES	
	Surfside Cams	Not available	
5/11/11	Galveston Cams	YES	Heavy
5/12/11	Galveston Cam	YES	Medium to Heavy
	SPI Report & Cam	YES	Light
	TX A&M Boat	YES	10miles offshore lots of balls – No mats
5/13/11	EFAI Sat Images	YES	*Heavy per Hu
5/20/11	NOAA Beach Survey	YES	Medium on beach

APPENDIX D

TPWD GULF TRAWL DATA

JANUARY – JULY 2011

Date	*Sargassum*	Lat/long	Time	Area	Minor Bay	Station	Converted Coordinates
JANUARY							
1/4/11	*fluitans*	28-28-30 96-10-37	1051	19	992	1434	28.4,96.2
1/4/11	*fluitans*	28-27-31 96-13-21	1456	19	992	1456	28.5, 96.2
1/4/11	*fluitans*	28-20-31 96-11-27	1422	19	992	1599	28.3, 96.2
1/4/11	*fluitans*	28-27-30 96-10-27	1152	19	992	1459	28.5, 96.2
1/4/11	*fluitans*	28-25-30 96-14-38	0932	19	992	1501	
1/4/11	*fluitans*	28-23-27 96-05-32	1244	19	992	1553	
1/4/11	*fluitans*	28-22-29 96-08-36	1343	19	992	1570	
1/7/11	vegnone	29-16-24 94-42-33	1121	18	990	529	
1/7/11	vegnone	29-20-20 94-36-35	0911	18	990	481	
1/7/11	vegnone	29-19-48 94-36-11	0941	18	990	495	
1/7/11	vegnone	29-18-18 94-42-44	1026	18	990	503	
1/7/11	vegnone	29-17-42 94-43-16	1052	18	990	515	
1/7/11	vegnone	29-13-46 94-37-16	1205	18	990	581	29.2, 94.6
1/7/11	vegnone	29-10-21 94-50-40	1319	18	990	626	
1/7/11	vegnone	29-07-46 94-46-17	1401	18	990	692	
1/17/11	vegnone	28-20-25 96-17-39	1111	19	992	1593	
1/17/11	*natans*	28-21-32 96-13-27	1018	19	992	1582	
1/17/11	*natans*	28-21-24 96-15-35	0932	19	992	1580	
1/17/11	*natans*	28-17-34 96-19-25	1152	19	992	1641	
1/17/11	both	28-16-33	1206	19	992	1506	

		96-15-25					
1/17/11	*natans*	28-15-35 96-21-24	1319	19	992	1676	
1/17/11	*natans*	28-12-26 96-20-27	1405	19	992	1741	
1/19/11	vegnone	29-26-12 94-35-52	1011	18	990	352	
1/19/11	vegnone	29-25-12 94-38-51	0940	18	990	376	
1/19/11	vegnone	29-25-47 94-31-06	1051	18	990	383	
1/19/11	vegnone	29-24-11 94-39-54	0916	18	990	401	
1/19/11	vegnone	29-22-52 94-34-20	0845	18	990	445	
1/19/11	vegnone	29-22-52 94-34-20	1211	18	990	451	
1/19/11	vegnone	29-20-53 94-35-12	1237	18	990	482	
1/19/11	vegnone	29-20-47 94-30-18	1130	18	990	487	
FEBRUARY							
2/11/11	*natans*	28-28-30 96-10-32	0957	19	992	1434	
2/11/11	*natans*	28-27-25 96-06-21	1151	19	992	1463	
2/12/11	vegnone	29-22-14 94-30-42	1054	18	990	455	
2/12/11	vegnone	29-24-46 94-36-21	1252	18	990	404	
2/12/11	vegnone	29-25-20 94-38-49	1321	18	990	376	
2/12/11	vegnone	29-25-16 94-35-48	1225	18	990	379	
2/12/11	vegnone	29-24-49 94-40-19	1348	18	990	400	
2/12/11	vegnone	29-23-36 94-36-20	1011	18	990	428	
2/12/11	vegnone	29-23-39 94-30-14	1123	18	990	434	
2/12/11	vegnone	29-22-12 94-37-34	0937	18	990	448	
2/23/11	vegnone	29-18-41 94-36-17	1022	18	990	509	
2/23/11	vegnone	29-18-14 94-34-48	1055	18	990	511	
2/23/11	vegnone	29-17-10 94-44-59	1450	18	990	514	
2/23/11	vegnone	29-17-48 94-35-12	1125	18	990	523	

2/23/11	vegnone	29-16-05 94-46-56	1419	18	990	525	
2/23/11	vegnone	29-16-05 94-41-58	1527	18	990	530	
2/23/11	vegnone	29-13-01 94-37-52	1212	18	990	581	
2/23/11	vegnone	29-09-48 94-50-22	1322	18	990	647	
MARCH							
3/2/11	*natans*	28-24-30 96-15-27	0926	19	992	1522	
3/2/11	*natans*	28-22-37 96-20-22	1524	19	992	1558	
3/2/11	*natans*	28-28-29 96-09-34	1059	19	992	1435	
3/2/11	*fluitans*	28-23-35 96-11-23	1316	19	992	1547	
3/11/11	vegnone	29-26-45 94-38-14	1458	18	990	349	
3/11/11	vegnone	29-24-11 94-41-45	1140	18	990	399	
3/11/11	vegnone	29-22-49 94-37-20	1217	18	990	448	
3/11/11	vegnone	29-22-17 94-33-43	1108	18	990	452	
3/11/11	vegnone	29-21-17 94-37-47	1420	18	990	466	
3/11/11	vegnone	29-23-45 94-42-21	1521	18	990	422	
3/16/11	Both	28-16-23 96-23-45	1549	19	992	1655	
3/16/11	*fluitans*	28-15-31 96-20-27	1025	19	992	1677	
3/16/11	both	28-14-34 96-28-24	1454	19	992	1689	
3/16/11	both	28-13-23 96-26-40	1416	19	992	1713	
3/16/11	both	28-12— 34 96-23-26	1146	19	992	1738	
3/16/11	*fluitans*	28-12-24 96-20-38	1109	19	992	1741	
3/16/11	both	28-11-30 96-26-34	1318	19	992	1757	
3/16/11	both	28-09-23 96-25-38	1236	19	992	1801	
3/16/11	*fluitans*	29-19-44 94-39-12	0940	18	990	492	29.3 94.7
3/16/11	*fluitans*	29-13-46 94-52-18	1136	18	990	566	
3/16/11	*fluitans*	29-12-16	1031	18	990	599	29.2

		94-38-52					94.6
3/16/11	*fluitans*	29-11-13 94-53-49	1209	18	990	603	
3/16/11	vegnone	29-10-44 94-46-21	1259	18	990	630	
3/16/11	*fluitans*	29-08-42 94-49-30	1400	18	990	668	
3/16/11	*fluitans*	29-08-44 94-47-21	1435	18	990	670	
APRIL							
4/1/11	*fluitans*	29-17-50 94-40-33	1037	18	990	566	
4/1/11	both	29-11-49 94-45-11	1456	18	990	654	29.2 94.7
4/1/11	*fluitans*	29-09-20 94-50-41	1202	18	990	669	
4/1/11	both	29-13-58 94-52-07	1324	18	990	670	
4/1/11	*fluitans*	29-09-20 94-43-37	1253	18	990	710	
4/1/11	both	29-08-54 94-48-21	1121	18	990	324	
4/1/11	both	29-08-01 94-47-49	1148	18	990	327	
4/1/11	*fluitans*	29-06-17 94-48-35	1005	18	990	446	
4/5/11	*fluitans*	28-29-30 96-12-23	1109	19	992	1406	
4/5/11	both	28-29-26 96-08-37	1149	19	992	1410	
4/5/11	both	28-27-36 96-09-25	1224	19	992	1460	
4/5/11	both	28-26-26 96-06-36	1331	19	992	1487	
4/5/11	*fluitans*	28-25-24 96-18-37	0957	19	992	1497	
4/5/11	both	28-22-31 96-07-28	1414	19	992	1571	
4/5/11	both	28-20-31 96-16-26	1607	19	992	1594	
4/5/11	*fluitans*	28-20-26 96-13-37	1531	19	992	1597	
4/27/11	both	28-24-27 96-20-11	1600	19	992	1517	28.4 96.3
4/27/11	both	28-22-21 96-19-41	1004	19	992	1559	28.4 96.3
4/27/11	both	28-18-23 96-16-37	1506	19	992	1627	28.3 96.3
4/27/11	both	28-17-36 96-19-20	1429	19	992	1641	

4/27/11	both	28-10-23 96-25-40	1201	19	992	1780	28.2 96.4
4/27/11	both	28-18-33 96-22-17	1054	19	992	1621	28.3 96.4
4/27/11	both	28-14-21 96-16-41	1344	19	992	1701	
4/27/11	both	28-11-30 96-20-33	1250	19	992	1763	
4/28/11	both	29-25-15 94-36-43	1044	18	990	378	29.4 94.6
4/28/11	*fluitans*	29-24-45 94-28-18	1245	18	990	412	
4/28/11	both	29-22-43 94-35-20	1418	18	990	450	
4/28/11	*fluitans*	29-22-42 94-29-23	1323	18	990	456	29.4 94.5
4/28/11	both	29-21-11 94-40-40	0933	18	990	463	
4/28/11	both	29-27-42 94-35-14	1121	18	990	324	
4/28/11	both	29-27-13 94-32-36	1148	18	990	327	
4/28/11	*fluitans*	29-22-47 94-36-15	1005	18	990	446	
MAY							
5/5/11	both	28-25-28 96-11-27	1009	19	992	1504	
5/5/11	both	28-24-32 96-14-28	0930	19	992	1523	
5/5/11	both	28-21-35 96-17-27	1423	19	992	1518	
5/5/11	both	28-21-27 96-08-30	1055	19	992	1587	
5/5/11	both	28-19-28 96-18-29	1340	19	992	1608	
5/5/11	both	28-19-30 96-15-31	1203	19	992	1611	
5/5/11	both	28-19-26 96-13-25	1136	19	992	1613	
5/5/11	both	28-14-37 96-18-30	1247	19	992	1699	28.2 96.3
5/6/11	*fluitans*	29-29-16 94-31-46	1325	18	990	271	
5/6/11	*fluitans*	29-27-46 94-35-12	1252	18	990	324	
5/6/11	both	29-27-43 94-30-12	1355	18	990	329	
5/6/11	*fluitans*	29-26-25 94-30-39	1429	18	990	357	
5/6/11	both	29-21-19 94-30-45	1204	18	990	473	29.4 94.5

5/6/11	both	29-20-41 94-37-20	1114	18	990	480	
5/6/11	both	29-18-48 94-41-18	0927	18	990	504	
5/6/11	both	29-15-11 94-39-43	1028	18	990	546	29.3 94.7
5/16/11	both	28-18-20 96-27-01	1403	19	992	1616	
5/16/11	both	28-15-28 96-28-29	1327	19	992	1669	
5/16/11	both	28-15-33 96-20-24	0946	19	992	1677	
5/16/11	both	28-14-32 96-27-26	1255	19	992	1690	
5/16/11	both	28-14-30 96-25-29	1057	19	992	1692	
5/16/11	both	28-14-32 96-23-18	1025	19	992	1694	
5/16/11	both	28-12-33 96-26-29	1132	19	992	1735	
5/16/11	both	28-11-28 96-26-28	1204	19	992	1757	28.2 96.4
5/16/11	both	29-13-51 94-48-07	0923	18	990	570	
5/16/11	both	29-13-16 94-42-41	1658	18	990	576	
5/16/11	both	29-13-08 94-38-43	1734	18	990	580	29.2 94.6
5/16/11	both	29-12-25 94-44-43	1604	18	990	593	
5/16/11	both	29-10-07 94-50-49	1002	18	990	626	
5/16/11	both	29-09-49 94-47-09	1046	18	990	650	
5/16/11	both	29-08-44 94-43-09	1443	18	990	674	29.1 94.7
5/16/11	both	29-07-07 94-46-44	1134	18	990	692	29.1 94.8
JUNE							
6/1/11	both	28-29-34 96-08-31	1206	19	992	1410	28.5 96.1
6/1/11	both	28-26-32 96-13-30	1113	19	992	1480	28.4 96.2
6/1/11	both	28-25-35 96-16-31	1036	19	992	1499	
6/1/11	both	28-24-29 96-04-27	1303	19	992	1533	
6/1/11	both	28-23-35 96-17-28	0923	19	992	1541	
6/1/11	both	28-23-33 96-14-30	1001	19	992	1544	28.4 96.2

6/1/11	both	28-19-30 96-14-31	1438	19	992	1612	
6/1/11	*fluitans*	28-19-29 96-13-32	1408	19	992	1613	
6/1/11	both	29-18-44 94-44-18	0944	18	990	501	29.3 94.7
6/1/11	Both	29-17-15 94-46-44	1022	18	990	512	29.3 94.08
6/1/11	*fluitans*	29-16-37 94-41-20	1108	18	990	530	29.3 94.7
6/1/11	both	29-10-03 94-42-56	1212	18	990	634	
6/2/11	both	29-13-19 94-47-31	1038	18	998	571	
6/2/11	*fluitans*	29-11-14 94-53-38	1157	18	998	603	
6/2/11	*fluitans*	29-11-44 94-32-14	1128	18	998	604	
6/2/11	both	29-07-39 94-46-19	1254	18	998	692	
6/2/11	both	29-39-40 93-55-10	1024	17	998	14	
6/2/11	both	29-39-25 93-53-48	0945	17	998	16	
6/2/11	both	29-39-28 93-52-11	0908	17	998	17	
6/2/11	both	29-37-28 94-02-09	1158	17	998	46	
6/2/11	both	29-37-29 94-00-51	1116	17	998	48	
6/2/11	both	29-36-28 94-03-49	1247	17	998	70	
6/2/11	both	29-31-26 93-51-04	1804	17	998	243	
6/2/11	both	29-39-35 93-48-44	0807	17	998	3714	
6/23/11	both	28-21-31 96-18-24	1009	19	992	1577	
6/23/11	both	28-21-16 96-22-40	1059	19	992	1573	
6/23/11	*natans*	29-26-57 94-35-19	1148	18	990	352	
6/23/11	both	29-23-54 94-42-10	1016	18	990	422	
6/23/11	both	29-23-21 94-38-53	1103	18	990	426	
6/23/11	both	29-22-55 94-35-20	1353	18	990	450	
6/23/11	*natans*	29-21-09 94-40-48	0939	18	990	463	
6/23/11	both	29-21-27	1308	18	990	473	

		94-30-58					
6/23/11	*natans*	29-19-53 94-36-33	1507	18	990	495	
6/23/11	*natans*	29-12-06 94-42-55	1628	18	990	595	
6/27/11	both	28-16-29 96-26-28	1340	19	992	1652	
6/27/11	*fluitans*	28-16-33 96-24-28	1418	19	992	1654	
6/27/11	*Fluitans*	28-16-32 96-19-29	1044	19	992	1659	
6/27/11	Both	28-15-40 96-25-29	1314	19	992	1672	
6/27/11	*fluitans*	28-13-36 96-19-30	1127	19	992	1720	
6/27/11	*fluitans*	28-09-32 96-25-28	1222	19	992	1801	
6/29/11	Both	29-44-23 93-37-49	1006	17	998	3651	
6/29/11	Both	29-42-30 93-39-07	0917	17	998	3677	
6/29/11	Both	29-40-28 93-48-45	0707	17	998	3699	
6/29/11	Both	29-38-28 93-39-11	1107	17	998	3738	
6/29/11	Both	29-36-30 93-46-54	1336	17	998	3760	
6/29/11	Both	29-36-20 93-43-23	1252	17	998	3763	
6/29/11	Both	29-36-27 93-38-54	1150	17	998	3768	
6/29/11	Both	29-33-09 93-45-30	1434	17	998	3790	
7/1/11	both	29-39-12 94-00-43	1252	17	998	9	29.7 94.0
7/1/11	*natans*	29-38-30 94-03-11	1333	17	998	23	29.6 94.1
7/1/11	both	29-37-31 94-03-49	1411	17	998	45	
7/1/11	*natans*	29-37-23 93-59-14	1146	17	998	49	
7/1/11	both	29-33-31 93-54-51	1056	17	998	170	
7/1/11	both	29-35-40 93-47-08	0949	17	998	3773	29.6 93.8
7/1/11	both	29-34-30 93-47-51	0907	17	998	3783	
7/1/11	vegnone	29-34-30 93-45-10	0812	17	998	3785	
7/5/11	*fluitans*	28-30-36	1412	19	992	1385	

		96-06-19					
7/5/11	both	28-29-36 96-09-36	1335	19	992	1409	
7/5/11	*fluitans*	28-28-32 96-14-18	1249	19	992	1430	
7/5/11	*fluitans*	28-27-23 96-11-35	1202	19	992	1458	
7/5/11	*fluitans*	28-26-37 96-10-16		19	992	1483	
7/5/11	*fluitans*	28-24-24 96-14-34	1048	19	992	1523	
7/5/11	*fluitans*	28-24-28 96-07-31	1519	19	992	1530	
7/5/11	*fluitans*	28-22-36 96-20-22	1647	19	992	1558	
7/7/11	*fluitans*	29-12-05 94-38-47	0903	18	990	599	
7/7/11	*fluitans*	29-13-42 94-37-13	1014	18	990	581	
7/7/11	*fluitans*	29-14-20 94-37-39	1050	18	990	564	
7/7/11	both	29-23-15 94-38-45	1211	18	990	426	
7/7/11	vegnone	29-27-39 94-36-09	1250	18	990	323	
7/7/11	*fluitans*	29-25-18 94-32-48	1325	18	990	382	
7/7/11	*natans*	29-26-50 94-31-21	1351	18	990	356	
7/7/11	*fluitans*	29-26-16 94-30-38	1417	18	990	357	
7/18/11	Both	28-22-46 96-19-30	1108	19	992	1559	
7/18/11	both	28-17-34 96-18-30	1200	19	992	1642	
7/18/11	*fluitans*	28-16-33 96-23-27	1604	19	992	1655	
7/18/11	*fluitans*	28-15-31 96-24-24	1535	19	992	1673	
7/18/11	*fluitans*	28-14-36 96-28-20	1431	19	992	1689	
7/18/11	*fluitans*	28-14-32 96-27-27	1500	19	992	1690	
7/18/11	*fluitans*	28-12-23 96-19-23	1251	19	992	1742	
7/18/11	*natans*	28-10-30 96-25-33	1344	19	992	1780	
7/20/11	vegnone	29-10-13 94-47-48	1319	18	990	629	
7/20/11	Both	29-11-10 94-45-44	1503	18	990	611	

7/20/11	both	29-08-53 94-46-11	1358	18	990	671	
7/20/11	*fluitans*	29-15-44 94-43-34	1111	18	990	542	
7/20/11	*fluitans*	29-13-11 94-41-44	1030	18	990	577	
7/20/11	*fluitans*	29-10-50 94-48-14	1254	18	990	628	
7/20/11	*fluitans*	29-14-14 94-49-52	1203	18	990	552	
7/20/11	vegnone	29-13-43 94-42-14	1004	18	990	576	
7/20/11	both	29-42-30 93-40-10	1758	17	998	3676	29.7 96.7
7/20/11	*fluitans*	29-41-25 93-47-45	0813	17	998	3684	
7/20/11	*fluitans*	29-41-19 93-40-49	1721	17	998	3691	
7/20/11	*fluitans*	29-40-33 93-38-06	1645	17	998	3709	
7/20/11	both	29-38-26 93-35-50	1417	17	998	3742	
7/20/11	both	29-37-26 93-44-11	0917	17	998	3748	
7/20/11	*fluitans*	29-36-26 93-44-53	1003	17	998	3762	

APPENDIX E

TPWD MAJOR AREA AND MINOR BAY CODES

MAJOR AREA	MAJOR AREA CODE	MINOR BAY	MINOR BAY CODE
GULF OF MEXICO			
	17	off Sabine Lake less than or = 10 miles	989
	17	off Sabine Lake greater than 10 miles	999
	18	off Galveston-Freeport less than or = 10 miles	990
	18	off Galveston-Freeport greater than 10 miles	991
	19	off Matagorda-San Antonio less than or = 10 miles	992
	19	off Matagorda-San Antonio greater than 10 miles	993
	20	off Aransas-Corpus Christi-upper Laguna Madre less than or = 10 miles	994
	20	off Aransas-Corpus Christi-upper Laguna Madre greater than 10 miles	995
	21	off lower Laguna Madre less than or = 10 miles	996
	21	off lower Laguna Madre greater than 10 miles	997

APPENDIX F

TPWD GULF TRAWL VEGETATION SPECIES LIST AND CODES

VEGETATION SPECIES LIST (2008)

(Scientific Name Order)

CODE NO.	REF.	COMMON NAME	SCIENTIFIC NAME
		Species, SCIENTIFIC.VEGETATION, 5/14/2008	
4023	20	Mermaid's wine cup	Acetabularia crenulata
4005		Algae – unidentified	ALGAE
4055	16	Alligatorweed	Alternanthera philoxeroides
4031		Giant cane	Arundinaria gigantea
4032		Black mangrove	Avicennia germinans
4045	32	Maritime saltwort	Batis maritima
4046	32	Bushy sea-ox-eye	Borrichia frutescens
4039		Carolina fanwort	Cabomba caroliniana
4056		(Algae - green)	Caulerpa mexicana
4057		(Algae - green)	Caulerpa prolifera
4030	20	(Algae - red)	Centroceras clavulatum
4067		Common hornwort (coontail)	Ceratophyllum demersum
4034	20	(Algae - brown)	Cladosiphon occidentalis
4064		(Green fleece)	Codium isthmocladum
4012	20	Manatee grass	Cymodocea filiformis
4019	20	(Algae - brown)	Dictyota dichotoma
4033	20	(Algae - red)	Digenia simplex
4048	32	Coastal saltgrass	Distichlis spicata
4021	16	Common water hyacinth	Eichhornia crassipes
4054	20	(Algae - green)	Enteromorpha lingulata
4027	20	(Algae - brown)	Family Ectocarpaceae
4020	20	(Algae - red)	Family Gracilariaceae
4022	16	(Hornward or coontail)	Genus Ceratophyllum
4038		(Waterweed - unidentified)	Genus Egeria
4016	20	(Sargassum - unidentified)	Genus Sargassum
4015	16	(Cordgrass - unidentified)	Genus Spartina
4069	20	(Sea lettuce - unidentified)	Genus Ulva
4013	20	Shoal grass	Halodule beaudettei
4010	20	Star grass	Halophila engelmannii
4062	33	Grassleaf mudplantian	Heteranthera dubia
4065	33	Umbrella water-pennywort	Hydrocotyle umbellata
4059		(Algae - red)	Jania capillacea
4029	20	(Algae - red)	Laurencia poitei
4028		Common duckweed	Lemna minor
4047	32	Shoregrass	Monanthochloe littoralis

4035	16	Eurasian water milfoil	Myriophyllum spicatum
4026	16	Yellow waterlily	Nymphaea mexicana
4043	16	Duck-lettuce	Ottelia alismoides
4036	20	(Algae - brown)	Padina vickersiae
4024	16	Common reed	Phragmites australis
4053	16	Water-lettuce	Pistia stratiotes
4040	16	Fennel-leaf pondweed	Potamogeton pectinatus
4063	33	Thin-leaf pondweed	Potamogeton pusillus
4014	20	Widgeon grass	Ruppia maritima
4051	32	Sugarcane plumegrass	Saccharum giganteum
4061	16	Delta arrowhead	Sagittaria platyphylla
4041		Annual glasswort	Salicornia bigelovii
4044	32	Creeping glasswort	Salicornia virginica
4052	16	Water spangles	Salvinia minima
4066		Giant salvinia	Salvinia molesta
4017	20	(Broad-leaf sargassum)	Sargassum fluitans
4018	20	(Narrow-leaf sargassum)	Sargassum natans
4042		Saltmarsh bulrush	Scirpus robustus
4060	16	Coast sea purslane	Sesuvium maritimum
4025	16	Smooth cordgrass	Spartina alterniflora
4049	32	Marshhay cordgrass	Spartina patens
4011	20	Turtle grass	Thalassia testudinum
4037	20	(Narrow-thallus sea lettuce)	Ulva fasciata
4068	20	(Broad-thallus sea lettuce)	Ulva lactuca
4050	31	Sea oats	Uniola paniculata
4058	16	American wild celery	Vallisneria americana
4004		Emergent vegetation	VEGEMERGEN
4000		No vegetation	VEGNONE
4003		Submergent vegetation	VEGSUBMERG
4001		Vegetation undetermined	VEGUNDETER
4002		Vegetation type unidentified	VEGUNIDENT

VITA

Wendy Hammond Tabone received her Bachelor of Arts degree in biology from The University of Houston-Clear Lake in 1992. She entered the Marine Science, Master of Marine Resource Management program at Texas A&M University in August 2009. She complimented her classroom education with long term internships with NOAA's Office of Law Enforcement, Sea Turtle Stranding Network and TPWD Coastal Fisheries department. Her research interests include pelagic sargassum, endangered sea turtles, and marine conservation policies. She plans a career in marine biology with a focus on coastal fisheries and ecosystem conservation.

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