SPACEBORNE SENSORS TRACK MARINE DEBRIS CIRCULATION IN THE GULF OF MEXICO

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ABSTRACT

Marine debris is a problem for coastal areas throughout the world, including the Gulf of Mexico. To aid the NOAA Marine Debris Program in monitoring marine debris dispersal and regulating marine debris practices, satellite-based sea surface height and height anomaly data provided by the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder, were utilized to help assess sources and transport of trash and other discarded items that routinely wash ashore in southeastern Texas, at Padre Island National Seashore. These data were generated from the NASA radar altimeter satellites TOPEX/Poseidon, Jason 1, and Jason 2, as well as the European altimeter satellites ERS-1, ERS-2 (European Remote Sensing Satellite), and ENVISAT (Environmental Satellite). Sea surface temperature data from MODIS were used to study of the dynamics of the Loop Current. Sea surface height data analysis was used to show that warm water in the core of eddies, which periodically separate from the Loop Current, can be as high as 70 cm above the surrounding water. These eddies are known to directly transfer marine debris to the western continental shelf and the elevated area of water can be tracked using satellite radar altimeter data. Additionally, using sea surface height, geostrophic velocity, and particle path data, foretracking and backtracking simulations were created. These simulation results suggested that debris on Padre Island National Seashore may originate from a variety of sources, such as commercial fishing/shrimping, the oil and gas industry, recreational boaters, and from rivers that empty into the Gulf of Mexico.

Keywords: marine debris, eddies, barrier island beach, Padre Island National Seashore, radar altimetry, surface circulation, Gulf of Mexico, NASA DEVELOP

INTRODUCTION

Marine debris is a problem for many of the world's coastlines, and the Gulf of Mexico is no exception. In the Gulf of Mexico, clockwise-rotating areas of warm water, or eddies, periodically separate from the Loop Current. These eddies vary in size from 100-200 km in diameter and travel westward towards the Texas coast at speeds ranging from 2-5 km per day (Coats, 1992). These eddies have the potential to directly transfer debris to the western continental shelf**.** The mean prevailing wind direction is to the west, and this force additionally drives and transports the debris to the western Gulf of Mexico's inner continental shelf. On the shelf, the oblique wind directions create two longshore transport cells. The convergence point of these two cells is located within Padre Island National Seashore in the Coastal Bend of southeastern Texas. Initially, the convergence point was a deposition site for submersed aquatic vegetation and shells. Presently, it accumulates vast quantities of anthropogenic marine debris (National Park Service, 2008).

The beaches of Padre Island are now routinely littered with water deposited debris from such sources as the petroleum industry, commercial fishing vessels, and recreational boaters (National Park Service, 2008). This debris can potentially generate a variety of human health risks to individuals who may frequent the island for recreational activity, such as locals or tourists. Padre Island's economy is heavily dependent on sport fishing, kayaking, and beach recreation, and ecotourism plays a major role in the Coastal Bend's tourism-based economy (Lee, 2009). The total impact of ecotourism on Coastal Bend household earnings is $233.5 million and on employment is 8,748 jobs (Lee, 2009). Marine debris on the coastline can influence the return rate of ecotourists and have a detrimental effect on the local economy. Padre Island National Seashore, which is nearly 70 miles long, is the largest undeveloped beach in the world and can accumulate up to one ton of marine debris per linear mile (National Park Service, 2005b). Due to the island's large extent, there is a substantial amount of marine debris accumulation, and this in turn can become a significant human health concern. For example, waste materials that accumulate along the seashore, like used medical syringes and broken glass, pose as physical hazards to humans. Other waste items, such as used condoms and tampon applicators, can transmit disease. Additionally, these items can affect water quality and could correspondingly result in illness (Sheavly, 2007). Water that has been polluted with harmful bacteria and viruses, upon consumption or skin contact, "can result in infectious hepatitis, diarrhea, bacillary dysentery, skin rashes, and even typhoid and cholera" (Sheavly, 2007).

The biota of Padre Island can also be threatened by the accumulation of marine debris. Padre Island is situated along the Central Flyway, which is an important migration route for American birds. Three hundred and eighty different bird species visit the island annually; this includes nearly half of all bird species documented in America, including migratory, overwintering, and resident bird species (National Park Service, 2011a). According to the National Park Service (2011a), thirteen of these species are known to be threatened or endangered. Endangerment of these migrating and resident shore birds could be increased if they were to ingest marine debris that was either toxic or non-food items. Debris, upon ingestion, could abate the absorption of vital nutrients, and/or upon entanglement, can suffocate the birds (Ryan, 1990). Furthermore, if adult birds consumed debris and then regurgitated it to feed their chicks, this can lead to the death of the young and lowers nesting colony production (Laist, 1987; Fry et al., 1987).

Throughout the Gulf of Mexico region, marine debris monitoring and cleaning up programs have been established, however, currents and eddies transfer marine debris over great distances, and these effects can challenge efficient monitoring and cleanup efforts. In 2006, President George W. Bush signed into law the Marine Debris Research, Prevention, and Reduction Act (NOAA Marine Debris Program, 2011). After Hurricanes Katrina, Rita, and Ike, NOAA created the Marine Debris Program under the Marine Debris Research, Prevention, and Reduction Act. This act established NOAA's Marine Debris Program, among other measures, to attempt to reduce the amount of marine debris in the Gulf of Mexico. Following the formation of a partnership with the US Coast Guard, the Marine Debris Program began to use sonar to survey the Gulf of Mexico coastline for underwater debris. However, the program does not currently utilize spaceborne sensors to analyze floating marine debris and its relationship to the Gulf of Mexico Loop Current and associated eddies. For large-scale monitoring of surface circulation processes which transport marine debris the Marine Debris Program and others similar would benefit from the capabilities that NASA satellites such as TOPEX/Poseidon, Jason-1, Jason-2 and other remote sensing platforms with radar altimeters provide.

For this project, the Stennis DEVELOP Marine Debris team partnered with NOAA's Marine Debris Program, the Padre Island National Seashore Education and Outreach Department, and the Colorado Center for Astrodynamics Research located at the University of Colorado, Boulder. The research from this project will provide NOAA's Marine Debris Program with a better understanding of how the Gulf of Mexico Loop Current and surface circulation patterns affect coastal marine debris dispersal. Padre Island National Seashore will use the maps, visualizations and satellite data products produced by this project in their education and outreach programs, such as Talking Trash. Each year the Talking Trash program educates over 10,000 Texas middle and high school students about marine debris and pollution by discussing its effects on the environment. Dr. Robert Leben and his colleagues at the Colorado Center for Astrodynamics Research have played a key role in developing the methodologies for marine debris monitoring by providing sea surface height anomaly (SSHA) data. These methodologies will be transferred to the project partners, enabling them to track and monitor the Loop Current in the future.

STUDY AREA

The study area for this project includes the entire Gulf of Mexico with a specific focus on Padre Island National Seashore, Texas (Figure 1). Padre Island is located along the southern Texas Gulf Coast (Figure 1) and "is the world's longest undeveloped stretch of barrier island" (National Park Service, 2011b). The island is oriented north-south, the Gulf of Mexico lies to the east and Laguna Madre lies adjacent to the west. In 1964, the artificiallydredged Port Mansfield Channel divided the island and as a result, the terms "North Padre Island" and "South Padre Island" are often used to refer to the separate portions of the island (National Park Service, 2005a). North Padre Island includes Padre Island National Seashore. The national seashore is approximately 70 miles (110 km) long with 65.5 miles (105.4 km) of Gulf beach. A variety of pristine beach, dune, and tidal flat environments can be found within the park.

Figure 1. Gulf of Mexico region with an inset ASTER satellite image of Padre Island, Texas.

Study Period

The project partners at NOAA's Marine Debris Program expressed interest in altimeter and remotely sensed data from 2008-2010. Therefore, the study period for this project ranges from the beginning of 2008 to the end of 2010. The Colorado Center for Astrodynamics Research provided SSH data for this time frame. This study period will also enable the analysis of the effects hurricanes, such as Gustav and Ike, have had on the dispersal of marine debris. After the 2010 BP oil spill incident, surface circulation processes in the Gulf of Mexico gained national attention. Since the oil spill occurred during the designated study period, data collected may also be useful for studying the dispersal of oil in coastal waters of this region.

METHODOLOGY

Data Acquisition

Sea Surface Height Anomaly. SSHA data were provided by the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado, Boulder. This daily dataset requires the use of many altimeter satellites including: TOPEX/Poseidon, Jason 1, Jason 2, ERS-1, ERS-2, and Envisat. The sea surface height anomaly was calculated by combining all of the raw altimeter data for each satellite into separate cycle files. The data were referenced to a mean sea surface height model to generate sea surface height anomaly. The along- track data were next interpolated to a reference ground track to insure there are always samples at the same geographic location for each cycle. Then, the data were detrended using a linear least squares smoothing filter to remove all of the low frequency data. To produce a daily product from satellites that have repeat cycles ranging from 10 days (Jason) to

35 days (Envisat), a specific amount of data are used from each satellite for the day of interest. For example, if data are being processed for January 15th, and Jason 1 and Envisat data are available, data is taken from Jason 1 for January 10th-20th and Envisat for December 28th - February 1st. A full 10-day cycle of Jason data and a full 35 day cycle of Envisat data around the day of interest are used. The two datasets are then combined using a weighting scheme that places less emphasis on data that is farther away from the day of interest. Using a multi-grid technique, the along track data is used to fully populate a 0.25-degree evenly spaced grid. Once the data is gridded, it is referenced to a model mean to produce an estimated absolute sea surface height of the Gulf of Mexico (Leben, 2002). The Colorado Center for Astrodynamics Research at the University of Colorado, Boulder conducted the processing to calculate SSHA.

Sea Surface Temperature. Four-kilometer spatial resolution, weekly, Moderate Resolution Imaging Spectroradiometer (MODIS) Sea Surface Temperature (SST) data were downloaded from NASA's Oceancolor Web (NASA, 2011) as a Level 3 mapped product. MODIS SST data is available in a variety of spatial and temporal resolutions; spatially at 4km and 9km, and temporally at daily, weekly (8 day), and monthly. The Level 3 mapped products used in this study are global gridded data sets with all points filled, even over land. The Level 3 binned products only contain bins with valid SST data. No land bins are kept. All mapped products are derived from the binned products. MODIS SST measurements are derived from the MODIS thermal infrared channels (11-12um). MODIS SST data was downloaded for the observation period from November 17th, 2009 to June 17th, 2010.

Wind Data. Wind data used in this study was acquired from the National Data Buoy Center (NDBC)'s historical data archives (NOAA, 2010). The NDBC is a branch of the National Oceanic and Atmospheric Administration (NOAA) that, "provides high quality meteorological/environmental data in real time from automated observing systems that includes buoys and a Coastal-Marine Automated Network (C-MAN) in the open ocean and coastal zone surrounding the United States" (NOAA, 2009). Meteorological measurements from the buoys are recorded every day, every hour, every ten minutes (Historical wind data available at http://www.ndbc.noaa.gov/maps/west_gulf_hist.shtml).

The primary wind parameters used for this project were wind direction and wind speed. Data was acquired from each of three NDBC buoy stations--42020, 42019, & 42002--over the past five years. For buoy 42020 the years were 2006, 2007, 2008, 2009, & 2010; for buoy 42019 the years were 2006, 2007, 2008, 2009, & 2010; for buoy 42002 the years were 2005, 2006, 2007, 2008, & 2009 (this buoy malfunctioned during the year 2010).

Data Processing

Geostrophic Flow Velocities. A Matlab program was written to calculate geostrophic flow velocities (Figure 2) using the sea surface height data that was provided by the Colorado Center for Astrodynamics Research. Geostrophic flow velocities were calculated as a balance of the horizontal pressure gradient and the Coriolis force. However, flow is also affected by other variables, such as friction. The equations used to calculate geostrophic flow assume that the flow has no acceleration, the horizontal velocities are much larger than the vertical, the only external force is gravity, and the friction is small. The equation used to calculate geostrophic flow follows Marshall et al. (2003):

Geostrophic Flow = $\sqrt{u^2 + v^2}$ Where: $u = -\frac{g}{f}\frac{\partial h}{\partial y}$ and $v = \frac{g}{f}\frac{\partial h}{\partial x}$

where:
g = gravity
$f = 2\Omega \sin(\varphi)$ where: Ω is the rotation rate of the earth (7.2921159 x 10^{-5} rad/sec), and φ is the latitude (This equation is the Coriolis parameter.)
h = sea surface height
y = latitude
x = longitude

After this equation is run in Matlab to calculate surface velocity, the "quiver" command is used to create a vector field showing flow direction and magnitude.

Particle Paths. Particle paths can be tracked by using a numerical integration method to integrate through time and space. The previous term's DEVELOP team used Euler's integration method to track a particle's path by using the following equation (Weisstein):

$$x_{n+1} = x_n + v(t_n) * \Delta t$$
$$t_{n+1} = t_n + \Delta t$$

where x = position, v = velocity, and t = time

For this term's DEVELOP team, a higher-order integration method was used to more accurately track particle paths. The second-order Runge-Kutta method, which uses a trial step at the midpoint of an interval to cancel out lower-order errors, was implemented. This particular method was chosen because it provided the necessary accuracy needed without requiring a significant amount of processing time (Weisstein):

Given a vector φ_n of unknowns at time t_n and the first order differential equation $\frac{d\varphi}{dt} = f(\varphi, t)$, the second order Runge-Kutta estimate for φ_{n+1} is given by:

$$k_1 = \Delta t * f(\varphi_n, t_n)$$
$$k_2 = \Delta t * f\left(\varphi_n + \frac{1}{2}k_1, t_n + \frac{1}{2}\Delta t\right)$$
$$\varphi_{n+1} = \varphi_n + k_2$$

where $\Delta t = t_{n+1} - t_n$

In our case, φ would be calculated for both the longitude and latitude components. This equation was applied in Matlab and built upon the equations for geostrophic flow.

Foretracking and Backtracking Simulations. A cluster of particles was initially placed near known oil and gas infrastructure. Foretracking analysis was performed to determine the possible dispersal and locations of these particles. The initial particles in Figure 4, (left map) are traced for a 60-day period. This procedure was done for each day in January 2008 and the cumulative results are shown in Figure 4 (right map). Particle backtracking was also performed to gain a better understanding of where debris on Padre Island National Seashore may have originated. Below, the initial particle positions shown in Figure 5 (left map), are traced back for a period of 60 days. This backtracking is done for each day in January 2010 and the collective resulting particle positions are shown in Figure 5 (right map).

MODIS SST Time Series. MODIS SST data was downloaded from NASA's Oceancolor Web (NASA, 2011) as compressed archive files (.tar.gz format) and then extracted to the original Hierarchical Data Format (HDF). Data was then converted from the original HDF format into the native ERDAS .img format using ERDAS Imagine. Then, the data was imported into ArcMap to apply a color ramp and date stamp. A stretched color ramp was used to symbolize the SST value. The goal of this procedure was to create an absolute color scale that allows direct comparison for each image. The files were then saved in .JPG format for later use in a time-series animation and graphics created using Windows Live Movie Maker. The animation consists of a simple time series slideshow of SST images with corresponding date ranges and color scales.

Wind Data. The meteorological program WRPLOT that was used to analyze the wind data only accepts data for every hour, so the raw data from the National Data Buoy Center has to be converted into an acceptable format (Lakes Environmental Software, 2011). The WRPLOT program only accepts data within certain formats, i.e. the Lakes Format, so the data was converted to this format. Since there was a large volume of raw data, a simple C++ program was written to automate the process of arranging the raw data files into the 'Lakes Format'. For this format, the raw data is arranged by columns in the order of year, month, day, hour, minute, wind direction, wind speed, GDR, GST and GTIME (descriptions and measurements of this data are available at www.ndbc.noaa.gov/measdes.shtml). The Lakes Format required the columns be arranged in the order of station ID, year, month, day, hour, wind direction and wind speed (all units of measurements being the same). Additionally, the first line of the Lakes Format data file must state "Lakes Format".

After the data were converted to Lakes Format, it was imported to the WRPLOT program (Lakes Environmental Software, 2011) which is then used to create a wind rose for visualizing the wind data. Then, the wind rose was exported directly to Google Earth; however, the point of location in degrees, minutes, and seconds must be known prior to exporting the wind rose. Wind roses for 5-year data from each of the four seasons were also created.

RESULTS

Analysis of Results

Radar Altimeter Data. Radar altimeter data from several NASA and European Space Agency (ESA) remote sensing platforms was processed to produce maps of sea surface height, sea surface height anomaly, geostrophic velocities, and to predict particle paths. A map of processed sea surface height and height anomaly data (Figure 1) demonstrated that the warm waters of the Loop Current can raise the local sea level by over 30 cm in the location where the Loop Current flows into and exits the Gulf of Mexico. The eddies that are separate from the loop current are warm core eddies, and the center of these eddies also have an elevating effect on local water levels. The results suggest that the water in the core of one of these eddies can also be as high as 70 cm above mean water level in the Gulf of Mexico (Figure 1). As an eddy moves across the Gulf of Mexico, it can be tracked by following the area of elevated water.

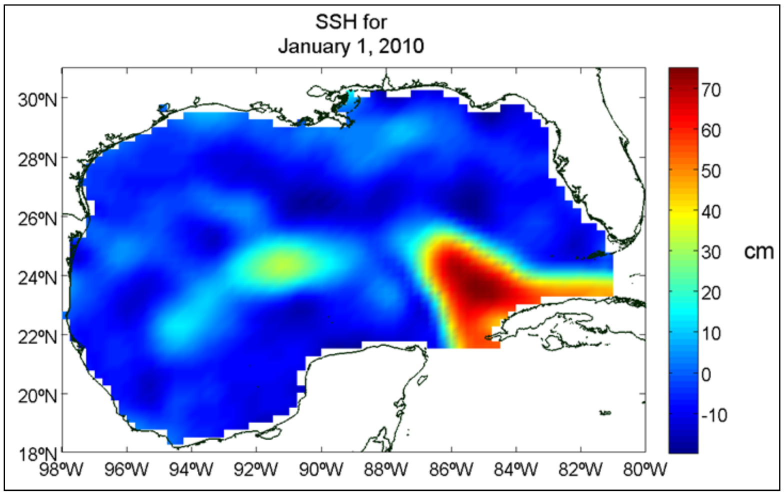

Figure 1. Example of SSH Product created from blended satellite altimeter data processed in Matlab.

A map of geostrophic velocities in Figure 2 shows the Loop Current is a relatively fast-moving current. The highest velocities were mainly observed where the Loop Current enters the Gulf of Mexico through the Yucatan Channel. Relatively high velocities are also observed where the current exits the Gulf through the Florida Straits. This could be due the flow of the current becoming narrower and more channelized as it goes though the Yucatan Channel and Florida Straits. As the flow of the current moves farther north into the Gulf of Mexico, its flow field begins to expand and loses stability. This loss of stability is what ultimately drives the eddy shedding process.

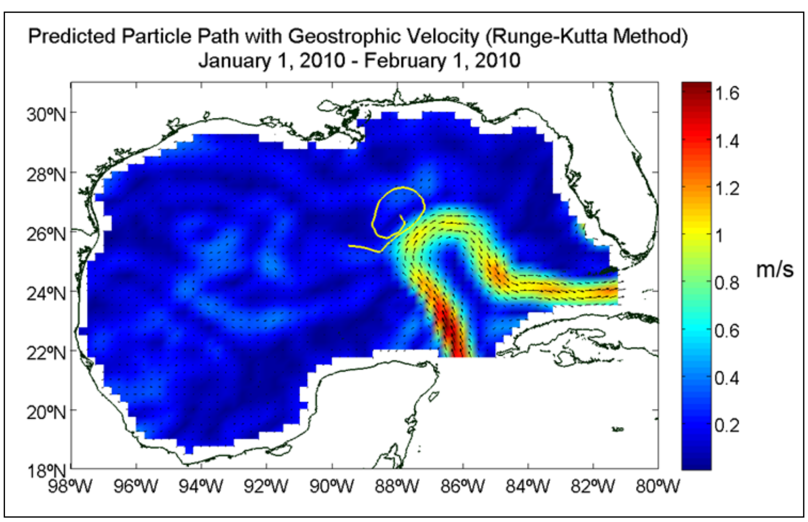

Figure 2. Geostrophic velocity with predicted particle path using Runge-Kutta integration.

Particle path prediction products (example shown between 26-28°N, 94-96°W, Figure 2) were initially produced using the Euler numeric integration technique. The Euler method proved to be fairly inaccurate due to the fact that some predicted particle paths left their respective eddies and re-entered the flow field of the Loop Current. This phenomenon is not observed in reality, and should not be occurring in the model. During the summer term, the DEVELOP team used a different integration technique known as the Runge-Kutta technique. According to advisers at the Colorado Center for Astrodynamics Research (personal communication with Dr. Robert Leben and Gabriel LoDolce, University of Colorado), using the Runge-Kutta method will improve the accuracy of the particle path prediction products.

MODIS SST. MODIS SST data was used to analyze the dynamics of the Loop Current's position, and to track its flow field and eddy shedding process. MODIS SST data shows the position of the loop current in the Gulf of Mexico is widely variable. The Loop Current will sometimes travel in a nearly direct path through the Yucatan Channel to the Florida Straits. This was seen in the MODIS SST data that was collected during late November and into mid December 2009. By mid to late December 2009 through March 2010, the flow of the Loop Current had taken a more northerly path and showed an extension of its flow field farther north and into the central Gulf. By mid-April 2010, MODIS SST data (Figure 3) showed the flow of the Loop Current began to lose its stability and initiate the shedding of a large eddy. By the middle of June 2010, the eddy appeared to completely separate from the main flow path. The eddy could not be tracked during the summer months of 2010 using MODIS SST data because the universally warm surface waters of Gulf of Mexico obscured the comparably warm waters of the Loop Current and its associated eddies.

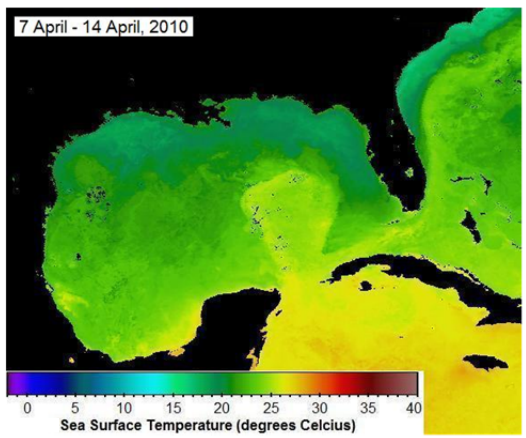

Figure 3. MODIS Sea Surface Temperature in the Gulf of Mexico.

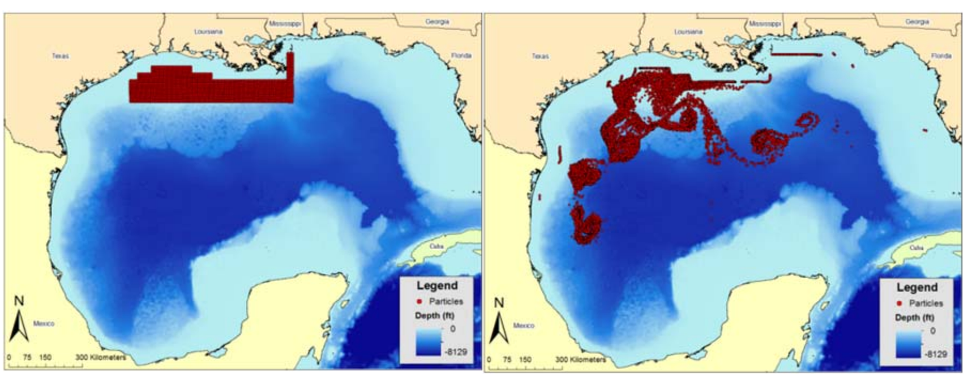

Figure 4. Image on left shows initial placement of particles before 60-day foretracking is performed. Image on right shows cumulative particle locations after the simulation is ran using each day in October, 2010, as the starting date.

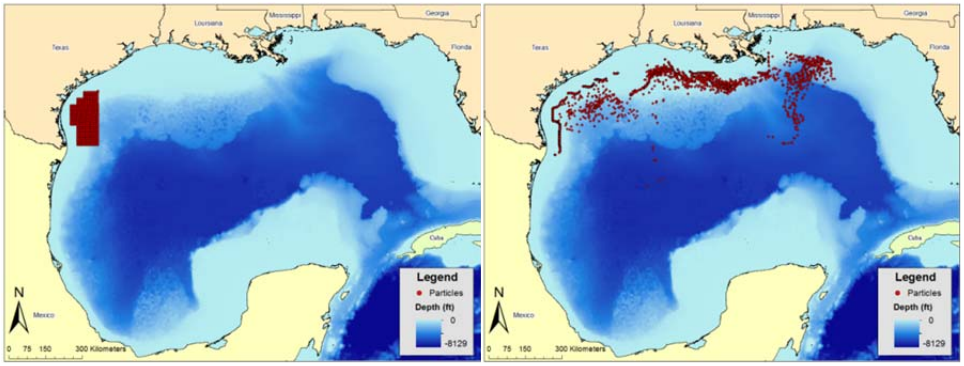

Figure 5. Image on left shows initial placement of particles before 60-day backtracking is performed. Image on right shows cumulative particle locations after the simulation is ran using each day in January, 2010, as the starting date.

Wind Data. Wind roses (Figure 6) were created for three separate buoys (42020, 42019, & 42002), using annual and seasonal data. The wind roses each use 36 ten degree bins and a contrasting color scheme. The wind rose can then be exported to a .kml file and imported into Google Earth. The maps created show all wind directions and wind speeds for each location. Maps were also created to depict dominant seasonal winds. Although winds are variable, a dominant South East (SE) to South-South East (SSE) trend was observed in the five-year mean wind data (Figure 6).

Errors and Uncertainty

Particle Path Prediction Products. During the DEVELOP team spring term of this project, Euler's integration method was used. This method has a truncation error of $O(h^2)$. After noticing unrealistic behavior in some of the predicted paths, our advisors at the Colorado Center for Astrodynamics Research suggested using a higher-order integration method to improve the accuracy. During the DEVELOP team summer term, a higher-order integration method was implemented, namely the second-order Runge-Kutta method. The truncation error associated with this method is $O(h^3)$. This method used the midpoint of an interval as a trial step, and as a result generated much smoother paths and apparent more accurate results.

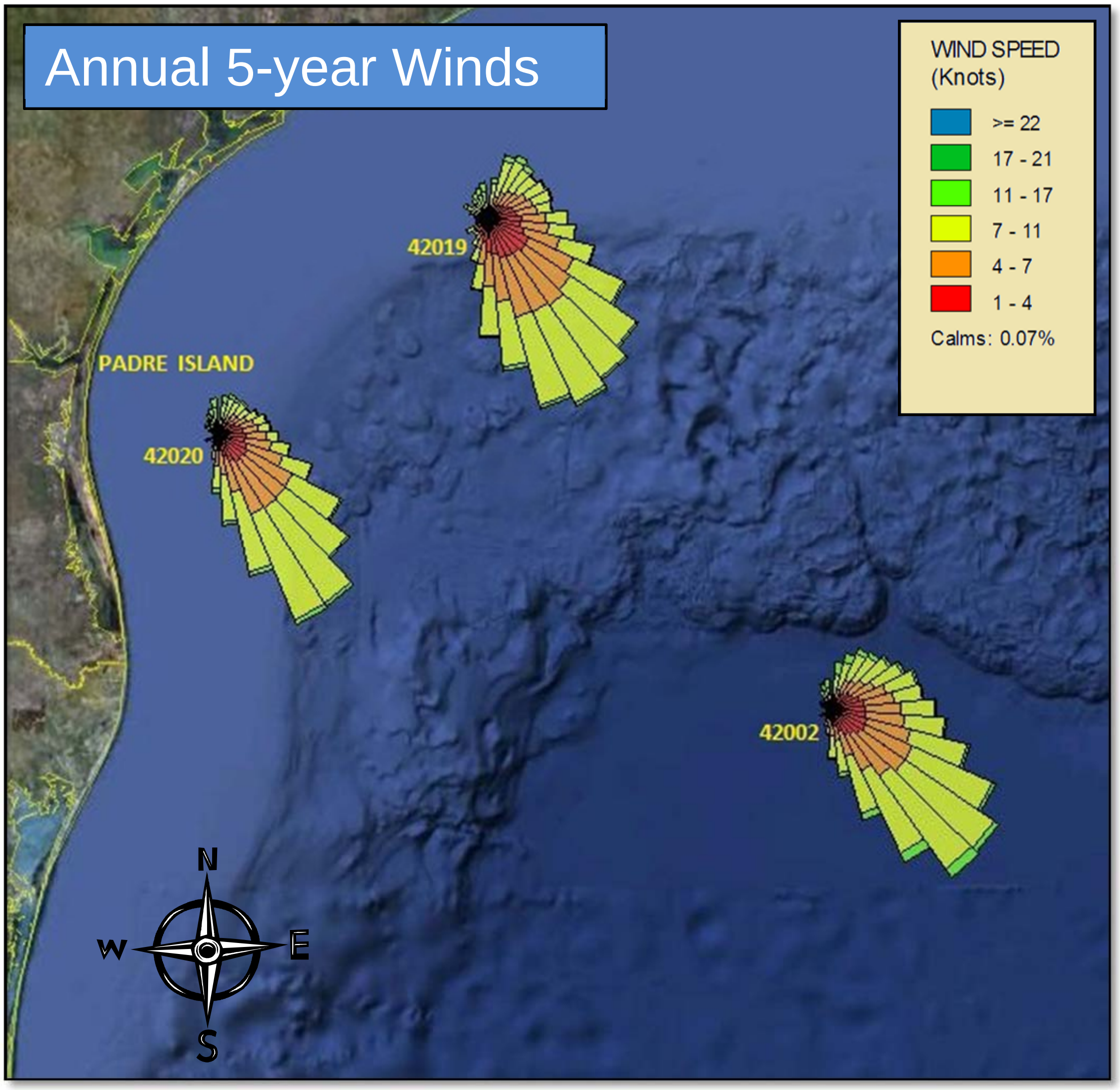

Figure 6. Five-year mean wind data from NDBC, processed using WR Plot software, exported as a .kml file and displayed using Google Earth.

Wind Data. The C++ program accepts the filename of the raw data file as well as the station ID for the observed buoy as user input. The program then proceeds to arrange the data into the Lakes Format as previously described. After arranging the data, it then writes the output to a new file. However, there are a several nuances that are noteworthy. The raw data from NDBC breaks down the hour further into ten-minute intervals. As a result, those values were averaged to obtain a desired single value per hour. Unfortunately, the Lakes Format only accepts wind direction and wind speed as integer values. The C++ program used for this project therefore rounds the resultant averaged numbers to the nearest integer. While the overall effect this has is likely minimal, it should be noted that there is some amount of error involved in the final Lakes Format output.

CONCLUSIONS

Marine debris may negatively impact both human and marine habitats by affecting the aesthetic value of the beaches, creating water quality issues, and leading to the death of birds and marine organisms. Debris on Padre Island National Seashore may come from many different sources, such as commercial fishing/shrimping vessels, the oil and gas industry, recreational boaters, and rivers that empty into the Gulf of Mexico. Regardless of the source, marine debris is an environmental issue and hazard that can directly affect coastal ecosystems and inhabitants.

Understanding surface circulation in the Gulf of Mexico will help provide decision makers and communities additional information that can be used for the in elimination and/or control of marine debris.

During the spring term, the DEVELOP team designed a methodology that was applied during the summer 2011 term. This methodology included the utilization of satellite altimeter and MODIS data, as well as in-situ wind data. The methodology developed will help NOAA's Marine Debris Program and the Padre Island National Park Service improve upon marine debris monitoring, cleanup, and education efforts.

RADAR altimeter data provided a useful dataset for creating visual geospatial depictions of SSH and SSHA, calculating geostrophic velocity, and predicting particle paths. The MODIS SST data proved useful for monitoring the Gulf Loop Current; however, during the summer months of 2010 the warm waters of Gulf of Mexico obscured the Loop Current and its associated eddies. Because sea surface temperatures in the Gulf of Mexico are universally warmer in summer months, MODIS SST data is only practical for monitoring the Loop Current in cooler months. Analysis of wind direction and wind speed data prove beneficial for understanding how marine debris may be ultimately dispersed to the shoreline after eddies dissipate as they interact with the continental shelf. Although wind is not the only force acting upon debris in a near-shore setting, it can play a key role in marine debris dispersal.

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