THE APPLICATION OF NASA EARTH OBSERVATION SYSTEMS FOR ANALYZING THE EFFECTS OF CLIMATE CHANGE ON THE SHORELINE AND COASTAL ECOSYSTEMS OF EASTERN NORTH CAROLINA

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ABSTRACT

North Carolina's dynamic coastal region, defined by the Outer Banks and nearby estuary systems, is vulnerable to the negative effects of climate change. Thermal expansion and melting ice which contributes to relative sea level rise which has led to the instability of the coast in northeastern North Carolina. This relative sea level rise combines with the increased temperature to create intense hurricanes that frequently hit the Outer Banks and nearby estuaries, causing significant damage to entire communities. These powerful storms have affected this coastal region's shoreline so the study applied remote sensing tools to delineate a shoreline envelope and predict the envelope's accuracy. Then, using Landsat imagery and NDVI values, the effects of these storms on vegetative cover were studied. Vegetation was classified in different categories based on ecosystems found in the coastal region to better understand how storms impact plant life in these ecosystems. Additionally, models based on historical data were also produced with the intention of forecasting future relative sea level rise along North Carolina's estuary and coastal shorelines. Using this methodology and NASA satellite instrumentation, the North Carolina Division of Coastal Management can more readily analyze shoreline delineation and erosion measurements. The effects of climate change researched in this study, such as relative sea level rise and inundation, will supplement explanations of shoreline loss and help forecast future impacts. This information has the potential to inform and assist officials in strategic planning and policy development of mitigation and adaptation procedures.

INTRODUCTION

Climate change and the resulting rise in sea level has recently become a grave concern in the coastal region of North Carolina. Historically, natural processes affected North Carolina's northeastern coast through steady rates of island migration and evolution. However, in recent years anthropogenic influence has led to climate change and relative sea level rise, which contributes to accelerated shoreline loss and vegetation depletion. For the two estuaries within the Outer Banks of North Carolina, increasing storm intensity, loss of the barrier islands of the Outer Banks, and relative sea level rise are likely to lead to heightened water levels, damage to ecosystems, alterations in water salinities, and other impacts that might have a negative effect on economic interests in the area (U.S Global Change Research Program, 2010). According to the National Conference of State Legislatures and the University of Maryland's Center for Integrative Environmental Research, coastal property value loss for an 18-inch relative sea level rise would cost an estimated $2.5 billion dollars for Dare County alone (Kirwan et al., 2008). This can prove to be a costly problem for North Carolina's Outer Banks and nearby counties, which collectively hold an estimated $9.4 billion dollars of real estate property in addition to a population of about 156,000 (U.S Census Bureau 2010).

The March 2010 assessment report done by the North Carolina Coastal Resources Commission's Science Panel on Coastal Hazards stated that all historical tide records and geologic evidence gives "undisputable evidence that a steady rise of sea level in North Carolina has been occurring" and given the "multiple indicators" that the Earth is warming, and asserts that accelerated relative sea level rise is likely (Overton et al., 2010). The concern of relative sea level rise for low-lying counties such as Hyde, Dare and Tyrrell is of special concern because these counties are only one to two feet above sea level, and inland from the Albemarle- Pamlico Sound.

With the increase in global temperatures and subsequent rise in sea surface temperatures, harsh storms such as hurricanes may become more powerful in the future. The catastrophic impacts of hurricanes are particularly worrisome considering the possibility of storm surges reaching levels higher than 18 feet in some areas (State Climate Office of North Carolina, 2010). These devastating hurricanes may not only destroy property in this region but also disrupt the local wildlife, leading to the overall destruction of ecosystems and fresh water sources. The fishing industry, valued at $169 million dollars in 1990, would be greatly affected, considering its dependence on a precise combination of salt and fresh water existent in estuaries (U.S Global Change Research Program, 2010). Unfortunately, the damage afflicted by intense hurricanes becomes more devastating with the increasing frequency of these harsh storms.

Due to the negative impacts of climate change and the resulting relative sea level rise, officials have begun to address this pressing issue. In response to these hazards, the North Carolina District of Coastal Management (NCDCM) has begun monitoring the coastlines of North Carolina to ascertain the location, magnitude, and severity of the impact on ecosystems. NASA remote sensing technology can assist with these observations in several ways. Most prominently, moderate-resolution (15-30m) satellite imagery of coastlines can provide relatively continuous, inexpensive monitoring of coastal erosion in a format that is commonly used with well-established methodologies. A comparison of satellite imagery to high-resolution aerial data has been deemed necessary because satellite imagery can provide more frequent coverage at a scale that meets the needs of the NCDCM. Therefore, NASA's Landsat satellite could effectively aid data collection efforts because of its frequent return schedule, which could allow continuous monitoring of major changes. Landsat is the primary platform because it is useful for the long-term goals of the NCDCM. In addition to coastal erosion, the NDCDM has also expressed an interest in monitoring changes in coastal marshes, as they provide a buffer to storm surges and other erosive impacts, as well as a habitat for a variety of wildlife. The collaboration of NASA and local officials may lead to the preservation of North Carolina's coast through the use of Earth Observation Systems.

While the rise of global ocean levels is inevitable, acquiring a more accurate and confident understanding of the particular aspects of climate change will enable policymakers to effectively utilize mitigation techniques. In the hopes of better understanding climate change's effects in North Carolina, this study focuses on seven counties in and near the Outer Banks. This study will generate a methodology for forecasting relative sea level rise along North Carolina's northeastern coast to identify areas most at risk of inundation. It will also investigate the combined effects of relative sea level rise and coastal inundation due to hurricanes. In addition, this study will research how hurricanes impact shorelines due to erosion from storm surge, wind-driven currents, and vegetation depletion, to measure both short and long-term changes in shoreline morphology. Loss in vegetative cover due to hurricanes leads to coastal erosion because the vegetation acts as a buffer and stabilizes sediment. For example, salt marsh vegetation is divided into "high marsh and low marsh floral zones…that reflect the varied tolerances of plant species to tidal flooding" (Engelhart et al, 2011). Using this information, the NCDCM will compare this satellite-based methodology to their own high-resolution shoreline data from aerial photographs. If the two compare well, it would demonstrate that the satellite methodology is useful in continuous, moderate-resolution monitoring of coastal change and storm impacts. NCDCM also seeks a methodology whereby coastal wetlands could be detected and separated from other habitats and human-influenced locations. Success in this form of identification would allow the development of a time-series of coastal wetland land cover, enabling NCDCM to observe how wetlands have changed since the launch of the Landsat 5 satellite in 1983. Furthermore, it could prove useful for large-scale coastal wetland delineation. The results of this study will provide insight into the nature of the climate change and relative sea level rise for use in enacting successful shoreline maintenance policies and decisions. Using these results, it is hoped that more efficient and cost-effective methods of monitoring climate and coastal changes in this region will be determined and implemented.

METHODOLOGY

Relative Sea Level Rise Model and Inundation

Mean sea level time series data was obtained from National Oceanic and Atmospheric Administration (NOAA) gauge station data from the Duck, Oregon Inlet Marina, Cape Hatteras Fishing Pier, Beaufort Duke Marine Lab, and Atlantic Beach SSS Pier stations. These stations were chosen due to their proximity to the areas of interest.

Using information from NOAA tides and currents taken from various locations along the North Carolina coast, mean sea level series data was obtained from the years 1983 to 2010. The resulting model of the mean sea level time series data represented the summation of the deterministic and stochastic components (Montgomery, 2008). The Autoregressive Integrated Moving Average (ARIMA) analysis was then used to generate a model for the stochastic component of the data. The average and variances were plotted for each data set in Matlab to see if the data was stationary, which tested whether the average and variances were constant irrespective of the change in time. If the data from ARIMA was determined to be non-stationary, meaning that it exhibited a trend, then the trend was removed and the resulting data was then input into Minitab. Minitab performed an autocorrelation and partial correlation on the dataset to determine the type and order of the model. The model was then used to forecast future estimates of the variable of interest.

Satellites such as TOPEX/Poseidon and Jason operate on various frequencies to observe crucial differences in mean sea level and can thus confirm trends identified in this study to ensure validity. The sea level anomaly was calculated using wet and dry tropospheric, atmospheric, tidal, wind, and wave corrections. Parameters, such as longitude and latitude were adjusted in Aviso's Live Access Server to isolate the counties studied. With this data, an inundation scenario map was produced using digital elevation models in ArcMap to study relative sea level rise projected for the future in North Carolina. Using Light Detection and Ranging (LiDAR) products from the North Carolina Department of Transportation database, elevation grids were acquired for the seven individual counties. Varying sea level heights and colors were applied to the inundation map to study whether relative sea level rise would flood particular areas of northeastern North Carolina. Using this flood scenario map, one could predict the effects of relative sea level rise and the resulting inundation in the seven counties.

Shoreline Envelope

To analyze changes in North Carolina's estuarine shoreline, ten images from Landsat 5 Thematic Mapper ™ were collected over the course of 2007 from the United States Geological Survey (USGS) Global Visualization Website (GLOVIS). These images were collected and utilized because estuarine tides are determined by wind speed and direction rather than by lunar cycles. Because of this, variable tide levels needed to be accounted for when establishing a shoreline envelope.

The ten images collected were first processed to the standard terrain correction level, or 1T, to improve topographic accuracy. For each image, the environmental correction feature in ERDAS Imagine software was used to eliminate cloud interference. After this process was completed, the images were rescaled to focus on the target areas of Tyrrell, Hyde, and Dare counties for a more narrow and accurate analysis.

The methodology for determining a shoreline envelope involves using several remote sensing techniques that transform or represents the pixel values differently to enhance shoreline features. For the delineation and extraction of the shoreline envelope, a tasseled cap transformation and a histogram threshold of band 5 were used to create binary images classified so that0= water and 1= land. A binary sequence was used for shoreline delineation because of its ability to identify all areas classified as water by using remote sensing techniques.

The tasseled cap transformation developed by Kauth-Thomas in 1976 rotates the axis of the data to transform the pixel values into brightness, greenness, and wetness values which are uncorrelated. The new co-ordinates (components) are linear combinations of the original spectral bands (Richards & Xiuping, 2006). First, Landsat band 3, which represented wetness, was used to alter images by indicating water bodies as brighter values. Using this feature, the tasseled cap image was transformed into a binary image which segments land and water.

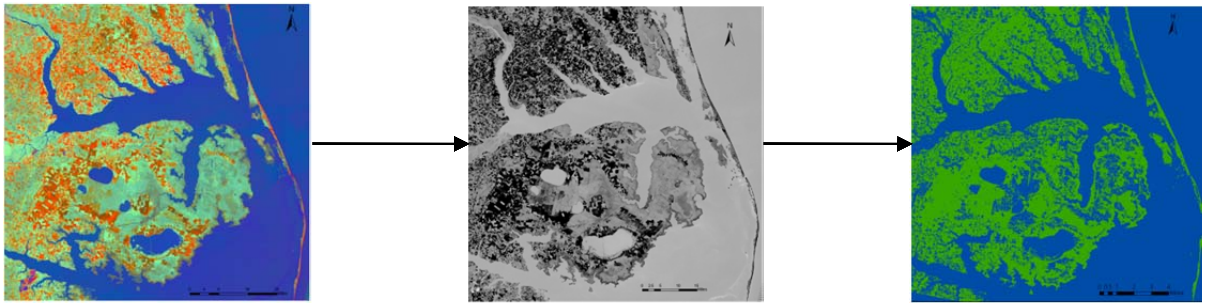

Figure 1. Kauth-Thomas Tasseled Cap Image, Kauth Thomas tasseled cap band 3 image, and binary image of band 3.

Next, Band 5, the infrared band, exhibits the reflectance of mid-infrared in vegetation and the absorption of mid-infrared by water. The segmentation of band 5 into land and water was determined by the Jenks "natural breaks" algorithm. This algorithm is an inductive classification scheme which minimizes variance within groups and maximizes variance between groups. It was used within ArcGIS to look for large jumps in data values or pixel values (Longley et al., 2005). The histogram of band 5 was bi-modal because of the smaller reflection of water compared to land. The area between the two peaks is considered the barrier or transition zone between land and water. The Jenks algorithm determined the exact transition point and segments each group accordingly.

A ratio shoreline envelope was determined by the land to water ratio of each pixel for the stacked images. This ratio was achieved by averaging the binary values of each pixel. The threshold for determining the ratio shoreline envelope was: water >80% and land >80%. All pixels that fall below 80% land or water were categorized as mixed pixels, which represented the boundary between land and water during different tidal cycles. The figure below depicts the application of the ratio envelope. The red pixels denoted areas that fall below the 80% threshold value and were thus classified as mixed.

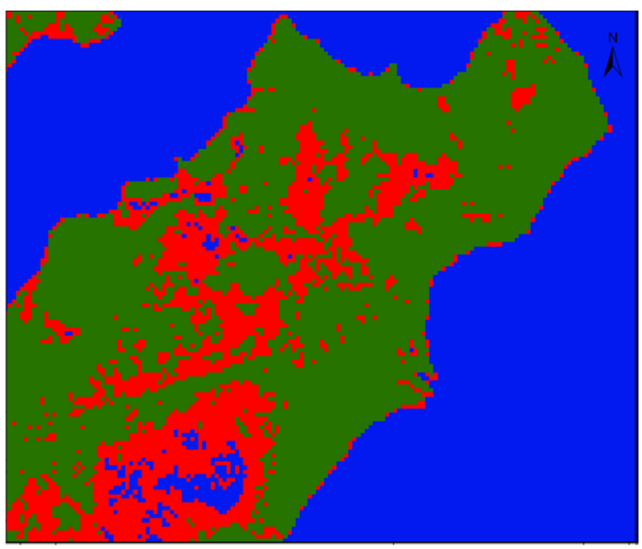

Figure 2. Example of a ratio envelope

Finally, a buffer shoreline envelope could be determined by stacking all images and converting them into a vector file. Out of this file, the shoreline envelope could be created by identifying shoreline with a buffer length of 1 pixel. The shoreline envelope delineated by this method can be seen in Figure 2. The line resulting from the pixel classification system was overlaid onto high-resolution coastline data provided by the North Carolina Department of Coastal Management. Visual examination was conducted to locate types of settings for which the delineation corresponds to high-resolution visualizations of the coastline and for which it may not. Specifically, both straight and sinuous areas of the coastline were examined to assess the accuracy of the coastline delineation.

Wetlands Classification

To study changes in water levels, data was obtained from partner organization servers, including those from the United States Geological Survey and the North Carolina District of Coastal Management. Landsat data from the USGS GLOVIS server as well as elevation data from the USGS Seamless server were obtained to identify coastal wetlands within the Inner Banks. Aerial imagery and ArcGIS shapefiles of coastlines and wetlands were also obtained from the North Carolina District of Coastal Management for this purpose.

Images from Landsat's 7 bands were combined as a virtual stack and imported into ERDAS. To identify changes in vegetation, a general NDVI algorithm was applied to the images. Standing water was identified by combining bands 3, 4, and 5 (visible, near-infrared, and mid-infrared respectively). Next, digital elevation models from the Seamless server were processed to exclude elevations above one meter. Based on results, the methodology for observing wetlands was refined into the usage of an NDVI with confirmation from Landsat band 5 and hydrothermal imaging (refer to discussion below). Using the standard NDVI model takes the red band (Landsat b3) and the infrared band, b4, and applies a manipulation based on the following equation:

$$\frac{(IR - R)}{(IR + R)}$$

where IR was band 4 and R is band 3; this gave a ratio between -1 and 1, where numbers closer to 1 indicated more chlorophyll. Since photosynthetic organisms never reflect more strongly in red than infrared, any value less than zero could be set to zero, giving a final value between 0 and 1. This was then normalized to the display of ERDAS Imagine, as a function of 255.

The images used to examine the coastline were characterized using an unsupervised classification of a stack of bands 5 and 3. These classified images were then reclassified such that land units were defined as 0 and water units were defined as 1. Following this reclassification, the raster images were added together to determine whether change from land to water or vice-versa had occurred.

To analyze the accuracy of the method mentioned previously, a comparison was made between the NDVI images and accurate shapefiles provided by the NCDCM which were created from high resolution aerial orthophotography. The NDVI images were converted from grayscale into a bright color scheme to highlight differences in chlorophyll levels which allowed for quick and easy identification of possible wetland locations. The wetland shapefiles were then overlaid onto the NDVI images. According to the color scale used, purple indicated the presence of negligible amounts of chlorophyll (water) and red indicated a high amount of chlorophyll (vegetation). Areas of green correlated strongly with the delineated wetland shapefiles.

Vegetation Loss Due to Hurricanes

Landsat images captured during a twenty year interval were processed using USGS GLOVIS, ERDAS, and NDVI to study the impact that hurricanes during this period had on North Carolina's vegetation. Landsat was useful because it has a long historical record of images of this locale and has collected enough data to analyze changes over a significant amount of time.

Landsat images from July 23, 1991 to August 16, 2010 were studied by using maps to research the long term changes in vegetation loss. After the data was collected from Landsat, it was transferred into the ERDAS Imagine 2010 software for viewing. Once in the ERDAS software, the data was converted into NDVI images to highlight the vegetation in the map. The NDVI pixel values were given life-like colors such as green and blue to make the map easier to understand, and to better show lines of demarcation in vegetation cover, allowing for easy detection of vegetation loss over the area of interest.

This process was repeated for images before and after Hurricane Isabel both for the northern and southern parts of the coast. In order to look at the hurricane's immediate effects, images from August 25, 2003 and September 26, 2003 were chosen for study. Later, both images were subset to focus on Dare County so that specific vegetation loss data could be obtained.

After all the NDVI images had been obtained involving Hurricane Isabel, the data was used in a Sea, Lake and Overland Surges from Hurricanes (SLOSH) model to see which areas of the Outer Banks and inland coastal regions were hit the hardest by storm surge. The SLOSH model provided an animation of the intensity and trajectory of Hurricane Isabel by showing storm surge changes in ten-minute intervals.

RESULTS

Relative Sea Level Rise and Inundation

The three data sets went through specific processing and analysis during this study. First, the data was divided in half to use the first half in order to generate a model to predict the second half. If the model was accurate, then it would be used to forecast future relative sea level rise. After trends were removed from the data, it was then separated into two sets: the test set and the validation set. The auto and partial correlation of the differenced test set data was done to determine the type and order of the ARIMA model to fit to the data. The autocorrelation of the data produced a damped sine wave implying that the data should be fit using an autoregressive model.

In addition, the following equations were used to forecast future relative sea level rise at three specific locations in northeastern North Carolina. The coefficients for the equations were obtained from the ARIMA model parameters. Future relative sea level rise data points were generated based on past data points represented by y(t-1) in this case. The noise was a combination of the standard deviation of the residuals and an error variable (e) that was added to account for the inherent fluctuations in the data. Additional adjustments were made to the final forecasting model equation to adjust for the fact that the model was generated using differenced data. Differencing was performed by subtracting the current term, y(t), by the previous term y(t-1) [i.e. y(t)-y(t-1)]. The following forecasting equations were obtained by setting this differencing equation equal to the forecasted equation and solving for y(t). Note special adjustments were made to ensure that the y(t-1) term was bounded by 1 because if not, the equation would become unstable and grow exponentially.

Predicted Oregon Inlet Difference Mean Sea Level = 0.00047 +0.8*y(t-1) + white noise [Equation 1]

Predicted Beaufort Difference Mean Sea Level = -0.000665+0.8723*y(t-1) + white noise [Equation 2]

Predicted Cape Hatteras Difference Mean Sea Level = 0.0001861 +0.3441*y(t-1) + 0.8052*e(i)+ 0.0244*e(i-1) + 0.1532*e(i-2) [Equation 3]

Shoreline Envelope

A comparison of the delineated shoreline envelope and high resolution NCDCM data indicated that certain geographic regions are more easily represented using the shoreline envelope method than others. Coastlines in the Outer Banks island chain were well represented using the methods described above, likely because the islands are low-lying and change rapidly. Straight coastlines along the inner banks were also apparent using shoreline delineation methods. However, sinuous coastlines with large-scale bends were not represented as well in the model, as they seem to exhibit less variety in terms of water/land changes.

Wetlands Classification

The correlation between green images indicated on NDVI images and known wetland areas as indicated by NCDCM images shows that Landsat images can provide moderately accurate assessment of wetland locations. One challenge presented by this method, however, is that the NDVI process tends to classify farmland as the same type of vegetation found in wetlands. One possible solution to this limitation, however, may be to compare images from different points during the year so that farmland fluctuations can be noted and accounted for. Though images from the summer months show less confusion between farmland and wetlands, they also show a weaker correlation between the wetlands and shapefiles. In addition to NDVI analysis, Band 5 from the multi-spectral Landsat images was examined because of this band’s usefulness in differentiating types of vegetation. This analysis revealed that while band 5 can provide information to locate wetlands, it does fail to differentiate between wetlands and farmland. Combining multiple image analysis types may be needed in the future to further refine wetland delineation efforts to exclude farmland. However, Landsat provides a significant advantage in that its long historical record of images may allow for long-term study of wetland change and movement.

Vegetation loss Results

After studying the NDVI images, it was clear that northeastern North Carolina suffered significant vegetation loss due to Hurricane Isabel which hit in 2003. This vegetation loss was significant because it could have led to the destruction of this region’s ecosystems.

The NDVI images that were taken before and after Hurricane Isabel are shown below. The increased level of vegetation depletion can be seen in the second NDVI image taken on September 26, 2003; roughly a week after Hurricane Isabel hit the North Carolina coast. The images depicting vegetation loss were created in ArcGIS using this data. In addition, the SLOSH model revealed that a high level of storm surge was experienced on the southern coast of Hyde County, directly correlating with select areas of vegetation depletion.

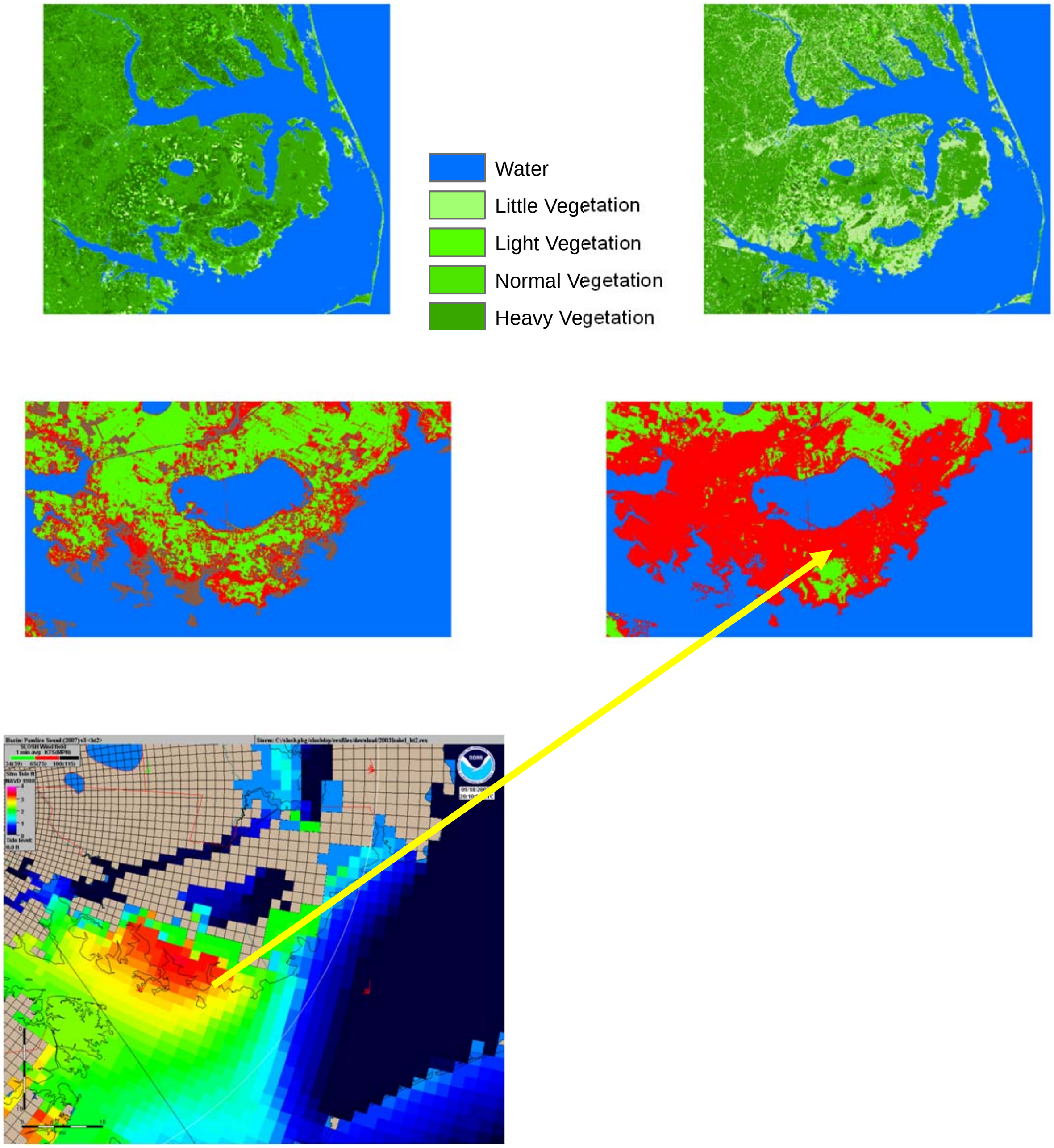

Figure 3. NDVI images from August 25, 2003 and September 26, 2003, showing short-term vegetation loss for Hyde County, correlated with the NOAA SLOSH model, showing storm surge.

DISCUSSION

Relative Sea Level Rise and Inundation

After studying relative sea level rise trends for three stations in North Carolina, the study concluded that the Oregon Inlet will experience an increase of nearly half a meter in the next century at a rate of 3.77mm/year, while Cape Hatteras and Beaufort are anticipated to experience much smaller increases in relative sea level rise at the rates of 0.8mm/year and 0.41mm/year. These results highlight the variability associated with relative sea level rise measurements and forecasting. Numerous factors contribute to the variability of relative sea level rise, and these factors and their effects are difficult to predict. Therefore, a model must take into account the uncertainty associated with this type of data. The ARIMA model was appropriate for this study because it took into account the inherent variability of the data and included it to provide the best fit for the data. In addition, using this information, the inundation scenario map was able to predict the effects of relative sea level rise on the North Carolina coast.

Shoreline Envelope

Each buffer envelope was validated using a digitized shoreline of Tyrell County which uses aerial imagery with a resolution of six inches. The accuracy of the shoreline envelopes was determined by defining the percentage of the digitized shoreline within the envelope. The ratio buffer only identified an area where there was a slight change in the estuary shoreline due to tides, so the validation of this envelope could not be administered at this time due to the unidentified areas that could be static shoreline. The validation of the ratio envelope will be done with further research. The tasseled cap and the histogram thresholds of band 5 were not exact techniques. The tasseled cap transformation assigned some land pixels as water. This could be due to the inland wet soils. Also, the histogram threshold of band 5 did not segment inland streams from land.

Wetlands Classification

The correlation between green images indicated on NDVI images and known wetland areas as indicated by NCDCM images shows that Landsat images can provide moderately accurate assessment of wetland locations. One challenge presented by this method, however, was that the NDVI process tended to classify farmland as the same type of vegetation found in wetlands. One possible solution to this limitation may be to compare images from different points during the year so that vegetation phenology and crop cycles can be studied to account for farmland. Though images from the summer months show less confusion between farmland and wetlands, they also show a weaker correlation between the wetlands and shapefiles. In addition to NDVI analysis, however, Band 5 from the multi-spectral Landsat images was examined because of this band’s usefulness in differentiating between vegetation types. This analysis revealed that while band 5 can provide information to locate wetlands, it does fail to differentiate between wetlands and farmland. Combining multiple image analysis types may be needed in the future to further refine wetland delineation efforts and exclude farmland. However, Landsat provided a significant advantage in that its long historical record of images may allow for long-term study of wetland change and movement.

Vegetation Loss Due to Hurricanes

The analysis of the NDVI maps revealed that the area had lost a significant amount of vegetation over a series of nine years and a longer time frame of twenty years. With this information, it can be predicted that future climate change in this region will further deplete and erode the vegetation. In particular, the vegetation in Hyde and Dare counties directly corresponded to the storm surge of Hurricane Isabel. To eliminate seasonal change as a factor in the vegetation loss, an NDVI image was taken for September 12, 1998, seasonally 14 days before the post-Hurricane Isabel NDVI image was taken. This image showed higher level of vegetation than the post-Isabel image, therefore ruling out seasonal responsibility. The coastal region of North Carolina has been visibly affected by relative sea level rise and the increasing intensity of storms. Climate change therefore has the potential to cause even more destruction to the vegetation and human inhabitants of North Carolina in the future.

CONCLUSION

Earth Observations Systems were used to study the effects of climate change on the Outer Banks and estuary systems of North Carolina. Utilizing Landsat data, models were made to research relative sea level rise and its impact on vegetation and the shoreline. Using satellite technology, the NCDCM is able to compare their high-resolution aerial photographs with the Landsat images to efficiently monitor long-term changes to the coastline. Additionally, the global increase in temperatures and the resulting rise in sea level have led to frequent and intense hurricanes which have depleted this region’s vegetation and negatively impacted the shoreline. By producing an inundation scenario map, flooding in northeastern North Carolina can be better predicted with the increase in relative sea level rise. From this map, we conclude that within North Carolina, the Oregon Inlet will experience an increase of about a third of a meter in the next century at a rate of 3.77mm/year, while Cape Hatteras and Beaufort are anticipated to experience slighter increases at the rates of 0.8mm/year and 0.41mm/year. Using satellite data, this study also classified wetland vegetation to determine the net vegetation change due to climate change. Wetlands represent a vibrant ecosystem and act as a buffer to protect the coast. With the findings of this study, it is hoped that this data has the potential to aid officials in making policy concerning climate change in northeastern North Carolina.

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In the conduction of this assessment we partnered with the North Carolina Division of Coastal Management and the North Carolina Department of Environmental and Natural Resources, who provided us with tools and advising that was invaluable in the completion of this study. The North Carolina Division of Coastal Management was in the process of digitizing their shorelines when we began work with them. The digitized shorelines of Hyde, Dare, and Tyrell counties they were finished with were handed over to us which were used in conjunction with our own digitized shorelines, created through our methodology to compare the effectiveness of the delineation methodology. Aerial photography of the counties in the area of interest was also provided, which while not used extensively to date, could be invaluable to future researchers.

Our science advisors Dr. Jeff Warren, from the North Carolina Division of Coastal Management, and Dr. Kenton Ross, from Science Systems and Applications Incorporated, were also instrumental to the success of this study. Dr. Jeff Warren met with us on several occasions and participated in several teleconferences with us to provide us constant direction for our study. Dr. Warren also aided us in the acquisition of the data and imagery we used for this assessment. Dr. Kenton Ross from SSAI aided us by coming up with the idea for our layer stacking methodology for shoreline delineation, which we later incorporated into our study and tested.

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