Estuaries and Coasts (2009) 32:496–507
DOI 10.1007/s12237-009-9138-z

The Impact of Hurricane Katrina on the Coastal Vegetation of the Weeks Bay Reserve, Alabama from NDVI Data

John C. Rodgers III · Adam W. Murrah · William H. Cooke

Received: 1 May 2008 / Revised: 26 November 2008 / Accepted: 12 January 2009 / Published online: 31 January 2009

Abstract Normalized Difference Vegetation Index (NDVI) data were used to investigate vegetation changes after Hurricane Katrina (2005) for the Weeks Bay Reserve and surrounding area of coastal AL. Landsat 5 satellite images were acquired before landfall (March 24, 2005), after landfall (September 16, 2005), and 8 months after landfall (April 28, 2006). The March 2005 to September 2005 image comparison showed that average NDVI values decreased by 49% after landfall. Continuing into the next year, average NDVI values were −44% lower in April 2006 than they were in March 2005. Among habitat types, the estuarine emergent wetland experienced the largest average NDVI value decrease (−64%). The estuarine emergent wetland NDVI values continued to decrease by −27% from September 2005 to April 2006, whereas other habitats increased in NDVI. This continued suppression of NDVI values was attributed to increased salinity from the storm surge and to regional drought conditions that occurred after landfall. These results provide insight into the sensitivity of coastal vegetation from the interactions of both tropical cyclones and long-term environmental conditions.

J. C. Rodgers III (✉) · W. H. Cooke
Department of Geosciences, Mississippi State University,
P.O. Box 5448, Mississippi State, MS 39762, USA
e-mail: jcr100@msstate.edu

W. H. Cooke
e-mail: whc5@msstate.edu

A. W. Murrah
Applied Geo Technologies,
Building 1100, Code RAO2, Stennis Space Center,
Mississippi, MS 39529, USA
e-mail: Adam.W.Murrah@nasa.gov

Keywords Normalized Difference Vegetation Index · NDVI · Weeks Bay · Hurricane Katrina

Introduction

Hurricane Katrina (August 29, 2005) was one of the most significant hurricanes to hit the US Gulf Coast (Knabb et al. 2005). Although the storm made landfall near the LA/MS state border, Hurricane Katrina had far-reaching influences on coastal processes throughout the northern Gulf of Mexico. Particularly in Mobile Bay, which was located nearly 100 km from the point of landfall, the National Hurricane Center (Knabb et al. 2005) reported sustained wind speeds up to 30 m s^{-1} and wind gusts up to 37 m s^{-1}. At Dauphin Island, AL Hurricane Katrina produced a 2-m+ storm surge that toppled portions of nearby barrier islands and inundated adjacent coastal areas (Byron and Heck 2006; Fritz et al. 2007). Close to the city of Mobile, AL storm tide estimates were reported to approximately 3.5 m (Knabb et al. 2005). In addition, Hurricane Katrina produced more than 80 mm of precipitation across Mobile and Baldwin Counties, AL (NCDC 2008). The combination of these hurricane events, including the high wind speeds, storm surge, and heavy precipitation, most likely had an adverse effect on the coastal AL vegetation, yet the extent and magnitude of the vegetation damage within the region has not been fully investigated.

Due to the possible changes in estuary salinity and exposure to the hurricane-force winds (Kuo et al. 1976; Wilson et al. 2006; Gong et al 2007), it is hypothesized that Hurricane Katrina negatively affected the vegetation of the Weeks Bay Reserve (WBR), which is located on the eastern shore of Mobile Bay. To date, no peer-reviewed research has been published on vegetation impacts due to hurricane

Katrina at Weeks Bay. From what has been published elsewhere, it appears that Hurricane Katrina damage to coastal vegetation was spatially dependent. Marsh loss in LA following both Hurricane Katrina and Hurricane Rita was estimated to be 562 km^2, which represents approximately 20% the total marsh area lost since 1956 (Barras 2006). Byron and Heck (2006), however, report no significant losses of AL seagrass shoot density near Dauphin Island, AL following Hurricane Katrina. The submerged aquatic vegetation changes from 2004 to 2005 could not be differentiated from normal background population variability. The question remains, what effect did Hurricane Katrina have on the nonsubmerged coastal vegetation in Weeks Bay? Did the 2-m+ storm surge, heavy rains, and strong winds significantly impact the vegetation health, and if so, did the vegetation recover during the following growing season? In order to address these questions, a regional vegetation health assessment for coastal AL before and after landfall is needed.

This research investigated changes in vegetation health in the Weeks Bay Reserve and the adjacent areas from Hurricane Katrina as measured by Normalized Difference Vegetation Index (NDVI) values. NDVI has been used extensively in ecological research and it has been found to be a robust and reliable estimator of vegetation change, biomass, leaf area index, primary productivity, and photosynthetic absorption (Samson 1993; Ramsey and Laine 1997 and reference therein). While NDVI has been shown to be indicative of the abundance and activity of chlorophyll absorption of broad-band red wavelengths and chlorophyll reflectance of broad-band near-infrared wavelengths (Myneni et al. 1995), NDVI capacity for radiometric normalization is a key component in studies that assess vegetation change over time (Coppin and Bauer 1994). NDVI has been successfully implemented within coastal environments and has been used, for example, to investigate the effects of salinity variability on estuary vegetation health (Keith et al. 2002), to quantify coastal algal concentrations (Jesus et al. 2006), and to monitor natural and anthropogenic changes in mangrove forests (Jupiter et al. 2007).

For this research, NDVI values were derived from Landsat 5 Thematic Mapper (TM) images from March 24, 2005 (pre-Katrina), September 16, 2005 (post-Katrina), April 28, 2006 (8 months post-Katrina), and August 7, 2002 (a control image). Specifically, we quantified the amount of NDVI change before and after landfall for the Weeks Bay area as a whole and for individual study plots. We also compared NDVI values from the March 2005 image and the April 2006 image to investigate differences in vegetation health approximately 1 year after the pre-Katrina image was acquired. Additionally, we examined the variability of NDVI change among upland forest, palustrine forests, and emergent wetland habitat types. Lastly, we explored the environmental factors, such as salinity, precipitation, and river discharge that might be related to the changes in NDVI. This research is important because it helps provide insight into the sensitivity and recovery of Gulf Coast vegetation after a major land-falling hurricane. Implementation of remote sensing techniques that measure vegetative response to hurricanes enables mapping of the broad spatial patterns of hurricane affects on coastal vegetation. Understanding the changes in vegetation health following a major hurricane may lead to improved management strategies.

Study Location

Weeks Bay National Estuarine Research Reserve, also known as the WBR, is located 64 km southeast of Mobile, AL along the eastern shore of Mobile Bay in Baldwin County, AL (NERR 2008; Fig. 1). The WBR includes Weeks Bay, a small estuary (8 km^2), and adjacent lands encompassing a total of approximately 2,600 ha (NERR 2008). Several different habitats are present, including tidal wetlands, swamps, salt marshes, aquatic grass beds, maritime and palustrine upland forests, pitcher plant bogs,

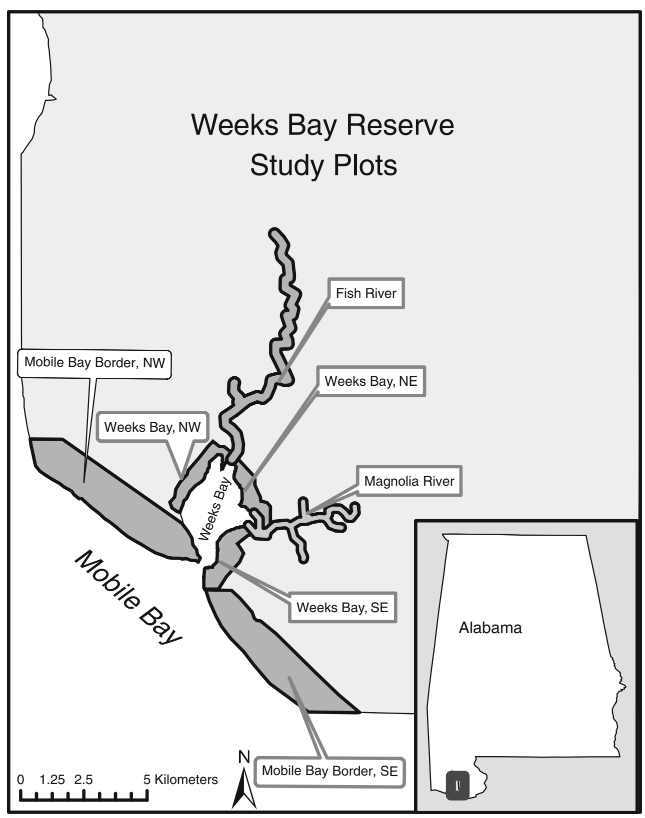

Fig. 1 The Weeks Bay Reserve study area and the location of individual study plot polygons

and benthic estuarine sediments (NERR 2008). Because of the national importance of these habitats and because of the threats from local development, Weeks Bay was designated a National Estuarine Research Reserve in 1986 (NERR 2008).

The WBR physical environment is strongly tied to both river and ocean processes. The Fish River and Magnolia River both empty into Weeks Bay (Fig. 1). Collectively, these rivers drain an approximately 51,000 ha watershed, but nearly three quarters of the inflow into Weeks Bay comes solely from the Fish River (NERR 2008). The mean combined discharge of these rivers is estimated at 9 $m^3 s^{-1}$, yet discharge values can be up to four times larger during rain events (NERR 2008). Salinity in Weeks Bay is strongly related to the salinity of the adjacent Mobile Bay. Seasonal runoff from the Mobile River has more of an influence on Weeks Bay salinity than the freshwater input from the Weeks Bay watershed (NERR 2008).

The Weeks Bay watershed is located in the humid subtropical climate region that is characterized by warm summers and relatively mild winters. The winter storms, summer thunderstorms, and tropical systems provide an annual precipitation accumulation of approximately 1650 mm (Stout 1996).

Materials and Methods

Satellite Image Data Acquisition and Justification

Landsat 5 TM images (path 21 and row 39) were used in this study to monitor changes in NDVI values before and after Hurricane Katrina. Even though Landsat imagery has a moderate resolution of 30 m, it is one of the more widely used remotely sensed data due to its relatively low cost. Numerous studies have used Landsat data to investigate landscape-scale patterns (Lillesand et al. 2004). For this research, the most important criterion for selecting images was the requirement that the WBR region must be cloud-free. Obtaining images without clouds for coastal AL was difficult due to the fact that the region has frequent precipitation. Furthermore, the Landsat satellite has a 16-day repeat coverage cycle, which further complicated obtaining images during the most ideal time periods.

The image used to represent pre-Katrina vegetation was from March 24, 2005. A March image was selected because it represents a time period in the growing season when most of the vegetation has greened (Scott Phipps, Research Coordinator of the Weeks Bay Reserve, September 16, 2008, personal communication). This image was also one of the clearest images during the 2005 pre-Katrina growing season and it offered an anniversary date comparison with a cloud-free images from the spring of 2006.

The image used to represent post-Katrina vegetation was from September 16, 2005. This was the only cloud-free image within a 30-day period after landfall (USGS Earth Explorer 2008). Even though the post-Katrina image was taken 18 days after landfall, there was only one minor rainfall event during this period (<16 mm, September 4 and 5, 2005; NWIS 2008), thus it is assumed that any vegetation influences from increased salinity or wind damage would still be present in the September 16th image. Furthermore, records from the US Geological Survey (USGS) Hydrologic Monitoring Station at the Fish River (NWIS 2008) showed that flood levels had receded to prestorm values within a 72-h time period after landfall. A personal communication with the research director at the Weeks Bay Reserve (Scott Phipps, September 16, 2008, personal communication) established that the inundation of the marsh vegetation lasted less than 96 h after landfall. It is presumed that the influence from prolonged flooding on NDVI differences with the September 16, 2005 image would be minor.

A third image from April 28, 2006 was also used to examine changes in vegetation health during the first growing season after Hurricane Katrina made landfall. This image was close to the anniversary date of the pre-Katrina image. Although the March 24, 2005 and April 28 2006 are more than a month apart, it is believed that the vegetation greenness values are comparable during these time periods. For one, the average last occurrence of frost for the region, specifically for Mobile Regional Airport, AL, is February 27 (Garoogian 2001). Secondly, there is less than a 10% probability of a 0°C temperature occurring after March 19th and only a 50% probability of a 0°C temperature occurring after February 25th for Fairhope, AL (Koss et al. 1988). Thirdly, the growing season for the region usually starts during early March and peaks during late March or early April (Scott Phipps, Weeks Bay Reserve Research Coordinator, September 16, 2008, personal communication). Notably, no other cloud-free images were available during the spring of 2006 (USGS Earth Explorer 2008).

A fourth image from August 7, 2002 was used as a control to examine NDVI variability in later summer during a non-hurricane year. Only tropical depression Hannah (September 14, 2002) occurred within 75 km of the study area.

Satellite Data Preprocessing

All Landsat scenes were obtained from the Earth Resources Observation and Sciences data center in Universal Transverse Mercator zone 16N, NAD 83 datum. Images were rectified to a June 2000 base image. Total root mean square for each image rectification process was less than 1/2 pixel (±15 m). Due to the low relief in the study area and the lack of a precise digital terrain model, terrain variation was not taken into account during the rectification process. The images were radiometrically corrected using standard remote sensing techniques (Lillesand et al. 2004). An automatic method was used to account for radiometric differences among scenes by first calculating top-of-atmosphere (TOA) reflectance, by converting brightness values to radiance, then converting radiance to TOA reflectance (Conese et al. 1993; Coppin and Bauer 1994; Yuan and Elvidege 1996; Eckhardt et al. 1990).

To reduce the volume of data and to speed processing time, a subset of the Weeks Bay study area was created. The subset was clipped from the original Landsat images and it was bounded to the extent of the WBR property plus adjacent areas (Fig. 1). The water bodies, including Weeks Bay, Mobile Bay, and the Fish and Magnolia Rivers were converted to "no data" before running the NDVI analyses. First, the water bodies were hand digitized to create an area of interest (AOI). Then, an image processing software subset function was used with the AOI to convert the water body pixels to "no data" values. This was done to insure that NDVI calculations would not be affected by reflectance differences from the water.

It is possible that difference in NDVI values among the four images may be related to tidal variations, especially for those pixels that are adjacent to the water bodies. Yet, the tidal range for the Weeks Bay estuary is less than 1 m (NERR 2008), which is a much smaller spatial scale than the 30 m image resolution. Therefore, due to the differences in scale, influences from tidal variation were assumed to play a negligible role in the NDVI comparisons.

In order to investigate spatial differences in NDVI across the study area, study plot polygons were established along the Weeks Bay shore (WB Northeast, WB Northwest, and WB Southeast), along the banks of the two main rivers (Fish River and Magnolia River), and along the Mobile Bay border (MBB Northwest and MBB Southeast; Fig. 1). It should be noted that much of the area within the Fish River, Magnolia River, and MBB Northwest study plot polygons were not part of the Weeks Bay Reserve property.

NDVI values were calculated for each of the four images. Prior to comparing images, a healthy vegetation mask was created by selecting NDVI values≥0.2 from the March 2005 image. The mask was applied to all images before analysis so that NDVI changes would only be calculated for those pixels within areas of healthy vegetation during the pre-Katrina date.

In addition to the NDVI transformations, the April 2006 Landsat image was also classified into land cover types based on spectral reflectance using an unsupervised classification method (Lillesand et al. 2004). Initially, the classification was set to 100 classes with a threshold convergence set to 95% and the number of iterations set to 12. The resulting 100 classes were then aggregated into six broad land cover classes based on National Land Cover Dataset (NLCD 2001) standards. These six classes included water, urban, herbaceous/cultivated, mixed upland forest, palustrine forested wetlands, and estuarine emergent wetlands. In order to validate the land cover classification, 70 random points were generated throughout the Weeks Bay watershed. Each random point location was visited on the ground and compared to the same locations on the April 28, 2006 image. Seventy-five percent of the random points were classified correctly, which indicates that the classification methods were successful.

Data Analysis

In order to quantify changes in NDVI values among the four images for the WBR as a whole, a geographic information system (GIS) was used to generate 400 spatially random points across to the study region. Nineteen of these random points were deleted because they fell within a water body. GIS was also used to intersect the random point layer with each of the four NDVI images. The resulting attribute table was then imported into a statistical software package and the mean, range, and standard deviation of NDVI values were computed.

Additionally, NDVI images were subtracted from one another by using map algebra, which is a cell-by-cell process performed on each coregistered pixel from both input images. The September 2005 and the April 2006 images were each subtracted from the March 2005 image to assess temporal changes in the vegetation. The August 2002 image was subtracted from the March 2005 image to assess a baseline of NDVI value change from earlier to later in the growing season during a nonhurricane scenario. Pixels from the March 2005 to September 2005 and March to April 2006 subtractions that had values greater than 0.38 were identified because they represented locations where NDVI values substantially decreased. The abundance of these pixels in relation to the Weeks Bay, Fish River, and Magnolia River shorelines were visually estimated.

In order to examine NDVI change within different regions of the WBR, a GIS point layer was created with 100 spatially random points allocated within each of the study plot polygons. A GIS overlay function implemented for the subtracted NDVI images (March 2005–September 2005 and March 2005–April 2006) resulted in an extraction of NDVI change values and the creation of an attribute table. The mean, range, and standard deviation in NDVI as calculated from this table were used to examine spatial and temporal changes among the four images.

NDVI change before and after landfall among three habitat types, upland forest, palustrine forested wetlands, and estuarine emergent wetland was also investigated. The aforementioned 100 random point layer was intersected with the April 2006 land cover image. This allowed the habitat type for each random point to be incorporated within the attribute table. The attribute table was imported into a statistical software package and the mean, range, and standard deviation of NDVI change were calculated for each of the three habitat types and for each of the four images.

Environmental Data

Salinity, climate, and river data during the study period were analyzed to help evaluate the changes in NDVI. Salinity data for the WBR were downloaded from the NERR Centralized Data Management Office (CDMO 2008). Four data loggers were present in the study area, including the outlet of the Fish River (30°24.97′ N, 87° 49.37′ W), the outlet of the Magnolia River (30°23.31′ N, 87°49.03′ W), the middle of the Weeks Bay (“Middle Bay”; 30°23.73′ N, 87°49.37′ W), and the outlet of Weeks Bay into Mobile Bay (“Weeks Bay”; 30°22.85′ N, 87°49.92′ W). The data loggers recorded salinity continuously every 30 min; however, the majority of salinity data for August 31, 2005 and September 1, 2005 were not recorded. Similarly, no daily salinity data were recorded for the Fish River from September 5 through September 20. Average monthly salinity was calculated from 2003 to 2008, the time period for which salinity data were available. Average daily salinity was calculated from August 1, 2005 until October 31, 2005 to examine salinity variability before and up to 2 months after Hurricane Katrina made landfall.

Daily precipitation, river discharge, and river stream height data were downloaded from the National Water Information System website (NWIS 2008) for two USGS gauging stations within the Weeks Bay watershed. The first station is located near the Fish River at Silverhill (30°32.71′ N, 87°47.92′ W) and the second was located on the Magnolia River (30°24.38′ N, 87°44.22′ W).

Average monthly precipitation and Palmer Drought Severity Index data were derived from the National Climatic Data Center (NCDC 2008). This data is specifically for AL Climate Division 8, which includes the two coastal AL counties, Mobile County and Baldwin County.

Results

Overall NDVI Comparisons

The overlay analysis using the 381 random points made it possible to generate descriptive statistics for each NDVI image (Table 1). The March 24, 2005 pre-Katrina image had the highest average NDVI value (0.71) and the largest maximum NDVI value (0.89). The August 7, 2002 image had the second highest average NDVI value (0.61) and the second largest maximum NDVI value (0.73). By comparison, the average NDVI value for the September 16, 2005 image (0.36) was nearly half that of the March 24, 2005 image. This post-Katrina image also had the smallest maximum NDVI value (0.51). The April 28, 2006 average NDVI value (0.39) was similarly low as the September 16, 2005 image; however, the maximum NDVI value was slightly higher (0.61). The April 28, 2008 was the only NDVI image that had a negative minimum value.

The average subtracted NDVI value between the March 24, 2005 and the August 7, 2002 images was 0.10 and the average percent decrease was −11.3%. In contrast, the average subtracted NDVI value from March 24, 2005 to September 16, 2005 was much higher (0.34) and represented an average percent decrease of −49%. There was a much greater vegetation change during this particular temporal comparison. Even after factoring in the March 2005 to August 2002 as a baseline of NDVI change during nonhurricane years, it is clear that average post-Katrina NDVI values were reduced by over a third (−38%) from the March 2005 image. The comparison between the September 2005 and April 2006 images produced an average subtracted NDVI value of −0.03 (9.1% change). The average subtracted NDVI value between March 2005 and April 2006 was 0.31 (−44.75% decrease). This subtracted value is similarly low as the March 2005–September 2005 comparison.

Spatial Variability of NDVI Change

From the subtraction of the March 24, 2005 and September 16, 2005 NDVI images (Fig. 2), it was evident that the

Table 1 Descriptive statistics of the NDVI values for each image

Image	Mean NDVI	Minimum NDVI	Maximum NDVI	Standard Deviation NDVI
August 7, 2002	0.61	0.00	0.73	0.10
March 24, 2005	0.71	0.33	0.89	0.14
September 16, 2005	0.36	0.00	0.51	0.10
April 28, 2006	0.39	-0.04	0.61	0.15

NDVI value statistics were derived from an intersection overlay of a random point layer with each image

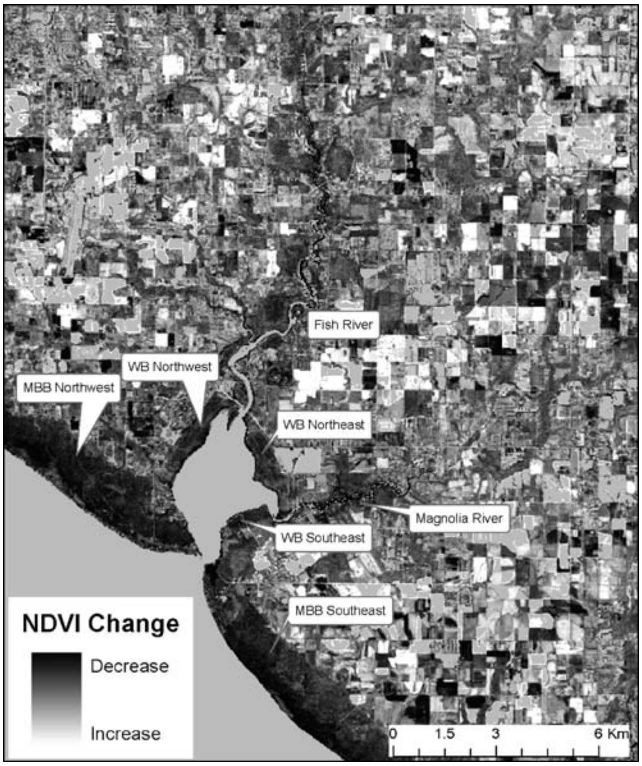

Fig. 2 Subtraction of the September 16, 2005 NDVI image from the March 24, 2005 NDVI image for the Weeks Bay Reserve and surrounding areas. The *darker shades* represent a decrease in NDVI. *Lighter shades* represent an increase in NDVI

areas with the most pronounced decreases in NDVI were adjacent to Mobile Bay and to Week Bay. Pixels with large NDVI decrease values (>0.38) occurred in abundance within locations that were adjacent to both the Fish River and Magnolia River. Within the individual study plots, the Fish and Magnolia River had the largest percent decrease in average NDVI from March 2005 to September 2005 (−52%; Fig. 3). This was followed by the Mobile Bay border (−51%)

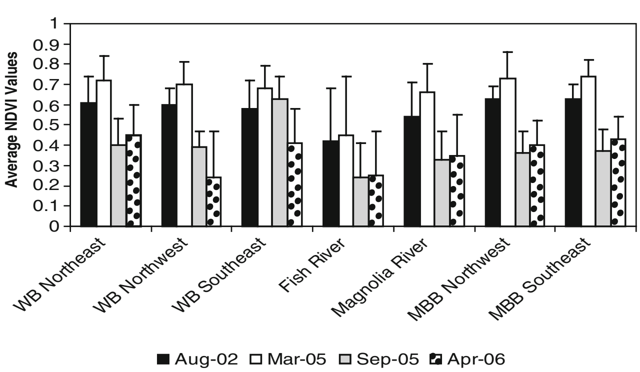

Fig. 3 Average NDVI values for each of the individual study plots and for each of the four satellite images: August 7, 2002, March 24, 2005 (pre-Katrina), September 16, 2005 (post-Katrina), and April 28, 2006. *Error bars* represent the standard deviation. *WB* Weeks Bay border, *MBB* Mobile Bay border

and the Weeks Bay (−45.8%) subregions (Fig. 3). Areas where NDVI values actually increased from March 24, 2005 to September 16, 2005 were likely associated with agriculture fields located further inland (Fig. 2).

Average NDVI values increased for most of the study plots from September 16, 2005 to April 28, 2006 (Fig. 3). Excluding the Northwest Bay plot, average NDVI values increased by approximately 15% in the Weeks Bay subregion. Within the Mobile Bay border subregions, the Southeast and Northwest study plots showed an increase in average NDVI by 19.4% and 14.28%, respectively. The River subregion showed the least average NDVI increase among the subregions, increasing by only 8.3% for the Fish River and only 13.3% for the Magnolia River.

The subtraction of the March 23, 2005 and April 28, 2006 NDVI images showed that NDVI values were substantially lower in April 2006 (Fig. 4). From this result, one location that clearly stands out is the Northwest Weeks Bay study plot, which decreased in average NDVI by 67% (Fig. 3). Besides this one site, the Fish River and Magnolia River study plots showed the largest decrease in average NDVI (50% ad 45%, respectively) from March 23, 2005 to April 24, 2006 (Fig. 3). The subregion with the second largest decrease in average NDVI from March 2005 to April 2006 was the Mobile Bay border (43%). The Weeks

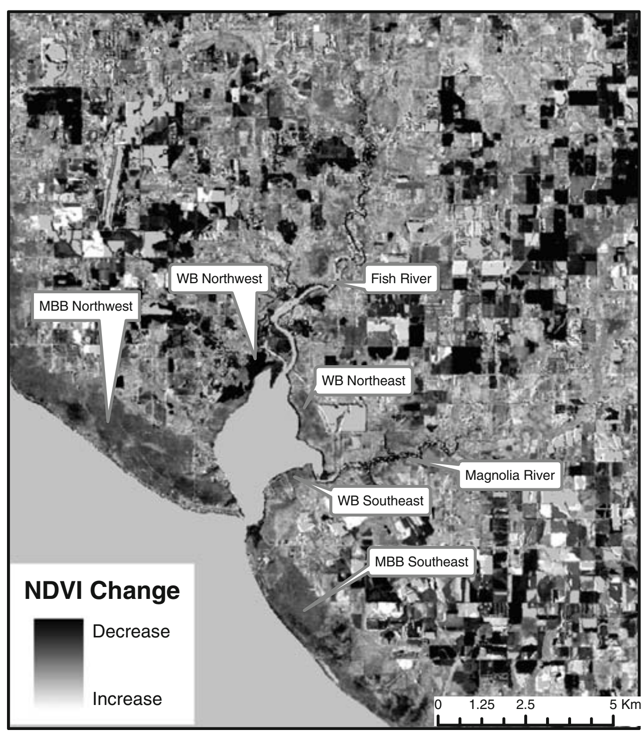

Fig. 4 Subtraction of the April 28, 2006 NDVI image from the March 24, 2005 NDVI image for the Weeks Bay Reserve and surrounding areas. The *darker shades* represent a decrease in NDVI values. *Lighter shades* represent an increase in NDVI values

Bay subregion had the lowest percentage average NDVI decrease (39%) from March 2005 to April 2006.

Variability of NDVI Change Among Habitat Types

The upland forest and palustrine forested wetland habitat types experienced an average decrease in average NDVI value from March 2005 to September 2005 of −42.5% and −45.6%, respectively (Fig. 5). From September 2005 to April 2006, both of these habitats increased slightly in NDVI value (4.8% and 8.8%, respectively). In contrast, the estuarine emergent wetland habitat had a substantially grater drop in average NDVI value from March 2005 to September (−62%), and this habitat was the only one that showed a continual decrease from September 2005 to April 2006 (−27.5%; Fig. 5). All three habitats had lower average NDVI values in April 2006 than in March 2005. In particular, the percent decrease in average NDVI value from March 2005 to April 2006 for the estuarine emergent wetland was −72.5%, which was a much greater change than the upland forest or the palustrine forested wetlands (−39.7% and −40.8%, respectively).

Environmental Variables

Salinity Following landfall of Hurricane Katrina, average daily salinity values in Weeks Bay increased for all four data loggers (Fig. 6); however, the degree of increase was lower than the annual range in salinity. The Weeks Bay data logger recorded maximum salinity readings during landfall of 18.9 ppt on September 2 and 18.7 ppt on August 27. These maximum salinity values were converted to standard normal scores (*z* scores) of 1.55 and 1.52, respectively, and they represent the 86th percentile of all 2005 salinity readings. In contrast, over 87% of all salinity values greater than 2 standard deviations (>17.9 ppt) occurred 2 months after landfall from October to December, 2005. The maximum salinity during landfall for the Middle Bay was

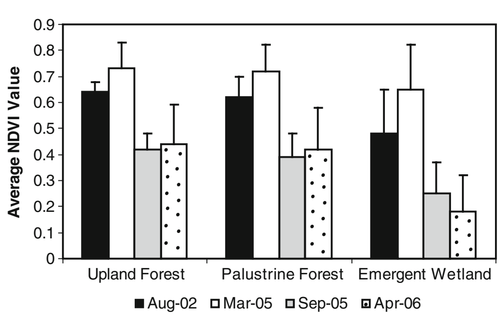

Fig. 5 Average NDVI value for the upland forest, palustrine forested wetland, and estuarine emergent wetland habitat types for each of the four satellite images: August 7, 2002, March 24, 2005 (pre-Katrina), September 16, 2005 (post-Katrina), and April 28, 2006. *Error bars* represent the standard deviation

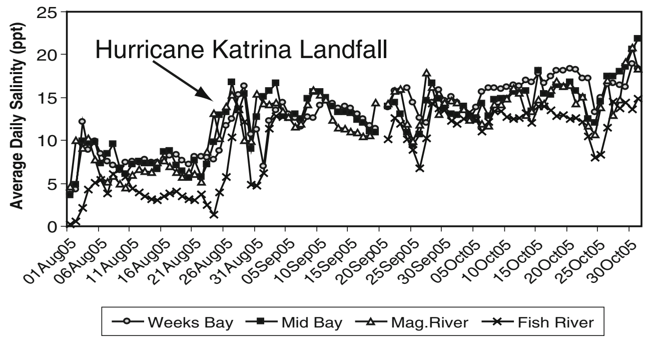

Fig. 6 Average daily salinity for the Weeks Bay, Middle Bay, Magnolia River, and Fish River data loggers, August 1, 2005 through October 31, 2005 (CDMO 2008)

18.8 ppt on August 27, 2005, which converts to a *z* score of 1.41. The majority of the Middle Bay salinity values for 2005 that were above 2 standard deviations (>22.42 ppt) occurred from January to April (53.5% of annual salinity values) and from October to December (46.5% of annual salinity values). The Magnolia River data logger reported a maximum value of 18.4 ppt on August 27, 2005, which converts to a *z* score of 1.63 (89th percentile of the 2005 salinity readings). Similar to the other data loggers, the majority of the highest salinity values for that year, above 2 standard deviations (20.68 ppt), occurred from January to April (27% of annual salinity values) and from October to December (79.5% of annual salinity values). The Fish River data logger reported a maximum salinity reading of 18.4 ppt on August 29, 2005, which lasted for nearly two consecutive hours. This maximum salinity value was converted to a *z* score of 2.09, which was the largest relative increase in salinity during landfall among all four data loggers. Other high salinity readings above 2 standard deviations (>17.9 ppt) occurred from January to April (51% of annual salinity values) or from October to December (41.5% of annual salinity values).

Long-term salinity values increased throughout Weeks Bay during the study period (Fig. 7). A linear trend was calculated from the average monthly salinity values and the

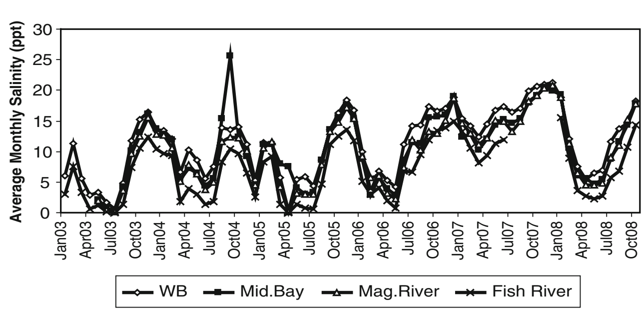

Fig. 7 Average monthly salinity for the Weeks Bay (*WB*), Middle Bay, Magnolia River, and Fish River data loggers from 2003 through 2007 (CDMO 2008)

linear equations of the trend lines were determined. Slope values of the linear trend lines represented change in salinity over time, and they were +0.077 for the Fish River, +0.120 for the Magnolia River, +0.098 for the Middle Bay, and +0.125 for Weeks Bay.

River Discharge An examination of the USGS Hydrologic Station records of discharge and gauge height for the Fish and Magnolia Rivers suggest that Hurricane Katrina only resulted in only moderate flooding. For the Fish River, the maximum discharge value recorded during Hurricane Katrina landfall was 18.6 m^3 s^{-1} on August 30, 2005 (NWIS 2008). By comparison, this discharge values were nearly half the maximum annual discharge reported earlier in April 2005 (322.8 m^3 s^{-1}; NWIS 2008). Similarly, the maximum gauge height during Hurricane Katrina was 2.7 m, but this is much less than the maximum gauge height of 6.2 m reported in April, 2005. Hurricane Katrina discharge values for the Magnolia River peaked at 8.6 m^3 s^{-1} on August 30, 2005. This value is less than a third of the maximum 2005 discharge value of 419.9 m^3 s^{-1} recorded on April 2005 (NWIS 2008). Additionally, the maximum gauge height for the Magnolia River during Hurricane Katrina was 2.1 m, which is less than half of the gauge height reported earlier in April, 2005 (4.4 m).

Precipitation The 30-year (1975–2004) average cumulative precipitation from March through August AL Climate Division 8 was 948 mm (NCDC 2008). Notably, cumulative precipitation from March through August for 2005 was substantially higher at 1,539 mm (NCDC 2008). Precipitation totals during landfall, specifically from August 27, 2005 through September 3, 2005, at the Fish River and Magnolia River USGS Hydrologic Stations were 99.6 and 72.4 mm, respectively. After landfall and continuing into 2006, the region experienced a prolonged drought (Fig. 8).

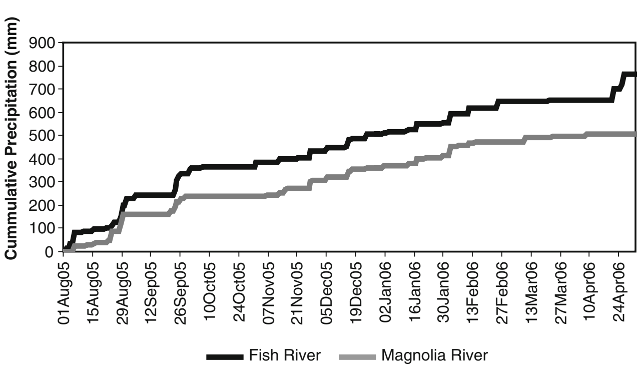

Fig. 8 Cumulative precipitation for the Silverhill USGS Hydrologic Gauging Station on the Fish River (*black shaded line*) and the Magnolia Springs USGS Hydrologic Gauging Station on the Magnolia River (*gray shaded line*) from August 1, 2005 through May 1, 2006 (NWIS 2008)

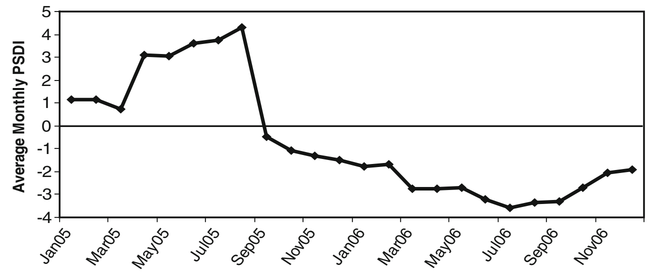

Fig. 9 Average monthly Palmer Drought Severity Index (*PDSI*) values from January 2005 to May 2006 for the AL Climate Division 8 region (NCDC 2008)

Only 8.6 mm of precipitation occurred during the month of October 2005 at the Fish River USGS Hydrologic Station. From August 5, 2005 to May 6, 2006, cumulative rainfall for the Fish River station was only 726.4 mm. This cumulative value is nearly half of the 30-year average precipitation for the AL Climate Division 8 (1,216 mm; NCDC 2008). Cumulative precipitation recorded at the Magnolia River USGS station from August 2, 2005 to May 06, 2006 was only 508 mm. This cumulative rainfall value represents a 58% decrease from the 30-year average precipitation amount. The lack of significant precipitation after landfall was also evidenced by the low Palmer Drought Severity Index (PDSI) values for 2005 and 2006 (Fig. 9). The average monthly PDSI dropped from +4.4 in August, 2005 to −0.5 in September, 2005. From September 2005, average monthly PDSI values dropped below −1 and remained negative for the duration of 2006 (NCDC 2008).

Climate data for AL Climate Division 8 showed that annual precipitation was higher from 2002 to 2005 than the 30-year mean (1977–2007; Fig. 10). This helps support the March 2005 to August 2002 image comparison because both image dates had abundant precipitation. In contrast, precipitation from 2006 to 2007 was much lower than the 30-year mean. Summer precipitation values for the months of June, July, and August follow a similar trend.

Discussion

Hurricane Katrina and the Weeks Bay Vegetation

Vegetation indices measured from Landsat satellite imagery showed a near 50% reduction in value from March 24, 2005 to September 16, 2005. However, there are several indicators that point to this vegetation reduction being related to Hurricane Katrina. First, Hurricane Katrina was the most significant tropical cyclone in 2005 to affect the region. Prior to Katrina, three tropical cyclones made landfall within 80 km of the study site, including Tropical Depression Arlene (June 11), Hurricane Dennis (July 6),

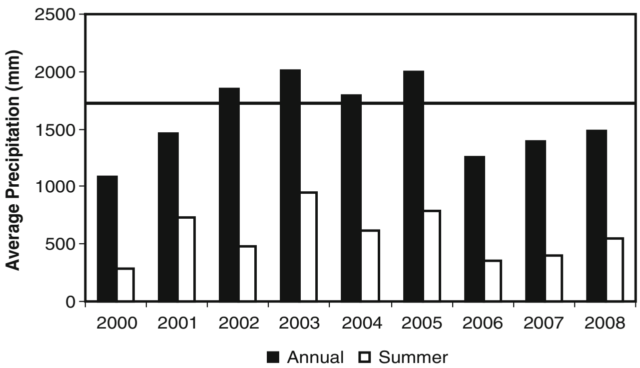

Fig. 10 Total annual precipitation and total summer precipitation (June through August) for the AL Climate Division 8 region from 2003 to 2007 (NCDC 2008). The *horizontal line* represents the 30-year (1977 to 2006) average annual precipitation (1,716 mm) for AL Climate Division 8

and Hurricane Cindy (July 11; Beven 2005). These other storms had much weaker maximum wind speeds and a much lower storm surge extent (Avila and Brown 2005; Beven 2005; Stewart 2006). Notably, the WBR experienced extensive vegetation denudation after Katrina made landfall (Scott Phipps, Research Director of the WBR, October, 15 2005, personal communications). This degree of denudation was not apparent during any other time from March to September of 2005.

Second, precipitation for March 1, 2005 through August 31, 2005 was higher than the 30-year average (NCDC 2008). The absence of drought conditions in the summer of 2005 is also evidenced by high PDSI values. Rodgers et al. (2006) showed that summer moisture was an important environmental factors related to tree ring widths within the Weeks Bay Reserve. Thus, any influences from lack of moisture before Hurricane Katrina made landfall can be ruled out as a contributor to the reduced NDVI.

Third, average monthly salinity values from March 1, 2005 until August 27, 2005 were at their lowest levels during the year. Even though the long-term trend since 2003 has been increasing salinity, the salinity values during the summer of 2005 were similar in value and range to the previous annual records of 2003 and 2004. Thus, above average salinity prior to landfall of Hurricane Katrina may also be ruled out as a contributor to the reduced NDVI within the September 16, 2005 image.

Finally, the measured decrease in average NDVI for the emergent estuarine wetland vegetation type (0.65 before landfall to 0.25 after landfall) was greater than what might be expected from nonhurricane, seasonal changes in vegetation greenness for this habitat. Although no regional estuarine NDVI studies were available for comparison, seasonal NDVI changes within estuarine vegetation of Galveston Bay, TX ranged from an average of 0.10 in winter to an average of 0.40 in spring (Keith et al. 2002). This range in NDVI is less than the NDVI decrease measured before and after landfall of Hurricane Katrina in Weeks Bay. Therefore, due to the extent of the storm surge and high wind speeds, to the reduced level of adverse environmental conditions from March 1, 2005 until August 26, 2005, and to the observed NDVI changes being possibly larger than background seasonal changes, the most likely scenario for the 49% NDVI reduction between the March 24, 2005 and September 16, 2005 images would have been from Hurricane Katrina.

Other studies have shown that the percent decreases in NDVI following hurricane disturbances ranges widely. As an example, Hurricane Georges (category 4) in Puerto Rico in 1998 resulted in a mean NDVI decrease of −124% within areas that were in the immediate path of the hurricane and a mean NDVI decease of −54% in areas that were over 32 km away from the hurricane track (Ayala-Silva and Twumasi 2004). At another extreme, Lee et al. (2008) reported that NDVI values only decreased less than 8% from Typhoon Herb (category 5, 1996) in Taiwan. Though this typhoon had higher reported wind speeds than Hurricane Katrina, the minimal change was attributed to NDVI values being under representative of the actual amount of vegetation damage (Lee et al. 2008). Compared to these other studies, it appears that the NDVI decrease following Hurricane Katrina in Week Bay, AL was moderate in value. It should be noted that the 49% decrease in NDVI is attributed to a hurricane that made landfall approximately 100 km away. This illustrates the broad-reaching influence that Hurricane Katrina had on the Northern Gulf Coast.

The literature strongly indicates that high wind speeds are one of the most significant factors explaining vegetation damage during hurricanes (Foster and Boose 1992; Everham and Brokaw 1996; Greenberg and McNab 1998). Although wind data were not directly available for the Weeks Bay study area during landfall, nearby Mobile, AL reported wind gusts up to 35 m s^{-1}. Therefore, it is likely that the reduction in NDVI is at least partially related to winds. Another factor that may have explained the reduced NDVI would be inundation from the storm surge. Berm heights at Mobile Bay border have been estimated at less than 1 m (Scott Phipps, September 25, 2007, personal communication). Berms or other elevated coastal structures are not present around Weeks Bay. Thus, the 2-m+ storm surge would have easily flooded the surrounding areas. This inundation would have saturated the adjacent soil and would have elevated soil salinity. It should be noted that salinity values reported in this study are for the Weeks Bay water body only. Salinity values for the adjacent soils have not been reported. Due to the fact that very little precipitation occurred for several months after landfall, the elevated soil salinity from the Hurricane Katrina storm surge may have persisted into the following growing season. These higher salinity values in conjunction with the reduced precipitation may explain why NDVI values were substantially lower in April 2006 than they were in March of 2005.

Spatial Variability of Vegetation Damage

Changes in average NDVI after landfall varied among different locations and habitat types. The location with the greatest change in average NDVI both from March 2005 to September 2005 and from March 2005 to April 2006 was the Fish River. The location with the least amount of change in average NDVI during the study period was the Weeks Bay subregion. During landfall of Hurricane Katrina, salinity values were elevated proportionally higher at the Fish River than at any other location. As previously reported, the maximum salinity for the Fish River during Hurricane Katrina was within the 95th percentile for the year. Hurricane-induced changes of estuarine river system salinity have been evidenced within Chesapeake Bay after Hurricane Agnes (Kuo et al. 1976) and within the York River, MD from Hurricane Isabel (Gong et al. 2007). Similar to these studies, the elevated salinity in the river may have led to saline stress for the adjacent vegetation, which may have resulted in lowering the average NDVI values.

The upland forest habitat experienced the least amount of decline in average NDVI from March 2005 to September 2005 and this habitat had the largest increase in average NDVI from September 2005 to April 2006. The most sensitive habitat, in contrast, was the estuarine emergent wetland. This habitat type decreased the most in average NDVI from March 2005 to September 2005 and this was the only habitat that exhibited continual deceases in average NDVI from September to April 2006. One explanation for the difference in average NDVI between these two habitats postlandfall could be their proximity to the major water bodies. The majorities of the estuarine emergent wetland areas were located adjacent to the shores of the Fish River, Magnolia River, Weeks Bay, and Mobile Bay border. Upland forest areas, however, were located further inland, and thus, these locations would be less exposed to the storm surge inundation. The estuarine emergent wetlands, on the other hand, would have experienced the full brunt of the storm surge. It has been shown that wetland species, such as those found within the estuarine emergent wetland habitat of Weeks Bay, have significantly reduced biomass after being inundated by a storm surge (Baldwin and Mendelssohn 1998). Thus, there is precedence to suggest that this is a sensitive habitat, and its closer proximity to the storm surge may have been a contributing factor to the decreased NDVI values after landfall.

Conclusions

This study investigated changes in NDVI before and after landfall of Hurricane Katrina in the Weeks Bay Reserve and surrounding regions of coastal AL. In the absence of other adverse environmental conditions during the summer of 2005, the 49% decrease in NDVI from March 24, 2005 to September 16 2005 was most likely caused by the hurricane. Given that Hurricane Katrina made landfall nearly 100 km away, this reduction in NDVI illustrates the magnitude and the broad scale by which the storm affected Northern Gulf Coast region.

One year later in April 2006, NDVI values for the region were still 44% lower than the previous year. This continued NDVI suppression is attributed to both Hurricane Katrina and longer-term climatic trends. It was presumed that soil salinity in the region greatly increased during landfall as the Hurricane Katrina storm surge toppled berms and inundated adjacent coastal areas. Even though the majority of flooding subsided within a few days after landfall, the lack of precipitation and drought-like conditions that followed into the spring of 2006 meant that salinity was not rinsed from the soil. The combination of both drought and increased salinity is the most likely cause of the reduced NDVI in April 2006. These results suggest that similar coastal research projects that assess NDVI change following hurricane landfalls must also be examined within the context of longer-term climatic and other environmental trends.

Another important finding from this study was that the estuarine emergent wetland vegetation was the most sensitive habitat from Hurricane Katrina. This habitat type had the largest NDVI decrease and showed the least amount of NDVI increase 8 months after landfall. The closer proximity of this habitat to the coastal water bodies probably resulted in it being more exposed to the storm surge. Additionally, the Fish River was the subregion that experienced the largest decrease in NDVI and the least amount of NDVI increase following landfall. The more pronounced increase in salinity may be a contributing factor that explains why this location was the most sensitive to NDVI change.

One limitation of this study is that the research was based on 30-m resolution Landsat imagery with a 16-day repeat coverage. Although this resolution, both spatially and temporally, enabled a regional interpretation of vegetation changes, it is suggested that future research focus on the actual species distribution. A more comprehensive on-ground investigation of the different taxa and their respective tolerances to environmental change, especially to changes in salinity, would help add to the body of knowledge that is oriented toward understanding how spatial patterns enable determination of relationships between hurricanes and coastal vegetation dynamics.

Acknowledgments This research was funded by NOAA through the NERR Graduate Research Fellowship. The authors wish to acknowledge the Weeks Bay Reserve Research Coordinator Scott Phipps. Dr. Phipps's help and knowledge of the area were extremely helpful, especially with the interpretation of the results. The authors also wish to thank the Weeks Bay Reserve for providing lodging and logistical support. The authors are indebted to John Cartwright for his help with the development of the research objective and for his help with the remote sensing methodology. Thanks go to Kate Grala for her editorial assistance. The authors wish to thank the Department of Geosciences at Mississippi State University for financially supporting this research. Lastly, the authors are indebted to Mississippi state climatologist Dr. Charles Wax for his help with the climate data.

References

Avila, L.A., and D.P. Brown. 2005. Tropical Cyclone Report, Tropical Storm Arlene, 8–13 June, 2005. http://www.nhc.noaa.gov/pdf/TCR-AL012005_Arlene.pdf. Accessed 3 April 2008.

Ayala-Silva, T., and Y.A. Twumasi. 2004. Hurricane Georges and vegetation change in Puerto Rico using AVHRR satellite data. *International Journal of Remote Sensing* 25: 1629–1640. doi:10.1080/01431160310001595037.

Baldwin, A.H., and I.A. Mendelssohn. 1998. Effects of salinity and water level on coastal marshes: an experimental test of disturbance as a catalyst for vegetation change. *Aquatic Botany* 61: 255–268. doi:10.1016/S0304-3770(98)00073-4.

Barras, J.A. 2006. Land area change in coastal Louisiana after the 2005 hurricanes—a series of three maps. U.S. Geological Survey Open-File Report 06-1274.

Beven, J. 2005. Tropical Cyclone Report, Hurricane Dennis, 4–13 July, 2005. 25 http://www.nhc.noaa.gov/pdf/TCR-AL042005_Dennis.pdf. Accessed 3 April 2008.

Byron, D., and K.L. Heck. 2006. Hurricane effects on seagrasses along Alabama's Gulf Coast. *Estuaries and Coasts* 29: 939–942.

CDMO (Centralized Data Management Office). 2008. National Estuarine Research Reserve Centralized Data Management Office. http://cdmo.baruch.sc.edu/. Accessed 19 November 2008.

Conese, C., M.A. Gilabert, F. Maselli, and L. Bottai. 1993. Topographic normalization of TM scenes through the use of an atmospheric correction method and digital terrain models. *Photogrammetric Engineering and Remote Sensing* 59: 1745–1753.

Coppin, P.R., and M.E. Bauer. 1994. Processing of multitemporal Landsat TM imagery to optimize extraction of forest cover change features. *IEEE Transactions on Geoscience and Remote Sensing* 32: 918–927. doi:10.1109/36.298020.

Eckhardt, D.W., J.P. Verdin, and G.R. Lyford. 1990. Automated update of an irrigated lands GIS using SPOT HRV imagery. *Photogrammetric Engineering and Remote Sensing* 56: 1515–1522.

Everham, E., and N.V.L. Brokaw. 1996. Forest damage and recovery from catastrophic wind. *Botanical Review* 62: 113–185. doi:10.1007/BF02857920.

Foster, D.R., and E.R. Boose. 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. *Journal of Ecology* 80: 79–98. doi:10.2307/2261065.

Fritz, H.M., C. Blount, R. Sokoloski, J. Singleton, A. Fuggle, B.G. McAdoo, A. Moore, C. Grass, and B. Tate. 2007. Hurricane Katrina storm surge distribution and field observations on the Mississippi Barrier Islands. *Estuarine Coastal and Shelf Science* 74: 12–20. doi:10.1016/j.ecss.2007.03.015.

Garoogian, D. 2001. *Weather America: A thirty-year summary of statistical weather data and rankings*. Lakeville, CT: Grey House.

Gong, W.P., J. Shen, and W.G. Reay. 2007. The hydrodynamic response of the York River estuary to tropical cyclone Isabel, 2003. *Estuarine Coastal and Shelf Science* 73: 695–710. doi:10.1016/j.ecss.2007.03.012.

Greenberg, C.H., and W.H. McNab. 1998. Forest disturbance in hurricane-related downbursts in the Appalachian mountains of North Carolina. *Forest Ecology and Management* 104: 179–191. doi:10.1016/S0378-1127(97)00246-6.

Jesus, B., C.R. Mendes, V. Brotas, and D.M. Paterson. 2006. Effect of sediment type on microphytobenthos vertical distribution: Modelling the productive biomass and improving ground truth measurements. *Journal of Experimental Marine Biology and Ecology* 332: 60–74. doi:10.1016/j.jembe.2005.11.005.

Jupiter, S.D., D.G. Potts, S.R. Phinn, and N. Duke. 2007. Natural and anthropogenic changes to mangrove distributions in the Pioneer River Estuary. *Wetlands Ecology and Management* 15: 51–62. doi:10.1007/s11273-006-9011-9.

Keith, D.J., H.A. Walker, and J.F. Paul. 2002. Terrestrial vegetation greenness of the Lower Galveston Bay watershed from satellite remote sensing and its relation to water use and the salinity regime of the Galveston Bay estuary (USA). *International Journal of Remote Sensing* 23: 905–916. doi:10.1080/01431160110040486.

Knabb, R., J. R. Rhome, D. P. Brown. 2005. Tropical Cyclone Report, Hurricane Katrina, 23–30 August, 2005. http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf. Accessed 19 November 2008.

Koss, W.J., J. R. Owenby, P. M. Steurer, and D. S. Ezell. 1988. Freeze/Frost Data. Climatography of the U.S. No.20, supplement No.1, I-3-I-5.

Kuo, A.Y., E.P. Ruzecki, and C.S. Fang. 1976. The effects of the Agnes Flood on the salinity structure of the lower Chesapeake Bay and contiguous waters. In *The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System*, eds. J. Davis, and B. Laird, 81–103. Baltimore: John Hopkins University Press.

Lee, M.F., T.C. Lin, M.A. Vadeboncoeur, and J.L. Hwang. 2008. Remote sensing of forest damage in relation to the 1996 strong typhoon Herb at Lienhuachi Experimental Forest, Taiwan. *Forest Ecology and Management* 255: 3297–3306. doi:10.1016/j.foreco.2008.02.010.

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman. 2004. *Remote Sensing and Image Interpretation*. New York, NY: Wiley.

Myneni, R.B., F.G. Hall, P.J. Sellers, and A.L. Marshak. 1995. The interpretation of spectral vegetation indexes. *IEEE Transactions on Geoscience and Remote Sensing* 33: 481–486. doi:10.1109/36.377948.

NCDC (National Climatic Data Center). 2008. Time bias corrected statewide–regional–national temperature–precipitation. http://www1.ncdc.noaa.gov/pub/data/cirs. Accessed 3 April 2008.

NERR. 2008. Weeks Bay Reserve, Alabama. National Estuarine Research Reserve. http://www.nerrs.noaa.gov/WeeksBay/welcome.html. Accessed 3 April 2008.

NLCD (National Land Cover Data). 2001. US Environmental Protection Agency, 1992 National Land Cover Data. http://www.epa.gov/mrlc/nlcd.html. Accessed 21 November 2008.

NWIS (National Water Information System). 2008.USGS real-time water data. http://waterdata.usgs.gov/al/nwis/uv?02378500. Accessed 19 November 2008.

Ramsey, E.W. III, and S.C. Laine. 1997. Comparison of Landsat Thematic Mapper and high resolution photography to identify change in complex coastal wetlands. *Journal of Coastal Research* 13: 281–292.

Rodgers, J.C. III, D.G. Gamble, D.H. McCay, and S. Phipps. 2006. Tropical cyclone signals within tree ring chronologies from Weeks Bay National Estuary and Research Reserve, Alabama. *Journal of Coastal Research* 22: 1320–1329. doi:10.2112/05-0515.1.

Samson, S.A. 1993. Two indices to characterize temporal patterns in the spectral response of vegetation. *Photogrammetric Engineering & Remote Sensing* 59: 511–517.

Stewart, S.R. (2006) Tropical Cyclone Report, Hurricane Cindy, 3–7 July, 2005. http://www.nhc.noaa.gov/pdf/TCR-AL032005_Cindy.pdf. Accessed 3 April 2008.

Stout, J.P. 1996. Estuarine habitats. In Weeks Bay National Estuarine Research Reserve: An estuarine profile and bibliography, ed. T. Miller-Way, 96–101. Dauphin Island Sea Lab technical report

USGS EarthExplorer Website. 2008. http://edcsns17.cr.usgs.gov/EarthExplorer/. Accessed 19 November 2008.

Wilson, M., S.D. Meyers, and M.E. Luther. 2006. Changes in the circulation of Tampa Bay due to Hurricane Frances as recorded by ADCP measurements and reproduced with a numerical ocean model. *Estuaries and Coast* 29: 914–918.

Yuan, D., and C.D. Elvidege. 1996. Comparison of relative radiometric normalization techniques. *ISPRS Journal of Photogrammetry and Remote Sensing* 51: 117–126. doi:10.1016/0924-2716(96)00018-4.