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SATELLITE OPTICAL AND RADAR DATA USED TO TRACK WETLAND FOREST IMPACT AND SHORT-TERM RECOVERY FROM HURRICANE KATRINA

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Abstract: Satellite Landsat Thematic Mapper (TM) and RADARSAT-1 (radar) satellite image data collected before and after the landfall of Hurricane Katrina in the Pearl River Wildlife Management Area on the Louisiana-Mississippi border, USA, were applied to the study of forested wetland impact and recovery. We documented the overall similarity in the radar and optical satellite mapping of impact and recovery patterns and highlighted some unique differences that could be used to provide consistent and relevant ecological monitoring. Satellite optical data transformed to a canopy foliage index (CFI) indicated a dramatic decrease in canopy cover immediately after the storm, which then recovered rapidly in the *Taxodium distichum* (baldcypress) and *Nyssa aquatica* (water tupelo) forest. Although CFI levels in early October indicated rapid foliage recovery, the abnormally high radar responses associated with the cypress forest suggested a persistent poststorm difference in canopy structure. Impact and recovery mapping results showed that even though cypress forests experienced very high wind speeds, damage was largely limited to foliage loss. Bottomland hardwoods, experiencing progressively lower wind speeds further inland, suffered impacts ranging from increased occurrences of downed trees in the south to partial foliage loss in the north. In addition, bottomland hardwood impact and recovery patterns suggested that impact severity was associated with a difference in stand structure possibly related to environmental conditions that were not revealed in the prehurricane 25-m optical and radar image analyses.

INTRODUCTION

Passive optical remote sensing systems support wetland management because of their utility to detect changes in landcover and biophysical processes and their ability to document regional and local disturbance impacts and assess recovery of coastal wetlands after storms such as Hurricane Katrina (e.g., Jensen et al. 1987, Klemas et al. 1993, Lunetta et al. 1998, Ramsey et al. 2001b). From an ecological monitoring perspective, information extracted from image data should be directly relevant to critical ecological processes related to wetland regeneration. Although the relevancy of the information has improved with advances in subpixel extraction methods and multiple source integrations (e.g., Ramsey et al. 2005) and time series analyses (Ramsey et al. 1998a), mapping consistency of optical collections is limited by clouds and atmospheric turbidity, particularly in subtropical regions such as the gulf coast of the United States. Consequently, even though information extractable from satellite systems is improving and expensive high-resolution and more timely collection systems exist, optical collection systems often fail to provide consistently reliable data sources, a critical issue in the use of these technologies in basic ecology and resource management applications (Ramsey et al. 2001b).

Microwave data offer a good alternative data source when timely collection is the dominant concern (Lyon and McCarthy 1981, Kasischke and Bourgeau-Chavez 1997, Ramsey 1998, 2005, Lu et al. 2005, Ramsey et al. 2006, Lu and Kwoun 2008). Active radar imaging systems operating within the microwave spectrum (~1–150 cm) can collect information day and night and in most weather conditions. Synthetic Aperture Radar (SAR) systems encompass a variety of operating wavelengths, polarizations, incident angles, spatial resolutions, and processing levels that uniquely identify each SAR system and largely characterize the type and range of land cover information extractable from each system (Elachi 1988, Ulaby and Dobson 1989, Dobson et al. 1995, Lewis et al. 1998, Ramsey 1998, Ramsey et al. 1999, Jensen 2000). Most SAR

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systems operate with a limited set of parameters (e.g., wavelengths, polarizations, and incidence angles) hindering the widespread application of these systems in resource management, although multiple mode systems are increasing, such as the Shuttle Imaging Radar (SIR), Environmental Satellite (ENVISAT), Advanced Land Observing Satellite (ALOS), and RADARSAT-2.

Satellite optical and SAR terrestrial mapping are fundamentally different (e.g., Ramsey 2005). Passive optical sensors collect reflected visible and near-infrared (VNIR, 0.4 μ to 1.3 μ) and shortwave infrared (SWIR, 1.3 μ to 2.5 μ) sunlight within a solid view angle defined by the sensor system optics and the satellite-sensor collection geometry. Calibrated and atmospherically corrected (or at least adjusted) VNIR reflectance data supply information about the general vegetation status and inferentially the canopy density and structure (one aspect is canopy gap). The SWIR augments this information with increased sensitivities to vegetation turgidity, soil moisture, and standing open water. In contrast, as the satellite moves along its orbital path the radar antenna transmits a microwave pulse at an angle orthogonal to its flight direction and then records the "backscatter" (i.e., response intensity). Radar backscatter intensity from a target is a function of frequency, imaging geometry, topography, surface roughness, and dielectric constant (Dobson et al. 1995, Waring et al. 1995, Ramsey 1998, 2005, Baran 2004, Lu et al. 2005). Differences between the optical and radar operational wavelengths, the passive versus active ramifications, and the dissimilar nature of image creations yield different representations of the landscape that can provide more accurate estimates of landscape features and changes (e.g., Treuhaft et al. 2002, Ramsey 2005, Ramsey et al. 2006).

Ustin et al. (1991) postulated that the integrated optical-radar sensor system could fundamentally change the understanding of ecological processes. Whereas integrated approaches have produced important results (e.g., Rebillard and Evans 1983, Lozano-Garcia and Hoffer 1993, Haack and Slonecker 1994, Ramsey et al. 1998b, Ramsey et al. 2006), key issues of consistency and relevance still hinder the usefulness of remote sensing to ecological management. Consistency is improved by integrating radar data into the more established optical monitoring of landscape changes and biophysical processes. To be relevant, image information should address ecological problems such as wetland forest regeneration and be directly useful for resource management.

Our studies focus on the impacts on and recovery of forested wetlands after the occurrence of Hurricane Katrina on 28 August 2005 (Figure 1). Hurricane Katrina first made landfall at Grand Isle, Louisiana, USA, with 204 kmph wind speeds and later made a second landfall near the mouth of the Pearl River, USA, with 180 kmph surface winds and hurricane-force winds extending outward 190 km (Campo and Rickenbach 2006, Wikimedia Commons n.d.). In comparison, Hurricane Andrew (26 August 1992) impacted the Atchafalaya River basin (ARB), USA, located in the central Louisiana coastal region with sustained wind speeds from just above 145 kmph to around 80 kmph. Although Hurricane Katrina wind speeds were higher, our studies built on methods and products created during a study of Hurricane Andrew's impacts on the forested wetlands of the ARB and their subsequent short-term recovery (Ramsey et al. 1997).

In the ARB project, a temporal suite of National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) 1-km image data were used to suggest three categories of forest impact: 1) no impact or only slight to moderate defoliation, 2) severe defoliation with branch loss, and 3) severe branch loss or downed trees (Ramsey et al. 1997). Subsequently, we combined a prestorm 30-m forest type classification created with Landsat Thematic Mapper (TM) (Ramsey et al. 1998a) with a wind-field model developed by Boose et al. (1994) to demonstrate that bottomland hardwood (bottomland) and *Taxodium distichum* (baldcypress) forests had different levels of susceptibility to wind magnitude and duration (Ramsey et al. 2001a). Because of the coarse mapping scale (1 km), stand-level ($<$ 100 m) forest regeneration studies were not accomplished.

Our purpose in using multitemporal optical and radar remote sensing is to gain an understanding of wetland forest regeneration and forest structure spatial patterns (e.g., composition, density) in order to predict how specific weather events such as devastating storms change these forested ecosystems. Understanding these processes requires determining the before and after storm vegetation structures of wetland forests recovering from storm damage (Middleton 2009). From a mapping perspective, this goal requires sufficient detail regarding 1) the characteristics of species and canopy, 2) the level of storm impact, and 3) the short and longer term reassembly of species throughout the landscape (Michener et al. 1997). In terms of satellite mapping and ecological relevance, our study objective is to advance the study of species regeneration processes by improving the consistency of the regional to

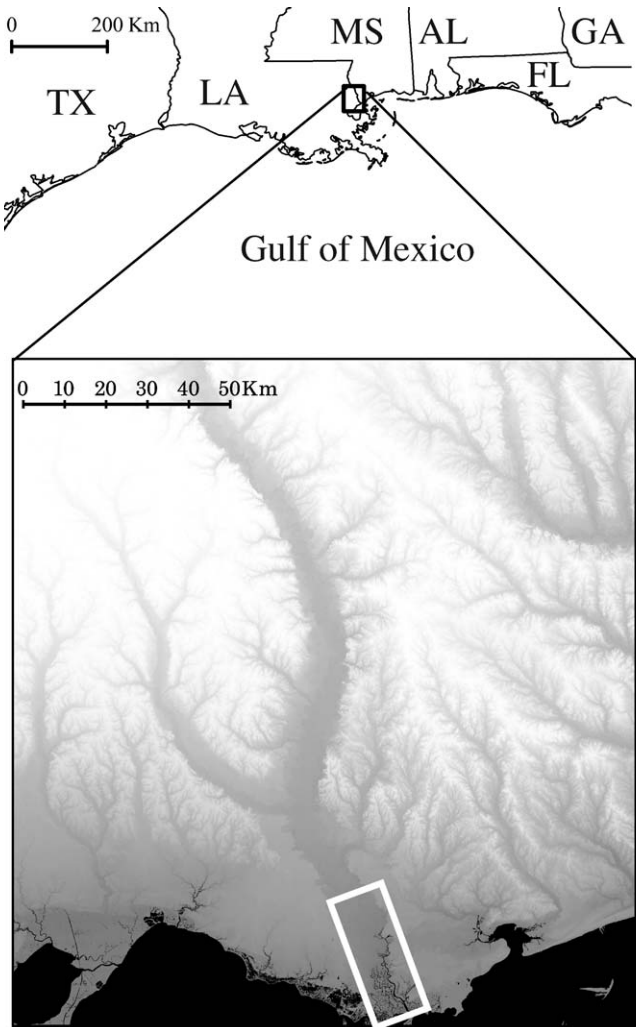

Figure 1. The white box approximates the location and extent of the image data subset containing the Pearl River Wildlife Management Area (administered by the Louisiana Department of Wildlife and Fisheries). The image portrays land elevations. Abbreviations stand for U.S. state names: LA-Louisiana, TX-Texas, MS-Mississippi, AL-Alabama, GA-Georgia, and FL-Florida.

stand-level information obtainable from optical and radar satellite image data.

STUDY AREA

Our study covers the Pearl River Wildlife and Management Area (PRWMA) owned by the Louisiana Department of Wildlife and Fisheries (Figure 1). The PRWMA contains 14,177 ha of flat terrain with poor drainage and is subject to annual flooding. Before Hurricane Katrina, the northern 60% of the PRWMA contained a bottomland forest of variable age and species that transitioned to a cypress forest occupying about 25% of the more southern PRWMA and intermediate marsh occupied the remaining 15% of the southern PRWMA.

METHODS

Image Data Collection and Post-Processing

Prestorm images of the PRWMA were collected as near as possible to the 29 August 2005 landfall of Katrina, and poststorm images within the first 1–3 months after impact. The prelandfall collections combined with postmultitemporal collections helped categorize impact severity and assess short-term forest recovery. Restricting the postrecovery analyses helped alleviate ambiguity in the impact assessments caused by changes brought on by fall senescence and by low-lying shrub and vine growth, particularly where tree fall was nearly spatially continuous and widespread.

Landsat 5 TM and RADARSAT-1 SAR image data were obtained from the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Data Center (EDC) and the Canadian Space Agency by way of the National Aeronautics Space Administration's Alaska Satellite Facility (ASF) located in the Geophysical Institute of the University of Alaska Fairbanks. All acquisitions were limited by availability, particularly image data collected before Hurricane Katrina. Useable optical data were further limited by cloud occurrences and TM data acquisitions were restricted to the Landsat5 satellite because of problems with the scan line corrector in the enhanced TM sensor onboard the Landsat7 satellite.

The TM data included six reflected bands in the visible (VIS), near-infrared (NIR), and SWIR, and one thermal band. To help minimize scene-to-scene variation caused by changing illumination path lengths (sun zenith) through the earth's atmosphere, the TM image data were converted to radiance units and normalized by an optical depth estimated by the sun's zenith position at the time of image collection. The RADARSAT-1 SAR sensor operated with a C-band microwave frequency of 5.3 GHz (5.6 cm) and horizontal return and send polarizations (HH). SAR data were calibrated to allow scene-to-scene comparability.

All satellite image data collected at different times and with different resolutions and sensors were rectified or registered into a common database with a Lambert Conformal Conic (LCC) projection that used the standard parallels, central meridian, and false northing and easting defined by the Southern Louisiana State Plane. The LCC projection eliminated problems of multiple UTM zones and provided a good spatial and directional reproduction throughout the central gulf coast.

Landcover Classification

The initial classification of the PRWMA was based on previous classifications performed within the USGS Gap Analysis Program (GAP) (Hartley et al. 2000). NOAA Coastal Change Analysis Protocol (C-CAP) and the USGS National Land Cover Dataset (NLCD) classifications of the study area were available; however, only the USGS GAP 2000 classification was aligned with Chabreck's (1970) marsh landcover designations that are used regionally (Hartley et al. 2000). For a comparison of GAP and NLCD datasets see Wardlow and Egbert (2003). All three classifications combined the cypress and bottomland hardwood wetland forests into a single wetland forest class.

The forest wetland class covering the study area was extracted from the GAP landcover classification covering the study area and overlaid on the LCC-projected TM image collected on 22 August 2005. An isodata classification (Tou and Gonzalez 1974, PCI Geomatics 1998) was performed under the wetland forest class in order to separate the baldcypress and water tupelo (hereafter referred to as cypress) forest from the bottomland forest.

Forest Canopy Foliage Index

The optical normalized difference vegetation index (NDVI) was used to determine change in canopy condition for each forest type as revealed in the reclassification of the GAP wetland forest classes. Even though atmospheric correction was not employed prior to the creation of the NDVI layer, the prenormalization of the TM image data by the optical depth estimates and the normalization built into the NDVI transform helped to minimize differences in NDVI between image dates caused by illumination and atmospheric variabilities and thereby to maximize the NDVI and canopy condition correspondence.

Optical NDVI normally estimates overall canopy green biomass, not canopy structure directly (Ramsey et al. 1997). In late August 2005, NDVI changes were dominantly indexed to canopy foliage changes, not leaf optical changes. Foliage changes were expressed as loss or gain in the amount of leaves in a fairly uniform distribution or an occurrence of gaps in the sensor ground resolution. We designated this specific use of NDVI as a canopy foliage index (CFI) that would more explicitly indicate canopy impact severity and short-term recovery. The CFI was justified because 1) this study objective did not rely on quantifying subtle canopy changes but dramatic changes in canopy foliage, 2) not all optical image data contained a blue band necessary for the application of other popular vegetation condition indexes (e.g., enhanced vegetation index), and 3) analyses of simultaneous radar image data helped substantiate canopy condition findings based on the optical-based CFI.

Temporal Assessment of Forest Recovery

Change in forest canopy condition was detailed with a temporal set of CFI layers created from TM images and a similar set of calibrated radar images. Layers of CFI representing landscape conditions 1) just before, 2) just after, and 3) about a month after Hurricane Katrina's landfall were portrayed as an image composite. Similarly, calibrated radar images collected 1) on a near-anniversary date 1 year before, 2) just after, and 3) about 3 weeks after the hurricane's landfall were portrayed as an image composite. A near-anniversary radar image collected 1 year previous to the third radar image was used to establish a second point of before-and-after change. A fourth TM image collected about 1.5 months after Hurricane Katrina's landfall was used to extend the CFI temporal trend analyses.

Modal Analyses of CFI Frequency Histograms. CFI frequency histograms representing forest canopy condition distributions were partitioned or "density sliced" at clearly discernable bimodal or trimodal features in the frequency histogram. Even though histogram representations elucidated the univariate frequency distribution of CFI as an indicator of forest canopy condition, the spatial association was lacking. Mapping the discernable features displayed on the frequency histogram to a spatial domain provided contextual information related to forest stand regrowth.

Forest impact severity and short-term recovery were related to stand differences prior to Hurricane Katrina (non-impacted). Image polygons representing the two modes exhibited in the posthurricane early October 2005 CFI distributions were overlaid on the prehurricane TM and radar images. Application of the modal polygons to the preoptical and preradar image data determined whether or not stand composition or canopy structural differences as represented by the optical and radar responses of the non-impacted forests could have influenced the impact patterns and recovery determined by the post-CFI canopy foliage measure.

Temporal Multidate Color Composite. To encapsulate the immediate and short-term changes in the forests and marshes, we created multidate color composite imagery from both the CFI and radar image data. First discussed by Sader and Winne (1992), the visualization technique employed additive color theory as a means to view and assess landscape change from multitemporal satellite data (e.g., Ramsey and Strong 2000). By assigning a primary color (red, green, and blue) to each date in the image set and overlaying the result, a color composite was created, revealing what remained unchanged and what changed in the landscape and further providing visual detail about the relative change (hue and saturation).

RESULTS

Database Creation

Spatial alignment error was estimated to be less than one-half the reprojected image pixel resolution, < 12.5 m for the TM and the radar images. No spatial location noncorrespondence was noticeable between the Digital Ortho Quarter Quads (DOQQ) and rectified TM and radar images and between all registered TM and radar images on a full-resolution display overlay. Even though differences in pixel resolution existed among images, all images within the created database were spatially aligned.

Forest Classification

Spectral classification of the 22 August 2005 TM image yielded two broadly different forest types within the GAP forest wetland class. Spectral separation of the cypress and bottomland forests partly relied on differences in canopy structure. As indicated by CFI, cypress forest stands generally exhibited lower foliage density or canopy closure than did bottomland forest, possibly exposing moist background that dampened the spectral return. Spatial locations and distributions of cypress and bottomland forest classes in the PRWMA broadly followed the Louisiana Department of Wildlife and Fisheries (n.d.) description.

Temporal Assessment of Forest Condition

Temporal Composite. As were also noted by mapping immediate forest damage (Chambers et al. 2007), there were dramatic changes in the wetland forests and marshes revealed by our color composites (Figures 2a and 2b). In addition, the temporal composite of CFI layers (Figure 2a) indicated that variability in impacts and responses occurred within the various land covers of the PRWMA. Marshes were heavily impacted and showed little progression to recovery nearly 1.5 months after Hurricane Katrina's landfall. The purple hue associated with the cypress forests suggested an immediate loss of canopy foliage that rapidly recovered within three weeks of impact. The blue represents elevated and the pink slightly lower cypress stand CFI's after Hurricane Katrina. The bottomland forests contained two fairly distinct zones, a red zone and a zone containing orange grading to a pinkish grey. The more pure red tones within the CFI composite suggested that a section of the bottomland forest region had suffered widespread defoliation and possible tree fall and failed to recover substantially within the study period. The more orange gradational zone included more moderately impacted bottomland forests that were progressively recovering to pre-Hurricane Katrina foliage densities. The pinkish grey represents light impact. The decrease in impact severity tending to the north possibly resulted from decreased wind speeds as the storm moved inland.

Similar to the CFI temporal composite, red tones in the radar composite (Figure 2b) depict land covers that experienced severe impact without exhibiting substantial recovery. The marshes exhibit red to pale purple tones, cypress forests pale purple to light blue, and the bottomland forest red to light pink. Purple tones represent somewhat higher post versus prehurricane responses (radar returns) in the marshes and cypress forest stands. The light blue color rendition associated with the cypress forest indicates elevated radar responses throughout the recovery period. The light green color associated with a majority of bottomland forest indicates a change in radar response magnitudes over the composite period with a peak in response magnitudes directly following Hurricane Katrina's landfall. The light pink tone within the more northern portion of the bottomland forest suggests a slight decrease in radar responses immediately following impact. Broadly, the zonal patterns indicated by the color composite of radar response highlighted changes in the marsh and forest impact and recovery broadly similar to those expressed in the CFI color composite. Additional details pertinent to the magnitude and timing of impact and recovery changes are contained in the CFI and radar color composites as variations in color saturations and intensities.

Wetland Forest CFI Histogram Mappings. As suggested by the composite renditions, CFI frequency histogram portrayals showed striking changes just after and trending through the short-term recovery

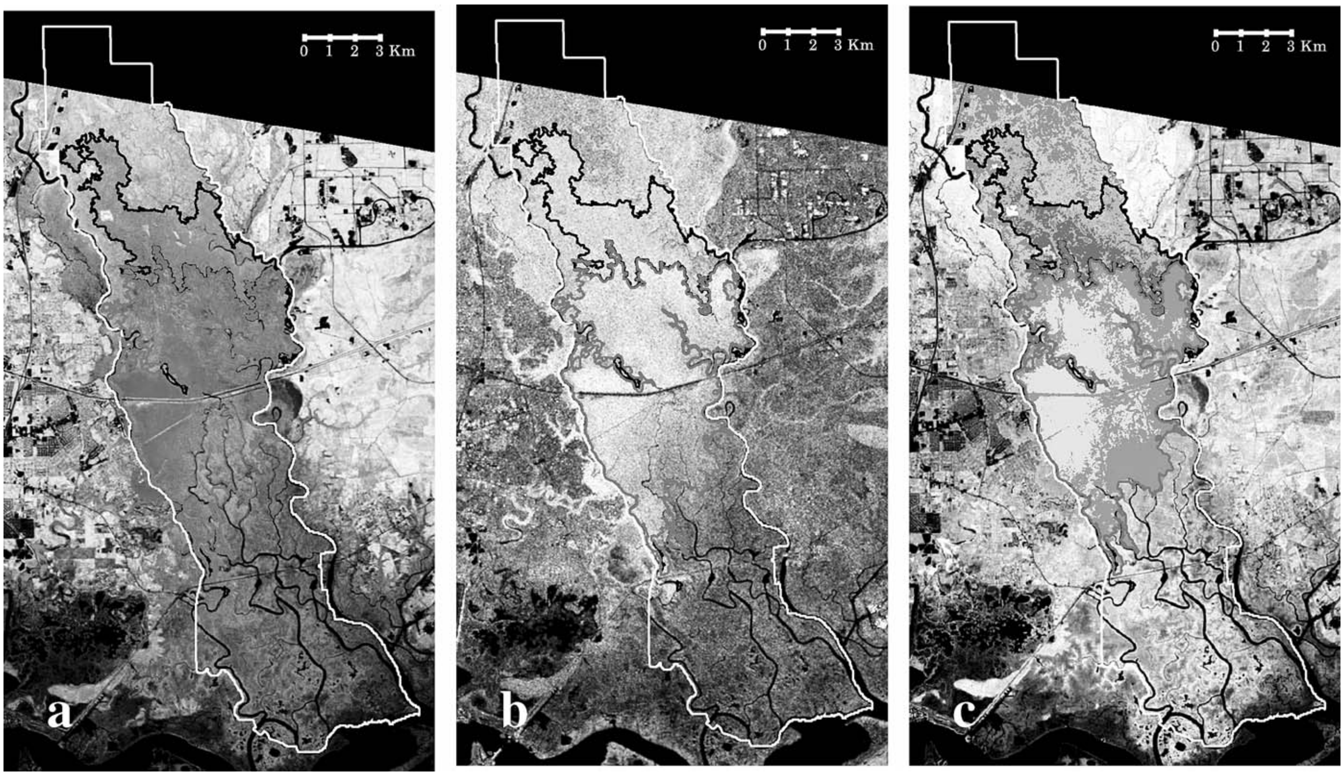

Figure 2. A) Canopy foliage index (CFI) layers calculated from before (22-08-05, red), immediately after (07-09-05, green), and about a month after (09-10-05, blue) Hurricane Katrina landfall displayed as a color composite renditions. B) A similar rendition applied to the calibrated radar images (07-08-04 [red], 02-09-05 [green], and 19-09-05 [blue]). The color hue, saturation, and intensities express differences in spatial and temporal patterns of recovery and differential rates of those patterns within and between forest types. The white outline denotes the Pearl River Wildlife Management Area, the blue line the cypress forest extent, and the black line the severely impacted bottomland hardwoods extent in early October. Marsh lies below and bottomland hardwood forest above the cypress forest. C) The modal features expressed on the early and late October bottomland hardwood and cypress forest frequency histograms (Figure 3) as translated to their spatial renditions. In the cypress forest, orange and yellow depict high foliage stands in early October (orange) and in late October (yellow) while green and olive show stands lagging in foliage recovery in early October (green) and in late October (olive). In the bottomland hardwood forest, the combined rust-red and dark green denote the decimated southern hardwoods in early October and those stands displaying little recovery by late October (dark green). By late October, improved southern stands (rust-red) combined with those stands moderately impacted but still lagging in recovery by late October (light orange) forming a middle frequency mode. The olive-green represents moderately or lightly impacted hardwood stands that had recovered to near before Hurricane Katrina conditions as expressed by canopy foliage index.

period (Figure 3). Histograms substantiated the widespread severity of impacts and that no forest stand within the study region was left unaffected. Although all forests were impacted, severity varied spatially and by forest type.

As judged by CFI magnitudes, initial impacts (foliage loss to downed trees) were highest in the cypress forests and in a portion of the bottomland forests. Cypress stands exhibited dramatic CFI decreases with magnitudes peaking in the lowest ranges which often reached zero. This dramatic decrease in CFI resembled changes in the moderately and most severely impacted bottomland forest. As indicated in the CFI image rendition and the high range of the near immediate post-Hurricane Katrina frequency plots, impacts to bottomland forests varied widely spatially. The lowest range mirrored the most dramatic and the peak the most moderate decreases in the cypress forest. In contrast, the higher CFI's depicted in the initial histogram suggested a large portion of the bottomland forest incurred less severe impacts than the cypress forest.

In early October about a month after Katrina's landfall, the bottomland forest displayed substantial recovery in forest foliage (Figure 3). The CFI distribution became clearly bimodal indicating the initial differences in impact severity and bottomland recovery rates. Overall, cypress forest recovery was more dramatic than that of bottomland forests (Figure 3). The cypress forest CFI histogram closely

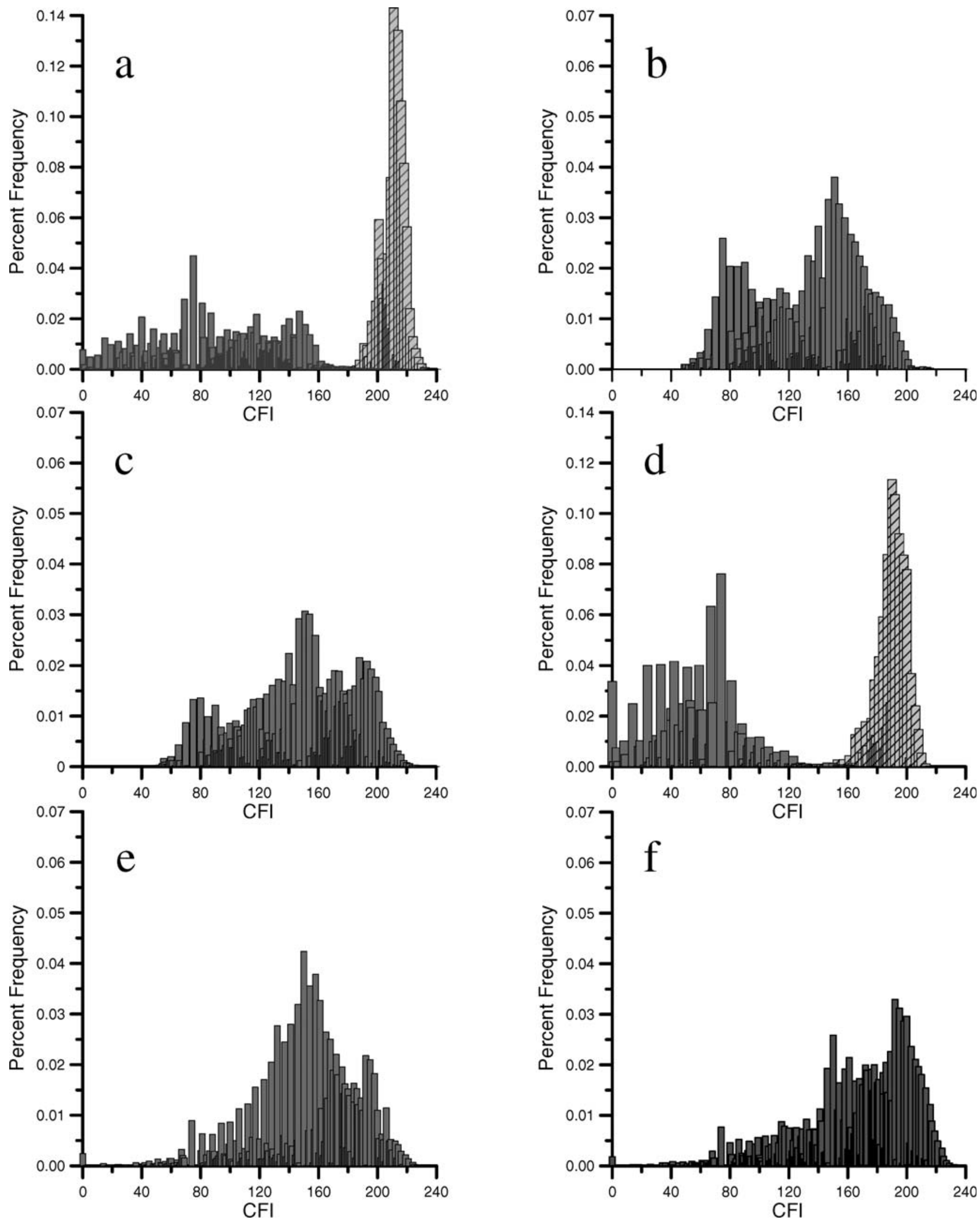

Figure 3. Frequency histograms depicting distributions of canopy foliage index (CFI) per (A, B, and C) bottomland hardwood and (D, E, and F) cypress forests. Light grey bars with diagonal lines portray distributions before Hurricane Katrina and dark grey bars depict posthurricane distributions. CFI magnitudes are directly comparable in all histograms. The hardwood distribution A) immediately after the hurricane ranges from about 0 to nearly 160 with a peak around 80 CFI, B) on 09-10-05 exhibits two peaks at 80 and near 150 CFI and C) on 25-10-05 exhibits the same peaks and an addition peak near 200 CFI. The cypress distribution D) immediately after the hurricane range from about 0 to nearly 120 with a peak around 80 CFI, E) on 09-10-05 exhibits two peaks at 150 and a secondary peak near 200 CFI, and F) on 25-10-05 exhibits the same two peaks. Differences in ordinate scales were used to promote clarity.

resembled the highest mode exhibited in the bottomland distribution. The cypress distribution included a minor mode displaying prehurricane CFI's.

By late October 2005, the bottomland CFI distribution had coalesced into three modes (Figure 3). The CFI peak frequencies of the two lower modes were about the same as portrayed in the early October 2005 frequency histogram, although a portion of the lowest mode members in the early October distribution had migrated to the next higher mode or the middle mode. More noticeably, the upper mode of the bottomland distribution from 2 weeks previous had split into two modes. The

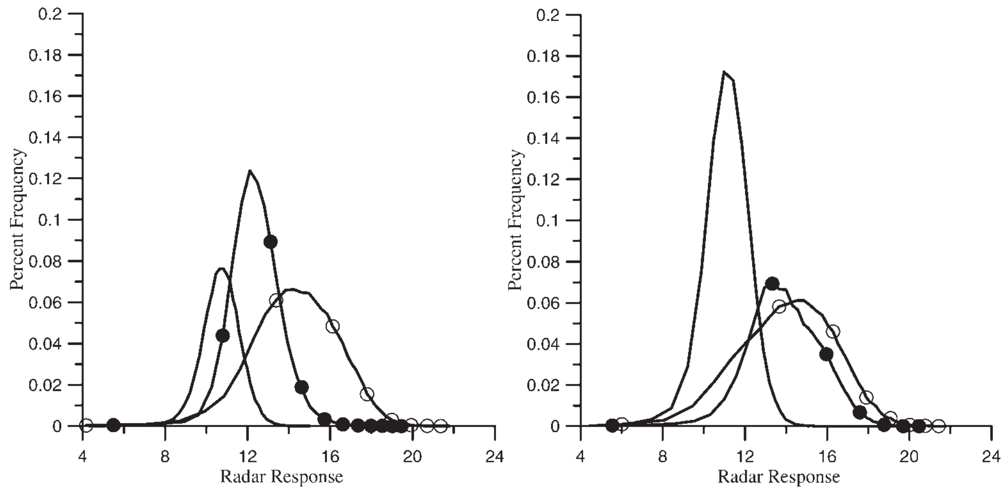

Figure 4. Radar response frequency curves per forest class for 7 August 2004 (solid line), 2 September 2005 (open circle), and 19 September 2005 (filled circle). (left) bottomland hardwood forest. (right) cypress forests. Note lack of modal features.

middle mode reflected the highest mode in the early October CFI histogram whereas the highest late October mode represented bottomland stands exhibiting near prehurricane CFI's. By late October, the early October distribution of the cypress forest had separated into three modes with a large portion of cypress stands reaching or slightly surpassing pre-Hurricane Katrina levels. A lower middle mode occurred at the majority mode peak expressed in the early October histogram whereas a portion of the cypress forest recovery continued to lag behind. In general, about 1.5 months after Hurricane Katrina's landfall, to a greater or lesser extent, some portions of all observed forests had recovered to conditions near to or existent before the hurricane's landfall. Although a part of all forests had nearly recovered in terms of CFI, both the bottomland and cypress forest recoveries were divided into groups exhibiting different recovery rates.

Radar Mapping of Wetland Forest Impact and Recovery. In contrast to the dramatic decrease in the optical measure of canopy condition (CFI), radar responses increased throughout almost all observed wetland forest type classes immediately after Hurricane Katrina's landfall (Figures 4 and 5a). From just after until about three weeks after landfall, mean radar responses remained nearly constant in the cypress but decreased to nearer prehurricane levels in the bottomland forests (Figure 4). The overall decrease combined a fair stability in lightly impacted and most severely impacted bottomland forest stands and a fairly dramatic decrease in the remaining bottomland forest (Figure 5b). Compared to prehurricane responses, by the latter part of September, radar responses remained slightly higher in the bottomland forest and higher in the cypress forests (Figures 4 and 5c). Radar responses from an additional image collected 1 year earlier, but within a few days of the last radar acquisition (3 weeks after landfall), confirmed the radar response changes that resulted from Hurricane Katrina, which were particularly evident in the cypress forest (Figure 6).

Another difference between the CFI and the radar backscatter responses after Hurricane Katrina's landfall was that the radar response histograms representing each of the forest types did not clearly exhibit multiple groups. Although the histogram representations of the radar responses per forest class remained fairly unimodal, the ranges associated with the responses increased in all forest types (Figure 4). The ratio of standard deviation and mean (std/mn) as a measure of relative variance increased from about 25% before landfall to nearly 40% a month after Katrina's landfall.

Modal Analyses of CFI Frequency Histograms. Cypress forest patterns of recovery between early and late October 2005 showed that the percent occurrences in the lower mode decreased relative to the higher mode (Figures 3 and 2c). In terms of forest condition, as the cypress forest recovered, the stands exhibiting higher canopy foliage were increasing at the expense of the lower foliage canopies. Temporal patterns defining the extent of nonrecovering cypress stands were similar to the adjacent fresh marsh. Possibly these regions were misclassified fresh marsh in the GAP wetland forest extent. Bottomland forest patterns also exhibited a three-tiered recovery pattern (Figures 3 and 2c). As the CFI distribution of bottomland forests shifted

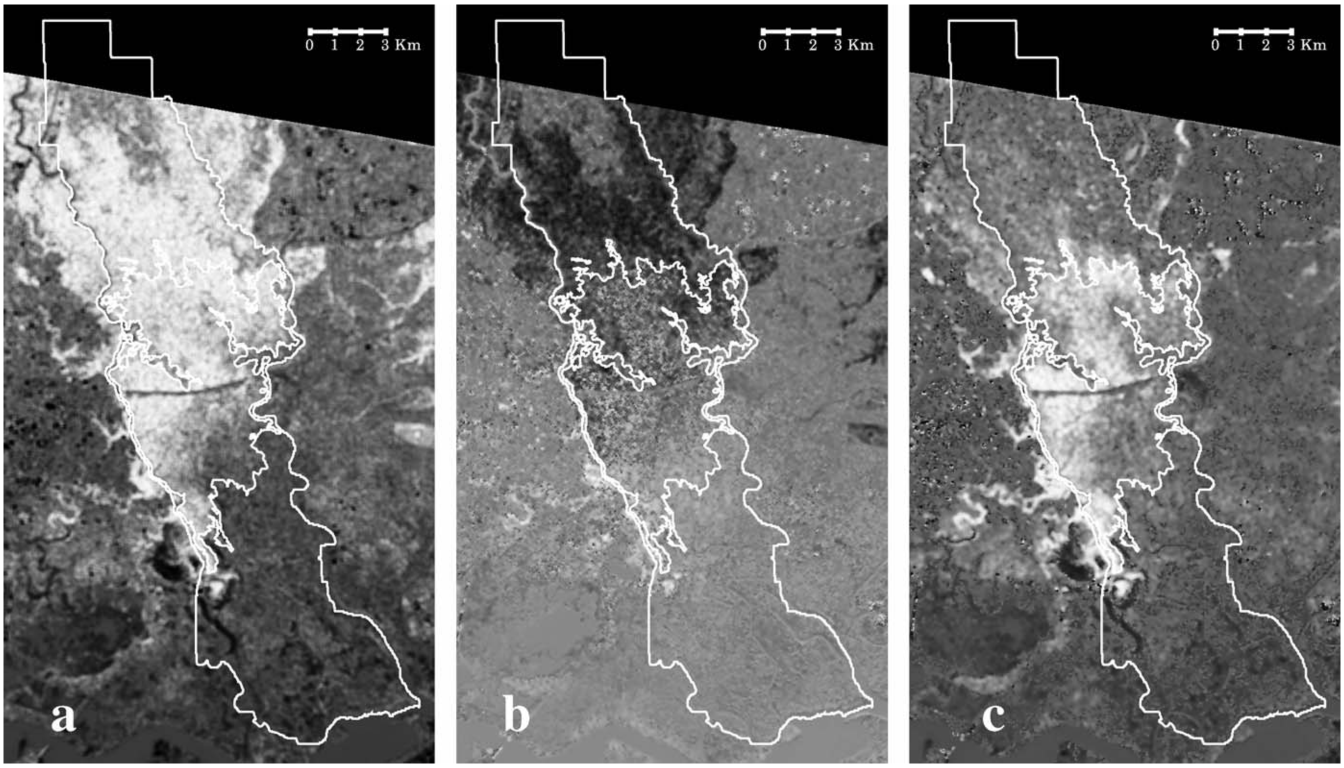

Figure 5. Radar response differences calculated with the RADARSAT-1 images from before and after Hurricane Katrina: A) 2 September 2005–7 August 2004, B) 19 September–2 September 2005, and C) 19 September 2005–7 August 2004. Negative differences increase from dark grey to black while positive differences increase from grey to white. Note the fair stability in lightly impacted northern and most severely impacted southern bottomland forest stands and the fairly dramatic decrease in the spatially intermediate bottomland forest stands. Boundary lines as shown in Figure 2.

higher, the middle mode increased at the expense of the lowest mode. Similar to cypress, this middle mode included forest stands exhibiting relatively higher foliage in early October that had not progressed in their recovery as rapidly as other stands also part of the higher CFI mode in early October. The highest mode represented bottomland forest canopies that had nearly recovered to prehurricane conditions.

An effort was made to determine whether or not the early-October short-term impact and recovery patterns in canopy foliage determined by the optical CFI were associated with stand composition or canopy structural differences as represented by the CFI and radar responses of the prehurricane (non-impacted) forests. Bottomland and cypress forest frequency histograms exhibited little or no differences on the prehurricane CFI and radar response frequency distributions (Figure 7, only cypress shown). Overall, the translation of the early October 2005 impact modes to their prehurricane spatial domain did not clearly depict differences in stand composition or canopy structure that were observable with the 25-m optical and radar images.

DISCUSSION

The impact and recovery information presented by the optical and radar temporal suite of data collected before, just after, and up to two months after Hurricane Katrina's landfall exhibited spatially disparate patterns throughout the wetland forests. Our earlier results provided an expectation of these impact patterns and associations; there was a selective association between impact severity and recovery and forest type (Ramsey et al. 1998a).

Bottomland forest, even though occurring more inland than cypress forests contained some of the most severe and longest lasting impacts found within our short-term response mapping. The Hurricane Andrew study found that bottomland forests could experience severe canopy impacts at tropical storm wind speeds whereas the severest impacts within cypress forests occurred in wind speeds exceeding hurricane strength (Ramsey et al. 2001a). In this study, we expect that the more quickly recovering bottomland forests occurring in the north-northeast portion of our study area suffered moderate to slight impacts. In contrast, the south-southwest bottom-

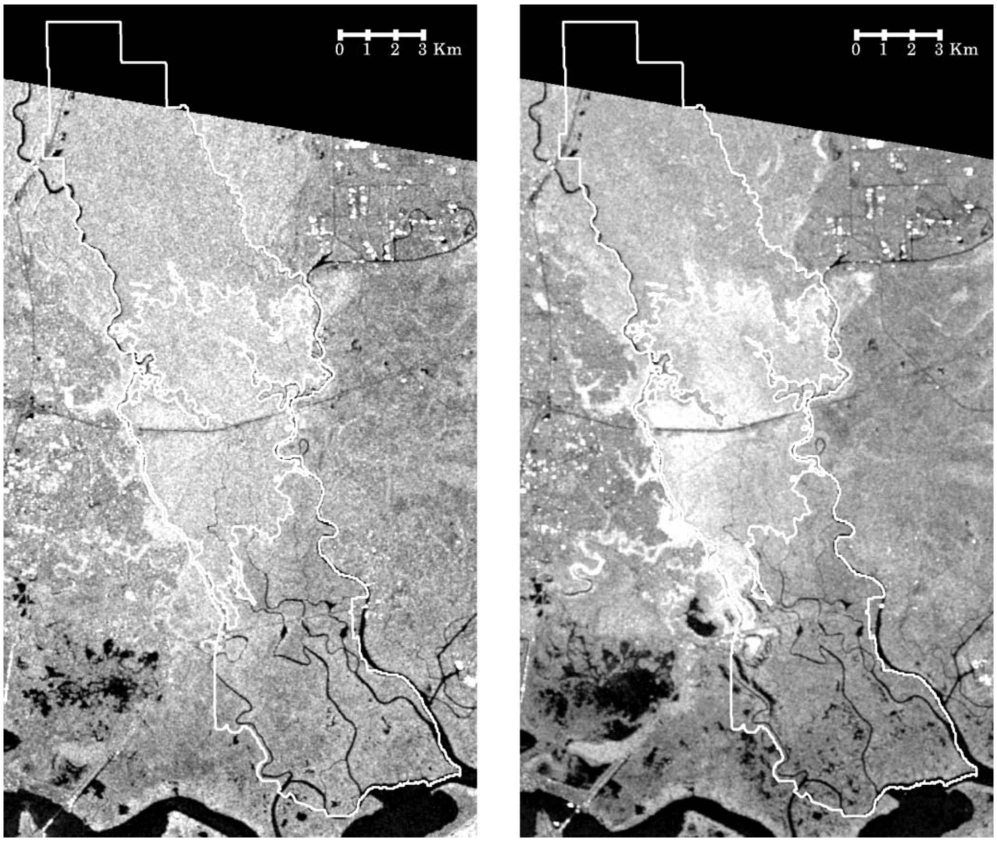

Figure 6. (left) 24 September 2004 and (right) 19 September 2005 images depicting increases in brightness corresponding directly to increases in radar response. Note the overall higher radar responses in the prehurricane versus posthurricane image. Boundary lines as shown in Figure 2.

land forest that exhibited little recovery had sustained widespread leaf-to-limb loss and windthrown and snapped trees. Also following our earlier results, the more southerly cypress forests experiencing the higher wind speeds generally recovered from the dramatic loss of canopy foliage to near or at prehurricane foliage conditions within a short period of time. Their overall rapid recovery substantiated cypress impact and recovery was mostly confined to loss and subsequent regrowth of canopy foliage.

Discernable modes in the bottomland and cypress CFI histograms overlain on the PRWMA provided a spatial context to the disparate recovery patterns exhibited as temporal CFI shifts. Within the bottomland and cypress forests, the analyses revealed spatially coherent regions incorporating similar recovery trends typified the PRWMA forests. The spatial continuity versus a more mixed or heterogeneous spatial pattern suggested that stand characteristics possibly linked to environmental condition, such as flood frequency, partly controlled the recovery patterns. This connection was further supported by the spatial progression of recovery, which spread from a core of stands exhibiting rapid recovery to adjacent stands over time. Recovery trends were spatially associated.

To further elucidate whether or not disparate recovery patterns exhibited in the bottomland and cypress forests were related to the non-impacted forest structural differences, modal features exhibited on their respective impact frequency histograms were transferred to their spatial coverage and conformed to the common spatial database. The same overlay procedures were used to isolate prehurricane optical and radar responses within impact and recovery zones identified in the posthurricane mapping. Even though recovery analyses indicated the existence of different large and contiguous stands in the bottomland and cypress forests, resultant histograms showed little difference in prehurricane optical and radar responses associated with posthurricane impact severities. As judged by these satellite optical and radar image data analyses, the bottomland or cypress stand compo-

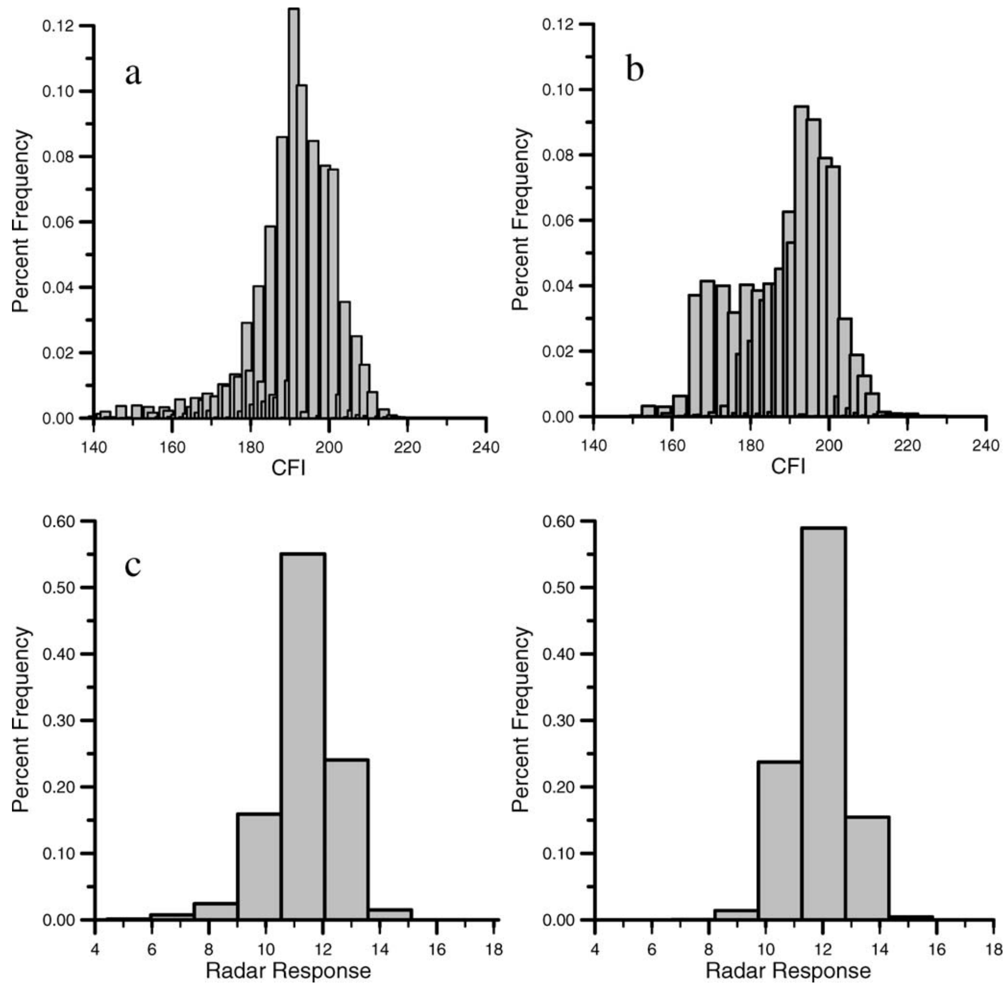

Figure 7. Lower and upper modal responses exhibited on the early (09-10-05) October cypress canopy foliage index (CFI) frequency histogram translated onto the prehurricane (a-lower and b-upper) optical-CFI and (c-lower and d-upper) radar images. Both lower and upper modal distributions representing different posthurricane impact and recovery responses were similar in the prehurricane cypress forest.

sitions or canopy structures did not clearly influence impact and recovery patterns.

In addition, optical analyses of cypress foliage recovery seemed somewhat incompatible with posthurricane elevated radar responses. By 9 October 2005, optical analyses indicated full foliage recovery within cypress stands that exhibited elevated radar responses from Katrina impact through 19 September 2005. Foliage increase enhances volume returns and thereby diminishes double bounce returns that tend to enhance overall radar response. Examples of how volume attenuation of double bounce returns decrease the overall radar response are illustrated in the prehurricane radar response histograms and images (Figures 4, 6, and 7). Although the optical image collection predated the radar image collection by 20 days, canopy foliage regrowth should have noticeably attenuated the radar response. Either regrowth was severely limited up to the last radar image collection, or the new growth was not as effective as mature leaves in attenuating the radar penetration through cypress canopy.

As observed in a previous study of forest responses to intense storm impacts (Ramsey et al. 1997), the copious new growth or ''spring-like bloom'' of leaves produced as a result of defoliation were brighter green and smaller than late summer leaves occurring just previous to impact. The brightness could have augmented the canopy greenness values over a similar number of leaves in the precursor canopy. In that case, canopy greenness could have increased while the canopy remained more transparent to the radar-transmitted and reflected responses enhancing the double bounce returns. Clear determinations of what return mechanism and therefore what physical condition of the canopy causes these abnormal responses requires the collection and processing of ground-based canopy structure measurements and fully polarimetric SAR images (Pope et al. 1997) straddling the time period before and after storm impact.

CONCLUSION

The time sequence of optical and radar image data collected before, a few days after, and about 3 weeks after Hurricane Katrina's landfall emphasized differences in the rates of recovery of the bottomland and cypress forests. The rapid recovery of the cypress forests indicated that impacts were for the most part limited to loss of stems and leaves. In the bottomland forests, the fairly quick recovery of the northern stands implied fairly light impact limited to some portion of foliage and stem loss. The more moderately impacted bottomland forests lost a higher proportion of foliage, stems, and branches and had downed trees. The nonrecovery of stands occupying the most southern bottomland stands alluded to the decimation of the canopy foliage accompanied by loss of branches and widespread tree fall. As represented on the pre-Hurricane Katrina 25-m optical and radar response images, impact patterns overlaid on the bottomland and cypress forests did not suggest that prehurricane differences in forest structure existed that would explain the spatial disparity in impact. Rather, recovery patterns suggested that multiple, large, and contiguous stands existed in the bottomland and cypress forests that differed in stand structure and possibly environmental condition. These differences were not discernable in the preimpacted forests.

In this study, we advanced comparability of hurricane impact and recovery mapping to wetland forest type mapping. Although differences existed, we documented that the nearly continuous coverage offered by radar can provide impact and recovery mapping and monitoring information at the forest stand level that is generally compatible with optical satellite mapping. Even though generally compatible, important differences were observed where radar provided higher sensitivity related to canopy recovery, particularly in the cypress forest. Improved consistency of regional to stand-level information was obtained by combining optical and radar satellite image data. Afforded spatial scales appropriate for mapping stand features, we were able to directly combine the short-term recovery and initial impact severity mapping information to deduce the types of forest stand damage caused by Hurricane Katrina. Even though cypress forests underwent some of the highest wind speeds, damage in those forests was largely limited to foliage loss. Bottomland forest, progressively experiencing lower wind speeds, incorporated a range of damage from partial foliage loss to downed trees. As expected, the most severe stand damage occurred at the more coastal extent of the bottomland forest; however, the impact and recovery patterns suggested that impact severity was associated with a difference in stand structure, possibly related to an environmental condition that was not revealed in the prehurricane 25-m optical and radar mapping. Ongoing studies are further pursuing the association of differential impact and forest type and structure and regeneration processes.

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LITERATURE CITED

Baran, I. 2004. Advanced satellite radar interferometry for small-scale surface deformation detection. Doctoral Thesis. Western Australia School of Mines, Department of Spatial Sciences, Curtin University of Technology, Bentley, Australia.

Boose, E., D. Foster, and M. Fluet. 1994. Hurricane impacts to tropical temperate forest landscapes. Ecological Monographs 64:369–400.

Campo, Kimberly D. and T. M. Rickenbach. 2006. Eyewall evolution of Hurricane Katrina near landfall using NEXRAD reflectivity and radial velocity data. *In* Proceedings of the 27th

American Meteorological Society Conference on Hurricanes and Tropical Meteorology, 24–28 April 2006. Monterey, California. http://ams.confex.com/ams/pdfpapers/108456.pdf

Chabreck, R. 1970. Marsh zones and vegetative types in the Louisiana coastal marshes. Ph.D. Dissertation. Louisiana State University, Baton Rouge, LA, USA.

Chambers, J., J. Fisher, H. Zeng, E. Chapman, D. Baker, and G. Hurtt. 2007. Hurricane Katrina's carbon footprint on U.S. Gulf Coast forest. Science 318(5853):1107.

Dobson, C., F. Ulaby, and L. Pierce. 1995. Land-cover classification and estimation of terrain attributes using synthetic aperture radar. Remote Sensing of Environment 51:199–214.

Elachi, C. T. 1988. Spaceborne Radar Remote Sensing: Applications and Techniques. IEEE Press, New York, NY, USA.

Haack, B. N. and E. T. Slonecker. 1994. Merged spaceborne radar andthematic mapper digital data for locating villages in Sudan. Photogrammetric Engineering and Remote Sensing 60:1253–57.

Hartley, S., R. Pace III, J. B. Johnston, M. Swan, C. O'Neil, L. Handley, and L. Smith. 2000. A GAP analysis of Louisiana. U.S. Department of the Interior, U.S. Geological Survey, Lafayette, LA, USA. Final report and data (2 CD-ROMs).

Jensen, J. 2000. Remote Sensing of the Environment. An Earth Resource Perspective. Prentice Hall, Englewood Cliffs, NJ, USA.

Jensen, J., E. Ramsey, H. Mackey, E. Christensen, and R. Sharitz. 1987. Inland wetland change detection using aircraft MSS data. Photogrammetric Engineering and Remote Sensing 53:521–528.

Kasischke, E. and L. Bourgeau-Chavez. 1997. Monitoring south Florida wetlands using ERS-1 SAR imagery. Photogrammetric Engineering and Remote Sensing 63:281–91.

Klemas, V., J. Dobson, R. Ferguson, and K. Haddad. 1993. A coastal land cover classification system for the NOAA Coastwatch Change analysis project. Journal of Coastal Research 9:862–72.

Lewis, A., F. Henderson, and D. Holcomb. 1998. Radar fundamentals: the geoscience perspective. p. 131–81. *In* F. Henderson and A. Lewis (eds.) Principles and Applications of Imaging Radar. John Wiley & Sons, Inc, New York, NY, USA.

Louisiana Department of Wildlife and Fisheries, Pearl River Wildlife Management Area. n.d. http://www.wlf.louisiana.gov/hunting/wmas/wmas/list.cfm?wmaid=35. 2 October 2008.

Lozano-Garcia, F. and R. Hoffer. 1993. Synergistic effects of combined Landsat-TM and SIR-B data for forest resources assessment. International Journal of Remote Sensing 14:2677–94.

Lu, Z., M. Crane, O. Kwoun, C. Wells, C. Swarzenski, and R. Rykhus. 2005. C-band radar observes water-level change in swamp forests. Eos, Transactions, American Geophysical Union 86(14):141–44.

Lu, Z. and O. Kwoun. 2008. Radarsat-1 and ERS interferometric analysis over southeastern coastal Louisiana: implication for mapping water-level changes beneath swamp forests. IEEE Transactions in Geoscience of Remote Sensing 46:2167–84.

Lunetta, R., J. Lyon, B. Guindon, and C. Elvidge. 1998. North American landscape characterization dataset development and data fusion issues. Photogrammetric Engineering and Remote Sensing 64:821–29.

Lyon, J. and J. McCarthy. 1981. Seasat imagery for detection of coastal wetlands, p. 1475–85. *In* Proceedings of the Fifteenth International Symposium on Remote Sensing of Environment. ERIM, ANN Arbor, MI, USA.

Michener, W. K., E. R. Blood, K. L. Bildstein, M. M. Brinson, and L. R. Gardner. 1997. Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. Ecological Applications 7:770–803.

Middleton, B. A. 2009. Regeneration dynamics of coastal marshes impacted by Hurricane Katrina along the Gulf Coast of Louisiana.

PCI Geomatics. 1998. Using PCI Software, Version 6.3 EASZIPACE. PCI Geomatics, Richmond Hill, Ontario, Canada (software documentation).

Pope, K., E. Rejmankova, J. Paris, and R. Woodruff. 1997. Detecting seasonal flooding cycles in marshes of the Yucatan Peninsula with SIR-C polarimetric radar imagery. Remote Sensing of Environment 59:157–66.

Ramsey, E. III. 1998. Radar remote sensing of wetlands, p. 211–14. *In* R. Lunetta and C. Elvidge (eds.) Remote Sensing Change Detection: Environmental Monitoring Methods and Applications. Ann Arbor Press Inc., Ann Arbor, MI, USA.

Ramsey, E. III. 2005. Remote sensing of coastal environments. p. 797–803. *In* M. L. Schwartz (ed.) Encyclopedia of Coastal Science, Encyclopedia of Earth Sciences Series. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Ramsey, E. III, D. Chappell, and D. Baldwin. 1997. AVHRR imagery used to identify Hurricane Andrew damage in a forested wetland of Louisiana. Photogrammetric Engineering and Remote Sensing 63:293–97.

Ramsey, E. III, D. Chappell, D. Jacobs, S. Sapkota, and D. Baldwin. 1998a. Resource management of forested wetlands: hurricane impact and recovery mapped by combining Landsat TM and NOAA AVHRR data. Photogrammetric Engineering and Remote Sensing 64:733–38.

Ramsey, E. III, M. Hodgson, S. Sapkota, and G. Nelson. 2001a. Forest impact estimated with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind field distribution. Remote Sensing of Environment 77:279–92.

Ramsey, E. III, Z. Lu, A. Rangoonwala, and R. Rykhus. 2006. Multiple baseline radar interferometry applied to coastal landscape classification and change analyses. GIScience and Remote Sensing 43:283–09.

Ramsey, E. III, G. Nelson, and S. Sapkota. 1998b. Classifying coastal resources by integrating optical and radar imagery and color infrared photography. Mangroves and Salt Marshes 2:109–19.

Ramsey, E. III, G. Nelson, and S. Sapkota. 2001b. Coastal change analysis program implemented in Louisiana. Journal of Coastal Research 17:55–71.

Ramsey, E. III, G. Nelson, S. Sapkota, S. Laine, J. Verdi, and S. Krasznay. 1999. Using multiple polarization L band radar to monitor marsh burn recovery. IEEE Transactions in Geoscience of Remote Sensing 37:635–639.

Ramsey III, E., A. Rangoonwala, and R. Ehrlich. 2005. Mapping the invasive species, Chinese Tallow with EO1 satellite Hyperion hyperspectral image data and relating tallow percent occurrences to a classified Landsat Thematic Mapper landcover map. International Journal of Remote Sensing 26:1637–57.

Ramsey, E. III. and M. Strong. 2000. Conveying multiple, complex themes and classes for natural resource assessments. Geocarto International 15(2):29–35.

Rebillard, P. and D. Evans. 1983. Analysis of coregistered Landsat, Seasat and SIR-A images of varied terrain types. Geophysical Research Letters 10:277–80.

Sader, S. A. and J. C. Winne. 1992. RGB-NDVI color composites for visualizing forest change dynamics. International Journal of Remote Sensing 13:3055–67.

Tou, J. and R. Gonzalez. 1974. Pattern Recognition Principles. Addison-Wesley, Reading, MA, USA.

Treuhaft, R., G. Asner, B. Law, and S. Tuyl. 2002. Forest leaf area density profiles from the quantitative fusion of radar and hyperspectral data. Journal of Geophysical Research 107(D21): 7-1–7-13.

Ulaby, F. T. and M. C. Dobson. 1989. Handbook of Radar Scattering Statistics for Terrain. Artech House, Norwood, MA, USA.

Ustin, S. L., C. A. Wessman, B. Curtiss, E. Kasischke, J. Way, and V. Vanderbilt. 1991. Opportunities for using the EOS imaging spectrometers and synthetic aperture radar in ecological models. Ecology 72:1934–45.

Wardlow, B. and S. Egbert. 2003. A state-level comparative analysis of the GAP and NLCD land-cover data sets. Photogrammetric Engineering and Remote Sensing 69:1387–97.

Waring, R., J. Way, E. Hunt, Jr., L. Morrissey, K. Ranson, J. Weishampel, R. Oren, and S. Franklin. 1995. Imaging radar for ecosystem studies. BioScience 45:715–23.

Wikimedia Commons. n.d. Hurricane Katrina winds 1500ut-c29Aug05 landfall MS.gif, http://commons.wikimedia.org/wiki/Image:Hurricane_Katrina. 30 September 2008.

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