3-2009

Water Level Observations in Mangrove Swamps During Two Hurricanes in Florida

William Conner
Clemson University, wconner@clemson.edu

Thomas W. Doyle
US Geological Survey

Terry J. Doyle
US Fish and Wildlife Service

Christopher Swarzenski
US Geological Survey

Andrew S. From
US Geological Survey

See next page for additional authors

Recommended Citation

Please use publisher's recommended citation.

Authors
William Conner, Thomas W. Doyle, Terry J. Doyle, Christopher Swarzenski, Andrew S. From, Richard H. Day, and Ken W. Krauss

WETLANDS, Vol. 29, No. 1, March 2009, pp. 142–149

NOTE

WATER LEVEL OBSERVATIONS IN MANGROVE SWAMPS DURING TWO HURRICANES IN FLORIDA

Ken W. Krauss[1], Thomas W. Doyle[1], Terry J. Doyle[2,6], Christopher M. Swarzenski[3], Andrew S. From[4], Richard H. Day[1], and William H. Conner[5]

[1]*U.S. Geological Survey, National Wetlands Research Center, 700 Cajundome Blvd., Lafayette, Louisiana, USA 70506. E-mail: kkrauss@usgs.gov*

[2]*U.S. Fish and Wildlife Service, Ten Thousand Islands National Wildlife Refuge, 3860 Tollgate Boulevard, Suite 300, Naples, Florida, USA 34114*

[3]*U.S. Geological Survey, Louisiana Water Science Center, 3535 South Sherwood Forest Blvd., Suite 120, Baton Rouge, Louisiana, USA 70816*

[4]*IAP World Services, Inc., USGS National Wetlands Research Center, 700 Cajundome Blvd., Lafayette, Louisiana, USA 70506*

[5]*Clemson University, Baruch Institute of Coastal Ecology and Forest Science, P.O. Box 596, Georgetown, South Carolina, USA 29442*

[6]*Present address: U.S. Fish and Wildlife Service, Division of Migratory Bird Management, 4401 N. Fairfax Dr Arlington, Virginia, USA 22203*

Abstract: Little is known about the effectiveness of mangroves in suppressing water level heights during landfall of tropical storms and hurricanes. Recent hurricane strikes along the Gulf Coast of the United States have impacted wetland integrity in some areas and hastened the need to understand how and to what degree coastal forested wetlands confer protection by reducing the height of peak water level. In recent years, U.S. Geological Survey Gulf Coast research projects in Florida have instrumented mangrove sites with continuous water level recorders. Our ad hoc network of water level recorders documented the rise, peak, and fall of water levels (± 0.5 hr) from two hurricane events in 2004 and 2005. Reduction of peak water level heights from relatively in-line gages associated with one storm surge event indicated that mangrove wetlands can reduce water level height by as much as 9.4 cm/km inland over intact, relatively unchannelized expanses. During the other event, reductions were slightly less for mangroves along a river corridor. Estimates of water level attenuation were within the range reported in the literature but erred on the conservative side. These synoptic data from single storm events indicate that intact mangroves may support a protective role in reducing maximum water level height associated with surge.

Key Words: forested wetlands, marsh, surge, tropical storm, Hurricane Charley, Hurricane Wilma

INTRODUCTION

Recent attention among wetland scientists has been directed toward understanding the impacts of hurricanes on coastal wetlands and other aquatic ecosystems (e.g., Conner et al. 1989, Michener et al. 1997, Cahoon 2006, Steward et al. 2006, Chatenoux and Peduzzi 2007). Of all wetland ecosystems studied, mangroves occupy some of the most vulnerable landscape positions to hurricanes. Indeed, hurricanes can alter the structure and function of mangrove vegetation during and shortly after impact (Craighead and Gilbert 1962, Stoddart 1963, Lugo et al. 1983, Roth 1992, Smith et al 1994, Doyle et al. 1995, Cahoon et al. 2003, Krauss et al. 2005), but these same ecosystems often recover structural integrity within decades (Ward et al. 2006), in part, owing to a reduced susceptibility of smaller statured trees to wind throw, abundant below-ground nutrient stores, rapid availability of those nutrients and high efficiency of use after disturbance, redundancy of keystone species, and the rapid re-establishment of regeneration pools (Roth 1992, Alongi 2008). It is hypothesized that persistent structural integrity of mangroves protects coastlines from repetitive storm surge or strong wind events (Dahdouh-Guebas et al. 2005, Danielsen et al. 2005); however, few data are available for making specific determinations.

Table 1. Past and current estimates of wave height reduction by Gulf Coastal wetlands during hurricane passage.

Wave Height Reduction (cm/km)	Habitat	Reference
4.4–5.0	Wetland	COE 2006
4.2–4.8	Marsh	LDNR 1998
6.3	Buffering wetlands	COE 2005
6.3–18.9	Wetland	COE 2002
6.9	Wetland complex[a]	HD 1965
7.0	Marsh	COE ND
4.2	Riverine mangrove	Current study
9.4	Mangrove-interior marsh	Current study

[a] Including wooded ridges that parallel the coast

The capacity for suppression of peak water levels during storms in wetlands depends, among other variables, on plant stem density, average root and stem diameter, topographic slope, local bathymetry, wave characteristics, tidal stage upon impact, direction of storm track, and specific meteorological characteristics of the storm (Alongi 2008). Hence, blanket assessments of suppression applicable to all wetland types are very difficult to make (Resio and Westerink 2008). Documents that provide water level height suppression values typically target marsh and are in the form of fact sheets, white papers, and government reports (Table 1), and the scientific basis for these reports is often uncertain. Published estimates range from 4.2 cm to 18.9 cm reduction in peak water levels for every linear km of wetland (HD 1965, LDNR 1998, COE 2002, COE 2005, COE 2006, COE ND).

A storm surge acts like a very high tide event that fosters a temporary increase in sea level above that expected from a normal high tide (Lowe et al. 2001). Storm surges result from reduced atmospheric pressure and the action of strong winds (Wells 1997), fed by a gently rising ocean floor and variable shoreline architecture (indented vs. open), to produce an unpredictable but rapidly rising tide (House Document (HD) 1965, Resio and Westerink 2008). Peak water level is only a component of surge, even though popular communication often links the two interchangeably.

Although peer reviewed accounts of peak water level suppression are rare, two primary sources of information exist. House Document (1965) provides an account of overland surge elevations from 7 storm events circa 1907–1957. Multiple observations ($N \sim 42$) from Louisiana as far as 50 km inland during actual surge events revealed that coastal wetlands, including wooded ridges parallel to the coast, suppress peak wave height by approximately 6.9 cm/km inland. Additional scientific accounts of water level height suppression came from coastal Louisiana during the passage of Hurricane Andrew (1992). Surge amplitude registered by in-stream tidal gages along the Houma Navigation Canal decreased from 2.8 m to 1.0 m over a distance of 37 km during one surge event (Swenson 1994), while in-stream gages from another location registered a 1.3 m decrease in water level height over approximately 31 km (p. 55, LDNR 1998). Water level height suppression was attributed to the influence of marsh, which made up a large percentage of the traversed habitat between the two tidal gage sets, with estimates of surge suppression varying conservatively from approximately 4.3 to 4.9 cm/km of marsh (Swenson 1994).

Tide gage data may not accurately assess hurricane impacts because gages are often damaged by surge and wind events, not placed at appropriate locations relative to storm angle, located in-stream and not in-wetland, and without experimental controls. In this paper, we use observations based on measurements from a network of water level recorders in two different mangrove ecosystems that collected continuous water level data during hurricane events in 2004 and 2005.

STUDY SITES

Water level recorders were deployed in a mangrove-interior marsh community within Ten Thousand Islands National Wildlife Refuge (NWR) and in a riverine mangrove swamp along the Shark River (Everglades National Park) in southwestern Florida, USA (Figure 1A). All water level recorders were located on the immediate right side, eyewall edge of their respective storm, positions that are associated with severe winds, surge, and tornadic activity (Jordan et al. 1960, Shea and Gray 1973, Wakimoto and Black 1994).

Mangrove-interior marsh sites in Ten Thousand Islands NWR represented a transition from mixed mangrove (*Rhizophora mangle*, *Laguncularia racemosa*, *Avicennia germinans*) to salt marsh (*Spartina bakeri*, *Distichlis spicata*, *Batis maritima*). Four

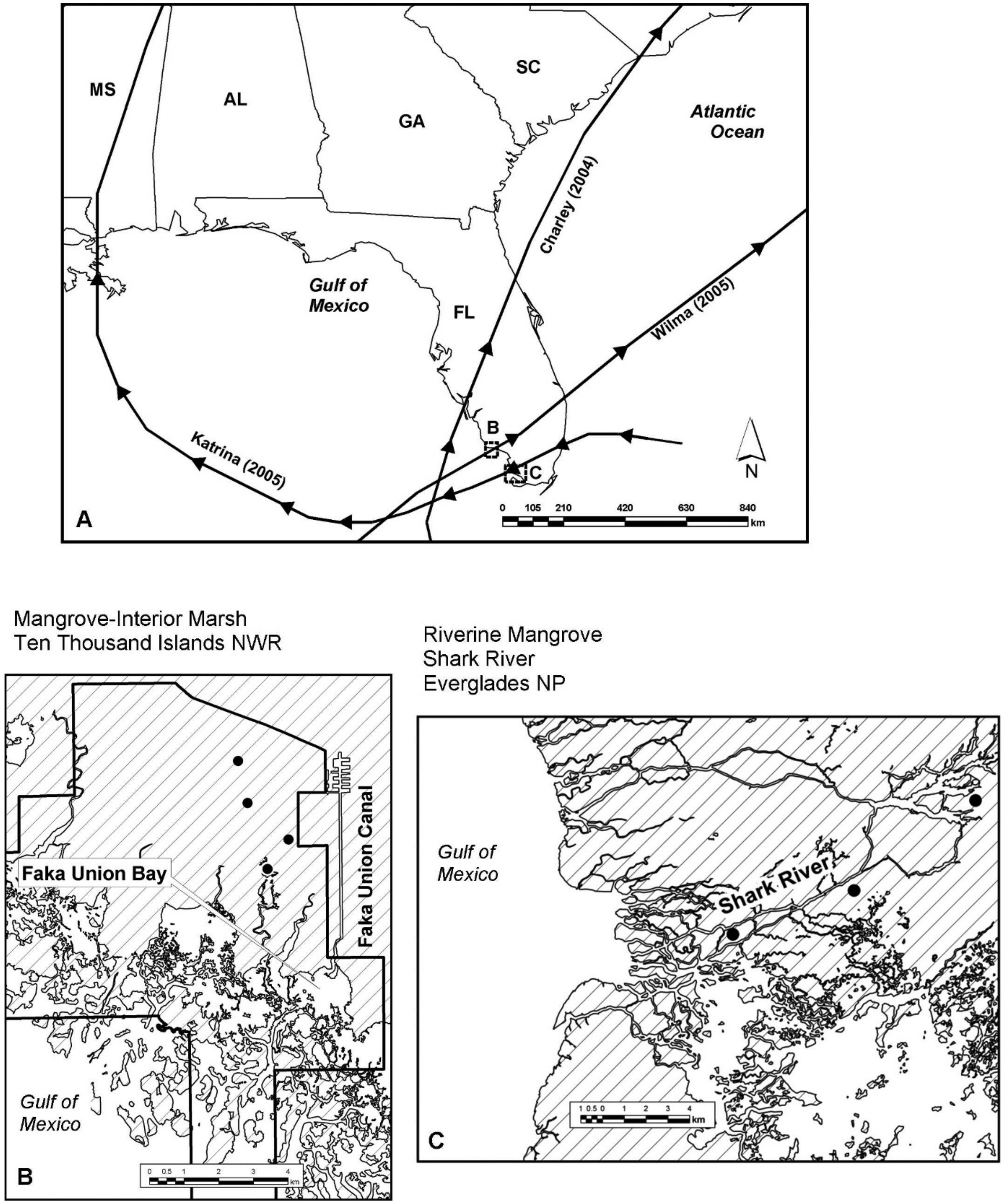

Figure 1. A) Location of interior water level recorder networks relative to the storm tracks of Hurricanes Charley (2004), Wilma (2005), and Katrina (2005) for B) mangrove-interior marsh (Ten Thousand Islands NWR, *demarcated by solid line*) and C) riverine mangrove (Shark River, Everglades NP) sites used for synoptic water level height measurements. Exact locations of water level recorders are depicted by symbols (•) on inserts.

water level recorders were installed approximately in line beginning at a point inside the mangrove forest at a distance of 2.3 km from Faka Union Bay on the Upper Little Wood River. Recorders were then placed at distances of 3.2 km (abrupt mangrove-marsh transition), 4.5 km (marsh), and 5.5 km (marsh) from Faka Union Bay (Figure 1B). These sites were affected by Hurricane Charley, which vectored strong winds over the mangrove-interior marsh of Ten Thousand Islands NWR on August 13, 2004. The storm had maximum sustained winds of 240 km/h at landfall (Wang et al. 2005, Pasch et al. 2005), and was positioned optimally for sending surge through Ten Thousand Islands NWR (Figure 1A, Weisberg and Zheng 2006). Rainfall depths for 3 rain gages in the immediate vicinity of Ten Thousand Islands NWR registered 2.59–6.17 cm on August 13 (DBHydro 2008).

In the riverine mangrove habitat, water level recorders were deployed within interior mangrove locations at distances ranging from 50 to 80 m from the river's edge at river-km 4.1, 9.9, and 18.2 (Figure 1C). These sites are part of the Florida Coastal Everglades Long-Term Ecological Research Network (see Chen and Twilley 1999). Water level recorders were closely coupled to Shark River stage, but were located at distances inland designed to reflect the hydrological cycles specific to backswamp mangrove sites. The Shark River discharges water at 112 m^3/s on average (USGS 2008), and serves as a major drainage conduit for the Everglades (see Bolster and Saiers 2002). Hurricane Wilma (2005), which moved in a northeastern direction over south Florida, passed just north of the Shark River on October 24, 2005, with maximum sustained winds of 195 km/h and crossed the Florida Peninsula in 4.5 h (Pasch et al. 2006). Rainfall depths for three rain gages in the immediate vicinity of the Shark River registered 5.64–10.11 cm on October 24 (G. H. Anderson and T. J. Smith III, U.S. Geological Survey, unpublished data). Hurricane Katrina also affected the area in 2005, but the trajectory registered little effect on water levels within the mangroves along the Shark River (Figure 1A).

METHODS

Water level recorders were installed on sites in 2001 and 2002. Screened PVC pipes were slotted to allow for water movement, inserted into augured 1–1.5 m deep holes, and, when necessary, backfilled with gravel. A combination of sonic and pressure transducer type water level recorders were used (Infinities USA, Inc., Port Orange, FL, USA and Global Water, Inc., Gold River, CA, USA). Water levels were recorded hourly during hurricane events. Peak water levels were not analyzed relative to NAVD88 because of the very different conditions associated with tidal versus non-tidal hydrological characteristics of the two locations. For the mangrove-interior marsh sites in Ten Thousand Islands NWR, peak water level height was calculated as deviation from the antecedent water level condition, or from the 5-h mean prior to the initiation of storm-induced water level change. Peak water level was determined as height above normal high tide for the one site that was solely vegetated by mangroves (especially *Rhizophora mangle*) in Ten Thousand Islands NWR (2.3 km inland). For the riverine mangroves along the Shark River, peak water level height was determined as absolute height above ground level for each location. The slope representing the change in peak water level height with distance inland was determined for each series of recorders and storm using SigmaPlot Version 10.0 (Systat Inc., Point Richmond, CA, USA).

RESULTS AND DISCUSSION

Peak water level height decreased by an average of 4.2 to 9.4 cm per km inland as hurricanes pushed water through mangrove forests at both locations. These data generally agree with the range of peak water level suppression of 4.2 cm to 18.9 cm per km inland reported for other wetland types but err on the conservative side (Table 1). Although increasing relief and complexity of the natural features may influence storm water level height (Resio and Westerink 2008), these influences are difficult to discern.

Peak water level as registered by multiple recorders in Ten Thousand Islands NWR crested at 40 cm above ground level at the abrupt habitat transition from mangrove to marsh, and was attenuated by 16.3 cm relative to antecedent water levels as water passed through approximately 2.3 km of additional marsh from the marsh-mangrove transition to a location 5.5 km inland (Figure 2). The mangrove community, on the other hand, reduced peak water level height from a maximum of 78.6 cm above ground level to a height of 40.0 cm over a distance of 0.9 km. On average, the location of peak water levels traveled at 0.4 km/h (0.1 m/s). Local rainfall had a slight effect on our determination of antecedent water levels for marsh at 5.5 km inland, but the overall water level increase from surge at that location was only 13.3 cm (Figure 2). As water from a storm moves inland, resistance from vegetation, changes in ground elevation, and large amounts of water already ponded within Ten Thousand Islands

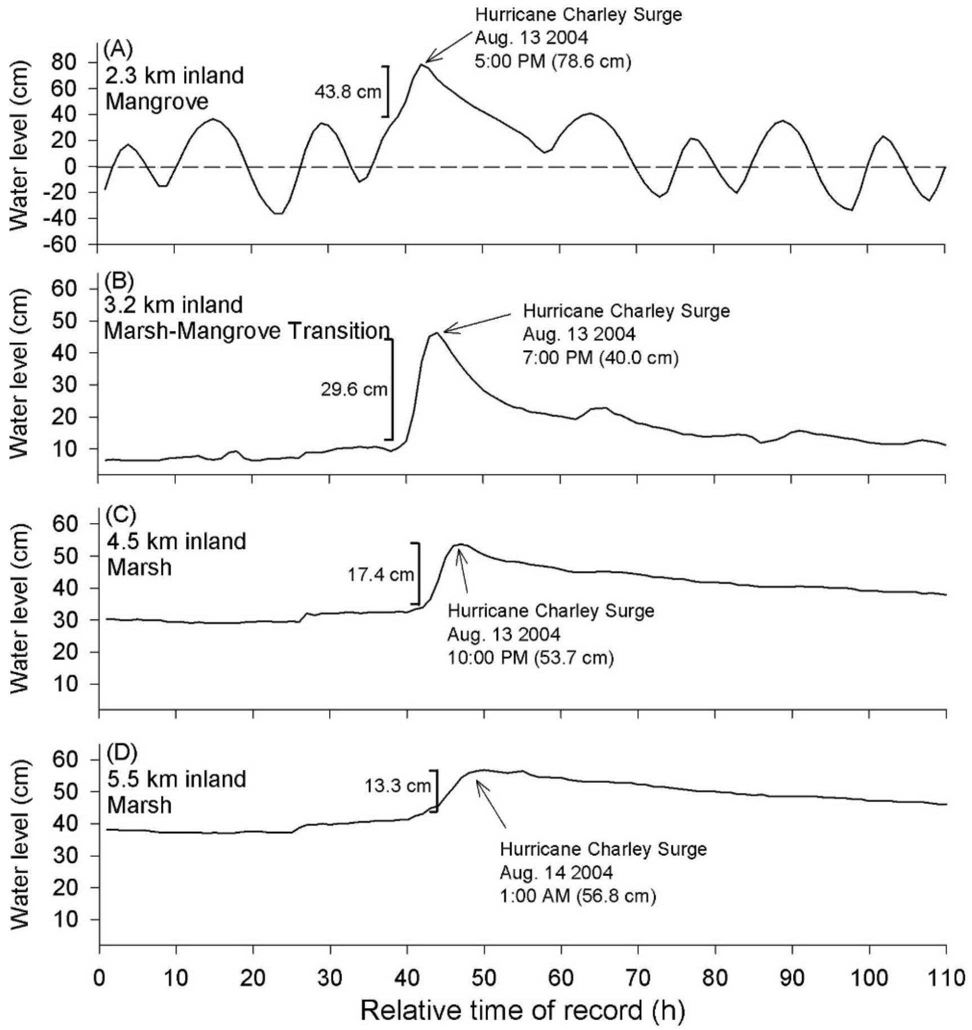

Figure 2. Hydrographs for mangrove-interior marsh sites in Ten Thousand Islands National Wildlife Refuge during the passage of Hurricane Charley (2004). Water level recorders were placed inland A) in a mangrove channel, B) at an abrupt marsh-mangrove transition, C) within a salt marsh at a distance of 4.5 km from Faka Union Bay, and D) within a salt/brackish marsh at a distance of 5.5 km from Faka Union Bay. Note the different *y*-axis scale for (A).

NWR (i.e., antecedent water depth of up to 42 cm) provided at least a component of the physical barrier to surge transgression.

Peak water level heights in the mangroves along the Shark River during Hurricane Wilma ranged from 103 cm at river-km 4.1 to 46 cm at river-km 18.2 (Figure 3). Peak water level might have been higher at river-km 9.9 than at river-km 4.1 as river water backed up; however, the recorder did not register water levels greater than 104 cm at that location. A water level increase of approximately 126 cm was recorded in-stream near river-km 9.9 (Sonderqvist and Byrne 2007). While peak water level resulting from the Hurricane Wilma surge was estimated as at least 5 m at some locations in Everglades National Park (Smith et al. 2009), energy dissipation, debris movement, river discharge, and eddies must have influenced the overall characteristics of hydrological impact considerably.

What we do know, however, is that attenuation in peak water level was approximately 4.2 cm per km inland (ranged from 4.0–6.9 cm per km inland for individual point estimates) along the Shark River during Hurricane Wilma. Values were not truly in-stream as recorders were placed in soil at a distance away from the main river and were surrounded by mangroves. Peak water levels in the mangroves at river-km 18.2 occurred 10 hours after the peak height registered in the mangroves at river-km 4.1, a river distance of 14.1 km (Figure 3). Without accounting for the actual trajectory of surge movement or the influence of local rainfall, the location of peak water level from Hurricane Wilma traveled at approximately 1.4 km/h up river (0.4 m/s). It is unlikely that 5–10 cm of rainfall tremen-

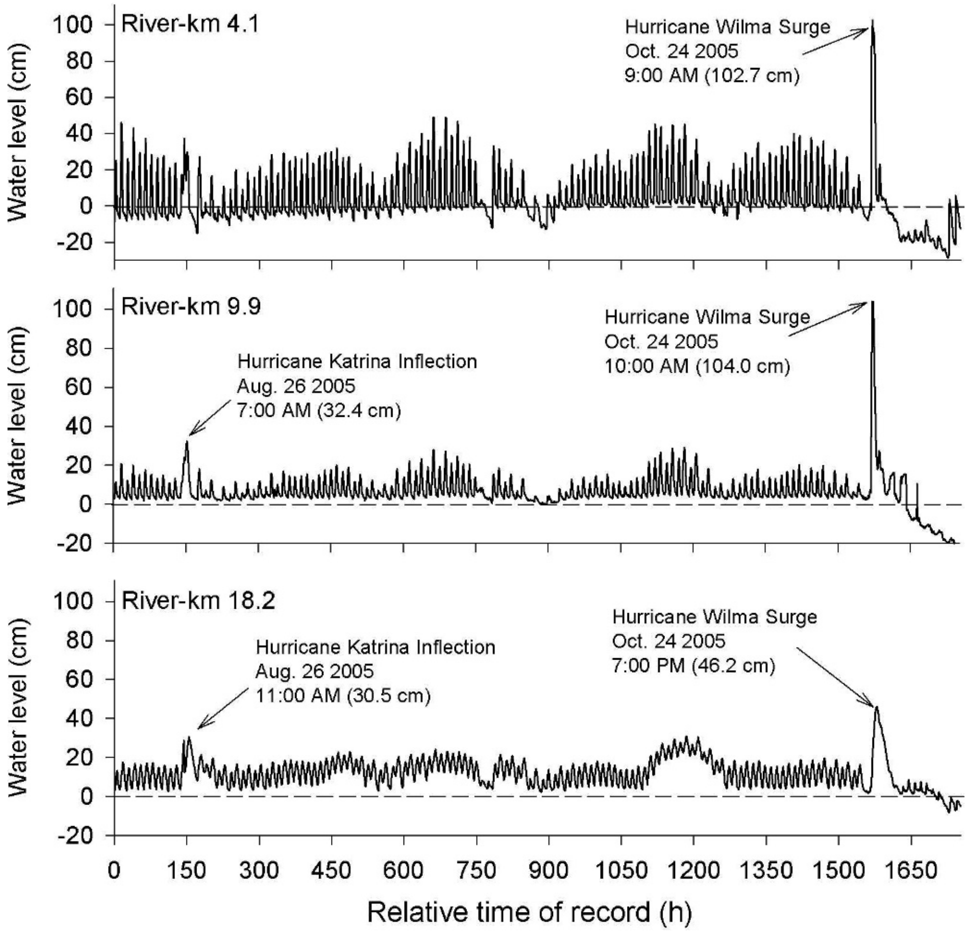

Figure 3. Hydrographs for mangrove sites along the Shark River (Everglades National Park) during Hurricane Katrina (2005) and Hurricane Wilma (2005). Interior forest water level recorders were placed within the mangroves, 50 to 80 m from the river's edge.

dously affected meter-deep water level height profiles in interior mangrove locales along the Shark River.

Peak water level height reduction from Hurricane Wilma was less for mangroves lining a river corridor (Figure 4), perhaps owing to different storm characteristics or the greater ease of surge conveyance through the more open waters of river-associated mangroves. Vegetation can certainly alter stream flow (Novitski 1978), and dense mangroves have even been shown to reduce normal wave heights by 20% over distances of only 100 m (Mazda et al. 1997a). Wave reductions are strongly related to drag, which is a function of vegetation volume and area (Mazda et al. 1997b). The mangroves of Ten Thousand Islands NWR are very dense between water level recorders at locations of 2.3 and 3.2 km from Faka Union Bay and are mostly *Rhizophora*-dominated at that position in the estuary. Although normal wave activity and surge produce different hydrological impacts, past investigation suggests that energy from normal waves can dissipate by 50% when passing through 150 m of *Rhizophora*-dominated forest (Brinkman et al. 1997). Over short distances, however, mangroves gave way to open marsh and to similar reductions in water height during Hurricane Charley.

The different characteristics of the two storms confound overall comparisons. The velocity of peak water level movement through Ten Thousand Islands NWR was low (0.1 m/s) relative to the 0.4 m/s average along the Shark River. For comparison, surge velocity was recorded as 0.42–0.64 m/s in an open back-barrier island tidal flat in Denmark after surge passed over an island during an anomalous storm event in the winter of 1999 (Bartholdy and Aagaard 2001). Where wetlands are absent, energy dissipation can be replaced by erosion and reduced water level height suppression during landfalling storm events (Goodbred and Hine 1995). While our observations indicate that water levels were reduced as storm surge moved through coastal mangrove ecosystems, uncertainty remains over the relative contribution of mangroves

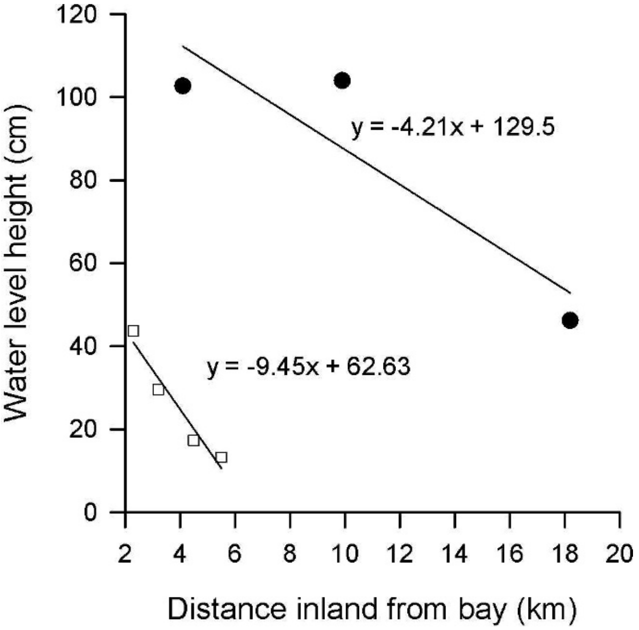

Figure 4. Trend analysis of wave height reduction from riverine mangrove (*filled circles*) and mangrove-interior marsh (*unfilled boxes*) during the passage of Hurricane Wilma (2005) and Hurricane Charley (2004), respectively.

over other wetland types, open water, or microtopographic relief along the Gulf Coast over similar distances.

ACKNOWLEDGMENTS

We thank Daniel Kroes, Torbjörn Törnqvist, Eric Swenson, Thomas J. Smith III, Gordon H. Anderson, Beth A. Middleton, and one anonymous reviewer for helpful comments on an earlier version of this manuscript. Jason K. Sullivan, Edward Castañeda, Mike Barry, and Russell J. Walters assisted with water level recorder installation and maintenance in south Florida, and Gary P. Shaffer and Linda Broussard provided references for storm surge estimates. This material is based upon work supported by the USGS Climate Change Science Program, USGS Priority Ecosystem Science Program, NPS Critical Ecosystems Initiative, and CSREES/USDA, under project number SC-1700271. Technical contribution No. 5369 of the Clemson University Experiment Station. Mention of trade names does not constitute endorsement by the U.S. Government.

LITERATURE CITED

Alongi, D. M. 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science 76:1–13.

Bartholdy, J. and T. Aagaard. 2001. Storm surge effects on a back-barrier tidal flat of the Danish Wadden Sea. Geo-Marine Letters 20:133–41.

Bolster, C. H. and J. E. Saiers. 2002. Development and evaluation of a mathematical model for surface-water flow within the Shark River Slough of the Florida Everglades. Journal of Hydrology 259:221–35.

Brinkman, R. M., S. R. Massel, P. V. Ridd, and K. Furakawa. 1997. Surface wave attenuation in mangrove forests. Proceedings of the 13th Australasian Coastal and Ocean Engineering Conference 2:941–79.

COE. N/D. Freshwater Diversion. U.S. Army Corp of Engineers, New Orleans District, Fact Sheet. http://www.mvn.usace.army.mil/pao/bro/FreshwaterDiversion.pdf Accessed online September 14, 2007.

COE. 2002. Water flows through Davis Pond. U.S. Army Corp of Engineers, New Orleans District, News Release. http://www.mvn.usace.army.mil/PAO/RELEASES/DavisPond.pdf Accessed online September 14, 2007.

COE. 2005. Louisiana Coastal Area (LCA) Ecosystem Restoration http://www.mvn.usace.army.mil/PAO/RELEASES/LCAFactSheet_050202.pdf Accessed online September 24, 2007.

COE. 2006. Breaux Act. Coastal Wetlands, Planning, Protection and Restoration Act, Task Force Meeting. http://www.mvn.usace.army.mil/pd/April_12_2006_Task_Force_ Binder.pdf Accessed online September 14, 2007.

Cahoon, D. R. 2006. A review of major storm impacts on coastal wetland elevations. Estuaries and Coasts 29:889–98.

Cahoon, D. R., P. Hensel, J. Rybczyk, K. L. McKee, C. E. Proffitt, and B. C. Perez. 2003. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. Journal of Ecology 91:1093–1105.

Chatenoux, B. and P. Peduzzi. 2007. Impacts from the 2004 Indian Ocean tsunami: analysing the potential protecting role of environmental features. Natural Hazards 40:289–304.

Chen, R. and R. R. Twilley. 1999. Patterns of mangrove forest structure and soil nutrient dynamics along the Shark River Estuary, Florida. Estuaries 22:955–70.

Conner, W. H., J. W. Day Jr., R. H. Baumann, and J. M. Randall. 1989. Influence of hurricanes on coastal ecosystems along the northern Gulf of Mexico. Wetlands Ecology and Management 1:45–56.

Craighead, F. C. and V. C. Gilbert. 1962. The effects of Hurricane Donna on the vegetation of southern Florida. Quarterly Journal of the Florida Academy of Science 25:1–28.

Dahdouh-Guebas, F., L. P. Jayatissa, D. Di Nitto, J. O. Bosire, D. Lo Seen, and N. Koedam. 2005. How effective were mangroves as a defence against the recent tsunami? Current Biology 15:R443–47.

Danielsen, F., M. K. Sørensen, M. F. Olwig, V. Selvam, F. Parish, N. D. Burgess, T. Hiraishi, V. M. Karunagaran, M. S. Rasmussen, L. B. Hansen, A. Quarto, and N. Suryadiputra. 2005. The Asian tsunami: a protective role for coastal vegetation. Science 310:643.

DBHydro. 2008. DBHydro Browser: Stations "ROOK", "COLLISEM", "BCA19". South Florida Water Management District, West Palm Beach, Florida. https://my.sfwmd.gov/portal/page?_pageid=2235,4688582&_dad=portal&_schema=PORTAL Accessed online May 1, 2008.

Doyle, T. W., T. J. Smith III, and M. B. Robblee. 1995. Wind damage effects of Hurricane Andrew on mangrove communities along the southwest coast of Florida, USA. Journal of Coastal Research SI 21:159–68.

Goodbred, S. L., Jr. and A. C. Hine. 1995. Coastal storm deposition: salt-marsh response to a severe extratropical storm, March 1993, west-central Florida. Geology 23:679–82.

House Document (HD). 1965. United States Army Corps of Engineers, Morgan City and vicinity, Louisiana: letter from the Secretary of the Army. United States Congress Serial Set, 1965–1966, Vol. 14-2, Serial 12690-2, House Document No. 167.

Jordan, C. L., D. A. Hurt, and C. A. Lowrey. 1960. On the structure of Hurricane Daisy on 27 August 1958. Journal of Meteorology 17:337–48.

Krauss, K. W., T. W. Doyle, R. R. Twilley, T. J. Smith III, K. R. T. Whelan, and J. K. Sullivan. 2005. Woody debris in the mangrove forests of south Florida. Biotropica 37:9–15.

LDNR. 1998. Coast 2050: Towards a Sustainable Coastal Louisiana. Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority. Louisiana Department of Natural Resources, Baton Rouge, LA, USA.

Lowe, J. A., J. M. Gregory, and R. A. Flather. 2001. Changes in the occurrence of storms surges around the United Kingdom under a future scenario using a dynamic storm surge model driven by the Hadley Centre climate models. Climate Dynamics 18:179–88.

Lugo, A. E., M. Applefield, D. J. Pool, and R. B. McDonald. 1983. The impact of Hurricane David on the forests of Dominica. Canadian Journal of Forest Research 13:201–11.

Mazda, Y., M. Magi, M. Kogo, and P. N. Hong. 1997a. Mangroves as a coastal protection from waves in the Tong King Delta, Vietnam. Mangroves and Salt Marshes 1:127–35.

Mazda, Y., E. Wolanski, B. King, A. Sase, D. Ohtsuka, and M. Magi. 1997b. Drag force due to vegetation in mangrove swamps. Mangroves and Salt Marshes 1:193–99.

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 7:770–801.

Novitski, R. P. 1978. Hydrological characteristics of Wisconsin's wetlands and their influence on floods, stream flow, and sediment. p. 337–88, *In* P. E. Greeson, J. R. Clark, and J. E. Clark (eds.) Wetland Functions and Values: The State of Our Understanding. American Water Resources Association, Minneapolis, MN, USA.

Pasch, R. J., E. S. Blake, H. D. Cobb III, and D. P. Roberts. 2006. Tropical cyclone report: Hurricane Wilma. National Oceanic and Atmospheric Administration, National Hurricane Center, Miami, Florida. http://www.nhc.noaa.gov/pdf/TCR-AL252005_Wilma.pdf Accessed online April 29, 2008.

Pasch, R. J., D. P. Brown, and E. S. Blake. 2005. Tropical cyclone report: Hurricane Charley. National Oceanic and Atmospheric Administration, National Hurricane Center, Miami, Florida. http://www.nhc.noaa.gov/pdf/TCR-AL032004_Charley.pdf Accessed online April 29, 2008.

Resio, D. T. and J. J. Westerink. 2008. Modeling the physics of storm surges. Physics Today 61(9):33–38.

Roth, L. C. 1992. Hurricanes and mangrove regeneration: effects of Hurricane Juan, October 1988, on the vegetation of Isla del Venado, Bluefields, Nicaragua. Biotropica 24:375–84.

Shea, D. J. and W. M. Gray. 1973. The hurricane's inner core region. I. Symmetric and asymmetric structure. Journal of Atmospheric Science 30:1544–64.

Smith, T. J., III, G. H. Anderson, K. Balentine, G. Tiling, G. A. Ward, and K. R. T. Whelan. 2009. Cumulative impact of hurricanes on Florida mangrove ecosystems: sediment deposition, storm surges and vegetation. Wetlands 29: 24–34.

Smith, T. J., III, M. B. Robblee, H. R. Wanless, and T. W. Doyle. 1994. Mangroves, hurricanes, and lightning strikes. BioScience 44:256–62.

Sonderqvist, L. E. and M. J. Byrne. 2007. Monitoring the storm tide of Hurricane Wilma in southwestern Florida, October 2005. U.S. Geological Survey, Reston, VA, USA. Data Series 294.

Steward, J. S., R. W. Virnstein, M. A. Lasi, L. J. Morris, J. D. Miller, L. M. Hall, and W. A. Tweedale. 2006. The impacts of the 2004 hurricanes on hydrology, water quality, and seagrass in the Central Indian River Lagoon, Florida. Estuaries and Coasts 6A:954–65.

Stoddart, D. R. 1963. Effects of Hurricane Hattie on the British Honduras reefs and cays, Oct. 30–31, 1961. Atoll Research Bulletin 95.

Swenson, E. M. 1994. Hurricane Andrew: the Inundation of the Louisiana Coastal Marshes. Report submitted to the Louisiana Department of Natural Resources, Baton Rouge, Louisiana, DNR Contract No. 256081-95-02.

U.S. Geological Survey (USGS). 2008. SOFIA South Florida Information Access Data Exchange, Hydrology Data. USGS Florida Integrated Science Center, Gainesville, FL, USA. http://www.sofia.usgs.gov/exchange/zucker_woods_patino/#Shark Accessed online April 29, 2008.

Wakimoto, R. M. and P. G. Black. 1994. Damage survey of Hurricane Andrew and its relationship to the eyewall. Bulletin of the American Meteorological Society 75:189–200.

Wang, R., M. Manausa, and J. Cheng. 2005. Hurricane Charley Characteristics and Storm Tide Evaluation. Beaches and Shores Resource Center, Institute of Science and Public Affairs, Florida State University, Tallahassee, FL, USA.

Ward, G. A., T. J. Smith III, K. R. T. Whelan, and T. W. Doyle. 2006. Regional processes in mangrove ecosystems: spatial scaling relationships, biomass, and turnover rates following catastrophic disturbance. Hydrobiologia 569:517–27.

Weisberg, R. H. and L. Zheng. 2006. A simulation of the Hurricane Charley storm surge and its breach of North Captiva Island. Florida Scientist 69:152–65.

Wells, N. 1997. The Atmosphere and Ocean. John Wiley, Chichester, UK.

Manuscript received 14 December 2007; accepted 24 September 2008.