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A numerical study of the impact of hurricane-induced storm surge on the Herbert Hoover Dike at Lake Okeechobee, Florida

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Abstract Hurricanes Frances, Jeanne, and Wilma passed over Lake Okeechobee, Florida, in September 2004 and October 2005, respectively. Strong winds caused a large surface seiche on the lake during all three storms. These storms resulted in erosion damage to the Herbert Hoover Dike (HHD) on Lake Okeechobee. In this paper, we use the Fully Adaptive Storm Tide (FAST) model (Kelly et al. in Coast Eng J 57(4):1–30, 2015, Nat Hazards 83:53–74, 2016) to study the response of the lake (in terms of the water level fluctuations and induced currents) to hurricanes Frances, Jeanne, and Wilma. Comparisons of the modeled surface water level with the observations are in overall good agreement for all three hurricanes. The modeled results suggest that the strong currents induced by the storm winds may be the dominant factor controlling the dike erosion observed at the lake side. The locations of erosion damage to the dike are consistent with the modeled high velocity zones during these three storms. In addition, numerical experiments have been conducted with eight hypothetical category 5 hurricanes approaching from different directions to investigate the erosion-prone zones related to high velocities in the vicinity of the dike. The results of the study should help to provide insight into vulnerable reaches of the HHD and inform flood control in the Okeechobee region.

Keywords Storm surge · Lake Okeechobee · Dike failure · Hurricane Frances · Hurricane Jeanne · Hurricane Wilma · Quad-tree · Adaptive mesh refinement

1 Introduction

The catastrophe at the Gulf Coast caused by Hurricane Katrina, especially the levee failure, brought the safety of dikes or levees to the attention of the general public. Breaching of the New Orleans levee was likely caused by stability failure of the foundation soils beneath the earthen embankment (Seed et al. 2005). Lake Okeechobee, located in the center of the South Florida, is the largest subtropical/tropical lake in the southeastern USA. Since the dike around the lake has an earthen base, there is now heightened concern about the potential failure of the surrounding Herbert Hoover Dike (HHD), particularly as Hurricanes Frances, Jeanne, and Wilma passed near the lake in 2004 and 2005. Associated with the high lake level generated by Hurricane Wilma in 2005, the HHD encountered significant dike erosion from the hurricane-generated wave setup, storm surge, and associated strong currents, which carved out flat benches at the lake side slope of the dike (Bromwell et al. 2006a). It was reported that Wilma "carved dramatic gouges into the dike, the largest of which was a 40-foot-thick swathe about 100 feet long near Pahokee" (www.palmbeachpost.com). These cavities on the dike might continue to deteriorate under certain conditions and ultimately lead to dike failure. If the dike does fail, a huge amount of water would flood onto the adjacent land surrounding the lake. The flood would be a disaster and have a direct impact on

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human life, agriculture, property, soils, vegetation, water resources, and habitat in and around the flooded area.

Internal erosion is the most common structural cause of earth levee or dike cavities and failures (Meyer 1971). Previous studies have shown that the surface layer sediment at the foundation of the HHD has a great influence on the stability of the HHD, as it acts to seal the porous limestone and sand foundation deposits (Meyer 1971). Disturbance of this layer by waves and currents might cause sediments to directly penetrate the porous deposits, and then be suspended into the water column. Continuous disturbance would reduce the available sediments to restore the seal. Previous studies have shown that strong winds during Hurricanes Frances and Jeanne disturbed consolidated sediments to a depth of 7–15 cm from the surface while Hurricane Wilma extended the disturbance to a depth of 25 cm (Jin et al. 2011). Concentrations of total suspended solids (TSS) in the water column increased four- to sixfold after the hurricanes. As a result of high TSS concentration, water quality degradation in the lake was also reported in many studies after the 2004 and 2005 hurricanes (Jin and Ji 2005; Ji and Jin 2006; Abtew and Iricanin 2008; James et al. 2008). Moreover, associated with the water level fluctuations generated by the wind on Lake Okeechobee, strong currents are often induced in the bowl-shaped shallow lake (Havens et al. 2001; Ji and Jin 2006; Jin et al. 2011). Strong alongshore currents could exacerbate dike erosion at the lake side by both transporting the sediment eroded by waves and eroding the bank directly. However, there have been very few studies to investigate the possible relationship between the dike internal erosion and strong alongshore currents caused by hurricanes. Most existing studies of erosion were for the open coastal and estuarine sediments, which are loose and different from those around HHD of the lake.

There have been several studies concerning the failure of the HHD (USACE 1955; Langhaar 1951; Kivisild 1954; Kriebel and Dean 1993; Dean and Dalrymple 2002). Field measurement and analytical solutions to the simplified hydrodynamic equations are the principal methods that have been used to investigate the stability and safety of the HHD. The U.S. Army Corps of Engineers (USACE) developed simplified equations governing wind setup to calculate the wind tides and waves in the lakes (USACE 1955; Langhaar 1951; Kivisild 1954). The analytical method of Kriebel and Dean (1993) and the erosion relationships presented in Dean and Dalrymple (2002) have also been applied to estimate the lake side dike erosion. Chimney (2005) studied the wind setup on Lake Okeechobee and the levee damage from Hurricanes Frances and Jeanne in 2004, using steady-state wind setup models and field data. However, it is difficult to depict all the features along the 225-km-long HHD with sparse measurements and analytical solutions based on numerous simplifications, since the inherent properties of the HHD and ambient hydrology for each section are complex.

Numerical models have often been used to investigate storm surges induced by hurricanes and the hydrodynamic characteristics of Lake Okeechobee. A two-dimensional surge model (SURGE-I) was used on the lake with special algorithms to treat flooding and drying, barriers, and flow over barriers (Reid and Bodine 1968). The upgraded Waterways Experiment Station Implicit Flooding Model (WIFM) has also been employed to investigate storm surges in the lake (Schmalz 1986). At present, the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model developed by the National Oceanic and Atmospheric Administration (NOAA) is used operationally to forecast surges on Lake Okeechobee during hurricanes (Jelesnianski et al. 1992; Shaffer et al. 1989). Another hydrodynamic model, modified from the Environmental Fluid Dynamics Code (EFDC), the Lake Okeechobee Hydrodynamic Model (LOHM), was used to study the lake circulation, gyres, and seiches, and hurricane impacts on sediment transport and resuspension (Jin et al. 2002, 2011; Jin and Ji 2004; Ji and Jin 2006). However, the horizontal grid resolution of the above models is around 1 km or larger, so it is a challenge to resolve the topography, subtle velocity structure, and water level fluctuation around the HHD. The Fully Adaptive Storm Tide (FAST) model has been developed and validated at the International Hurricane Research Center (Kelly et al. 2015, 2016). The FAST model can employ high resolution locally via a priori mesh refinement. Thus, the FAST model is particularly well suited to studying storm surges on Lake Okeechobee and their effects on the HHD. The objectives of this research are (1) to simulate the storm surges induced by Hurricanes Frances, Jeanne, and Wilma; (2) to explore the possible relationship between the dike internal erosion and strong currents caused by hurricanes; and (3) to investigate the zones of the dike that are most vulnerable to internal erosion. The remainder of the paper is arranged as follows: Section 2 describes the study area, Section 3 presents the methodology for computing storm surges, Section 4 comprises the results, and Section 5 presents the discussion and conclusions.

2 Study site: Lake Okeechobee

A bathymetric map of Lake Okeechobee is shown in Fig. 1. The surface area of the lake is 1732 km^2, with 20 % littoral habit near the western shore shown as red in Fig. 1 and 80 % open water (shown as blue). The lake is relatively shallow with an average water depth of 2.7 m. The lake serves the region providing flood control for the surrounding watershed, water supply for regional agriculture, and ground water recharge for the urban areas to the south and east.

In 1926, a hurricane made landfall to the south of Lake Okeechobee (Fig. 2), and the induced storm surge overtopped the earth levee that was there at the time; this event resulted in

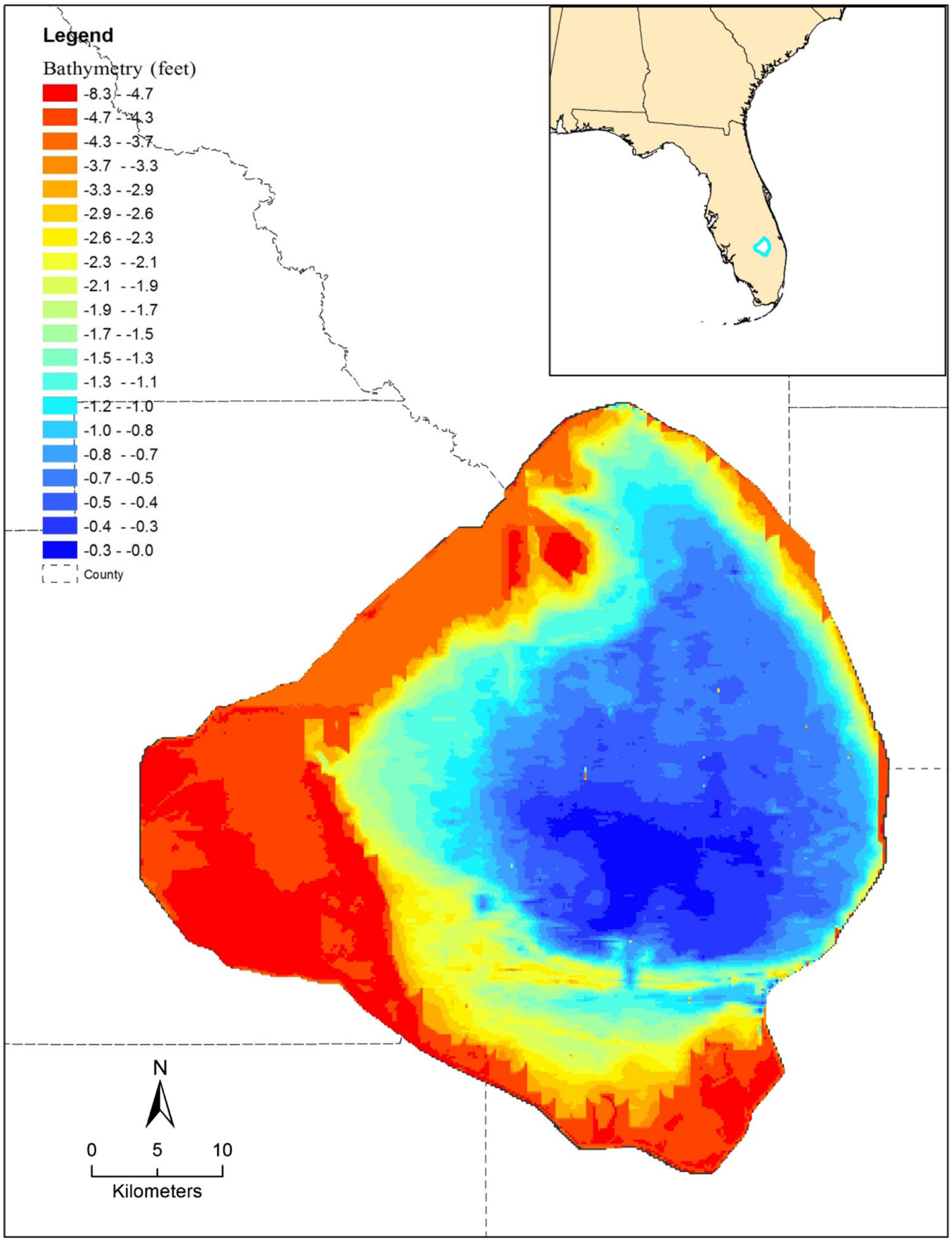


Fig. 1 Lake Okeechobee bathymetry above NGVD

392 fatalities (Bromwell et al. 2006a). In 1928, a hurricane storm surge overtopped the levee again and this time the event resulted in 2700 fatalities making it the second deadliest hurricane in US history (Bromwell et al. 2006a). In the 1930s, the HHD was built from porous materials, including rocks, shells, gravel, and sand using hydraulic dredging and dragline techniques, and was placed on soft soils and highly permeable foundations (US Army Corps of Engineers 1955). Over time, agricultural peatlands on the south side of the lake have subsided several feet, resulting in lake levels well above the surrounding ground levels for most of the year. At present, the HHD is 225 km long with a height varying between 9.8 and 14 m above National Geodetic Vertical Datum (NGVD 1929). Water levels are regulated through numerous water control structures in the levee. Concerns regarding the safety of the HHD during high water stages have been expressed for many years (Bromwell et al. 2006a, b; USACE 2007a, b).

Lake Okeechobee was directly affected by hurricanes in 1947, 1950 (King), 1999 (Irene), 2004 (Frances and Jeanne), and 2005 (Wilma) (Fig. 2). No significant hurricane-induced storm surge flooding has occurred, since the current HHD was built. However, the HHD has experienced extensive internal erosion and piping and suffered damage especially under the associated strong wind conditions. Huge amounts of money have been spent to repair the erosion damage to the HHD. For example, after Hurricanes Frances and Jeanne of 2004, $4.4

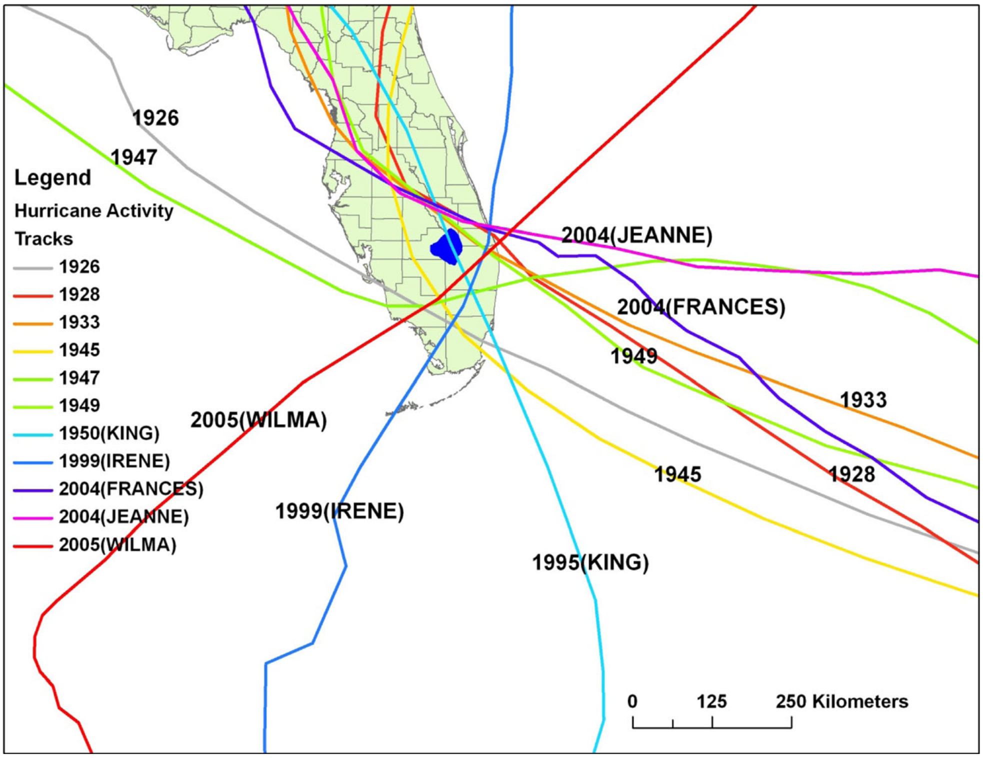


Fig. 2 Major hurricane activity around Lake Okeechobee since 1926

million was used to repair the damaged dike near Port Mayaca (Bromwell et al. 2006b). Hurricane Wilma of 2005 caused significant dike erosion (Bromwell et al. 2006a), and over $2 million was spent to repair the damaged section. The locations of damage to the dike by Frances, Jeanne, and Wilma are shown in Fig. 4.

After the hurricanes of 2004 and 2005, in 2006, the South Florida Water Management District (SFWMD) contracted an expert panel to review the stability and safety of the HHD. The panel's technical review concluded that the HHD poses a serious and impending danger to the people and the environment of South Florida in its current condition (Bromwell et al. 2006a). In 2007, the USACE ranked the HHD an “Urgent and Compelling (Unsafe)” and “critically near failure or extremely high risk” dike (USACE 2007a). The same classification and characterization was arrived at independently through an external review (USACE 2007b).

3 Numerical model

3.1 The Fully Adaptive Storm Tide (FAST) model

The FAST model is a state-of-the-art Godonov-type finite volume model developed at the International Hurricane Research Center (IHRC) to simulate the storm surges and overland flooding induced by hurricanes (Kelly et al. 2015, 2016). When developing the FAST model, specific emphasis was placed on ensuring that the model was well balanced in the sense of satisfying the C- and extended C-properties (Castro et al. 2005) and could handle wetting and drying over complex terrain. The FAST model uses an interfacial approach of the type suggested by Jin (2001) to achieve balancing of the geometric source and flux gradient terms. In order to maintain the self-similar solution structure for the Riemann problem, the water level bottom topography (WLTF) approach (Hui and Pan 2003) is used. This enables the model to maintain quiescent steady states to machine precision for even the most complex of terrain. The model handles wetting and drying naturally by solving the associated intercell Riemann problem. At wet-dry fronts, FAST employs the exact Riemann solution of Toro (1992) adapted for varying bathymetry according to the WLTF approach. The FAST model utilizes dynamic and static adaptive mesh refinement of the generic-tree type in order to optimize computational accuracy and efficiency (Fryxell et al. 2000). Thus, while the mesh blocks follow a quad-tree structure, each of the component blocks can contain an arbitrary $n \times n$ number of cells (where n is any even integer); see Kelly et al. (2016) for details. The FAST model is depth-averaged (i.e., it assumes no velocity variation in the vertical direction) and utilizes the conservation (divergence) form of the nonlinear shallow water equations (Kelly et al. 2015). In order to speed up model run times, the FAST model employs distributed memory parallelization via the Paramesh library (MacNeice et al. 1999), meaning that the resulting code is massively parallel (Kelly et al. 2016). The FAST model can be forced by winds and the atmospheric pressure drop from simple parametric wind models, kinematic

Table 1 Hurricane wind statistics and simulation setup for Frances, Jeanne, and Wilma

Hurricane	Frances	Jeanne	Wilma
Maximum hourly and 15-min wind speed (km h^{-1})	106 (108)	113 (119)	126 (146)
Storm persistence (days wind >29 km h^{-1})	4.7	2.5	1.5
Simulation start time (UTC)	2004 September 03 00:00 a.m.	2004 September 24 12:00 p.m.	2005 October 23 11:00 a.m.
Simulation end time (UTC)	2004 September 07 00:00 a.m.	2004 September 27 12:00 p.m.	2005 October 25 11:00 a.m.
Duration of simulation (h)	96	72	24

analysis winds (e.g., H*Wind, Powell et al. 1998, 2009), or the mesoscale weather models (e.g., the Weather Research and Forecasting model, known as WRF), and astronomical tides or a time series of water levels at open boundaries. A set of tools in MATLAB (www.mathworks.com) have been developed at the IHRC to convert model output files into ArcGIS (www.esri.com) shapefiles for visualization and analysis of simulated storm surge.

The FAST model has been internally verified at the IHRC by comparing calculated surges with data from many historical storms; examples include Hurricanes Sandy (Teng et al. 2016), Ike, and Wilma (Kelly et al. 2016). A detailed account of the parallel FAST model as well as validation for storm surges due to Hurricanes Wilma and Ike is given in Kelly et al. (2016).

3.2 Wind field computation

The parametric wind model used by the SLOSH model (Jelesnianski et al. 1992) is employed here to estimate the hurricane wind and pressure field, although the FAST model can accept the wind field (H*Wind) generated by the Hurricane Research Division of NOAA (Powell et al. 1998, 2009) as inputs. The wind field at each model time step was specified using the SLOSH parametric hurricane wind model with the use of the best track data of historical hurricanes. The “best track” data for a hurricane are based on poststorm analysis carried out by the National Hurricane Center (NHC) to estimate the atmospheric pressure and wind fields. The best track data include storm center position, maximum sustained wind, and central pressure for

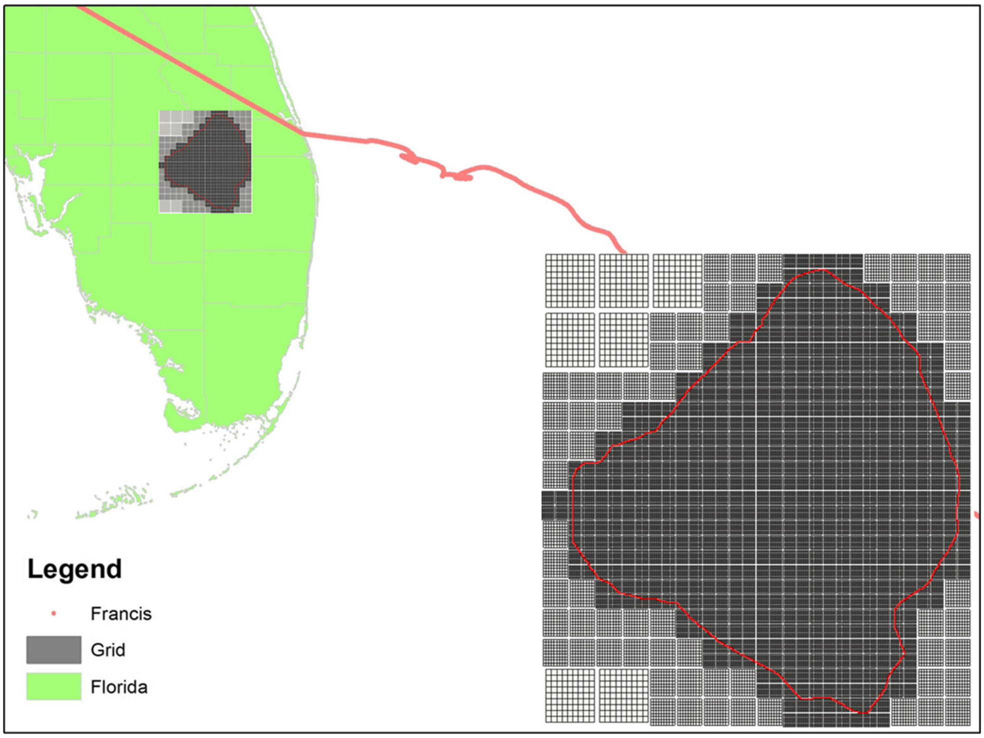


Fig. 3 The storm surge model grid and the track of Hurricane Frances showing a detailed track every 2 min

every 6 h. The wind drag coefficient is computed using the Garratt (1977) formulation.

3.3 Setup for modeling storm surges

The model domain employed extends from −81.4° W to −80.4° W in longitude and from 26.5° N to 27.3° N in latitude. Point measurements of the Lake Okeechobee bathymetry were downloaded from the U.S. Geological Survey (USGS) South Florida Information Access (SOFIA) website (http://sofia.usgs.gov/). The digital elevation model (DEM) for Lake Okeechobee was then generated by interpolating point measurements using the kriging method. All domain boundaries are set as reflective. For the numerical simulation, the Manning friction coefficient n was set to be 0.015 in wet cells. For the initially dry cells (land), the Manning coefficient was calculated based on the National Land Cover Dataset (NCLD) 2006. The initial water level for the whole domain was set according to the average water level estimated from eight water level stations before the storms passed by Lake Okeechobee. The duration of the simulation for each of the storms is shown in Table 1 using coordinated universal time (UTC).

A statically refined mesh was employed for all the simulations presented in this paper. The mesh employs 100 cells per grid block (10 × 10) and refinement on the computational tree-based mesh is set to be between levels 2 ($10\Delta x = 0.1L_x2^{-2}$, $10\Delta y = L_y2^{-2}$) and 6 ($10\Delta x = L_x2^{-6}$, $10\Delta y = L_y2^{-6}$) based on the initial water depth h_0 according to the binary monitor function γ, where:

$$\gamma = \begin{cases} 1 \text{ if } 0 < h_0 < h_c \\ 0 \text{ otherwise} \end{cases} \tag{1}$$

the depth refinement criterion $h_c = 6$ m is employed. For clarity, the mesh used for the simulation of all the hurricane events is shown in Fig. 2.

3.4 The integral kinetic energy

Using the composite trapezoidal rule (Press et al. 1994) at each model time step, the integral kinetic energy (IKE) is calculated from the model output using the following equation:

$$\text{IKE} = \sum_{i=1}^{n-1} \left(\frac{1}{2} \left({v_i}^2 + {v_{i+1}}^2 \right) \Delta t \right), \tag{2}$$

where v_i is the velocity magnitude at the ith time step, n is the total time step, and Δt is the length of the time step.

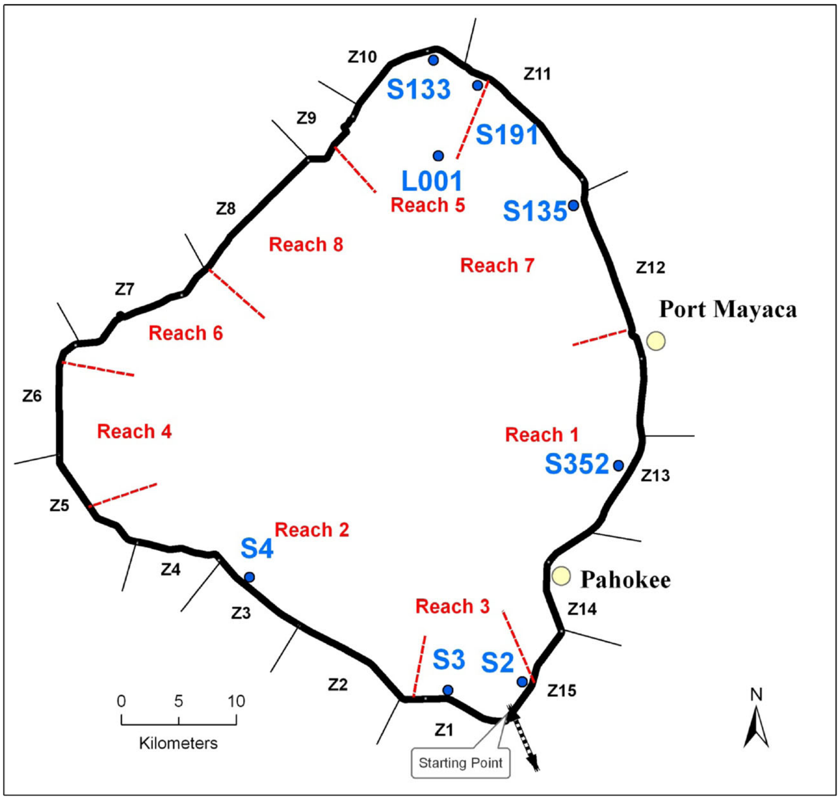


Fig. 4 Water level stations around Lake Okeechobee measured by SFWMD, the definition of the zones along the Herbert Hoover Dike, the definition of the reaches along the Herbert Hoover Dike by USACE (1993), and the location of damage to the dike by hurricanes on 2004 (near Port Mayaca) and 2005 (near Pahokee Airport). The *blue circles* represent water level stations. The *black solid lines* outside of the lake represent zones. The *red dash lines* inside of the lake represent reaches. The *yellow circles* represent locations of damage

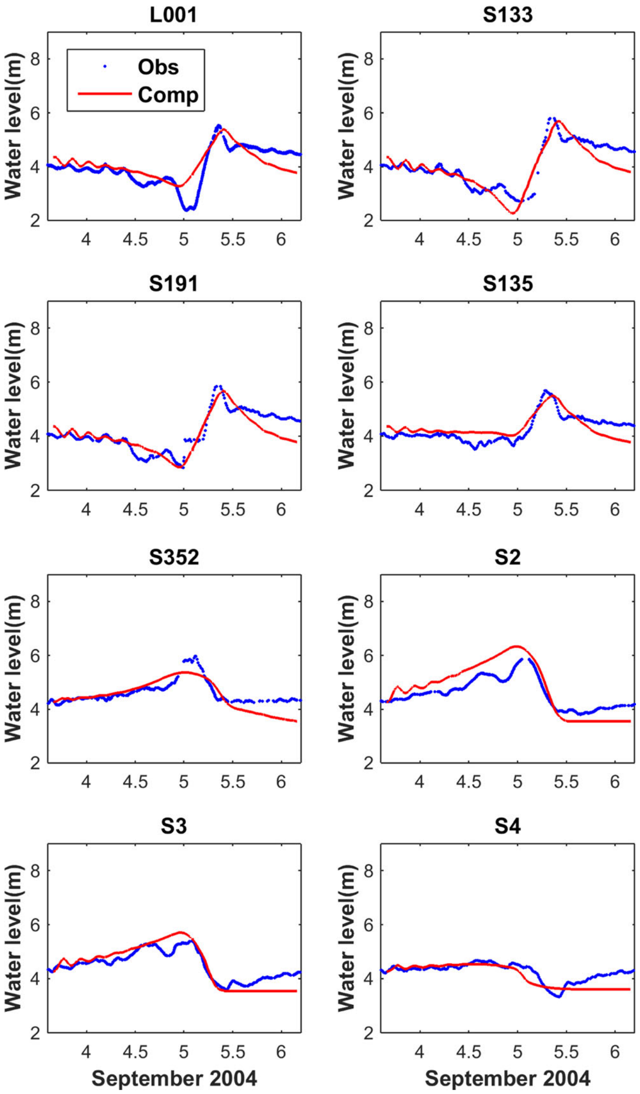


Fig. 5 Time series of observed (Obs) and computed (Comp) water levels at eight stations above NGVD on the lake during Hurricane Frances of 2004

4 Results

4.1 Storm surge hindcast

The tracks of three hurricanes are presented in Fig. 3. Both Hurricanes Frances and Jeanne passed north of the lake in the west-north-west direction. Both hurricanes had very similar intensities and tracks (James et al. 2008); however, Frances moved much more slowly than Jeanne. Wilma passed through east south of the lake to the east-north direction and was the fastest of the three hurricanes in terms of its translational speeds (Table 1). The lake stage is monitored at many of the water control structures that surround it. Data from eight of these sites (Fig. 4) were used in this study. Note that by using the Coastal and Estuary Storm Tide (CEST) model (Li et al. 2016), we also have successfully simulated surges in Lake Okeechobee with wave effects. However, the wave effects cause a negligible change in the water setup and setdown and are therefore neglected in this study.

4.1.1 Time series comparison—Hurricane Frances

Model predictions were compared against time series of observed water level at L001, S133, S191, S135, S352, S2, S3, and S4 stations (Fig. 4). The modeled water levels at the eight SFWMD stations are in good agreement with the observations in terms of the phases and magnitudes of peak surge (Fig. 5). The simulated water levels are close to the measured data at stations L001, S133, S191, S3, and S4, while the simulated peak surge is slight higher/lower than measured data at stations S3/S352.

It is noted that the computed water level does not capture the first setdown/setup, which occurred around 12:00 p.m. on September 4th, 2004, at station L001/S2. This is somewhat expected because the actual direction of Hurricane Frances changed several times over a very short period just before the hurricane made landfall, which is observed in the high-frequency track data (output every 2 min, see Fig. 3). However, the frequency of “best track” data is every 6 h, which will clearly struggle to resolve the details of the wind field for Hurricane Frances before it made landfall.

Both observed and computed water levels show similar patterns of setup and setdown at all eight stations. Before Frances passed by the lake, the initial west-northern wind pushed water setup at the east-south of the lake (stations S352, S2, and S3) and setdown at the north of the lake (stations L001, S133, S191, and S135). After Frances passed by, the following west-southern wind pushed water setup at the north of the lake and setdown at the east-south of the lake.

4.1.2 Time series comparison—Hurricane Jeanne

The direction and position of Jeanne’s track are similar to the track of Frances (Fig. 2); however, the translational speed was faster and the size of wind field was smaller. Therefore, a similar pattern of setup and setdown process at eight SFWMD stations is expected. Figure 6 shows a comparison of the modeled water level time series and the observed water levels at eight stations for Hurricane Jeanne. Overall, the model results are acceptable, and the setup and setdown of the water level are well simulated. The computed phases and magnitudes of setup and setdown at all stations are close to the measured values. The modeled setup is overpredicted at stations S2 and S3, and the modeled setdown is slightly overestimated at station S4 (Fig. 6).

4.1.3 Time series comparison—Hurricane Wilma

Modeled water level time series are also compared to the observed water levels for Hurricane Wilma (Fig. 7). At all

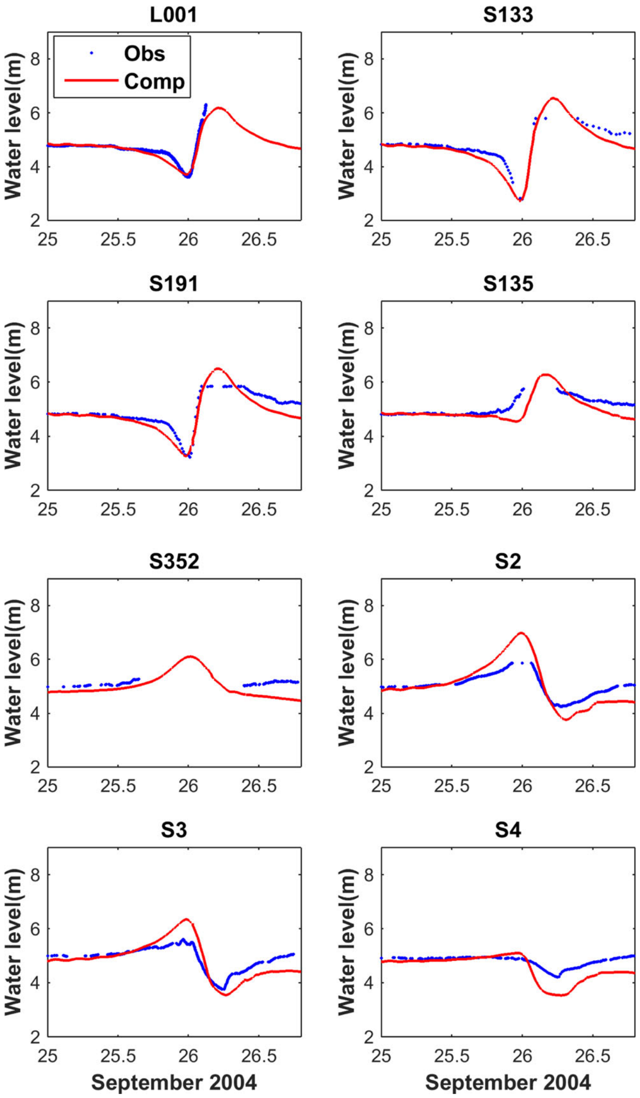


Fig. 6 Time series of observed (Obs) and computed (Comp) water levels at eight stations above NGVD on the lake during Hurricane Jeanne of 2004

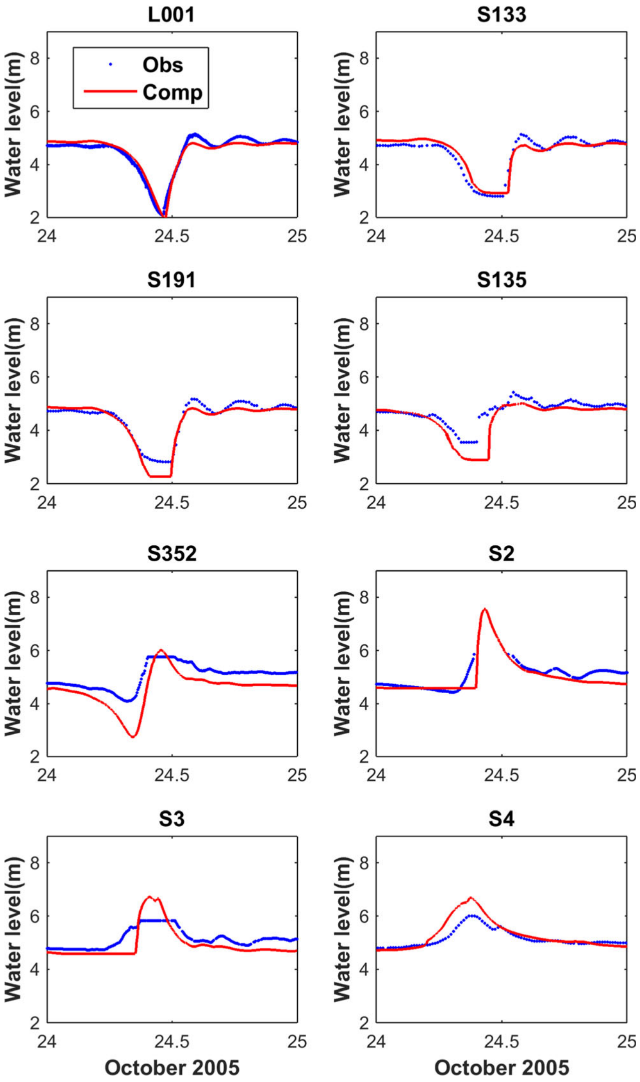


Fig. 7 Time series of observed (Obs) and computed (Comp) water levels at 8 stations above NGVD on the lake during Hurricane Wilma of 2005

stations, the model produced acceptable results for both the setup and setdown with a few exceptions. The modeled setdown was overestimated at stations S191, S135, and S352. The setup produced by Hurricane Wilma exceeded the maximum reading capacity of water level recorders on the perimeter of Lake Okeechobee at station S2. The time series show different patterns of setup and setdown compared to Hurricanes Frances and Jeanne. Before Hurricane Wilma made landfall, the initial east-northern wind forced water setup at the west-south of the lake (station S4), slight setdown at the east-south of the lake (stations S352, S2, and S3), and considerable setdown at the north of the lake (stations L001, S133, S191, and S135). After Wilma made landfall, the following east wind pushed water setup at the east-south of the lake (stations S352, S2, and S3).

The RMS error is frequently used to evaluate the difference between measured and modeled storm surge heights (Zhang et al. 2012; Zhang and Sheng 2013). A comparison of observed surge heights with those modeled using FAST shows considerable scatter without obvious bias (Fig. 8a–c). The RMS error values for simulating Frances (Fig. 8a), Jeanne (Fig. 8b), and Wilma (Fig. 8c) are 0.38, 0.31, and 0.36 m at all eight stations.

Overall, the simulations of the three hurricanes reproduce the water levels and general water setup and setdown on the lake reasonably well. A similar water movement occurred during all three hurricanes. The water first setdown, then setup and then setdown again at the stations nearby the track to the left side, stations L001, S133, and S191 for Hurricane Frances and Jeanne, and stations S135, S352, and S2 for Hurricane Wilma. The reversed sequence happened at the stations far away from the tracks. This phenomenon is well captured by the FAST model for all three hurricane events.

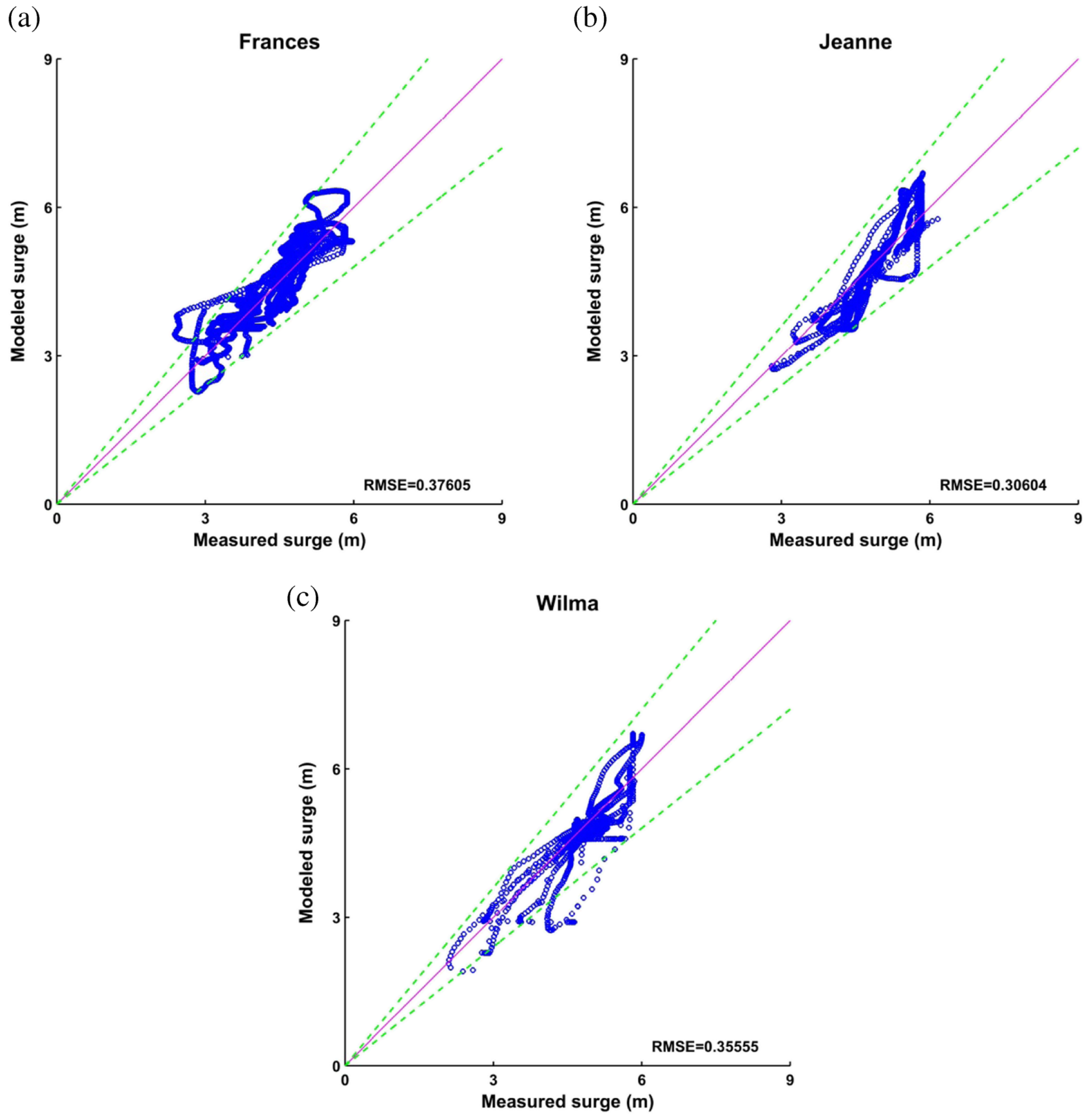


Fig. 8 Scatter plots of measured surge height versus the simulated one of Hurricanes Frances (**a**), Jeanne (**b**), and Wilma (**c**). The *purple solid line* represents perfect simulations and the *green dashed lines* represent the boundaries of 80 and 120 % of perfect simulations. Both computed and observed peak surge heights are referenced to the NGVD vertical datum

4.2 Spatial distribution of maximum surges

The HHD is vulnerable to failure caused by water seepage and piping, possibly induced by high water levels from hurricanes. Figure 8 presents the spatial distributions of computed maximum storm surge heights of Hurricanes Frances (a), Jeanne (b), and Wilma (c). The maximum storm surge of Frances and Jeanne both occurred at east-south and north portions of the lake, whereas the water levels adjacent the damaged location by these two hurricanes were moderate (Fig. 9a, b). The maximum storm surge heights due to Wilma occurred at east-south and west-south portions of the lake. The water levels adjacent to the locations that were damaged due to Hurricane Wilma were not overly perturbed (Fig. 9c). The inconsistencies between the locations of high water level and the damaged dike imply that there may be other, more dominant, factors that are causing the erosion of the HHD. The other potential explanation of dike erosion is wave setup. However, according to the results from wave modeling (Li et al. 2016), there are no significant waves generated around the damaged portion of the HHD to cause internal erosion for these three hurricanes. Thus, erosion due to wave setup is likely not be a dominant factor impacting on the safety of the HHD during Hurricanes Frances, Jeanne, and Wilma.

4.3 Wind-induced current

Strong alongshore currents caused by storm winds can exacerbate dike erosion at the lake side by transporting the

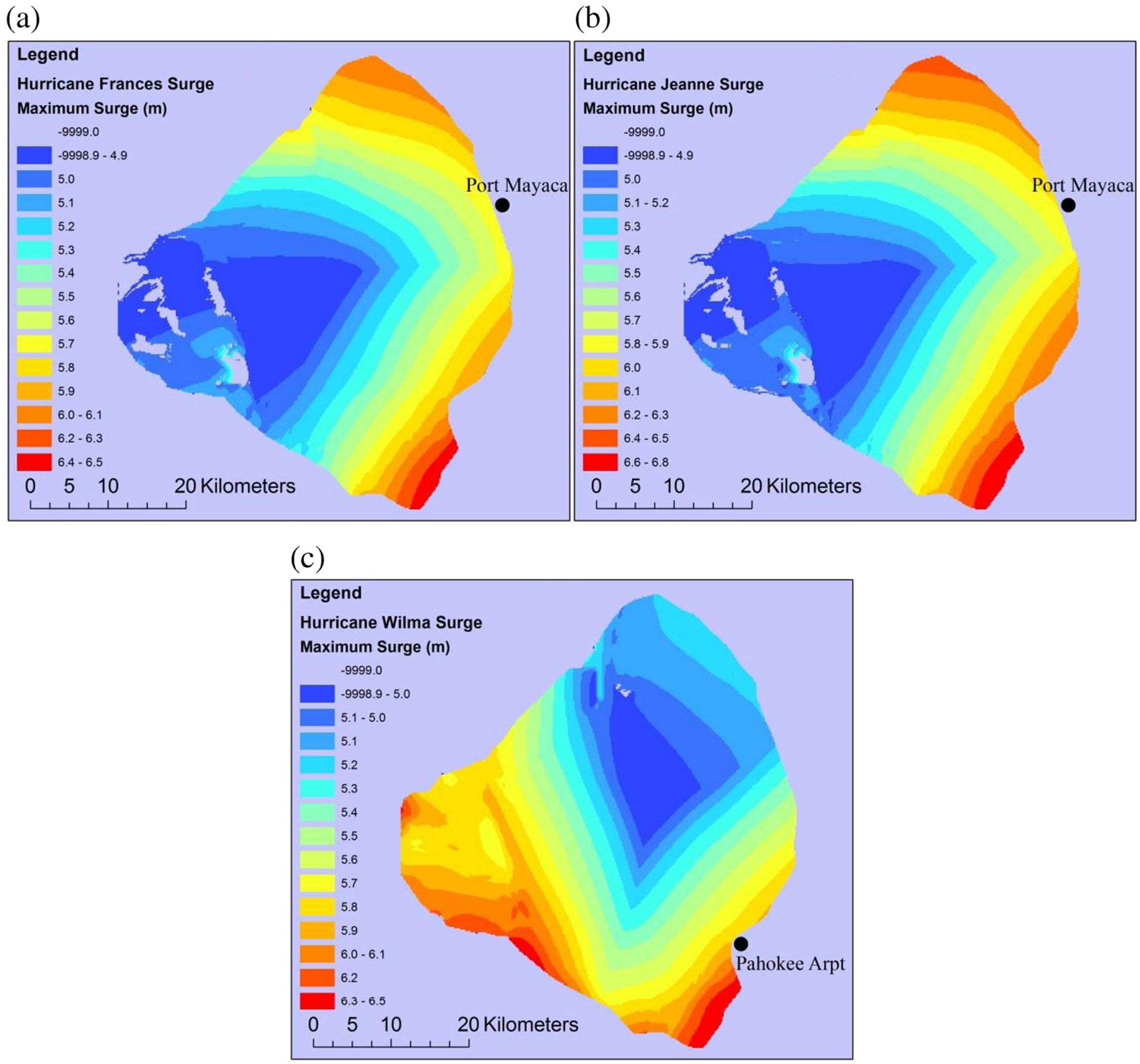
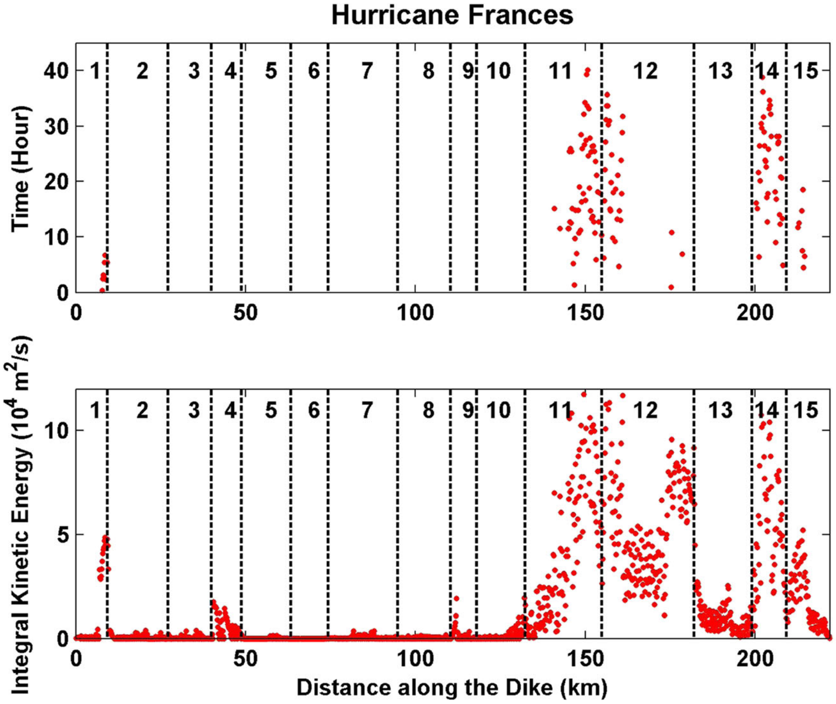


Fig. 9 Spatial distributions of computed maximum storm surge heights of Hurricanes Frances (**a**), Jeanne (**b**), and Wilma (**c**)

sediment eroded by waves and eroding the bank directly. Since erosion is a time-dependent process requiring certain duration to remove a specified volume of material, it is important to extract the velocity information along the HHD during hurricanes. Here the velocity threshold used to calculate the IKE is estimated using the Hjulstrom curve, which shows the relationship between the size of sediment and the velocity required to erode, transport, and deposit it (Hjulstrom 1935). A threshold value of 0.8 m/s is adopted since the HHD was constructed primarily from gravel, rock, and shell (USACE 2016). Figure 10 presents the duration of velocity magnitudes greater than 0.8 m/s and the integral kinetic energy along the HHD during Hurricane Frances. The IKE is calculated using the composite trapezoidal rule at each model time step. The duration of strong currents reaches up to 40 h in zones 11, 12, and 14 (Fig. 10), whereas no strong velocity occurred in the other zones. Higher values for the IKE also appear in the same zones and are not so significant in the other zones. A similar pattern is also observed during Hurricane Jeanne (Fig. 11), except that the magnitude of the duration and the IKE is smaller. This is not surprising as the wind field from Frances is much larger than that of Jeanne, and the duration of strong winds during Frances was longer (Table 1). Hurricane Wilma shows a different pattern (Fig. 12), with the longest duration of strong velocity occurring in zones 4 and 14 and the highest IKE in zone 14. The magnitude of the duration and IKE of Wilma is the smallest of the three hurricanes, due to Wilma having the fastest translational speed.

Modeled velocity time series of Frances and Jeanne (near Port Mayaca, the HHD damage location) and Wilma (near Pahokee Airport, the HHD damage location) are shown in Fig. 13. The time series of Frances and Jeanne share similar features. South-south-east velocity was induced first, and then the direction reversed to north-north-west velocity over a very short period. Hurricane Wilma also showed a rapid velocity reversal from south-west direction to north-east. This sudden change of velocity direction may possibly be responsible

Fig. 10 Computed duration of strong currents (≥0.8 m/s) and integral kinetic energy (v2*t) along the dike for Hurricane Frances. The *dash line* represents the zone segmentation. The number between two *adjacent dash lines* (or *solid line*) represents the zone definition consistent with Fig. 4

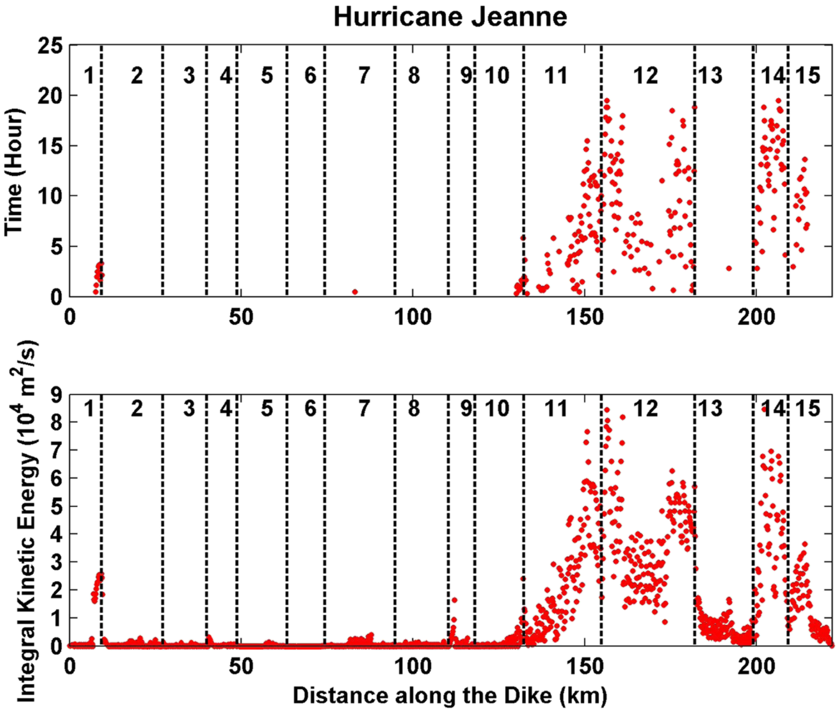


for removing the surface layer sediment at the foundation of the HHD and have an impact on the stability of the HHD. These results suggest that strong velocities induced by hurricane winds may well be one of the, if not the, major factors contributing to the erosion and associated damage of the HHD.

4.4 Numerical experiments: hypothetic hurricanes

The Design Criteria Memoranda for the Comprehensive Everglades Restoration Program (CERP) provides a set of potentially more stringent criteria for new high-hazard dams (SFWMD 2005, 2006). One of them is a 100-year

Fig. 11 Computed duration of strong currents (≥0.8 m/s) and integral kinetic energy (v2*t) along the dike for Hurricane Jeanne. The *dash line* represents the zone segmentation. The number between two *adjacent dash lines* (or *solid line*) represents the zone definition consistent with Fig. 4



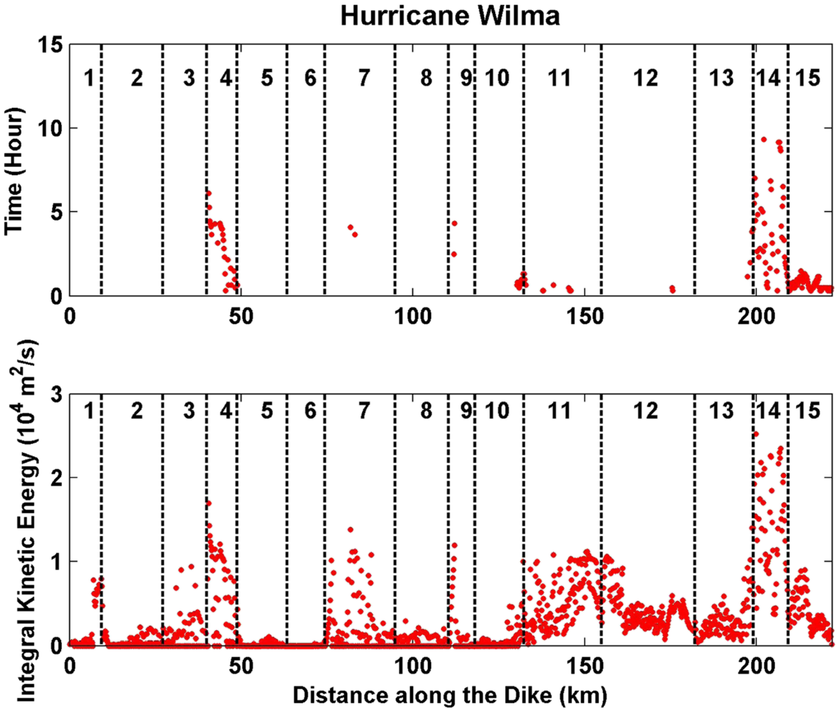


Fig. 12 Computed duration of strong currents (≥0.8 m/s) and integral kinetic energy (v2*t) along the dike for Hurricane Wilma. The *dash line* represents the zone segmentation. The number between two *adjacent dash lines* (or *solid line*) represents the zone definition consistent with Fig. 4

rainfall event with a category 5 hurricane, 156 mph wind (70 m/s). To investigate zones of high velocity, that may potentially damage the HHD, eight hypothetical category 5 hurricanes were generated based on the historical tracks (Fig. 14). The moving speed of eight hurricanes is set as 25 miles per hour (11 m/s).

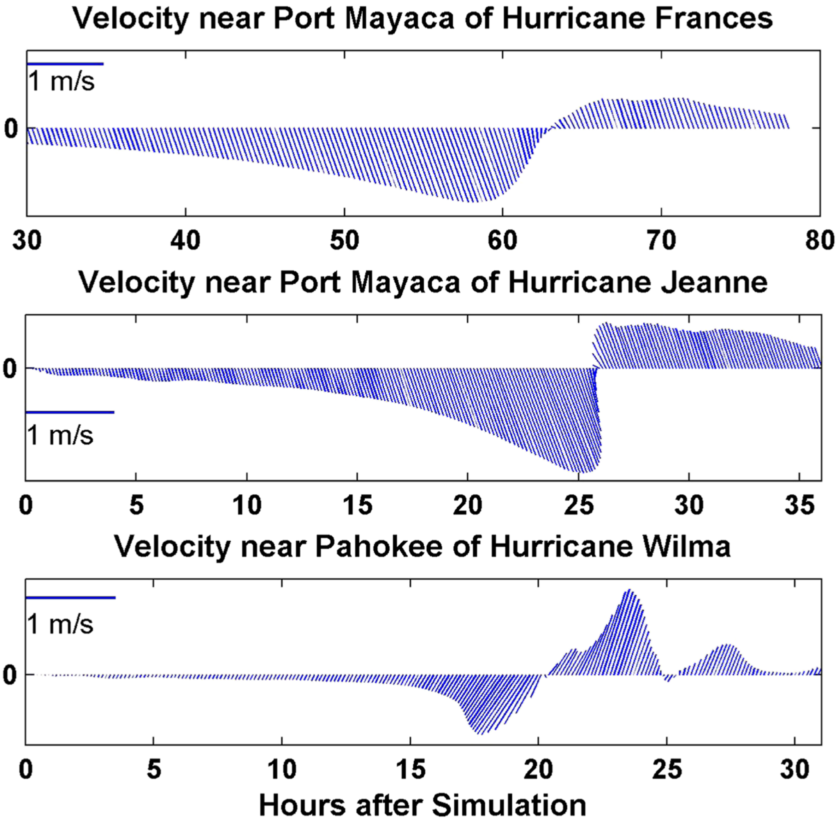


Fig. 13 Computed velocity time series near Port Mayaca of Hurricanes Frances and Jeanne and velocity time series near Pahokee of Hurricane Wilma

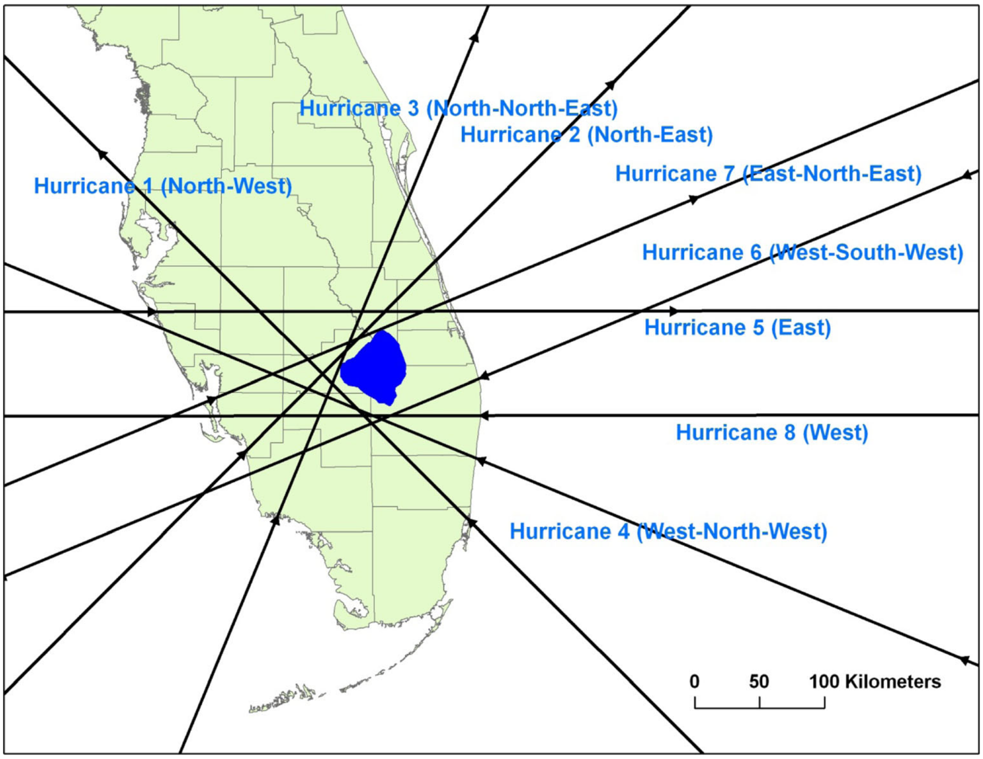


Fig. 14 Tracks of eight hypothetic hurricanes coming from different directions around the lake

The computed duration of high velocity and IKE is presented in Fig. 15 for all eight hurricanes. It is obvious that the relatively high velocities and high IKE occur in zones 4, 7, 9, 11, 12, 13, and 14. The strong currents caused by these hurricanes occurred at zones 11 to 14 located at the east side of the lake, where the shoreline is relatively straight and smooth. These same current patterns were also reported in the previous study (Jin et al. 2002, 2011; Ji and Jin 2006). The depth at the adjacent eastern pelagic portion is also higher than other portions (Fig. 1), and there is no vegetation to attenuate the strong currents and associated water level fluctuations. These results provide a reasonable foundation on which to suggest that

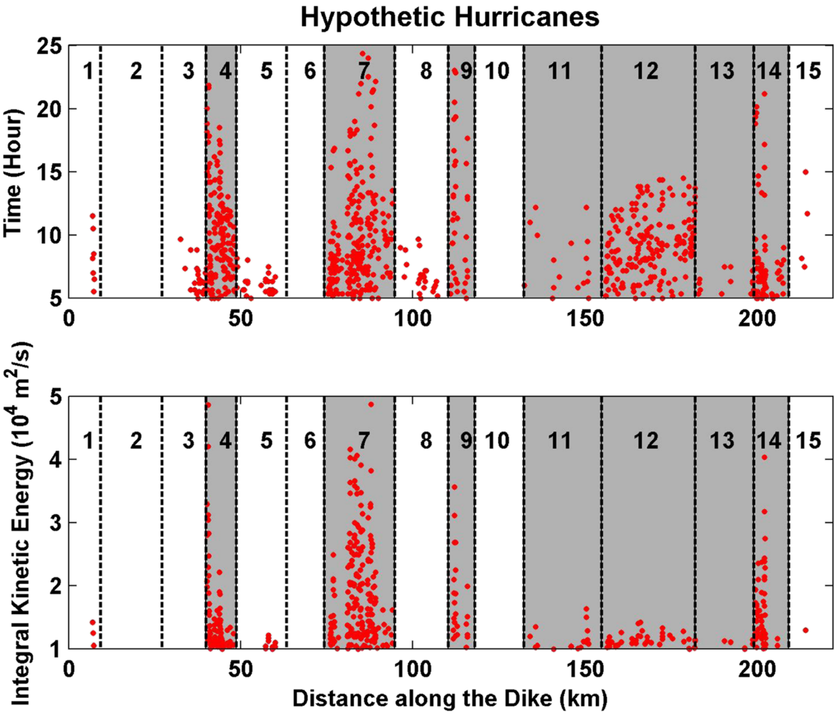


Fig. 15 Computed duration of strong currents (≥0.8 m/s) and integral kinetic energy (v2*t) along the dike for all 8 hypothetic hurricanes. The *dash line* represents the zone segmentation. The number between two adjacent *dash lines* (or *solid line*) represents the zone definition consistent with Fig. 4. The *shadow zone* represents the zone with stronger current and longer duration

these portions of the HHD may be likely to experience cumulative damage and progressive deterioration from internal erosion and seepage caused by strong hurricane winds.

5 Discussion and conclusion

Reliable estimates of the potential damage to dikes caused by hurricanes are essential for the design of many coastal engineering works (USACE 1977). According to the Standard Project Flood, the design of the HHD is to remain safe for lake elevations up to 25 ft (7.6 m) above NAVD88 (USACE 2010). This is the maximum lake stage that the dike is designed to safely handle under a category 5 hurricane and probable maximum wind of 200 mph at normal full reservoir level (SFWMD 2005, 2006). It is unknown whether HHD could meet these criteria.

In response to repeated water setup and setdown processes during hurricanes, at certain locations, the water velocities adjacent to the HHD are often high and frequently exhibit short period cyclic behavior. This fast, back-and-forth motion of the water, caused by the wind, clearly has a large erosive capability. Even though there is no available piezometer data for the HHD, Bromwell et al. (2006a) point out that this could be "[…] a potentially significant factor in promoting cumulative damage during successive high-water events". The numerical study presented in this paper suggests that the magnitude of the velocities and the IKE was highly local to the sites of internal erosion and associated damage of the HHD during Hurricanes Frances, Jeanne, and Wilma.

In 1993, USACE also established priorities to address structural problems at individual sections of the dike according to the perceived risk at that time (USACE 1993). The reaches designated 1 to 8, in descending order of priority, remain in use today (Fig. 4). Consistent with the findings of this study, zones 12, 13, and 14 (which have a relatively high IKE*)* are located at the first priority reach 1, and zone 4 is located at the second priority reach 2. Recent studies also indicated that the probability of a failure of the dike in reach 1 is 45 % when lake stages are approximately 17.2 ft (5.2 m) above NAVD88, and 100 % when lake stages are approximately 20 ft (6.1 m) or higher (USACE 2010). However, the vulnerable zones 7 and 9 are located at the lower priority reaches 6 and 5, respectively. One reason for this discrepancy is that the seepage and stability of the dike was investigated according to normal hydrological conditions in previous studies, whereas this study is based on the worst possible hurricane conditions. Under normal circumstances, the water levels at zones 7 and 9 are relatively shallow and surrounded by the littoral zone compare with zones 12 to 14 (Fig. 1). Therefore, the velocity magnitude at these two zones is relatively low due to attenuation by vegetation, and internal erosion is negligible. Under extreme weather conditions, however, high water levels and the associated strong water current can be generated under certain hurricane conditions. These two zones of the dike have the potential for erosion and subsequent instability. It should be noted that in reality, it is difficult to quantify the magnitude and duration of the strong velocities likely to cause dike erosion. This is because the diverse foundation types and vegetation around the HHD complicate matters significantly. The accurate estimation of potential erosion and instability for each single section of the HHD requires further investigation and evaluation. One option would be to employ a full 3D free surface flow model based on the incompressible, Reynolds averaged, Navier-Stokes equations at locations local to the dike. Approaches such as this, using open source solvers, have already been successfully employed in the coastal engineering community (Richardson et al. 2013). The 3D model could have boundary conditions provided by a larger scale 2DH area model such as FAST, CEST, or SLOSH.

In conclusion, the FAST modeling system (comprising a high-resolution 2DH storm surge model and parametric wind model) was used to analyze the storm surge behavior and its impact for Lake Okeechobee during Hurricanes Frances, Jeanne, and Wilma. The results show that the strong wind field produced pronounced setup and setdown and associated strong currents in Lake Okeechobee for all three events. The computed water levels at eight stations were in overall reasonable agreement with the observations. The water setup and setdown processes caused by strong winds were reproduced successfully. Further analysis showed that the locations of internal erosion and cavities on the HHD during Hurricanes Frances, Jeanne, and Wilma were consistent with the high IKE zones. This result suggests that the internal erosion to the HHD caused by storm winds corresponds to the magnitude of current adjacent to the dike. As sediment transport due to currents is typically assumed to take the form of a velocity power law, this result is not altogether unexpected. Numerical experiments with eight hypothetical category 5 hurricanes were conducted to investigate the potential damage and failure of the HHD. Importantly, several sections including zones 4, 7, 9, 11, 12, and 13 of the HHD, associated with strong currents and high IKE, were recognized as the most vulnerable to the internal erosion (Fig. 4). This erosion together with seepage and piping could potentially trigger dike failure in places where the dike may already have been weakened from accumulated damage from previous hurricane events. Finally, it should be noted that there are other processes, not modeled here, that may be highly significant in causing damage to the HHD during a hurricane surge event. Examples of such processes include wave run-up and overtopping which will form the focus of future studies.

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