HURRICANE ISABEL STORM SURGE SIMULATION FOR CHESAPEAKE BAY

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ABSTRACT

On 18 September 2003, Hurricane Isabel made landfall on the Outer Banks of North Carolina between Cape Lookout and Cape Hatteras as a Category 2 hurricane. This storm caused substantial flooding in the lowland areas of North Carolina, Maryland, Washington, D.C., and Virginia. High storm surge was observed along the Outer Banks and in the Chesapeake Bay. Measured water levels showed a 1.5-m storm surge above normal tide levels at the coastline about 125 km north of the landfall (*http://coastal.er.usgs.gov/hurricanes/isabel*) and a 2.2-m surge near the center of the west bank in Chesapeake Bay (*www.mgs.md.gov/coastal/isabel/isabel2.html*).

This paper presents numerical modeling of the wind field and water surface elevation time series associated with Hurricane Isabel for Chesapeake Bay. The numerical modeling served as one of several calibrations for the prediction of extreme water levels based on major tropical and extratropical storms occurring in the Bay for the last 150 years. The paper describes meteorological and oceanographic input parameters used and compares model results with measured data. Surface wind fields were generated from a Planetary Boundary Layer (PBL) model [1, 2]. The storm track for Isabel was obtained from the North Atlantic Hurricane Track Database *(http://weather.unisys.com/hurricane)*. Water surface elevations were calculated with the ADvanced CIRCulation (ADCIRC) model [3]. Calculated winds and water levels were compared to data from 12 NOAA meteorological stations along the perimeter of the Bay. Model results show overall agreement with measured wind and water levels [4, 5]. A key to successful modeling was topographic representation of the river tributaries that flooded during the storm and are areas that store large quantities of water at peak surge. Comparisons of model results around the Bay are given.

INTRODUCTION

The numerical modeling of Hurricane Isabel was performed by the U.S. Army Engineer Coastal & Hydraulics Laboratory for the U.S. Army District, Baltimore as part of a life-cycle analysis for restoration of three island sites in Chesapeake Bay [4]. The life-cycle analysis required water level information from a suite of storms. Hurricane Isabel was selected as one of 95 tropical and extratropical storms studied in this analysis.

Tasks for the numerical modeling effort were: 1) identifying historical tropical and extratropical storms that passed through the Chesapeake Bay region; 2) acquiring wind fields for historical storms identified as potential storms to model; 3) adjusting wind fields over the land and over the Chesapeake Bay as necessary to represent overland wind adjustments and over-Bay wind adjustments; 4) analyzing existing historical data from regional anemometers to develop local winds over Chesapeake Bay; 5) developing a high-resolution numerical finite element grid of Chesapeake Bay, including overland areas; 6) validating the hydrodynamic model ADCIRC to several historical storm events; 7) applying ADCIRC to the suite of historical storm events to compute storm water levels; and 8) extracting water levels at the three island sites.

SELECTION OF STORMS

The North Atlantic Hurricane Track Database *(http://weather.unisys.com/hurricane)* was used to determine the set of tropical storms that traversed the Chesapeake Bay region. Fifty-two hurricanes were selected from the database from 1851 to 2003 for simulation based upon the following criteria: storms with maximum wind speeds greater than 50 knots in the area between 75 and 79 degrees W longitude and 36 and 39 degrees N latitude.

The database contained the maximum wind speed and minimum pressure as each storm tracked across the Atlantic Ocean and/or Gulf of Mexico. Wind and pressure fields were generated for a given track using the Planetary Boundary Layer (PBL) model [1, 2]. Adjustments for overland and over-Bay were made to the wind fields as follows:

$$U_L = U_W / R_L$$

where U_L is the wind speed over land, U_W is the wind speed over water, and R_L is an adjustment factor. Procedures described in Part II, Coastal Engineering Manual (*http://chl.erdc. usace.army. mil/CHL.aspx?p=s&a=ARTICLES;104)* were followed. The factor R_L ($1 < R_L < 1.5$) is a function of wind speed and percentage of overland and over-water areas in a rectangular wind field cell. Both wind and pressure fields were applied in the ADCIRC model simulations for the Chesapeake to attain the response of the Bay to each storm.

NUMERICAL MODEL ADCIRC

ADCIRC is documented in technical reports and technical notes, as well as in the literature of study applications and engineering projects. A short description of the model is given here for broad understanding of the model's function. The references provide additional details.

ADCIRC is a highly developed numerical model for solving the equations of motion for a moving fluid on a rotating earth [3, 6, 7]. It serves as the Corps of Engineers' regional oceanographic and storm surge model as certified by the Federal Emergency Management Agency. The equations are formulated with hydrostatic pressure and Boussinesq approximations and are made discrete in space with the finite-element method and in time with the finite difference method. ADCIRC can be run either as a two-dimensional depth-integrated (2DDI) model or as a three-dimensional (3D) model. Water elevation is obtained from the solution of the depth-integrated continuity equation in the generalized wave-continuity equation (GWCE). Velocity is solved from 2DDI or 3D momentum equations with all nonlinear terms retained. ADCIRC has robust wetting and drying algorithms for lowland flooding predictions.

ADCIRC can be operated in either a Cartesian or a spherical coordinate system. ADCIRC boundary conditions include specified elevation (harmonic tidal constituents or time series), specified normal flow (harmonic tidal constituents or time series), zero normal flow, slip or no-slip conditions for velocity, external barrier overflow out of the domain, internal barrier overflow between sections of the domain, surface stress (wind and/or wave radiation stress), atmospheric pressure, and outward radiation of waves (Sommerfeld condition). ADCIRC can be forced with elevation, normal flow, or surface stress boundary conditions, tidal potential, and earth load/ self-attraction tide.

Recently, regional-scale ADCIRC studies were completed on high-performance computers to provide accurate tidal constituents for the Atlantic coast, Gulf of Mexico coast, and Pacific coast of the United States to furnish reliable tidal constituents for project-scale simulations [8, 9]. In the present study, the 2DDI ADCIRC is used to predict wave levels and all nonlinear terms (including wetting/drying function for circulation dynamics) are retained in the model. The forcing at the ocean boundary consists of eight tidal constituents (K1, O1, M2, N2, S2, K2, P1, and Q1). The model was run using a 1-second time step with default control parameters (weighting factor of 0.01 in GWCE and drag coefficient of 0.0025 for quadratic bottom friction) and Coriolis term.

ADCIRC GRID DEVELOPMENT

A regional scale ADCIRC grid with a rudimentary representation of Chesapeake Bay was developed through previous studies by the Coastal Inlets Research Program and Offshore and Coastal Technologies, Inc. This grid was refined in Chesapeake Bay and far-field areas for the present study using National Ocean Service Digital Navigation Charts. In this hydrodynamic study, the existing-condition bathymetry was assembled from three sources: Virginia Institute of Marine Science (VIMS) bathymetric data, the GEOphysical DAta System (GEODAS) database, and survey data from the US Army Corps of Engineers. Detailed Chesapeake Bay coastline and bathymetric data were obtained from VIMS and incorporated into the refined ADCIRC grid. Chesapeake & Delaware Canal bathymetric data were obtained from the US Army Engineer District, Philadelphia. Further grid development included the incorporation of overbank areas into the Chesapeake Bay tributaries to predict storm surge accurately in these relatively narrow branches of the Bay (Figure 1). The

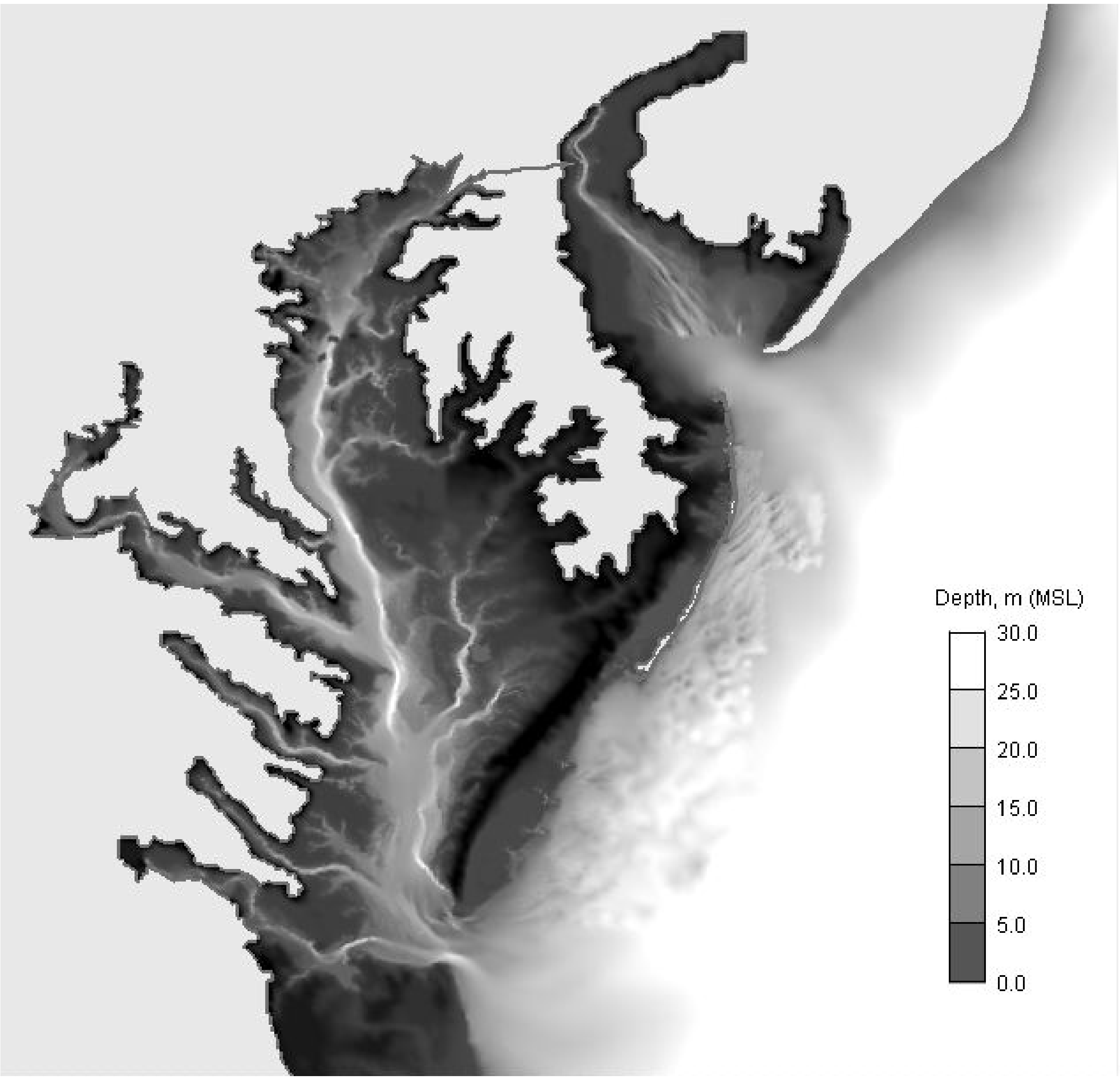

Figure 1. The portion of the ADCIRC grid showing overland bathymetry around the Chesapeake Bay.

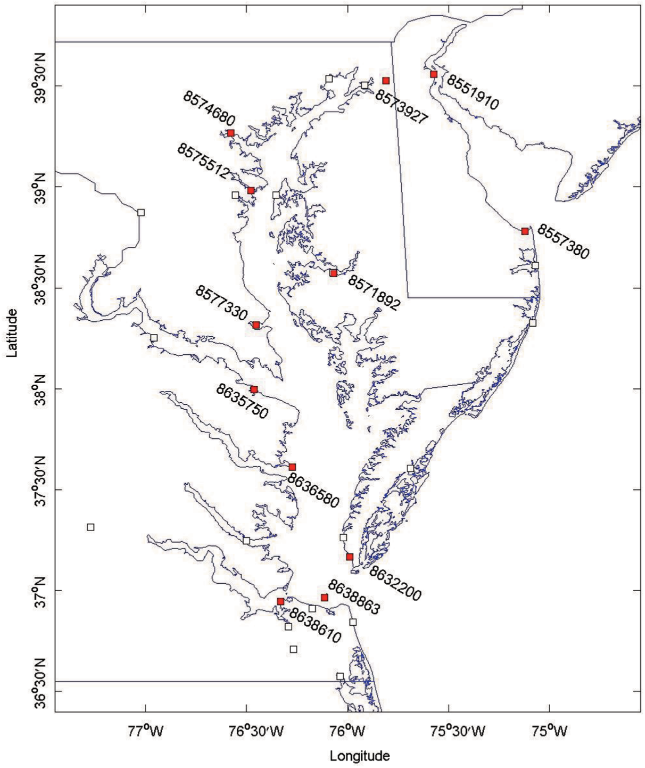

Figure 2. NOAA stations.

ADCIRC grid was extended to include lowland topography data to +10 m, mean tide level, from USGS Digital EEM database GTOPO30—30-second arc resolution *http://edcdaac.usgs.gov/gtopo30/gtopo30.asp*. The grid was constructed with a minimum resolution (node-to-node spacing) of 50 m at shallow water areas and a maximum resolution of 500 m in the open ocean. The grid contained 180,684 elements and 93,095 nodes. The ADCIRC grid generated in this process was applied to tidal current and storm surge simulations to calculate water level at the three island sites for the main project study. The numerical grid was developed to represent the existing Bay condition as closely as possible, especially at the three island study sites. This paper focuses on the simulation of Hurricane Isabel.

VALIDATION TO TROPICAL STORMS

The validation process for tropical storms (hurricanes) applying PBL wind and pressure fields involved comparison of water levels at twelve NOAA stations (Figure 2 and Table 1) to water levels produced by ADCIRC for two major hurricanes—Fran (1996) and Isabel (2003)—and four moderate hurricanes—Bertha (1996), Bonnie (1998), Earl (1998), and Floyd (1999). Fran and Isabel approached the Bay from the ocean with similar storm tracks nearly perpendicular to the coastline and made landfall south of the Bay. They continued in a northwest course to move further

Table 1. NOAA stations for wind/water level measurements (1996–2003), Chesapeake Bay, and Delaware Bay.

Station No.	Station Name	Coordinates
8551910	Reedy Pt, C&D Canal, DE	39° 33’ 30” N, 75° 34’ 26” W
8557380	Lewes, Ft. Miles, DE	38° 46’ 54” N, 75° 07’ 12” W
8571892	Cambridge, Choptank River, MD	38° 34’ 24” N, 76° 04’ 06” W
8573927	Chesapeake City, MD	39° 31’ 36” N, 75° 48’ 36” W
8574680	Baltimore, MD	38° 16’ 00” N, 76° 34’ 28” W
8575512	US Naval Academy, MD	38° 59’ 00” N, 76° 28’ 48” W
8577330	Solomons Is, MD	38° 19’ 00” N, 76° 27’ 12” W
8632200	Kiptopeke Beach, VA	37° 10’ 00” N, 75° 59’ 18” W
8635750	Lewisetta, Potomac River, VA	37° 59’ 48” N, 76° 27’ 48” W
8636580	Windmill Pt, VA	37° 36’ 42” N, 76° 16’ 30” W
8638610	Sewells Pt, VA	36° 56’ 48” N, 76° 19’ 48” W
8638863	Chesapeake Bay Bridge Tunnel, VA	36° 58’ 00” N, 76° 06’ 48” W

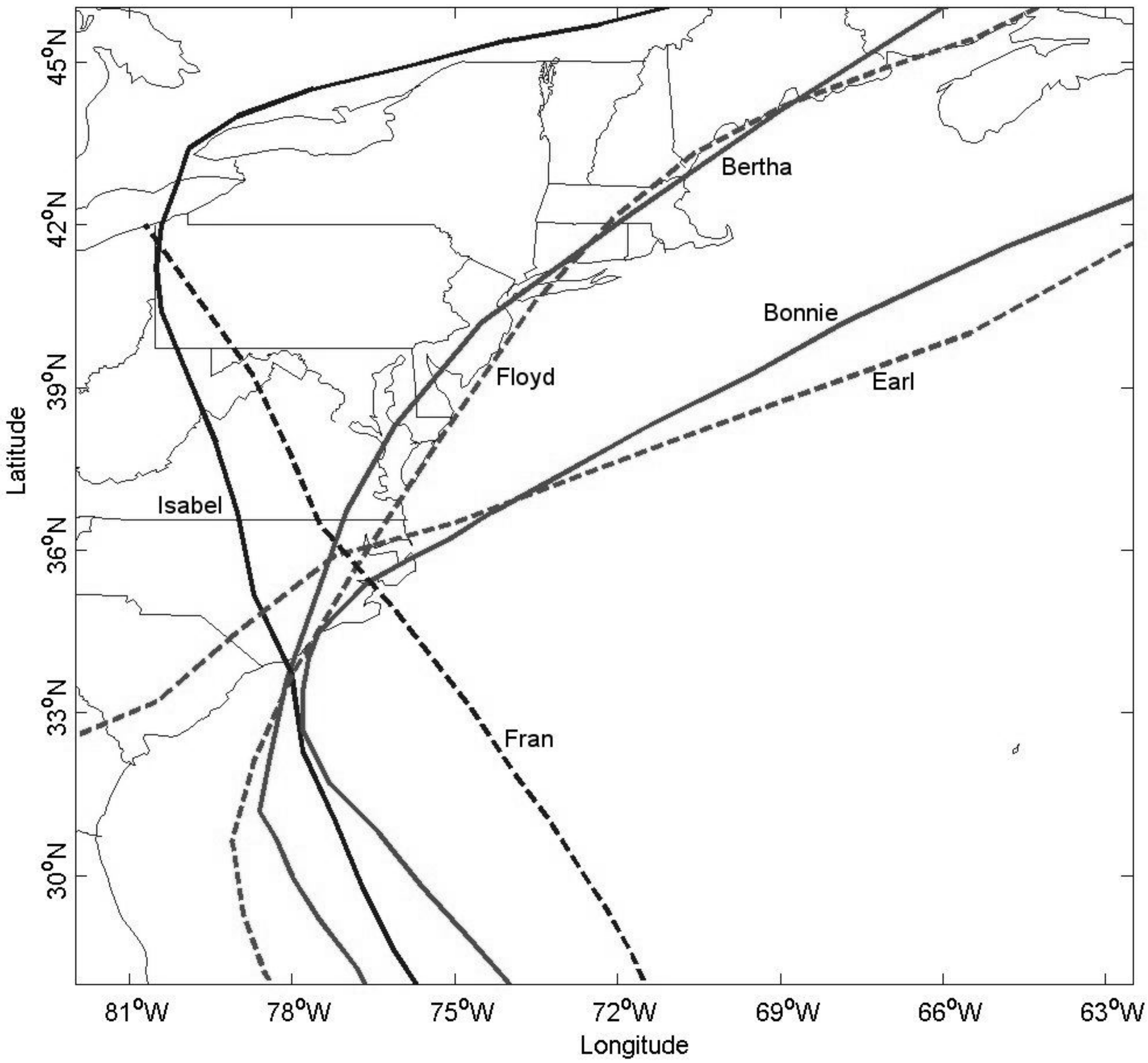

Figure 3. The storm tracks of Bertha (1996), Fran (1996), Bonnie (1998), Earl (1998), Floyd (1999), and Isabel (2003).

inland west of the Bay. The passage of Bertha was similar to Floyd; both hurricanes approached and passed the Bay paralleling the Atlantic coastline east of the Bay. Bonnie and Earl, on the other hand, followed a northeast track from land to ocean crossing the coastline south of the Bay. Figure 3 shows storm tracks of these six hurricanes. Hurricanes of similar track to Fran and Isabel can generate higher storm surge as the onshore wind traps more water along the coastline and in the Bay.

As part of the validation process, NOAA historical water level data (1996–2003) for Chesapeake Bay were extracted from *http://co-ops.nos.noaa.gov/data_res.html* to determine seasonal water level variations and for validation of numerical model results. The mean water level (non-tidal signals) is generally higher from the spring to the fall compared to winter, but this is not modeled in the ADCIRC. In the present study, an average water level increase of 0.1 m in the interval

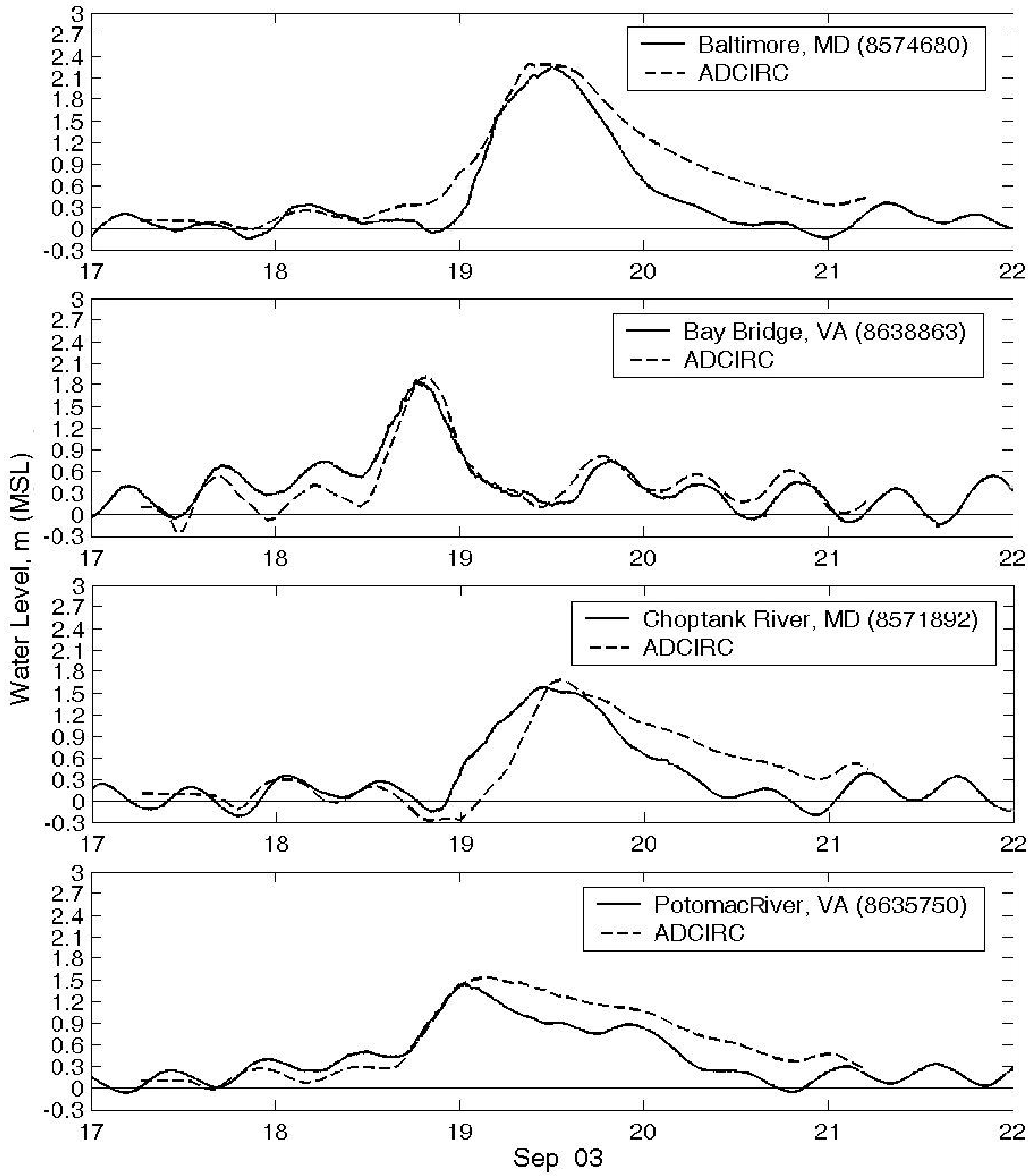

Figure 4. Measured and modeled water levels for Hurricane Isabel at four stations in Maryland and Virginia.

of March to November has been added to model results to account for the seasonal variation [4, 5].

Figures 4 and 5 show the measured and modeled water level time series at eight stations for Hurricane Isabel. Model results agree well with measured data. At Station 8574680 (Baltimore, Maryland), measured and modeled peak water levels are 2.2 and 2.3 m, respectively. At Station 8638863 (Bay Bridge Tunnel, Virginia), both measured and modeled peak water levels are 1.9

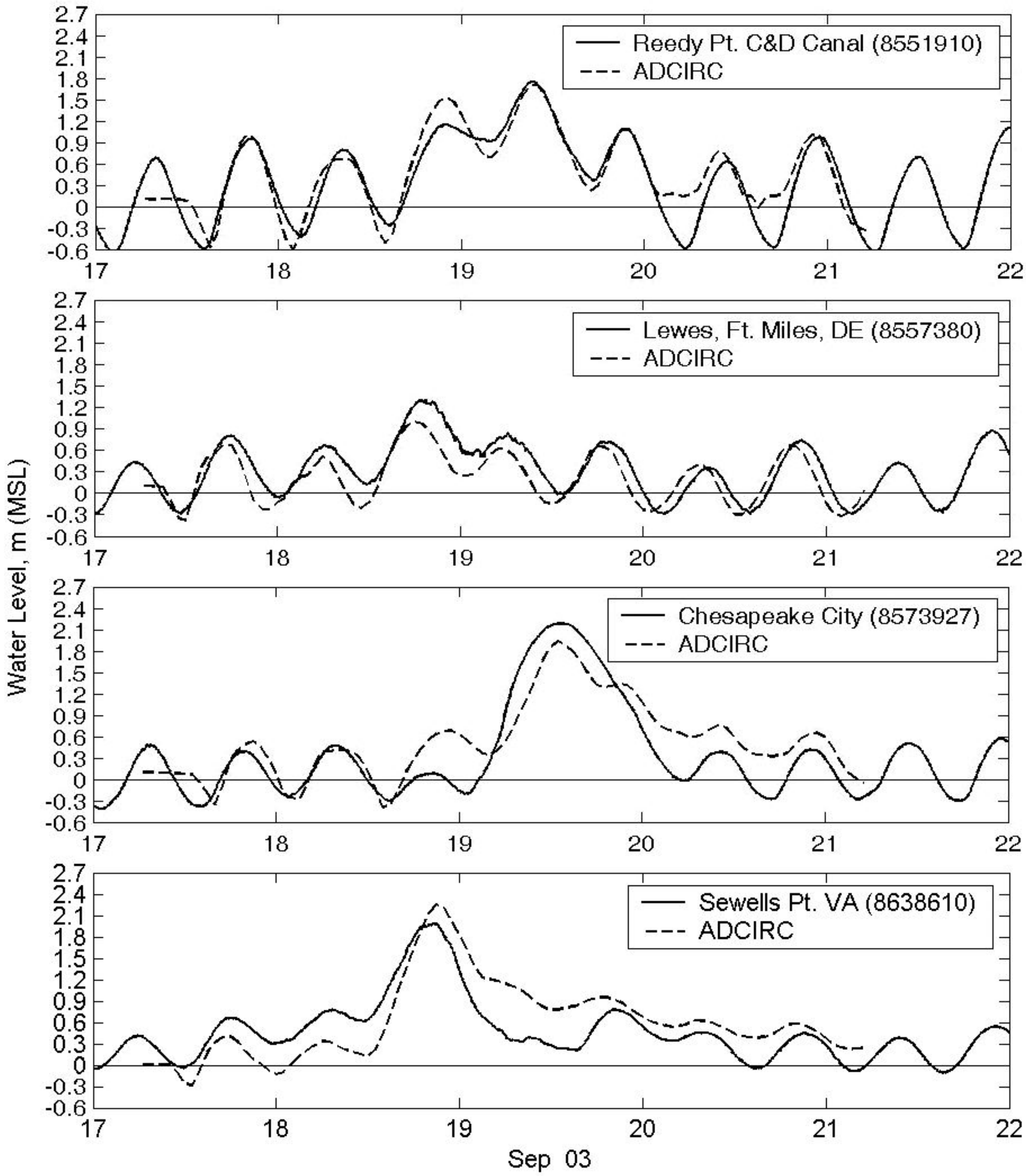

Figure 5. Measured and modeled water levels for Hurricane Isabel at four additional stations.

m. Table 2 compares measured and modeled peak water levels for Hurricane Isabel. The difference of predicted and measured peak water level, ranges between –0.31 and 0.36 m. The root-mean-square error of predicted peak water level versus measured data was 0.20 m. The bias of the predicted peak water level is 0.02 m. The largest errors were at stations 8557380 (Lewes, Ft. Miles, Delaware) and 8638610 (Sewells Point, Virginia). Differences can be attributed to applied model bathymetry, grid resolution, or accuracy of the input wind field (particularly at great distances from the track). Using correct water depth at and around NOAA stations in the model grid is critical for water level prediction as compared to the data. Model results tend to overestimate water levels for Isabel after the surge peak, particularly in the upper Bay. This overestimation occurred when the storm started to weaken and moved further inland in the NNE direction west of the Bay. It is suspected that the PBL model overpredicts wind fields for the weakened storm and error can be induced by the uncertainly of storm parameters used in generation of the wind field. Other factors not modeled in this study (river discharge, non-tidal oceanic setup, variable quadratic friction coefficients for more damping in the shallow northern Bay area) may improve estimations of water levels.

Model water levels are generally more reliable for hurricanes with tracks similar to Fran (1996) and Isabel (2003) than for those with storm tracks similar to Bonnie (1998) and Earl (1998) as compared to the measured data. Hurricanes Isabel and Fran tracked along the main axis of the Bay, whereas Bonnie and Earl skirted away such that the Bay was on the weaker side of the hurricane path. Hurricanes with tracks similar to Fran and Isabel can generate higher storm surge, as the onshore wind tends to trap more water along the coastline and in the Bay.

SUMMARY

Numerical modeling of Hurricane Isabel was performed by the US Army Corps of Engineers Coastal & Hydraulics Laboratory for the U.S. Army District, Baltimore as part of a life cycle analysis for restoration of three island sites in Chesapeake Bay. The modeling served as the calibration for the prediction of extreme water levels based on historical tropical and extratropical storms occurring in the Bay for the last 150 years. Model results show overall reasonable agreement with measured water levels, especially at the peak of surges. The difference of predicted and measured peak water levels ranged between -0.31 and 0.36 m. The largest errors were at Lewes, Deleware and Sewells Point, Virginia. Differences can be attributed to inaccurate bathymetry, grid resolution, or accuracy of the input wind field (particularly at great distances from the track).

A key to the successful modeling was representation of the topography of river tributaries —which flooded during the storm and store large

Table 2. Comparison of measured and predicted peak water levels during Hurricane Isabel.

Station name	Measured (m)	Predicted (m)	P-M, (m)
Reedy Pt, C&D Canal, DE	1.75	1.69	-0.06
Lewes, Ft. Miles, DE	1.31	1.00	-0.31
Cambridge, Choptank River, MD	1.58	1.68	0.10
Chesapeake City, MD	2.18	1.94	-0.26
Baltimore, MD	2.24	2.28	0.04
US Naval Academy, MD	1.98	2.30	0.32
Solomons Is, MD	1.85	1.80	-0.05
Kiptopeke Beach, VA	1.55	1.70	0.15
Lewisetta, Potomac River, VA	1.44	1.53	0.09
Windmill Pt, VA	1.48	1.30	-0.18
Sewells Pt, VA	1.99	2.35	0.36
Chesapeake Bay Bridge Tunnel, VA	1.87	1.91	0.04

Root-mean-square error of predicted peak water level = 0.20 (m) Bias = mean of (predicted – measured) = 0.02 (m) quantities of water at peak surge. Model water levels were generally more reliable for hurricanes with tracks similar to Fran and Isabel than those with tracks similar to Bonnie and Earl (as compared to the measured data). Hurricanes Isabel and Fran tracked along the main axis of the Bay, whereas Bonnie and Earl skirted away such that the Bay was on the weaker side of the hurricane path.

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